Point discharge in atmospheric electricity

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POINT DISCHARGE IN ATMOSPHERIC ELECTRICITY

by

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ABSTRACT.

Investigations of the current from an earth-connected point 0.002 cm in diameter, supported by masts at heights of 20m, 27m and 34m are described. Simultaneous measurements of the potential gradient at the ground to windward of the point, and wind speed at the point, indicate that the current can be represented by the equation

$$I = K(W + C)\ (F - M)$$

where I is the point discharge current in microamps

W the wind speed in metres per second

F the potential gradient in volts per metre

M the onset value of the potential gradient

(200 v/m at 20m, 135 v/m at 27m, 100 v/m at 34m)

C and K are constants

($C = 4$ m/s and $K = 2.56 \times 10^{-4}$ μa per v/m per m/s at 27m)

The general equation still holds when the potential gradient is measured 7m below the 34m mast but at 2m below the 20m point the equation is

$$I = A(W + D)\ (F - M)^{n}$$

where A and D are constants

n is dependent on wind speed.

Measurements of point discharge currents down the trunk of a tree indicate that these are somewhat lower than those through a single point of corresponding height in similar

conditions.

The results are compared with those of previous workers and discrepancies are attributed to wind speed and wind direction effects, whilst good agreement is found between the present findings and the theoretical work of Chalmers and Mapleson (1955) and Chapman (1956). A reassessment of the Alti-Electrograph results of Simpson and Scrase (1937) is made and suggests that the potential gradients measured by this means immediately below thunderclouds are of the same order of magnitude as those measured by observers in aircraft (Gunn 1953).

FOREWORD.

The work described in this thesis falls into two distinct parts.

Firstly, the work undertaken at the Science Laboratories during the period from October 1952 to August 1954, when a 65 ft single pole mast was used to support the discharging point and secondly, the work carried out at the Durham Colleges Observatory from September 1954 to May 1956, when a triple pole mast extending to 90 ft and later 110 ft was used.

These periods are treated separately and in chronological order, but the subsidiary problem of point discharge from natural objects, studied during both the above periods, is reported in a separate chapter towards the end.

Wherever possible free use has been made of diagrams and photographs in order that lengthy descriptions of the various pieces of apparatus constructed may be avoided.

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CHAPTER I.

INTRODUCTION.

1. General.

The study of the electrical properties of the earth's atmosphere is conveniently confined to the region between two equipotential surfaces, the earth and the ionosphere.

The concentricity of, and the difference in potential between these highly conducting surfaces suggests an analogy to a spherical condenser, which, having between its plates the poorly conducting atmosphere, is therefore leaky.

Gish (1951) estimates this leakage current to be 1,800 amps across the effective atmospheric resistance of 200 ohms, giving a difference in potential between ionosphere and earth of 360,000 volts and a potential gradient at the earth's surface of about 100 volts per metre.

Scrase (1933) has shown that, under the influence of this current the earth would lose its net negative charge in a few minutes, but as no such loss occurs some kind of charging mechanism must be operative.

The suggestion made by Wilson (1920) that negative charge might be expected to arrive at the earth in regions experiencing stormy weather, was later confirmed by Wormell (1927, 1930), Schonland (1928) and others, whilst Whipple (1929) and Whipple and Scrase (1936) were able to show a close correlation between diurnal variation of world-wide thunderstorm activity and potential gradient in unperturbed conditions. This, together with the estimated 3,000 - 6,000 daily thunderstorms and Gish and Wait's (1950) average value of current between ionosphere and thundercloud top of 0.5 amps per storm, leaves little doubt as to the origin of the recharging process.

1.1 Process of Charge Transfer.

There are four main processes by which charge can reach the earth:-

(a) Ionic Conduction: The continuously operative leakage current caused by the motion of ions in the atmospheric potential gradient.

(b) Point Discharge Current: A form of conduction current, but differing from (a) in magnitude and its dependence on potential gradient. It occurs naturally when ions, moving into the local intensified potential gradient about a pointed conductor, produce fresh ion pairs by collision. Currents through conductors such as trees and buildings are of the order of microamps in the large potential gradients associated with thunderclouds.

(c) Precipitation Currents: These intermittent currents are due to charges carried on rain, hail and snow moving under the influence of gravity.

(d) Lightning Currents: Occasionally electrical breakdown between cloud and earth occurs, large quantities of charge being transferred.

In order that the charge on the earth should remain constant, it is essential that the charge brought down by stormy weather processes, point discharge, precipitation and lightning, should balance the fair weather conduction current. It was in attempting to assess the contribution of these processes to the balance that the practice of long term continuous recording of point discharge current was evolved.

1.2 The Nature of the Point Discharge Current.

Consider an earthed pointed conductor situated below a negatively charged cloudbase. The potential gradient, already many times the fair weather value at the ground, will be intensified in the region close to the raised point. Of the ions naturally present in the air, those that are negatively charged and moving towards the point under the influence of the potential gradient may acquire sufficient energy to produce fresh ion pairs by collision with gas molecules. The original and the negatively charged of these ions in further and repeated collisions propagate the growth of an ion population in such a manner that the term 'avalanche' is suggested and applied.

The point eventually receives a burst or pulse of negative ions, a series of which constitute the discharge current, whilst the positive ions motivated by the potential gradient, move upward from the point.

Thus in negative potential gradients this localised breakdown brings negative charge to earth via the point; in similar periods of positive potential gradient the earth receives a positive charge.

1.3 Point Discharge Current and the Balance of Charge.

Following the recognition by Wilson that point discharge currents might play an important part in the transfer of charge to earth, Wormell (1927), using both microvoltameter and discharge apparatus, measured the ratio of positive to negative charge brought to earth through an artificial point 8.3m high. By assuming that trees higher than this would collect similar currents, he was able to estimate the point discharge current density at Cambridge; after infering the densities of precipitation, lightning and conduction currents he drew up an 'electrical balance sheet' which showed that, over an area of one square kilometre, 40 coulombs of negative charge were brought to earth during one year.

Wormell points out that these estimations were approximate, displaying either a crude balance or a slight excess of negative charge in that area.

In order to avoid the difficulty of interpreting currents through artificial points in terms of natural points, Schonland selected a tree typical of those in the neighbourhood, supported it on insulators, and measured the currents flowing through a galvanometer connected across the insulation. As well as noting the quantity of charge transferred, he attempted to relate the discharge current with the simultaneous potential gradient at the earth's surface. He concluded that an excess of negative charge was brought to earth by point discharge currents in disturbed weather; Wormell's results showed that the ratio of negative to positive charge arriving in similar periods was approximately two to one.

Measurements of this ratio were subsequently made in various countries. Whipple and Scrase (1936), Chalmers and Little (1947), Immelmann (1938), Allsop (1952), Starr (1933), Perry, Webster and Bagueley (1942), Chiplonkar (1940), Yokouti (1939) and Lutz (1944), all concur that in disturbed weather over land, an excess of negative charge is carried to earth by point discharge currents.

From measurements at Kew, Chalmers (1953) made a further assessment of the 'electrical balance sheet' concluding that, over land point discharge currents brought down an excess of negative charge which might be balanced by an excess of positive charge over the oceans. Nevertheless, he later showed that for clouds with a definite rate of separation of charge the point discharge current density is only slightly affected by the nature of the surface below the cloud (1952a).

Attempts to determine this current density below clouds either from currents through individual points (Schonland (1928), Chalmers (1939) (1944), Meinhold (1948)) or by other means (Simpson (1949)) have produced only approximate results.

1.4 Point Discharge Current and Potential Gradient.

After comparing the point discharge current with the simultaneous potential gradient at the earth's surface, Whipple and Scrase postulated a relationship of the form

$$I = A(F^2 - M^2)$$

I is the discharge current in microamps.

F is the potential gradient in volts per centimetre.

M is the value of the potential gradient at the onset of the discharge.

A is a constant.

No indication of the goodness of fit of this equation is given although Chalmers (1952b) has deduced it from various assumptions for points in a rectangular array.

Hutchinson (1951) achieved similar results to those of

TABLE I.

Ratios of negative to positive charge brought to earth and values of 'A' and 'M' in the equation $I = A(F^2 - M^2)$ for various observers.

Observer	A and M		Height	Ratio
	Negative	Positive		
Whipple & Sorase	A = 0.001 M = 8.6 v/cm	A = 0.0008 M = 7.8 v/cm	8.4m	1.7
Chiplonkar	≠ A = 0.0006 ≠ A = 0.003 (multiple points)		8.4m	3.1
Hutchinson	A = 0.0005 M = 4 v/cm	A = 0.0009	11m	-
Schonland	A = 0.00016		4m	-
Yriberry	A = 0.000086 M = 21.4 v/cm	A = 0.000063 M = 51.5 v/cm	3.12m	-
Wormell			12.3m	2.0
Chalmers & Little			≠ 9m	1.36
Immelmann			7m	2.8
Allsopp			6m	2.2
Starr	12 v/cm		9.3m	-
Perry, Webster & Begueley			10.9m	2.86
Lutz	6 v/cm		17m	2.0
Yokouti				2.1

≠ Estimate.

Whipple and Scrase, although he tentatively suggested that the initial increase of point discharge current with the square of the potential gradient gave way to a linear relationship for higher values of potential gradient.

Confirmation of the square law equation is also given by Chiplonkar (1940) and Yriberry (1954), but the four values given by Schonland, like the balloon results of Davis and Standring (1947) and the kite studies of Rengs (1942) do no more than suggest an increase of current with increasing potential gradient.

Details of the points used by the various workers are given in Table I.

More recently Chalmers and Mapleson (1955), after a theoretical discussion, arrived at the general equation

$$I = KW^{3-q}(Fh)^{q-1}$$

which when fitted to the results obtained with a balloon-borne point becomes

$$I = 0.015\,W^{\frac{1}{4}}(Fh)^{\frac{7}{4}}$$

where I is the current in microamps, W the wind speed in m/s, F the potential gradient in v/m and h the height of the point in metres. The power of the potential gradient is slightly lower than that found by Whipple and Scrase.

It is interesting to note that Chapman (1955), using dimensional analysis, arrived at a further general equation relating corona current from a point attached to an aircraft to potential and windspeed (or aircraft velocity), i.e.

$$I = E(FkV^2/l + GvV + Hlv^2/k)$$

E_0 = permittivity of free space

F, G, H = non-dimensional coefficients

k = the mobility of the ions

V = the potential of the discharging point relative to the aircraft skin.

v = the airspeed

l = some geometrical length

He considered the three cases in turn when two terms inside the bracket disappeared, e.g. in still air v = 0 and an equation similar to that of Whipple and Scrase is obtained. The derivation of the formula is theoretical [redacted] but convincing experimental results have been offered. See section 8.3.

1.5 Point Discharge Currents and the Height of Point.

The variation of the constant 'A' with height of point in Table I is rather nebulous; at these heights this is expectedly so for the separation of these from points of similar height also needs consideration. Chalmers (1952a) has given reasons for supposing that in steady conditions a constant point discharge current density must be maintained [redacted]regardless of the nature of the surface below the charged cloud base. Decreasing the height of the discharging points would eventually increase the overall potential gradient to a value at which the required current density would again be maintained. Records from individual points, however, would show a reduction in the constant 'A' (and an increase in M) with this decrease of height although little can be gained in attempting to correlate 'A' and 'h' for points of widely differing locations and exposures.

In the case of balloon and kite results, where the point is the sole discharging agency, the variation of current with height might be expected to be shown were it not for the effects of natural space charge as discussed by Chalmers and Mapleson (1955). In favouring the 7/4 relationship mentioned earlier, they are opposed to the linear dependence of current on height found by Davis and Standring.

1.6 Point Discharge Current and Wind Speed.

The space charge, liberated in the environs of the point, produces a reduction in potential gradient at the point itself thus choking off the discharge which recovers only when this charge has been moved to a distance at which it is ineffective. This removal is achieved partly by the overall potential gradient and partly by the wind. It would seem then that the higher the wind speed the greater the rapidity of its removal and hence the greater the resulting pulse frequency of the point discharge current.

Large and Pierce (1955) have shown that under certain conditions these pulses are of constant size and therefore an increase in their frequency will be manifest as an increase in the point discharge current. Thus an increase in current might be expected to accompany an increase in wind speed even though the undisturbed potential gradient, measured at the ground, may remain constant.

Davis and Standring gave evidence of such an increase with wind speed, a factor which Whipple and Scrase had earlier proposed as a cause of scatter in their results. Chalmers and Mapleson found the current to be proportional to the $\frac{1}{4}$ power of the wind speed although their method of wind speed measurement, Mapleson (1953), was rather inaccurate.

1.7 Point Discharge Current and the Number and Separation of Points.

The idea of obtaining the point discharge current density from the current through a single point and the estimated number of like points in a given area, gave rise to a number of experiments with multiple point dischargers.

Currents through Chiplonkar's (1940) four point discharger were about sixty per cent of those through his single point in similar conditions which substantially agrees with Chalmers and Mapleson's fifty per cent reduction for currents through their eight point discharger. On these grounds the assumption that an artificial point is equivalent to a tree of similar height seems therefore invalid.

In contrast to this the laboratory investigations of Kreielsheimer and Belin (1946) disclosed that once point-to-plane corona had been established, the current was proportional to the number of points; they therefore had no hesitation in 'scaling up' the results for a seven point system to obtain the calibration for a thirteen point discharger used in balloon experiments. Too much weight must not be given to these results as the vast difference in scale and the rapid removal of the associated space charge in the laboratory experiments, generally render such findings inapplicable to atmospheric phenomenon.

1.8 Point Discharge Current and Space Charge.

Under the influence of the circumjacent potential gradient, ions of one sign move to the point and form the point discharge current whilst a space charge of the oppositely charged ions moves upward from the point.

The magnitude of this space charge in disturbed weather is often considerable; Lutz (1941) observed periods when a reversal of potential gradient between point and ground level persisted for several minutes. Lueder (1943) and Hutchinson

(1951) cited this as the agency responsible for the frequent time delays between changes of sign of point current and potential gradient.

The calculations of Davis and Standring (1947) showed that this space charge would be expected to produce a reduction of the potential gradient at the ground equal to

$$F = \frac{2I}{VH}\left[1 - \frac{d}{(d^2 + H^2)^{\frac{1}{2}}}\right]$$

where F is measured at a distance 'd' to windward of the discharging point, I is the current, V the windspeed and H the height of the point. They assumed that the liberated space charge under the influence of the wind, would give rise to a horizontal line of charge stretching to infinity. Any other motion or influence on the space charge was neglected.

Whitlock (1955) has indicated reasons why the reduced value of 'F' detected in his investigations are at variance with the product of the idealised assumptions of Davis and Standring. The absence of any such effects in the work of Chalmers and Mapleson illustrates the need of potential gradient measurements well to windward of the discharging point.

Whipple and Scrase deduced that the space charge from the point would also produce an increase in potential gradient just below the cloudbase many times that at the earth's surface, although the Alti-electrograph results of Simpson and Scrase (1937), Simpson and Robinson (1940) and later work by Kreielsheimer and Belin (1946) and Chapman (1953) failed to detect this increase. It has been shown by Simpson (1949) that rain and snow can at times remove most if not all of this space charge, although this sporadic extraction no more assists in resolving the discrepancy between theory and experiment than do the attempts of Chalmers (1939) (1944), Melan (1952) and Chalmers and Mapleson (1955).

1.9 Laboratory Investigations of Point Discharge Currents.

Early investigations by Warburg (1899) discovered a dependence of point-to-plane corona currents on gap geometry and voltage. Zeleny (1907) (1908) substantiated these findings and made a further investigation of the effect of temperature and pressure. (See also Tamm (1901)).

A wider study of the phenomena of point-to-plane corona has been made by Loeb (1947) (1948) and co-workers. The effect of variation of gap width, voltage, pressure and sharpness of point were demonstrated by Trichel (1938) who, using a cathode ray oscilloscope, found the current through a negative point to be a series of regular pulses. English (1948) later extended the study to include positive point-to-plane corona.

It is interesting to note that Large and Pierce (1955), using similar techniques, have shown that this pulsed nature exists also in atmospheric positive and negative point discharge currents. They showed that the shape and frequency of these pulses though subject to certain fluctuations, could be reproduced in the laboratory point-to-plane discharges.

It would seem then that the corona discharge observed in the laboratory experiments and the atmospheric point discharge currents have certain common properties. The extent of this correspondence is still uncertain.

1.10 Conclusions.

Previous investigators have shown that the atmospheric point discharge current is a major contributor to the maintenance of the earth's negative charge. Their work also indicated that this current might be expected to be proportional to:-

(a) some power of the potential gradient between one and two. (The potential gradient is measured at the ground to windward of the discharging point).

(b) some power of the wind speed between one quarter and one.

(c) some power of the height of point between one and one and three-quarters.

A reduction in the current is expected when multiple points are substituted for a single point but in this case the separation of such points also needs consideration. Further variations of the current with air pressure and sharpness of the point might also be expected.

A degree of correspondence between laboratory and atmospheric results has been obtained, i.e. the pulsed nature of the discharge, but the extent of this similarity has not yet been established.

The foregoing conclusions, particularly (a), (b) and (c) are somewhat vague, especially when one considers the fundamental nature of point discharge currents in numerous other experiments. It was decided, therefore, that a further investigation of the subject was warranted and, in the interests of accuracy, that emphasis should be placed on the elimination of as many variables as was possible.

CHAPTER 2.

THE OBJECT OF THE RESEARCH AND THE METHOD OF APPROACH.

2. The Object.

The object of this investigation was to determine the relation between point discharge current and various parameters.

2.1 Preliminary Considerations.

In order that no question of the validity of the results should arise, atmospheric rather than laboratory investigations were made. A single artificial point was used, primarily because of its simplicity, but later a system was devised whereby currents down a tree trunk could also be measured.

The method of supporting the point was selected from three techniques used by previous workers:-

(a) Balloons.

(b) Kites.

(c) Masts.

(a) Balloons.

A period of a few weeks was spent assisting with measurements taken with a captive balloon to support the discharging point (Mapleson 1953). The limitations on the parameters measured by this method were most severe. Balloon flights were made only in fine weather when invariably small positive fields existed. These were anti-cyclonic periods with wind velocities small, but large enough to cause uncontrollable changes in height of a rolling balloon. The lift of the balloon determined not only the weight of the apparatus carried but also the maximum operating height because of the weight of the trailing wire and securing cable.

Point discharge currents under these conditions varied from 0 to + 5μa at heights up to 200m in positive potential gradients up to 250 v/m.

The method did, however, provide for large variations in useful height up to 150m and the low onset value of the potential gradient at the ground enabled numerous results to be taken in brief flights.

(b) Kites.

The disadvantage of change of height with wind velocity, restricted weight of apparatus and confinement of measurement to undisturbed conditions, mentioned in the previous paragraph, are again applicable with the further qualification that light breezes are required for launching. Kites, on the other hand, have a distinct economic advantage over the hydrogen filled balloons.

(c) Masts.

The main drawbacks to this method of supporting the point are first, the difficulty of erecting a mast

220 v/m for a height of 20m.

140 v/m for a height of 25m, at this site.

The fair weather potential gradient at Durham frequently exceeds 200 v/m so that one could, using a 20m mast, expect sufficient results over a wide enough range of conditions for a thorough analysis to be made.

It was decided, therefore, to erect a single pole 65 ft. mast to support the point.

Primarily the aim was to relate point discharge current with the wind speed measured close to the point and also with the undisturbed potential gradient at the ground, this being measured well to windward of the discharging point where the adverse effect of liberated space charge on the potential gradient would be negligible. If these results were sufficiently accurate, a dependence of current on atmospheric pressure and small variations of height would be sought, whilst investigations with multiple points of varying separation were also envisaged.

2.2 The Site.

A convenient site for the erection of the mast was found in the nearby gardens at the junction of three pathways some 100 ft. to the East of the recording room. Here the mast would not hinder existing atmospheric measurements as the prevailing wind was from the West. Guy anchorages could be made in each of the three pathways and the cost of cable from

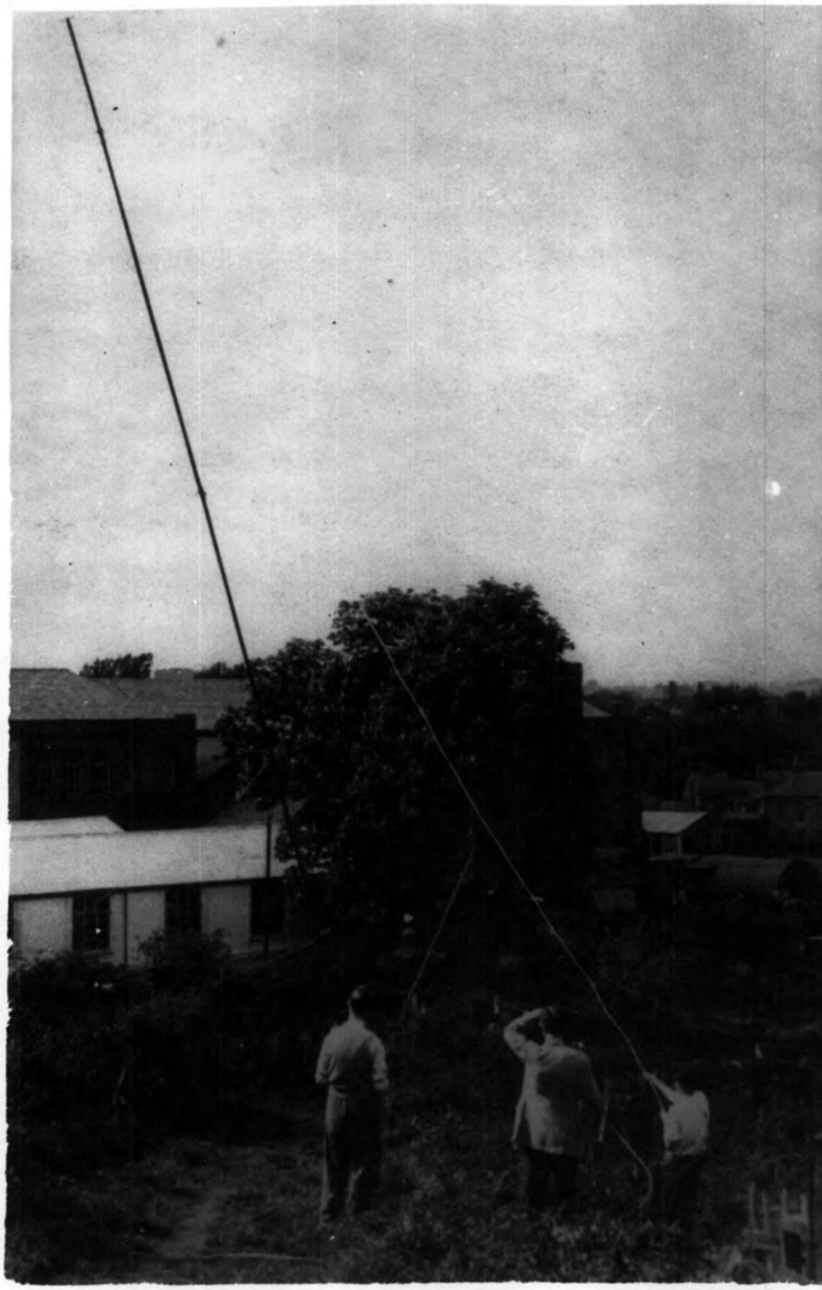


Fig. 1 Erecting the 20m Mast.

here to the recording room would not be exorbitant. The mast was 100 ft from the nearest tree which was 40 ft high, although several trees in Little High Wood, 150 yds. distant, were about 100 ft high.

2.3 The Mast.

The mast was made in four tubular steel sections (2" internal diameter) joined together with ferrules, each joint strengthened on the inside by a length of 2" diameter tubing. It was supported by three sets of three 1_8" galvanised wire rope guys connected to the mast at points close to the ferrules. The mode of erection, using one set of guys attached to a 25ft lifting bar, whilst the other freely hanging guys were used to steady the mast, is clearly shown in the photograph. Over a pulley at the top ran a rope with which the stainless steel point and other apparatus was lifted on a subsidiary mast which, when correctly secured, brought the point to a height of 65 ft above the base of the mast. By increasing the length of this subsidiary mast, a moderate change of height could be achieved if desired.

2.4 The Point.

This was made from stainless steel rod 0.15 c.m. in diameter, 1.75 cm long, tapering to a radius of 0.002 cms at the tip. Fig. 2 shows the cable connection and the

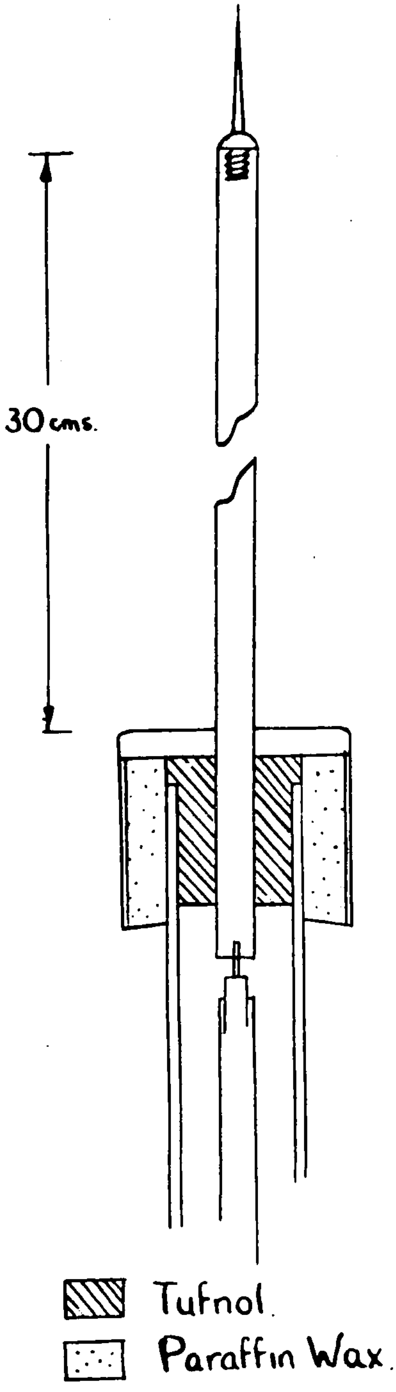


Fig. 2 The Point.

