

AIR EARTH CONDUCTION CURRENT MEASUREMENT

BY THE DIRECT METHOD

by

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## ABSTRACT

A device was designed, constructed and tested to measure the air earth conduction current. A one square meter wooden tray filled with earth was used as a current collector. The signal received was amplified and sent to a measuring station where it was recorded. A simultaneous potential gradient signal was measured. The potential gradient readings were used to compensate for the displacement current. The device was tested under conditions typical to the non-mountainous areas around Tucson, Arizona. The results of the experimental testing were in general agreement with the values of air earth current measured at other locations in the world.

## CHAPTER 1

### INTRODUCTION

#### 1.1 The Problem

In the middle of the eighteenth century, C. A. De Coulomb observed that an electrically charged object slowly loses its charge in ordinary air. This loss of charge is due to a small but finite conductivity of the air, which is in turn due to the presence of ions<sup>1</sup> in the atmosphere. Since there is an average potential between the earth and the ionosphere of approximately 360,000 volts, one would expect a current to flow from the ionosphere to the earth, which is in fact the case.

The purpose of this paper is to discuss the design, construction, and testing of a system that gives a continuous record of the air earth conduction current. The direct method of measurement is used. A means is included to account for the effect of the displacement current in the results. The important effects of the displacement current can readily be seen from a look at Maxwell's equation

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (1)$$

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1. The distinction should be noted between the Atmospheric Electrician's meaning for ion and the more common meaning. The smallest common ions in the atmosphere consist of from perhaps six to twelve molecules with a single charge supplying the adhesive force.

where  $H$  represents the magnetic field intensity,  $J$  represents the current density and  $D$  represents the electric flux density. By taking a surface integral on both sides of equation (1), it may be rewritten in the form

$$\int_S \nabla \times \vec{H} \cdot d\vec{S} = \int_S \vec{J} \cdot d\vec{S} + \int_S \frac{\partial \vec{D}}{\partial t} \cdot d\vec{S} \quad (2)$$

Applying Stoke's theorem to the left side of equation (2) puts it in a more familiar form,

$$\oint_C \vec{H} \cdot d\vec{L} = \int_S \vec{J} \cdot d\vec{S} + \int_S \frac{\partial \vec{D}}{\partial t} \cdot d\vec{S} \quad (3)$$

which stated in words indicates the total current in a closed contour is equal to the sum of the conduction current and the displacement current on the surface of the closed contour.

## 1.2 Justification

Atmospheric electric parameters are very difficult to measure. No one totally understands the interdependent effects of the many variables involved, and no one has been fully able to duplicate atmospheric conditions in a laboratory. One might reason that weather, time of day, season, latitude, magnetic storms, solar activity, etc., all have some effect on the various atmospheric electric phenomenon. Understanding the air earth current will serve as the key to a better understanding of other atmospheric electric parameters. To quote Chalmers, "It has become increasingly evident as the study of atmospheric electricity has progressed that the air earth conduction current is of more fundamental importance than the potential gradient,

although less easily measured."<sup>2</sup> He goes on to say that in the absence of horizontal currents, convection currents, and accumulation of charges, the air earth current is the same at all levels in the atmosphere. The device designed, constructed, and tested in this paper will be used in the future in connection with a larger study of thunderstorm activity.

### 1.3 Definition of Terms

One cannot begin to adequately describe the phenomenon of the air earth current until some terms have been defined. In general, air earth current can be defined to be any transfer of charge between the ionosphere and the earth. This is a broad definition. The types of air earth current can be further classified according to the process by which charge is transferred. Conduction current is the slow steady drift of ions caused by an electric field in a media of finite conductivity. One ion may not traverse the whole circuit, but passes a given cross section at a detectable rate. Displacement current is caused by the time rate of change of potential gradient. Currents developed by moving media which depend on the laws of motion, as opposed to Ohm's law, are called convection currents. It is the movement of charge that constitutes the current. Percipitation current is a form of convection current where the charge is attached to the particle of percipitation. Point discharge current due to an excessive potential gradient is of occasional interest in atmospheric current measurements. In general, these are the terms commonly used to describe the transfer of charge. Other terms will be defined as needed.

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2. J. Alan Chalmers, Atmospheric Electricity, p. 142.

## CHAPTER 2

### THEORY

#### 2.1 Approaches to the Problem

There are basically two ways in which the air earth current can be measured; the direct method and the indirect method. The direct method is one in which an ammeter is effectively inserted in an imaginary conductive column between the ionosphere and the earth ground. In the indirect method, the potential gradient and the conductivity are measured. From this, the conduction current is computed using the relation  $J = \sigma E$ . The direct method gives a measure of the total current, whereas the indirect method measures only the conduction current. This paper is solely concerned with the direct method.

There have been many attempts, of varying degrees of success, to record the air earth current using the direct method. These attempts essentially involved isolating a section of earth without disturbing the electric field, and measuring the charge that this section of the earth receives in a unit of time. The first attempt to measure the air earth current directly was made by Ebert in 1902. The results were not too successful. His measuring plate was neither parallel to the earth, nor at the earth's potential. In 1906, Wilson made a successful measurement of the air earth current. He used a covered and insulated conductor at zero potential. When the cover was removed, the conductor was exposed to the earth's electric field, raising the potential of

the conductor above zero. The potential was at once brought back to zero by means of a compensator. The subsequent displacement of the compensator gave a measure of the charge the plate received. This method was valid except for the displacement current, but not suitable for a continuous recording of the air earth current.

Perhaps the most active investigator in recent years has been Hans W. Kasemir. In a paper written in 1955, he indicated that the air earth current density could be measured directly without the effects of the displacement current by using the proper parameters in the measuring circuit. It turns out, however, that his presentation supposes that the conductivity and permittivity do not change with time (see appendix A). The fact that the conductivity does change quite radically with time, requires the RC product in the measuring circuit to change accordingly.

Chalmers and Little (1938-39) measured the air earth current using a wooden tray approximately one meter square, filled with soil. This type collector more nearly represents the earth's surface and seems to be an improvement over the metal plate used previously. Their measurements were conducted from the roof of their laboratory. The measurements were made by allowing the charge to collect on a capacitor for approximately ten minutes, and recording the discharge through a galvanometer. The current measured is the average over a ten minute period, and does not compensate for the displacement current which accompanies potential gradient changes.

Kondo reports during the I.G.Y., (July 1957-58) that a brass plate was used to record the air earth current directly. Some

significant difficulties encountered were: the effect of field changes was greater than was anticipated; the leakage from the receiving plate was severe; abnormal changes in air earth current at night seemed to be caused by dew deposits on the receiving plate; the receiving plate was repeatedly contaminated with radioactive substances.

## 2.2 The Selected Approach

This project is one of many that is currently being carried on at the University of Arizona in the study of the thunderstorm and its related phenomenon. It was decided that an earth filled tray would be used as a current collector since this more nearly approximates conditions as they exist in nature. The current measuring device was a Kiethly model 410 C micro-microammeter. Potential gradient measurements were made simultaneously so the displacement current could be computed. A switching device was employed so the air earth current and the potential gradient could be recorded alternately for one minute intervals on a single recording.

