Point discharge in atmospheric electricity

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POINT DISCHARGE IN ATMOSPHERIC ELECTRICITY

BY

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ABSTRACT

Investigations of the potential gradient beneath the ion stream liberated in point discharge in the atmosphere are described. The electrostatic effects of the ions are analysed theoretically and the results of simultaneous measurements of the potential gradient on the upwind and downwind side of an artificial point, wind speed, wind direction and temperature gradient reported.

It is concluded that for distances from the base of the point less than $\sqrt{3}$ h times the height of the point and excluding conditions of snow and very heavy rain the electro-static field of the ion stream can be computed on the assumption that the ions take up an infinite line distribution.

These conclusions are then applied to measurements made on a line of trees at Durham University Observatory and around a sycamore tree at the Durham City Golf course. The results for the line of trees indicate a change in point discharge characteristic with season; for the sycamore tree the current down the tree was found to be less than 1 μa for a potential gradient of + 7,000 V/m. The changes of characteristic with season might be correlated with the appearance of the leaves on the trees.

The implications of these results are discussed with reference to the assessment of point discharge current density basedon the equivalence of an artificial point and tree of a similar height.

It is concluded that this equivalence is not in general justified and that a more comprehensive study of a similar nature is required before a reliable estimate of mean point discharge current density can be obtained from measurements with artificial points.

CONTENTS

CHAPTER I

INTRODUCTION

1.1. General

The study of atmospheric electricity can be conveniently confined to that part of the atmosphere lying between two concentric conducting surfaces, the earth and the ionosphere. There is a potential difference of $3 - 4 \times 10^5$ volts between the two surfaces and the small, but finite conductivity of atmosphere gives rise to an integrated leakage current of the order of 1800 amps.

Earliest measurements had established the existence of an almost constant negative bound charge on the earth and a positive charge located somewhere above the earth. The realisation by Linss in 1887 that the finite conductivity of the atmosphere should, but does not, lead to the rapid removal in fine weather of the earth's bound charge raised one of the fundamental problems of atmospheric electricity. The object of the present work was to help assess the magnitude and importance of corona discharge in the replacement of the earth's bound charge.

Wilson (1920) was the first to realise the importance of thunderstorms and highly active shower clouds as the principal mechanism for the maintenance of the leakage current between the earth and the ionosphere. The thundercloud is a region of intense electrical activity and Wilson propounded the theory that there was a continual flow of positive electric charge to the ionosphere and of negative electric charge to the earth, the time constants of the two surfaces being so small that charge would be rapidly transferred from disturbed to undisturbed regions.

A striking verification of the electrical importance of thunderstorms came when Whipple (1929) and Whipple and Scrase (1936) from a suggestion by Appleton (1925) demonstrated the close correlation existing between the world variation of potential gradient and the total thunderstorm activity; conclusive evidence of charge movement above a thundercloud comes from the work of Gish and Wait (1950) and Stergis, Rein and Kangas (1957) who measured the current above thunderstorms and found a mean positive current upwards of 0.5 amps/thundercloud (G. & W.) and 1.3 amps/thundercloud (S.R. & K.). With an estimated world thunderstorm activity of 3,000 - 3,600 these results give a total current of the correct order of magnitude.

Charge transfer beneath a Thundercloud

Charge transfer beneath an active thunder or shower cloud is more complex than charge movement above the cloud and has three possible modes.

a) Charge brought down by precipitation elements.

b) Lightning discharges.

c) Corona or brush discharge from natural objects resulting from the high potential gradients that exist beneath active clouds.

Several authors have attempted to draw up "charge balance sheets" for certain limited regions of the earth's surface.

These determine whether, in a given period of time, the three processes of charge transfer bring down a sufficient excess of negative charge to balance the positive fine weather conduction current over a similar period.

The various assessments have been extracted and listed in Table 1.

All charges in Coulombs/Km^2/year.

Place	Author	Fine weather conduction	Point Discharge	Precipitation	Lightning	Total
Cambridge	Wormell (1930)	+ 60	− 100	+ 20	− 20	− 40
Cambridge	Wormell (1953a)	+ 60	− 170	+ 20	− 5.6	− 96
Durham	Chalmers & Little (1947)	+ 60	− 90	+ 40	− 35	− 25
Durham	Revised	+ 60	− 180	+ 40	− 5	− 85
Kew	Chalmers (1949)	+ 35	− 125	+ 22	− 45	− 113
Kew	Revised	+ 35	− 300	+ 22	− 6	− 249
World	Wait (1950)	+ 100	− 30	+ 20	− 20	+ 70

All estimates but one indicate a total excess of negative charge which the authors consider neutralises the positive excess of non-stormy regions, e.g. polar regions and deserts.

The greatest variations in Table 1 occur in the assessment of the effect of point discharge; it is relevant to the present work to examine in more detail the compilation of the corona discharge contribution.

1.2. Contribution of Point Discharge to Charge Replacement

From electrostatic considerations there must be a considerable increase in electric field strength close to any raised earthed point in the atmosphere. In the high potential gradients that exist beneath active clouds the electrostatic field strength in the region of the point may be of sufficient magnitude to cause ions to be accelerated towards the point to undergo ionising collisions. This ion multiplication produces a separation of charge in the region of the point, charge of one sign being conducted to earth through the point and charge of the other sign moving upwards under the influence of the field.

Wormell (1927 and 1930) at Cambridge, Whipple and Scrase (1936) at Kew, Chiplonker (1940) at Colaba, Chalmers and Little (1947) at Durham all raised artificial metal points in the atmosphere to heights of 8 - 12 metres and measured the total charge brought to earth over considerable periods of time. All results showed an excess of negative charge to positive charge in the ratio of approximately 2:1. From the total excess of charge and an estimate of the number of equivalent points per square kilometer the total charge brought to earth was computed. It is in this extrapolation from a single artificial point to the number of similar points per square kilometre that the difficulties and variations in the assessments occur.

It is convenient at this point to introduce the concepts of mean point discharge current density and effective separation of discharge points. Wilson conceived the idea of a large number of points streaming ions into the base of the thundercloud; at a certain distance above the ground these ions will unite and give rise to a continuous current of varying horizontal density. It is convenient for the purposes of calculation to consider the point discharge current to be of uniform density beneath the cloud and to have been derived from a series of similar points in rectangular array. For a given point discharge current density the lattice spacing, or effective separation, is a measure of the charge transferred by each point.

Wormell's 1929 estimate of equivalent point density was made by counting the number of trees higher than his point in a known area surrounding the point. In this, however, he ignored smaller trees occurring in a dense plantation. His estimate was revised in 1953 to bring the point discharge current density into agreement with some indirect determinations made by Smith (1950) from lightning discharges.

Wait based his estimates on the results published by Wormell etc. but considered that there was no point discharge over the oceans and hence arrives at a considerably lower point discharge current contribution. Chalmers (1952) has advanced arguments which prove that the total point discharge current beneath thunderstorm is independant of the number and height of discharging points and one would therefore expect corona discharge even over the oceans, and this would considerably affect Wait's balance of charge calculation.

Direct determination of the effective density of points by counting trees must be regarded with suspicion as it now seems improbable that an artificial point in the atmosphere has the same discharging efficiency as a tree of similar height and exposure. Chiplonkar (1940) and Chalmers and Mapleson (1955) obtained smaller currents when a multiple array replaced the single point discharger, indicating that there is considerable interference between adjacent discharging points.

Indirect determination of the effective separation of discharging points have been made by Simpson (1949) for Kew, Chalmers (1951) for Durham and Smith (1948) for Cambridge. Simpson attributed the asymptotic maximum attained by rain current in heavy rain to the complete sweeping out the upward moving point discharge ions, and calculated that the effective separation of points required to produce such a current was approximately 22m. Chalmers performed a more detailed examination of rain currents and obtained values for the effective separation 14.5m for Kew and 6.1m for Durham.

Chalmers (1953) has obtained a further value of 11m for Kew by assuming a simple dipole form for the thundercloud and then calculating the point separation required to produce a total point discharge current of 0.5 amps per thundercloud.

These estimates of the effective separation of points may suffer from oversimplification in that one process is assumed to be predominant on each occasion. All disturbed weather phenomena are extremely complex and estimates based on them need corroborating evidence from direct measurements on natural objects before the results can be accepted as more than indications of the order of magnitude expected.

Schonland (1928) in South Africa, circumvented the difficulties of working with artifical points by mounting a small tree, characteristic of the neighbourhood, on insulators and measuring the flow of charge to earth. His results gave a maximum point discharge current density of 0.16 amps/m^2 under the centre of an active cloud, which is considerably higher than the 0.018 amps/m^2 obtained at Cambridge and the 0.02 amps/m^2 at Kew.

Inspection of the published photograph suggests that the tree used by Schonland was more exposed, and consequently a more efficient discharging element than the average tree in the neighbourhood. This might well account for the difference between the English and South African results.

1.3. Point Discharge Current Density and Precipitation Electricity.

Apart from the fundamental problem of the replacement of the earth's bound charge a knowledge of the point discharge current density is of vital importance in the interpretation of the charge carried to earth by precipitation.

Under certain conditions precipitation is thought to build up charge by a process postulated by Wilson in 1921 and examined theoretically by Whipple and Chalmers in 1944. In the Wilson process, as a result of their movement through an electro-static field the precipitating elements are able to sweep the small ions in the atmosphere; the sign and magnitude of the resultant charge depends on the ion density, field strength, fall velocity and drop size.

Simpson (1949), Hutchinson and Chalmers (1952) and Smith (1957) have shown that for potential gradients greater than 12,000V/m a definite correlation exists between the total rain current and the corona current through a single artificial point. The observed potential gradients at the point are, however, too small by an order of magnitude to obtain any agreement with the predictions of Wipple and Chalmers (1944). Consequently to explain the charge on rain by the Wilson process it is necessary to assume a considerable increase of potential gradient with height.. It is thought that the point discharge currents create a space change blanket beneath the precipitating cloud which prevents apparatus at the ground from measuring the electric field at the base of the cloud.

The only measurements that have been made of the variation of potential gradient with height below a thundercloud are the alti-electrograph measurement of Simpson and Scrase (1937) and Simpson and Robinson (1940) and the radio-sonde measurements of Kreielsheimer and Belin (1946) and Chapman (1957). All flights indicated little variation of field with height and the maximum field recorded by Chapman was little over 21,000 V/m. It is very difficult to reconcile these results to the concept of a high point discharge current density. Though the absolute value of the field might be in error, relative changes in field should have detected if they existed in the flight path.

Chapman (1956) has since revised his own results on theorectical grounds and obtained values for the potential gradient in the middle and upper parts of the cloud comparable to those obtained by Gunn (1948) in an aeroplane. At the same time Chapman recalculated the published values of Simpson and Robinson, but it is difficult to see how the corrections can apply to these results because at Kew the Balloon was calibrated at the ground before being allowed to ascend into the cloud.

The matter is further confused by consideration of the potential gradient changes associated with close lightning flashes. In the majority of cloud to ground discharges the potential gradient changes from a small negative to a very large positive value; which can be interpreted as the removal of the negative charge in the base of the cloud leaving a space charge blanket of opposite sign. Considerable point discharge currents could be the only possible means of creating andmaintaining this space charge blanket against the neutralising effect of the base of the cloud.

1.4. Dependence of Point Discharge Current on Wind Speed and Potential Gradient.

Wilson's original paper aroused much interest in the behaviour of a single elevated earthed point in the atmosphere under enhanced field conditions and the dependence of the corona current on the value of potential gradient and wind velocity close to the point.

Whipple and Scrase (1936), Chiplonkar (1940), Hutchinson (1950) and Yriberry (1954) fitted their results to an expression of the form.

$$I = A\left(F^2 - M^2\right)$$

Where I is the point discharge current in micro-amps, F the value of the potential gradient at the earth's surface and M & A are constants. This relationship has been examined theoretically by

Chalmers (1952) and derived for points in rectangular array.

When wind speed is taken into consideration the above relationship is modified but the exact form seems dependent on the method of observation.

Chalmers and Mapleson (1955) used a tethered balloon and obtained -

$I = 0.015W^{\frac{1}{4}} (Fh)^{7/4}$ where W is the wind speed in m/sec, h the height of the balloon in metres and I & F as before.

More recently Kirkman (1956) working on a single elevated point found -

$I = K (W + C) (F - M)$ where K, C and M are constants. Chapman (1956) has suggested, on theoretical grounds, that the relationship between potential gradient wind speed and point - discharge should be of the form -

$I = A (V - Vo)v$, where V is the potential of the point, v is the compounded velocity of removal of ions from the neighbourhood of the point.

Large and Pierce (1957) have verified the Chapman formula for high potentials applied to a point in the free air, and more recently Chalmers (to be published) has re-analysed the results of Mapleson and Kirkman and found that with a suitable choice of constants, a relationship of the Chapman form is an equally good representation of the experimental points.

In common with Large and Pierce, Chalmers expressed the relationship in the form -

$I = A\ (V - Vo)(W^2 + C^2\ V^2)^{\frac{1}{2}}$ where the term $(W^2 + C^2\ V^2)^{\frac{1}{2}}$ is the vector sum of the wind and ionic velocities. The constants A, $\overset{V}{\pounds}o$ and C^2 are most probably a function of the point shape, height and exposure factor.

Laboratory experiments on corona discharge have to be transposed to atmospheric conditions with great care as boundary conditions greatly influence the form and progress of the discharge. Large and Pierce have demonstrated some interesting similarities in the pulsed nature of laboratory point-to-plane discharge and discharge form an elevated single point in the atmosphere. It must be very doubtful whether this similarity still exists when the multiple point discharge from a tree is considered.

1.5. Conclusion

The importance of the thunderstorm in the circulation of charge between the earth and the ionsphere has been conclusively established. The exact processes involved, particularly below clouds, are not completely understood.

The only published direct evidence of the magnitude of point discharge from natural objects is the work of Schonland (1928) in South Africa, and the results he obtained are considerably larger than the best estimates for this country. The significance of this difference will be unknown until more reliable information is available on the exact correspondence between corona discharge from a single point and from a tree. Such measurements would be of particular value $\overset{i}{o}$f made in areas where the point to tree extrapolation had already been attempted.

Considerable evidence exists on the nature of corona current down a single artificial point and its dependence on the value of the potential gradient and wind speed in the region of the point, no similar results exist for corona discharge from a natural object.

The accurate interpretation of the origin of the charge on rain from electrically active clouds depends on a knowledge of the point discharge current density beneath the precipitating cloud. Without more conclusive measurements of the point discharge current density it is not possible to decide whether the Wilson process can account for the total charge on rain.

The long standing problem of the correct interpretation of the potential gradient changes with height beneath thunderclouds and highly active showerclouds, as indicated by the alti-electrograph work of Simpson et al., may also be furthered by a re-assessment of point discharge current density.

These problems were considered to be of sufficient importance to merit research into a possible method for investigating the behaviour and magnitude of point discharge currents down trees without interfering with the tree in any way.

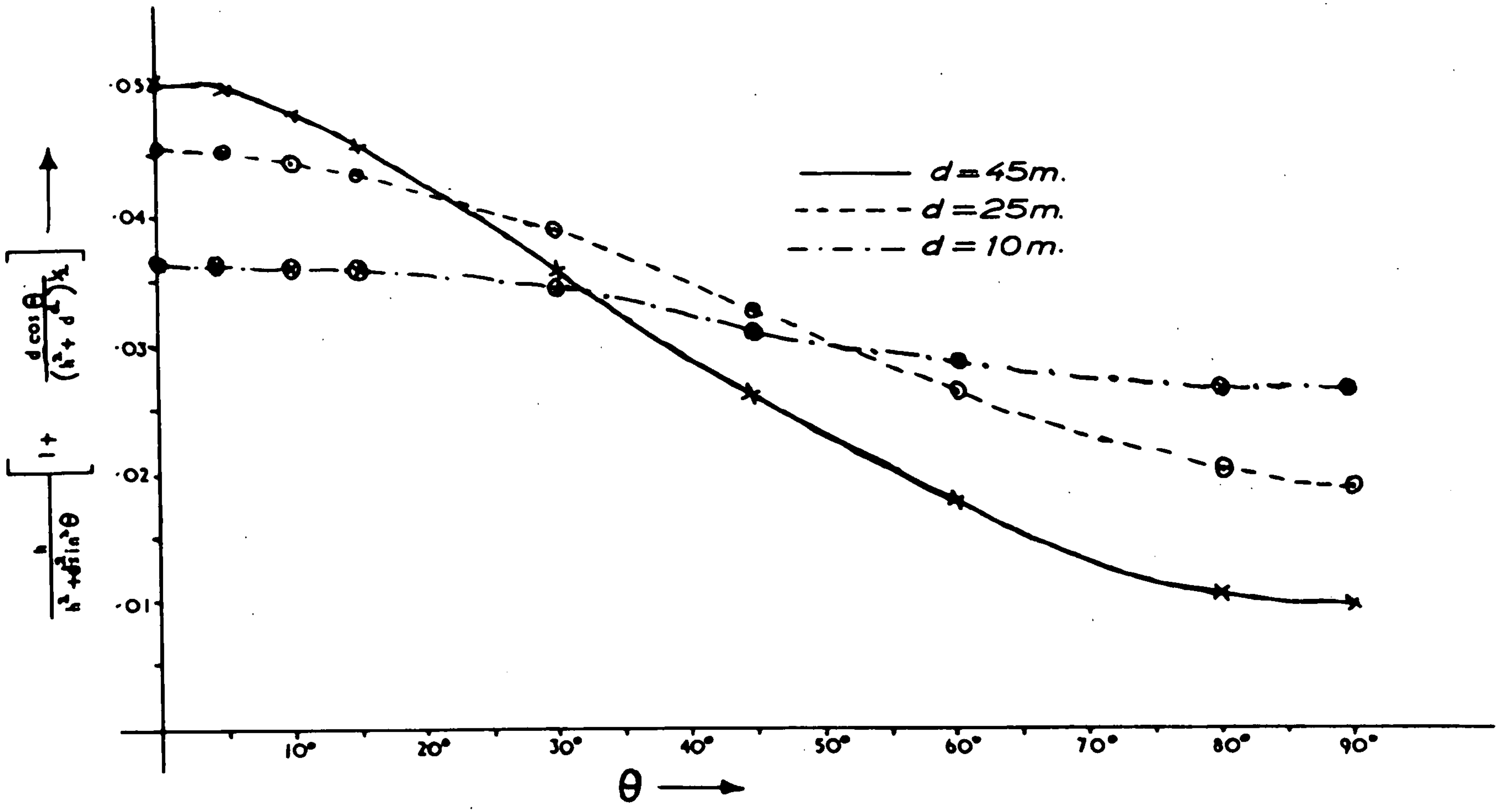


FIG.2. Effect of Wind Direction on Potential Gradient Beneath Ion Cloud.

CHAPTER 2

ANALYSIS OF PROBLEM

2.1. Object of Research

The object of the present investigation was to examine a method for measuring the corona discharge current down natural objects, and having done so to apply the method to single trees and small clumps of trees.

2.2. Nature of Point Discharge

Consider the behaviour of an isolated earthed point in a high, negative potential gradient. In the high electric field region close to the point negative small ions may be accelerated towards the point with sufficient energy to make ionising collisions. Each negative ion initiates an electron avalanche and a burst of negative charge is received by the point. The remaining positive ions accumulate and in time may decrease the field at the point sufficiently to stop the discharge; the discharge remains cut-off until the positive ion cloud is no longer able to influence greatly the field at the point. The resultant discharge, is therefore, a series of regular pulses.

The discharge in positive potential gradients progresses in a manner which can again result in regular pulses. The discharge is initiated by a random positive ion moving towards the point releasing a secondary electron from the point, which then gives, by the avalanche process, a dense cloud of positive ions. This space charge cloud further reduces the field at its outer periphery and the electrons lose energy rapidly and form negative ions by attachment. The positive ions then move into the point and give a burst of positive current. The removal of the positive ions re-establishes the electric field and the process is repeated.

Both types of pulse are characteristic of space charge limited discharges and the frequency of the pulses is a function of the rate of removal of the limiting ion cloud by the wind and electric field. The types of discharge described are ideal as usually irregularities are introduced at high and low and electric fields and by the wandering of the exact point of discharge to different regions of the point.

The two possible methods for an indirect measurement of the corona current to earth are immediately suggested.

(a) The point to ground ~~to~~ connection could be made the primary of a transformer and an effort made to detect the pulses and measure their frequency.

(b) The reduction of the potential gradient by the ions liberated in the discharge could be measured and correlated with the point discharge current.

Preliminary measurements had already been made in Durham of the difference in the potential gradient on opposite sides of a discharging point and indicated the practability of method b. It was therefore decided to measure the potential gradient on the upwind and downwind sides of a single elevated point in the atmosphere and endeavour to correlate the measured current to earth from the point with the differences in potential gradient observed.