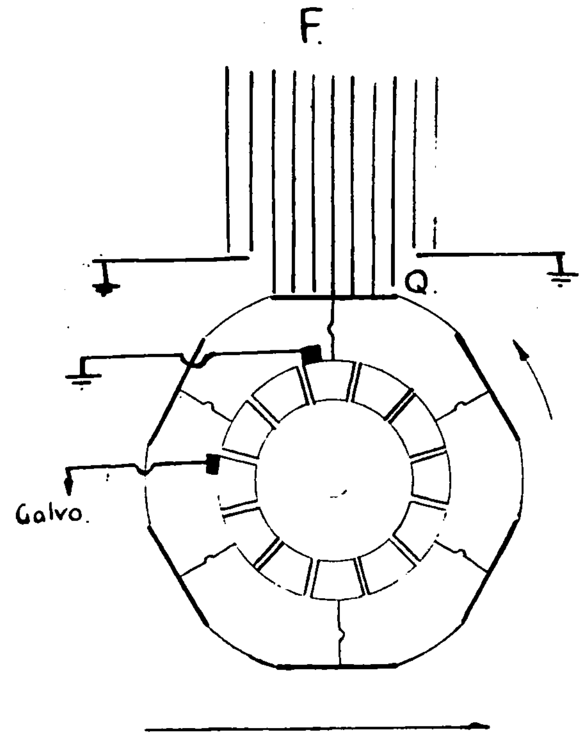


Fig. 3 Diagrammatic end-on view of Dr. Chalmers' Agrimeter.

method of attaching the point to the $\frac{3}{4}$" diameter extension which also carried the anemometer.

The leakage resistance of the point to earth was checked periodically and after each recording a current of known magnitude was passed through the point discharge galvanometer for calibration purposes. A series of shunts enabled currents up to 30μa to be handled with ease.

2.5 <u>Measurement of Potential Gradient.</u>

The Agrimeter, described elsewhere (Chalmers 1953), situated in the enclosure some 30m from the base of the point discharge mast, gave continuously the value of the earth's electric potential gradient. The current output was passed through a high sensitivity mirror galvanometer, the deflection of which was recorded photographically. The maximum sensitivity of the system was 0.53 cm deflection for a potential gradient of 100 v/m. Calibrating voltages were applied every hour and the collecting plates were covered by an earthed plate every five minutes for half a minute in order to check the zero potential gradient reading. Recordings were made when the wind was from the West, when the Agrimeter was to windward of the mast and therefore unaffected by the space charge liberated by the point itself. The simplicity of the design contributed towards its reliability in both fine and prolonged adverse weather.

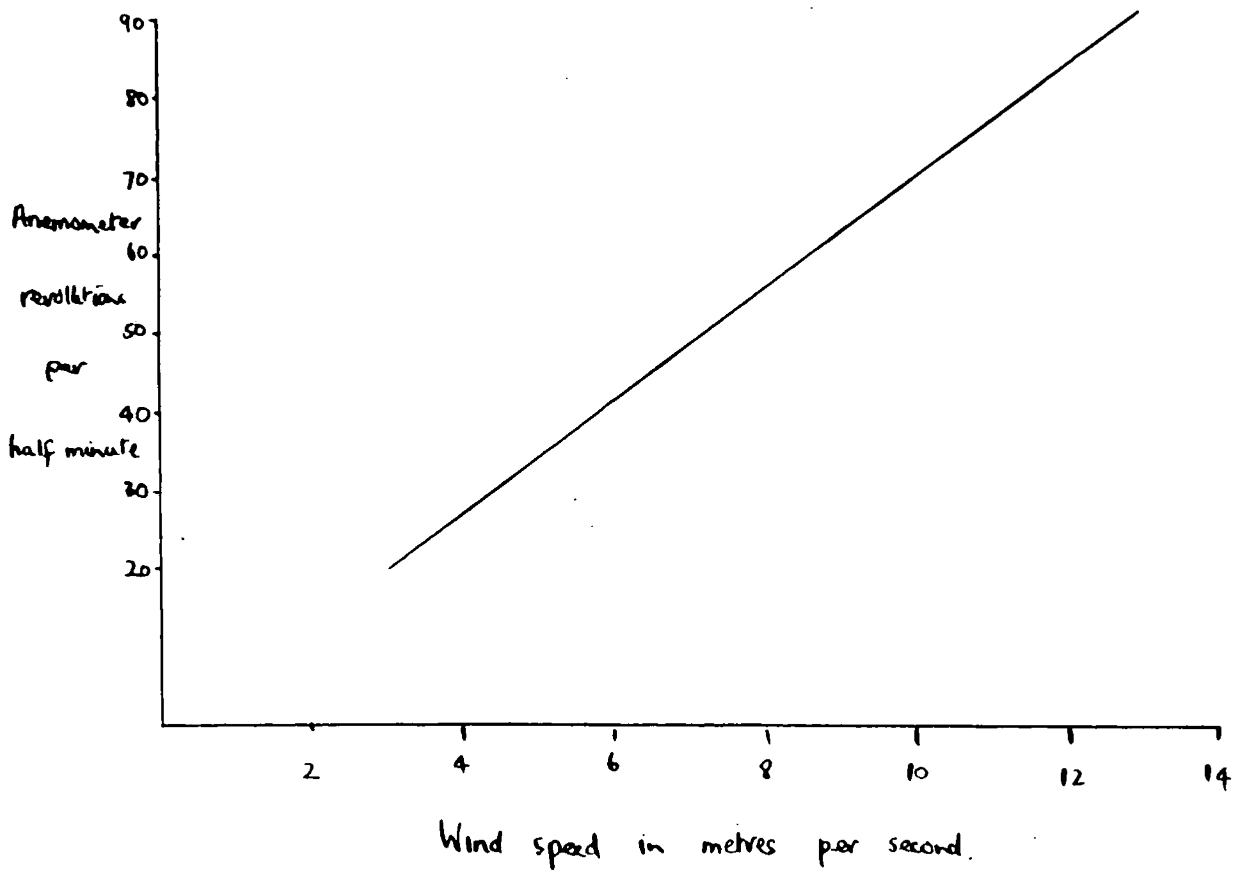


Fig.4 <u>The Anemometer Calibration.</u>

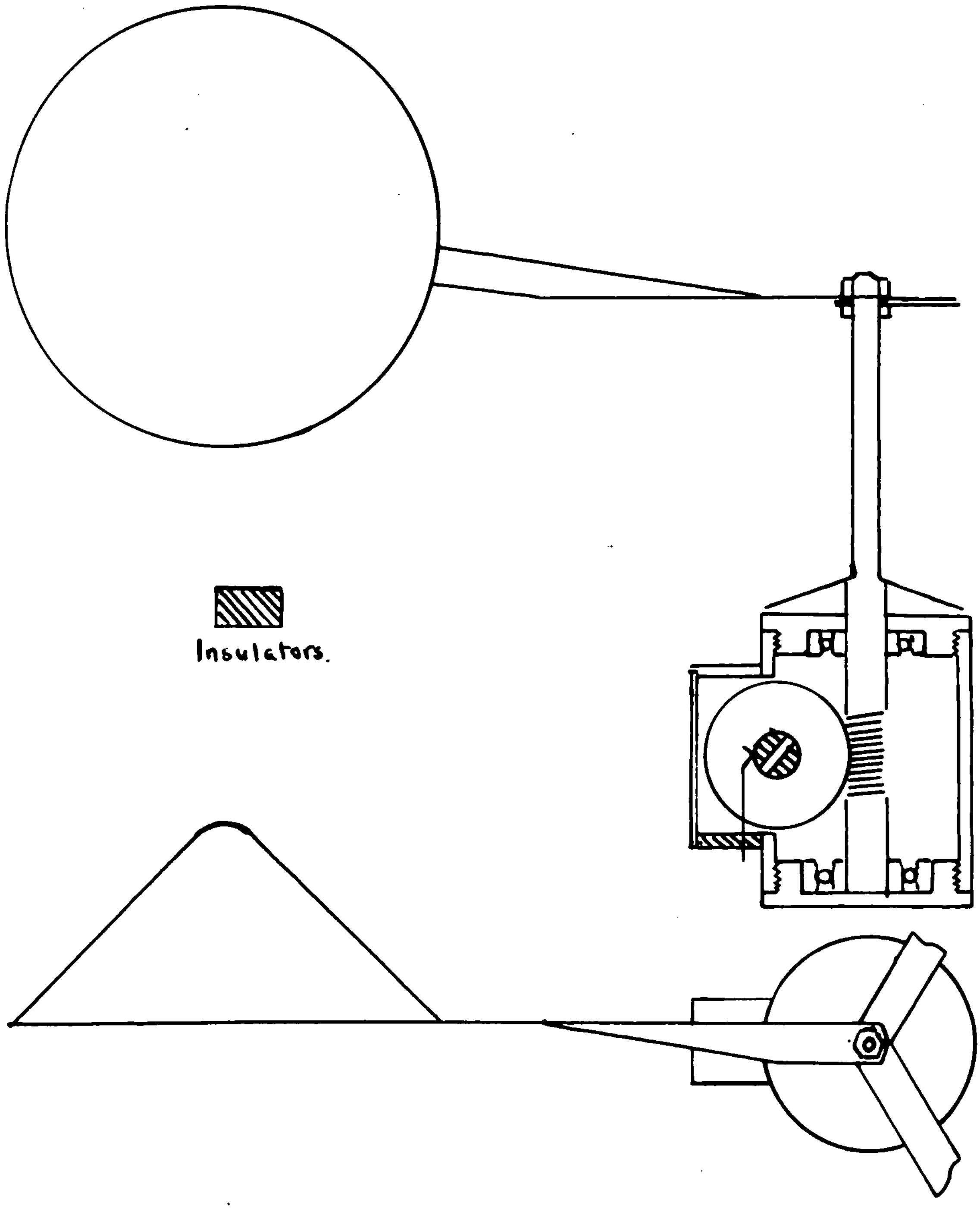


Fig.5 The Anemometer Details (full size).

2.6 Measurement of Wind Speed.

The design of this anemometer follows closely that of the standard radiosonde ascent indicator in which an electrical contact is closed for six revolutions of the cups and opened for a further twenty-four.

When closed the contacts switched on a 2.5v .03 watt bulb in the dark room which fogged the recording paper. As the speed of the camera was constant, one could obtain the windspeed from the width of this background fogging or, in high winds, from the number of fogging 'lines' in a given time interval.

In view of the local nature of wind gusts, the anemometer was fixed below and as close to the point as possible; at a distance of two metres its effect on the exposure of the point was negligible.

The anemometer was calibrated against a Meteorological sub-standard and as Fig. 4 shows, its response was approximately linear over the range of wind speeds measured.

Details and relevant dimensions are given in the working drawing Fig. 5.

2.7 Trigger Circuit.

In order to increase the number of results, recourse was made to automatic recording. A beam of light reflected from the point discharge galvanometer was allowed to fall on a

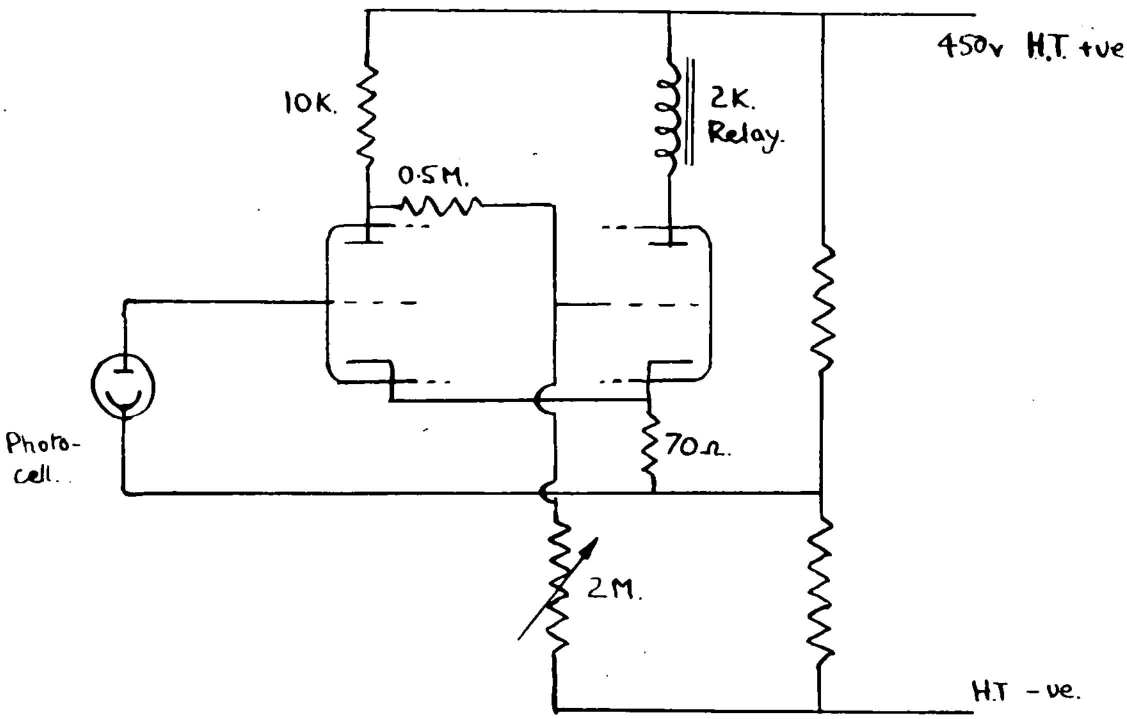


Fig.6. The Schmitt Circuit.

barrier layer type photocell, the output from which triggered one half of a double triode at the onset of point discharge. The relay in this Schmitt arrangement (Williams 1946) shown opposite, switched on galvanometer lamps, camera, anemometer lamp and the timing circuit. The onset and duration of such recording was established by comparison with a less sensitive record taken each night in a separate room, hence the wind direction, pressure and other meteorological conditions could be determined from other records taken at the Observatory.

2.8 Timing Circuit.

This mechanism, constructed by earlier research students, was a series of relays operated every half minute by pulses derived from the electric clock. The relays switched off the galvanometer lamps for two seconds every half minute thus providing a time scale on the recording and a convenient interval over which to average the values of the various parameters.

2.9 The Field Mill.

As recording proceeded it became apparent that spurious space charge, affecting the potential gradient at the Agrimeter and not at the point, was responsible for irregulatities which arose on the current - potential gradient relationship.

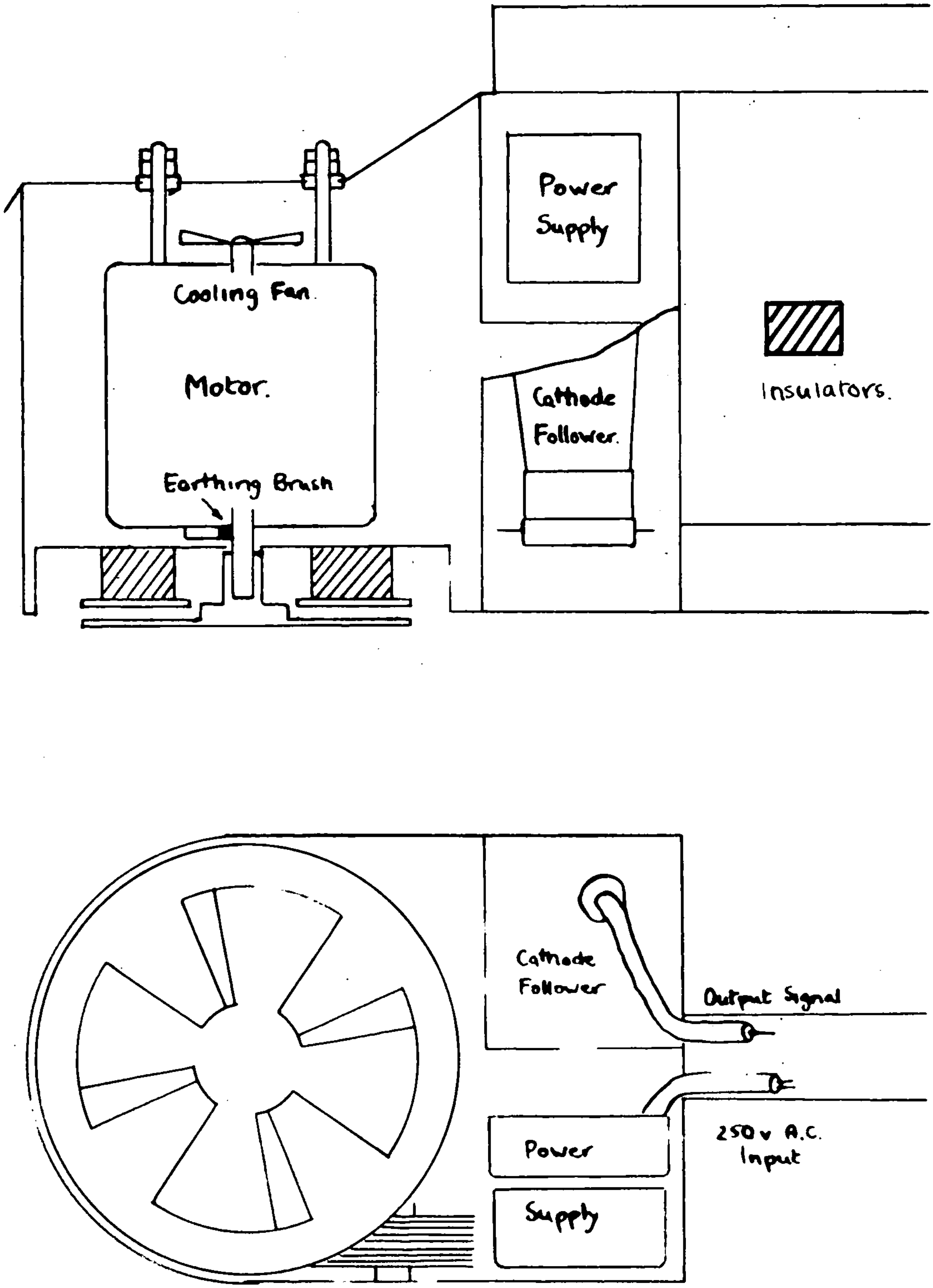


Fig.7 The Field Mill (half full size).

If the distance between the Agrimeter and point were decreased this effect might be reduced, but in this closer position the potential gradient would now be influenced by the space charge from the point itself.

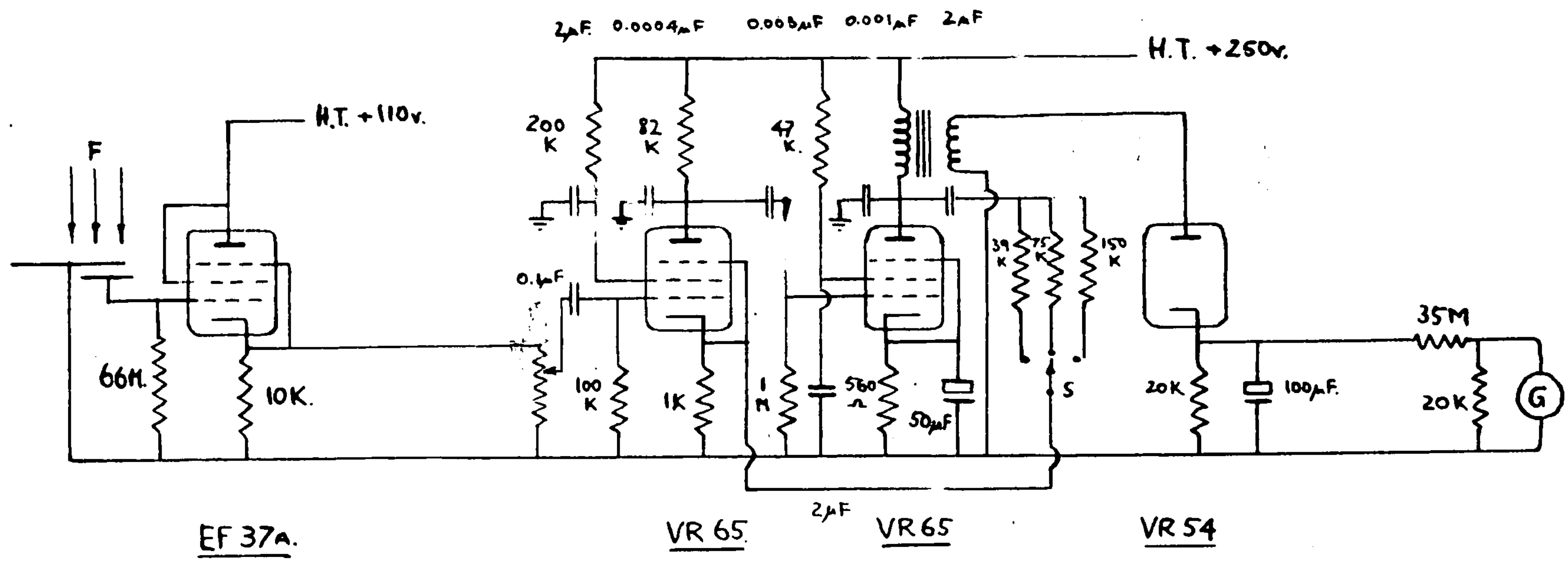
When the potential gradient about the point becomes large enough for ionisation by collision to occur, 'avalanches' are formed and ions of one sign feed into the point. This leaves behind a space charge which reduces the potential gradient about the point to such an extent that ionisation ceases. A field mill some few feet below the point would be susceptible to this reduction.

As suggested in section 1.6 an increase in wind speed might be expected to produce an increase in point discharge current and hence a larger space charge about the point. This may not, however, bring about a further reduction in potential gradient at the mill as the removal of space charge is greater with this increased wind speed.

Thus the effect of wind speed, apparent on the current - Agrimeter curves might not be so pronounced on the current field mill graphs and the nature of these latter curves might be altered. Nevertheless, it was decided that such a position would be of value in spite of the inability to calibrate absolutely the mill in this elevated position.

2.10 Mill and Amplifier Design.

Intended for use two metres below the point on the



S. - gain selector switch.
G - Galvanometer. (Tinsley 1500 mm/μa.)

Fig.8 Circuit Diagram of Cathode Follower and Amplifier.

subsidiary mast, desired features of the mill were lightness, compactness and a minimum of accompanying cables; it would have to be waterproof and self starting. As the sign of the potential gradient could easily be determined from the point current, no reference signal or phase sensitive device was required and the design was thus simplified.

Rotor and stator profiles were of the segment type (Macky 1937) as distinct from the Malan and Schonland (1950) 'stud and hole' pattern which for the same stator area would be rather more bulky.

The first stage of the amplifier, a cathode follower, with its A.C. mains operated power supply was carried in the same casing as the mill. Thus cable requirements were a twin TRS cable carrying 250v A.C. for the cathode follower power unit and the shaded pole induction motor driving the mill and a 'Permenoid' coaxial line carrying the output signal to the amplifier in the recording room.

This two stage amplifier incorporated negative feedback, the amount of which was variable to adjust the gain. The output from the second valve was transformer fed to a rectifier in series with a 20 K resistor. Connected across the latter was a 100μf smoothing condenser and a galvanometer which had a periodic time of two seconds.

The mill in this well exposed position was too sensitive;

potential gradients of 100 v/m at the ground produced signals of 1.5v peak to peak at the grid of the cathode follower. Saturation soon occurred with increased potential gradients and a 150pf condenser was connected between stator and earth to reduce the sensitivity. The system was then capable of measuring potential gradients from 0 - 10,000 v/m (at the ground) of either sign.

CHAPTER 3.

3. PERFORMANCE OF APPARATUS.

Once installed the equipment gave little trouble; occasionally in mist the point insulation would break down and recordings had to be abandoned, but invariably a leakage resistance to earth of over 3×10^7 ohms was maintained.

The mast itself withstood high winds and a severe February gale in which the anemometer recorded gusts of approximately 70 m.p.h. before two of its cups were carried away. These were later replaced although the results showed that the calibration had been affected. In calmer weather the subsidiary mast with apparatus could be raised and lowered single-handed although in anything stronger than a gentle breeze the help of a second person was required to control the swinging 12 ft extension and prevent damage to the apparatus.

Initially the mill on the subsidiary mast was switched on only when required but later it was run continuously when it was found that the heat conducted from the motor prevented dew, fog and mist settling on the collecting plates and insulators. In its inverted position it functioned continuously for five months in snow, sleet, rain and mist until recording was terminated.

Under similar conditions the Agrimeter too was extremely reliable; with the zero checks every five minutes, any slight drifts were not serious and, requiring no amplifier, the system theoretically could not be saturated. The maximum potential gradient recorded by the system in this investigation was 12,000 v/m beneath towering cumulus from which no rain appeared to reach the earth.

The first record was taken on 1st June 1953 and the last on 26th March 1954 after which the mast, rendered unsafe after being struck by a tractor, was lowered. No attempt was made to repair and re-erect the mast as arrangements for a more ambitious project were being made. The investigation was therefore closed and the results analysed.

3.1 Recording Procedure.

Whenever the potential gradient approached the onset value of 195 v/m, the anemometer and galvanometer lamps, timing circuit and camera were switched on. Throughout the record attempts were made to note the onset and cessation of precipitation, but this was not always possible, especially in rapidly changing conditions when attention had to be paid to galvanometer deflections in order that the correct shunts and sensitivity of the Agrimeter, Field Mill and Point current measuring devices could be selected.