## 2.3 Mathematical Analysis

According to the equation  $i_{\text{total}} = i_{\text{conduction}} + i_{\text{displacement}}$ , the total current within a closed contour is equal to the conduction current, plus the displacement current. The conduction current density is represented by  $J = \sigma E$ , and the displacement current density is represented by  $dD/dt = \epsilon dE/dt$ . The displacement current was obtained by multiplying the differentiated field mill reading by a constant. In fair weather, convection current and point discharge being

negligible, the conduction current can be found by subtracting the displacement current from the total current measured.

#### 2.4 Water Drop Analysis

An important consideration in the measurement of the air earth current is its behavior during rain and other disturbed weather conditions. Very little difficulty is occasioned by the presence of precipitation currents, corona currents, and static charge from dust and snow since these are natural processes. They are just as likely to occur at the point of measurement as at any other spot, and the resulting transport of charge to or from the earth will be reflected in the electrometer reading. However, water dropping from the insulated measuring tray is a source of error since its charge is not measured by the electrometer. The magnitude of this error must be considered and minimized. This source of error does not seem to have been recognized by investigators in the past.

The analysis of this problem in its entirety is almost impossible since no adequate theory is available for the charge separation during drop formation and breakup. However, a variation of the theory presented by Chalmers<sup>3</sup> will give an insight to the magnitude of the error.

$C_0$  = capacitance of the collecting tray to ground

$C$  = capacitance of the average drop

$V_0$  = voltage of the tray with respect to ground

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3. Op. cit., p. 83.

$V$  = voltage of the drop with respect to the tray at the instant of drop breakoff

$Q_0$  = total charge on the tray

$Q$  = charge on the drop

$D$  = vertical distance from the tray to ground

$d$  = distance from tray to drop at breakoff

$k$  = geometric constant to account for the increased field near a forming drop

The electrometer measures the total current by means of the potential of the tray with respect to ground. Therefore, the important consideration is the change of the tray potential due to the charged drops.

$$Q_0 = C_0 V_0 \quad (4)$$

$$Q = CV \quad (5)$$

$$V_t = V_0 + \Delta V_0 = \frac{Q_0 + Q}{C_0 + \Delta C} \quad (6)$$

Assume  $\Delta C$  is negligible

$$V_0 + \Delta V_0 \approx \frac{Q_0}{C_0} + \frac{Q}{C_0} \quad (7)$$

$$\text{hence } \Delta V_0 = \frac{Q}{C_0} \quad (8)$$

$$\text{or } Q = C_0 \Delta V_0 \quad (9)$$

$$i_{\text{loss}} \approx \frac{C_0 \Delta V_0}{\Delta t} \quad (10)$$

In equation (10)  $\Delta t$  is the time between drops. This time can be estimated by considering the rate of rainfall and the average drop radius of the drops. If the rate of rainfall is  $A$  meters per second on an area  $S$  square meters, the rate of flow will be  $SA$  cubic meters per second. If the average drop radius is  $r$  meters, the volume per drop will be  $4\pi r^3/3$  cubic meters.  $\Delta t$  will then be equal to  $4\pi r^3/3SA$ .

The current lost through this mechanism will then be given by equation (11), in which Q is approximated.

$$i_{\text{loss}} = kV_0 (d/D)C(3SA/4\pi r^3) \quad (11)$$

The capacitance C will be approximately its free space value.

$$i_{\text{loss}} = kV_0 (d/D) 4\pi\epsilon_r (3SA/4\pi r^3) \quad (12)$$

Finally, making the substitution d equals approximately 2r

$$i_{\text{loss}} = kV_0 (6\epsilon_r SA/Dr) \quad (13)$$

A fair estimate for k is 2,  $V_0$  for the Keithley electrometer is  $5 \times 10^{-3}$  volts,  $\epsilon_r$  is approximately  $10^{-11}$ , heavy rain falls at a rate of  $10^{-5}$  meters per second, S is one square meter, D is about 0.2 meters and r is in the neighborhood of  $10^{-3}$  meters. Evaluating equation (13) with these values it is found the  $i_{\text{loss}} = 3 \times 10^{-14}$  amperes. This current is very small when compared with the fair weather air earth conduction current density. During disturbed weather, the air earth current is generally much stronger than the fair weather current and hence the  $i_{\text{loss}}$  computed appears to be a negligible part of the whole.

The above analysis is very crude, but even the next improvement would involve the investigation of static charging processes for which no adequate theories exist. In addition, there is good reason to believe that water that has trickled through normal soil will have sufficient conductivity to negate most of these static charging processes. In this latter case, the above analysis is applicable.

In conclusion it should be noted that, had the collecting tray been allowed to come to a voltage of 50 volts, the current loss would have been as large or larger than the quantity being measured.

## CHAPTER 3

### THE EXPERIMENT

#### 3.1 The Preparation

The experiment was performed at the University of Arizona's lightning observatory, east of Tucson's city limits. This location was selected because of its remoteness from man made contamination.

The observatory served as the focal point of the experiment. The recorder, field mill amplifier, and switching network were kept in the observatory. The current collector and micro-microammeter were located approximately one hundred feet north of the building, and the field mill was set approximately fifty feet east of the building (see Fig. 1).

The current collector used in this experiment was a wooden tray, one meter square and ten centimeters deep (see Fig. 2). The tray was made of three quarter inch marine plywood which had been painted with several coats of varnish to make it suitable for exposure to the outdoors. A copper screen was placed in the bottom of the tray, and dirt piled on top of the screen until it was flush with the top of the tray. Several small holes were drilled in the bottom of the tray to allow water to pass through in the event of rain. It is anticipated that the device will be used during thunderstorms and light rain to provide data during inclement weather as well as fair weather.