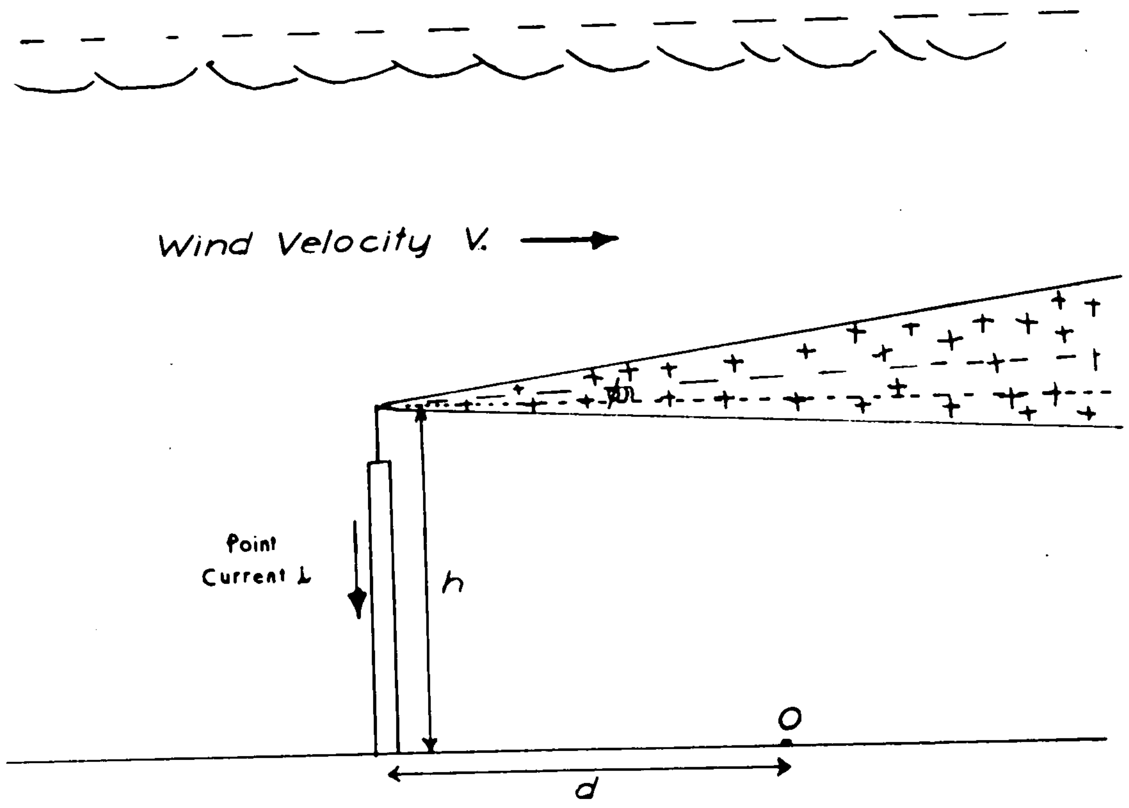


FIG. 1. Movement of Ions from the Point.

If the investigation revealed a definite physical relationship between the reduction of the potential gradient and the corona current it was hoped to make potential gradient measurements on the upwind and downwind sides of a tree and thereby derive the corona current down the tree.

2.3. Relation between Potential Gradient and Ions Liberated in Corona Discharge

The space charge liberated in the corona discharge at a single point moves away from the point under the influence of both the wind and potential gradient. The mobility of small ions in the atmosphere is of the order of 1 cm/sec/v/cm; under the most disturbed atmospheric conditions the potential gradient rarely exceeds 150 v/cm, consequently wind is the controlling factor in all but the enhanced field regions very close to the point.

The ions are blown away from the point and move downwind in a gradually diffusing stream forming a cone of charge (Fig.1) the axis of which is inclined away from the earth at an ~~on~~ angle.

$$\phi = \tan^{-1} \frac{WX}{V}$$ where W is the mobility of the ions, X the potential gradient and V the wind velocity. The angle ϕ is small for all but very high potential gradients and small wind velocities.

Davis and Standing (~~1948~~ 1947) calculated the potential gradient directly beneath an infinite line of charge moving horizontally in a wind of velocity V metres/sec from a point at a height h metres giving current i micro-amps (Fig.1). At O, a distance d metres from the base of the point, they calculated the potential gradient due to the ion stream to be.

$$Ev/m = \frac{i}{2 \pi \varepsilon_o \circ V h} \Big\} 1 + \frac{d}{(d^2 + h^2)^{\frac{1}{2}}} \Big\}$$

Mapleson (1952) and Whitlock and Chalmers (1956) examined their results in the light of this expression and found the reduction of the potential gradient due to the presence of the corona discharge ions to differ by a factor of a ½ to a 1/5. In the light of these results it was decided to re-examine the treatment of Davis and Standring in an effort to drive a more exact relationship.

As a consequence of the analysis and subsequent measurement which confirmed the conclusions of the analysis, the results of Whitlock and Chalmers and Mapleson were re-analysed and it was found that Whitlock and Chalmers and Mapleson had made an error of a factor of 2 in the formula they had used, and the remaining discrepancy lay in the experimental technique.

2.4. Removal of Ions by Recombination

At first sight the recombination of ions with those of an opposite sign would seem to play an important part in reducing the effect of the ion stream on the potential gradient beneath, but further consideration shows that this is not so. If there are n_1 positive ions and n_2 negative ions in unit volume and then N negative ions are introduced by point discharge, no matter how, or at what rate, recombinations occurs there will be an excess of $N + n_2 - n_1$ negative ions, and it is this excess of ions which is responsible for the reduction in potential gradient since the motion of the ions is almost entirely governed by the wind; the change in mobility when small ions become attached to uncharged nuclei is unimportant.

2.5. Effect of Changes in Wind Direction

If the wind does not lie in the direction along which d is measured but is at some angle θ to it then a reduction in the vertical potential gradient due to the ion stream must be anticipated. If the charge stream is diffused into a cone of charge in θ would have less effect than if the line distribution had been maintained.

The following analysis is based on an infinite line of charge and its results will therefore predict the maximum dependence on wind direction. Any experimental procedure developed as a result of the analysis should therefore be more than adequate for the diffuse cone that is normally assumed by the ion cloud.

The downwind potential gradient resulting from a line of charge inclined at an angle θ to the line along which d is measured is given by:-

$$E = \frac{i\,h}{2\pi\epsilon_o V\,(h^2 + d^2 \sin^2\theta} \left\{ 1 + \frac{d\cos\theta}{(h^2 + d^2)^{\frac{1}{2}}} \right\}$$

This expression has been plotted in Fig.2 for h equal to 34 metres and for a series of values of d.

Potential gradient measurements with field mills cannot be made to an accuracy greater than 5% so that, for the maximum value of d plotted in 'Fig 2, if the measurements are restricted to values of θ less than 10° errors will not be introduced greater than those inherent in the apparatus. For values of d less than the maximum considerably greater values of θ could be permitted.

2.6. Wash Out of Ions by Precipitation

For rain to remove more than a negligible proportion of ions in the ion stream the initial charge on the rain must be of opposite sign to that of ions liberated in the discharge. It is only in very heavy rain that this condition is likely to arise (Smith 1951).

The effect of rain can be estimated if the drops $\overset{\text{are}}{\text{and}}$ assumed to collect charge by the Wilson process. From Whipple and Chalmers (1944) the final charge Q_2 on a drop of initial charge Q_1, after falling through a volume of charge of opposite sign is given by

$$Q_2 = Q_1 \exp^{-\alpha N} \quad \text{with} \quad \alpha = \frac{4\pi e W_2}{U}$$

where e is the electronic charge, W_2 the ion mobility U the fall velocity of the drop and N the total number of ions in the path area of 1 sq.cm.

For drops with a terminal velocity of 7 m/sec falling through the space charge volume created by a corona discharge of one micro-amp in a wind of 10 m/sec. αN is equal to 24. Therefore all the original charge on the rain drop will be neutralised and the drops will leave the volume with a charge of

$\frac{-12 X a^2}{\cancel{4\pi\epsilon}\, o}\pi\epsilon_0$ where X is the potential gradient in V/m and a= radius of the drop (Whipple and Chalmers). This charge is negligibile in the potential gradients under consideration compared with the observed values of Q_1.

The possible effects of heavy rain can now be evaluated. Consider a rain current of 10^{-10} amps/m^2 falling through the space charge liberated by a uniform discharge of 1 μa in a wind of velocity 10 m/sec. If the ion stream is taken to be 1 metre wide then the ion density will be 10^{-7} C/m^2 and rain will remove $\frac{1}{1000}$ part of the space charge per metre. Thus, providing measurements are restricted to the first 1-200 metres of the ion stream and the rain current does not exceed 10^{-9} amps/m^2, rain should not alter the potential gradient beneath the ion stream. This upper limit for rain current is only normally exceeded in the centre of heavy storms when recording becomes impossible owing to rapid variations of potential gradient.

If results that can be attributed to the wash out of ions by rain are obtained within these limits, the final charge on the drops must be considerably in excess of that predicted by Whipple and Chalmers.

2.7. Diffusion of Ions from Idealised Line Flow

Excluding conditions of extreme inversion, all flow in the atmosphere can be considered to be turbulent and therefore all suspended matter will be subject to turbulent diffusion. This will cause the ions emitted in point discharge to diffuse away from the ideal line flow, the degree of diffusion being determined by the existing micro-meteorological conditions. The motion of the ions must be very similar to that of smoke emitted from a tall chimney and an equation derived for the volume distribution of smoke in the plume can be applied to find the distribution of ions in the ion stream from a raised point undergoing corona discharge.

Sutton (1947), working from a statistical theory of turbulent diffusion, reached an approximate solution for the volume distribution of smoke emitted from a point source at ground level.

For a point source at $x = y = z = 0$ producing Q gms/sec and allowing for reflection in the plane $z = 0$ be obtained.

$$X\,(x,y,z,) = \text{concentration} = \frac{2\,Q}{\pi\ Cy\ Cz\ Vx^{2-n}} \exp - \frac{1}{x^{2-n}} \left\{ \frac{x^2}{C^2{}_y} + \frac{y^2}{C^2{}_z} \right\}$$

Where V is the wind velocity and C_x and C_y are virtual diffusion coefficients which depend on the kinemetic viscosity of the air, the eddy velocities in the directions x and y and the parameter n. The quantity n is a pure number between 0 & 1 and is related to the diffusing power of the turbulence. An indication of the magnitudes of C_y, C_z and n can be obtained from the temperature gradient at the time of diffusion. Sutton's expression can be extended to an elevated source and simplified if the reflections due to wind structure at the plane $z = - h$, where h is the height of the source, are ignored. This is justified as the apparatus used measured the vertical component of electric field at the ground and the reflected components will not reach a sufficient height to influence the vertical field at the mills before they are out of the sensitive range of the mills.

For a source at the point $x = y = 0 \quad z = -h$ the distribution becomes

$$X\,(xy\ z) = \frac{Q}{\pi\ Cy\ \ Cz\ x^{2-n}} \exp - \frac{1}{x^2 - n} \left(\frac{y^2}{Cy^2} + \left(\frac{z + h}{C_z{}^2} \right)^2 \right)$$

For values of h greater than 20 m. Cy and Cz tend to a common value C.

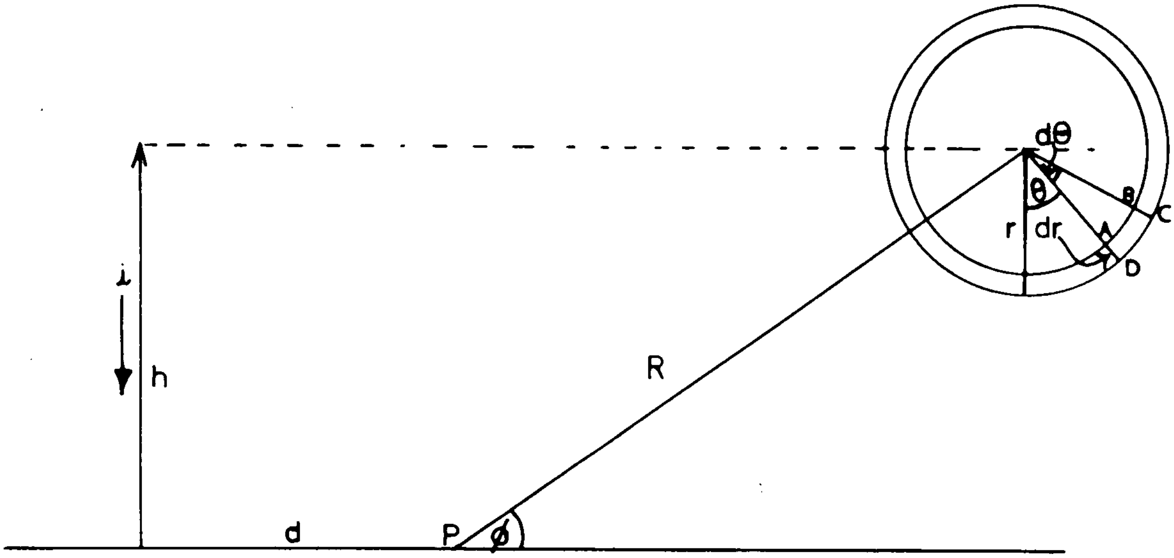


FIG. 3.

The vertical electric field at a point $x = d$ $y = 0$ $z = 0$ for a source of ions at $x = 0$, $y = 0$, $z = h$ and for h 20 m is

$$Ev = \frac{1\ i}{2\pi\epsilon_o \quad VC^2} \iiint_{-\infty}^{+\infty} \frac{z + h}{\left.(z + h)^2 + (x - d)^2 + z^2\right\}^{3/2}} \exp - \frac{1}{x^{2-n}} \left\{ \frac{y^2 + (z + h)^2}{C^2\, x^{2-n}} \right) dx\,dy\,dz$$

where i is the corona current, V the wind speed and ϵ_o the permitivity of free space.

The limit of the integral with respect to z can be extended from -h to - ∞ without any significant loss of accuracy. A factor 2 has been introduced to account for the image charge in the earth.

No analytical method could be found for solving this equation and numerical integration was tried and found to be impracticable without the aid of an electronic computor.

However an approximate solution was obtained as follows.

Consider the annular ring of charge depicted in Fig.3; the plane of the ring is perpendicular to the plane of the paper.

The potential at P due to a small element of charge ABCD is

$$\frac{1}{4\pi\epsilon_o} \quad \frac{\sigma \quad r\,dr\,d\theta}{(r^2 + R^2 - 2R\,r \sin\theta\ \mathrm{ccs}\ \phi)^{\frac{1}{2}}}$$

where θ is the area density of charge.

The potential P due to a ring of charge is

$$\frac{\sigma}{4\pi\epsilon_o} \quad \frac{r\,dr}{(r^2 + R^2)^{\frac{1}{2}}} \quad \int_0^{2\pi} \frac{d\theta}{(1 + A\cos\theta)} \quad \text{where } A = \frac{2\,Rr\sin\phi}{(r^2 + R^2)}$$

by integration and expansion

Potential P =

$$\frac{\sigma r\,dr}{4\pi\epsilon_0(R^2+r^2)^{1/2}}\left\{2\pi+\frac{3}{8}A^2\pi+\frac{3}{4}\frac{35}{128}\pi A^4\right\}$$

$$A^6\to 0 \quad \text{for } R\gg r$$

but $A = -\dfrac{2Rr\sin\phi}{(R^2+r^2)} = -\dfrac{2r\sin\phi}{R}\left\{1-\dfrac{r^2}{R^2}+\dfrac{r^4}{R^4}\right\}$

and $\dfrac{r}{(r^2+R^2)^{1/2}} = \dfrac{r}{R}\left\{1-\dfrac{1}{2}\dfrac{r^2}{R^2}+\dfrac{3}{8}\dfrac{r^4}{R^4}\right\}$

Higher powers of $\frac{r}{R}$ than the 4th are again considered neligible.

Substituting in these expressions and writing

$$\sin\phi = \frac{h}{R}$$

Potential at P $= \dfrac{dr\,\sigma}{4\pi\epsilon_0}\cdot\dfrac{r\pi}{R}\left\{2+\left(\dfrac{r}{R}\right)^2+\left(\dfrac{3}{2}\left(\dfrac{h}{R}\right)^2-1\right)\right.$

$$\left.+\left(\frac{r}{R}\right)^4\left\{\frac{3}{4}-\frac{15}{4}\frac{h^2}{R^2}+\frac{105}{32}\frac{h^4}{R^4}.\right\}\right.$$

From Sutton's theory of turbulent diffusion

$$\sigma = F(r) = B\exp -\frac{r^2}{D}$$

where $B = \dfrac{i}{\pi v C^2 x^{2-n}}$ & $D = C^2 x^{2-n}$

Substituting in and integrating with respect to r over the range $r = 0$ to $r = \infty$

Potential at P $= \dfrac{i}{8\pi\epsilon_0 VR}\left\{2+\dfrac{C^2x^{2-n}}{R^2}\left\{\dfrac{3}{2}\dfrac{h^2}{R^2}-1\right\}+\right.$

$$\left.\frac{C^4x^{4-2n}}{R^4}\left\{\frac{3}{2}-\frac{15}{2}\frac{h^2}{R^2}+\frac{105}{16}\frac{h^4}{R^4}\right\}\right.$$

Vertical potential gradient at P $= \dfrac{d\,(\text{Potential})}{dy}$

$$= \left\{ \frac{\partial v}{\partial z} + \frac{\partial V}{\partial R}\frac{h}{R} \right\}$$

The potential gradient at P

$$= -\frac{\partial v}{\partial z} = E_v = \frac{i h}{4\pi\epsilon_0 R^3 V}\left\{ 2 - \frac{c^2 x^{2-n}}{R^2}\left(6 - \frac{15}{2}\frac{h^2}{R^2}\right) + \frac{c^4 x^{4-2n}}{R^4}\left(\frac{45}{2} - \frac{315}{4}\frac{h^2}{R^2} + \frac{945}{16}\frac{h^4}{R^4}\right)\right.$$

Allowance has again been made for the image charge in the earth.

The final integration with respect to x is too complex to be performed analytically but the right hand side was computed and integrated graphically.

The only major approximation introduced in the analysis is that R $\gg$ r. This can be justified for values of x from 0 to ∞ providing d is less than $\sqrt{3}$ h. Sutton (1952) quotes observations of smoke in moderate lapse rates in which the maximum angle made by the visible edge of the plume to the horizontal was of the order of $\tan^{-1}\frac{1}{10}$

From Fig.3.

$$\frac{r}{R} = \frac{x \tan\alpha}{\left((x-d)^2 + h^2\right)^{1/2}}$$

where α is the angle the extreme edge of the ion stream makes with the horizontal.

This has a maximum value at the point $x = \dfrac{h^2+d^2}{d}$

i.e. where $\dfrac{\tan\alpha\,(R^2+d^2)^{1/2}}{h} = \dfrac{r}{R}$

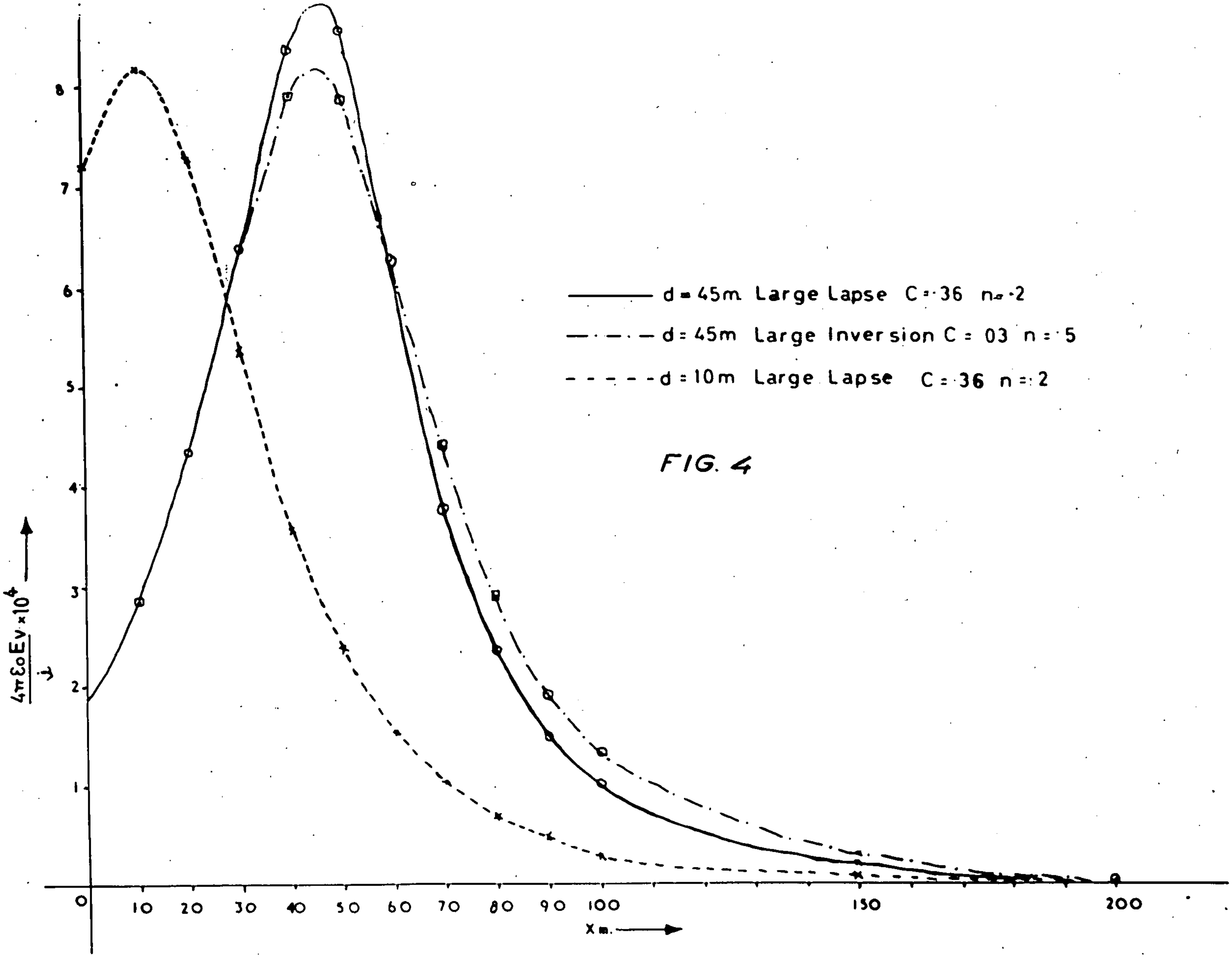

d = 45m Large Lapse C = ·36 n = ·2
d = 45m Large Inversion C = ·03 n = ·5
d = 10m Large Lapse C = ·36 n = ·2
$\frac{4\pi\varepsilon_0 E v}{i} \times 10^4$
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
150
200
X m.

