POINT DISCHARGE IN ATMOSPHERIC ELECTRICITY

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CHAPTER 1. INTRODUCTION

1.1. GENERAL.

Atmospheric Electricity is concerned with the study of the electrical phenomena of the atmosphere below the ionosphere.

Phenomena between the earth and the ionosphere may conveniently be divided into those which occur in fine weather and those which occur in stormy weather.

1.2. FINE WEATHER PHENOMENA.

In fine weather an electric field exists between the earth and the ionosphere such that the ionosphere is positive with respect to the earth. Ions in the atmosphere, produced by cosmic rays and radioactivity, move in the electric field thereby forming a conduction current which tends to discharge the earth-ionosphere condenser. Conditions are fairly steady: generally being subject only to small and comparatively slow variations.

1.3. STORMY WEATHER PHENOMENA.

In stormy weather the situation is much more complex; a variety of processes of charge separation and movement are in operation. Conditions are very disturbed; usually being subject to large and rapid variations.

Violent charge separation processes occur in storm clouds producing intense electric fields in, below and above the clouds. In addition to the movement of charge by a much increased conduction current, charge is carried down to the earth on precipitation, point discharge occurs from trees and buildings and large quantities of charge are rapidly transferred within clouds and between clouds and earth by lightning flashes.

There is now a considerable quantity of evidence in support of the theory that the electrical activity in those parts of the earth experiencing stormy weather provides a sufficient "supply" current to the ionosphere to counterbalance the conduction current over the rest of the earth, which is experiencing fine weather.

1.4. THE STUDY OF THE SEPARATION AND MOVEMENT OF CHARGE.

Thus it seems probable that the primary processes of Atmospheric Electricity are those of charge separation and that processes of charge movement are secondary.

While it is clear that both these types of process must be studied in order to achieve a thorough understanding of Atmospheric Electricity, it might appear preferable to concentrate on the primary processes. Studies of the secondary processes, however, have certain peculiar advantages: in general they may be carried out more conveniently and cheaply, and from them indirect deductions can often be made of the primary processes.

1.5. PROCESSES OF CHARGE MOVEMENT.

Close to the earth four processes of charge movement are distinguishable:

1.) Ionic conduction, normally referred to as the air-earth current,

2.) Point discharge current,

3.) Precipitation current,

4.) Lightning flashes.

The air-earth current consists of the movement of ions in the electric field of the atmosphere and is continuously operative.

Point discharge current is essentially a part of the air-earth current but is usually distinguished from it since its behaviour is somewhat different: it occurs only when the local concentration of field around a pointed conductor is sufficient to produce ionisation by collision, and the current which results is many times greater than that due to the normal conductivity of the air. In general, point discharge occurs naturally only during periods of intense electric field and flows through projections above the earth's surface such as trees and buildings.

The precipitation current consists of charges attached to rain drops, snow flakes and hailstones moving under the force of gravity and, of course, is only intermittently operative.

Lightning flashes consist of the rapid movement of large quantities of charge due to the propagation of an electrical breakdown of the atmosphere from cloud to earth (or within a cloud)and occur comparatively rarely.

Close to the ionosphere it would appear that only one important process is operative: the movement of ions in an electric field.

At intermediate heights there are the numerous complex processes of charge separation and movement in clouds.

For a complete understanding of the movement and separation of charge in the atmosphere all these processes must be studied. As a contribution towards that understanding the present investigation is devoted to point discharge.

1.6. EARLY INVESTIGATIONS OF POINT DISCHARGE.

Point discharge in its luminous form (St. Elmo's Fire) has been known to man for some centuries but it was not until 1751 that any deliberate investigation was made. In that year Dalibard (22) and Franklin (27) working independently obtained sparks between pointed conductors and earth during thunderstorms. Dalibard used an iron rod 40 ft. high and Franklin used a kite with a conducting string. In both cases the sparks were clearly due to point discharge at the top of the conductor raising its potential. Independently of Franklin,de Romas (24) in 1753 obtained much larger sparks from a kite in thunderstorms and also observed some effects in fine weather.

Lutz (55) notes several subsequent observers who measured point discharge current by inserting a galvanometer between the point and earth: Colladon (20,21), Peltier (67), Quetelet (69), Lamont (45,46), Lemstrom (48-50) and Weise (88) but concludes that they merely demonstrated the existence of large and varying currents in the presence of strong electric fields.

1.7. POINT DISCHARGE AND THE MAINTENANCE OF THE EARTH'S NEGATIVE CHARGE.

It was Weber (87) who, in 1886, first realised that the magnitude of point discharge currents over an area must be considerable and Wilson (95) who, in 1920, first suggested that point discharge, particularly during thunderstorms, might play a considerable part in the maintenance of the earth's negative charge.

This theory was first tested by Wormell (98). Over a period of two years he made continuous measurements of the current through an artificial discharge point at Cambridge. By assuming that similar currents would flow through trees higher than his point and counting their number, he arrived at an estimate for point discharge current density; and by estimating current densities due to the fine weather air-earth current, precipitation currents and lightning discharges he arrived at an "electrical balance sheet" for the area under consideration. This showed that over a period of a year an excess of 40 coulombs per square kilometre of negative charge was brought down to the earth but, as Wormell points out, the estimates were very approximate and no more could be concluded than that there was an approximate balance, with perhaps a slight excess of negative charge downwards, in that area.

Almost simultaneously Schonland (73) took similar measurements in South Africa using an actual tree, typical of those in the region, cut down and set up on insulators. He obtained much smaller currents than Wormell but then his tree was only 4 metres high as opposed to 12.3 metres for the height of Wormell's point in the bulk of his observations.

Subsequently numerous investigators have made continuous measurements of point discharge currents over long periods in various places: in England by Whipple and Scrase (90) and Chalmers and Little (17); in South Africa by Immelman (40) and Allsopp (1); in Nigeria by Perry, Webster and Bagueley (68); in Japan by Yokuti (100); in India by Chiplonkar (19) and in Germany by Lutz (55,56).

Chalmers (10) has made an assessment of the "electrical balance sheet" for Kew and finds a negative excess of about 100 coulombs per square kilometre for a year.

These results suggest a definite excess of negative charge brought down to the earth, mainly in thunderstorms, at the places of measurement. This negative excess may well be balanced by a positive excess in regions where thunderstorms are few.

Confirmation of the idea that thunderstorms are the principal source of the earth's negative charge is given by Whipple (89) and by Whipple and Scrase (90), who, following a suggestion of Appleton (2), showed the very close correlation between the diurnal variations of world thunderstorm activity and electric field. Although Wichmann(93) has questioned the inclusion of ocean thunderstorms, largely on the grounds that point discharge would not occur below these, Chalmers (13) has shown that the total ionic current (air-earth current plus point discharge current) below a storm must be substantially independent of the presence of obvious discharge points.

Further confirmation comes from Gish and Wait (28,29, 85) who estimated the total vertical current through a thunderstorm by taking measurements of field and conductivity from an aeroplane flying over a thundercloud. They studied 21 storms and obtained a mean value of 0.8 amps or, ignoring one very large value, 0.5 amps for the vertical current. They point out that in order to agree with a value of 1800 amps for the total vertical current in all fair weather areas the total number of storms in progress at any one time must be 2200 or 3600 for currents of 0.8 and 0.5 amps respectively. They consider these to be likely figures since Brooks' (6) estimate of 1800 as the thuderstorm population was based on statistics for "days with thunder" and took no account of more than one storm in a day.