At the end of each record when no further point discharge

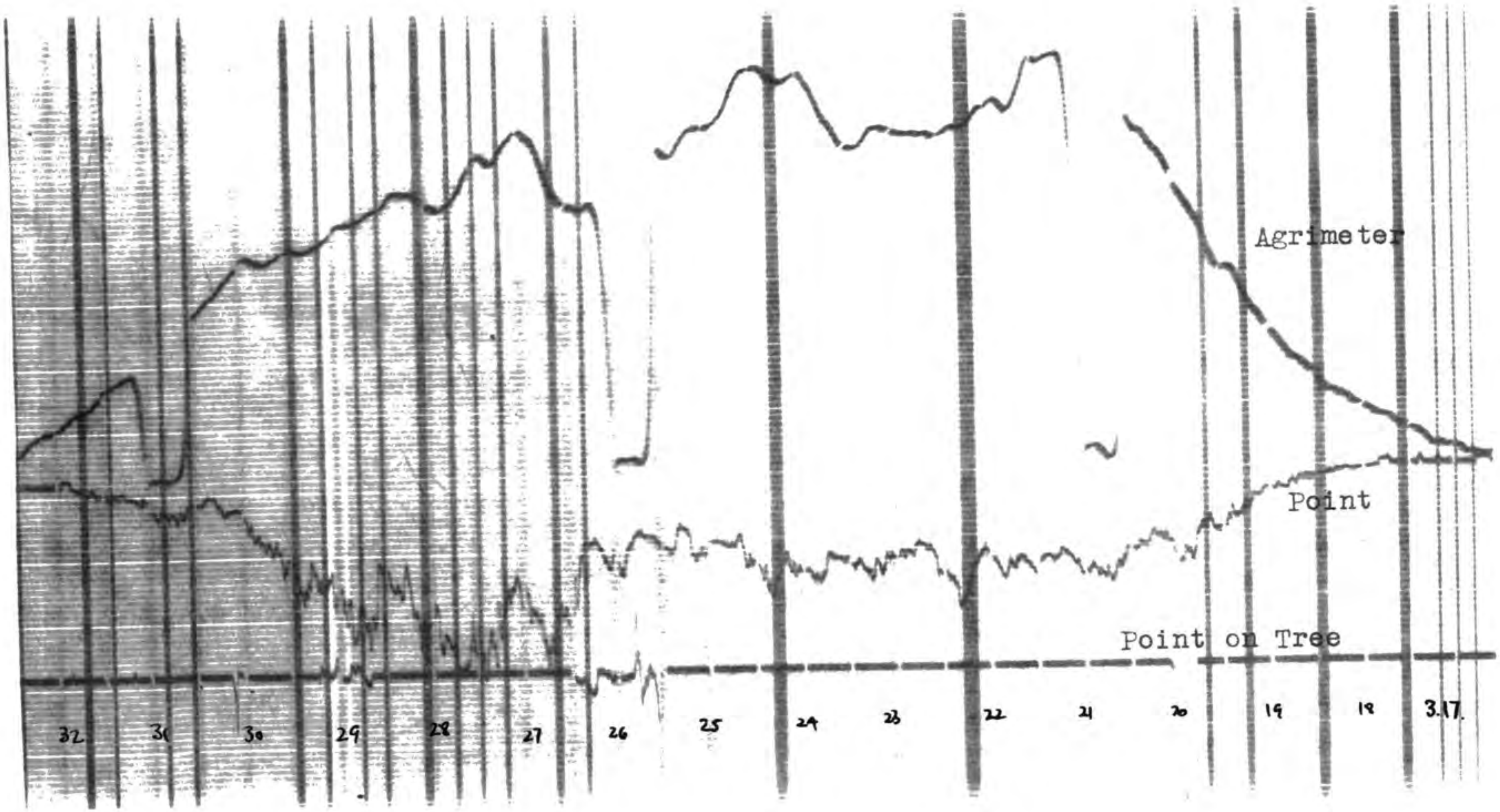


Fig.9 Typical Record (full size).

seemed likely, a calibrating potential gradient was applied to the Agrimeter and 1.5μa was passed through the point discharge galvanometer. Thus deflections could be interpreted directly as either volts per metre or micro-amps.

3.2 Typical Records.

Sections of some typical records are shown opposite - Fig. 9 is part of one of the earlier records when only point discharge current and potential gradient were recorded. The corresponding time is marked on the record at minute intervals, three Agrimeter five-minute zeroings are shown. The traces are deflected in opposite directions in order to avoid over-lapping - both the current and potential gradient in this case are negative.

After a brief gust at the beginning of the record, the wind speed falls; that the anemometer stalls occasionally is shown by the width of the six revolution fogging background, but there is a sharp increase at 3.26 hrs. Here the point discharge current almost doubles in value, although the potential gradient is generally decreasing.

Another period of very low wind speed is shown in Fig 10 a record taken during showers of large soft snowflakes. The third trace, that due to the field mill, is unidirectional - from its obvious zero change-over points and the point discharge current trace, the sign of the potential gradient

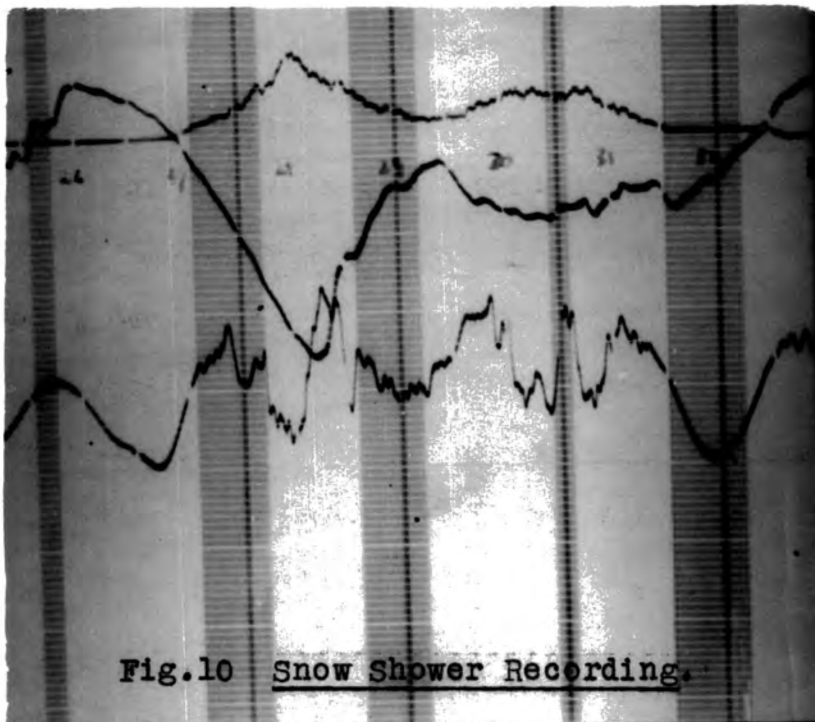


Fig.10 Snow Shower Recording.

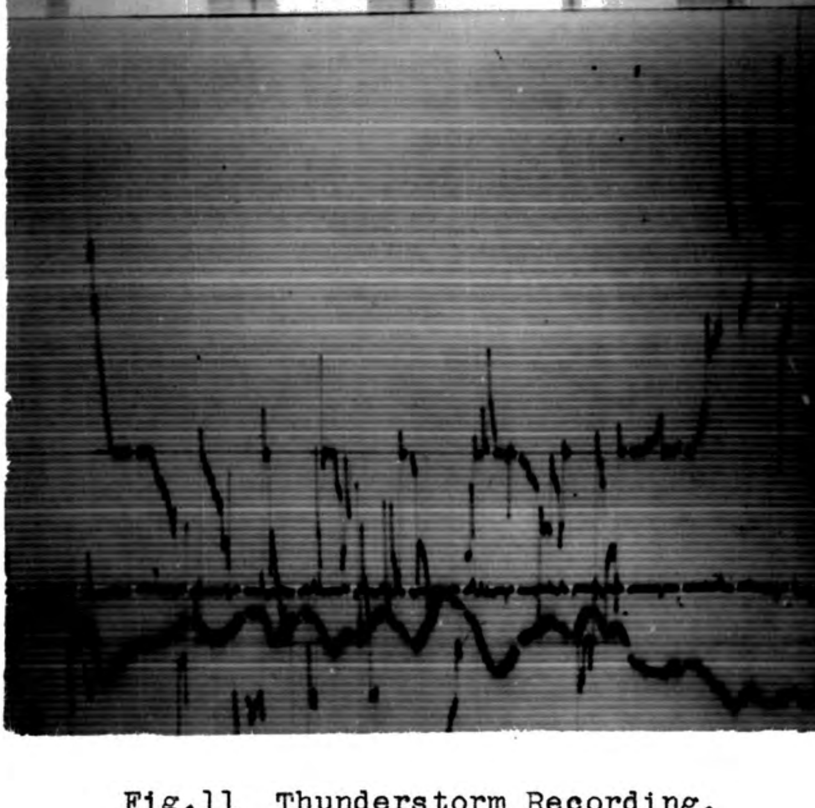


Fig.11 Thunderstorm Recording.

it records can be easily deduced.

With the onset of point discharge the field mill trace, hitherto smooth, begins to show fluctuations which immediately develop to such an extent that the field mill output is almost reduced to zero. The effect was attributed to the presence near the mill of charged snowflakes which, as Simpson has pointed out, are capable of removing a larger proportion of the liberated space charge than are raindrops, which produce only a fine structure on the field mill trace.

The third record Fig. 11 was taken during a thunderstorm when only point discharge current and potential gradient at the ground were recorded. It serves to illustrate the futility of attempting accurate measurements of these parameters using instruments with such relatively long response times.

3.3 Measurement.

For each half minute period, average values were taken for point discharge current, wind speed and potential gradient; these were tabulated along with the appropriate time and brief notes regarding the existing meteorological conditions.

3.4 Selection and Summary of Recordings.

During the period 1st June 1953 to 26th March 1954, fifty separate recordings were made, having a total duration of 36 hours. Until the 1st January 1954 the parameters measured were point discharge current, wind speed and potential gradient to windward of the discharging point; after this date the field mill immediately below the point was brought into operation, yielding an additional set of readings.

Not all of the records, however, were suitable for analysis; three taken in thunderstorms were rejected because of the violent fluctuations of point current and potential gradient. Abrupt changes in wind direction, faulty point insulation in mist and heavy downpours and the shedding of anemometer cups in gusts of 70 m.p.h. were the prime reasons for the withdrawal of another eight records.

On individual records discrimination was also needed when current and potential gradient changed sign; invariably the time of change-over of the two traces did not coincide, delays of one minute were not uncommon, and readings in the vicinity of the zero point were therefore excluded from the analysis. Similarly no attempt was made to include measurements taken from regions where current and potential gradient were of different sign.

In all, a total of 25 hrs. 32 mins. were suitable for scrutiny, affording a total of 1399 values of all three parameters, with values of point discharge currents up to 20μa, potential gradients up to 4,500 v/m and wind speeds up to 33.5 m/s.

3.5 Outline of Procedure.

In attempting to solve the general equation

$$I = f(W.F)$$

where I represents point discharge current, W wind speed and F potential gradient, it was decided to group together those I and F values occurring within a given small range of wind speed. The functions relating I and F could then be determined for a number of such ranges and hence the dependence of these functions on wind speed could be investigated.

From the trend of the points on the current - potential gradient graphs drawn for each range of wind speed, it was possible to deduce the forms and limit the number of equations to be considered in the statistical analysis.

3.6 Choice of Wind speed Groups.

The division of the results into groups of constant wind speed began immediately the first record was measured and before the anemometer was calibrated. It was convenient, therefore, to use ten revolutions of the anemometer per half minute period, up to 100 revolutions, as the width of a particular wind speed group. Beyond this (14.3 m/s), the sparsity of the results allowed only two more groups, i.e. over 100 and over 200 revolutions per half minute. Stalling speed of the anemometer corresponded to 25 revs. per half minute, therefore, in all, a total of 10 wind speed groups units. In this set 525 points falling into 6 wind speed ranges were available for analysis.

Both sets of results had too few values of positive current and potential gradient and a rigid analysis was only possible with the negative values. In both cases the indication was that the equations for positive curves were similar to the negative, except for higher onset values of potential gradient and decreased slopes of the current potential gradient curves.

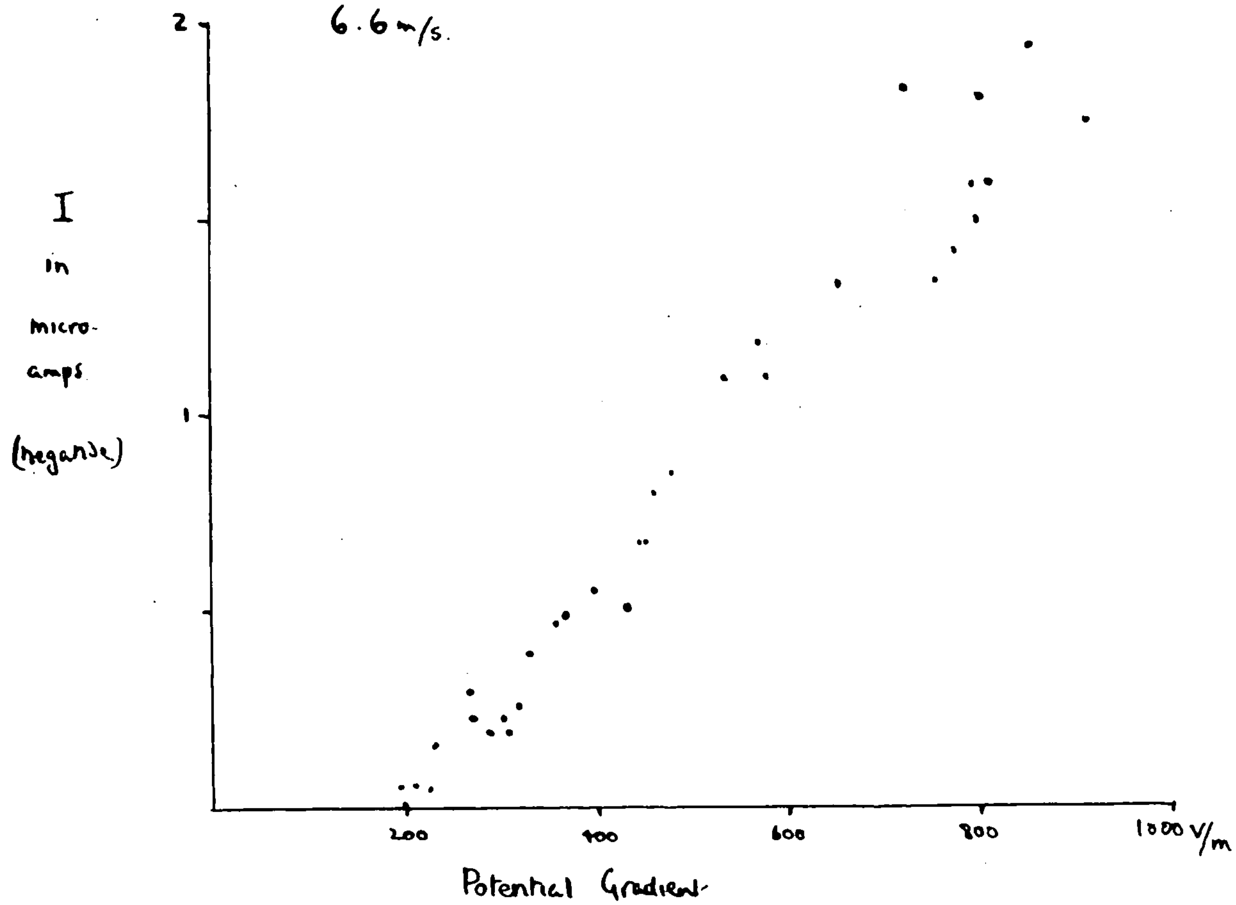


Fig.12 <u>Variation of Current with Potential Gradient.</u>

CHAPTER 4.

RESULTS.

4. Variation of Point Discharge Current with Potential Gradient at the Ground to Windward of the Point.

The bulk of the readings, on which the results of this section are based, lay between 0 - 5μa (negative) for potential gradients up to 2,500 v/m whilst the width of each wind speed group was approximately 1.25 m/s.

The graphs showing the variation of current with potential gradient for these small ranges of wind speed, of which Fig.12 is an example, indicated the existence of a linear relationship of the form

$$I = a(F - M)$$

where M is the value of the potential gradient at which point discharge commences, i.e. 195 v/m.

As this was a departure from the trend of the results of previous workers and as, in a few cases, the unevenness of the distribution and the scatter of the points rendered this simple dependence questionable, it was decided that rather than the best straight line, the best values of 'a' and 'n' in the following equation should be calculated.

$$I = a(F - M)^n$$

The adoption of this more general equation enabled direct comparison with the current-field mill results of Section 4.2

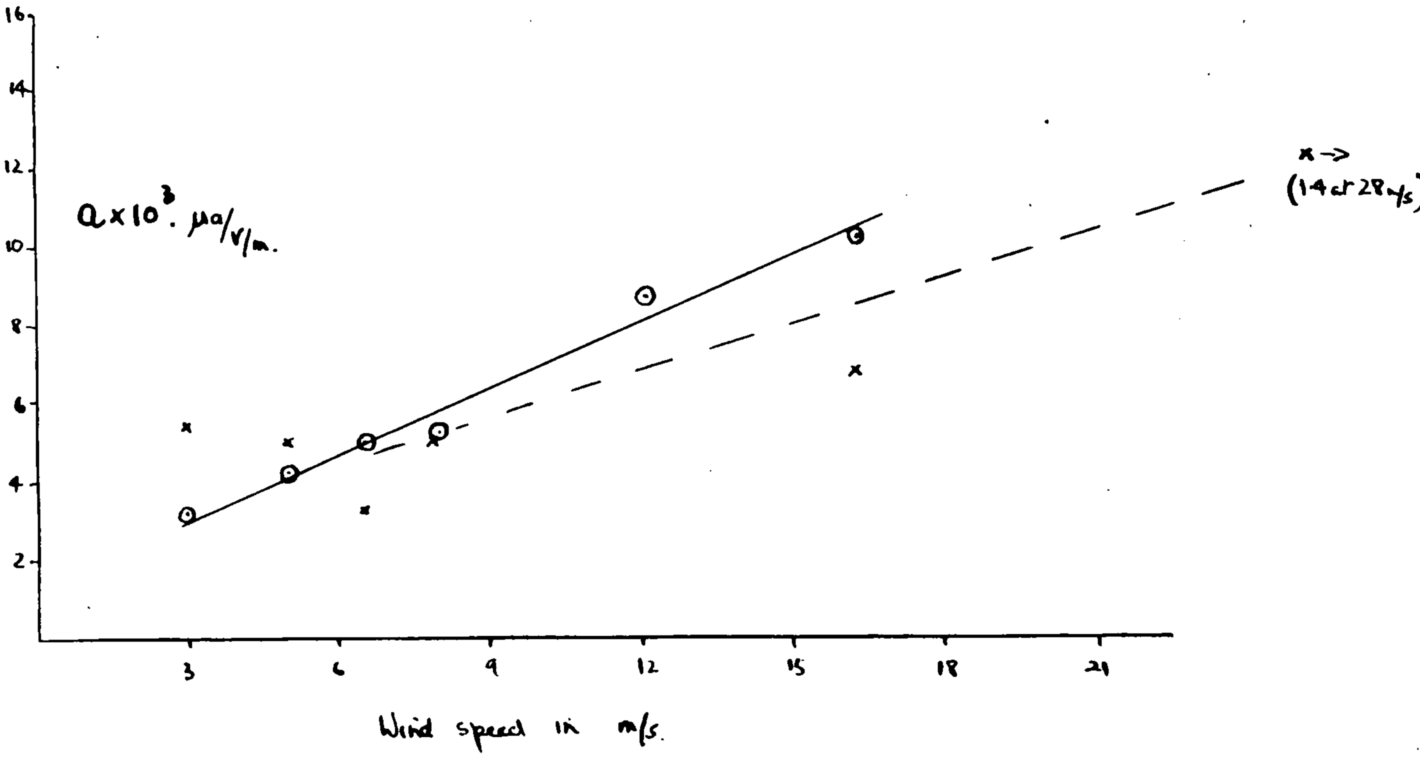


Fig. 13 Variation of 'a' with Wind Speed.

<u>TABLE 2. Values of 'n' for Various Wind Speeds.</u>

Wind Speed m/s	3	5.2	6.6	8	12.2	16.3	21.3
Agrimeter '53	0.96	0.92	0.98	1.08	1.03	-	-
Agrimeter '54	0.98	0.99	1.14	0.94	-	0.92	0.93

and provided 'n' had values close to unity, no great error was introduced provided extrapolation was not attempted. As the analysis proceeded, it became clear that the value of 'n' was, within the limits of experimental error, independent of wind speed and could be taken as unity. Table 2 gives the values of 'n' in the above equation for the ranges of wind speed considered.

4.1 The effect of Wind Speed.

One of the graphs showing the variation of the constant 'a' with wind speed, in the equation $I = a(F - M)^n$, suggested a further linear relationship but a second graph was inconclusive. However, the best straight lines through each set of points was calculated and found to be $a = 5.8 \times 10^{-4} (W + 2)$ for the Agrimeter 1953 and $a = 5.9 \times 10^{-4} (W + 5.9)$ for the Agrimeter 1954 results. This latter set was rejected.

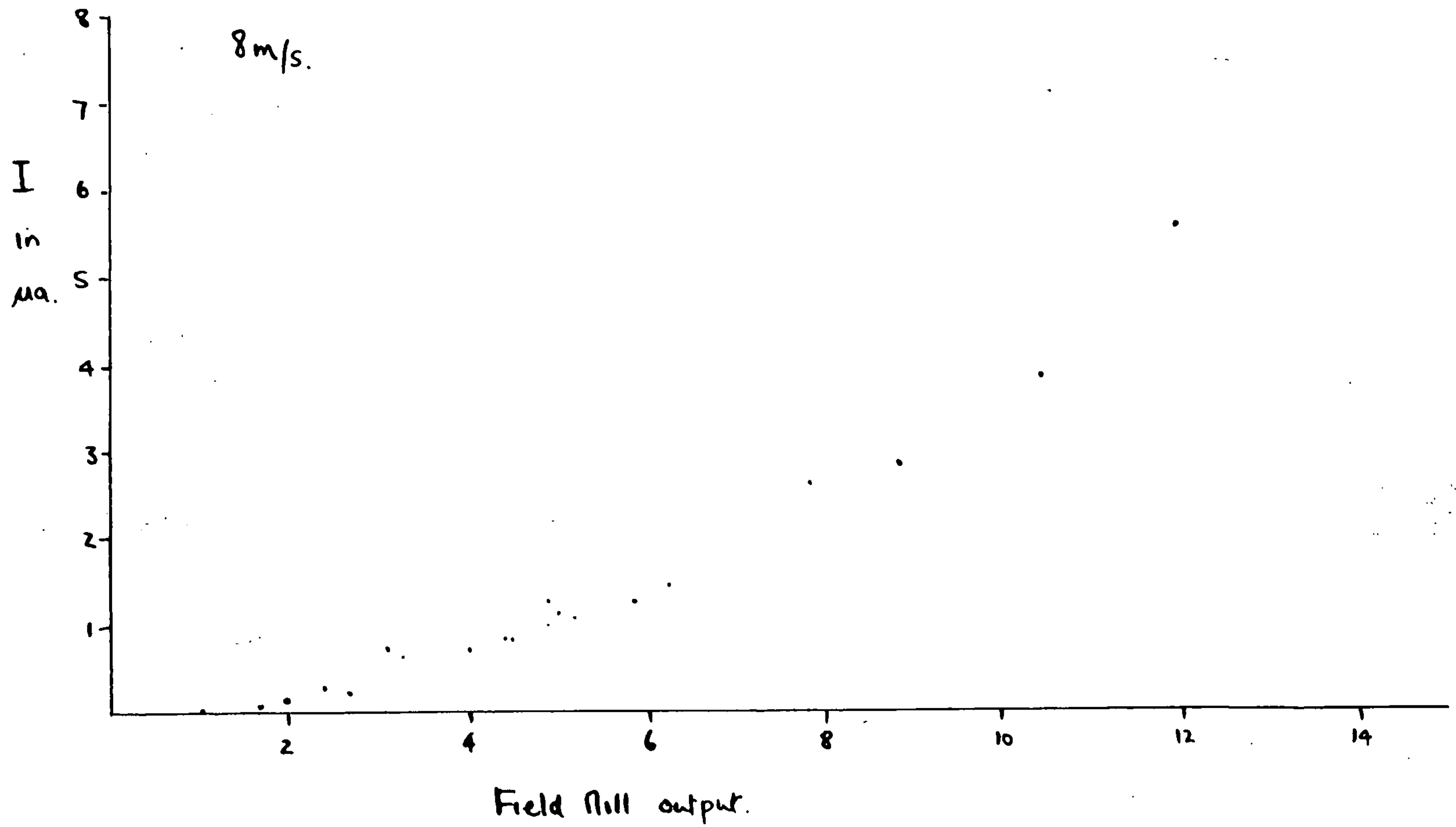
The difference in slope of these two regression lines was attributed to the large error in the second and the use of a single calibration for the anemometer both before and after two of its cups had been replaced.

The final equation relating negative point discharge current with wind speed and potential gradient was

$$I = 5.8 \times 10^{-4} (W + 2)(F - 195)$$

where I is in microamps, W is in metres per second and F is in volts per metre.

Fig.14 Variation of Current with Field Mill output.



The factors influencing the accuracy of this equation are mentioned in section 4.4; its estimated error was 15-20%.

4.2 <u>Variation of Point Discharge Current with Potential Gradient Measured Two Metres below the Point.</u>

Unlike those of the previous section, the graph relating point discharge current and potential gradient for a given small range of wind speed no longer showed a linear relationship. There was also an improvement in the correlation, as Fig.14 shows, and higher values of point discharge current were recorded, i.e. up to 18μa.

Attempts were made to fit the following equations to a particular set of readings.