FIG. 4

If the maximum permissible valve of $\frac{r}{R} = \frac{1}{5}$

$$\text{then} \quad \frac{1}{5} = \frac{(R^2 + d^2)^{1/2}}{h} \cdot \frac{1}{10}$$

$$\text{i.e.} \quad d^2 = 3h^2$$

This is the limiting value of d for which the analysis can be applied without incurring excessive error.

For h = 34 m the maximum permissible value of d is 58m.

Sutton (1947) has published values of the parameters C and n for a range of atmospheric stability and these have been used to compute the value of $\frac{4\pi\epsilon_0 VE}{i}$ for a point source at 34 metres above the ground and for values of d of 10 and 45 metres.

The results of the calculations have been plotted in Fig.4, the potential gradient at the position P is proportional to the area under the graph.

The analysis indicates that for d less than 50m and for Sutton's diffusion parameters the potential gradient under the ion stream from a point is practically independent of the stability of the atmosphere. It is not until d is considerably larger than 50m that the diffusion of the ion stream will greatly reduce the measured potential gradient beneath.

When the calculations were first performed it was thought that the potential gradient must be considerbly affected by diffusion and that Sutton's parameters might not be applicable to the present problem. The published values of C and n have not been experimentally verified for moderate and high lapse rates and since the effects of diffusion increase rapidly for $C > 0.4$ and $n > 0.5$ it was thought necessary to conduct experiments using a single point in as great a range of atmospheric stability as possible.

If this apparent independence of the potential gradient beneath an ion stream on the degree of diffusion were established it would greatly facilitate any measurements attempted on single trees and small groups of trees.

2.8. Summary of Equipment Required

After the preceding analysis it became apparent that the following apparatus and facilities would be needed in the preliminary investigation using a single isolated point in the atmosphere.

a) Site for a mast to carry the point.

b) A method of measuring the potential gradient at a single point upwind and simultaneously at several points downwind of the point.

c) A method of measuring point discharge current, wind speed, wind direction and temperature gradient over the first 30m of the atmosphere.

d) A method of simultaneously recording all the above parameters.

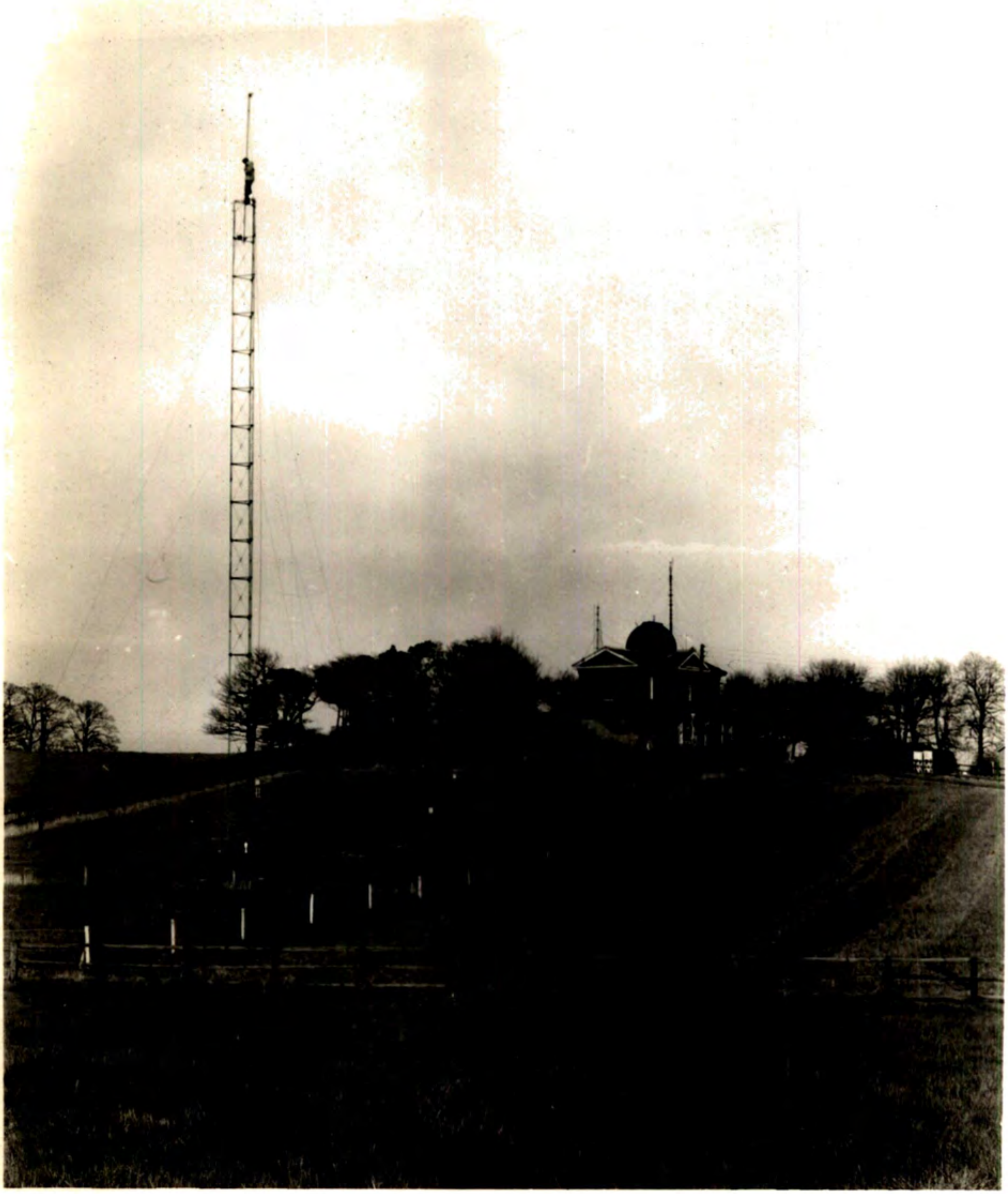


FIG. 5. MAST LOOKING EAST.

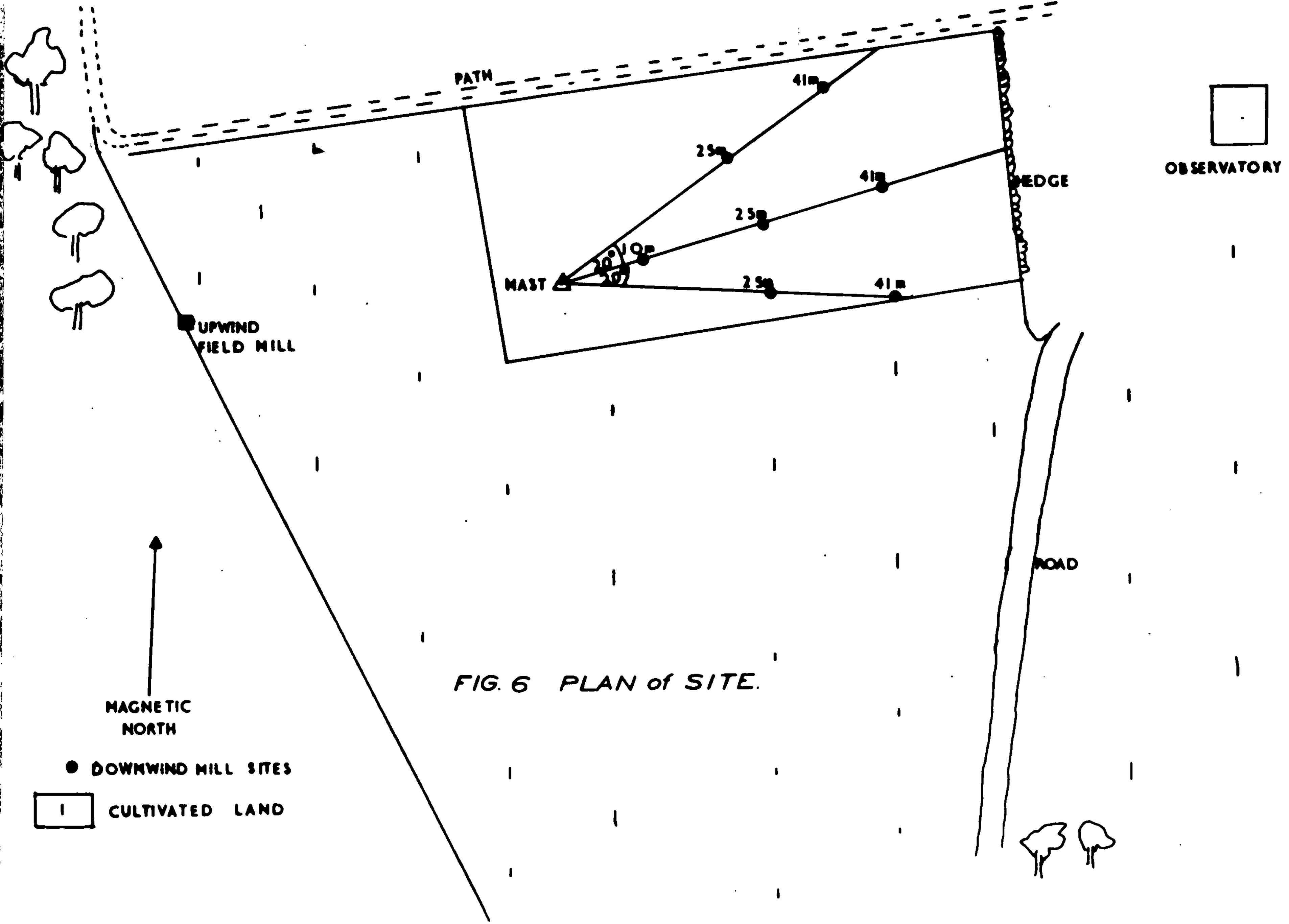


FIG. 6 PLAN of SITE.

CHAPTER 3

APPARATUS AND EQUIPMENT

This present work was part of a general investigation of point discharge and some of the equipment used, viz: the anemometer, upwind field mill and recording camera had been designed and built for the other half of the project. This apparatus has been fully described elsewhere (Kirkman 1956) and will only be mentioned briefly in this thesis.

3.1. Site and Mast

The mast, Figure 4, selected for the project was a braced triple pole structure of height 27.6 m which carried a single pole extension of length 5 m taking the tip of the point to a height of 34 m. The triple pole section was climbable and the extension piece could be lowered for servicing of the equipment carried.

The mast was erected in a small field adjoining Durham University Observatory (Figure 5.). The prevailing wind direction was westerly, so, as it was necessary to have space to leeward for some of the observations the mast was sited as far west as possible. Unfortunately there is a drop in ground level of 5 m from the observatory buildings to the mast so that the effective height of the mast was probably less than the full 34 m.

It was realised from the outset that the measurement of potential gradient at one point upwind and several points downwind of the mast would involve large quantities of highest quality cable.

To minimise the cable required and to make measurements more feasible a small hut containing power supplies and a junction board was built at the foot of the mast. The hut housed 250V AC, 200V DC and 24 VDC supplies and the junction board was linked to the observatory buildings by an 18 cored co-axial cable. All signals from the equipment were relayed to the observatory through this junction board.

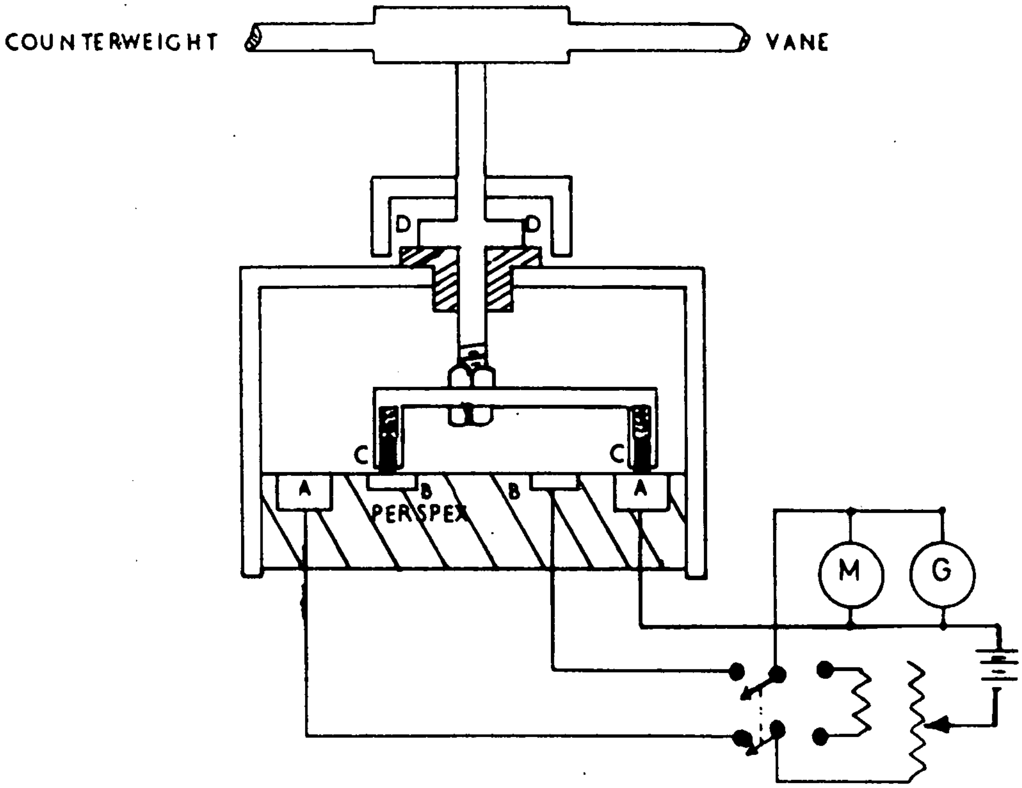
In selecting sites for the downwind field mills the effect of variation of wind direction (Chapter 2) had to be considered. The maximum distance to leeward that mills could be placed before being shielded by a small hedge was 41 m. From section 2.5 for d = 45 m fluctuations in wind direction of $\pm 10^{\circ}$ about the mean direction could be tolerated before significant errors were introduced, consequently field mill sites were situated on lines at 20° intervals, see Figure 5. Three lines of sites were surveyed and small brick mountings constructed at distances of 10 m, 25 m and 41 m from the foot of the mast.

After eight months recording on these sites the downwind field mills were remounted in an inverted position at the 41 m site to enable measurements to be made in very heavy rain.

Two adjoining rooms were available in the observatory building one of which was converted into a darkened recording room and the other into a combined workshop and monitoring room.

3.2. The Point

The point was machined from stainless steel studding let into 1 m of ¼" dia. brass rod. The rod was fixed to the top of the single pole extension by a 6" polished polystyrene stand-off



AA = 120° Potentiometer.
BB = Brass Ring.
CC = Carbon Brushes
DD = Waterproof Gland.

FIG. 7. THE WIND VANE.

insulator and the connecting wire was brought down the mast through a series of similar insulators to the junction board at the base.

The insulators were cleaned at regular intervals with alcohol and leakage resistance to earth of $> 10^8 \Omega$ was easily maintained.

The current from the point was passed through a resistive galvanometer of periodic time 2 sec. and shunted to give a range of sensitivities from $1\frac{1}{2}\,\mu a$ to $70\,\mu a$ for full scale deflection. A calibrating current could be passed through the galvanometer at the end of each recording period.

3.4. The Wind Vane

A remote recording wind vane was constructed that would indicate direction to 2° and was sufficiently rapid in its response to give some indication of gustiness. The vane, Figure 7, moved a carbon brush over a circular wire wound resistance and continuous contact was maintained to this brush by a second carbon brush bearing on a brass ring.

The voltage from the vane could be observed on a meter M, mounted on the control panel, Figure 9, or recorded photographically from g, a galvanometer with a periodic time of 2 secs. A second potentiometer was incorporated in the system so that calibration marks corresponding to the direction of the field mill sites could placed on the record.

3.5. The Anemometer

The anemometer used had been constructed for the other half of the project (Kirkman 1956) and was of the generating cup type. It was mounted 1 m below the point and the output was transmitted to the observatory where it was rectified and measured by a critically damped galanometer of periodic time 2 sec. An earthing switch was provided to obtain a zero position at the beginning and end of each record.

Calibration was carried out in the wind tunnel of the Northumberland Division of the N.C.B. The starting wind speed of the anemometer was approximately 1.5 m/sec and after an initial lag the calibration was linear over the rest of the observable range. Simultaneously with the calibration the number of cup revolutions for a given output was measured so that changes in magnet strength could be detected.

3.6. Measurement of Potential Gardient

Apparatus was required that would continuously measure the sign and magnitude of the earth's potential gradient and also be sufficiently transportable to be used at any one of the prepared sites. Field mills were the obvious solution, particularly as the department had considerable experience in their design and operation.

A field mill was already situated 47 m upwind of the mast and it was only necessary to construct the field mills that would be required on the downwind side. It was decided that four field mills would given an adequate coverage of the leeward potential gradient and not be too difficult to operate and maintain.