Thus there now seems to be considerable evidence in support of the theory that thunderstorms are the main cause of the maintenance of the earth's negative charge although this has been questioned as recently as 1951 by Wichmann (93) and considerable doubt remains, especially in the mind of Loeb (52), as to the exact magnitude of the part played by point discharge -- which appears to make the largest single contribution. Clearly the important factor to consider is current density, whereas all measurements have been of the current through a single point or close group of points, usually artificial, and an effective separation has had to be assumed. Simpson (74) has deduced the separation indirectly, from results for rain charges, at Kew and Chalmers (11) has applied similar considerations for both Kew and Durham. Schonland (73), who used an actual tree, quotes the separation of similar trees in the vicinity. However, the photograph in his paper shows that the exposure of his tree was considerably better than those growing naturally in the vicinity so that his estimate of current density is probably somewhat high. Thus no reliable direct estimate of point discharge current density is available.

To arrive at such an estimate Chalmers (12) has suggested making measurements on a tree in a Forestry Commission plantation which would clearly be ideal. An alternative approach is to investigate the manner in which various parameters affect point discharge current so that it would become possible to estimate the current through various natural discharge points under certain conditions.

1.8. POINT DISCHARGE CURRENT AND ITS RELATION TO VARIOUS PARAMETERS.

Surprisingly little attention has been paid to this problem in the atmosphere apart from the largely qualitative correlation between the occurence of point discharge and the presence of rain producing clouds, and studies of the sudden change of current produced by lightning flashes.

(a) Point Discharge and Electric Field.

The most important investigation is that of Whipple and Scrase (90) who, during six thunderstorms in 1934 took simultaneous measurements of point discharge current and electric field at the ground in the vicinity. Confining themselves to fairly steady periods they took one minute averages of current and field and obtained 200 such measurements. They plotted these results on a graph and drew through them curves of the form: $I = a(F^2 - M^2)$

where I = point discharge current

F = electric field

a and M are constants, M being an estimate of the minimum field necessary for point discharge.

With a point 8.4m high they obtained values of a = 0.0008 $\mu a/(v/cm)^2$ and M =7.8 v/cm for positive currents entering the point and a = 0.0010 $\mu a/(v/cm)^2$ and M = 8.6 v/cm for negative currents entering the point, I being measured in μa and F in v/cm.

They give no reason for using this particular equation, nor do they make any claims about the goodness of fit but it is most interesting to note that Chalmers (12) has deduced the equation theoretically, on certain assumptions, for points in a regular array.

Hutchinson (38) also made simultaneous measurements of point discharge current and electric field and obtained results broadly similar to those of Whipple and Scrase. Fitting a curve of the form $I = a(F^2 - M^2)$ to his results he found a = 0.0009 $\mu a/(v/cm)^2$ and M = 4 v/cm for positive currents entering the point and a = 0.0005 $\mu a/(v/cm)^2$ and M = 4 v/cm for negative currents. He explains that the lower value of M is to be expected because of the greater height of his point (12m). He also notes that for high fields, stronger than +40v/cm and -50v/cm, current appears to be directly proportional to field.

Schonland (73) took some measurements of field during his investigation and quotes the approximate averages recorded in columns(a) and (b) below:

(a) Field (v/cm)	(b) Current (μa)	(c) Field^2	(d) Field^3
-35	-0.07	0.12×10^4	-0.04×10^6
-55	-0.20	0.30 "	-0.17 "
-110	-1.00	1.21 "	-1.33 "
-160	-4.00	2.56 "	-4.10 "

Columns (c) and (d) suggest that the current is more nearly proportional to the cube of the field than to the square. If, however, a curve of the form $I = a(F^2 - M^2)$ is fitted to these results the best values obtainable(by the method of least squares) are $a = 0.00016$ μa/(v/cm)^2 and $M = 46$ v/cm (for negative currents entering the point.)

Chiplonkar (19) took simultaneous observations of the discharge current through a point 8.3m high and electric field nearby. Selecting periods free from violent fluctuations he plotted one minute or two minute averages of current against field. He drew a "mean curve" through the points so obtained. He quotes no details of the curve but from measurements of the graph printed in his paper it has been determined that it is of the same form as that used by Whipple and Scrase and that the parameters have the following values:

$a = 0.0008$ μa/(v/cm)^2
$M = 6.5$ v/cm
for positive currents

$a = 0.0013$ μa/(v/cm)^2
$M = 9.4$ v/cm
for negative currents

As one would expect, these results are very similar to those of Whipple and Scrase.

Lutz (55) also made simultaneous measurements of point discharge current and electric field but unfortunately does not quote comparable values of field and current.

Two other investigations remain to be considered: those of Rangs (70) and Davis and Standring (23). In all the investigations considered so far in this section the discharge pointwas comparatively low, Lutz's at 17m being the highest, so that discharge occurred only during stormy weather. On the other hand Rangs, by using a kite with a rather blunt point attached, and Davis and Standring by using a barrage balloon, raised a conductor to heights of several hundred metres and obtained discharge in fine weather. Davis and Standring did not use any deliberate discharge point but conclude that the field at the cable surface or, at any rate, at the surface of the rigging wires and any sharp points that might be associated with their end splices, was sufficient to produce ionisation by collision. Rangs measured the electric field at the ground, as nearly as possible vertically below the kite and, on comparing field and current, irrespective of the height of the point which varied between 1000 and 2000m, found a very wide scatter but an approximately linear correlation between them. Davis and Standring usually operated their balloon at a height of 900m and measured the electric field at the ground "near" the foot of the cable.

They,also,found a wide scatter in their results; concluding only that there was some tendency for an increase of current with an increase of field.

From all these investigations the following conclusions may be drawn.

1.) Point discharge current increases with electric field at the ground in the vicinity.

2.) The nature of the relationship between field and current is uncertain: it appears to be some power law and the relation $I = a(F^2 - M^2)$ of Whipple and Scrase appears to be a fair approximation for their results and those of Hutchinson and Chiplonkar.

3.) The parameters of any relation, and possibly also its form, may change when conditions of the point (height, exposure, sharpness etc.) alter and possibly even for very high fields.

(b) Point Discharge Current and Height and Separation of Points.

The only work covering a direct investigation of this problem is that of Davis and Standring (23). On four occasions they measured the current in the flying cable of their balloon during the ascent and descent. They found an approximately linear relationship between current and height up to 2400 metres.

Mention may also be made of an investigation by

Nukiyama and Nakata (66) who attempted to measure the potential of a kite balloon at heights up to 500metres. From the extremely low values which they obtained this does not appear to have been very successful but it is of interest that on one occasion they earthed the balloon through a galvanometer and recorded current and height. The currents they observed were of the same order as those found by Davis and Standring, and there was an increase of current with height, but their observations are too few to warrant drawing any conclusions as to the nature of the relationship.

From the previous section the following results may be summarised:

observer	a ($\mu a/(\overline{v}/cm)^2$)	Height of point (m)
Whipple and Scrase	0.0008 to 0.0010	8.4
Hutchinson	0.0009 to 0.0005	12.0
Chiplonkar	0.0008 to 0.0013	8.3
Schonland	0.00016	4.0

It would be rash to make any direct deductions as to the variation of current with height or separation of points from these results but some interesting indirect deductions have been made by Chalmers (12). From considerations of space charge he has derived the $I = a(F^2 - M^2)$ formula of Whipple and Scrase theoretically and found that a depends on h and d where h is the height of each point in a regular array of separation d. By using the results of Whipple and Scrase, Schonland and Hutchinson and assuming that a is proportional to $h^p d^q$ he finds p =1.7 and q = 1.0. He points out that these figures must be regarded as very approximate and it is also important to realise that these results, which apply to points in an array, all discharging simultaneously, are not necessarily comparable with those of Davis and Standring whose balloon cable would normally be the only source of "point" discharge in the vicinity.

(c) Point Discharge Current and Number of Points.

An interesting auxiliary experiment of Chiplonkar's (19) consisted of replacing his usual single point by a group of four similar points, each eight inches long and joined together at their base. With this arrangement he found that the total current through the four points was noticeably less, for a given field, than that through his single point.