Figure 1

EXPERIMENTAL SITE

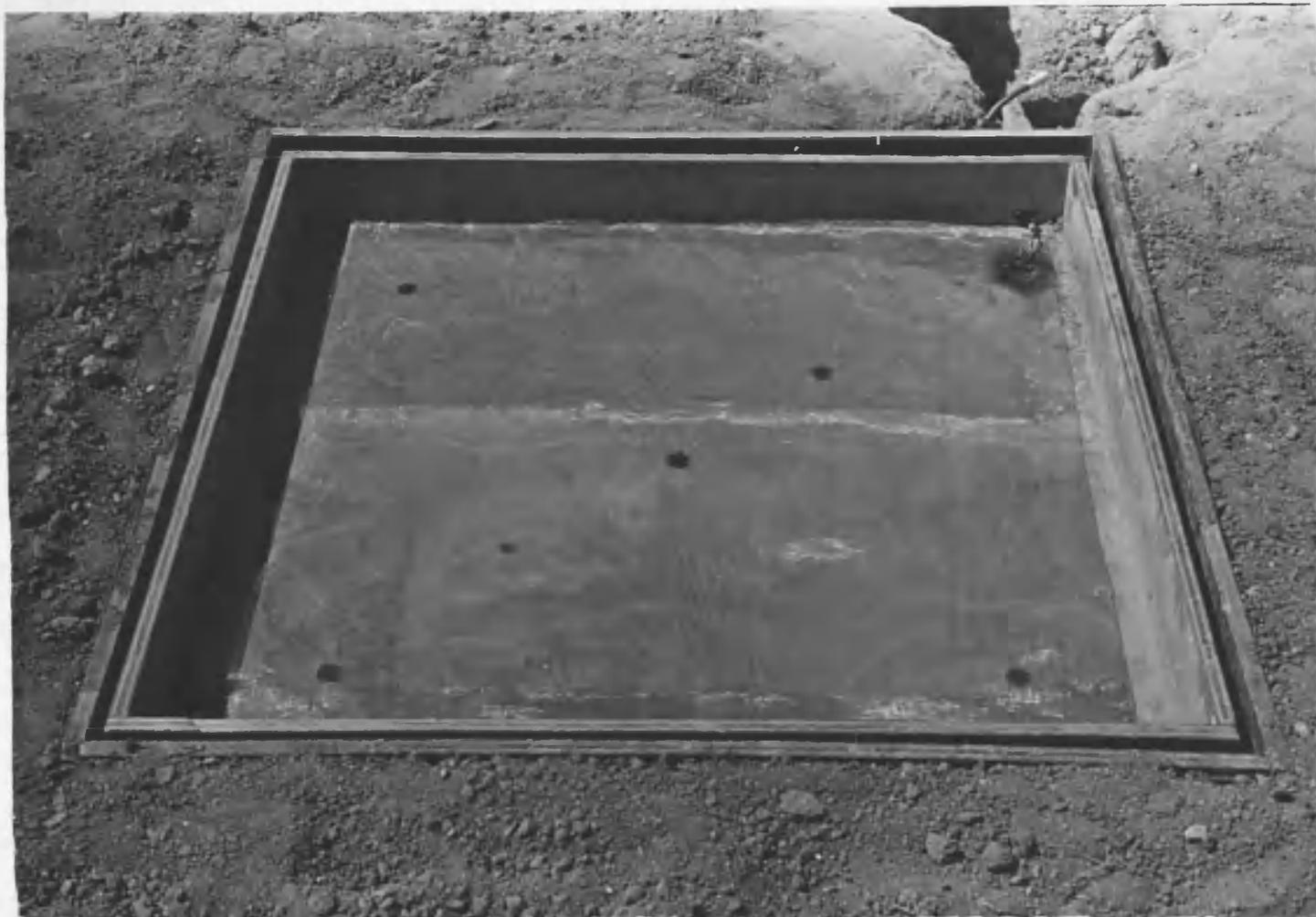


Figure 2

CURRENT COLLECTOR TRAY

The current collector was placed inside another tray similar in construction, but larger. This tray was put into a hole in the ground. The larger tray supported the current collector, and provided the proper insulation. The supporting tray was five centimeters larger in length and width, and approximately thirty centimeters deeper. The larger tray also had drain holes in its base. A wooden support utilizing cylindrical sections of teflon was used to provide electrical insulation (see Fig. 3). The effective resistance was considered in determining the depth of the supporting tray because the effective input resistance of the Kiethly 410 C micro-microammeter for the range of measurements anticipated was very high; approximately  $1.5 \times 10^9$  ohms. This was also the reason for not putting the ammeter in the observatory with the other instruments. Most of the signal current would have leaked to the ground through the one hundred foot coax cable before getting to the amplifier.

The supporting tray was covered on its exterior with a screen. The screen was grounded with copper wire to four, 4 foot ground rods beneath the tray (see Fig. 4). The shield on the cable that was between the collector tray and the micro-microammeter, grounds the outside of the instrument with the screen on the supporting tray. The center lead in the cable was connected to the screen in the collector tray and to the input of the micro-microammeter. The micro-microammeter was placed inside a waterproof box which was buried approximately two feet from the supporting tray (see Fig. 5). The 410 C furnishes five volts full scale signal to drive a recorder. In this experiment, a Brown recorder was used. The micro-microammeter and recorder were



Figure 3

CURRENT COLLECTOR TRAY SUPPORT



Figure 4  
GROUNDING SYSTEM

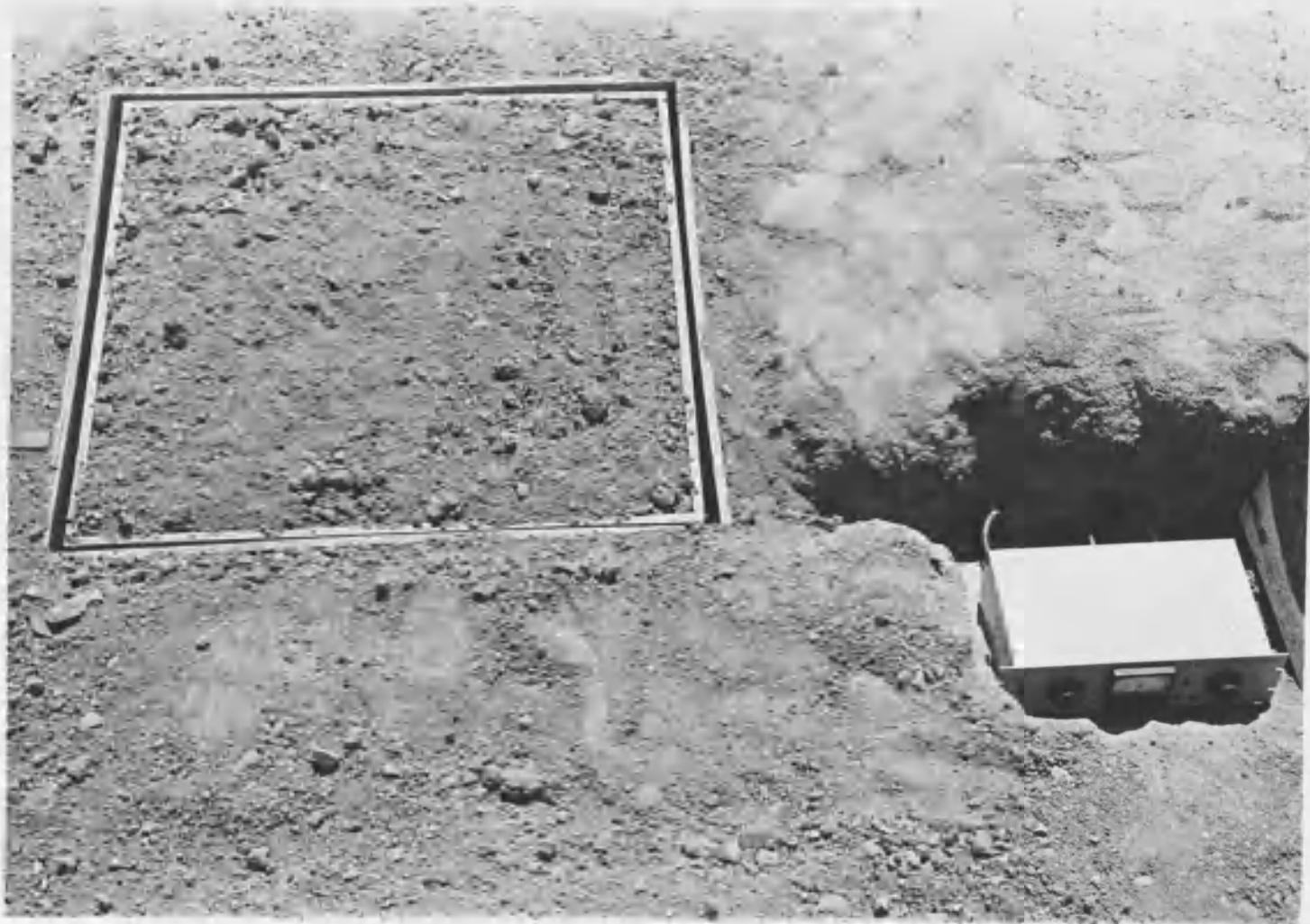


Figure 5

CURRENT COLLECTOR

connected by one hundred feet of RG-8 coaxial cable which led into the observatory. The coaxial cable, as well as the power cord to the microammeter, were buried separately. In dealing with such small values of current, it takes little interference to constitute a significant error.