(1) $I = a + bF = a'(F - M)$

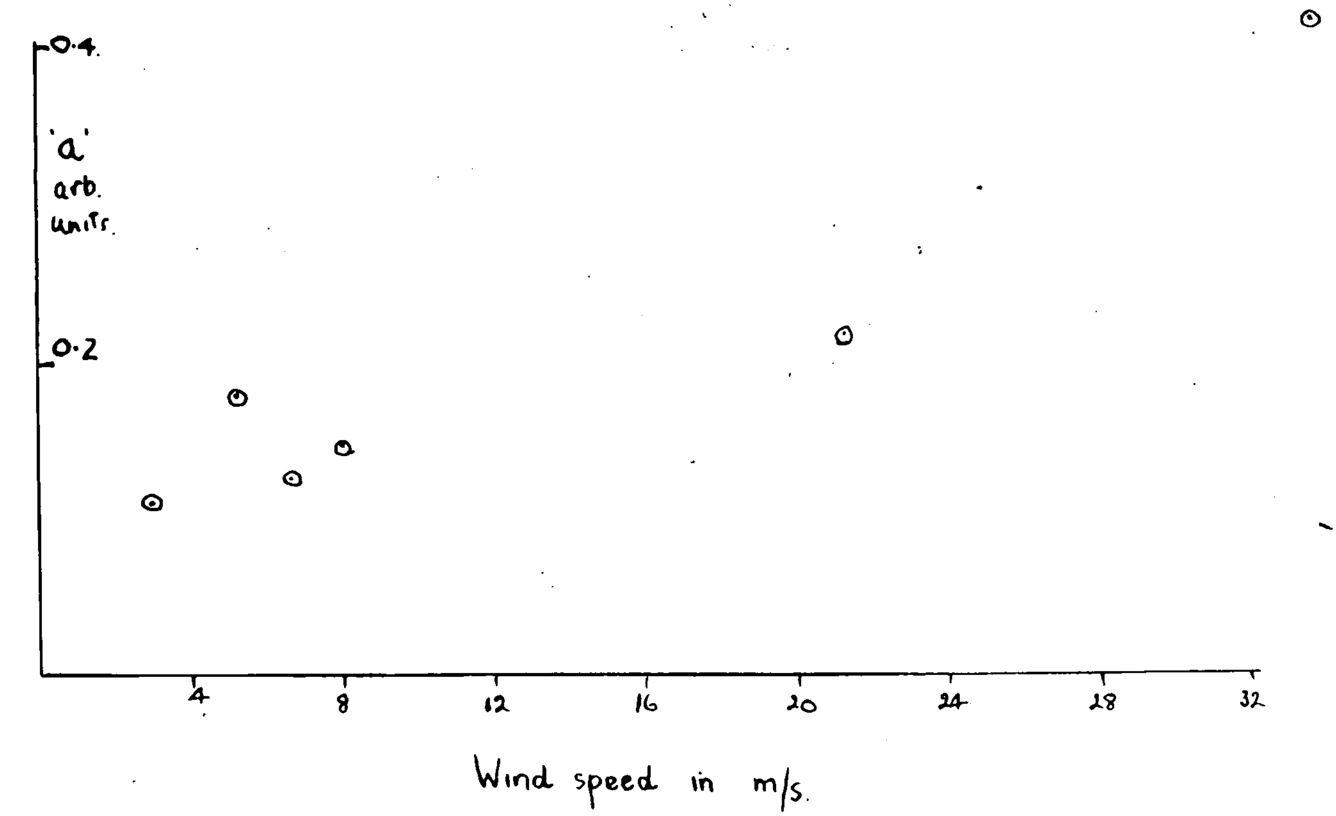
(2) $I = a + bF^{\frac{3}{2}} = a'(F^{\frac{3}{2}} - M^{\frac{3}{2}})$

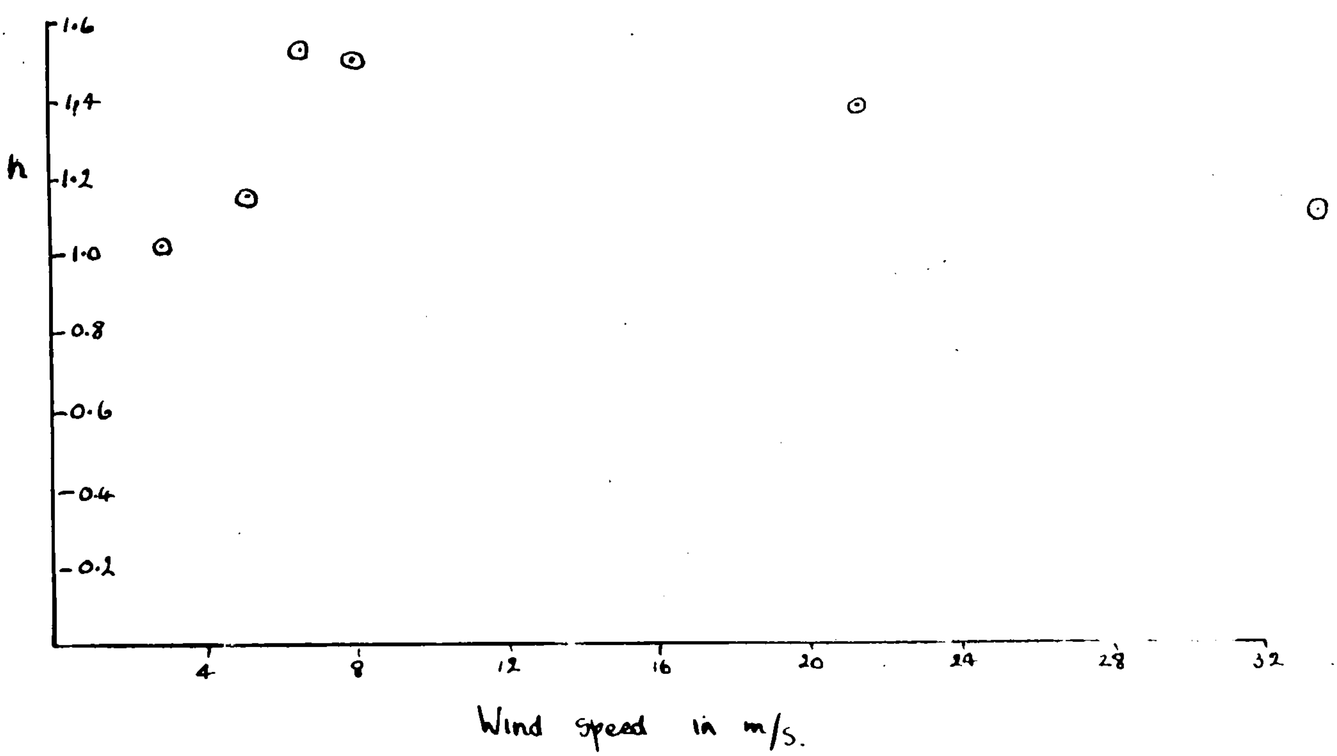
(3) $I = a + bF^{2} = a'(F^{2} - M^{2})$

(4) $I = a(F - M)^{n}$

A rapid indication of the goodness of fit of the first three equations was obtained by comparing the observed and the various calculated values of 'M'. These values and the corresponding equations are shown below.

	M.Calc.	M.Obsd.
(1) $I = 0.1F - 2.59$	25.9	12
(2) $I = 0.0071F^{\frac{3}{2}} - 0.52$	12.67	
(3) $I = 0.0004F^{2} + 1.05$	imaginary	
(4) $I = 0.025\,(F - 12)^{1.23}$		





Figs.15 and 16 <u>Variation of 'a' and 'n' with Wind Speed.</u>

Whilst equation (2) agreed quite well with the observed value of 'M' in this case, marked deviation occurred with other wind speed ranges, so that when considering the sum of the root mean square deviation for equations (2) and (4) the superiority of the more general equation was felt. As Fig.16 shows, the selection of results falling in the wind speed range 6 - 8 m/s was rather unfortunate when a comparison of the general and the 3/2 power equation was desired. Equation (4) was finally adopted.

4.3 Variation with Wind Speed.

Inspection of the graph, Fig.15, showing the variation of the constant 'a' in equation (4) with wind speed revealed a linear increase which persisted even to wind speeds of 33.5 m/s. No indication of 'saturation' was detected.

As 'F' was measured in arbitrary units no quantitative comparison of the value of 'a' with that obtained in the previous section could be made, although the percentage increase between given wind speeds could be compared, i.e.

5.2 - 16.3 m/s	Agrimeter	150% increase.
	Field Mill	70% increase.

Thus the effect of wind speed on 'a' was less than half in moving the mill from the ground to a point 2m below the discharging point.

This was not the only wind speed effect in this closer position; Fig. 16 shows that the power of 'n' in the equation $I = a(F - M)^n$ also varied with wind speed. With little or no wind 'n' had a value of unity but this value increased rapidly with increasing wind speed up to a maximum of 1.6 at 5.2 m/s. Thereafter 'n' decreased slowly and gave the impression of a return to unity at very high wind speeds, i.e. 1.1 at 33.5 m/s.

4.4 Conclusions.

As was mentioned earlier, the scarcity and relative inaccuracy of these results was realised and the object of their analysis at this stage was simply to discover general trends. Detailed discussion and comparison with the results of previous workers is therefore reserved until a later Chapter (8), nothing more than a brief summary being attempted at this juncture.

The current discharged by the earthed point 20m high appears to increase linearly with both wind speed and over-all potential gradient, being represented by the equation

$$I = (aW + b)\ (F - M)$$

a and b are constants

W - wind speed

F - potential gradient at the ground

M - onset potential gradient.

When the potential gradient is measured immediately below the point the equation is modified to

$$I = (a' W + b') (F - M)^n$$

where the ratio a'/b' is less than the previous a/b but 'n' is now dependent on wind speed.

The analysis provided a useful guide for further work and brought to light methods of increasing the number and accuracy of the results.

(a) Increase of height of the point. This would bring about a reduction of the onset value of the potential gradient (M) resulting in a greater number of positive values of current in fair weather when conditions are relatively calm.

(b) Higher camera speed. The errors involved in the averaging of values over periods of 30 seconds could be decreased by shortening these periods to 10 seconds. A corresponding increase in camera speed would be required to facilitate measurement of the parameters in this reduced interval.

(c) Generating type anemometer. With the shortening of the averaging interval the intrinsic error involved in revolution counting becomes more pronounced, especially at low wind speeds, unless individual revolutions are counted. This latter procedure can involve constructional complications which can be avoided by selecting an electro-magnetic generating type anemometer.

(d) <u>The Agrimeter calibration.</u> Whilst the Agrimeter itself gave reliable service the calibrating plate mechanism occasionally proved troublesome. Small changes in height of the plate gave apparently different sensitivities of the machine and led to the rejection of several records. A better reproducibility of height would therefore be required if its use was to be continued. A subsequent change of site necessitated a new field mill and this modification was therefore not attempted.

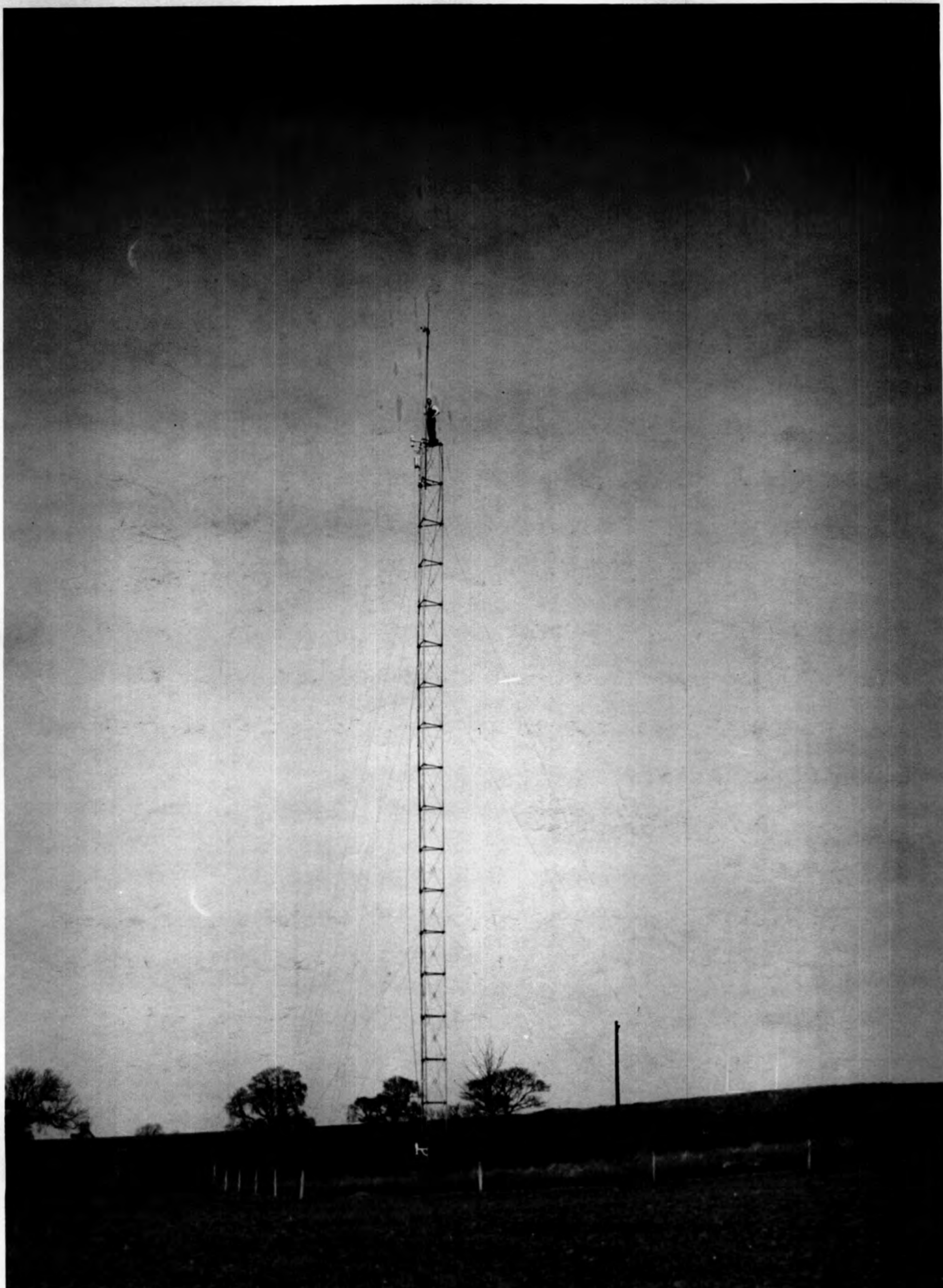


Fig.17 The 34m Mast.

PART II.

CHAPTER 5.

At this stage a reassessment of the whole problem was made. The financial backing for the project had been considerably increased, a more exposed site and a higher mast could thus be afforded.

Investigations were directed towards the verification of the wind speed and potential gradient dependence of the current with a greater accuracy than had previously been obtained. A mast of greater height would ensure an abundance of results at lower potential gradients and facilitate the study of the discharge current pulse size and frequency. Potential gradient measurements immediately below the point were also continued.

SITE AND APPARATUS CHANGES.

5. The Mast.

Following difficulties encountered in servicing equipment which was suspended from the single pole mast, it was decided that the next mast would be climbable. A braced triple pole structure carrying at the top a single pole extension of variable length was decided upon. The triple pole portion originally 70 ft (21.5m) was later increased to 90 ft (27.6m) which with the single pole fully extended, supported the point at 90 and 110 ft (33.8m) respectively. It was thus considerably higher than the surrounding trees. The guy anchorages were set in concrete 35 ft from the central concrete base.

The first 50 ft was erected in one piece in a manner similar to the single pole mast described earlier. Beyond this height, assembly was completed by the addition of individual 10 ft lengths of single pole followed by cross bracings and cross bars.

Advice on lightning protection was obtained from the British Electricity Authority who also provided a set of Magnetic Links to facilitate the measurement of the lightning current amplitude should a discharge to the mast occur.

The point was that used previously on the 65 ft mast.

5.1 <u>The Site.</u>

The recording instruments were set up in a dark room of the Durham Colleges Observatory, which stands on the brow of a hill in an exposed position. Downhill, 95m to the West, was erected the point discharge mast; in a line with these and 45m beyond the mast the field mill was set up. Recordings were made only when the wind was in a Westerly direction. A general view of the site and mast is shown in Fig. 17. Apart from a rather better exposure of the point, this location was relatively free from the polution which had handicapped the previous work.

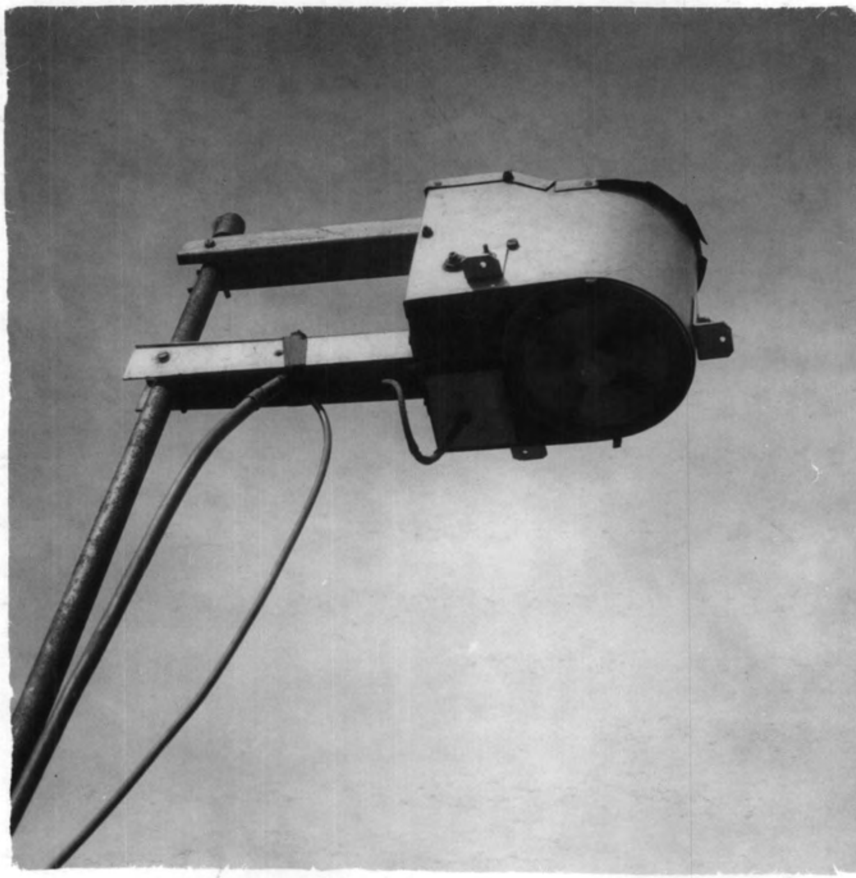


Fig.18 The Field Mill.

5.2 The Field Mill.

The field mill described in Part I was used to measure the potential gradient at the ground to windward of the point. As before, it was used in the inverted (weatherproof) position and fixed 1.7m above the ground. The full sensitivity was restored by the removal of the 150 pf shunting condenser between stator and earth when the amplifier gains required were 50, 25 and 12.

Again no attempt at sign discrimination was made as preceeding records had shown that this information could be inferred from the sign of the point discharge current. Calibration of the mill in this position was now possible and was carried out with a stretched wire, lead nitrate fuse and electrostatic voltmeter.

5.3 The Anemometer.

Whilst giving a reasonable average of wind speed over a period of some thirty seconds, the cup contact anemometer was not sensitive to individual gusts of wind, a necessary attribute when attempting to correlate the sharp rise of point current with these gusts. An electro-magnetic type, with spun aluminimum cups as before, was constructed. Alternating currents induced in the fixed coils were rectified with a germanium diode and fed to a galvanometer. The output was in micro-amps and the instrument calibrated

Fig.19 The Anemometer - Generator Type.

in a wind tunnel of the National Coal Board. In addition, the output for different speeds of revolution of the cups was obtained thus keeping a check on the strength of the rotating magnet.

The anemometer was mounted 2m below the point.

5.4 <u>The Camera.</u>

The single-speed 'Cambridge' camera was discarded and a new instrument constructed, paper width was increased to 240mm(9.4 ins) when several traces could be accomodated comfortably. A variable speed drive was arranged giving paper speeds of 2.5 - 6 cm/min when intervals of two seconds (the periodic time of the galvanometer) could be detected with ease.

A synchronous motor switched off the background fogging lamp every ten seconds providing a convenient time scale on each record.

5.5 <u>The Agrimeter.</u>

The removal of the field mill to the ground position occassioned the construction of a further potential gradient measuring device to be used a few metres below the point.

The particularly intense potential gradient encountered at the top of the 65 ft mast (25,000 v/m perpendicular to the mast for potential gradients of about 200 v/m at the ground) indicated that a 'scaled-down' Agrimeter type of

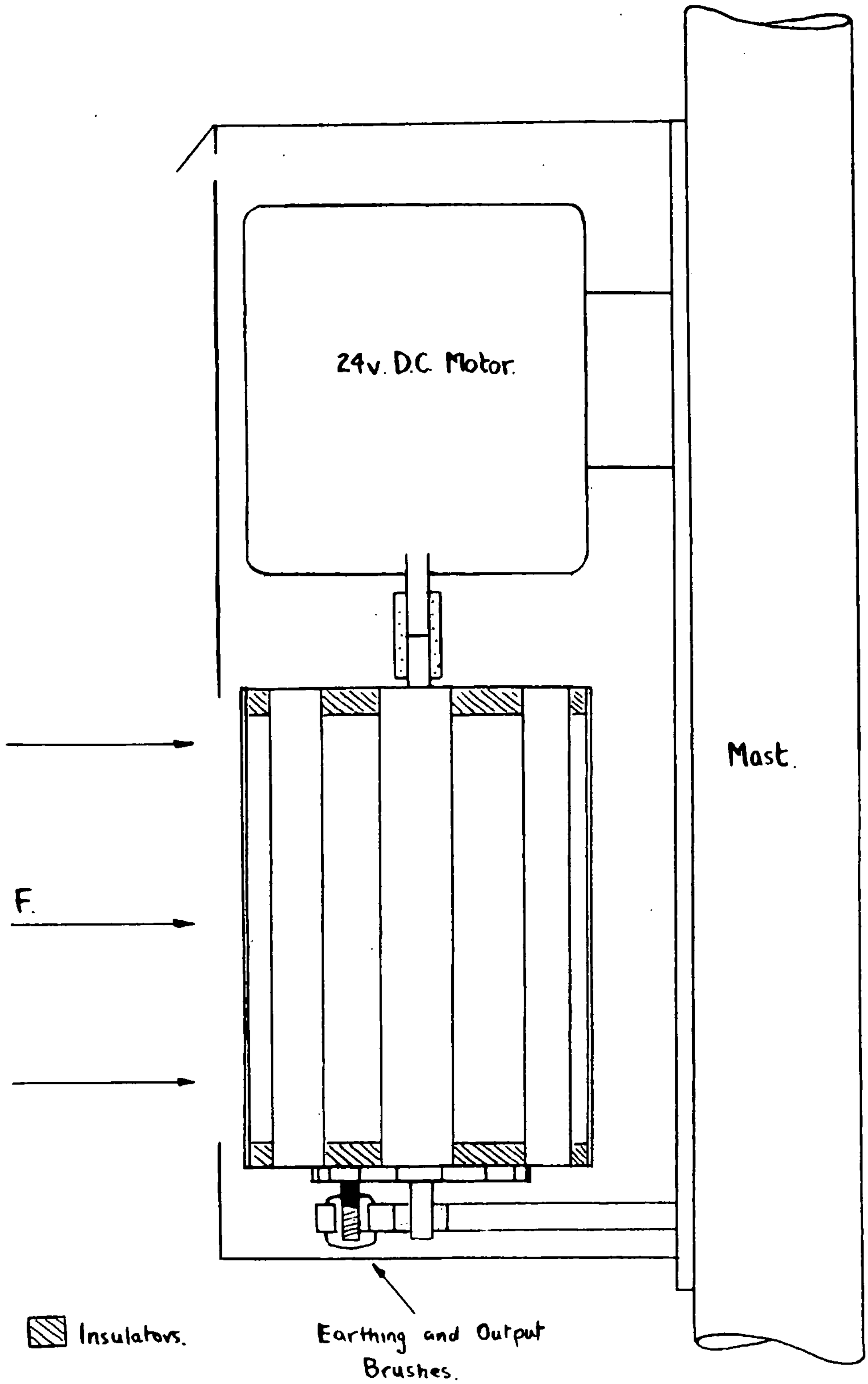


Fig.20 Diagrammatic Side View of Agrimeter (half full size).

instrument could be used. The basic simplicity of such a machine, compact and robust, assured a superiority over the conventional field mill in this exposed position.

The accompanying diagram shows the essential features of the machine which was driven by a 24v D.C. motor at 2000 r.p.m. An earthed plate was moved over the opening periodically to give a zero position on the trace but no calibration voltage was applied in view of the arbitrary nature of the output. The linearity of the output was checked for applied fields up to 5,400 v/m and the Agrimeter was mounted on the top of the triple pole mast at a distance of 7m below the point. A further linearity check for the extremely high potential gradients encountered in this position, was obtained by comparing the Agrimeter and field mill outputs. The ratio of these two was also of interest when space charge distortion of the potential gradient at the mill was observed.

As point discharge commenced the output from the Agrimeter corresponded to that for an applied potential gradient of 50,000 v/m.

5.6 Performance and Procedure.

The 21.5m triple pole mast with single pole extension to 27.6m was completed in the Spring of 1955. It carried the point and the anemometer whilst the field mill, 45m to the West, recorded the potential gradient.

Recording procedure was similar to that of the previous section and again brief notes were made of meteorological conditions. First recordings were made in April 1955 and continued for three months before the results were tabulated, divided into wind speed groups and analysed as previously.

Although the maximum value of the point discharge current included in the analysis was 10.5μa with a potential gradient of 2,100 v/m and wind speed of 9 m/s this was not the highest value recorded. On occasions the current varied between 20 - 30μa but the field mill trace indicated potential gradients of 400 - 500 v/m which were clearly too low. This vast reduction of potential gradient was attributed to the space charge liberated by trees, upwind of the mill, which were themselves discharging. Thus an upper limit to the useful potential gradient was set.