From measurements of the graph printed in his paper values of a and M have been calculated for the set of four points. They are set out below together with the values for the single point.

	Single point	Four points	
a	0.0008μa/(v/cm)^2	0.0005μa/(v/cm)^2	for positive currents
M	6.5 v/cm	6.6 v/cm	entering the point.
a	0.0013μa/(v/cm)^2	0.0007μa/(v/cm)^2	for negative currents
M	9.4 v/cm	7.5 v/cm	entering the point.

Thus the effect of using four points has been to reduce the values of a to about 0.6 of their value for a single point. There is also some increase of M, but how much is uncertain because the graph is heavily printed to a small scale.

Chiplonkar remarks that this throws some doubt on the equivalence of a single artificial point to a tree and it seems possible that the low value of a given by Schonland's results is an extension of the effect found by Chiplonkar. On the other hand it may be almost entirely due to the small height of the tree.

(d) Point Discharge Current and Sharpness of Point.

This relationship does not appear to have been investigated in the atmosphere. Some results of laboratory experiments are, however, mentioned in section 1.11.

(e) Point Discharge Current and Wind Speed.

Whipple and Scrase (90) remarked that some of the scatter in their results might be due to variation of wind speed and the results of Davis and Standring (23) show some evidence for increase of current with wind speed.

(f) Point Discharge Current and Space Charge.

It seems quite clear that, for a given height at any rate, a closer correlation could be expected between point current and potential between ground and the height of the point, than between point current and field at the ground; since space charges between the ground and the point could produce a considerable change of field with height. This factor probably explains much of the scatter in the results of Davis and Standring (23), who normally operated their balloon at a height of 900m, and some of the scatter in Rangs' results; although in the latter case most of the scatter would be explained by the variation in height from 1000 to 2000m which Rangs ignored in plotting his results.

The effect would also be marked for investigations on low points in stormy weather because of intense space charges between ground and the artificial point, produced by lower natural discharge points. Lutz (55) first suggested this process and used it to explain the occurrence of point current in the opposite sense to field at the ground. His measurements of space charge gave quantitative agreement. Lueder(53) and Hutchinson (38) used the process to explain changes of sign of point current lagging on changes of sign of field. Hutchinson also found the interesting fact that after the field had reached a certain value (about 15 to 20 v/cm) a further increase (of about 15 to 25 v/cm) produced little increase of point current, while further increases produced a resumed increase of point current. By re-analysis he found a similar effect in the results of Whipple and Scrase (90). He attributed this "displacement" effect to the commencement of point discharge from natural points between the field measuring apparatus (3m above ground) and the point. He was able to estimate the space charges needed to explain these displacements and found values of the same order as those measured by Lutz.

(g) Point Discharge Current and Conductivity.

Whipple and Scrase (90) suggested that some of the scatter in their results might be due to conductivity variations and Wichmann (91) in a brief reference seems to attach considerable importance to the possibility, but it seems improbable that conductivity would have a direct effect on point discharge current since the discharge produces its own copious supply of ions. There would, however, be some indirect effect in that high conductivity is associated with low field and hence with low point discharge current but it seems unlikely that it would affect the relation between field and current.

1.9. POINT DISCHARGE AS A TOOL.

When a relationship has been established between two variables it is possible to use one as a measure of the other and this clearly applies to point discharge current and electric field. Since current measurement is much simpler than field measurement the use of point discharge current as a measure of field has much to commend it. On the other hand its use is limited by the extent of the knowledge of the relationship between the two and it has the disadvantage, as noted by Chapman (18), that a much wider range of values must be covered beaause of the quadratic nature of the relationship.

It is interesting to note that Wormell (98) in the course of his pioneer work in the continuous measurement of point discharge, used the instantaneous values of point discharge current as a rough measure of field when it was too strong to be measured by his raised sphere. A number of other investigators -- Noto (64), Perry, Webster and Bagueley (68), Wichmann (91,92) and Chapman (18) -- have used point discharge measurements in a similar manner. More recently a number of investigators have used point discharge current as a more or less precise measurement of electric field when direct measurement of the field would have been difficult or impracticable. These will be considered in turn.

(a) The Work of Simpson.

Simpson (74), in an investigation af Kew, made use of the same mast and point as Whipple and Scrase (90), moving it to a new site of similar exposure. He was therefore able to use, with considerable confidence, the relationship established by Whipple and Scrase and thereby use point discharge current as a measure of electric field when this was too strong to be recorded by his Benndorf electrometer. It is interesting to note, in passing, that while his original intention was to investigate the relationship between rain charge and electric field he found that, when point discharge occured, there was a linear relationship between rain charge and point discharge current.

(b) The Work of Wichmann.

In order to investigate the diurnal variation of electric field Wichmann (93) measured the current in the cable of a captive balloon flying at heights of from 1000 to 3000m. He considered that this method was preferable to taking direct measurements of field at the earth on the grounds that it would be less subject to local disturbances. He used the Whipple and Scrase (90) square law relation to interpret his results, neglecting M, which would certainly be very small in the circumstance, and since he was concerned only with variation of field he did not need to allot any specific value to a.

(c) The Work of Davis and Standring.

A brief mention must be made of the primary objective of Davis and Standring's work which was to study the danger of lightning flashes to barrage balloons. They developed an extremely practical use of point discharge by suggesting that a simple milliameter be inserted between the flying cable and earth and that operating crews be instructed to haul in the balloon when the milliameter needle reached a suitably placed red mark!

(d) The Work of Simpson and Scrase.

Simpson and Scrase (76) and, in continuation, Simpson and Robinson(75) investigated the electrical structure of thunderstorms by attaching their "alti-electrographs" to free balloons and releasing them below thunderclouds. The alti-electrograph consisted essentially of a 20m length of 30 S.W.G. copper wire hanging below the balloon, at the two ends of which point discharge would occur in strong electric fields, causing a current to flow through the wire. The lower discharge point was simply the end of the wire while at the upper end the discharger consisted of six pins attached to the corners of a bamboo cage. They used pole finding paper to show the direction of the current.

They found that from the width of the stain on the paper they could estimate the magnitude of the current: this led them to attempt an estimation of the field strengths corresponding to the currents recorded. They did this by comparing the current recorded immediately after the release of the balloon with field strength as measured at the ground. They considered that the number of observations they obtained was not sufficient to check the Whipple and Scrase relationship but by assuming it to hold true and ignoring the value of M they obtained the relationship $I = 0.03F^2$ where I = current in μa and F = field in v/cm. They also applied a correction for height of the form $I/I_o = \exp(0.2h)$, derived from a simplified version of the current-pressure relation due to Tamm (77), where I = current recorded, I_o = equivalent current at ground level and h = height in km.

From their records they obtained valuable information on the distribution of charge in thunderclouds but their estimates of field strength gave two surprising results. Firstly, they found that, in general, there was no apparent increase of field with height below the cloud base, contrary to the prediction of Wilson (96) and Whipple and Scrase (90); and secondly that the electric field within the cloud rarely appeared to exceed 100v/cm. In the later paper Simpson and Robinson are careful to emphasise the approximateness of their estimations of field strength and with this caution further consideration of their results will be deferred until section 1.10.

(e) The Work of Kreielsheimer and Belin.

This investigation has been reported by Kreielsheimer (44) and, less fully by Belin (4,5). They made observations similar to those of Simpson and Scrase but used the current from their discharge points to vary the modulation frequency of a radio sonde. Their dischargers were 64ft. (= 19.5m) apart and connected by 30 S.W.G. copper wire with the radio sonde mid way between them. The dischargers consisted of sets of pins, usually either 7 or 13 in number, the upper set being 10ft. below the balloon.

The most remarkable feature of their experiments lay in the calibration, which was made in the laboratory.