Next a portable field mill was used to record the potential change in the ionosphere with respect to the earth (see Fig. 6). A field mill is a device which gives a continuous measurement of the potential gradient. It operates on the principle that the surface density of bound charge on the earth is proportional to the potential gradient. A collecting plate connected to ground through a measuring device alternately covered and uncovered by a grounded shield. The potential gradient acting on the exposed collecting plate induces a bound charge on the plate. The alternate movement of charge from the ground to the plate as the collecting plate is exposed and shielded, constitutes a small measurable current which is proportional to the potential gradient.

The field mill was placed some distance from the current collector and the observatory. The signal from the field mill was amplified and fed via buried coaxial cable to the observatory. The field mill signal was then fed into the recorder (see Fig. 7). This completes the description of the air earth current collector apparatus.



Figure 6

FIELD MILL



Figure 7

FIELD MILL AMPLIFIER AND BROWN RECORDER

### 3.2 Conduct of the Experiment

The cables were connected so the current collector signals could be recorded from the output of the ammeter. The recording showed many fluctuations and changes in current (see Fig. 8) which could also be seen from watching the micro-microammeter indicator. In order to minimize the fluctuations and obtain a smoother looking trace of the current variation, a passive intergating circuit was placed between the output of the micro-microammeter and the recorder. This gave a more readable signal (see Fig. 9). Next the field mill was put into position and connected to the recorder. The field mill, with its amplifier, was tested extensively in the summer of 1964 under the direction of Dr. Evans, and hence there was not much difficulty getting a good reading. The field mill amplifier was designed to give response directly proportional to the potential gradient. The constant of proportionality was determined the previous summer. The next step was to construct a timing device which would alternately record the air earth current signal for one minute, and the potential gradient signal for the next. At first two micro-switches were used, but the problem in trying to synchronize the switches led to large spikes in the recording (see Fig. 10). Two micro-switches were tried since each device has a floating ground. The next approach was to use alternating current relays. This was not the final solution because the relay used seemed to be tempermental in making the field mill connections. All manner of coaxing, cleaning, and bending did not insure the consistent making of the field mill contacts. The results were too many off scale readings.