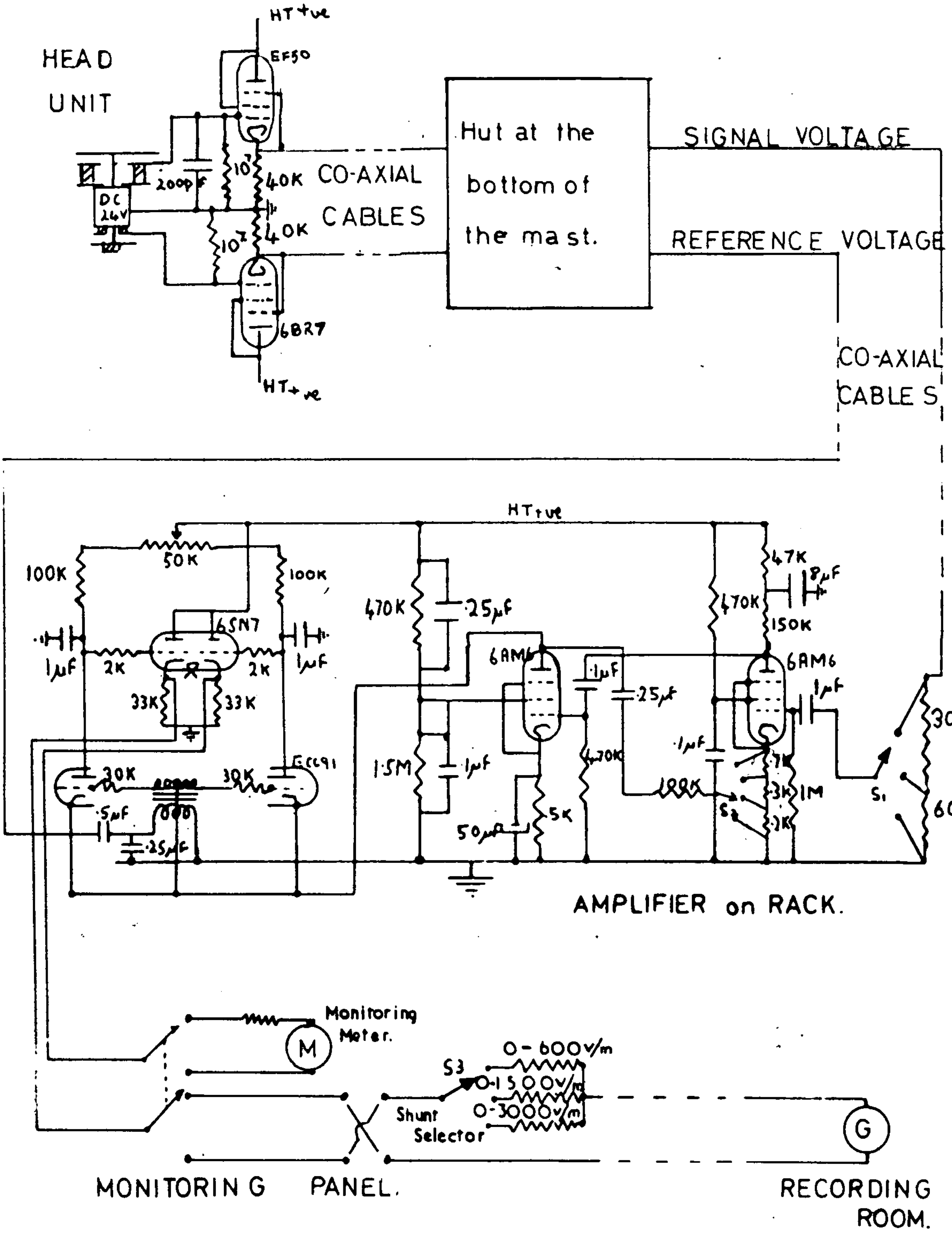


FIG. 8 FIELD MILL CIRCUIT

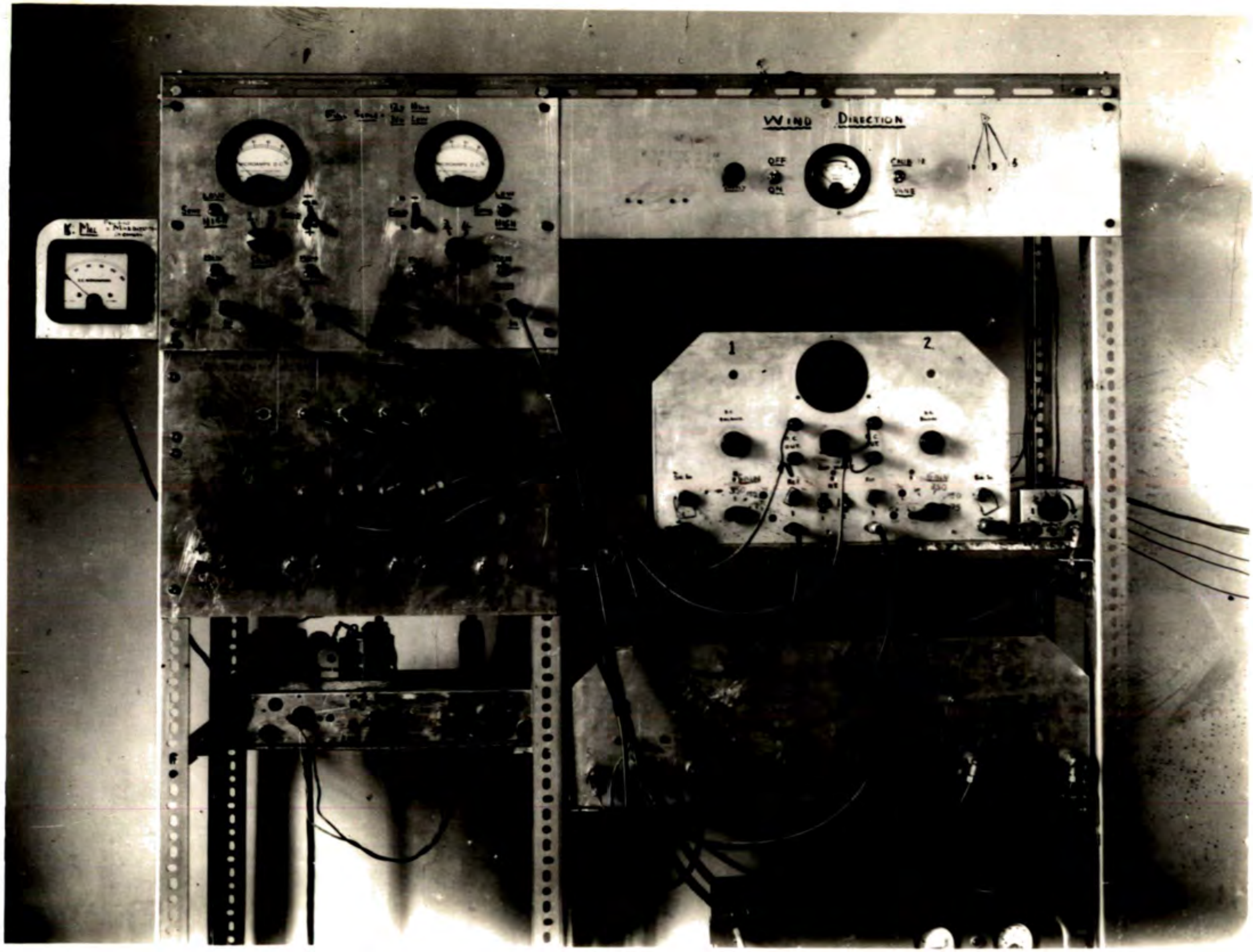


FIG. 9. MONITORING PANEL at OBSERVATORY.

Two field mills had been inherited from a previous student and have been fully described by him elsewhere (Whitlock 1955) since these mills had already proved both themselves and their design two similar instruments were constructed. Slight modifications were made to the reference generators, and the amplifiers were reduced from three to two stages as it was found that the original amplifier tended to be unstable at high gains.

The modified circuit from head unit to recording galanometer is shown in Figure 8. The useful range of potential gradient was restricted to 0 ± 2000 V/m. by a line of trees at the end of the site which began to discharge and disrupt measurements at higher potential gradients. It was therefore possible to operate the amplifiers at a fixed gain and make all changes in sensitivity with the shunt selector switch S3. The galvanometers (g) were critically damped and had a periodic time of .2 seconds and a maximum sensitivity of 6.7 mm/μa.

From the outset it was realised that the recording procedure would be too complex to attempt automatic recording and that it would be a great advantage if the number of adjustments could be kept to a minimum and those that had to be made could be done outside the darkened recording room. Consequently the four downwind mill amplifiers were housed on a rack in the room adjoining the recording room and the monitoring meters (M) input selectors (S1) and shunt selectors S3) were mounted in a panel on the same rack (Fig.9). Thus all changes in sign and magnitude of the potential gradient could easily

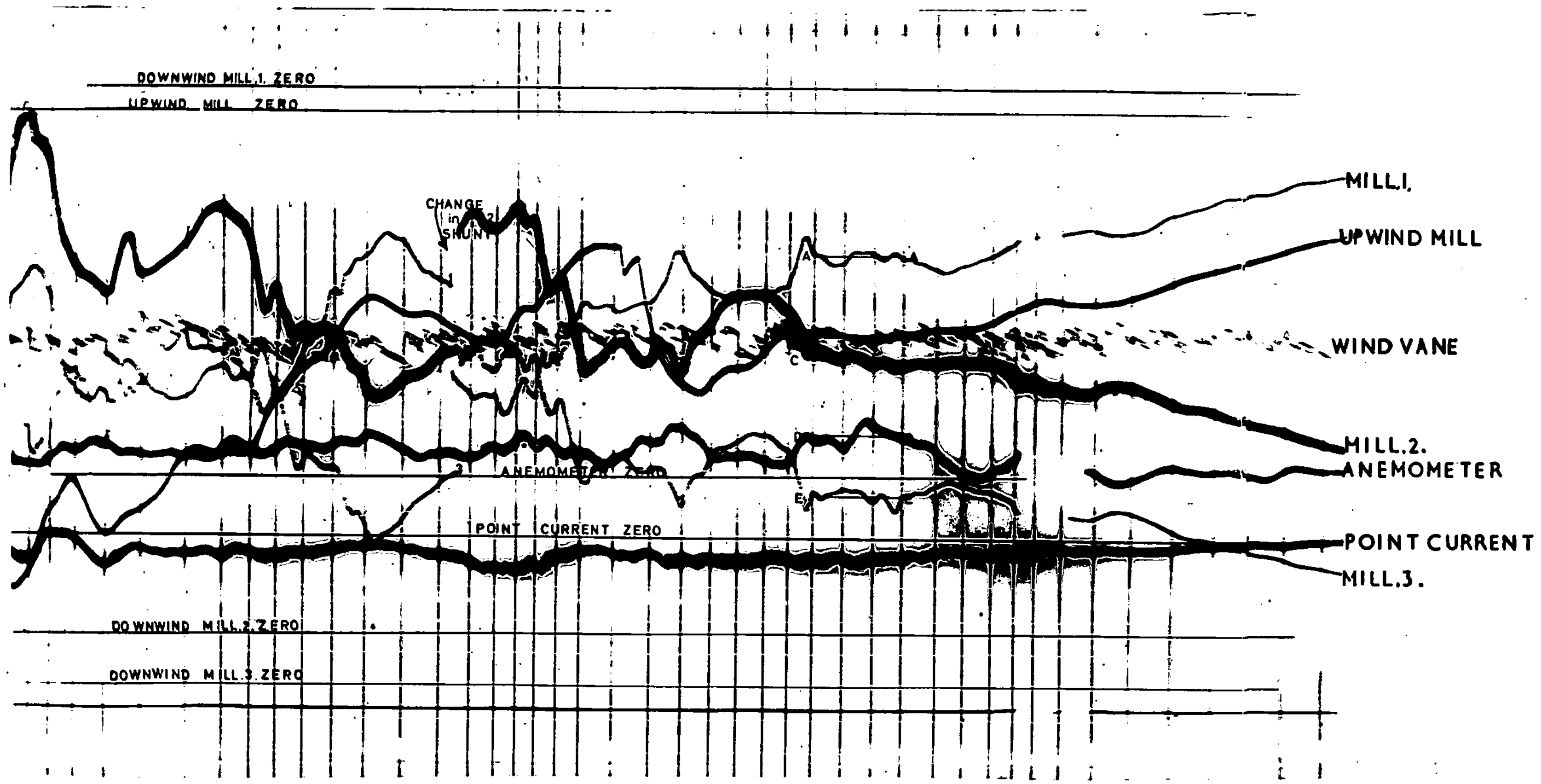


FIG. 10 TYPICAL RECORD

be followed.

The upwind field mill was of different design and unable to differentiate between + ve and - ve potential gradients. This proved to be no great disadvantage as the sign of the potential gradient could always be inferred from the direction of the point discharge current. A monitoring meter and gain selector switch for this field mill were also mounted on the panel. The upwind field mill was run continuously and provided a readily available indication of the potential gradient.

3.7. Recording of Signals

The signals from the point, wind vane, anemometer, four downwind field mills and one upwind mill were all recorded photographically on 240 mm sensitised paper driven through a camera at a rate of 4 cm/min. A time check was obtained from a fogging lamp which was switched on by a synchronous motor at 10 second intervals. The full width of the paper was utilised by zeroing the mill galvanometers at the extreme edges of the paper; changes in sign of the potential gradient, and consequently of output, were counteracted by reversing switches on the control panel.

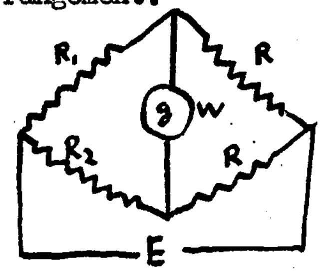
Figure 10 is part of a typical record and clearly shows the arrangement of traces on the photographic paper.

3.8. Measurement of Temperature Gradient

Sutton's theory of turbulent diffusion only differentiates between coarse gradations of temperature gradient, consequently a piece of apparatus was required would give a quick, reliable, but not necessarily very accurate measure of the temperature gradient over the first 30m of the atmosphere. Above all, the day to day stability of the apparatus had to be of a high order as time could not be spared during recording for elaborate calibration procedures.

The aim was to design apparatus that would measure temperature difference of 0.2°C over the ambient temperature range - 5°C to + 20°C.

The alternatives available were either thermo-electric elements and a resistive potentiometer or thermo-resistive elements and a wheatstone net. The development of semi-conductors of high stability and resistance/temperature coefficient prompted the adoption of the latter arrangement.



Consider the above wheatstone net.

The current through the galvanometer is given by:-

$$ig = \frac{RE\ (R2 - R1)}{W\ (R2 + R)\ (R1 + R) \left\{ R1\ (R1 + R2) + R2\ (R + R1) \right\}}$$

$$ig = \frac{2REg}{W\ (X + R)^2 - g^2 + R\ (2\ (X^2 - g^2) + 2RM)}$$

where $R2 = X + g \quad R1 = X - g.$

If the bridge is adjusted to make $X \gg g$ then g^2 can be neglected in comparison with X^2.

$$ig = \frac{2REg}{W\,(X + R)^2 + 2R\,(X^2 + RX)}$$

Thus for the condition $X \gg g$ the current through the galvanometer is proportional to the difference in resistance between R1 and R2. If R1 and R2 were two temperature sensitive elements, the current through the galvanometer would be proportional to temperature difference to which the elements were subjected. If the elements could be made to have identical thermal characteristics then the bridge would indicate temperature difference over the range in ambient temperature for which the characteristics were identical.

Two "Stantel" thermistors type F/200 of similar characteristics were selected for the temperature sensitive elements. These thermistors are of a robust construction and are ideal for outdoor work.

The temperature/resistance characteristic of a thermistor is of the form $R = a\,E^{-b}/T$, where T is the absolute temperature, and can be made linear over a limited range in T by shunting the thermistor with a resistance equal to the resistance of the thermistor at the mid-point of the range over which linearity is desired. This property was utilised in producing two temperature sensitive elements of nearly identical characteristics.

One of the thermistors selected was calibrated in a water bath over the range -5°C to 20°C, shunted with a resistance equal to its mid-point value and re-calibrated. From a knowledge of resistance of the second element at -5°C and 20°C it was possible

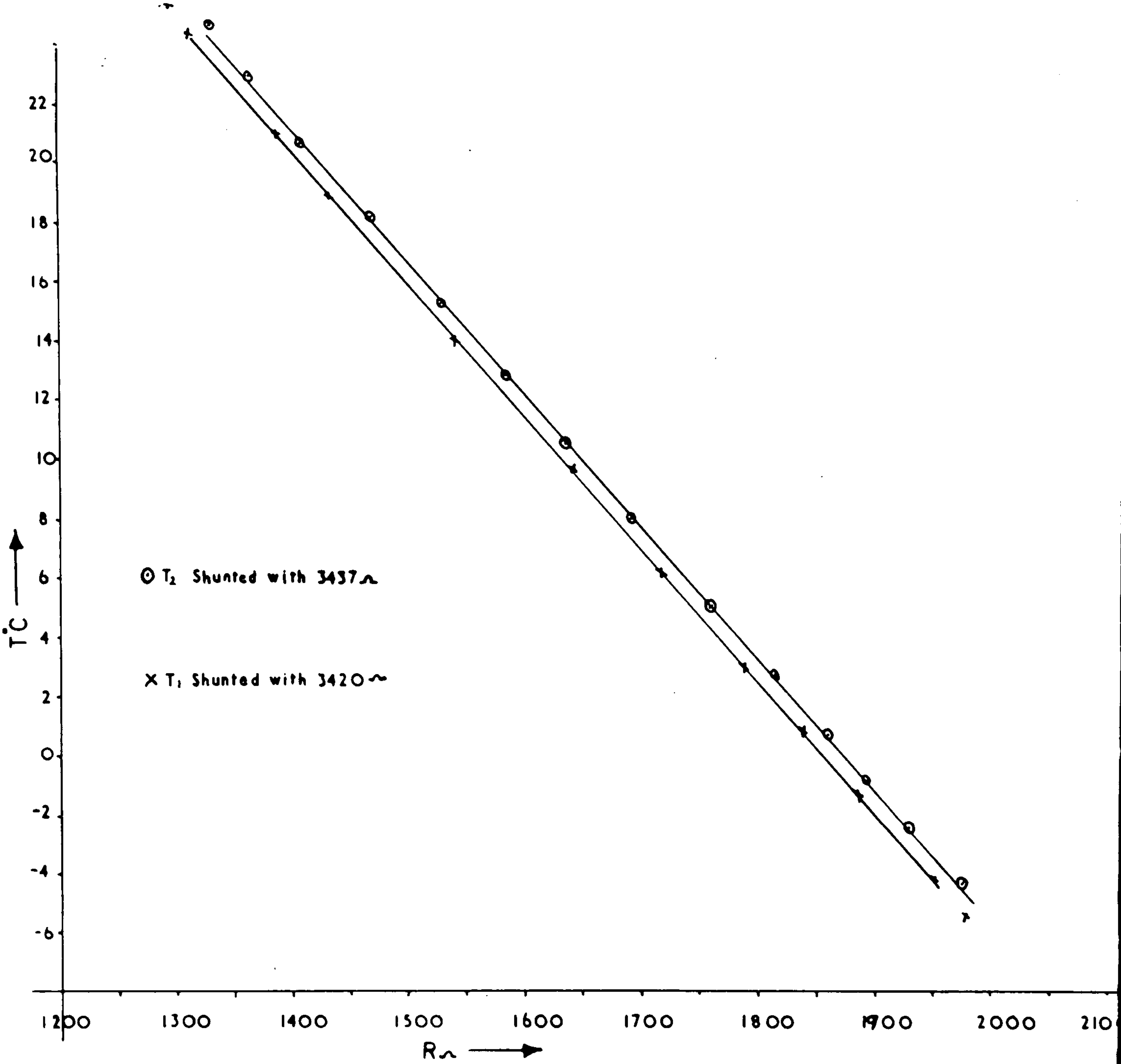
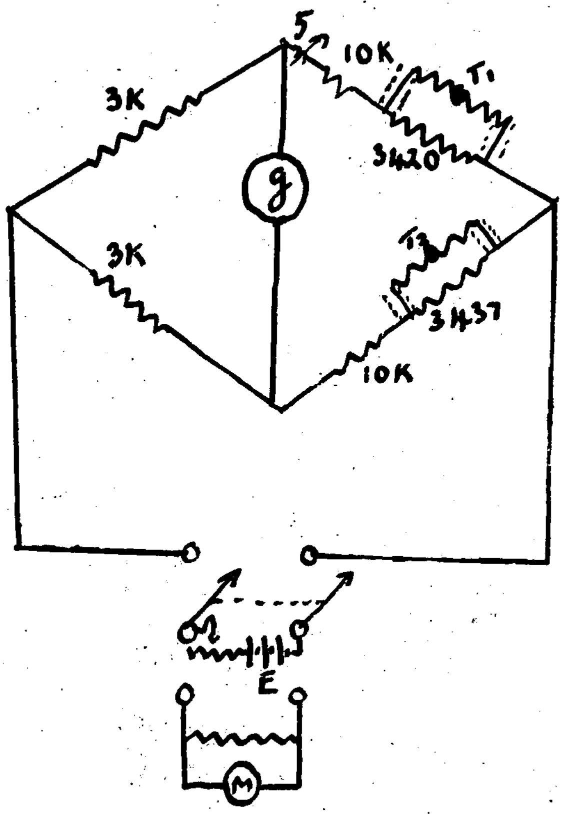


FIG. 11 THERMISTOR CHARACTERISTICS.

to calulate the value of a shunt which would make the second characteristic similar to the first. The two characteristics obtained have been plotted in Figure 11. The two curves are nearly linear and parallel and the divergence from linearity over the temperature range - 5°C to 20°C is not greater than 2 Ω and well within the hoped for accuracy of 0.2°C. The slight displacement of curve 1 relative to curve 2 was corrected in the final bridge by the inclusion of a small series resistor.