They discovered, there, that although the minimum field for point discharge was independent of the number of points; the current, once discharge had started, was directly proportional to the number of points -- in almost complete contradiction to the results of Chiplonkar (19), which showed a reduced total current on increasing the number of points from one to four.

Now, if the discharge current from a number of points is proportional to the number of points, they must all be acting independently and it seems clear that the tendency to act independently will decrease as the separation decreases. Unfortunately neither Kreielsheimer nor Belin give any dimensions for their dischargers but the photograph given by Belin suggests that the separation of their points was not greater than those of Chiplonkar. Therefore it does not seem possible to explain the discrepancy in terms of the arrangements of points. An explanation must therefore be sought in other experimental conditions.

It is unfortunate that neither Kreielsheimer's nor Belin's description of their calibration apparatus is very detailed. However, since, according to Kreielsheimer, they exposed their dischargers in an artificial field developed between parallel metal gauzes four or five feet square and succeeded in obtaining a uniform field (they used a much shortened connecting wire between the two dischargers) the separation between the gauze and the discharger must have been fairly small. In that case it seems probable that the points would have a greater effective separation (and would therefore act more nearly independently) in the calibration than when in use during a sounding. If this explanation is correct then Chiplonkar's conclusions are to be preferred to those of Kreielsheimer and Belin. Thus, although no firm decision can be taken until some further evidence is available, it will be wise in the meantime to accept Kreielsheimer's and Belin's calibration, and therefore their results, with some reserve.

They found that their calibration agreed fairly closely with the Whipple and Scrase (90) $I = a(F^2 - M^2)$ law but do not quote the value of a. However, by fitting a curve of that form to the results of measurements of the calibration graph printed in Belin's paper it has been found that $a = 0.10 \mu a/(v/cm)^2$ and $M = 3.8 v/cm$ (for positive fields), if the curve is made to go through the centre of gravity of the measurements, or $a = 0.09 \mu a/(V/cm)^2$ if it is made to pass through his observed value of 3.5v/cm. Since the calibration curve is for seven points in each discharger, presumably for one point in each discharger a would equal 0.014, to be compared with the value of 0.03 for Simpson and Scrase's alti-electrograph with one point at the bottom and six at the top. When the radio sonde was in operation they used a correction for height identical with that employed by Simpson and Scrase.

They quote the results of one sounding which shows the presence of a negative charge at the top of the cumulo-nimbus cloud, a positive charge towards the centre and a negative charge either at the base of the cumulo-nimbus or at the top of some fracto-stratus underneath. This charge distribution is somewhat unusual but as they do not quote results for any other soundings, no firm conclusions can be drawn.

(f) The Work of Chapman.

Chapman (18) made some soundings of thunderstorms and snowstorms with apparatus very similar to that of Kreielsheimer and Belin. He was able to cover a much greater range of field values by means of three different resistors which were switched, in turn, in series with the connecting wire. He also varied the separation of the discharge points , from 25 to 1000ft., according to the magnitude of the fields he expected. His description of the experiment is rather brief but it would appear that he used only one discharge point at each end of the wire (or conducting string) so that his calibration, although made in the laboratory, is probably more reliable than Kreielsheimer's and Belin's.

Like Simpson and Scrase (76) he found no evidence of intense electric fields; the strongest he recorded was 210v/cm.

1.10. DISCUSSION OF BALLOON SOUNDINGS.

Whipple and Scrase (90) using a theory due to Wilson (96) have calculated the effect of the (positive) space charge produced by point discharge below the (negatively) charged base of a cloud. They predicted a considerable increase of field with height up to the cloud base. This is in contradiction to the observations of Simpson and Scrase (76) and Simpson and Robinson (75) who, in general, found no such increase and, presumably, those of Chapman (18) for, although he quotes no detailed results, the fact that the maximum field he encountered was 210v/cm leaves little room for increase with height in thunderstorm conditions. Little information can be obtained from Kreielsheimer (44) and Belin's (4,5) results since, in the one ascent which they record, the fields were mostly beyond the very limited range of their apparatus and conditions below the cumulo-nimbus cloud were complicated by the presence of some fracto-stratus.

As noted by Chalmers (8) (in a slightly different arrangement) there appear to be three possible explanations of this contradiction:

1.) The field does not increase with height below the cloud base.

2.) The interpretation of the currents measured by the balloon soundings in terms of field is invalid.

3.) Any increase of field with height is restricted to certain parts of the area below a cloud which were missed by the balloons.

Chalmers (7,9) has considered the first possibility in some detail. He concludes that even to obtain agreement with the most "favourable" of Simpson and Scrase's soundings (an increase from 40v/cm to 100v/cm) the separation of discharge points similar to that used by Whipple and Scrase (90) at Kew would have to be far in excess of their original estimate -- or subsequent estimates by Simpson (74) and Chalmers (11). By considering the effects of ions coming down from the cloud, of charge on rain and of vertical air currents he reduces the discrepancy but does not eliminate it.

Furthermore, the discrepancy cannot be relieved by modifying the more questionable assumptions of Wilson, for if the charge in the cloud is assumed to be concentrated rather than widespread, or if the small ions produced by point discharge are assumed to become large ions before reaching the cloud, the increase of field with height would, in general, be even greater.

So far as the second possible explanation is concerned it must be realised that the estimates of field strength obtained from balloon soundings involve the assumption that a relation between current and field which has been firmly established in the laboratory or approximately determined in the atmosphere at ground level holds good during ascent, with a correction for pressure, at all heights in the atmosphere. Certainly this seems a reasonable assumption but in view of the contradiction which has been found its possible invalidity must be borne in mind; as pointed out by Chalmers (10, p103). It should be noted, however, that Banerji's (3) argument that the alti-electrograph records should be multiplied by a factor of 20 does not follow from his premises for he has misunderstood the principle of the apparatus, ignoring the discharge process and regarding the points as potential collectors.

As for the third possible explanation it would clearly be higly improbable that the balloons missed the regions of high field by pure chance. There would, of course, be a systematic tendency for them to be entrained by the upward air currents in a thunderstorm, but then the ions from point discharge would be somewhat similarly entrained (see Malan and Schonland 59,60), their velocity in a field of 100v/cm being about 1 m/sec compared with 5m/sec for the rate of ascent of Simpson and Scrase's balloons. Thus on these grounds the balloons should tend to"hit" rather than "miss" any field increases due to space charge.

Some light is thrown on the problem by the work of Gunn (34) and Wait (85) who measured field by means of electric field meters carried on an aeroplane. Gunn found that strong fields existed only inside thunderclouds but that there they were frequently as large as 1000v/cm over considerable areas. Wait, who measured the fields existing above thunderclouds, frequently encountered fields of 30v/cm and sometimes as high as 600v/cm whereas the maximum field Simpson and Scrase recorded there was 30v/cm and usually the values were less than 10v/cm.

Since these values were obtained by direct measurement of the field and since due account was taken of the effect of the free charge on the surface of the aircraft (by using one field meter on each surface of each wing), they are to be preferred to the estimates of field strength obtained from balloon soundings. In that case the difficulties are increased rather than decreased since the observations of Gunn and Wait suggest both that the results from balloon soundings are faulty and also that any increase of field with height below a thundercloud is not as great as that predicted by Whipple and Scrase.

1.11. LABORATORY INVESTIGATIONS OF POINT DISCHARGE.

It will be shown in section 2.2 (a) that results of laboratory investigations of point discharge are not, in general, applicable to discharge in atmospheric electricity, but this introduction would not be complete without some brief mention of the subject.

One of the earliest investigators was Warburg(86) who, in 1899, investigated the discharge current from a point to a plane. He found a relationship I = cV(V - M) where I = current, V = voltage between point and plane, M = minimum voltage for discharge and c a constant. He also found that M was sensibly independent of D, the separation between point and plane, over the range 1 to 7 cm, but that c was inversely proportional to a power of D slightly greater than one. He found M to be rather less than 3000v for a point 0.235 mm in diameter.