Several recordings were made at this height but as a greater frequency of point discharge current was required for other purposes, it was decided that a lower onset value, i.e. a higher mast, might in some small way compensate for the

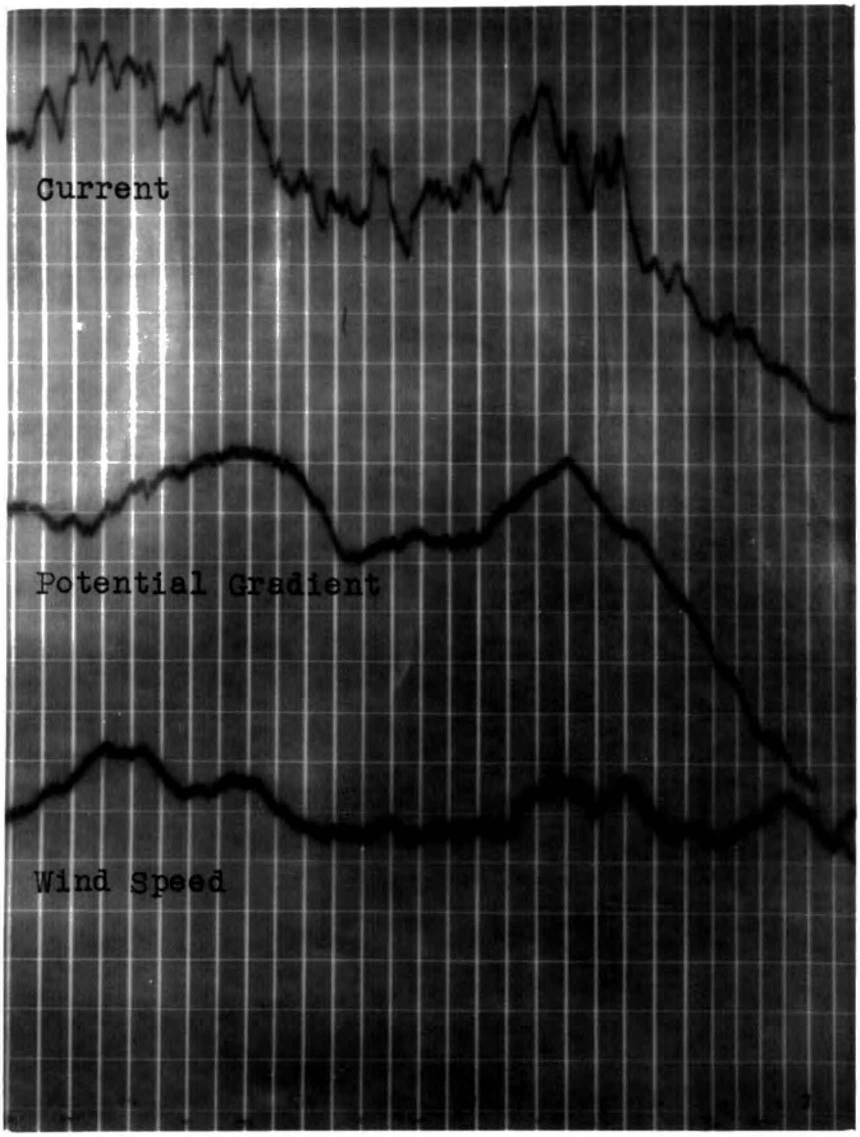


Fig.21 Showing the Fluctuations of Current with Wind Speed.

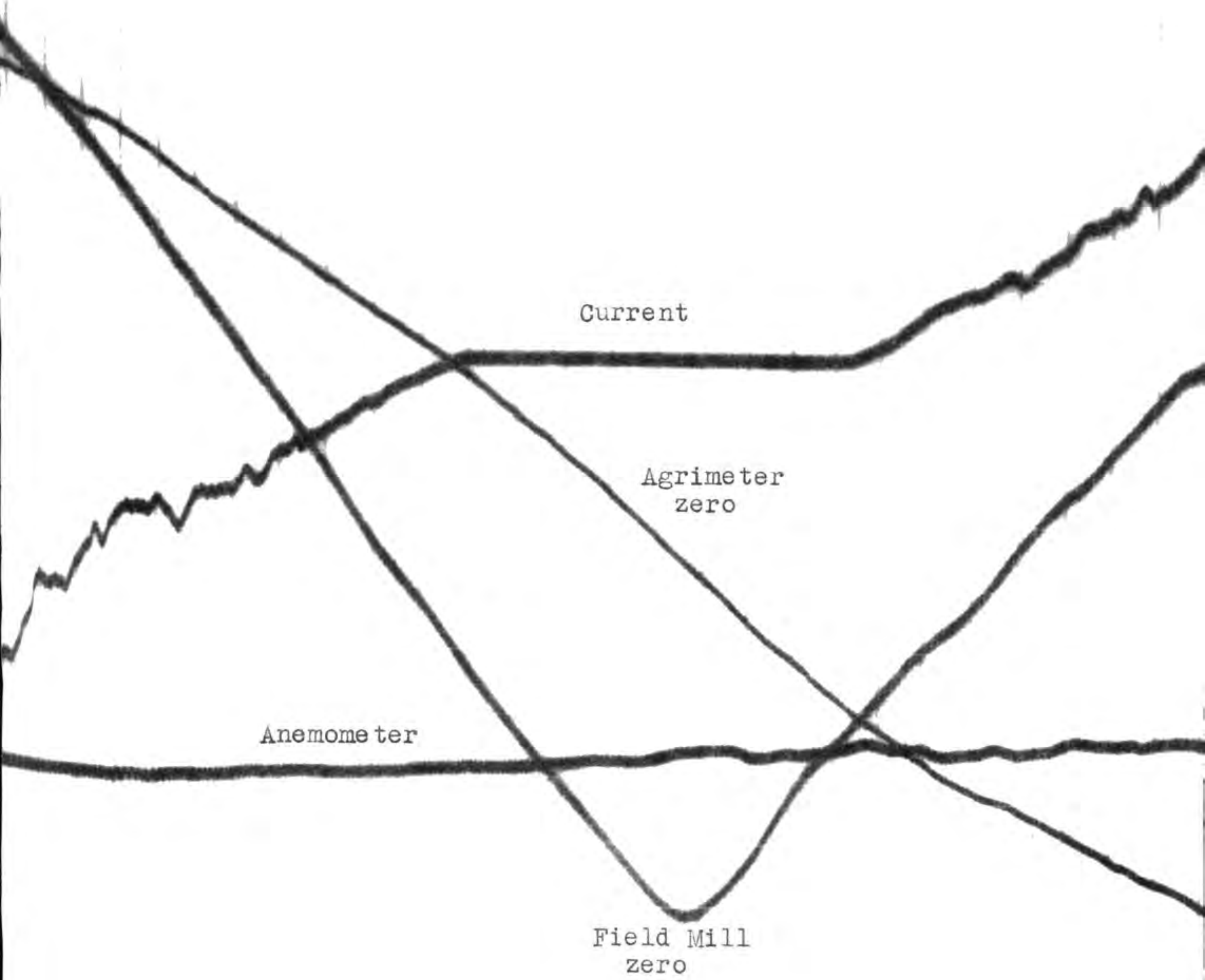


Fig.22 Potential Gradient Reversal.

upper potential gradient limitation. Whilst awaiting delivery of this extra 6.2m of triple pole mast, the Agrimeter was constructed.

5.7 Typical Records.

A section of a record of positive point discharge current from the 27m mast is shown in Fig. 21. The upper trace shows the current, the middle the potential gradient at the ground and the lower the wind speed. The zero point of each trace is shown. The vertical white lines indicate ten second intervals, the whole section covering five minutes.

This record shows the close correlation between peaks in the current and wind speed traces, whilst the general trend of the former follows the potential gradient.

The second record shows a slow change from positive to negative potential gradient, (reading from right to left) with the point discharge current trace showing the characteristic 'plateau' between the onset values of the potential gradients. In reproducing the record this time scale has been inverted, time therefore increases from right to left as indicated at the bottom of the record. The field mill output, being independent of the sign of the potential gradient, falls to a minimum at the mid-point of this change over, whilst the Agrimeter indicates that this gradual simultaneous reversal of potential gradient takes place 7m below the mast.

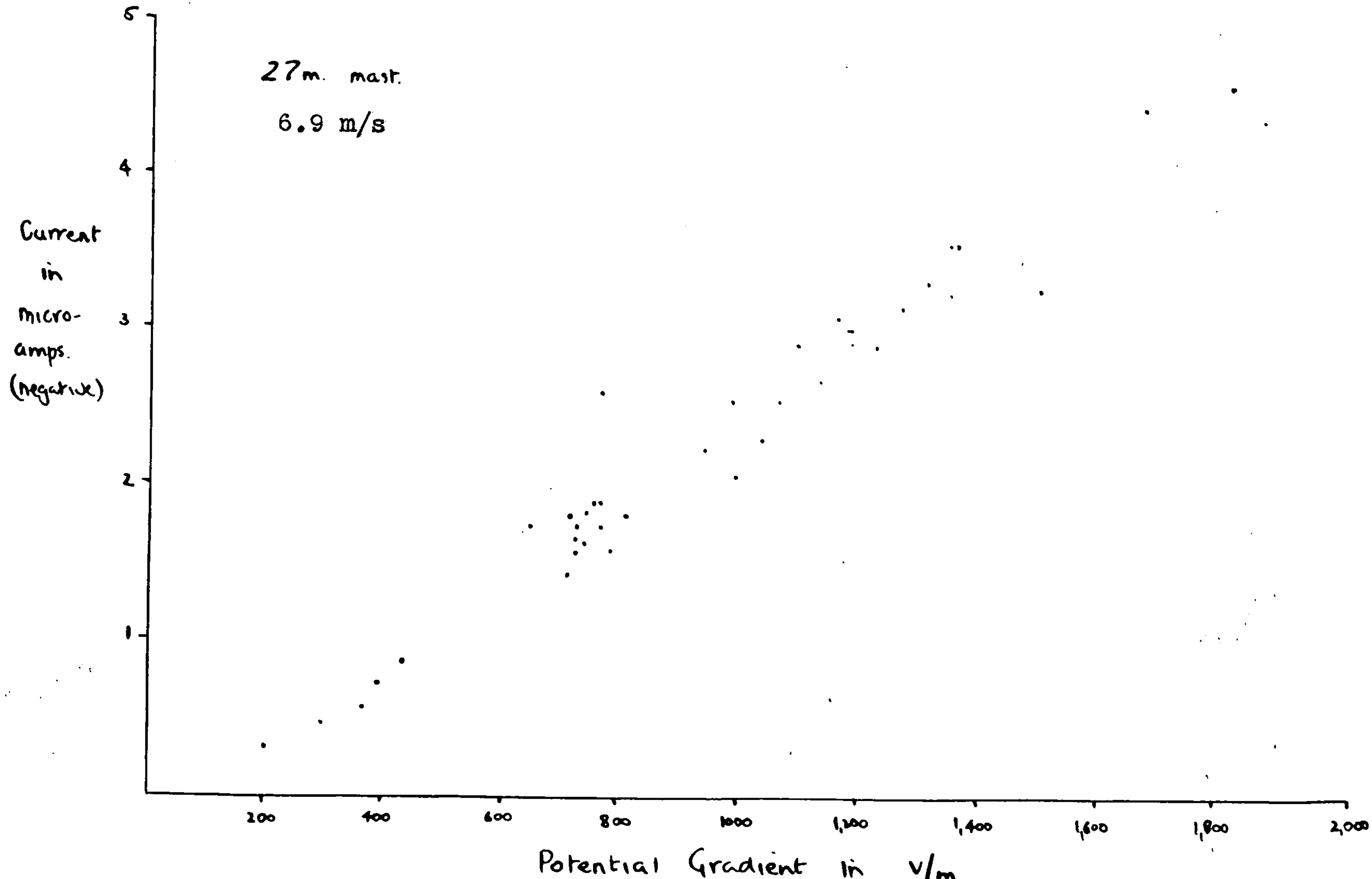

27m. mast.
6.9 m/s
Current in micro-amps. (negative)
5
4
3
2
1
200
400
600
800
1000
1,200
1,400
1,600
1,800
2,000
Potential Gradient in v/m.

Fig.23

CHAPTER 6.

RESULTS FROM THE 27m AND 34m MAST.

6. Point Discharge Current and Potential Gradient at the Ground to Windward of the Point.

As with the results from the 20m mast, divisions were made into wind speed groups which now corresponded to wind speed ranges of approximately 1 m/s width. The graphs obtained by plotting current against potential gradient, measured at the ground, were linear in every case having the form

$$I = a(F - M)$$

M was constant and had a value of 135 v/m for the 27m and 100 v/m for the 34m mast in negative potential gradients.

At the former height negative potential gradients occurred more frequently and hence these were used in the final analysis. Results with positive potential gradient indicated a linear relationship but with a higher value of 'M' and a lower value of 'a'.

In the short time that the 34m mast was in operation, positive and negative potential gradients were encountered in equal proportion but the effects of time delays on reversals of the potential gradient, space charge etc., again prevented an accurate comparison of these constants.

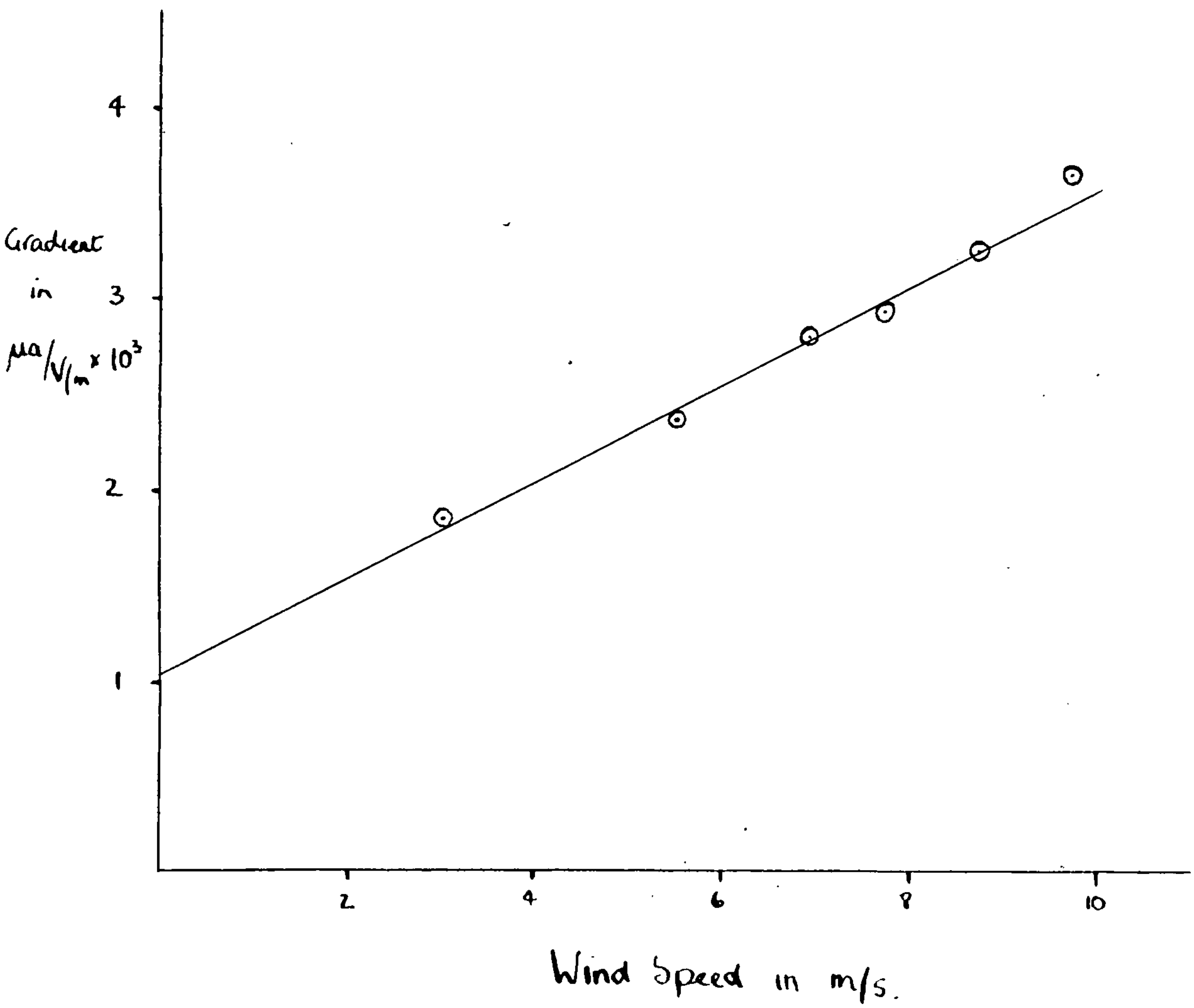


Fig.24.

6.1 <u>The Effect of Wind Speed.</u>

The value of the constant 'a' in the equation

$$I = a\ (F - M)$$

was again found to increase linearly with wind speed throughout the range considered (0 - 10 m/s). This gave a final formula

$$I = K(W + C)\ (F - M)$$

or

$$I = 2.56 \times 10^{-4}(W + 4)\ (F - 135)$$

for negative potential gradients with the point at 27m.

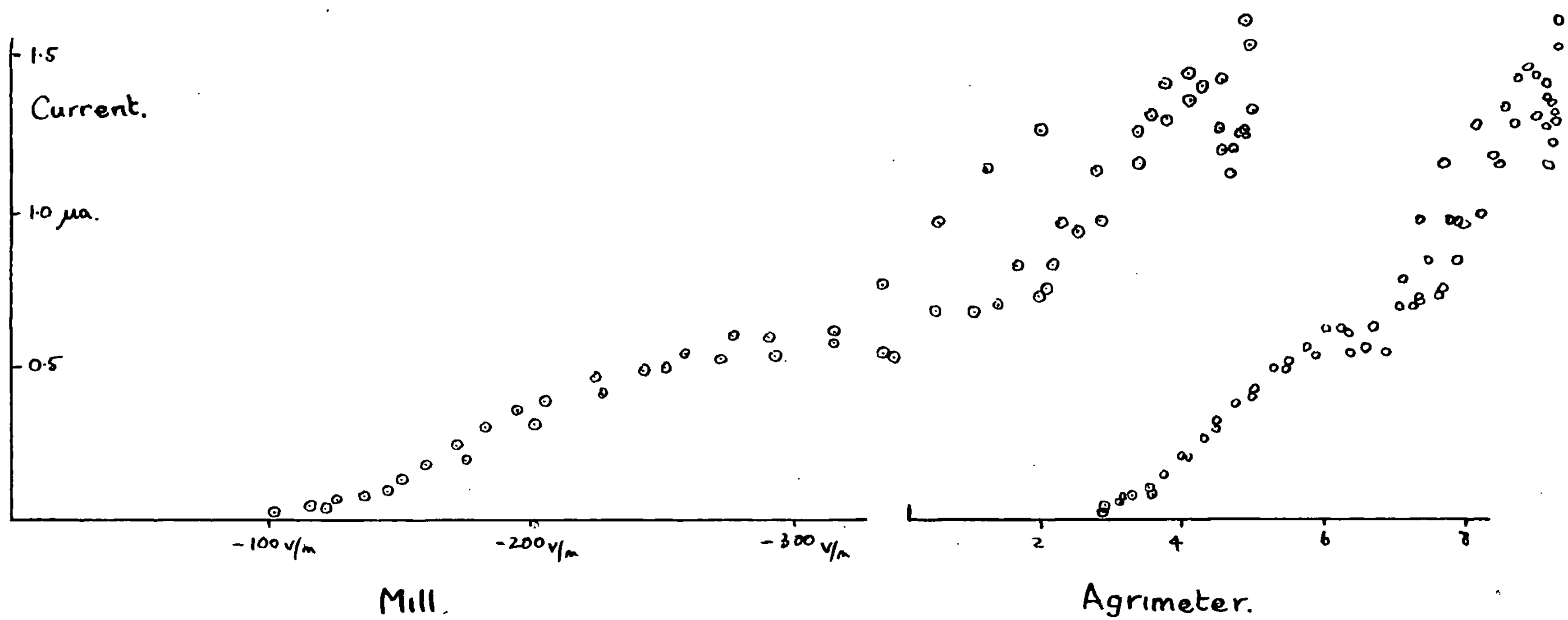
The scarcity of high wind speed results with the 34m point made a complete analysis impossible but from the few values of high wind speed obtained, the indication was that the constants 'K' and 'C' had values such that the final equation was

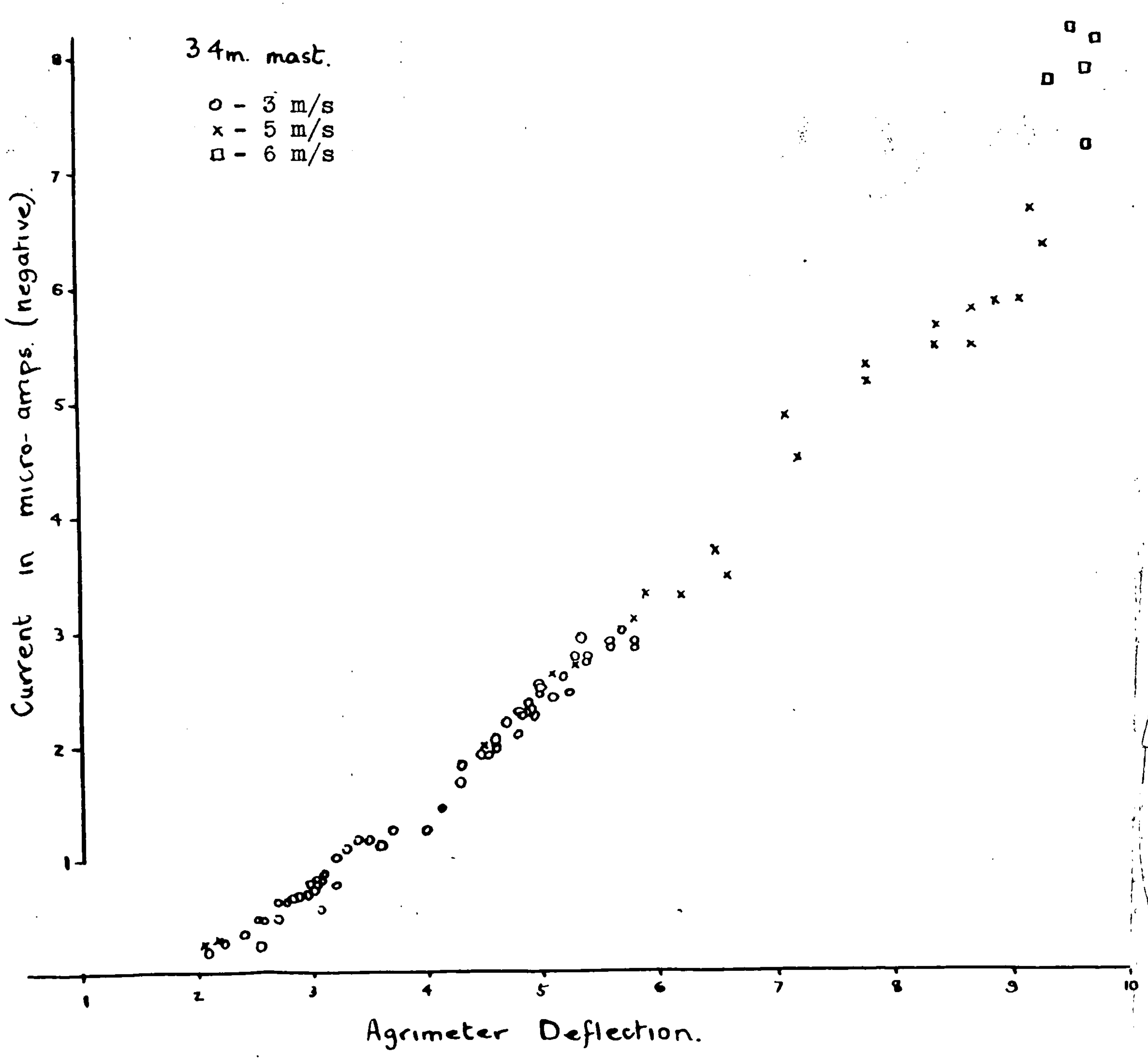
$I = 4.8 \times 10^{-4}(W + 6.8)\ (F - 100)$ for negative potential gradients.

6.2 <u>Variation of Point Discharge Current with Potential Gradient Measured by the Agrimeter 7m Below the Point.</u>

Unlike the results reported in section 4.2 where the potential gradient was measured 2m below the point, the current-Agrimeter curves for narrow wind speed ranges were found to be linear. Again no absolute value of the potential gradient could be given in this elevated position and the

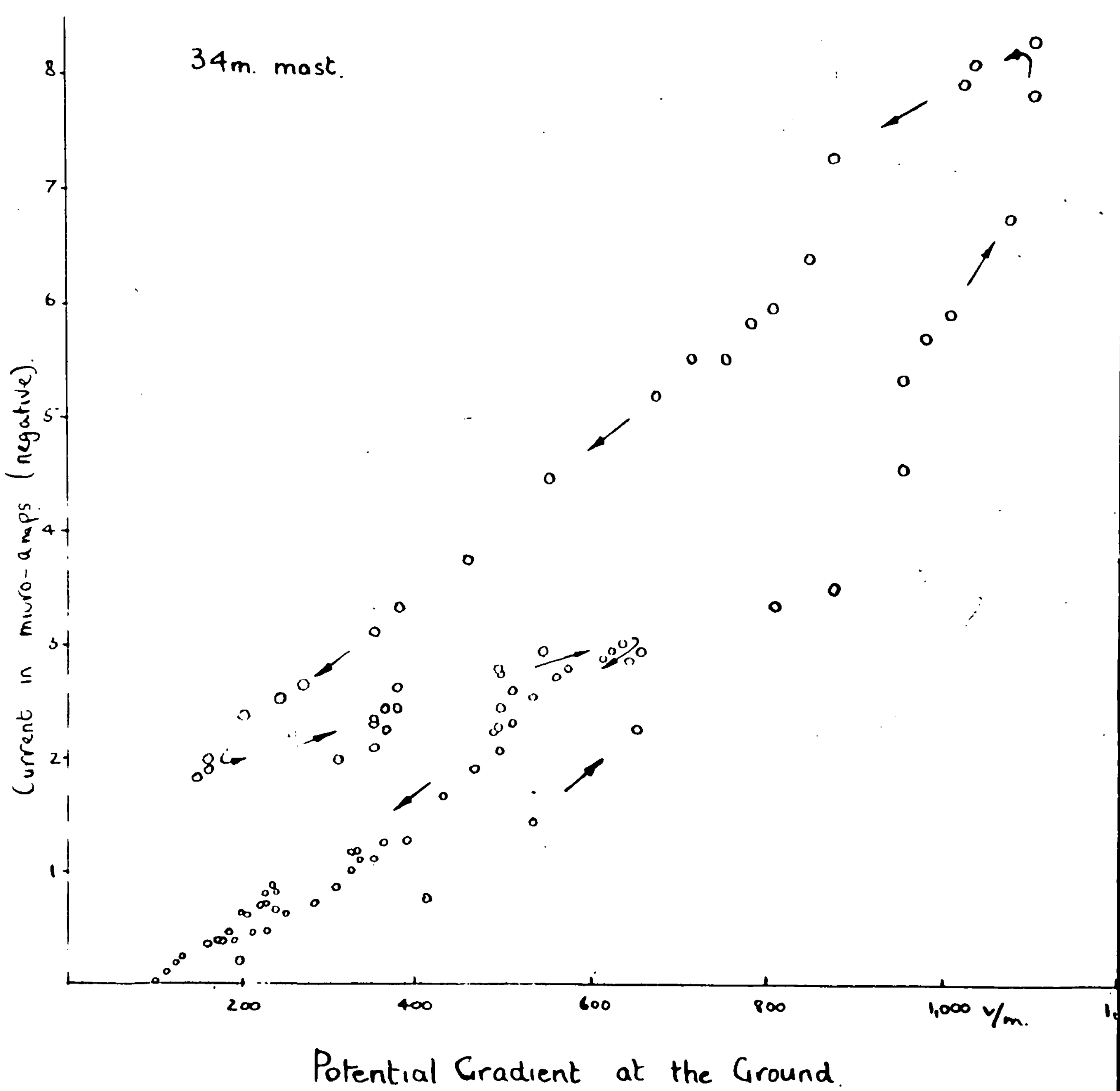
Fig.25.