The final bridge circuit was



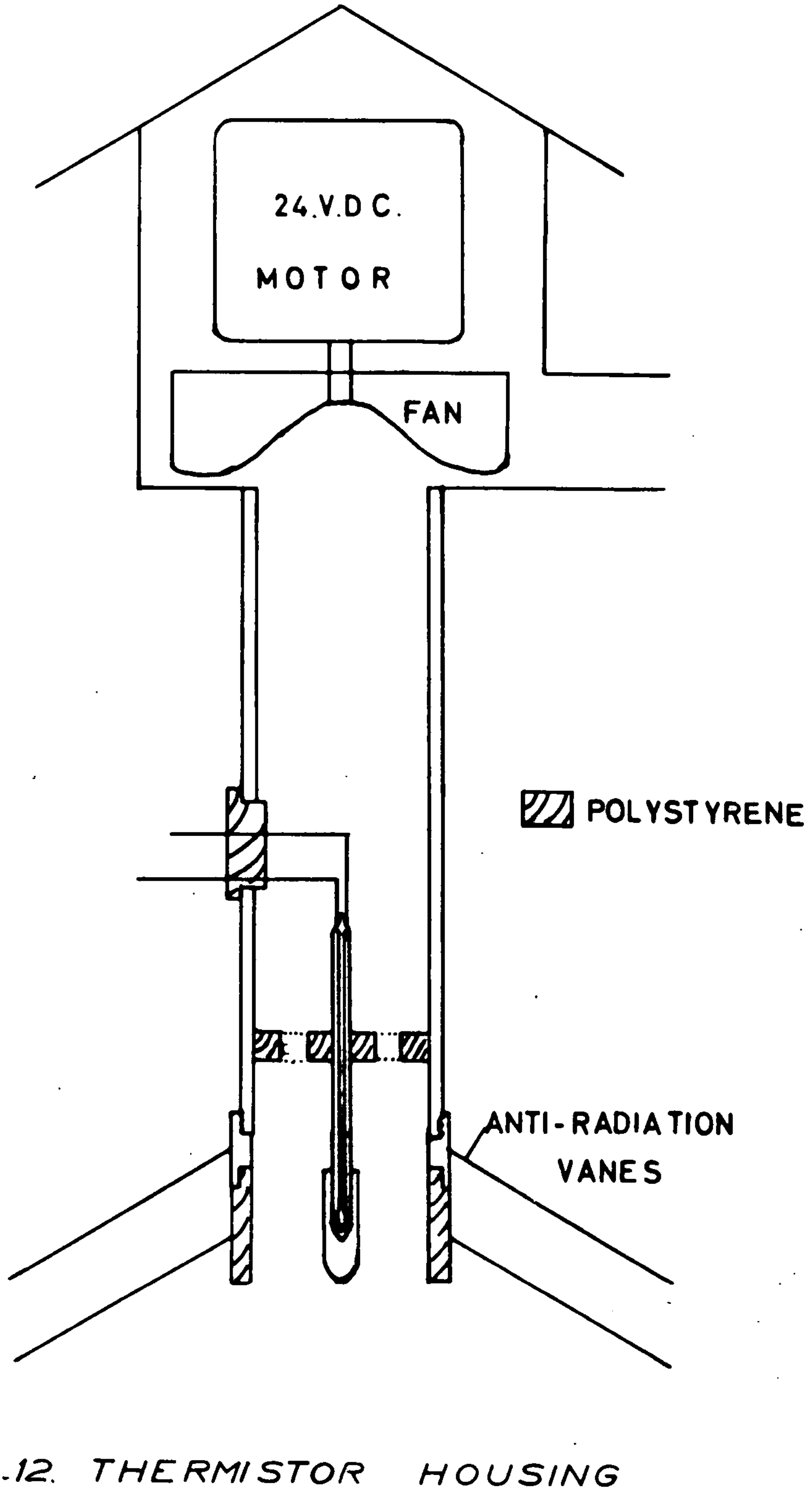


FIG.12. THERMISTOR HOUSING

FIG. 13 HOUSING on MAST.

The condition $X \gg g$ was satisfied by the inclusion of a 10K resistor in series with each thermistor. In selecting a value for E the power dissipated in each thermistor had to be no greater than 10 mW otherwise self heating of the element would become of a magnitude sufficient to influence the bridge reading. For E = 4V the power dissipated is of the order of 0.5 mW and well within the limit of 10mW. The resistance R, switch S and meter M enabled the bridge voltage to be brought to the value of 4 V before readings were taken.

Matched wire-wound "Precistors" with a stability of better than 0.1% were used throughout.

With the two sensitive elements in the same water bath the bridge did not go out of balance by more than 2 Ω over the temperature range - 5°C to 20°C.

The dry adiabatic lapse between 1 and 30 meters is 0.3°C or a 7 Ω difference between T_1 and T_2. The bridge was therefore capable of measuring temperature gradients to an accuracy of $\frac{1}{3}$ the dry adiabatic lapse from 1 m to 30 m over the ambient temperature range - 5°C to 20°C.

3.9. Thermistor Housing

The thermistor housing is shown in Figures 12. and 13. All metal parts were of copper or brass and polystyrene was used both as an electrical and thermal insulator. The anti-radiation vanes were spun from 22 gauge copper sheet. To help prevent the radiation absorbed by the whole casing warming the incoming air the lower anti-radiation vane was thermally isolated from the rest of the housing. Heating of the thermistor bead by conduction along the connecting wires was prevented by passing the wires through a large polystyrene window.

Preliminary trials showed that the thermistors were responding to insignificant, small scale temperature fluctuations so their thermal capacity was increased by sliding identical polished brasleeves over the thermistor beads.

Air was drawn through the housing and expelled downwind by a 7 cm diam; centrifugal fan driven at 5,000 r.p.m. by a 24V DC motor. Since it was only intended to record when the wind lag in a certain quarter the slight dependence of aspiration rate on wind direction was of little importance.

All surfaces were painted white.

3.10. Operating and Calibration

The bridge was placed in the darkened recording room and two sensitive elements clamped to the windward side of the mast (Figure 13.). The bridge was balanced when the two elements were mounted at the same height on the mast; after balancing, one element was fixed at 1.5 m and the other at the top of the tripble pole structure. The bridge balance was checked periodically by bringing the two elements to the same height.

Readings were taken visually from a lamp and scale arrangement and the galvanometer was shunted to give full scale deflection for ± 3°C between T_1 and T_2 - i.e. approximately ten times the dry adiabatic lapse between 1.5 m and 30 m. From switching on the fans and checking the bridge voltage the elements were left for ten minutes to come into equilibrium with their surroundings before a reading was taken.

Since it was an indication of atmospheric stability that was required it was decided that the calibration of the complete bridge in a water bath was sufficient and that it was not necessary to carry out an accurate calibration in the atmosphere.

Checks were made on the efficiency of aspiration by heating the housing and observing the changes, if any, in thermistor resistance. A considerable excess housing temperature had to be induced before any changes in thermistor resistance could be observed.

The bridge functioned successfully over the entire recording period. After eight months working, the housings had to be removed for servicing and the opportunity was taken to recalibrate the thermistors. Over the range $- 5^{o}C$ to $+ 20^{o}C$ it was impossible to detect any changes in resistance/temperature characteristic greater than those inherent in the measuring apparatus.

CHAPTER 4

PERFORMANCE AND CALIBRATION OF APPARATUS

4.1. Performance of Field Mills

The upwind field mill had been mounted 1.75 metres above the ground in an inverted position, that is with the vanes directed towards the ground, and performed well in all types and conditions of weather. The four downwind mills had to be movable and for the majority of the time were operated in an upright position on small bases close to the ground. They worked well in all but very heavy or prolonged rain when there was a tendency for the insulation of the lower vanes of the mills to break down and render them useless.

Towards the end of the investigation a study was attempted of corona discharge in heavy rain and for this three of the mills were remounted in an inverted position 1 metre above the ground. No insulation difficulties were experienced after the mills had been remounted.

4.2. Calibration of Field Mills

The majority of electrical measurements in the atmosphere have been concerned with phenomena in which relative changes in potential gradient have been more important than absolute values. The success of the present investigation, however, was very dependent on the accuracy to which the absolute calibration of the field mills could be performed.

The classical methods of calibration involve the use of some form of potential equaliser coupled to an electro-static voltmeter or quadrant-electrometer. Experiments were carried out using an insulated stretched wire with a burning fuse potential equaliser and measuring the steady potential reached by the wire with both quadrant and valve electrometers. It was found impossible to record simultaneously the signals from the field mills and electrometers without mounting the electrometer in the observatory and using so much cable that the impedance of the electrometer was reduced below the limiting value of $10^{15}\Omega$ To operate the electrometer close to the wire and take the visual observations of wire potential and at the same time record the output from the field mills restricted recording to very steady conditions when the potential gradient was not high enough to give a critical calibration. It was therefore decided that the classical method would have to be abandoned and a method of calibration devised that would be accurate, reproducible and have a range from 0 to ± 400V/m.

The five field mills were first calibrated over all sensitivity ranges by applying a series of positive and negative voltages to a close fitting insulated plate which was placed just above the rotating vanes on the mill (Whitlock 1956). This provided an easily reproducible check on the gain and sensitivity of the head units, amplifiers and galvanometers. A factor was now required to convert these plate voltages into equivalent absolute values of potential gradient.

At a point 35 m. from the foot of the mast one of the downwind field mills was let into the ground until the lower vanes were flush

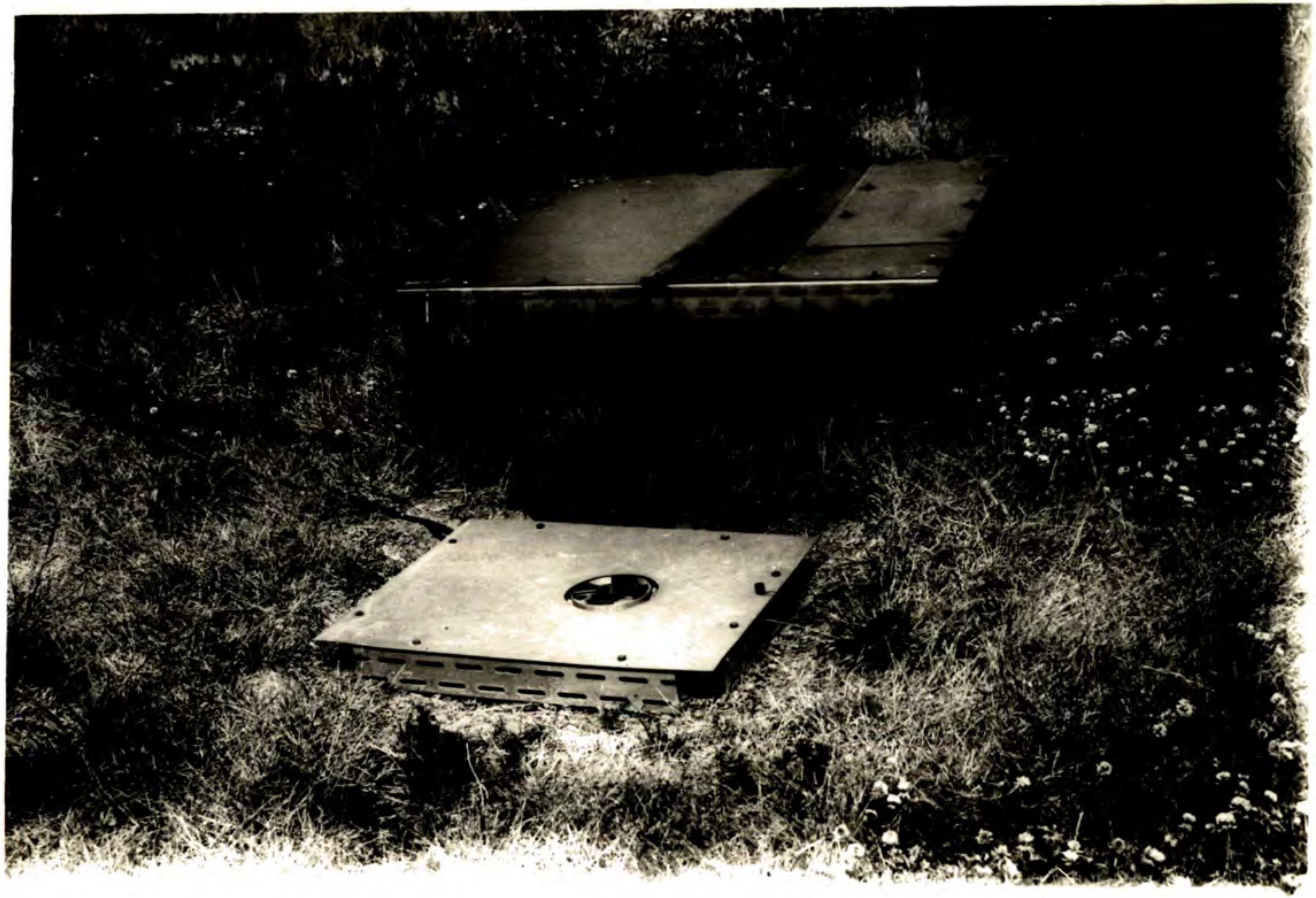


FIG. 14. CALIBRATION PIT.

with the surrounding earth. A large aluminium plate was placed over the mill and a hole cut to allow the vanes to protrude Figure 14. A second plate was mounted on insulators parallel to, and 40 cm above, the first plate. The result was a parallel plate condenser with the field mill vanes just projecting into the uniform field region in the centre of the plates. The mill was then calibrated over the potential gradient range 0 to ± 400 V/m. by applying a series of voltages to the plate. On removing the upper plate the mill in the pit could then be used as an absolute standard against which the field mills could be calibrated.

The remaining field mills were placed on prepared sites, similar to those on the lines of sites, at 2 metres from the standard and at points equidistant from the foot of the mast. The top plate was taken off the standard field mill and the outputs from all four instruments were recorded. Days were chosen for the calibration on which the potential gradient varied slowly between + or - 300 to 400 V/m. Immediately after the comparison with the standard, the mills were re-calibrated with the close fitting plate so there was no possibility of the calibration changing between the absolute and relative calibrations of the field mills.

The upwind wind mill was calibrated by removing the point and comparing the signal from the upwind mill with one of the downwind mills placed 47 m. from the mast. That the mast did not act as a point discharge element was apparent from the correlation between the measured upwind and downwind potential gradients with the point removed.

Changes in calibration could be expected to occur in two ways.

(1) Changes in zero output and amplifier-galvanometer characteristic.

These were easily detected by applying voltages to the fixed plate at the beginning and end of any recording period. The appropriate corrections were applied when the records were analysed.

(2) Changes in exposure factor, i.e. changes in the geometry of the sites which might result in a distortion of the lines of force ending on the field mills.

These were kept to an absolute minimum by frequently cutting the grass around the sites and periodically running a motor-scythe over the entire field.

The sites at distances of 10 m. and 25 m. from the base of the mast were shielded by the mast and the exposure factor of each site was measured by taking measurements of potential gradient on all sites at potential gradients less than the onset value for the point and then referring all the measurements to the 41 m. site on the central line of sites.

Several absolute calibrations of the equipment were performed in the course of the investigation with the single point. Though there were slight variations in mill performances, when the results were scaled in proportion to the changes as indicated by the close fitting plate the calibrations were not significantly different.

The absense of variation between sucessive calibrations indicate that all changes in calibration had either been eliminate or were being detected by the frequent checks applied.

It was concluded that the absolute value of the potential gradient could be measured by the equipment used to an accuracy of ± 5% over the range 0 to ± 3,000 V/m.

The calibration of the downwind mills when mounted in an inverted position was performed in a similar manner. In this case the mills could not be moved from their mountings and the calibrations w were made relative to the 35 m mark.

4.3. Recording Procedure

When the wind lay between NW and SW and the potential gradient reached a value ± 250V/m recording was commenced and the following recording procedure observed.

The wind direction was studied and depending on whether the mean wind direction was changing or constant the mills were placed either across or along the appropriate lines of sites.

The downwind field mills, wind vane and temperature gradient apparatus were switched on and left for ten minutes for the amplifiers to warm up and the thermistors to come into equilibrium with their surroundings. At the end of this period the phase sensitive rectifiers of the mills were balanced, the recording camera started and the zero positions of the galvanometers recorded with all the inputs to the amplifiers earthed.

The recording was then started and all significant changes in sign and magnitude of potential gradient were followed on the monitoring meters and the appropriate shunt or reversing switch changes made. It was usually found possible to record on only three of the downwind mills and use the fourth for monitoring purposes. This reduced the number of meters to be observed to one for the upwind mill and one for the three downwind mills and made recording a little less exacting. The point current galvanometer shunt was invariably left on the 0 to ± 15 μa range but this was changed if the wind speed reached particularly high values.

The scale reading on the temperature bridge was noted every ten minutes and a record kept of the type, intensity and duration of any precipitation.

When the potential gradient returned to its undisturbed value and there was no likelihood of any further point discharge the close fitting plate was placed over each mill in turn and the zero signal and signal for a fixed voltage on the plate recorded, the inputs to the amplifiers were then earthed and a second galvanometer zero obtained. The anemometer was earthed, the point galvanometer calibrated and calibrating marks corresponding to the line of field mill sites placed on the record of wind direction.

After the mills had been remounted for heavy rain recording the same procedure was adopted with the exception that measurements could only be made at the one site for a given wind direction.

Under normal working conditions the zero drift on all field mills was less than 2%/hour, if the recording period extended over an hour further galvanometers zero's were obtained at suitable points on the record.

Close adherence to this procedure ensured that the electrical and meteorological history of each period of point discharge was obtained.

CHAPTER 5

RESULTS FOR A SINGLE ISOLATED POINT AT THE OBSERVATORY

5.1. Range of Recording Conditions and Analysis of Results

The apparatus was ready for operation in May 1956 and results were obtained whenever conditions permitted up to July 1957. Recording was restricted to wind directions which resulted in the ion stream being blown directly over one of the three lines of field mill sites.

There were 23 occasions on 15 separate days on which recording was attempted. The following conditions have to be satisfied before the results could be accepted for analysis.

(1) The fluctuations in potential gradient should not be too rapid and so render any analysis meaningless.

(2) The potential gradient should not exceed ± 1300 V/m for any considerable period of time. At values of potential gradient above this limit a line of trees close to the upwind field mill apparently started to discharge and the ions liberated had a greater effect on the upwind field mill than the downwind mills. Records rendered useless for analysis in this way were later employed in a study of the corona discharge current to earth through the line of trees.

There remained for analysis 11 periods with a total point discharge time of 9½ hours. Of the 9½ hours, 7 hours involved positive potential gradients with a positive flow of current to earth and 2½ hours negative potential gradients and negative flow of current

FIG. 14

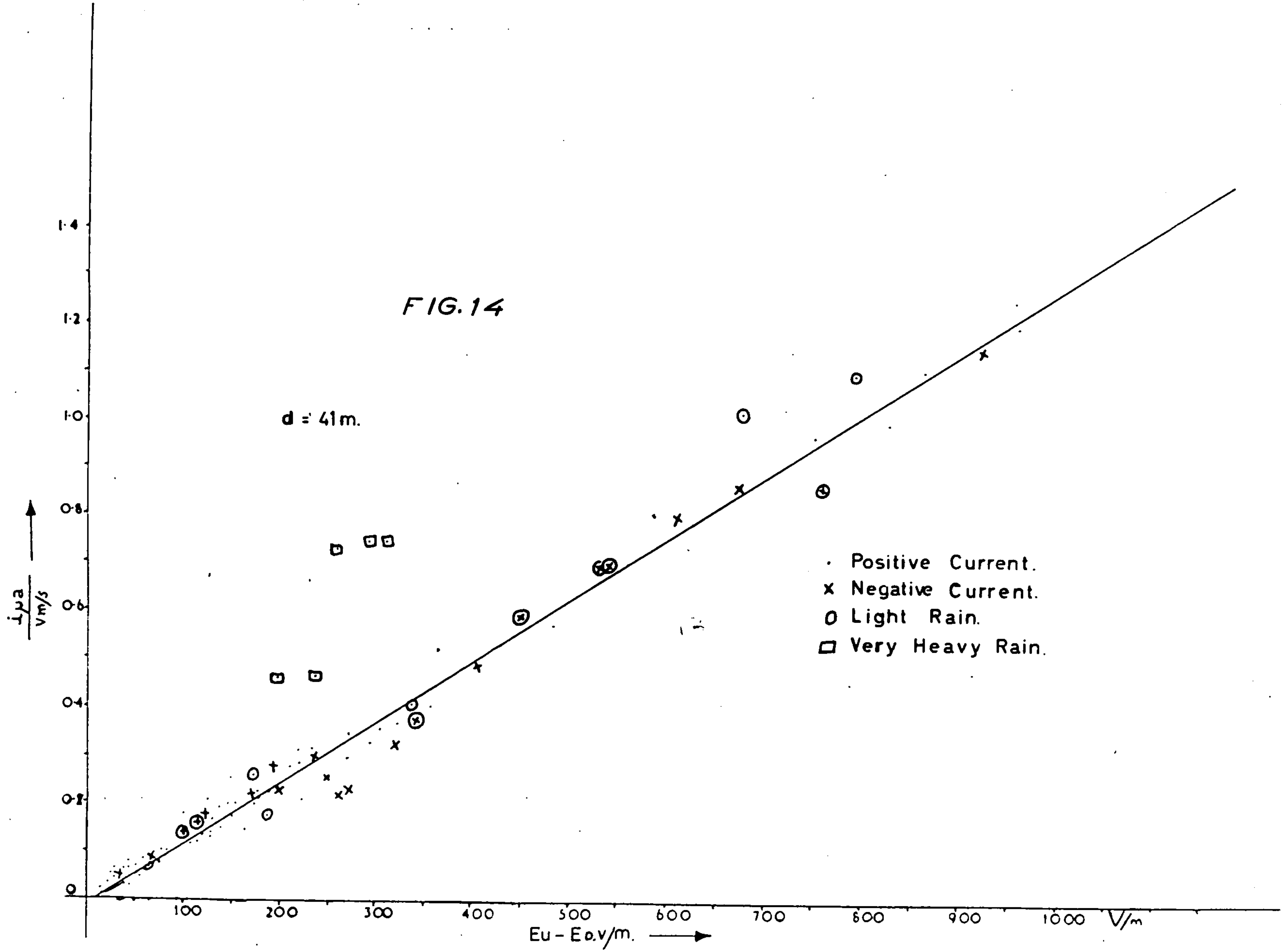

d = 41m.
i μa / v m/s
0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
100
200
300
400
500
600
700
800
900
1000
V/m
Eu - Eo.v/m.
· Positive Current.
x Negative Current.
O Light Rain.
□ Very Heavy Rain.

FIG. 15.