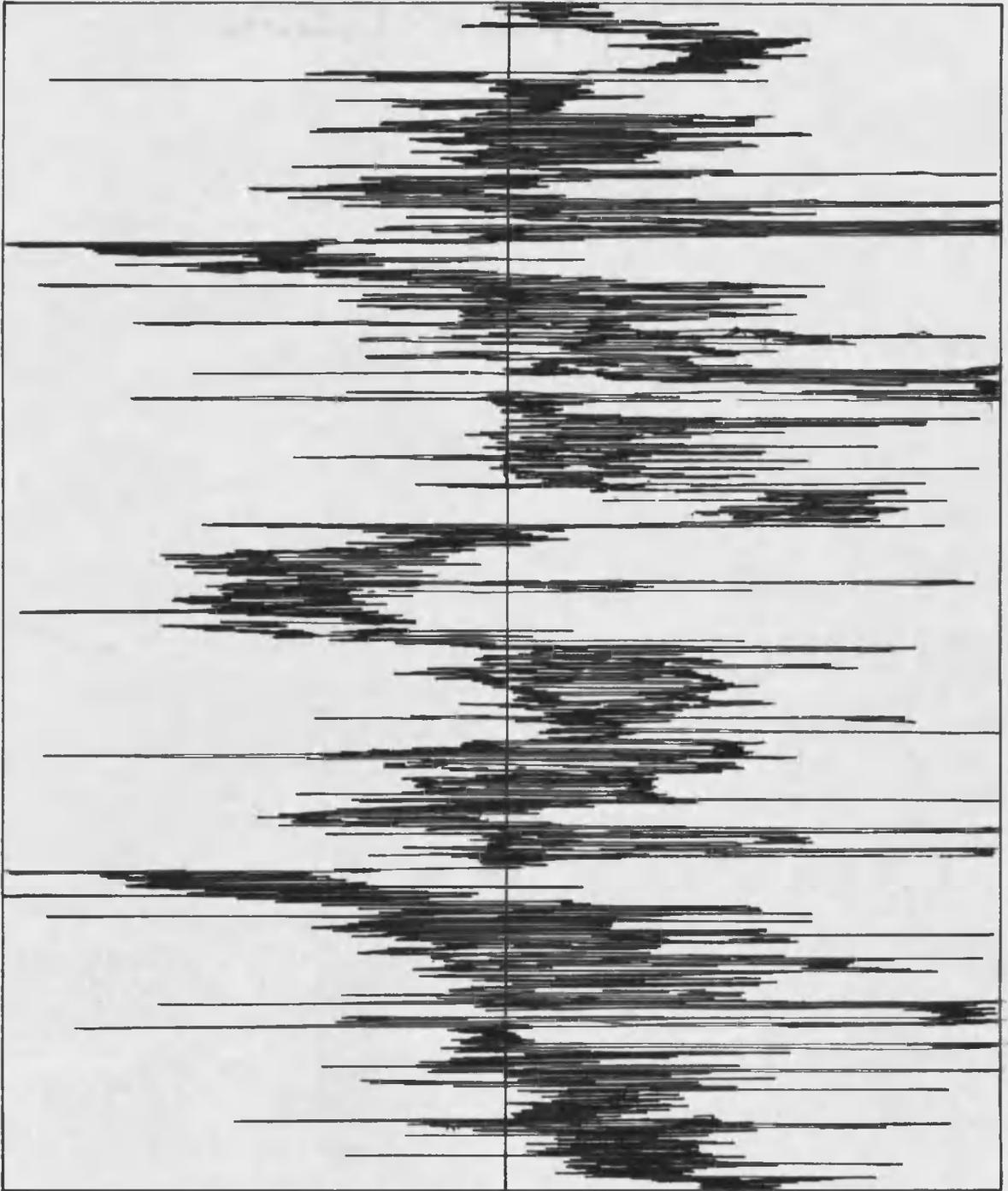


Figure 8

Air Earth Current Record

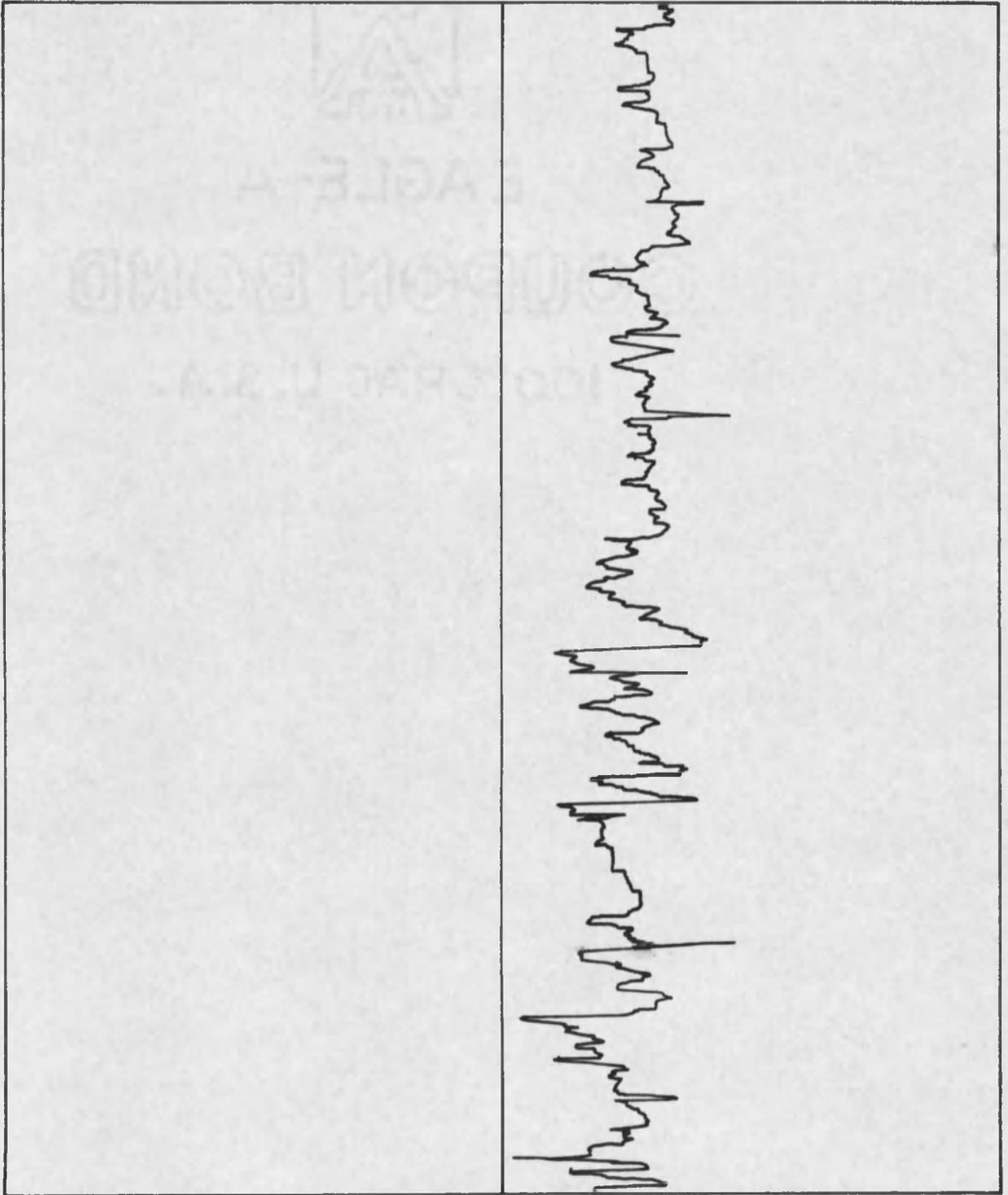


Figure 9

Integrated Air Earth Current Record

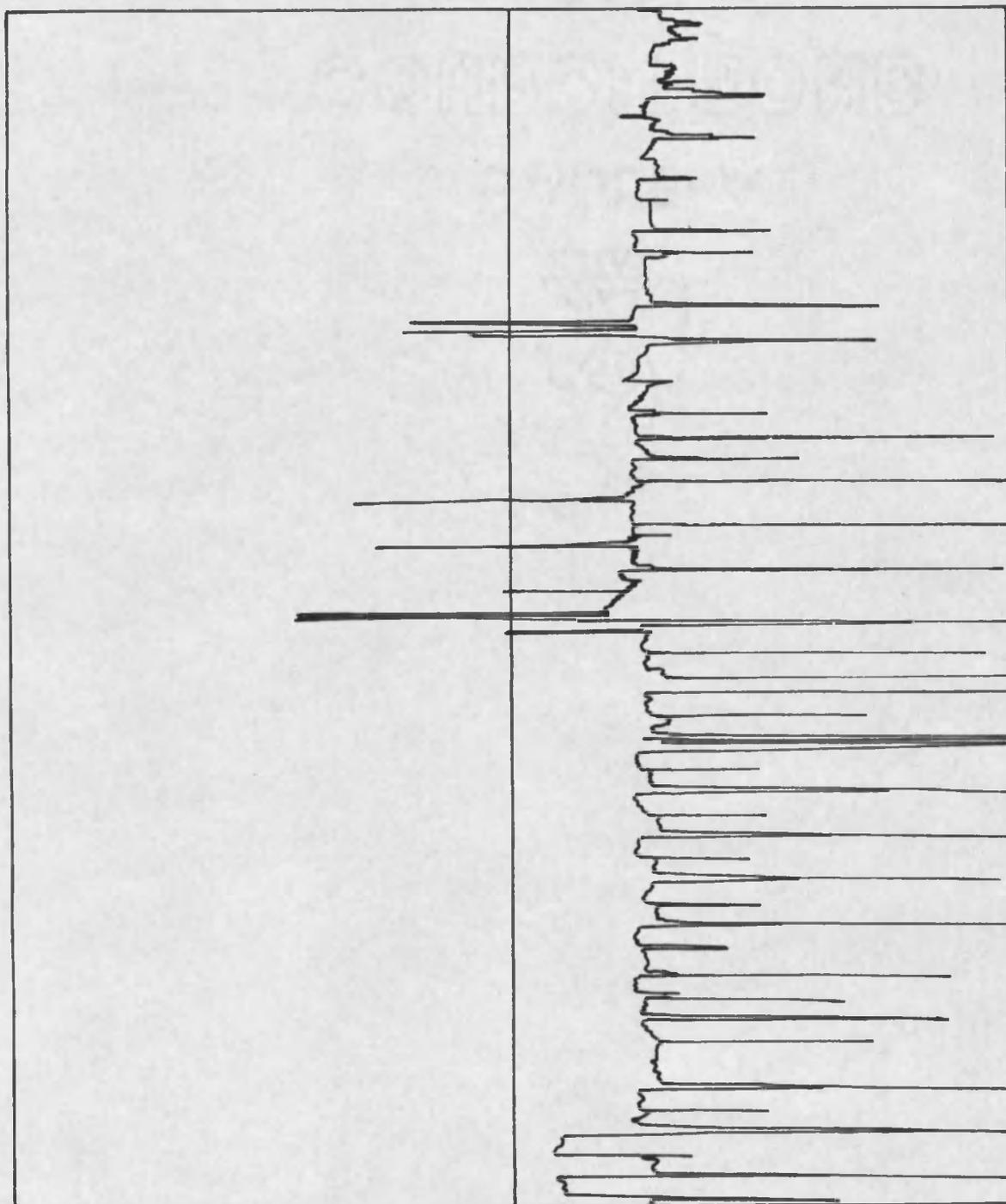


Figure 10

Air Earth Current and Potential Gradient Record

The final solution of the problem was the use of a double pole, double throw micro-switch, and a one revolution per minute motor with cam.

The results are shown in Figure 11.

### 3.3 Specifications of the Equipment

The Kiethly Model 410 C Micro-microammeter is a line operated vacuum tube electrometer. It is designed to measure currents from  $10^{-4}$  to  $10^{-13}$  amperes. The meter has twenty switch positions. Readings are given every decade with intermediate expanded scale reading from zero to three full scale. The input voltage drop for a full scale reading is less than five millivolts on any measuring scale. The zero drift is less than four percent of the full scale reading in eight hours. The instrument can be used as an amplifier to feed a recording device, supplying plus to minus five volts at five milliamperes maximum on a full scale reading. Noise in the output is due primarily to power frequency, and is a maximum of six tenths of one percent at full scale. Grid current is less than  $5 \times 10^{-14}$  amperes. The speed or response depends on the current range and the capacitance which appear across the input. For the scales used in this experiment, the response time to reach sixty-seven percent of the final value of a step input is approximately one second.