34m. mast.
o - 3 m/s
x - 5 m/s
□ - 6 m/s
Current in micro-amps (negative)
1
2
3
4
5
6
7
8
1
2
3
4
5
6
7
8
9
10
Agrimeter Deflection.

Fig.27.



34m. mast.
Current in micro-amps (negative)
1
2
3
4
5
6
7
8
200
400
600
800
1,000 v/m.
Potential Gradient at the Ground.

Fig.26.

current was plotted against the output of the Agrimeter which had earlier been checked for linearity.

Corresponding deflections could, however be plotted on graphs as in Fig. 25 and the Agrimeter readings could then be converted to give the equivalent potential gradient at the ground.

Caution was required as Fig.26 and Fig. 27 indicate. Here the point discharge values are shown at ten second intervals with arrows indicating the direction of the current change with time. The output from the Agrimeter is shown in Fig. 27 and the corresponding potential gradient, measured at the ground, in Fig.26.

After rising quite rapidly from 0 - 6.75μa in under two minutes, deviations began to occur in the ground potential gradient curve which, as the current increased, could not wholly be attributed to an increase in wind speed. The current then decreased linearly to 1.8μa along a line which was displaced by 300 v/m from the normal curve which was resumed after an interval of two minutes when the current fell slowly to zero.

During this time the current-Agrimeter graph shows no such aberrations although the effect of wind speed on the current was obvious with high potential gradients. The value of the potential gradient at the onset of this phenomenon (1,000 v/m) suggested that it was due to point discharge occurring from trees in the vicinity of the field mill which experienced a reduction in potential gradient due to the liberated space charge. An indication of the magnitude of the positive space charge necessary to produce such a shift can be calculated on the assumption that the space charge density (σ) is uniform between the Agrimeter at 27m and the field mill at the ground. Thus

$$\varepsilon_0 \frac{d^2V}{dx^2} = \sigma$$

$$= 8.8 \times 10^{-12} \quad \frac{300}{27}$$

$$= 0.98 \times 10^{-10} \quad C/m$$

or $\sigma = 0.29$ E.S.U./m.

6.3 Effect of Wind Speed.

During the record described above there was a slight change of wind speed which is indicated on the current-Agrimeter graph by different methods of marking the points. The few high values of point discharge current occurring with high wind speeds tend to give the impression of a non-linear dependence of current on potential gradient. This is discussed more fully in section 8.3.

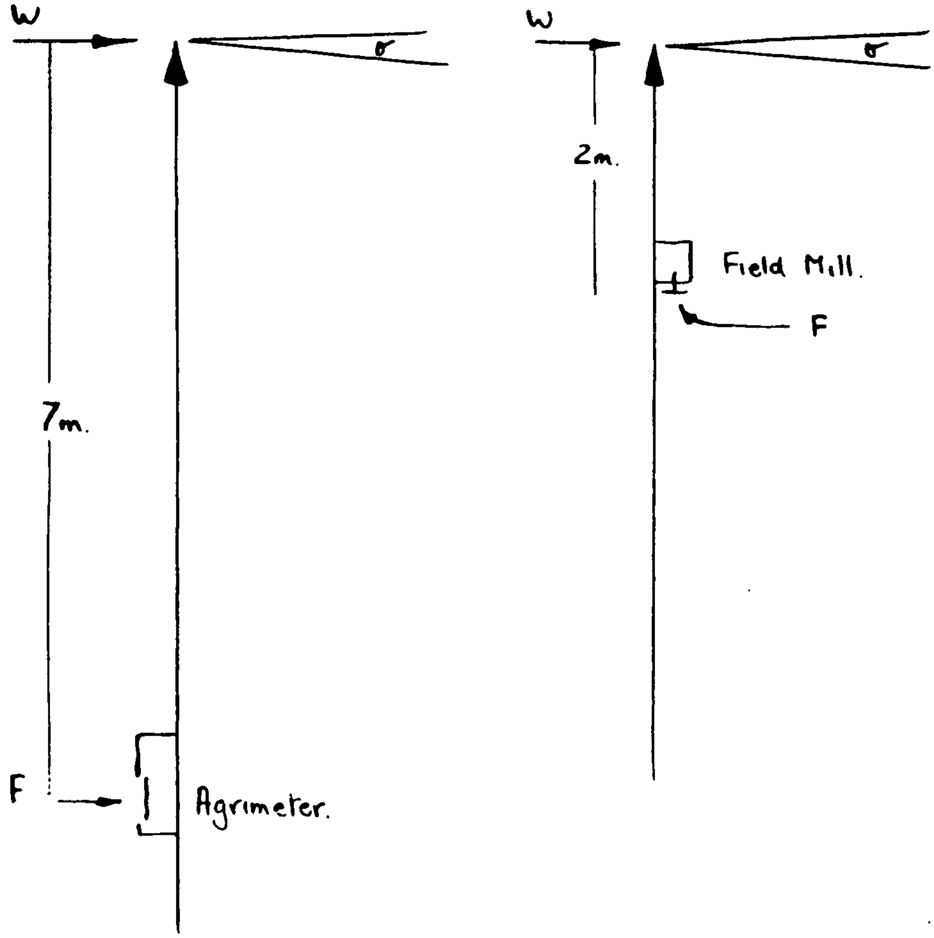


Fig.28 Relative Positions of Field Mill and Agrimeter with respect to the space charge σ .

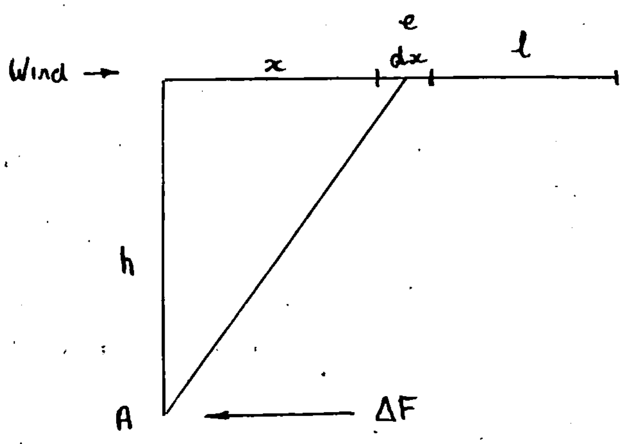
6.4 Comparison with the Results of Section 4.2

As was mentioned in section 4.2 the point discharge current variation with potential gradient measured 2m below the point could be represented by the equation

$$I = a(F - M)^n$$

where both 'a' and 'n' were dependent on wind speed. The results from the Agrimeter recording potential gradient 7m below the point again indicated that 'a' was dependent on wind speed but that 'n' was constant and unity. Fig. 28 shows the relative positions of both Agrimeter and field mill with respect to wind direction and the space charge liberated from the point. The potential gradient at these heights may be regarded as being perpendicular to the mast; the Agrimeter, by virtue of its distance from, and position with regard to the liberated space charge, is thus less sensitive to fluctuations of this charge. The field mill, however, being down-wind of and much closer to this charge, would suffer a variation of exposure as the wind speed altered the contour of the space charge volume.

Assuming that the space charge is a uniform horizontal line charge, the magnitude and length of which is dependent on wind speed, the value of the horizontal component ΔF of potential gradient at a point distance 'h' below the discharging point can be calculated as follows.



As both I and l increase linearly with wind speed E, the charge contained in unit length dx may be regarded as constant, the horizontal component of the potential gradient at A is

$$\Delta F = \frac{e}{4\pi \varepsilon_0} \int_0^l \frac{x\,dx}{(h^2 + x^2)^{3/2}}$$

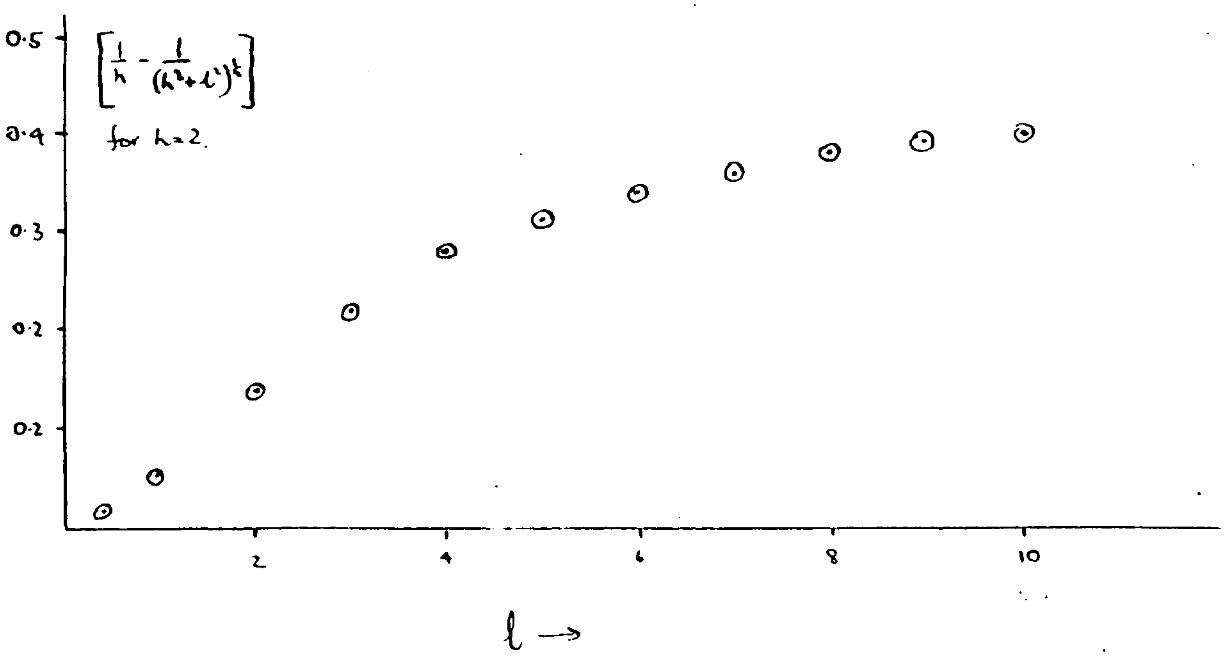
which reduces to

$$\Delta F = \frac{e}{4\pi \varepsilon_0} \left[\frac{1}{h} - \frac{1}{(h^2 + l^2)^{1/2}} \right]$$

F = 0 when l = 0 i.e. no wind.

F is maximum when l = ∞ i.e. high wind.

Consider the effect of ΔF on the current potential gradient relationship in this exposed position. The current I, from the previous results, increases linearly with the over-all potential gradient F. The potential gradient



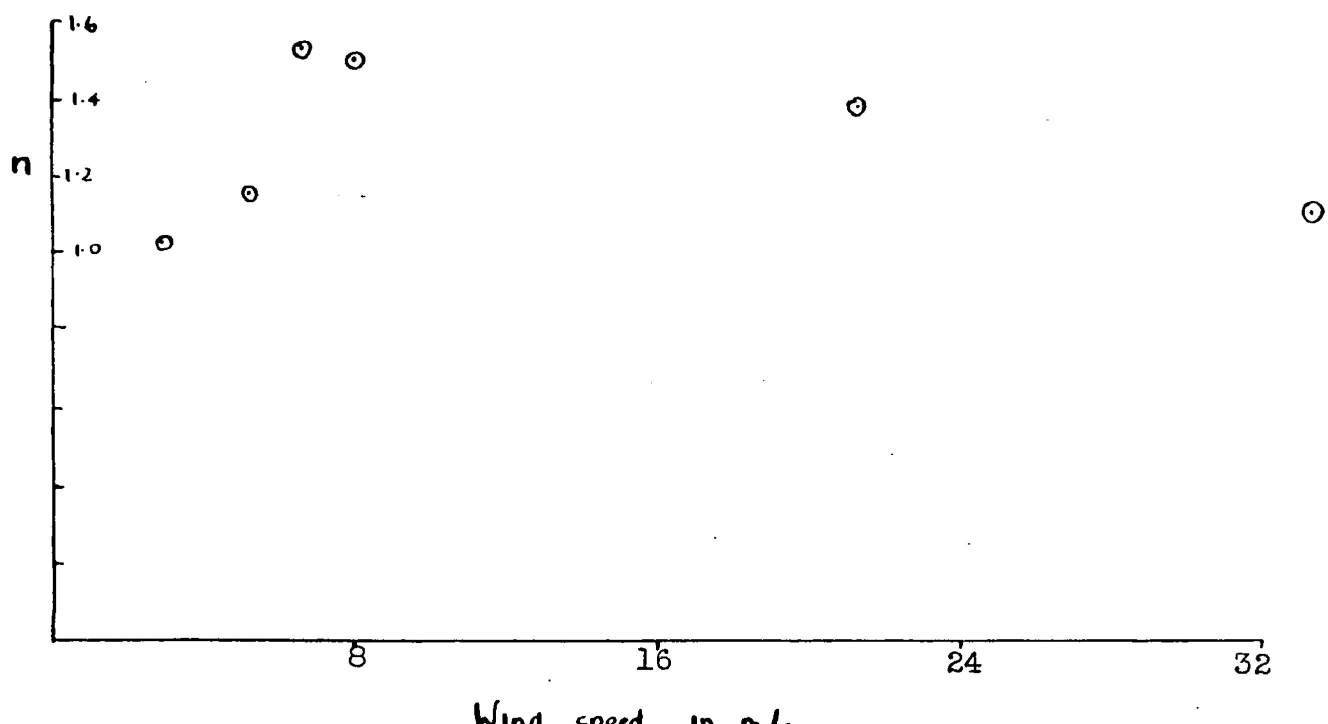


Fig.29 Comparing the Variation of 'n' and F with Wind Speed.

measured at 'h' will be

$$F' = KF - \Delta F$$

$$F = \frac{1}{K}(F' + \Delta F)$$

and as

$$I \doteqdot aF$$

$$I \doteqdot a/K(F' + \Delta F)$$

Therefore correlating I and F' and ignoring the contribution of ΔF, in order to preserve the equality sign the power of F' and of the constant a/K must be increased with wind speed as the contribution due to ΔF would also have been increased.

Comparison of the predicted curve for ΔF and the variation of 'n' in the equation $I = a(F' - M)^n$ shows that whilst an initial rapid rise is obvious in both curves, the gradual decrease of 'n' with wind speed is not predicted by this simple theory.

As the Agrimeter did not show any such effect and as the correlation between I and F in this elevated position was very good, it was concluded that the point discharge current gave a reliable indication of the potential gradient 7m below the point and hence the over-all potential gradient, provided wind speed was also recorded.

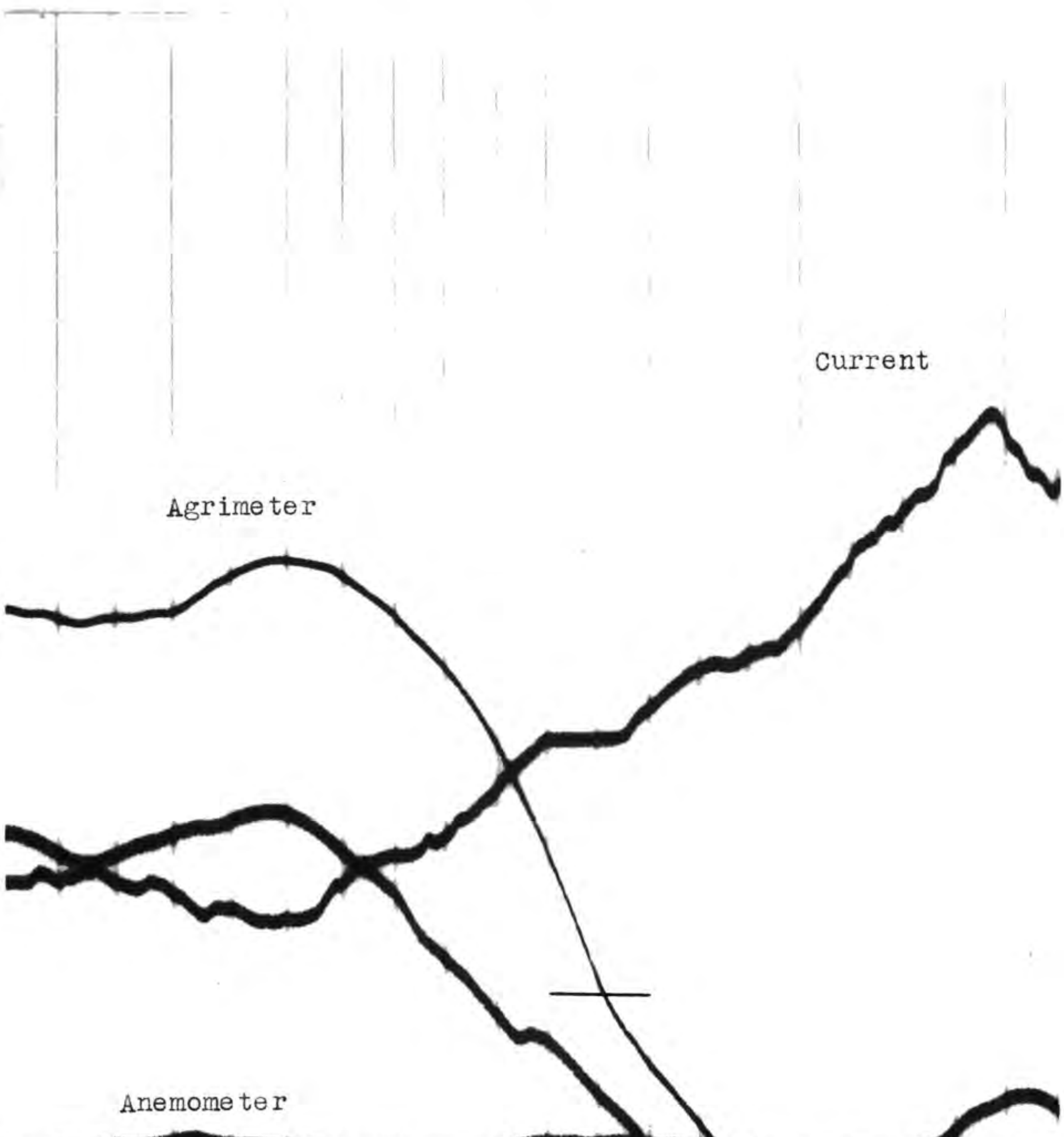


Fig.30 <u>Time Delay.</u>

Time Increasing. ←

6.5 Other Effects.

(a) Time Delays.

Quite frequently in disturbed conditons a potential gradient reversal at the ground preceded a current reversal by more than a minute. This time interval was greatly reduced in the case of the potential gradient measured 7m below the point.

This is illustrated in the section of a record shown in Fig. 30 where the potential gradient at the ground and that 7m below the point precede the current reversal by 34 seconds and five seconds respectively.

Similar periods have also been reported by Lutz (1941) and Hutchinson (1951), the explanation of which was given by Lueder (1943) by considering the screening action of the space charge produced by points in the region of the potential gradient measuring device. This charge is such that it reduces the over-all potential gradient and a low value of this parameter is recorded at the ground. With decrease and reversal of polarity of the over-all potential gradient, the ground potential gradient is reduced and then enhanced by this space charge until such time as this charge is neutralised or dispersed. This previous reduction and ensuing enhancement is clearly visible on the field mill trace in Fig.30.

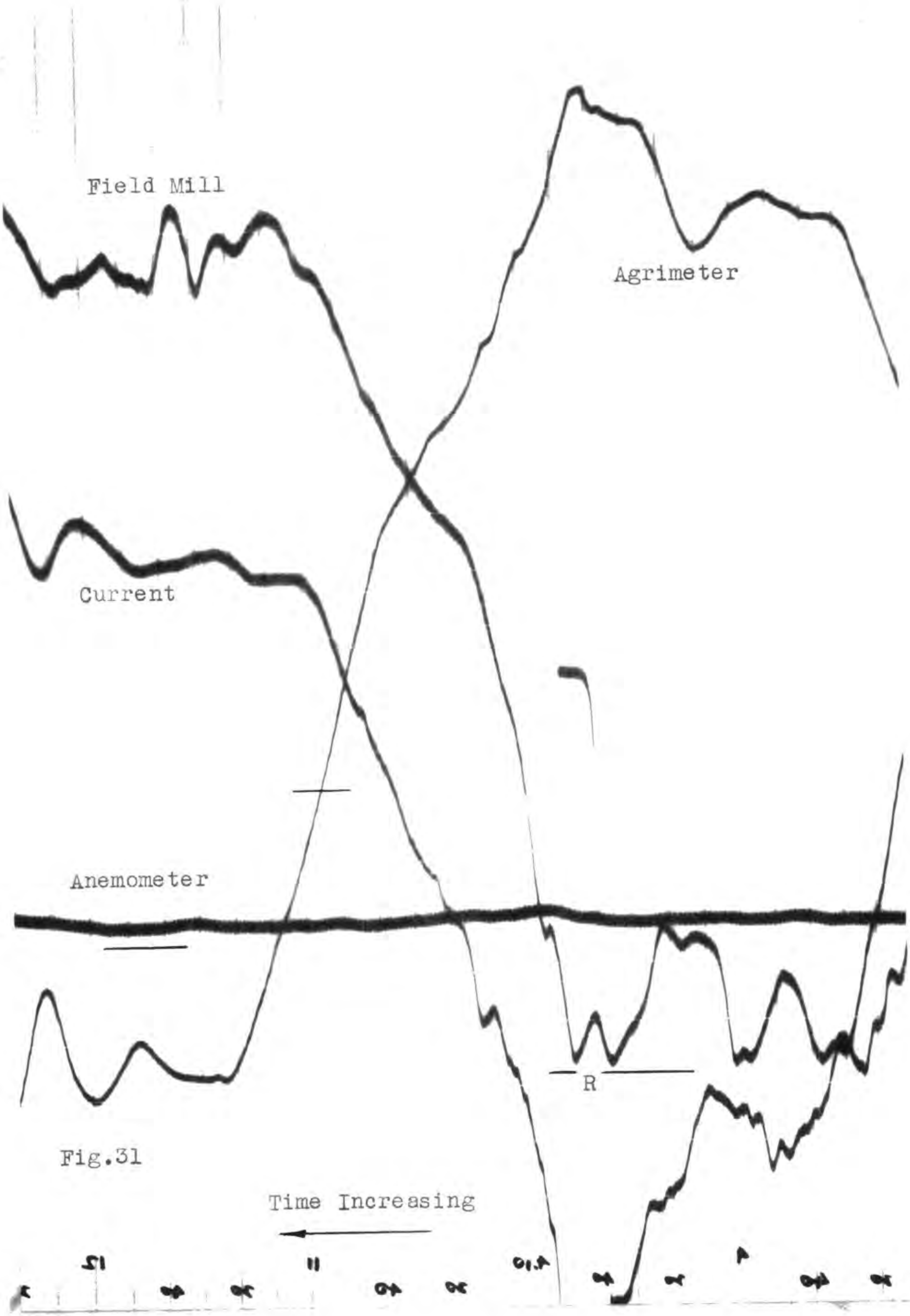

Field Mill
Agrimeter
Current
Anemometer
R
Time Increasing

Fig.31

Fig. 31 is a more extreme case of this time delay where a reversal of potential gradient between point and ground has occurred (at 'R', time 4h.9m.40s.) a positive potential gradient being recorded with a maximum of negative point discharge current. The time interval between reversal of current and potential gradient in this case being 65 secs. at the ground and 10 secs. at 7m below the point.

The current at this time (the galvanometer sensitivity was decreased) was 10.2μa corresponding to an undisturbed potential gradient of 1,250 v/m. From this figure the average value of the space charge necessary to produce this change in a height of 34m was found to be 3.2×10^{-10} C/m^3 (·98 E.S.U./m^3). This is of the same order of magnitude as that measured by Lutz (1944).

These instances illustrate the need of potential gradient measurements as close to the point as is possible bearing in mind the possible effects of the space charge from the point itself on the potential gradients in these positions, as mentioned in section 6.4.

It is also obvious from these two records that the inclusion in the final analysis of periods close to such reversals can lead to a great deal of scatter in the results. Further, in shorter time delays, this persistence of point discharge current can lead to a false value of 'M' and a suggestion of a dependence of current on a power of potential gradient greater than one.

(b) The Effect of Wind Speed on 'M'.

From recordings made when the fair weather potential gradient periodically produced point discharge current from the 34m mast, it was found that the onset value 'M' was independent of wind speed.