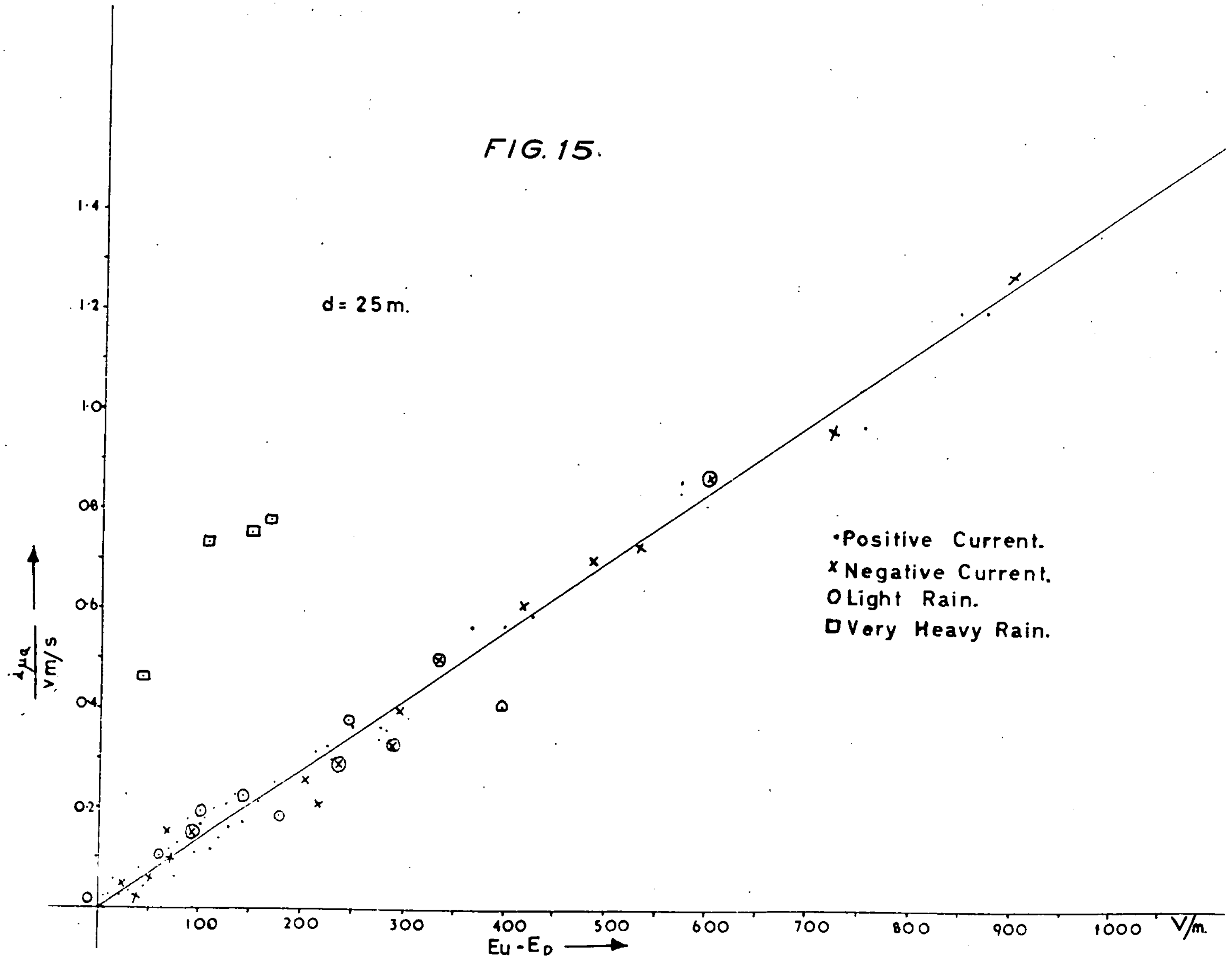
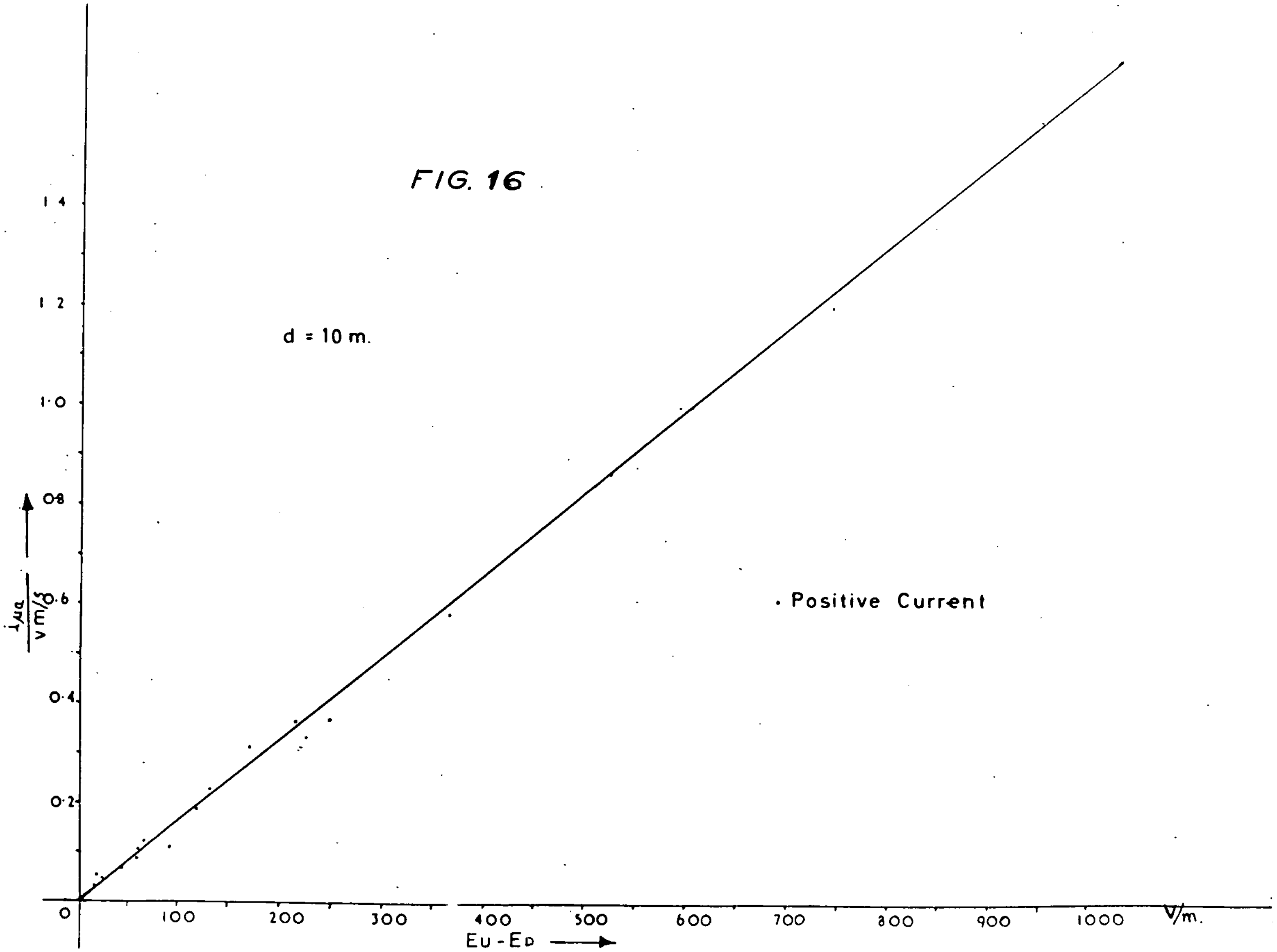

d = 25 m.
$\frac{i_{\mu a}}{v\,m/s}$
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
100
200
300
400
500
600
700
800
900
1000
V/m.
Eu - E$_D$
• Positive Current.
x Negative Current.
O Light Rain.
□ Very Heavy Rain.

FIG. 16


d = 10 m.
· Positive Current
$\frac{i\,\mu a}{v\,m/s}$
0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
100
200
300
400
500
600
700
800
900
1000
V/m.
Eu - Ed

to earth. This predominence of positive current down over negative current down was a result of the method of selection of periods for analysis and is not of any fundamental significance.

The wind speeds varied between 4 m/sec and 15/sec.

When analysing the results the wind vane trace was first studied and those field mill(s) lying most nearly beneath the ion stream marked. From figure 4 it can be seen that once the ions liberated in the discharge have moved 100m downwind of the point they have a negligible effect on the vertical potential gradient at any of the prepared field mill sites.

For average wind speeds it takes 25 seconds or more for the ions to move out of range of the most distant downwind field mills. It also takes a similar period of time for any large scale potential gradient disturbance to become effective 90 m away at the furthest downwind field mill. Periods on the records were therefore selected for measurement in which the traces remained sensibly constant for not less than 25 sec; a typical period is marked A - A etc: in Figure 10.

Proceeding in this manner the 9½ hours of record were analysed. The results obtained for both positive and negative discharge currents to earth and distances of 10, 25 and 41 metres from the base of the mast have been plotted in Figures 15, 16 and 17. The ordinates are the point discharge current to earth in micro-amps divided by the wind speed in metres/second and the abscissae the difference between the upwind potential gradient Eu and the downwind potential gradient Ed.

First order regression lines were fitted to the 75 points for d = 41m, 75 points for d = 25m and 25 points for d = ~~25~~10m.

The fitted lines are:-

(a) for d = 41 m

$$Eu - Ed = 779 \frac{i}{v} + 5$$

error in regression coefficient 779 = ± 28

(b) for d = 25m

$$Eu - Ed = 722 \frac{i}{v}$$

error in regression coefficient 722 = ± 15.8

(c) for d = 10m

$$Eu - Ed = 602 \frac{i}{v} + 6$$

error in regression coefficient 602 = ± 35

In all cases i is measured in micro-amps, v in metres/sec and Eu - Ed in Volts/metre.

The potential gradient difference between the upwind and downwind sites was calculated assuming the ions to take up an infinite line distribution and the following results obtained.

(a) d = 41 m

$$Eu - Ed = 803 \frac{i}{v}$$

(b) d = 25 m

$$Eu - Ed = 720 \frac{i}{v}$$

(c) d = 10 m

$$Eu - Ed = 609 \frac{i}{v}$$

The similarity between these two sets of expressions is very apparent and it was decided to examine the similarity between the corresponding expression statistically.

The significance of the regression coefficients was first examined using a Student't' test and in all cases was found to be extremely significant ($P < 0.01$). Next the significance of the difference between the experimental and calculated results was examined again using the Student 't' test.

for d = 41m P = 0.7

for d = 25m P = 0.9

for d = 10m P = 0.9

P is a measure of the probability of the difference between the experimental and calculated results being greater than by pure chance.

Probabilities greater than 0.9 can be regarded as highly significant. For d = 41m the Student test does not seem to give a significant result but in view of the greater liability to error due to fluctuation in wind direction at 41m it is thought that the significance of the similarity between the observed and calculated result is greater than that revealed by the Student test.

As a further indication of the differences between the regression coefficients for 10_m, 25_m and 41_m tested and again found to be highly significant ($P < 0.01$).

The constant terms appearing in the expression for d = 10_m and 41 m are not significantly different from 0 (P again < 0.01).

Certain limitations to the validity of the approximation to an infinite line distribution were suggested during the work;

these and other possible limitations were studied.

5.2. Sign of Potential Gradient

Throughout the analysis no differences between positive and negative potential gradients were observed; which is in agreement with the concept of wind being the prime factor in ion distribution.

5.3. Effects of Atmospheric Stability

Measurements were made in conditions of atmospheric stability ranging from moderate inversion 5 - 6 times dry adiabatic lapse from 1m to 30m, to quite high lapse rate, 8 - 9 times the dry adiabatic, lapse from 1m to 30m, but no significant difference in the results could be detected. Difficulties were experienced in conditions of high inversion due to low wind speeds and a tendency for the wind to change direction in a random manner (fanning) making measurements, particularly at 41m, unreliable. Measurements made under these conditions were not included in the final analysis.

For distances from the base of the mast considerably greater than 50m the effects of ion diffusion might well become important, but the analysis of Chapter 2 and the dependence on wind direction would have to be reconsidered as the simplifying assumption of $(\frac{r}{R})^6 \rightarrow 0$ would no longer be valid.

Measurements made at distances greater than 50m might have applications in the field of atmospheric diffusion.

5.4. Effect of Rain

Light to moderate rainfall had little or no effect on the results.

In heavy rain there seemed to be differences between the upwind and downwind potential gradients that could not be attributed to the point discharge ions. Towards the middle of 1957 the downwind mills were inverted and measurements made in very heavy rain. The same discrepancies were observed but it was not possible to conclude whether the results were due to space charge liberated when the rain struck the ground or actual wash out of ions from the ion stream. Measurements of rain current directly beneath the ion stream would have to be made before any conclusions could be drawn from the observed results in torrential rain.

5.5. Effect of Snow

Correlation between the upwind and downwind field mills broke down during heavy snow showers; this was very probably due to the creation of small localised regions of space charge by the frictional electrification of snow flakes.

5.6. Conclusion

It is therefore concluded that providing snow and very heavy rain conditions are excluded the electric field beneath the stream of ions liberated by an elevated point in the atmosphere undergoing point discharge can be computed, to within the limits of normal experimental error, for points at a distance from the base of the discharging point less than $\sqrt{3}h$ times the height of the point by assuming the ion stream to take up an infinite line distribution. For points at a distance greater than $\sqrt{3}$ h away from the base of the point the effects of turbulent diffusion of the stream would have to be considered.

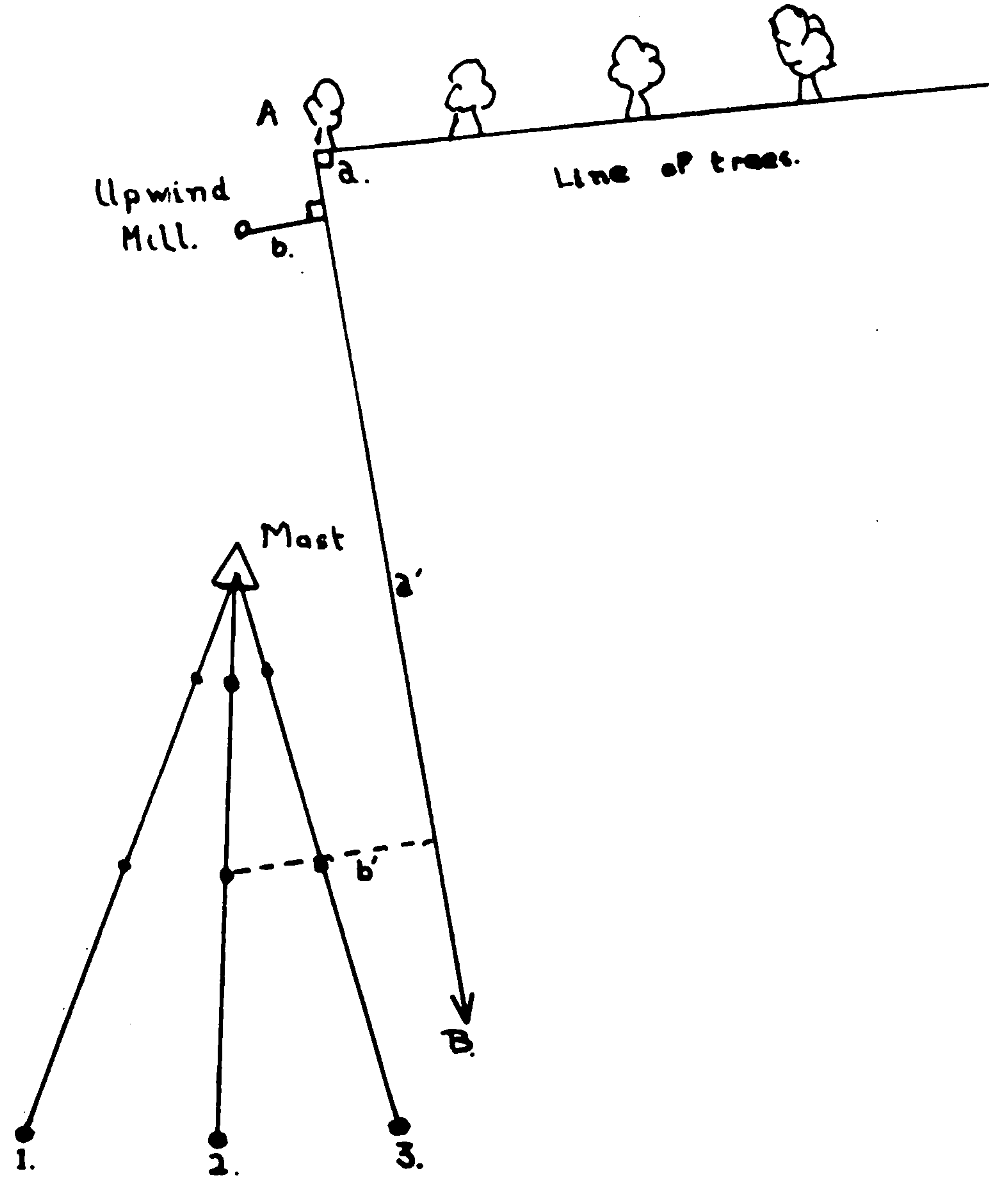


Fig. 17 Line of Trees at Observatory.

Evaluation of $E_u = \frac{ih}{2\pi\epsilon_0 V} \int_0^\infty \frac{h}{(b^2 + h^2)^{1/2}} \left\{ 1 + \frac{a}{(b^2 + a^2 + h^2)^{1/2}} \right\} db$

for May 16th.

A A′ B B′ = area associated with ash tree.

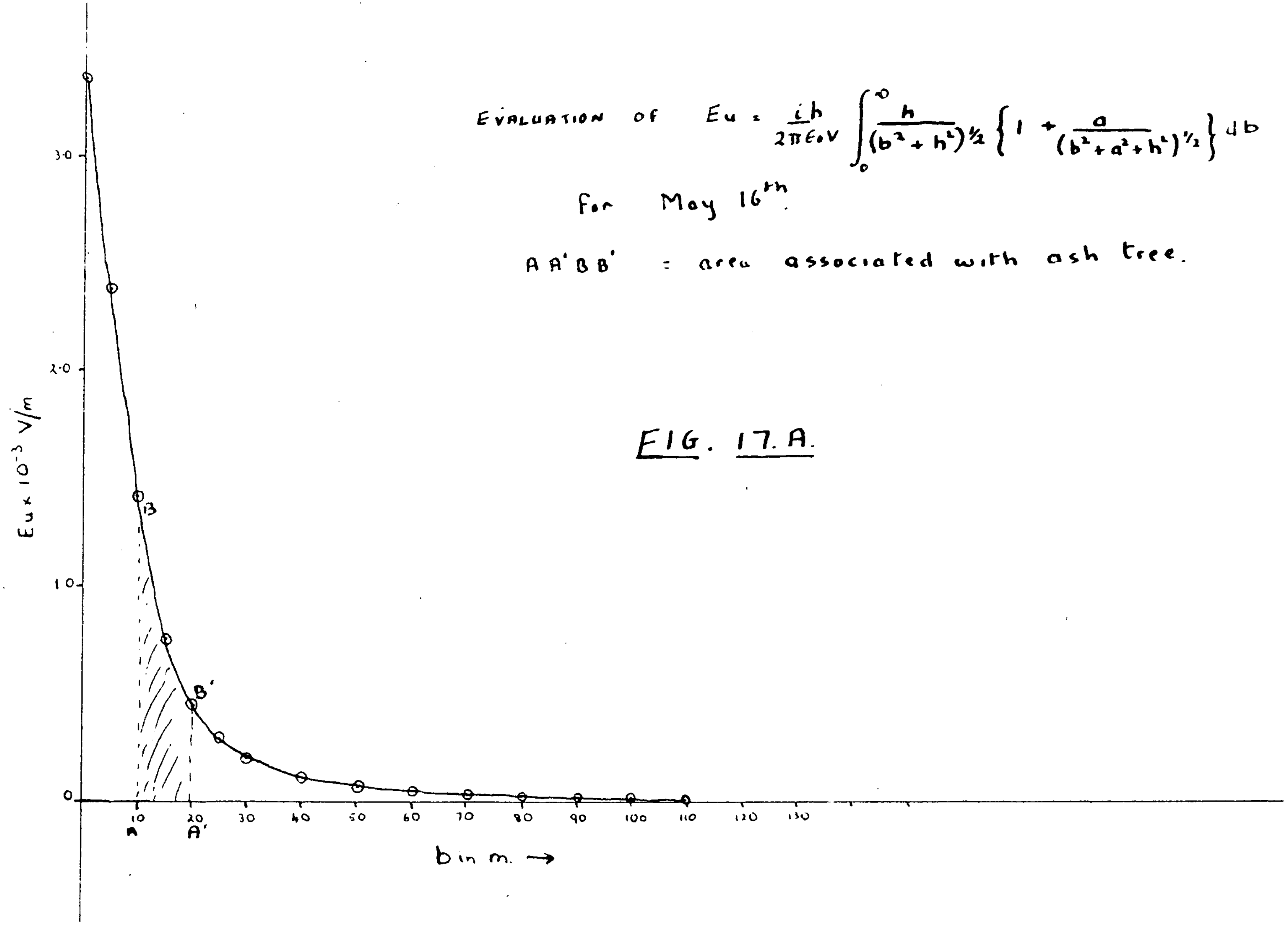


FIG. 17. A.