In 1907 and 1908 Zeleny (101,102) found a similar current-voltage relation and studied the effect of the shape of the point in some detail. He found that both c and M increased with the diameter of the point but that neither c nor M was greatly affected by the shape of the end of the discharge wire for a given diameter: a cylindrical wire with a plane end gave a current only about 5 per cent higher than one with a hemispherical end. He also investigated the effect of pressure (as did Tamm (77)) and temperature. In a much later paper (103) (1941) he surveys more recent work, quoting an extensive bibliography, and confirms the early current voltage relationship.

Trichel (80) studied point discharge currents with a Cathode Ray Oscilloscope and found that the current from a negative point was not continuous but consisted of a series of pulses all of approximately the same size but whose frequency, consequently, was proportional to the average current. The current from a positive point was found to contain a large steady component with some random pulses superimposed.

Loeb has done a great deal of work on the electric processes occurring in the gas close to the point and in 1948 published a valuable survey (51) of recent research on the subject by many workers.

Utsu (81) has recently made a most interesting investigation in the laboratory. In an attempt to simulate the conditions which occur in the atmosphere he produced a dense volume charge by means of a water spray initiated in a strong electric field. He then set up an earthed point in the volume charge and compared the current from it with the pressure of the spray jet and the field which charged the water drops. This makes it difficult to compare his results with any others, but one feature stands out very clearly: according to his diagram, although positive currents increase according to some power,greater than one, of the drop charging field, negative currents increase, most surprisingly, according to some fractional power of the field -- despite the fact that he shows that the rate of production of volume charge is essentially the same for negative and positive fields.

1.12. CONCLUSIONS.

It is apparent from the foregoing sections that remarkably little work has been done on the relation between point discharge current in the atmosphere and various electrical and physical parameters for, although agreement with the relation between current and electric field established, under certain conditions, by Whipple and Scrase (90), has been found by other observers under roughly similar conditions very little has been done to study how this relation is affected by changes of other parameters and the results of balloon soundings suggest that it may change to a considerable extent.

A detailed study of these relations may be expected to yield valuable results. In particular they may lead to a reassessment of the point discharge current density below a thunderstorm and to a more reliable interpretation of the results of balloon soundings.

The present investigation is intended as a contribution to that study.

CHAPTER 2. PRESENT INVESTIGATION -- PRELIMINARY CONSIDERATIONS

2.1. OBJECT.

The object of the present investigation is to examine the relation between point discharge current and various parameters.

2.2 CHOICE OF METHOD.

It is quite clear that any investigation of the relationship between a number of variables must consist essentially in taking simultaneous observations of those variables and then examining the results obtained. In the present case, however, two basic methods are available:

a.) Investigation in the laboratory,

b.) Investigation in the atmosphere.

(a) Investigation in the Laboratory.

Laboratory investigations have the considerable advantage that most of the experimental conditions can be closely controlled; so that, of the factors which may be expected to be related to point discharge current, any one may be varied, while the others are kept constant, and its effect examined.

However, this method is subject to important limitations which make it extremely difficult if not impossible to reproduce in the laboratory the conditions which obtain in the atmosphere. Firstly, the most obvious limitation is that of scale; it is hardly practicable to produce a field which extends more than a few metres in the laboratory whereas in the atmosphere the extent is to be measured in kilometres or at least hundreds of metres. Secondly, in the laboratory, the point will invariably discharge to a metal electrode whereas in the atmosphere the "electrode" to which the point discharges will be a more or less diffuse volume charge either in the ionosphere or a cloud. Thirdly, space charge in the air will, in general, play a different and, usually, more important part in the atmosphere because it will persist for some time instead of being collected by a metal electrode as in the laboratory.

It is interesting to note that the first objection was overcome to a considerable extent in an investigation of corona discharge from aircraft by Gunn and Parker (35). They obtained results for aircraft both in flight and suspended in a giant hangar some 30m by 60m, by 20m high. They found that the two sets of results agreed within the limits of experimental error which were, however, wide. On the other hand Utsu's (81) attempt to overcome the second objection and the surprising results he obtained, as noted in section 1.11 and the contradiction between the results of Chiplonkar (19) in the atmosphere and Kreielsheimer (44) and Belin(4,5) in the laboratory, as noted in section 1.9(e) may perhaps be examples of the incomparability of laboratory and atmospheric point discharge.

Hence it is apparent that laboratory investigations will be of only limited value in increasing the understanding of point discharge in atmospheric electricity and extreme caution must be observed in applying results obtained in the laboratory to investigations in the atmosphere.

The present investigation, therefore, was made in the atmosphere.

(b) Investigation in the Atmosphere.

For investigations in the atmosphere there is less question of the validity of the results but since many of the factors involved are uncontrollable, usually varying simultaneously and often independently, large numbers of observations must be taken and statistical analyses made in order to obtain significant results.

Investigations in the atmosphere may be subdivided into two systems:

(i) Those in which a point is set up a few metres high so that it may be taken to be very approximately equivalent to natural discharge points in the vicinity. In this case the artificial point will form one of an array and discharge will occur only in disturbed conditions when the field is intense.

(ii) Those in which a point is raised to a considerable height above its surroundings such that discharge will occur in the comparatively steady conditions of fair weather when the electric field is weak. In this case the artificial point will, in general, be the only one in the vicinity producing a discharge.

Some system intermediate to these two could, of course, be adopted and some useful results obtained but from the following considerations it seems that these two show more promise.

The first system should give results primarily applicable to natural point discharge below a thunderstorm and by using an actual tree or extending the scope of Chiplonkar's (19) work a more reliable estimate of point discharge current density might be hoped for. The disadvantages of this method are that in England, at any rate, and particularly in the North, point discharge occurs but rarely -- for a total of perhaps only a few dozen hours in the year --- and then only in very disturbed conditions such that the electrical condition of the atmosphere is subject to rapid and violent fluctuations.

The second system will yield far more results in a given time and under comparatively steady conditions so that the correlation of point discharge current with the various parameters should be somewhat easier. The results will have to be applied to individual members of an array of points only with considerable caution, but they should be peculiarly applicable to the problem of the balloon soundings since an isolated point projecting from the surface of the earth will form a much closer parallel to half the length of wire used in a radio-sonde or the alti-electrograph, than will one member of an array of simultaneously discharging points.

From the foregoing it appears that the method which is most likely to give the maximum number of reliable results in a given time is that in which a discharge point is raised to a considerable height in fine weather and accordingly this was the method adopted.

2.3. METHOD OF SUPPORTING POINT.

There appear to be three methods for supporting the point at an adequate height:

(a) High mast or pylon,

(b) Kite,

(c) Captive balloon.

(a) High mast or pylon.

This method has the considerable advantage that continuous records of point discharge current can be taken over long periods. It would, however, be quite unsuitable for investigating the effect of height on point discharge current since the lowest height at which discharge can be expected in fair weather is about 30m.

(b) Kite.

This method has the advantage of extreme cheapness but the present site is so restricted that the launching would be very difficult and the cost and inconvenience of moving all the auxiliary equipment to a suitable open field would nullify that advantage. A further disadvantage is that the height is very dependent on wind speed and would therefore be subject to considerable and fairly rapid variation.

(c) Captive Balloon.