This was to be expected as the effect of wind speed is felt only when it assists the potential gradient in removing the limiting space charge from the vicinity of the point. It was therefore necessary that the space charge be established, i.e. point discharge commence before any wind speed effect can be noticed and hence this parameter would not be expected to influence 'M' except in so far as the ion velocity due to wind might be comparable with the ion mobility in the potential gradient about the point. The results indicate that this latter condition was never satisfied.

(c) Variation of 'M' with Height.

From the onset value 'M' and the height of the point the difference in potential between the point and the surrounding air can be calculated, assuming no decrease of potential gradient with height. These values were

3,900v	-	20m
3,645v	-	27m
3,400v	-	34m

A constant value of this voltage at all heights might have been expected but comparison with the balloon results of Mapleson show that the discrepancy is even greater at greater heights. Mapleson concluded from his results that there was no significant difference between the statistics involved in taking

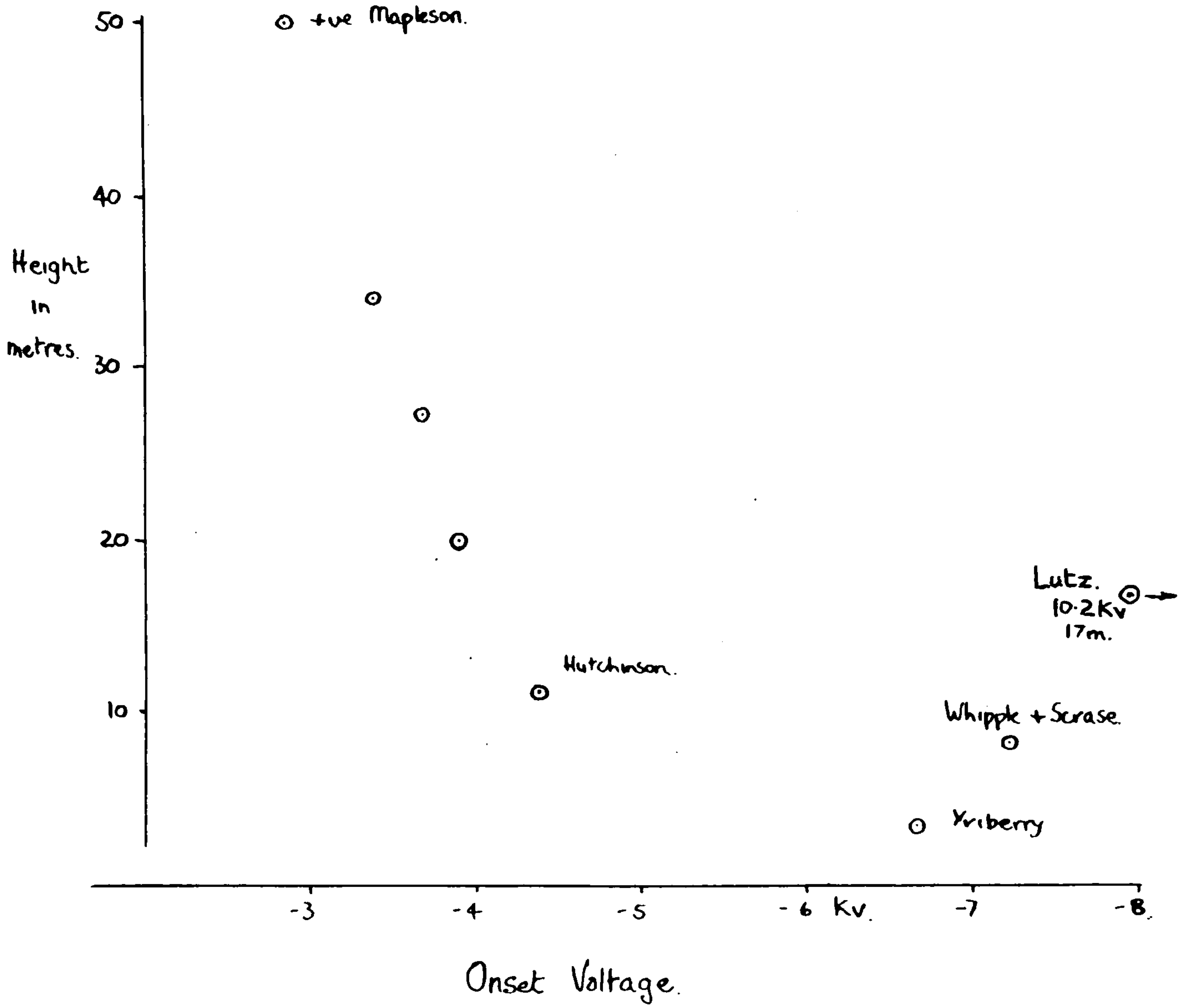
$$M = V/H^2 \quad \text{or} \quad M = V/H$$

where V is a constant and H the height of the point, and selected the latter equation with a value

$$V = 2{,}860\text{v}$$

as being correct for heights of 50 - 150m. This was in close agreement with the value of 2,880v found by Warburg (1899) in laboratory measurements to be the minimum critical voltage for a point of similar diameter to his.

If one can assume the value of 2,860v given by Mapleson to be correct, and obtaining a further voltage from Hutchinson's results (also taken at Durham), the onset



50
40
30
20
10
Height in metres.
+ve Mapleson.
Hutchinson.
Lutz.
10·2Kv
17m.
Whipple + Scrase.
Yriberry
-3
-4
-5
-6 Kv.
-7
-8.
Onset Voltage.

Fig.32.

voltage for point discharge at various heights can be illustrated. (Fig. 32). A further point on this curve would be $H = \infty$, $M = 0$.

Here some positive correlation between H and onset voltage seems to exist, but it must be remembered that minor variations from the curve will arise as the sharpness of the points of Mapleson and Hutchinson differed from that used in the present investigation.

If, as one might have expected, the difference of onset potential (V) between the point and its surroundings were constant for all heights, the decrease of V with higher points might be only an apparent one, which an increase in potential gradient with height would account for. As this is contradictory to the accepted 4% decrease in the first 10m of the atmosphere an alternative explanation regarding the possible screening effect of the mast was sought.

If the screening of the field mill by the mast increased with higher masts, then the output from the mill, for a given over-all potential gradient, would be slightly lower. This might have occurred as the mill calibration was made with the 34m mast and thus a slight divergence between the results at 27m and 34m might be expected: the argument may not be extended to the 11m, 20m and 50m results, especially the latter, where the calibration was made in the absence of the point.

A further explanation may arise from the fact that the height used in the calculations may not have been the effective height of the point; this would have been the case if the equipotential surfaces at each site, in the absence of the mast, had not been horizontal. Chalmers and Mapleson (1955) concluded from their consistently low results at 50m that the effective height of their point was only 40m.

This, together with the other possible minor variations mentioned, could have accounted for this apparent decrease of onset potential with height.

(d) <u>Comparison of Positive and Negative Point Discharge Current.</u>

Results from the 20m and 27m mast indicated that the onset value 'M' of the potential gradient for negative point discharge was lower than that for positive. The value of the constant 'a' was correspondingly lower for the positive results. This is in agreement with the results of Yriberry (1954), partly in agreement with those of Whipple and Scrase (1936) (for 'a' values) but not with Hutchinson's (1951) results. This difference in 'a' with sign of potential gradient is generally attributed to the difference in mobility between positive and negative ions, although an alternative suggestion is given by Loeb (1941).

He considers the fundamental mechanism of the discharge and regards the positive ions as being almost stationary with regard to the mobility of the negative ions, i.e. electrons. With positive points the electrons in the front portion of the 'avalanches' are moving towards the point and into a potential gradient which is being continuously decreased by the positive space charge left behind.

With negative points the electrons, moving away from the point, leave behind a positive space charge which enhances the field close to the point.

Thus the positive space charge in the rear of the 'avalanche' increases the potential gradient between itself and the negative electrode (point or cloud base), while in the weak and declining field ahead of the 'avalanche' the potential gradient to the positive electrode is not enhanced in equal measure. He concludes that where the potential gradient diverges rapidly, the difference might be significant.

Fig.33 The Point above the Tree (left) and the Lime Tree (extreme right).

CHAPTER 7.

POINT DISCHARGE FROM THE TREE AND FROM A POINT IMMEDIATELY ABOVE A NEIGHBOURING TREE.

7. The Point Mounted 2m above a Tree.

At the commencement of this work there was already in operation a point attached to but insulated from the upper branches of a tree and projecting 2m beyond the tree top. (See Fig. 33 opposite). The construction of this point was similar to that described in section 2.4 and it had been erected to obtain an indication of point discharge current magnitudes down trees.

It was decided that further records of current from the point together with the potential gradient as measured by Dr. Chalmers' Agrimeter, 7m from the tree, might be of value for further comparisons, although this work was regarded as secondary to the main point discharge investigations being undertaken.

Several such records were taken, although the high onset value of 1,000 v/m limited recording to disturbed conditions, when, with the space charge from trees and buildings close to the Agrimeter, the variation of I with potential gradient was subject to a great deal of scatter. As no recording was available of wind speed during these periods, a further source of error was thus introduced into the results. However, Fig.34,

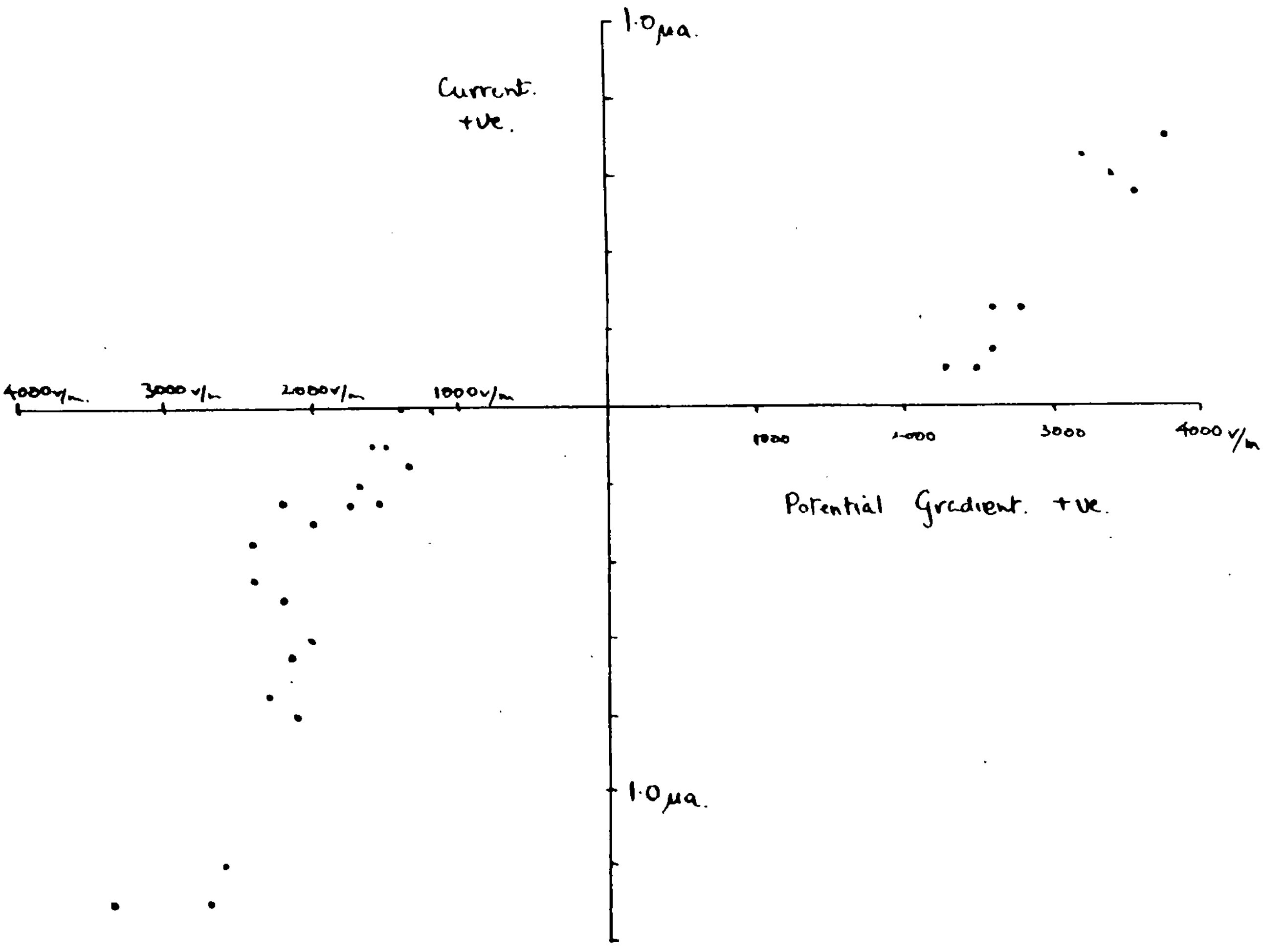


Fig.34 Variation of Current with Potential Gradient for Point 2m above a Tree.

based on results taken in a particularly 'well-behaved' period, shows that the point discharge current was approximately proportional to F. The onset value of positive potential gradient was somewhat higher than the 1,000 v/m required for negative currents to commence. The indication was that the presence of the tree in no way altered the current-potential gradient relationship which did not seem fundamentally different from that obtained with an isolated single point.

Consequently there seemed little to be gained in studying this relatively infrequent discharge when results were readily available from the mast, where the onset value was approximately 10 per cent of that for the point on the tree.

7.1 Point Discharge from Natural Objects.

Previous Work.

Although the greater portion of charge transferred to earth by point discharge is accomplished by natural points, surprisingly little work has been done on these objects. Schonland, in an attempt to determine the charge brought down by a collection of trees, mounted a typical tree on insulators, connected the tree to earth through a recording instrument and noted the variation of current with potential gradient. Four values of current, corresponding to four potential gradient

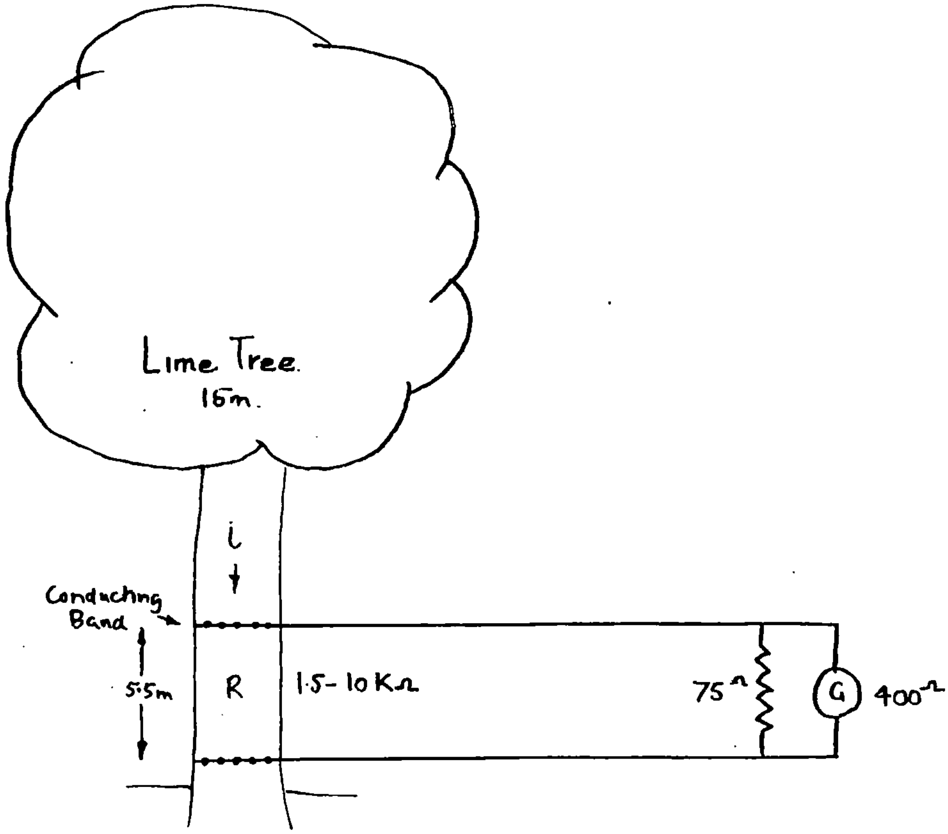


Fig.35 Diagrammatic View of Tree Connections.

values, were given which did not fall on a square law curve. The tree may have been typical at the time of felling, but its properties would have changed rapidly and no continuous representative record throughout the seasons could have been expected.

Method Employed.

In order to obtain continuous records of the point discharge down a tree, it was decided to fix two conducting bands, some 5.5m apart, around the trunk and measure the current flowing through a low resistance galvanometer connected between these bands.

A lime tree about 15m high was selected (see Fig. 33), a number of brass screws were driven through the bark, 6m up the trunk, until they made electrical contact with the outer conducting layer of sapwood. A copper wire soldered to each of these screws formed one output lead whilst a similar arrangement at the base of the tree provided the other. A coaxial lead connected these bands to a galvanometer in the recording room.

The resistance of this external circuit was kept as low as possible (63 ohms) in order that the greater portion of the point discharge current would flow through the galvanometer. This proportion, however, would be dependent on trunk resistance which, in view of its probable variation with season, was

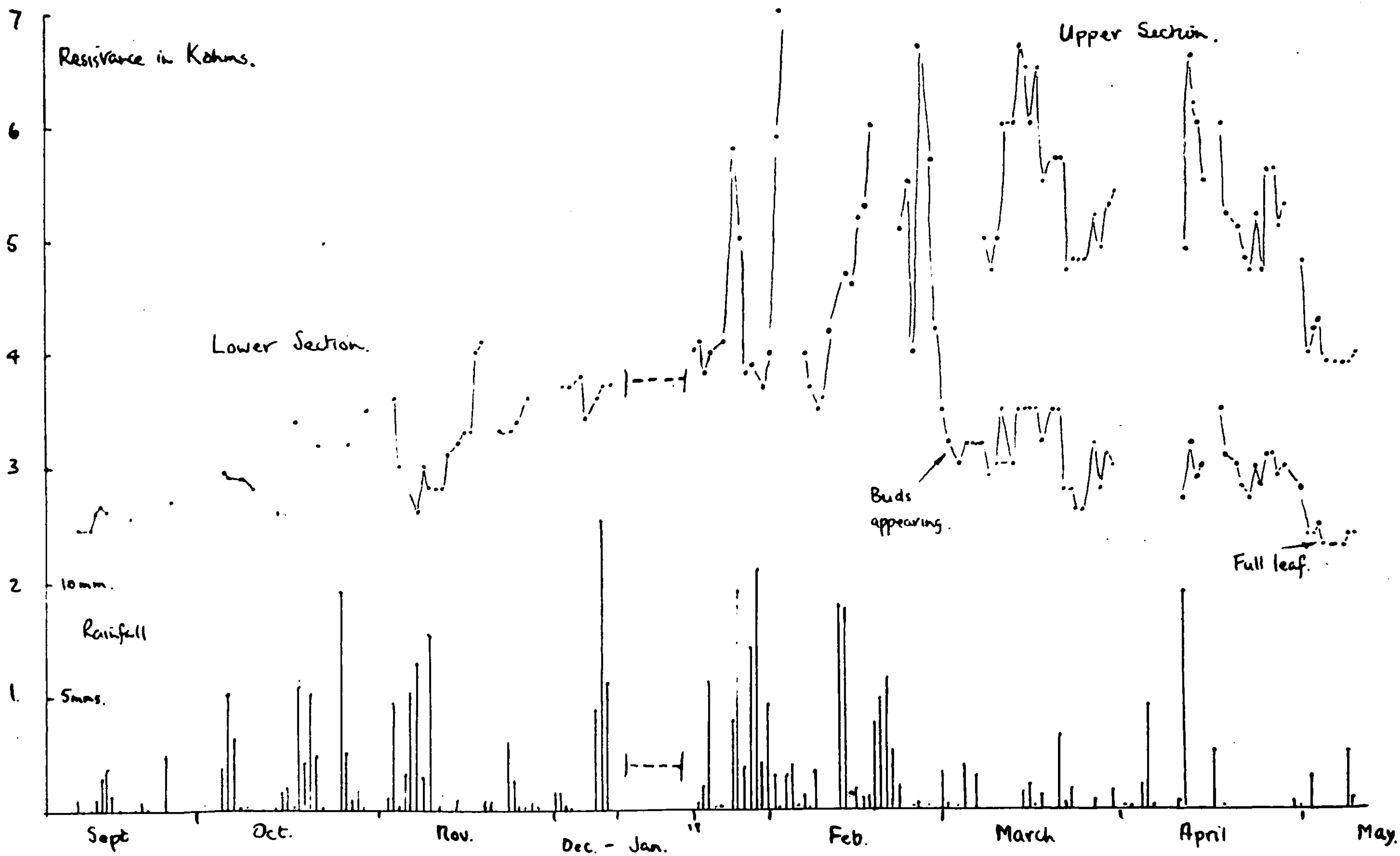


Fig.36 Variation of Trunk Resistance with Time and Rainfall.

checked daily with the aid of an alternating current Wheatstone bridge.

This variation, over a period of nine months, is shown in Fig. 36. Apart from the annual variation of resistance a seemingly sporadic variation was also noticed which was later associated with rainfall. It was found that a decrease of resistance occurred from 12 - 24 hrs. after rainfall, an effect which was attributed to the increased dissociation of the electrolyte (sap etc.) with increase of dilution. This effect was most noticeable in the Winter months when the sap was most concentrated.

As a subsidiary experiment, a third band was placed at a further 5.5m above the second band, when it was possible to determine the resistance of the two equal lengths of trunk and obtain an indication of the height to which the water was rising.

Results.

No accurate quantitative results have so far been obtained using the conducting bands, although the records shown opposite indicate that the method was feasible. The general trend of the current trace resembled that of the potential gradient although several differences were immediately obvious.

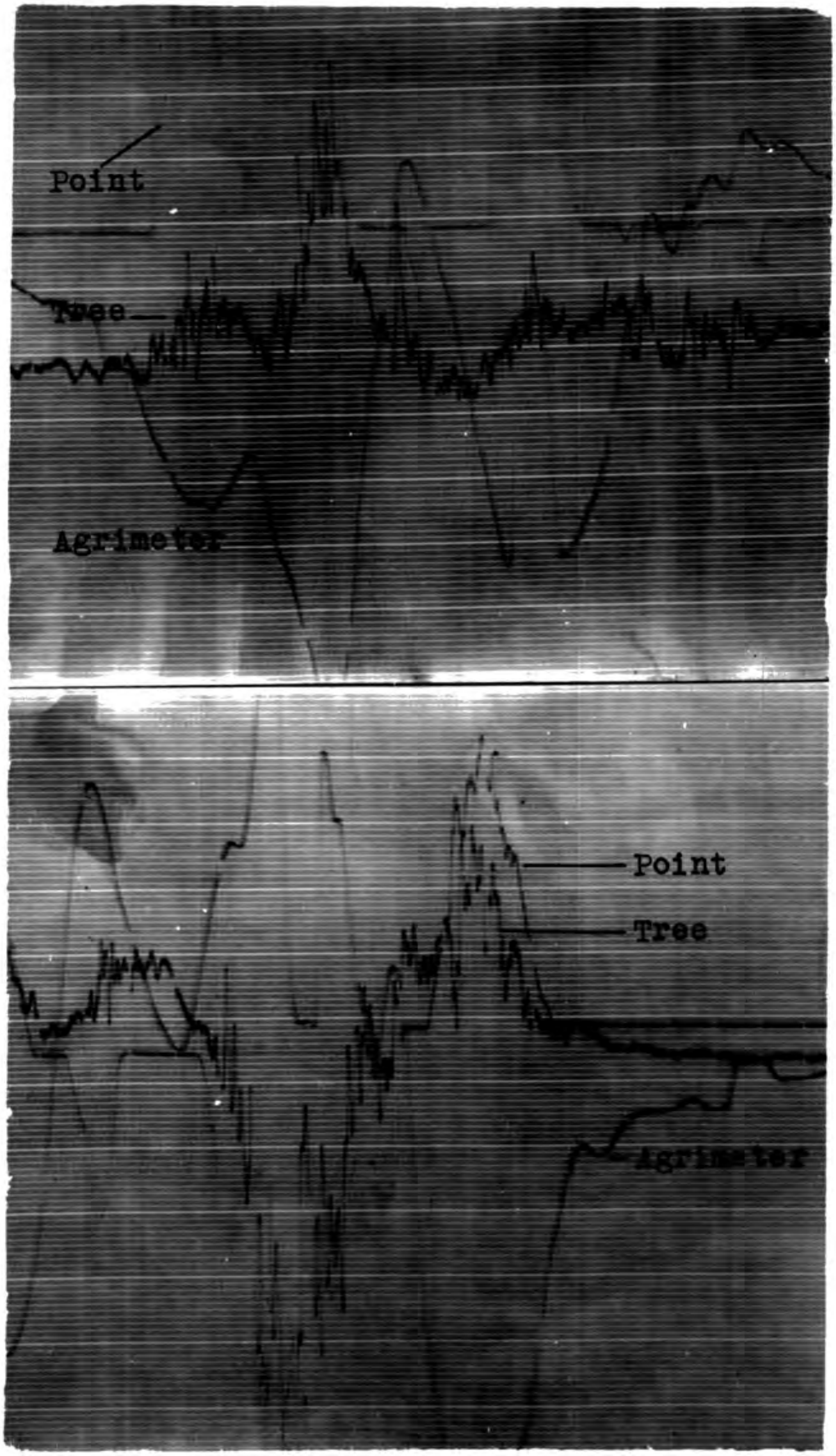


Fig.37 <u>Current and Potential Gradient for Tree and Point above a Tree.</u>

(a) Variations of zero position.

During the recording the zero position of the current trace seemed to alter. This was obvious especially with a reversal of potential gradient when the familar change-over 'plateau' did not appear. These zero fluctuations were of the order of 10^{-1} μa and were thus rather large to be accounted for by either precipitation currents or changes in the bound charge on the tree during potential gradient fluctuations, i.e. with the tree of area $30m^2$ and a maximum precipitation current of $10^{-14}a/cm^2$, current down the trunk = 3×10^{-3} μa. With potential gradient changes of 1,000 v/m in 10 secs., current = 2.4×10^{-2} μa.