CHAPTER 6

RESULTS FROM THE LINE OF TREES AT THE OBSERVATORY

6.1. Line of Trees at the Observatory

As stated in the previous chapter certain of the records from the work on the single elevated point at the observatory had to be rejected owing to the masking of the potential gradient by space charge presumed to be liberated from a line of trees located upwind of the field mill system. The trees were of similar shape and size and evenly spaced in a line lying to the North of the upwind field mill and at right angles to the line of field mill sites. It was decided to re-examine the rejected records in the hope of finding instances during which conditions were sufficiently stable to enable the discharge characteristics of the line of trees to be assessed.

All the available records were examined and at the time of writing three records, each of approximately one hour duration, taken on December 12th and 13th 1956 and May 16th 1957 were considered suitable for analysis.

6.2. Potential Gradient due to Ions Liberated from the Line of Trees

Figure 17 shows the position of the line of trees relative to the field mill sites.

AB is the wind direction for the period under consideration.

The calculation for a sheet of charge involves an unsolvable integral so it was decided to evaluate the vertical potential gradient resulting from a succession of line charges and perform the final integral graphically.

The vertical potential gradient at the point P due to an infinite line of charge along AB is given by.

$$Ev = \frac{i}{V} \frac{h}{2\pi \epsilon_0} \left\{ 1 + \frac{a}{(b^2 + h^2 + a^2)^{1/2}} \right\} \frac{1}{(b^2 + h^2)}$$

Where i is the current to earth in micro-amperes, V the wind speed in metres/sec and h the estimated height of the stream of ions in metres.

Ev was calculated for a range of values for b at 10 metre intervals and for h = 8 metres.

The value selected for h was three quarters of the extreme height of the trees. The results of the calculations for May 16th are shown in Figure 17b. For most values of a for b $>$ 40 metres Ev rapidly approaches zero so if AB lay in such a direction that "b" for the downwind mills was greater than 40m the effect of the ion stream on the downwind mills could be discounted.

The final graphical integration gave

$Ev = 34 \frac{i}{v} \times 10^3$ V/m for the wind direction on December 12th and 13th.

and $Ev = 40 \frac{i}{v} \times 10^3$ V/m for the wind direction on May 16th.

6.3. Measurement of Potential Gradient Reduction at Upwind Field Mill

On the first two occasions, December 12th and 13th, the wind lay in the South West and the downwind field mills were across the line of sites. Thus field mill 1, Figure 17, was greater than 40m away from the edge of the ion cloud liberated at the trees and therfore unaffected by the ion cloud. After correction for the known current down the mast the signal from field mill 1 was used as a measure of the actual potential gradient.

On May 16th the wind was blowing from the West and it was not possible to use the downwind mills to measure the potential gradient as the space charge liberated by the trees had begun to divide into dense and less dense regions which caused large and upredictable fluctuations in mill output. In this case the point discharge current was used to measure the undisturbed potential gradient.

Kirkman (1957) working on the same point established that the point discharge current i, wind speed W and potential gradient M were related by

$$i = a\,(W + C)\,(F - M)$$

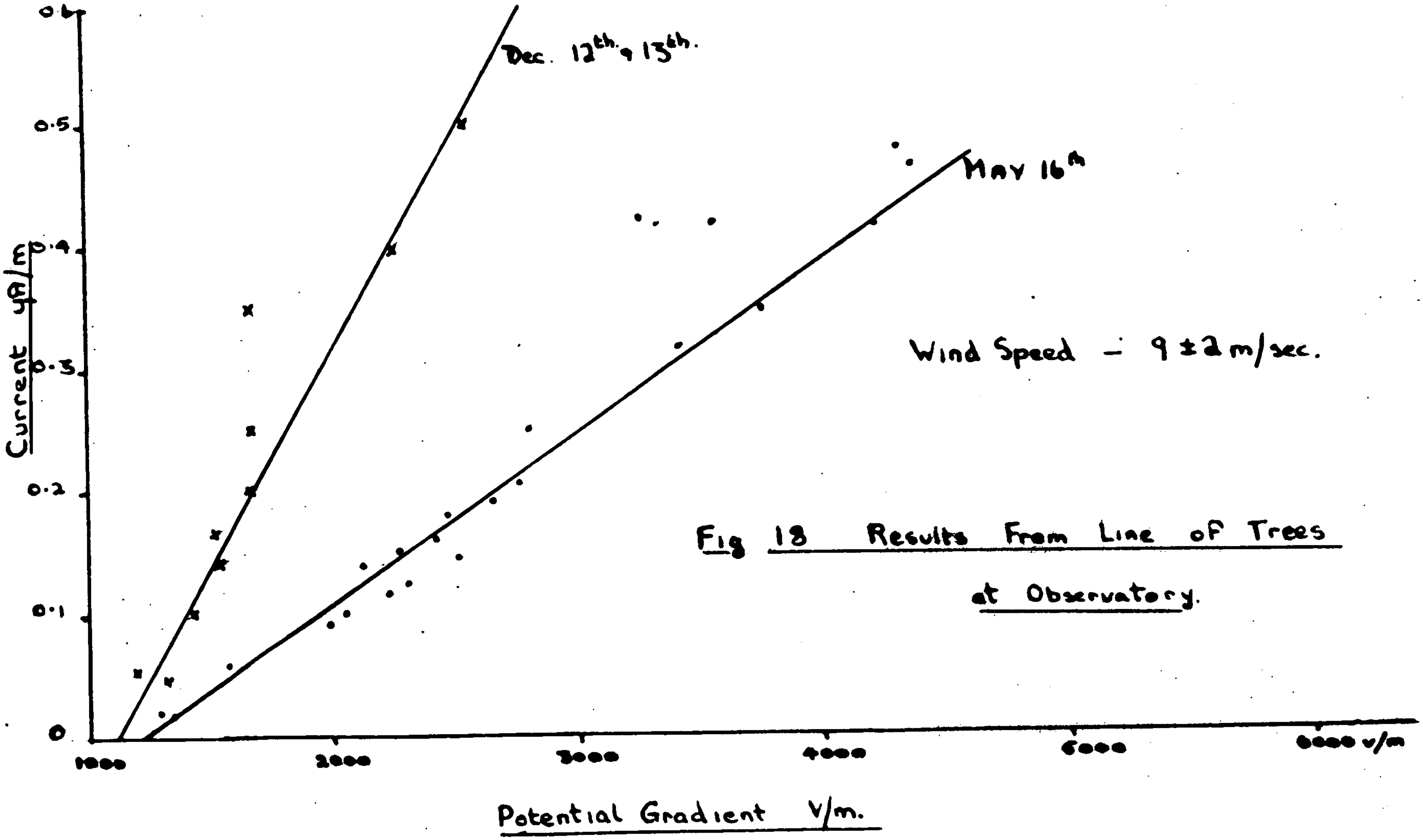
Where C and M are constants characteristic of the point and its location.

When analysing the record of May 16th those parts of the record which were unaffected by space charge liberated by the trees, that is those regions during which the potential gradient was less than ± 1200 V/m, were measured and the results fitted to the above expression.

The family of curves obtained were then extrapolated beyond 1200 V/m and the absolute potential gradient for the entire record obtained from the measured point discharge current and wind speed.

6.4. Results for Line of Trees

The records were examined and periods selected in which the measured parameters remained reasonably steady for periods not less than 30 seconds. The undisturbed potential gradient was obtained from either one of the downwind mills or the point discharge current down the mast, and the reduction by space charge of the potential gradient



Wind Speed – 9 ± 2 m/sec.

Fig 18 Results From Line of Trees at Observatory.

at the upwind field mill calculated.

The point discharge current/metre along the line of trees was evaluated and the results have been plotted in Figure 18.

The ordinates are in micro-amps/metre and the abscissae undisturbed value of the potential gradient in volts/metre. The wind speed was reasonably constant and in the region of 9 metres/sec on all three occasions.

It must be noted that the value of the current down the line of trees given Figure 18 cannot be assumed to be the true value of the current as the wind speed used to calculate the current was measured 35 m above the ground and might bear no relation to the wind speed to the leeward of the trees. The measured value of the windspeed could not be transposed to 8 m. by the normal 1/7 power law since this does not apply in such undulating country. The value of the results is in the relation between point discharge current and potential gradient and the change in gradient between summer and winter.

The results show a surprising and remarkable difference between the two periods on which they were taken. It is difficult to explain why the two curves should have gradients in the ratio 3.1:1. This difference is very apparent on inspection of the records. On the December records, for constant wind speed, when the potential gradient reached the onset value of the line of trees there was a rapid reduction in the signal from the upwind field mill even though the point discharge current continued to rise. On the occasion in May the corresponding reduction in potential gradient at the upwind field mill was gradual and very significantly different from the December records.

The only observable difference between the two occasions was the condition of the leaves on the trees. All the trees were deciduous and on May 16th all but one of the trees, an ash tree, were fully covered. This ash tree was situated near the upwind mill and the possibility of the ash tree alone being responsible for the May results will be discussed later in conjunction with results obtained from a single tree on the Durham City Golf course.

It was thought that there were an insufficient number of recordings to attempt some quantitative analysis of the point discharge characteristics of trees. However similarities with the characteristics of single points were suggested and these similarities indicate the possible value of a more comprehensive study by this method.

Results would have added value if they could be made around a single isolated tree when the measurements of potential gradient would become much easier and the assessment of controlling factors simpler. For this reason it was decided to build transportable equipment and make measurements around a single isolated tree situated in the middle of the fairways of the local golf course.

CHAPTER 7

APPARATUS FOR MEASUREMENTS AROUND A SINGLE ISOLATED TREE

7.1. Apparatus Required

The results from the line of trees at the observatory showed that it was possible to obtain the point discharge current down natural objects from suitable potential gradient measurements. The results also indicated the potential value of measurements around a single isolated tree in that there seemed to be unexplained changes in point discharge characteristics with the season of the year. It was therefore decided to build equipment to make potential gradient and wind speed measurements around an isolated sycamore tree located on the local golf course.

The apparatus required for measurements was a direct reading anemometer and two field mills capable of working in all weather conditions and measuring potential gradients between ± 10,000 V/m.

Unfortunately it was not possible to establish a permanent observing station at the tree and consequently all the apparatus required had to be transported to the golf course whenever conditions were considered suitable for recording. A van was available for transporting the equipment but it was not entirely at our disposal and the anemometer and recording equipment had to be self-contained and capable of being quickly lifted in and out of the van.

7.2. The Anemometer

A cup generating anemometer was similar to that used in the work at the observatory was constructed and mounted on a sectional aluminium mast 5 metres long. The output was rectified and passed through a sensitive galvanometer and the signal recorded photographically as described in a later section.

Calibration was carried out in the wind tunnel of the Northumberland Division of the National Coal Board.

7.3. The Field Mills

It was originally intended to build two self-contained field mills which would only require a power supply for the motor and give a D.C. output proportional to the sign and magnitude of the potential gradient. It was hoped to use transistor amplifiers throughout and rectify the output with a commutator mounted on the same shaft as the rotating vane of the mill.

An experimental instrument was constructed on these precepts but it was found that the input impedance (50K) of the transistors available at the time, even when run in grounded collector working, was too small by an order of magnitude and the input stage of the amplifier had to be replaced by an electrometer valve. An electrometer was selected because of its low heater power consumption and small H.T. voltage.

The electrometer followed by an OC71 transistor gave an adequately stable voltage amplification of 20X, but this stability was destroyed when the output was rectified by the commutator when the variations in sliding resistance of the brushes caused unwanted fluctuations in the output. This was a consequence of the output impedance of the transistor being of the same order of magnitude as the

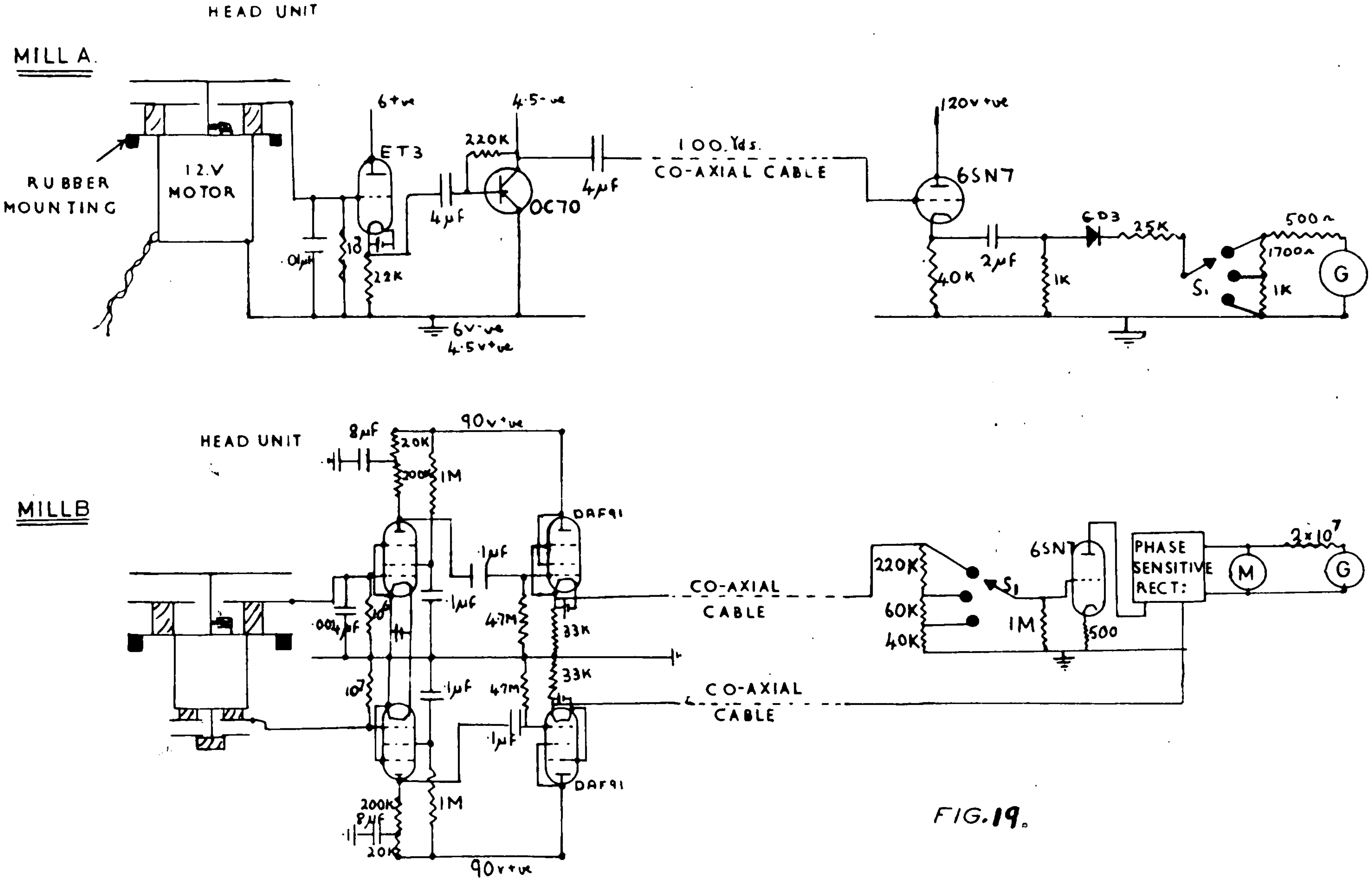

HEAD UNIT
MILL A.
RUBBER MOUNTING
12.V MOTOR
·01µF
10
22K
6+ve
ET3
4µF
220K
4·5-ve
OC70
4µF
6V-ve
4·5v+ve
100.Yds.
CO-AXIAL CABLE
120v+ve
6SN7
40K
2µF
1K
GD3
25K
S₁
500Ω
1700Ω
1K
G
HEAD UNIT
MILLB
8µF
20K
200K
1M
90v+ve
DAF91
·1µF
·1µF
·004µF
10⁷
47M
33K
33K
10⁷
·1µF
47M
·1µF
DAF91
200K
8µF
20K
1M
90v+ve
CO-AXIAL CABLE
CO-AXIAL CABLE
220K
60K
40K
S₁
1M
6SN7
500
PHASE SENSITIVE RECT:
M
2x10⁷
G

FIG. 19.

brushing resistance and therefore the power output from the amplifier became a function of the brushing resistance. Since it was impossible at the time to obtain transistors with a higher output impedance the only solutions were to abandon transistors and use normal valves or dispense with sign discrimination. For the intended application it was not necessary to have two field mills able to discriminate between positive and negative potential gradients so it was decided to build one transistor field mill without sign discrimination and a second mill similar in design to those employed in the project at the observatory.

The circuit finally adopted for the first field mill is shown in Figure 19. The first two stages were in a vibration proof mounting in the head unit and the 6SN7 and point contact rectifier on a small rack carried in the van. The second cathode follower had to be incorporated to obtain an output that was independant of the temperature induced fluctuations in the diode. The selector switch S1 was so designed that through a range in sensitivity of 3:1 was available a constant load was presented to the cathode follower output.

The complete circuit for the second field mill, Mill B, is also shown in Figure 19. Experience in the laboratory indicated that nothing could be done to kepp the brushing resistance constant at the required commutator diameter so recourse was made to a reference generator and phase sensitive rectifier. To reduce the number and weight of the cables to the head unit, and thereby make handling easier the amplifiers were designed to use battery powered valves.

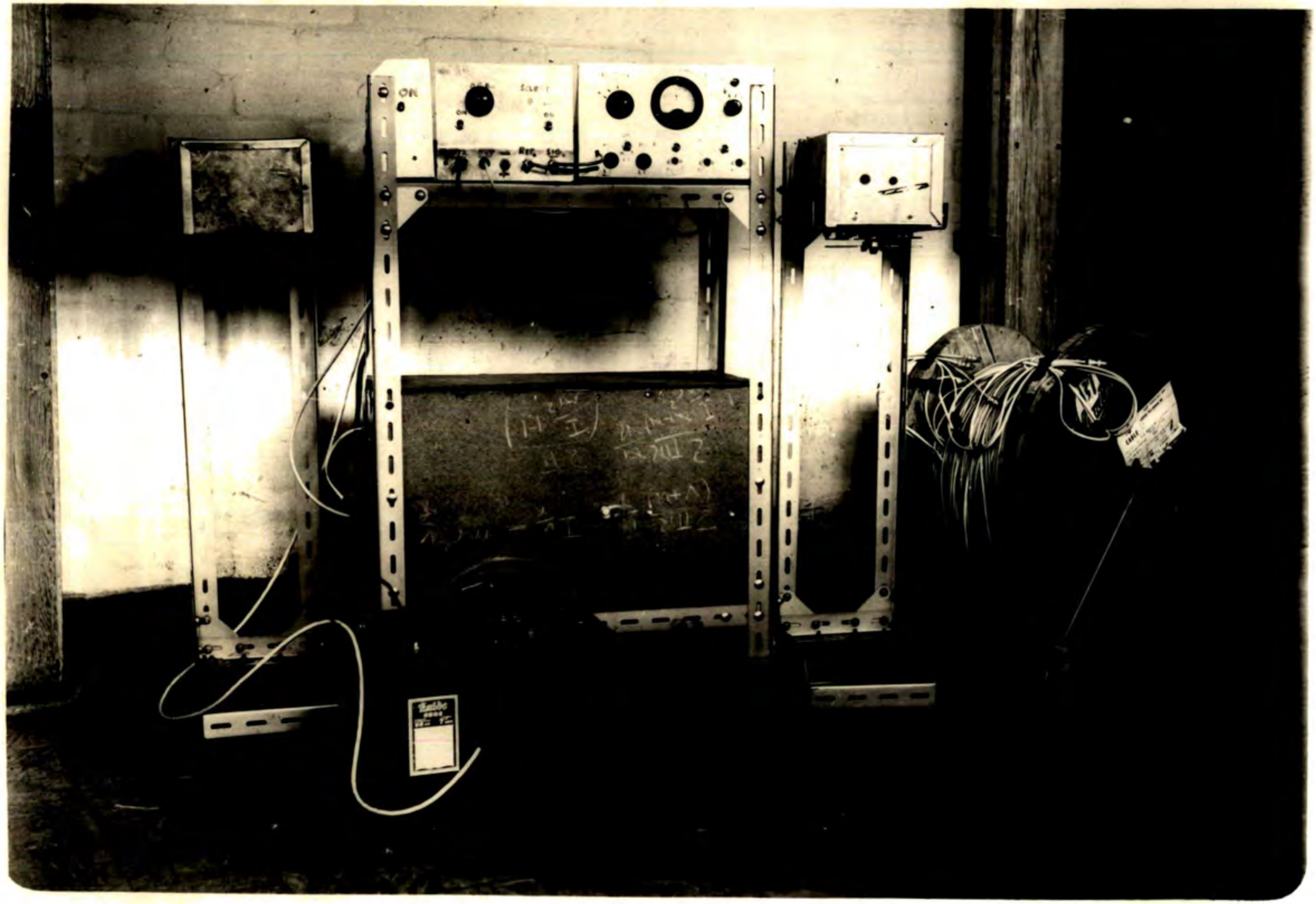


FIG.20. EQUIPMENT FOR WORK ON GOLF COURSE

This involved carrying three separate low tension supplies as the cathodes of the two output cathode followers had to be electrically isolated. To have used independently heated cathodes and run the motors off the low tension supply to the motors would have greatly increased the current to be supplied to the mill and consequently increased the low tension voltage lost in the cables.