The Elektronik Recorder is an automatic balancing potentiometer. The amplifier detects any unbalance between the incoming signal and the voltage on a reference potentiometer. The error voltage is amplified and powers a motor which adjusts the potentiometer to eliminate the error, and at the same time, moves the recording pen an amount

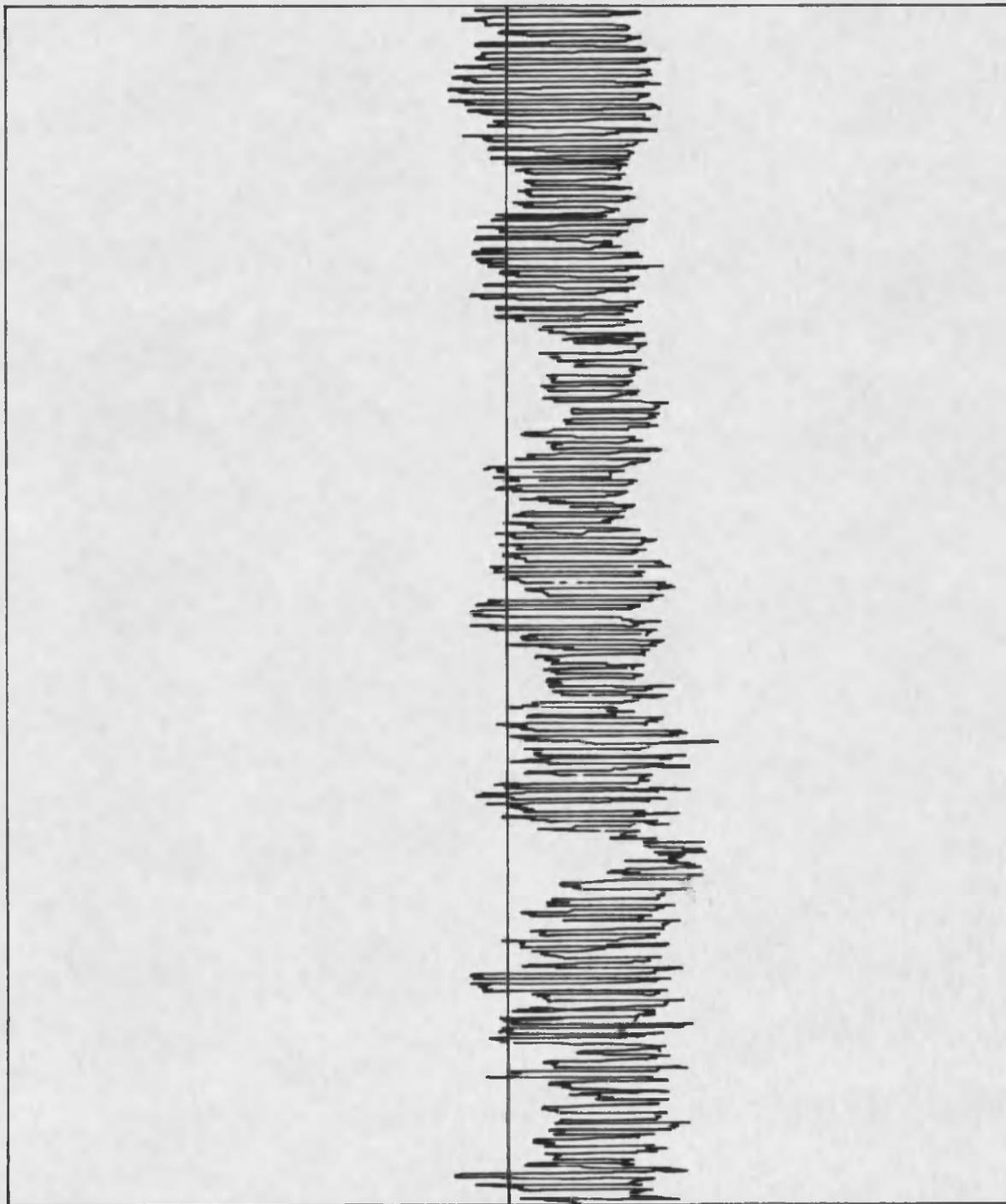


Figure 11

Air Earth Current and Potential Gradient Record

proportional to the voltage to be measured. The recorder can be adjusted to give zero readings at any position on the scale. The recording paper is marked with a zero line down the center which is convenient to show plus and minus readings. The response of the recorder is adequate to follow the input signals; it is approximately two seconds full scale.

The electric field mill and amplifier were designed and tested previously by Dr. Evans. The signal delivered by the field mill and amplifier can easily be calibrated. A device designed for this purpose shields the field mill collecting plate from the earth's potential gradient. A known voltage is then applied to the calibrating shield. This voltage subjects the collecting plate to a known electric field of so many volts per meter. The volts per meter are computed by knowing the voltage on the calibrating shield and the distance of the calibrating shield from the collecting plate. The reading on the recorder is noted with zero volts and 50 volts on the calibrating shield. From the two measurements, one is able to use linear interpolation to get all other measurements.

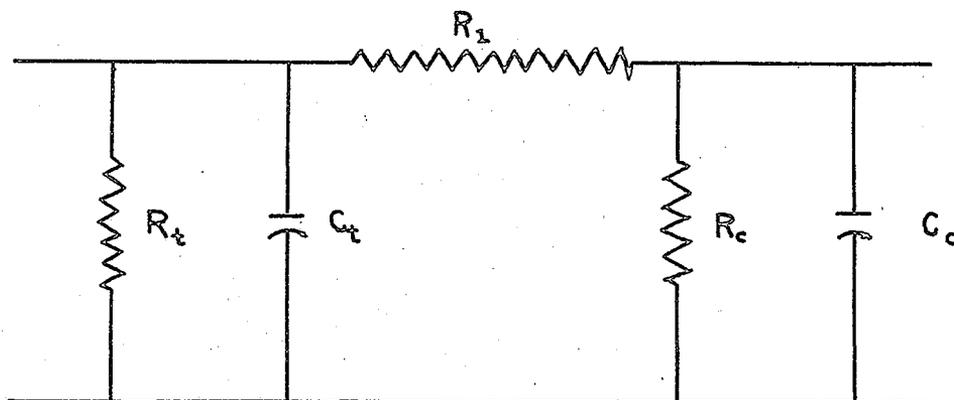
The inverted position of the type field mill used requires the use of a compensating constant since the field mill would not terminate as many lines of flux as it would had it not been inverted. This compensating constant was determined previously by making simultaneous measurements with another field mill which was not inverted.