This method has the advantage that, in general, the height may be closely controlled and is easily variable. Unfortunately when the type of balloon to be used is considered it is found that the cost increases rapidly with the suitability. The ideal is some kind of fabric kite balloon in which the drag is reduced by streamlining and the displacement lift supplemented by the aerodynamic lift of the stabilising fins. The balloon then remains stable in quite high winds and its declination is not greatly affected by wind speed. The cost, however, is of the order of £500 which proved prohibitive for the present investigation and exhaustive attempts to obtain one cheaply from various sources proved unsuccessful. The only balloons found to be available at a moderate cost were those of the spherical rubber type designed primarily for use as free balloons in radio-sonding. They have a small displacement lift and no aerodynamic lift but a considerable aerodynamic drag, so that the declination is rather sensitive to wind speed. They have the further disadvantage of a very short life -- only a few hours.

In the circumstances it was concluded that spherical rubber balloons provided the best compromise on the method of supporting the discharge point.

2.4. CHOICE OF PARAMETERS.

In an investigation of this type it is clearly desirable to include as many parameters as possible; the chief limitations are time, money and equipment available. The final choice must depend on these limitations and on an assessment of the probable value of, and ease of obtaining, results for any particular aspect of the problem.

It is to be noted at the outset that probably the most fundamental parameter is the potential between the earth and the air at the height of the point, but since it would be extremely difficult to measure directly it must be estimated indirectly.

The following parameters, then, seemed worthy of consideration:

<u>A Uncontrollable parameters.</u>

(a) Electric field

(b) Normal Space Charge

(c) Conductivity

(d) Wind speed

(e) Wind direction

(f) Air pressure

<u>B Controllable parameters.</u>

(g) Height of point

(h) Number and spacing of points

(i) Shape of point

(j) Nature of wire from point to ground.

<u>(a) Electric Field.</u>

It was abundantly clear from the literature that the most important single parameter affecting point discharge current, for a given height of the point, was electric field; so this was necessarily included.

<u>(b) Normal Space Charge.</u>

Any space charge in the atmosphere will produce a change of field with height and hence affect the potential between the ground and the air at the height of the point.

This space charge which is normally present, independent of the discharge point, will be referred to as the "normal" space charge to distinguish it from the "point" space charge discussed in Chapter 5. It was difficult to estimate in advance the magnitude of this effect but the measurements of Lecolazet (47) suggested that it would be small in fine weather, and since space charge varies with height it seemed unlikely that construction of suitable apparatus for its measurement would be worth while.

(c) Conductivity.

As has been explained in section 1.8(g) it seems improbable that conductivity will have any appreciable direct effect on point discharge current but since an appabatus for measuring air-earth current was occasionally working it was hoped to obtain estimates of conductivity by comparing the readings of this apparatus with the readings of the field measuring apparatus.

(d) Wind Speed.

Since the results of Davis and Standring (23) suggested some correlation between point discharge current and wind speed and since it is fairly easy to measure wind speed this parameter was included in the investigation.

(e) Wind Direction.

It seemed highly improbable that wind direction would have any direct effect upon point discharge current but it was decided that it must be recorded since certain indirect effects might arise from such causes as the topography of the site producing a change in the effective height of the balloon supporting the point as the wind direction changed, and local sources of pollution affecting current and field differently. This parameter will also be seen to be of great importance when the reaction of the discharge on the field nearby is considered in Chapter 3.

(f) Air Pressure.

The effect of air pressure on point discharge current has been investigated in the laboratory by Tamm (77) and while in the case of this parameter it seems improbable that the relation would be substantially different in the atmosphere the results of the balloon soundings of Simpson and Scrase (76), Kreielsheimer (44), Belin (4,5) and Chapman (18) indicate that it would be as well to check the relation in the atmosphere. However, since, as will be shown in section 2.5(a), the experiments were restricted to conditions of light wind, observations were made almost entirely in anticyclonic conditions and the range of air pressure experienced was too small to be worth taking into account.

(g) Height of Point.

It seemed quite clear that the importance of the effect of this parameter would be comparable to that of electric field so that it was necessarily included.

(h) Number and Spacing of Points.

In view of the complete contradiction between the results of Chiplonkar (19) and Kreielsheimer(44) and Belin(4,5) on the effect of these parameters they were necessarily included.

(i) Shape of Point.

Although this parameter has been investigated in some detail in the laboratory it seems to have escaped attention in the atmosphere. However, since it was considered to be of comparatively minor interest it was allotted a low order of priority.

(j) Nature of Wire from Point to Ground.

It was realised that unless the wire connecting the point to earth was well insulated some corona discharge could be expected from the higher portions of it if the field were strong enough and the wire were thin enough. Thus the possible effect of this parameter had to be borne in mind although it was felt that a detailed investigation would be of doubtful value.

Thus it was decided that attention should be concentrated on electric field, wind speed, height of point and number and spacing of points, due account being taken of any possible indirect effects of wind direction. There was also the hope of obtaining some estimates of conductivity and the possibility of later extending the investigation to cover shape of point and nature of wire from point to ground.

2.5. RANGE OF PARAMETERS.

(a) Uncontrollable Parameters.

So far as the uncontrollable parameters were concerned it was clearly desirable to cover as wide a range of values as possible, as and when they occurred; in practice, however, certain limitations were imposed. The low lift/drag ratio of the balloon made it impracticable to work in wind speeds greater than about 20 km/hr (12 knots) and this limitation had a number of others associated with it. The very small range of air pressure was referred to in section 2.4(f) and in addition it may be noted that negative fields, and positive fields greater than 250 v/m, were rarely encountered.

(b) Controllable Parameters.

(i) Height of Point.

A minimum value for the height of the point was determined by that value which was necessary in order to obtain point discharge. With the fields encountered it was found that, in general, there was little object in operating below 50m. In determining the maximum height of the point consideration was given to the fact that as the height of the point is increased so the measurements of field at the ground will give an increasingly poorer estimate of the potential between the ground and the air at the height of the point. In view of this a value of 200m was selected as the maximum height, at least for preliminary work. In later work it would certainly be worth while going above 200m and then a limitation would be imposed by the maximum length of flying cable which the balloon would support.

(ii) Number and Spacing of Points.

There seemed to be no obvious limitation to the ranges of these parameters but for a preliminary test arrangements were made for the use of any number from one to eight.

(iii) Shape of Point

As this parameter was given a low priority it seemed that provided the shape of the discharge point was kept constant its effect could be ignored although it was felt that an occasional set of observations in which all sharp points had been carefully eliminated from the wire would be of interest.

(iv) Nature of Wire from Point to Ground.

In view of the small lift of the balloons used a well insulated wire was out of the question and the range of gauges of wire which would be suitable was severely limited: a very thin wire would break too easily; a very thick wire would be too heavy.

2.6. MEASUREMENT OF PARAMETERS.

Although the apparatus is described in detail in Chapters 4 and 5 and possible techniques for the determination of the undisturbed field are considered in Chapter 3 it will be convenient here to provide a key to these chapters by mentioning briefly the methods of measurement employed.

For the measurement of point discharge current it was sufficient to connect the point to earth through a galvanometer.

Initially the Agrimeter of Dr. Chalmers (14) was used for field measurement but when the problems discussed in Chapter 3 had been worked out it became necessary to use a second field measuring device. An apparatus of the "Field Mill" type was therefore developed and constructed. Galvanometers were used as the indicating instruments for both the Field Mill and the Agrimeter so the deflections of these two and of the point discharge galvanometer were recorded photographically on a single drum camera.

Wind speed was determined by visual observation of the declination of the balloon. The declination was calibrated in terms of wind speed in two special ascents in which a light cup anemometer was attached to the balloon.

Visual observation was used for the determination of wind direction.

The height of the point was determined by marking off metre lengths on the flying cable; a correction was applied for the declination of the balloon.

2.7. NECESSARY EXPERIMENTAL CONDITIONS.

It will now be clear that an earthed discharge point was to be attached to a captive spherical rubber balloon and raised to heights of between 50 and 200 metres in light winds. Simultaneous observations were to be made of point discharge current, electric field, wind speed, height of point and, possibly, conductivity. It was also hoped to extend the work to cover the effect of different types of discharger and different gauges of wire from point to ground.