The use of the triode valve before the phase sensitive rectifier avoided having to pass the high tension voltage from the signal output valve down 100 yds of the co-axial cable. Sensitivity changes were made by selecting all or part of the input to the pre-amplifying triode. The meter M enabled all changes in the sign and magnitude of the potential gradient to be easily followed.

The final outputs from both field mills were passed through sensitive mirror galvanometers of periodic time 2 seconds and the deflections were recorded photographically.

The two mills were mounted on 1m high portable aluminium stands and were inverted to avoid insulation breakdown during very heavy rain.

A small rack, Figure 20, carried the two rectifiers and the head units rack were coupled together by 100 yd lengths of high grade co-axial cable which were wound on a large drum and unrolled as required. The low tension supply for the mill motors and various equipment on the rack was supplied by a 12v car battery and two 2V accumulators.

7.4. Method of Recording Signals

The recording of the two field mill anemometer signals presented rather a difficult problem. It would have been conceivable

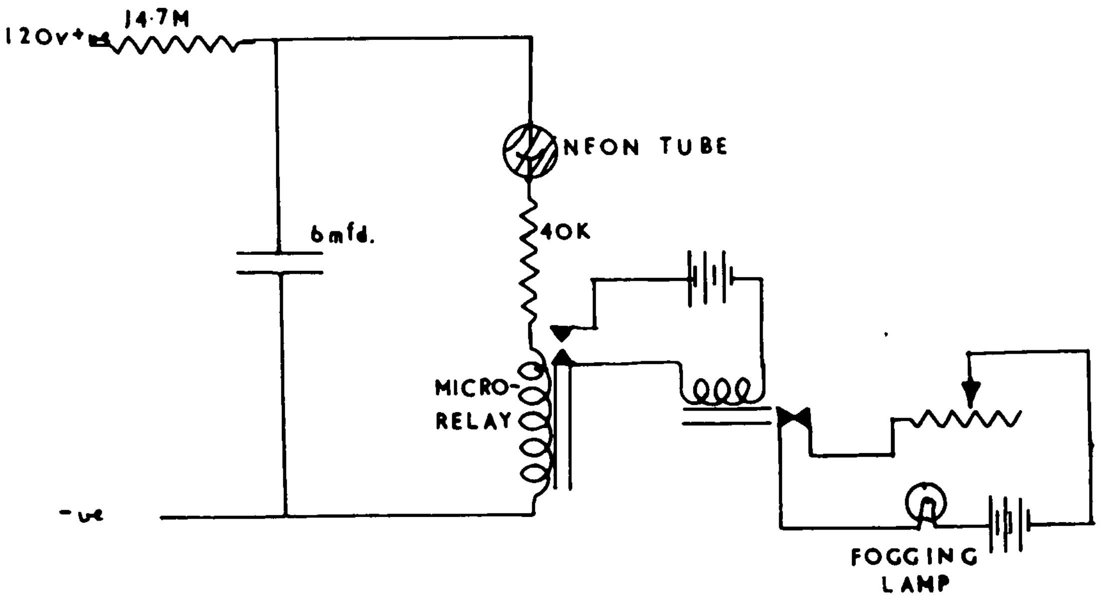


FIG. 21. TIMING CIRCUIT

to record the two field mill outputs visually on milliameters but this was impossible for the anemometer from which the maximum power output was only a fraction of a micro-watt. The only possible solution, without recourse to expensive chart recording, was to try and record the signals photographically using mirror galvanometers and sensitised paper.

The lower half of the small rack was boxed in and the galvanometer rigidily mounted at one end. The galvanometer lamps were altered to focus down to 61 cms and the reflected spots focused onto a small camera mounted just beneath the lamps. The camera was built to carry 12mm. wide photographic paper and was driven through the camera at a speed of 2cm. a minute by a small motor mounted inside the camera case.

Time checks were placed on the record by a neon discharge tube circuit (Figure 21) which switched off a fogging lamp for a period of 2 secs at half minute intervals.

Three levelling screws were fixed to the base of the rack.

Under normal operation the rack was left in the rear of the van and once levelled, provided the galvanometers were kept dry, could be relied upon to give trouble free recording.

7.5. Performance and Calibration of Apparatus

The two field mills were calibrated on all sensitivity ranges by applying positive and negative voltages to a metal plate placed under the mill close to the rotating vanes. The potential gradient equivalent to a given voltage on the plate was determined by comparing

FIG. 21. A. SITE AT DURHAM CITY GOLF COURSE.

the output from the field mill with that from another field mill which had been calibrated in a manner similar to that described in Chapter 4.

In normal working the sensitivity was adjusted to give a full scale deflection for potential gradients of magnitude 0-2000 V/m, 0-4,000 V/m and 0-10,000 V/m. For the purposes of absolute calibration the large shunting capacitor across the output from the field mill vanes had to be removed.

The working point of Mill B showed a slight tendency to wander and it was necessary to earth the input at ten minute intervals throughout all recording. This wandering was partly due asymmetry in the switching valve of the phase sensitive rectifier and partly due the leakage caused by the damp conditions under which the equipment was normally operated to earth across the recording galvanometer.

Calibration checks equivalent to two-thirds of the full scale deflection were applied means of the close fitting plate at the beginning and end of each recording period.

7.6. Site and Arrangement of Equipment

The tree selected for the measurements was a 12m.high sycamore situated in the centre of the fairways of the Durham City golf course. It was surrounded on all sides by closely mown grass, Figure 21A The nearest trees were over 100m away and could in no way influence potential gradient measurements made near the base of the sycamore.

Whenever conditions were considered suitable for recording the apparatus was transported to the golf course and the van parked on a level piece of ground beneath the tree Figure 21.A. The wind direction was observed and one field mill placed 15m. upwind and the other 15m. downwind of the tree. The sign discriminating mill was used on the upwind side as it was hoped to use relatively rapid response time of the meter M to make visual qualitative observations of the more rapid fluctuations in downwind potential gradient.

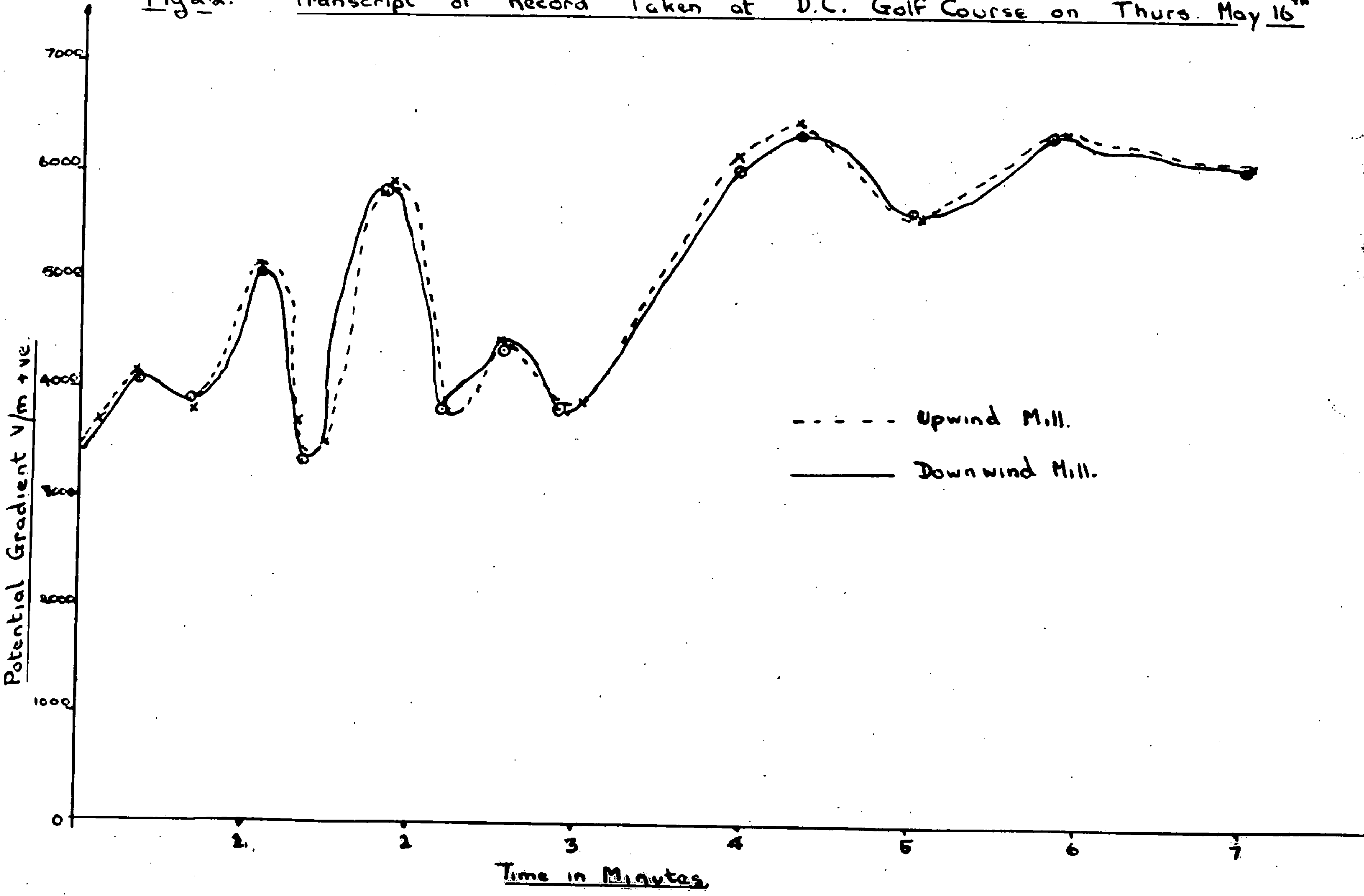
The tree was sufficiently symmetrical for any distortion of the potential gradient by the tree to affect both field mills to an extent no differing by an amount greater than the inherent error of the instruments. Wind direction changes of 20° either side of the line of the field mills could be tolerated before any significant changes in output would be reasonably expected to occur. (Chapter 2).

The anemometer was placed in a position in which it could in no way interfere with the measurements of potential gradient either by screening the field mills or by liberating ions by point discharge in very high potential gradients.

If the significant changes in wind direction during the progress of a record were observed the appropriate changes were made to the arrangement of the field mills and anemometer mast.

As previously stated calibration marks were placed on the record at convenient intervals and any zero drift followed by earthing the input to the amplifiers on the rack at ten minute intervals.

Fig 22. Transcript of Record Taken at D.C. Golf Course on Thurs. May 16th



CHAPTER 8

RESULTS FROM DURHAM CITY GOLF COURSE

8.1. Introduction

From April to August 1957 it was possible to record on only three occasions, with a total recording time of three hours.

The dearth of periods of high potential gradient was a consequence of the position of Durham City, Situated between the eastern edge of the Pennine chain and the sea, and with prevailing wind directions in an E - W line, cloud forms of the type required were either building up off the sea or dying away after crossing the Pennines and the full electric potential was very rarely experienced.

The first recording was beneath a dying cumulo-nimbus cloud and the complete transit of the cloud was recorded, on the other two occasions lightning flashes were observed from the cloud and the recording had to be terminated when the potential gradient fluctuations became too variable to have any real significance.

The potential gradients varied between +7,000V/m and -3000 V/m and the wind speed from 3m/sec to 9 m/sec.

8.2. Results

Throughout the three recording periods no significant differences were observed between the potential gradient recorded by the upwind and downwind field mills. A transcript of part of one of the records is shown in Figure 22. Time scale of the downwind mill has been adjusted in proportion to the wind speed ($\simeq$ 5m/sec) so brining the two traces into coincidence and emphasising the similarity.

The transcript clearly illustrates the degree of correlation that existed between the two field mill outputs and the results shown are characteristic of the entire three hours recording.

Even if an insufficient number of ions had been liberated by the tree to make a quantitative assessment of the current their presence should have been revealed qualitatively as small fluctuations of the downwind field mill trace. These fluctuations are characteristic of any potential gradient measurements made on the downwind side of a discharing point and have been observed and published by Whitlock and Chalmers (1956) and Large and Pierce (1957) and also by ourselves in all the work with a single point at the Observatory.

It must be concluded, therefore, that any ions liberated at the tree during our investigations must have been below the level of detection of the equipment employed.

8.3. Discussion of Results

There can be little doubt that the potential gradients measured were of the correct order of magnitude since the site was a mile away from the observatory buildings and on the first occasion simultaneous recordings were made at both sites. The difference in absolute maximum value of potential gradient reached at the two sites, 5,000 V/m at the observatory and 7,000 V/m at the golf course, can be accounted for by the considerably better exposure of the golf course and that the centre of the cloud passed over the golf course and not the observatory.

The constant check made of the calibration would have detected any changes during the progress of a record or from one record to the next.

If the upwind mill is assumed to be screened from the space charge by the tree and the centre of any liberated ions is considered to be 10m above the ground - the tree was 12m high to the tip - then the difference in potential gradient at the downwind mill is given by

$$Eu - Ed = 4.1 \frac{i}{v} \times 10^3 \text{ V/m}$$

where i is current down the tree in micro-amps and v the windspeed in metres/sec.

For the section of record shown in Figure 22 the wind speed was of the order of 5 m/sec,

$$\therefore \quad Eu - Ed = 820 \, i \text{ V/m}$$

The field mills were capable of measurements to an accuracy of ± 5% therefore for an upwind potential gradient of 7000 V/m, the maximum observed, a difference of 700 V/m or greater between the upwind and downwind field mills could be regarded as significant. Therefore for the assumed conditions of charge height and wind speed on the instance under consideration the point discharge current down the tree must have been less than 1 μ amp. This is the most conservative estimate of the sensitvity of the equipment but a current down the tree of less than 1 micro-amp at 7,000 V/m and wind speed of 5 m/sec will serve for comparison with other workers results.

With an 8m artifical point at Kew Whipple and Scrase measured currents of the order of 2.5 μ at 7,000 V/m and Wormell at

Cambridge with a 12m point observed currents some three times those obtained at Kew.

From the descriptions published the site at Cambridge had an exposure very similar to that of the tree on the golf course so that, if the equivalence of point and tree were an established fact, one would have expected a current of 7 µa down the tree at 7,000 V/m. This current would have a difference in potential gradient between the two field mills of over 5,000 V/m and could not possibly have escaped detection.

The only other published results of the discharge current down a single tree are those of Schonland (1928) for a 4m tree in South Africa and his published results were:-

Potential gradient V/m	Current µa
- 3,500	0.07
- 5,500	0.20
-11,000	1.00
16,000	4.00

For ± 7,000 V/m the current down the tree would be of the order of .3 µa. The results of Kirkman and Chalmers (1956), as analysed by Chalmers (1957) give the current to ~~the~~ be linearly dependent on the height of the point which when applied to Schonland's results predict a current of .9 µa for 1 12m. tree in a potential gradient of -7000 V/m. In the present case this would have been on the limit of quantitative measurement but should have been detected as irregularities in the downwind field mill trace.

The results from the line of trees at the observatory indicate a significant change in characteristics from winter to summer which can only be attributed to the presence of leaves on the trees and a general smoothing of the outline of the tree. Schonland's tree was a small thorn bush without leaves which could be expected to pass a higher current to earth than a heavily leaved sycamore of similar height.

It might be interesting to discuss what the onset potential gradient for point discharge current to pass down a symmetrical tree in full leaf might be. Wilson (1925) reported experiments in which the potential gradients were of the order of 20,000 V/m. The tree on the golf course was regular in outline (Figure 21A) and might be approximated to a hemisphere. A potential gradient of 20,000 V/m at the surface of the supposed hemisphere would correspond to a potential gradient of 7,000 V/m at the surrounding level ground - the maximum field reached in the present experiments.

8.4. Re-Appraisal of the Results from the Line of Trees at the Observatory

The results from the line of trees at the observatory are ~~in~~ at first sight somewhat confusing as one would expect the effect of leaves to appear as a change in onset potential; but for the summer results an ash tree quite close to the tree was without leaves and would still be expected to commence discharging at 1200 v/m. This means that the majority of the point discharge current passed to earth via the ash tree and that the most dense regions of the ion cloud would be in line with the ash tree. On this assumption it is possible to calculate the reduction of the potential gradient, the result is.

$$Eu - Ed = 9.2 \frac{i}{v} \times 10^3 \text{ V/m (see Fig. 17b)}$$

or a fraction $\frac{9.2}{34.0} = \frac{1}{3.6}$ of the reduction expected from the entire line of trees. From figure 18 the measured ratio is $\frac{1}{3.1}$ which indicates a measure of agreement with the predicted value. Any discharge from the remainder of the line of trees would, of course, decrease the theoretical value for the ratio.

The results from the observatory and golf course could therefore be reconciled if it is assumed that there is a very significant change in the discharge characteristics of trees between summer and winter and that this difference is in some way correlated with the appearance of the leaves.

The appearance of leaves on a tree does significantly change the specific resistance of the trunk. Measurements made in conjunction with J.R. Kirkman over a period of twelve months on a growing lime tree at Durham University Science Laboratories gave a resistance to earth approximately equal to 50 K in the winter and 15 K in the summer for a tree 10m high, with fluctuations about these values with the dampness of the ground. For currents of the order of microamps the change in potential at the top of a tree would be several orders of magnitude tooosmall to influence the progress of the discharge.

The only other conceivable effect of the leaves is a general smoothing of the outline of the tree and a reduction of the potential gradient irregularities at the surface of the tree.

Schonland commented that he could observe no difference in the current down the tree when he wired leaves into his tree mounted on insulators but it is difficult to conceive him obtaining anything like the coverage of the naturally occurring foliage.

8.5. Implications of Results

The implications of the results from the golf course are immediately apparent. The assessments of the total point discharge current towards the base of a cloud based on the equivalence of point and tree would have to be revised.

There can be little doubt that the results of Gish and Wait and Sturgis, Rein and Kangas are substantially correct and indicate a total current upwards above the average thundercloud of 0.5 - 1.5 amps. Since the majority of measurements of the electrical structure of thunderclouds give nearly equal quantities of positive and negative charge residing in the cloud there can be no accumulation of space charge within the cloud and the electric conduction current existing beneath the cloud must be equal to the magnitude and direction of the electric current measured above the cloud.

As mentioned in the introduction, assuming that the rain current measurements are not grossly in error due to undetected splashing effects, the only possible source of positive electric conduction current towards the base of a thundercloud is corona discharge from objects (trees etc.) beneath the cloud. If the results obtained from the Durham Golf course are characteristic of all trees this corona discharge commences at a considerably higher potential gradient that previously considered. Existing estimates of the corona discharge current density are based on the excess of positive over negative upward current through an elevated point, raising the onset potential would reduce the total current passed but would also increase the ratio of positive current to negative current. Whether the increase of the positive/negative ratio would be sufficient to offset the loss in magnitude and give the same excess of positive current is impossible to infer from the present results. Only continuous observation over several years could yield a significant answer to this question.

Unfortunately the results are of little help in a re-appraisal of the alti-electrograph results of Simpson et al. Though they might be interpreted as indicating a reduction in the point discharge density no other solution of the balance of charge problem between the regions above and beneath the thundercloud has been suggested.

8.6. Conclusions

Within the bounds imposed by the somewhat limited recording time the following conclusions can be drawn.

(1) For the sycamore tree under consideration the corona discharge current is less than 1 microamp for potential gradients up to ± 7,000 V/m.

(2) The corona discharge characteristics of a tree in summer are significantly different from those of an isolated artificial point of similar height and exposure. The principal difference is a considerable increase in onset potential gradient.

(3) There is an apparent change in corona discharge characteristics with season which may be correlated with appearance of leaves and consequent change in outline.

8.7. Suggestions for Further Work

(1) Measurements similar to those made at Durham City Golf course should be taken over both winter and summer months and if possible to potential gradients greater than ± 7,000 V/m.

From experience gained on the present project the work would be greatly facilitated if a small van could be instrumented for the purpose as this would save valuable time getting to the site when conditions were suitable for recording.

(2) If possible the measurements on a single tree should be extended to single trees of different shape. Comparison of onset potential should reveal the importance of outline on discharge characteristics.

(3) Measurements made on the line of trees at the observatory are more sensitive than single tree measurements and could be used for a continuous check on seasonal changes in discharge characteristics.

(4) The results of the analysis of the effect of rain on the ion cloud from a discharing point suggests a method for directly checking the Whipple and Chalmers analysis of the Wilson charging process. The analysis showed that the falling drops leave the ion cloud with a charge of $-\frac{12\times a^{2}\bar{E}}{4\pi\epsilon_{0}}\epsilon$, measurements of rain current beneath and to one side of the ion cloud would directly test this result and could be used to

the charging process. The method has the advantage that the ion cloud be artifically created quite close to the ground and the measurements carried out under steady state conditions.

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