## CHAPTER 4

### ANALYSIS OF RECORDS

#### 4.1 Possible Sources of Error

Assuming that the micro-microammeter will accurately feed the recorder a linearly amplified reproduction of the input, that the field mill and associated amplifier will feed the recorder a linearly amplified reproduction of its input, and that the recorder will accurately display the signals received; the greatest source for error is in the circuit between the current collector screen and the input of the micro-microammeter. These assumptions are reasonable since the useable accuracy is of the order of five per cent. An equivalent circuit for this problem (see Fig. 12) shows an impedance from the collector tray to ground, and from the coaxial cable to ground with a relatively small series resistance. The effective input impedance to the micro-microammeter is  $1.5 \times 10^9$  ohms on the  $10^{-12}$  ampere scale. There is very little loss in the shunt resistance. However, the effective reactance of the collector tray as a capacitor at a frequency of one cycle per second, is approximately the same order of magnitude as the input resistance. This indicates that there is likely to be a significant loss of displacement current at higher frequencies.



$R_t$  = the DC resistance of the tray to ground

$C_t$  = the capacitance of the tray to ground

$R_1$  = the series resistance from the collecting screen to the input terminals of the micro-microammeter (approximately zero).

$R_c$  = the DC resistance of the coaxial conductor to its ground shield

$C_c$  = the capacitance of the coaxial conductor to its grounded shield, plus input capacitance of the electrometer.

Figure 12

Equivalent Circuit

From the equivalent circuit diagram we may make the following calculations.

$$C_t = 50 \text{ uuf}$$

$$C_c = 100 \text{ uuf}$$

$$\therefore X_c = \frac{1}{2\pi f (C_t + C_c)}$$

There is approximately a 30 percent error when

$$X_c = \frac{R_t R_c}{R_t + R_c} = 1.5 \times 10^9$$

or when

$$\frac{1}{2\pi f (C_t + C_c)} = 1.5 \times 10^9$$

$$\therefore f = \frac{1}{2\pi (C_t + C_c) (1.5 \times 10^9)} = \frac{.159}{150 \times 10^{-12} \times 1.5 \times 10^9} = 0.7 \text{ cps.}$$

Therefore, variations in less than approximately 10 seconds are not accurately recorded. This error can be decreased by using an electrometer with a lower input voltage, which is equivalent to lowering its input resistance. Decreasing the length of the coaxial cable between the tray and the electrometer will also improve the response time of the system.

The coaxial cable connecting the collector tray to the microammeter is a sensitive element in the measuring circuit. Efforts to obtain a zero reading were improved by resoldering the cable and connector plug. An additional source of error here is the piezoelectric noise generated by the coaxial line due to small deflections. This can be improved by shortening the coaxial line and by the use of low-noise cable.

The remaining error at the input was substantially eliminated by using the  $10^{-11}$  ampere scale. The use of this scale also provides for reading a current ten times larger than the average fair weather air earth current. In the event stormy weather causes stronger currents to flow, it will be necessary to use a logarithmic compressor at the input to the micro-microammeter.

Care must be taken to insure that spider webs, and blades of dry grass that blow across the desert do not bridge the gap between the current collector tray and the surrounding ground. They would serve as current leakage paths.

#### 4.2 Interpretation of Data

Measuring the air earth current for a small area is a relatively simple matter if one has the equipment. The accuracy seems to be merely a function of the money one has for the sophisticated equipment plus the knowledge and experience one has in making this type of measurement. As mentioned earlier, the difficulty enters the picture when one tries to evaluate the percentage of the total current measured that results from a particular process. In air earth current measurements, conduction current will always exist. For all practical considerations, displacement current is also always present since the potential gradient does change constantly. Convection currents have generally been neglected. They are assumed to be small, and they are difficult to compute; however, they result in charge transfer and therefore it is normally desirable to include them with the conduction currents. Precipitation current exists whenever there is precipitation, by definition, but its presence makes

it difficult to measure the conductivity. One does not worry about point discharge until the potential gradient gets over 800 volts per meter. However, since the total current to earth is desired in each case, only the displacement current need be separated.

With these facts in mind, one should note that this device was tested in relatively fair weather. Hence the air earth current recorded consists essentially of the conduction current and the displacement current. The experimental results compared favorably with the results reported elsewhere for fair weather measurements. Visual observation of the micro-microammeter indicates a varying current having an average value in the  $10^{-12}$  ampere range. Table I gives some of the recorded values.

#### 4.3 Calibration

Some difficulty was encountered in zeroing the recorded air earth current. A metallic shield was constructed to isolate the collector screen. The shield covered the measuring tray and was electrically grounded (see Fig. 13). An unexplained  $10^{-14}$  ampere current was indicated with the shield in position. This could have been due to static charging or radio activity. It appeared as zero current on the  $10^{-11}$  ampere scale however. Readings were made on that scale, and this proved satisfactory. To calibrate values other than zero, a six volt battery and voltage divider were used. The instructions on the micro-microammeter recommended at least three hundred millivolts to drive the measured current. There was no trouble in calibration of the field mill. It was designed with an integral arrangement to

TABLE I

<u>Date</u>	<u>PG</u>	<u>I</u>	<u>Remarks</u>
Fri. 14 May 65 1100 hrs.	225 V/M	$3 \times 10^{-12}$	
		$4 \times 10^{-12}$	
	360 V/M	$2 \times 10^{-12}$	
Sat. 15 May 65 1000 hrs.	130 V/M	$4 \times 10^{-12}$	
1300 hrs.	120 V/M	$6.6 \times 10^{-12}$	Strong Winds
	180 V/M	$4 \times 10^{-12}$	Strong Winds
	60 V/M	$4 \times 10^{-12}$	Strong Winds
1800 hrs.	120 V/M	$1.3 \times 10^{-11}$	Strong Winds
	180 V/M	$2.6 \times 10^{-11}$	Strong Winds
Sun. 16 May 65 1300 hrs.	1000 V/M	$4 \times 10^{-11}$	Storm
Mon. 17 May 65 1000 hrs.	275 V/M	$6 \times 10^{-12}$	Storm Clouds
		$4 \times 10^{-12}$	
Fri. 21 May 65 1500 hrs.	150 V/M	$2 \times 10^{-12}$	Windy
Mon. 29 May 65 0900 hrs.	350 V/M	$5 \times 10^{-12}$	
1400 hrs.	600 V/M	$6.6 \times 10^{-11}$	Windy
		$4 \times 10^{-11}$	Windy

This table represents values of potential gradient in volts per meter and air earth current in amperes.