CHAPTER 3. INTERACTION BETWEEN POINT DISCHARGE CURRENT AND ELECTRIC FIELD.

3.1. GENERAL.

The phenomenon of an electric field, in the vicinity of a pointed conductor, producing a discharge from the point has already been considered in some detail. Attention must now be given to the complementary effects whereby the pointed conductor and the discharge distort the electric field responsible for the discharge.

The practical significance of these effects in the present investigation is that whereas the discharge current may be expected to be determined by the "undisturbed" field (the field which would exist in the absence of the point and discharge) the field which is measured at the ground near the point may be expected to differ, to some extent, from the undisturbed field and in a manner which will depend on the position of the point, the direction and velocity of the wind and the magnitude of the discharge current.

In order to determine how best to allow for these effects in determining the undisturbed field some estimate must be made of their magnitude in various positions near the point -- the fact that their magnitude is sufficient to demand consideration was shown by the big reduction in field encountered close to the flying cable as the balloon ascended in the early experiments.

In the present case the distortion produced by the "pointed conductor" can be considered in terms of the charge which necessarily resides on the flying cable to maintain it at earth potential and will therefore be referred to as the "Cable Charge Effect"; the distortion produced by the discharge can be considered in terms of the space charge "liberated" by the ionisation process of the discharge and will be referred to as the "Point Space Charge Effect" -- in order to distinguish this space charge from the "normal" space charge (referred to in section 2.4(b)) which is present in the atmosphere independent of the point discharge.

3.2. CABLE CHARGE EFFECT.

In the case of a point fixed to the top of a rigid mast this effect can be allowed for by comparing the field at some position near the mast when there is no point discharge with that at some exposed site nearby, and hence obtaining the exposure factor; but in the case of a point supported by a captive balloon, particularly if the balloon has a low lift/drag ratio, the position of the cable, and hence the value of the exposure factor, will change with changes of wind speed and direction. The problem must therefore be considered in more detail.

It should be noted at the outset that in the present investigation the flying cable of the balloon was a heavy whipcord of fairly high electrical resistance and that a separate length of 26 S.W.G. copper wire was used to carry the discharge current to the ground. For the moment the effect of only the copper wire will be considered.

(a) Distribution of Charge on Cable.

Davis and Standring (23) considered the effect for a vertical cable. They started by assuming that the charge on the cable at any point was given by Kx per unit length where x was the distance along the cable from the ground and K a constant. This gave the potential of the wire due to the charge on it at some distance a along the wire from the ground as

$$\int_{-h}^{+h} \frac{Kx \ dx}{\{(x - a)^2 + r^2\}^{1/2}} \qquad (3.1)$$

where h = overall length of cable

r = radius of cable

on integration this gave the potential as

$$K \left[\sqrt{(h - a)^2 + r^2} - \sqrt{(h + a)^2 + r^2} + a \log \frac{h-a+\sqrt{(h-a)^2 + r^2}}{\sqrt{(h+a)^2 + r^2} - (h+a)} \right]$$

then, provided $r \ll (h - a)$, which will apply to all but the extreme tip of the cable

$$\text{potential} = Ka \left[\log \frac{4(h^2 - a^2)}{r^2} - 2 \right] \qquad (3.2)$$

Then in so far as $\log 4(h^2 - a^2)/r^2$ may be taken equal to $\log 4h^2/r^2$ the potential of the wire at any point (due to the charge on it) will be proportional to height if the charge density on the cable is proportional to height. Actually the effect of the factor $\log 4(h^2 - a^2)/r^2$

is to require a slight extra charge density near the top of the cable, but a few numerical calculations show the effect to be small except at the extreme top.

Thus Davis and Standring were able to assume that a charge distribution on the cable of the form Kx per unit length gave a constant potential gradient along the cable. Then, if the cable were set up in a uniform electric field, charge would be induced on the cable such that the value of K gave a potential to the cable which was everywhere equal and opposite to the potential due to the electric field.

i.e. $Ex = -Kx(\log 4h^2/r^2 - 2)$ where E = the electric field.

$$\text{or } K = -E/(\log 4h^2/r^2 - 2) \qquad (3.3)$$

The argument must now be extended to the present case of a sloping wire. Let θ be the angle between the ground and the line joining the base of the wire to the point, and assume that the wire is straight and lies along this line. Assume again that the wire carries a charge Kx per unit length. It will be convenient to consider the actual wire and its image in the ground separately. Writing

Pot_A = potential at a from ground along wire due to actual charge

Pot_I = potential at a from ground along wire due to image charge

Pot_T = potential at a from ground along wire due to actual and image charge, then $$\mathrm{Pot}_A = \int_0^h \frac{Kx\,dx}{\{(x-a)^2 + r^2\}^{1/2}}$$

$$= K\left[\sqrt{(h-a)^2+r^2} - \sqrt{(a^2+r^2)} + a\log\frac{h-a+\sqrt{(h-a)^2+r^2}}{\sqrt{a^2+r^2} - a}\right]$$

$$\mathrm{Pot}_I = \int_{-h}^0 \frac{Kx\,dx}{\{(x-a)^2\sin^2\theta + (x+a)^2\cos^2\theta + r^2\}^{1/2}}$$

$$= K\left[\sqrt{a^2+r^2} - \sqrt{(h - a\cos 2\theta)^2 + a^2\sin^2 2\theta + r^2}\right.$$
$$\left. - a\cos 2\theta \log\frac{\sqrt{a^2+r^2} + a\cos 2\theta}{\{(h-a\cos 2\theta)^2 + a^2\sin^2 2\theta + r^2\}^{1/2} - (h-a\cos 2\theta)}\right]$$

Therefore $$\mathrm{Pot}_T = \mathrm{Pot}_A + \mathrm{Pot}_I = K\left[\sqrt{(h-a)^2 + r^2}\right.$$
$$- \sqrt{(h - a\cos 2\theta)^2 + a^2\sin^2 2\theta + r^2}$$
$$+ a\log\frac{h-a+\sqrt{(h-a)^2+r^2}}{(a^2+r^2)^{1/2} - a}$$
$$\left. - a\cos 2\theta\log\frac{\sqrt{a^2+r^2} + a\cos 2\theta}{\sqrt{(h-a\cos 2\theta)^2 + a^2\sin^2 2\theta + r^2} - (h-a\cos 2\theta)}\right] \quad (3.4)$$

When $\theta = \pi/2$ this reduces to the expression derived by Davis and Standring (equation 3.2). If the case of $\theta = \pi/4$ is considered (which approximately represented the limit of working conditions) and $r \ll h-a$ the expression

$$\mathrm{Pot}_T(\pi/4) = K\left[h-a - \sqrt{h^2+a^2} + a\log\frac{h-a+h-a}{a(1+r^2/a^2)^{1/2} - a} - 0\right]$$

is obtained, which reduces to

$$Ka\left[\log\frac{4a(h-a)}{r^2} - \left(1 + \frac{1a}{2h} - \frac{1a^3}{8h^3} + \frac{1}{16}\frac{a^5}{h^5} - \dots\right)\right] \quad (3.5)$$

A few calculations for a sample of values of a show that the expression in the square brackets is only slightly larger than $(\log 4h^2/r^2 - 2)$ except when a closely approaches 0 or h when it becomes appreciably larger. Therefore it may be taken that the error involved in assuming that a charge distribution along the wire of the form Kx per unit length produces a potential on the wire proportional to height, is not large for $\theta = \pi/2$ or $\theta = \pi/4$ and there seems no reason to suppose that it would be large for intermediate values of θ. Therefore, provided that the field at the ground due to the charge on the wire is small compared with the undisturbed field, the error in assuming that the charge on the wire is given by Kx per unit length is small and may safely be ignored. The value of K may now be taken from

$$Ex\sin\theta = -Kx(\log 4h^2/r^2 - 2)$$

$$\text{or } K = -E\sin\theta/(\log 4h^2/r^2 - 2) \qquad (3.6)$$

(b) Field at Ground due to Cable Charge. (F_W).