No immediate variation of trunk resistance was found with the onset of heavy rain but a probable cause of these zero fluctuations could be electrolytic action between the sap and the brass connecting screws. It was decided to apply a low alternating current to the trunk in the hope of removing any polarisation which might occur. So far no results have been obtained with this alternating current 'bias' but the work is being continued.

(b) Oscillations

Oscillations frequently occurred in the current, particularly in heavy rain, which were not apparent in the potential gradient. There was then no correlation between the potential gradient and current traces, the latter being a series of oscillations about the zero point whenever the potential gradient was above the onset value. This may have been due to the liberated space charge being carried back to the tree or to further electrolytic action which it was hoped might be avoided by the 'bias' current mentioned above.

Comparison of Currents down the Tree Trunk with those through the Point Mounted in a Nearby Tree.

From the simultaneous measurement of these two currents and potential gradient an approximate comparison between the efficiencies of the tree and the point could be obtained. It must be remembered that the tree was effectively a series of multiple points, the 'M' values of which would vary with surrounding foliage and height above the ground, etc. and therefore a linear dependence of current on potential gradient would not be expected.

Onset of point discharge by the tree occurred in potential gradients of 600 - 700 v/m whilst that of the point in the tree corresponded to 1,000 v/m. This was not surprising as, in this latter case, the presence of the tree some 2m below the point greatly reduced its effective height. Simultaneous currents through tree and point in potential gradients of 2,000 v/m were 1.5μa for the tree and 2.5μa for the point. Wind speed was not at this time being recorded. The resistance of the trunk was 3,000 ohms and that of the external circuit 63 ohms; the measured value of the current down the trunk was thus only 2% low.

The point above the tree was thus more effective in discharging currents at this high value of potential gradient in spite of its higher onset value. This was compatible with the findings of Chiplonkar (1940) and Chalmers and Mapleson (1955) who measured decreased currents with the substitution of multiple points for a single point.

CHAPTER 8.

DISCUSSION.

It was not surprising that with the isolation of the wind speed and wind direction effect, the point discharge current should be dependent on a different power of the potential gradient than had hitherto been maintained. The elimination of these two variables resulting in a measurement of potential gradient undisturbed by spurious space charge and within a given range of wind speed, did much to reduce scatter.

Whipple and Scrase suggested that a certain amount of scatter found in their results could be attributed to variations in wind speed but Hutchinson would not admit of this; Chiplonkar and Yriberry and others made no mention of either wind speed or direction. Of a totally different nature are the balloon results of Chalmers and Mapleson who considered both these factors.

8.1 Comparison with Previous Fixed Point Results.

In attempting to explain the divergence of the present results from the $I = a(F^2 - M^2)$ formula favoured by Whipple and Scrase, Hutchinson, Chiplonkar and Yriberry, it is necessary to consider

(a) the effect of the difference in height of the points

(b) the effect of wind direction

(c) the effect of wind speed.

(a) The Difference in Height of the Point.

It is doubtful whether the height of the point up to say 150m (where Chalmers and Mapleson found errors arising due to natural space charge) will affect the power of the potential gradient upon which the point discharge current is dependent. The presence of trees, higher or lower than the discharging point, would serve only to affect its exposure. The ratio of the potential gradient at the point and at the ground, though depending on the surrounding objects, would be none the less constant for values of potential gradient up to that at which the surrounding objects themselves give point discharge. Here a discontinuity in the current-potential gradient curve would be obvious as the records in section 6.2 show, and high values of current would occur for abnormally low values of the potential gradient. Beyond this point the current potential gradient relationship will be influenced by the relative location of point and field mill positions with regard to the wind direction as mentioned in section (b) below.

This non-dependence of the power of the potential gradient on the height and presence of surrounding trees was indicated in the results from the 20m mast which was itself a few metres higher than the closest trees (30m upwind) and even more so by the results from the point fixed to the top of the tree (section 7), although in this latter case, the effect of wind speed was not considered.

(b) <u>The Effect of Wind Direction.</u>

The effect of the liberated space charge from trees upwind of the field mill mentioned above, would be to give an unexpectedly high value of point discharge current for a low recorded potential gradient. Effects similar to this are observed when the space charge from the mast itself is carried over the field mill. The net effect of disregard of wind direction would be thus expected to introduce scatter into the results and possibly to enhance the value of I when high over-all potential gradients are encountered.

(c) <u>The Effect of Wind Speed.</u>

Further scatter would result as the foregoing results have shown when simultaneous measurements of I and wind speed were not taken. As this factor was not measured by previous workers, it is interesting to speculate its effect on their results in the light of the present equation

$$I = K(W + C)\ (F - M).$$

For a wide range of wind speed and potential gradient the values of point discharge current from a given point will, according to the above equation, lie within a cone whose apex is at the point $I = 0$, $F = M$. The distribution of

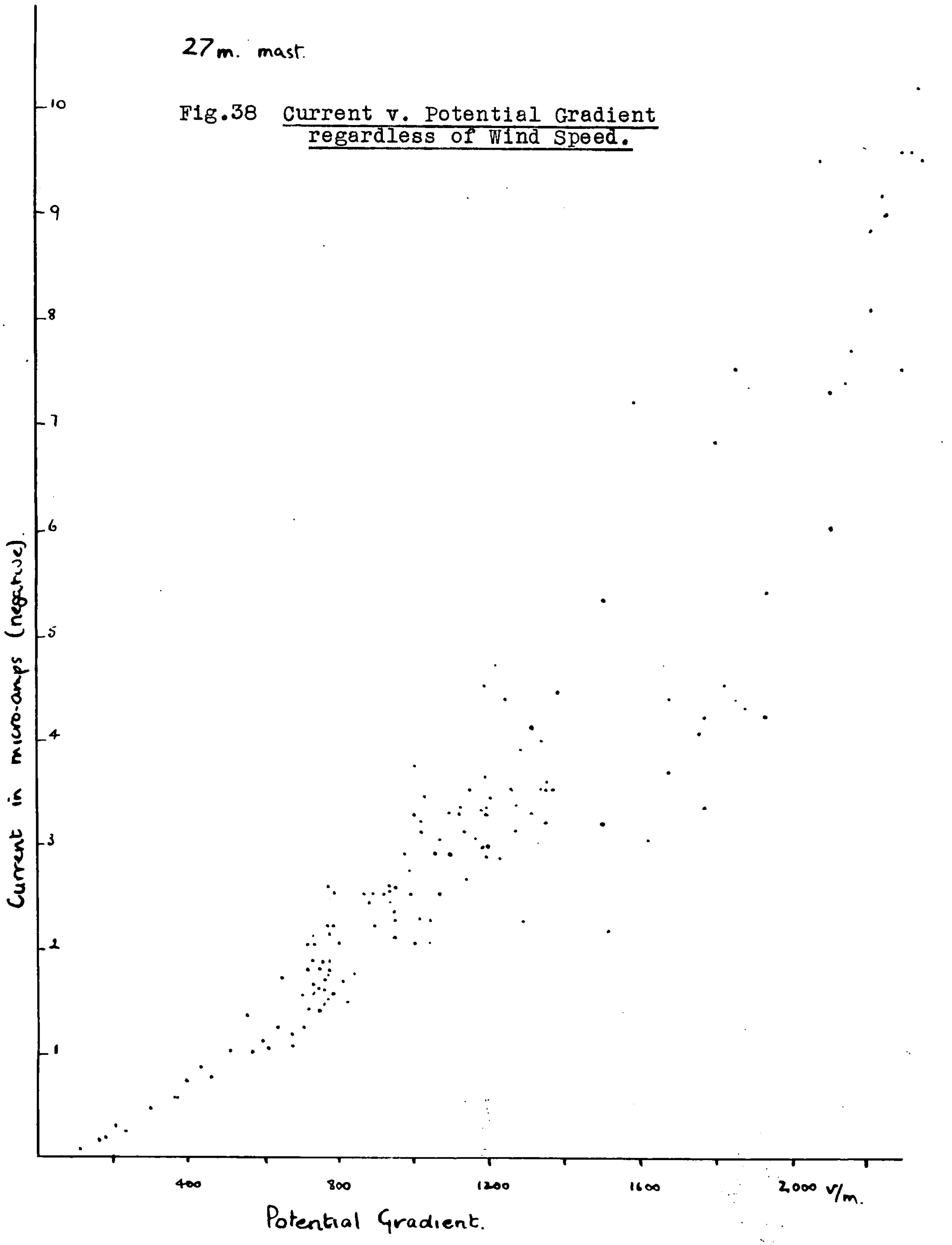


Fig.38 Current v. Potential Gradient regardless of Wind Speed.

points within this region will depend on the wind speed-potential gradient relationship which, taken over a long period, ought to be random. With a limited number of points however, and a few high values of wind speed occurring with high potential gradients, the dependence of I on the second power of F could easily be suggested. This is noticeable in the current-Agrimeter graph, Fig. 27 and in Fig. 38, where the points have been plotted regardless of wind speed.

Had this occurred with previous workers, then the fitting of the equation $I = a(F - M)^n$ to their results ought to give values of 'n' close to unity.

A statistical analysis of the published results of Whipple and Scrase for negative currents and potential gradients was therefore undertaken. A logarithmic plot of current I against potential gradient F was made and best value of 'n' in this general equation was found to be 1.07 ± 0.13, the full equation being

$$I = 0.03506\ (F - 8.6)^{1.07}$$

compared with the original

$$I = 0.001\ (F^2 - M^2)$$

where I is in microamps and F in volts per centimetre. Surprisingly enough the former, by the method of least squares, was found to be the better fitting equation.

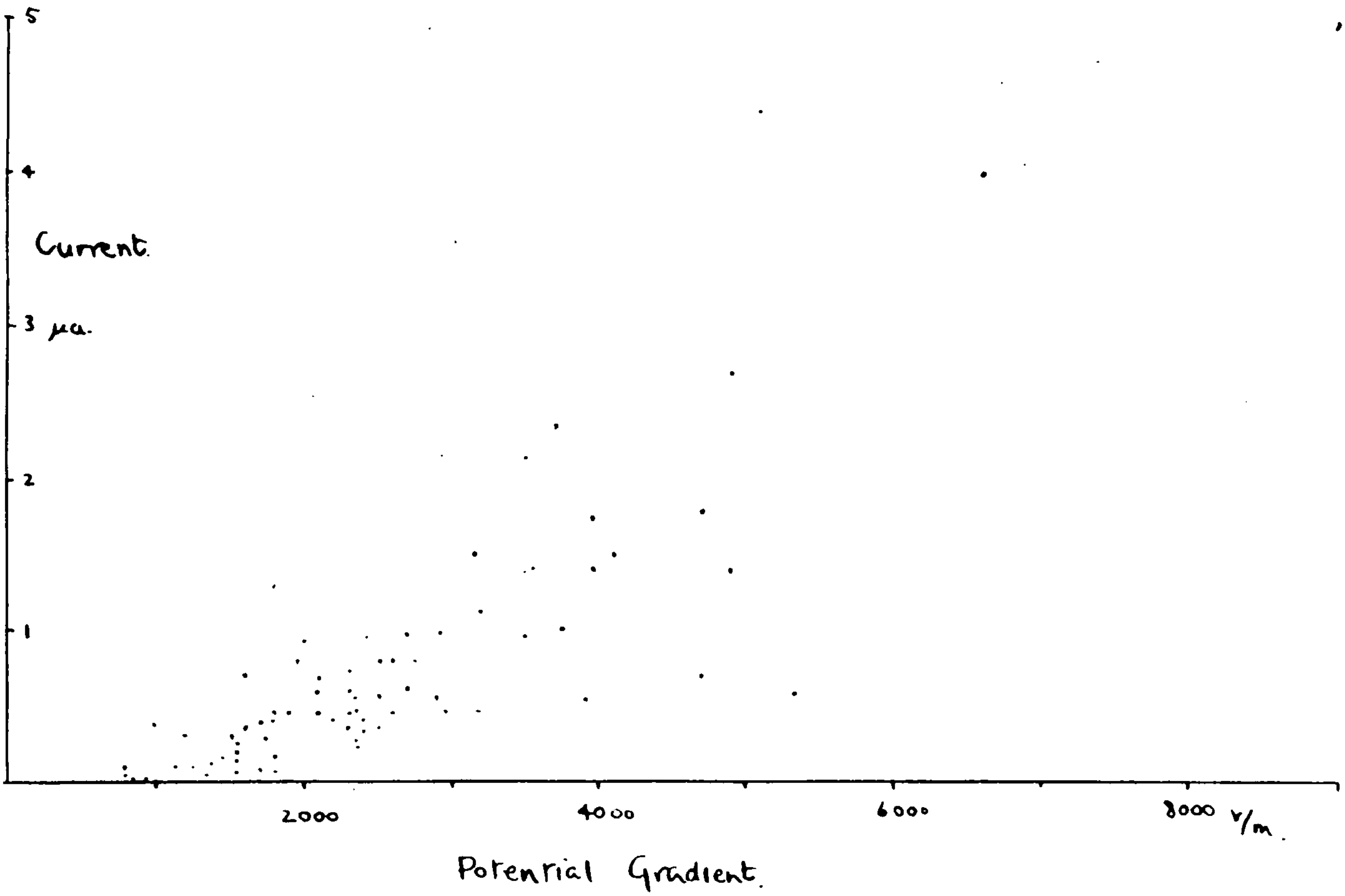


Fig.39 Current v. Potential Gradient (Whipple and Scrase, 8.4m).

Similar treatment of the negative half of Hutchinson's results yielded the formula

$$I = 0.000116\,(F - 4)^{1.09 \pm 0.06}$$

with similar units as above, which again, was a better fitting curve than his.

$$I = 0.0005\,(F^2 - 4^2)$$

The close proximity of 1.07 and 1.09 to unity suggests that, had wind speed and direction been taken into consideration in these cases, a linear relationship between I and F quite probably would have been detected and that a few values of high wind speed coincided with high potential gradients tending to obscure this relationship.

It is interesting at this point to note that the value of 'n' for the whole of the results of the current-Agrimeter (20m mast) readings regardless of wind speed was 0.94 ± 0.1, although no significant variation of wind speed with potential gradient could be detected. A similar analysis of results from 27m (Fig. 38) yielded a value $n = 1.05 \pm 0.1$ but here high values of wind speed and potential gradient did coincide.

8.2 <u>Comparison with Balloon Results</u>.

Of chief concern in this category is the divergence of the present results from the balloon results of Chalmers and Mapleson where the equation was

$$I - KW^{\frac{1}{4}}\,(FH)^{\frac{7}{4}}$$

The effect of increased height will, by the logic of the preceding section, be incidental in resolving the difference of power observed as the maximum potential gradient they measured was 250 v/m when surrounding objects were not discharging. The previous reasoning concerning the possible enhancement of the power of the potential gradient by wind speed seems now invalid as this parameter, together with wind direction was considered in their analysis.

The presence of a charge on the rubber balloon is of little help in resolving the discrepancy between the wind speed and potential gradient effects as the following cases indicate.

(a) Assume that the balloon was charged and retained this charge for a time which was long compared with the existing potential gradient changes. With varying potential gradients the presence of the charged balloon would bring about a variation in the ratio of the potential gradient at the point to that at the earth's surface. This ratio would vary not only with the potential gradient but also from day to day with the different charges carried by the differently shaped balloons. The over-all effect would be to introduce scatter into the current-potential gradient curve.

(b) When the decay of charge was rapid compared with the potential gradient changes, it would be expected to be proportional to the applied potential gradient. The configuration of the equipotentials would thus have been independent of the potential gradient and hence the presence of the balloon would not be expected to affect the power of the current-potential gradient curve.

Further sources of scatter discussed by Mapleson (1953) were the rolling of the balloon and hence the removal of the limiting space charge from the region about the point and consequent reduction in height of the point. The conversion of the results giving his general equation

$$I = (cW + d)\ H^{p}(F^{n} - V_m^{n}/H^{n})$$

where c,d, are constants

W the wind speed

H the height of the point

F the potential gradient

V_m the onset voltage

$n = 1.5$ or 2

$p = 1.5 - 3$

to fit the theory of Chalmers and Mapleson must have involved a further loss of accuracy in view of the absence of an onset value in the equation

$$I = KW^{\frac{1}{4}}(FH)^{7/4}$$

8.3 Comparison with Theoretical Equations.

Having established an emperical equation and having discussed its apparent diversion from those of other investigators, it now remains to compare this equation with those predicted by theory.

(a) Chalmers' Theory.

Chalmers (1955) has considered the case of a single point discharging in calm conditions in a steady potential gradient. If this potential gradient is, say positive, positive ions will move into the point and negative ions will move upwards and outwards along the lines of force. Potential gradients at the point will be diminished by this negative space charge which effectively screens the point. Considering time intervals which are long compared with the intervals between individual pulses, he considers the 'quasi-static' state when a balance is established between the current from the point and this limiting space charge. The volume through which these negative ions move he calls the 'space charge volume' in which he assumes there is a uniform vertical component of the potential gradient throughout each horizontal section; across these sections, in steady conditions, the total current I will be constant and equal to the current from the point.

Applying Gauss' theorem to neighbouring cross sections of the space charge volume and integrating throughout the total volume, Chalmers arrives at the equation

$$(Xs)^2 - (X_0 s_0)^2 = \frac{2I}{w\varepsilon_0}\int_{x_0}^{x} s\,dx = \frac{2I}{w\varepsilon_0} v$$

where X is the vertical potential gradient and s the cross sectional area at a distance x above the point. X_0 and s_0 have the same significance at a distance x_0 above the point where ionisation by collision is beginning to occur.

w is the ionic mobility

v is the volume between the cross sections at x and x_0.

Assuming a shape given by $s = kx^q$ for the space charge cross section where k and q are constants with respect to x and that $(X_0 s_0)$ and v_0 are small compared with Xs and v it follows that

$$X^2 = \frac{2I\,x^{1-q}}{wk\varepsilon_0(q+1)}$$

and that the potential V at a distance x from the point is

$$V = \int_{x_0}^{x} X\,dx = \left[\frac{2I}{w\varepsilon_0 k(q+1)}\right]^{\frac{1}{2}} \frac{2}{(3-q)} x^{(3-q)/2}$$

Further assumptions that at a given level the wind velocity is comparable with the ionic velocity and that here the potentials inside and outside the space charge volume are equal, yield the final formula

$$I = \frac{\varepsilon_0 k(q+1)(3-q)^{q-1} \omega^{q-2} W^{3-q} (Fh)^{q-1}}{2^q}$$

or

$$I = KW^{3-q} (Fh)^{q-1}$$

where K is a constant, W the wind speed, F the potential gradient at the ground, h the height of the point above the ground and q a constant having a value between 1 and 3.

In this form I is required to be zero when either W or F = 0 which is not in agreement with observation. However, since in the comparison of potentials inside and outside the space charge volume the reference points were taken as the ground and the point $X_o s_o$, it seems reasonable to assume that F might be taken as the value of the potential gradient in excess of the onset value if X_o and s_o are to represent conditions at the point where ionisation by collision is beginning to occur.

The inclusion of a similar constant in the wind speed term might be achieved by supposing that F and W were not the only agencies by which ion removal from the space charge volume was possible, i.e. with W = 0 and F small, removal by recombination and diffusion processes might be considerable.

With these inclusions the results of the present investigations show good agreement with this theory where q has a value of 2. Under these conditions the non-dependence of I on w, the mobility, is indicated. This suggests that the difference in the value of 'a' (mentioned in section 6.5d) for positive and negative potential gradients should be ascribed to the mechanism suggested by Loeb (1941).

(b) Chapman's Theory.

Of a somewhat different nature from the theoretical considerations of Chalmers is the work of Chapman (1956) who, using dimensional analysis, determined a relationship between the current I, flowing through a point attached behind an aircraft, the velocity of the aircraft v and the difference in potential V between the aircraft and its surroundings. He deduced that

$$I = \varepsilon_0(FkV^2/l + GvV + Hlv^2/k)$$

where F, G and H are constants

k the mobility

l some dimensional length.

In laboratory and atmospheric point discharge, the latter term, containing no reference to voltage, is not of interest.

From point to plane corona results in his laboratory he concludes that for a point 0.007cm diameter

$$I = Av\,(V - V_o)$$

where $A = 1 \times 10^{-11} - 3 \times 10^{-11}$ depending on the pressure.

v is the ion velocity.

V is the potential difference between the point and its surroundings

V_o is the onset potential

i.e. the current is proportional to the product of the ion velocity and the point potential.

This he concludes is equivalent to the kV^2/l term in his equation and that it is wrong to assume that in the case of an isolated point in wind (a further source of ion velocity) that the current is proportional to V^2.

Support for this statement is given by his measurements of point current made in a wind tunnel where, at atmospheric pressure, a linear dependence of I on v (wind velocity) and V was demonstrated for I = 10 - 90μa, v = 9 - 200 m/s for V = 5 - 45 Kv.

No opportunity has been afforded to study the assumptions on which Chapman's theory is based although the results agree with Chalmers' theory for q = 2 as suggested by the results of the present investigation. It seems from this that the removal by wind of the limiting space charge is quite as effective in the direction upwards from the point as when it is blowing perpendicular to the mast.

8.4 Application of the Results to the Alti-Electrograph Recordings.

It has been shown by Wilson (1925) and Whipple and Scrase (1936) that point discharge current must give rise to a considerable space charge between the cloud base and the earth. Whipple and Scrase indicated that in typically disturbed conditions this space charge would give rise to a potential gradient below the cloud some 35 times that existing at the earth's surface.

Simpson and Scrase (1937), using a balloon to support a wire 20m long with a single point at the bottom and a six point discharger at the top, measured the point discharge current flowing through the system as the balloon moved up to and through the cloud. From this current they were able to make an estimate of the potential gradient at various heights and their results suggested that nowhere did the potential gradient exceed 100 v/cm.

Attempts to reconcile the results of theory and experiment by considering mechanisms whereby this space charge can be removed, have so far been unsatisfactory as none of these is sufficient to account for the low values of potential gradient recorded by the Alti-Electrograph.

The possibility of an incorrect determination of the potential gradient from the value of the point discharge current has been discussed by Chalmers and Mapleson (1955), using the relationship

$$I - KW^{\frac{1}{4}}(Fh)^{\frac{7}{4}}$$

found from the balloon results, giving a possible value of 190 v/cm for the potential gradients encountered by the Alti-Electrograph. A further reassessment of the problem is given below using the results of the present investigation.

With the few results obtained when the Alti-Electrograph was close to the ground, Simpson and Scrase (1937) were able to obtain an approximate value of 'a' in their equation $I = aF^2$ by comparison with point discharge current through the 8.4m point where the relationship $I = a(F^2 - M^2)$ had earlier been obtained by Whipple and Scrase. It seems likely then that the F^2 dependence was assumed in this calculation of 'a'.

The re-analysis in section 8.1 has shown that this equation was not valid and it suggests that the equation $I \approx aF$ would be more suitable in this connection. With this lower power of F the value of 'a' (0.03) would need to be increased say, to 0.06μa/v/cm which is of the same order of magnitude as 0.058μa/v/cm found from the results with 20m mast in section 4.1. Thus a maximum current of 300μa would correspond to 5,000 v/cm rather than the 100 v/cm at 760mm pressure suggested by Simpson and Scrase.

Support for this proposed linear dependence of I on F is given by the theoretical considerations of Chapman (1956) who re-analysed his own balloon results in the light of his equation

$$I \approx AvV$$

and concluded that the potential gradient encountered by his balloon corresponded to 2,000 v/cm rather than the 200 v/m reported earlier.

These interpretations of the Alti-Electrograph and Chapman's results indicate that potential gradients below thunderclouds are of the same order of magnitude as those measured by observers in aircraft (Gunn 1953).

8.5 Conclusions.

Investigations of the point discharge current from an earth-connected point 0.002 cm in diameter at heights of 20m, 27m and 34m indicate that I is given by the equation

$$I = K(W + C)\ (F - M)$$

where I is the point discharge current (maximum 15µa)

W is the wind speed (maximum 33 m/s)

F is the potential gradient at the ground to windward of the discharging point (maximum 4,500 v/m)

M is the onset value of the potential gradient measured at the ground varying from 200 v/m at 20m to 100 v/m at 34m and being independent of wind speed.

C and K are constants.

When the potential gradient was measured 7m below the 34m point, equation (1) still held and therefore the effect of the space charge liberated at the point on the potential gradient was negligible in this case. However, with the field mill 2m below the 20m point the equation

$$I = A(W + D)\ (F - M)^n$$

was found to hold.

A and D were constants

n was now dependent on wind speed W.

Discrepancies between these results and the results of other workers using fixed points can be shown to be attributable to the effects of wind speed and wind direction but simular considerations do not resolve the differences between these and the balloon results of Chalmers and Mapleson.

The results are in good agreement with the theory of Chalmers, the finding of the dimensional analysis of Chapman and his wind tunnel and laboratory measurements of point discharge.

The application of the present findings to the Alti-Electrograph results of Simpson and Scrase concur with the conclusions of Chapman that the potential gradients measured in and below thunderclouds are consistent with the values obtained in measurements from aircraft.

Measurements of point discharge currents down the trunk of the tree indicated that these were somewhat lower than those through a single point of similar height but insufficient results were obtained to find a definite correlation between current and potential gradient.

8.6 Suggestions for Further Work.

The relative frequency with which point discharge occurs from the 34m mast will facilitate the study of the pulse nature of the discharge. This could be carried out in a manner similar to that employed by Large and Pierce (1955) with the addition of simultaneous wind speed measurements. The potential gradient in this case could probably be measured 7m below the mast to avoid scatter in the results. Similar investigations in the laboratory of positive and negative point to plane corona may prove an interesting comparison with the atmospheric measurements.

Further work with points of varying separation may be useful in deciding the effect of wind speed on the current through such arrays although, when estimates of the total point discharge current density below clouds are required, the work on trees might be more profitable.

Here a change from brass to platinum for the connections to the conducting region of the tree would assist in the eradication of the electrolytic effects. Variation of current down the trunk with potential gradient and wind speed would lead to a more accurate estimation of the part played by trees in the transference of charge to earth and might also help the research at present being undertaken to determine this current indirectly.

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