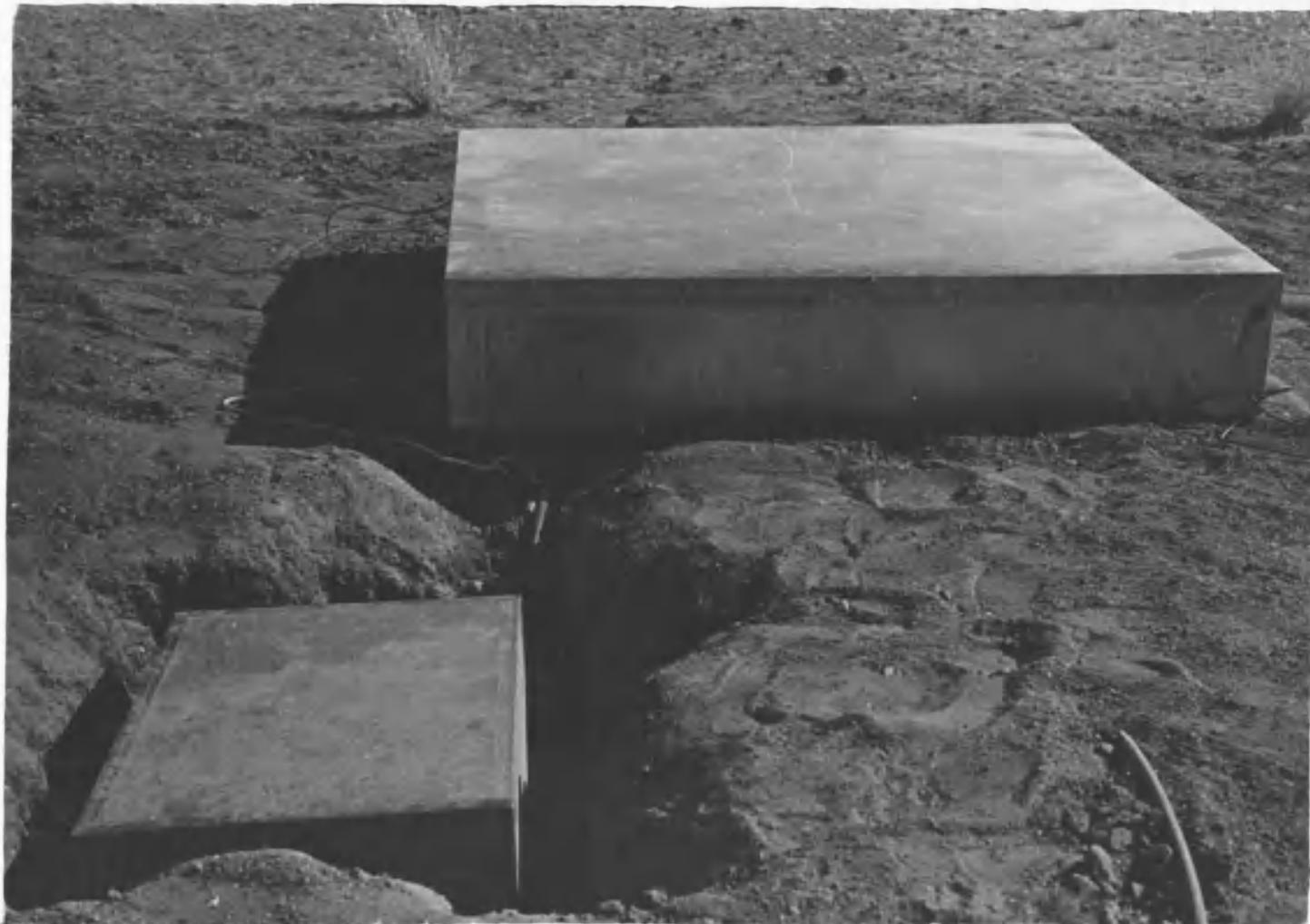


Figure 13

SHIELD USED TO ISOLATE COLLECTOR

feed zero and five hundred volts per meter to itself for calibration. Unknown readings could be determined by a linear interpolation from the calibrated points.

## CHAPTER 5

### CONCLUSION

#### 5.1 Summary

An air earth current collector was designed, constructed and tested. Advantage was taken of the modern equipment available today. The construction was not elaborate or costly since the micro-microammeter, field mill with amplifier, and recorder were items available in the University's Engineering Research Laboratories. The micro-microammeter was placed in the air earth circuit between the earth's surface and the earth's electrical ground. A simultaneous potential gradient measurement with the field mill provided information necessary to compute displacement current. The measured data was continuously recorded. The data corresponded favorably with values computed and found in similar studies. The average value of daily current change during the day can be seen by the figures in table I.

#### 5.2 Suggestions for Further Study

The air earth current collector will be used by the atmospheric electricity group in the study of the phenomenon of thunderstorms. In this instance, the measurements will be a small part of a larger study. However, there are many interesting questions the study of the air earth current alone can generate. One could study the daily, yearly, and geographical variations correlated with other meteorological parameters.

A study of convection currents might prove interesting. This suggestion is based on the observation of change in air earth current which seems to accompany strong surface winds.

A further sophistication of the device designed would be the electrical manipulation of the field mill signal so the recorder displays the displacement current. With a multichannel recorder, it would then be possible to record simultaneously the air earth current, potential gradient, the conduction current and displacement current.

### 5.3 Conclusion

The testing of the device showed the design and construction to be satisfactory. The drainage proved adequate in the several moderate spring storms. No extensive attempt was made to analyze the data recorded other than to establish the fact that the quantities measured were what they were suppose to be. The author hopes that this small step will aid in the current research of atmospheric electricity.

## APPENDIX A

To follow Kasemir's derivation,<sup>4</sup> one starts with Maxwell's equation

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (1)$$

Now taking the divergence of both sides of equation (1), one gets

$$\nabla \cdot (\nabla \times \vec{H}) = \nabla \cdot (\vec{J} + \frac{\partial \vec{D}}{\partial t}) = 0 \quad (2)$$

since the divergence of a curl is equal to zero. From this, one can see that the current flowing out of a volume is equal to the current flowing into the same volume. Now consider the volume formed by an imaginary column extending from the earth to the ionosphere with a base of area  $A$ . The air earth current flowing through this volume can be represented by the expression  $A(\vec{J} + \frac{\partial \vec{D}}{\partial t})$ . If a collecting plate at the earth's surface completes the circuit to ground through a resistance  $R$  in parallel with a capacitance  $C$ , then one can say

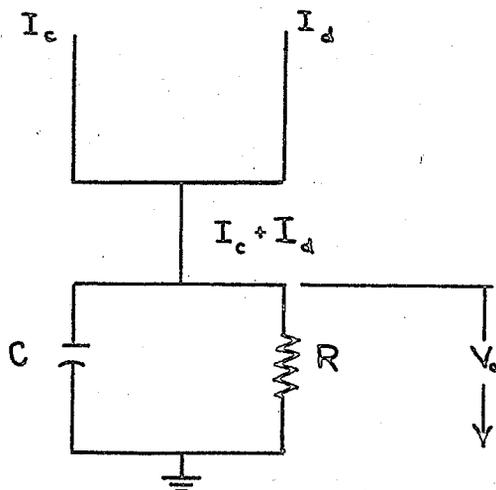
$$A(\vec{J} + \frac{\partial \vec{D}}{\partial t}) = I_c + I_d \quad (3)$$

where  $I_c$  represents the conduction current which flows through the resistance  $R$  and  $I_d$  represents the displacement current flowing through the capacitor  $C$ . The displacement current term in the air earth current can be rewritten

$$I_d = A \frac{\partial D}{\partial t} = A \frac{\partial \epsilon E}{\partial t} = A \frac{\partial}{\partial t} \left( \frac{\epsilon J}{\sigma} \right) = \frac{A \epsilon \partial J}{\partial t} = \frac{\epsilon}{\sigma} \frac{\partial I_c}{\partial t} \quad (4)$$

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4. Hans W. Kasemir, Wentworth Conference, pp. 91-95.



$$I_c + I_d = \frac{V}{R} + C \frac{dV_o}{dt} = I_r + RC \frac{dI_r}{dt} \quad (5)$$

$$I_c + \frac{dI_c}{dt} = I_r + RC \frac{dI_r}{dt} \quad (6)$$

In which  $I_c$  is obviously equal to  $I_r$  if  $RC = \frac{C}{\sigma}$ , therefore,  $V_o = I_c R$ . This solution is quite correct as long as  $\sigma$  is a constant, which is seldom true.

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