Davis and Standring showed that the vertical component of the field at the ground, due to the cable charge, at a distance d from the base of the cable, was given by $F_W = K\int_{-h}^{+h} \frac{x^2\,dx}{(x^2+d^2)^{3/2}}$ (taking account of the image wire)

which, on integration, gave

$$F_W = 2K\left[\log \frac{h + (d^2 + h^2)^{1/2}}{d} - \frac{h}{(d^2 + h^2)^{1/2}}\right] \qquad (3.7)$$

Extending the argument to a sloping wire: the vertical component of the field at the ground due to the charge on the wire which, at a distance d from the base of the cable in a direction making an angle ϕ with the direction of the projection of the wire on the ground (that is the direction towards which the wind is blowing),

TABLE I

Values of k in $F_W = kF_u$ where F_W = field due to cable charge and F_u = undisturbed field.

A: h = 50m

θ	φ	d=10m	d=50m	d=100m
π/2	all values	0.118	0.015	0.002
	0	0.186	0.036	0.004
π/4	π/2	0.059	0.007	0.001
	π	0.031	0.004	0.001

B: h = 200m

θ	φ	d=10m	d=50m	d=100m
π/2	all values	0.201	0.084	0.041
	0	0.232	0.154	0.101
π/4	π/2	0.100	0.042	0.020
	π	0.043	0.016	0.009

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is given by

$$F_W = 2K\sin\theta \int_0^h \frac{x^2\,dx}{(x^2 - 2dx\cos\theta\cos\phi + d^2)^{3/2}} \quad \text{(taking account of the image wire)}$$

$$= \frac{2K\sin\theta}{1-\cos^2\theta\cos^2\phi}\left[\frac{h(2\cos^2\theta\cos^2\phi - 1) - d\cos\theta\cos\phi}{(h^2 - 2dh\cos\theta\cos\phi + d^2)^{1/2}} + \cos\theta\cos\phi \right.$$

$$\left. + (1-\cos^2\theta\cos^2\phi)\log\frac{h - d\cos\theta\cos\phi + (h^2 - 2dh\cos\theta\cos\phi + d^2)^{1/2}}{d(1 - \cos\theta\cos\phi)}\right] \quad (3.8)$$

Table I shows values of the field due to the cable charge for h = 50m and 200m and $\theta = \pi/2$ and $\pi/4$ -- the approximate limits of these values used in the observations -- and for $\phi = 0$, π and 2π and d = 10m, 50m and 100m.

(c) Errors in F_W.

The values of F_W have been given to three places of decimals in Table I in order to illustrate clearly the extent of the variation but it should be borne in mind that there is some doubt in the second significant figure as the following considerations will show.

1.) The errors involved in the assumptions made on the distribution of cable charge have already been considered and probably make the calculated values of F_W a few per cent low.

2.) It is difficult to know what allowance to make for the presence of the flying cable in addition to the current carrying wire but it seems that its most probable effect will be to increase somewhat the effective radius of the current carrying wire. However, since K is rather insensitive to changes of r, it seems that this also will make the calculated values of F_W only a few per cent low.

3.) The fact that the current wire is not straight but lies approximately in the form of a catenary will produce a systematic decrease in the value of θ. This means that for values of ϕ between 0 and about $\pi/2$ the quoted values of F_W will be slightly low, and that for values of ϕ between about $\pi/2$ and π F_W will be slightly high.

4.) The space charge generated by the point discharge will distort the field which induces the charge on the cable and hence introduce some errors in the quoted values of F_W.

Thus it seems that the first three considerations involve only slight errors in F_W probably making the calculated values consistently a little low. The errors involved in the fourth consideration cannot be estimated until the space charge effect has been considered in detail.

3.3. POINT SPACE CHARGE EFFECT.

(a) Field at Ground due to Point Space Charge (F_S).

In considering this effect Davis and Standring(23) assumed that the discharge was concentrated at the top of their flying cable and then stated that: "In fields in which the discharge current is steady, ion velocities will be negligible in comparison with wind velocities, so that the space charge generated will drift approximately to leeward." They then deduced that for a discharge current I at a height h in a wind velocity v the vertical field at the ground at a distance d to windward of the cable, due to the point space charge, neglecting recombination, was given by

$$F_s = 2\int_0^\infty \frac{Ihdx}{v\left[h^2 + (x+d)^2\right]^{3/2}} = \frac{2I}{vh}\left(1 - \frac{d}{(d^2 + h^2)^{1/2}}\right) \quad (3.9)$$

To extend this to the present case it will be convenient to let θ be the angle between the ground and the line joining the base of the cable to the discharge point and h the length of this line. Let F_s be calculated for a position distance d from the base of the cable in a direction making an angle φ with the projection of the cable on the ground (i.e. with the direction towards which the wind is blowing). Then the symbols will have the same meaning as in the discussion of the cable charge effect. Further let I, v and F_s have the same meaning as above. Then

$$F_s = 2\int_0^\infty \frac{Ih\sin\theta\, dx}{v\left[h^2\sin^2\theta + d^2\sin^2\phi + (x + h\cos\theta - d\cos\phi)^2\right]^{3/2}}$$

$$= \frac{2I\sin\theta}{vh(\sin^2\theta + d^2\sin^2\phi/h^2)}\left[1 - \frac{h\cos\theta - d\cos\phi}{(h^2 + d^2 - 2dh\cos\theta\cos\phi)^{1/2}}\right] \quad (3.10)$$

Table II shows values of F_s for various representative value of h, I, v, d and φ use having been made of the relation between v and θ which will be considered

TABLE II

Values of F_s in v/m

h=50m I=0.2μa v=0.5km/hr.

d \ φ	0	π/2	π
10m	1240	1010	840
50m	1770	520	300
100m	1970	210	110

h=50m I=0.2μa v=27km/hr.

d \ φ	0	π/2	π
10m	12	8	5
50m	38	5	2
100m	51	2	1

h=200m I=8.0μa v=0.5km/hr.

d \ φ	0	π/2	π
10m	10900	10400	9900
50m	12900	9300	7900
100m	15000	8300	5800

h=200m I=8.0μa v=27km/hr.

d \ φ	0	π/2	π
10m	86	80	74
50m	125	76	53
100m	196	67	38

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in section 5.5(c). 50m and 200m represent the operational limits of h and 0.2 and 8 μa are reasonable values of I for these heights for a field of 100 v/m. 27 km/hr is the upper operational limit of v and 0.5 km/hr has been used, arbitrarily, as a lower limit since the formula for F_s clearly breaks down at v = 0.

(b) Errors in F_s.

The values of F_s for low wind speeds appear to be exceptionally high and would involve huge reversals of the undisturbed field. Although one or two occasions of positive current with negative field were encountered the large negative values predicted by F_s were certainly never found and it would be wise to search for an explanation of these large values.

There appear to be two possible sources of error:

1.) Although, in the normal fair weather field of about 100 v/m, the velocity of the ions due to their mobility will be small (about 1.5 cm/sec.) compared to their velocity due to a wind even as low as 0.5 km/hr (= 14cm/sec); close to the discharge point very intense fields will be encountered so that the ions may be carried to a height somewhat greater than that of the point before the wind becomes the predominating force acting upon them. This state of affairs could be approximately represented by raising the horizontal line of space charge somewhat. However, so little is known about the configuration of the field near the point that it does not appear practicable to make any estimate of this effect.

2.) Davis and Standring noted that the point space charge would be somewhat diminished by recombination but considered that "knowledge of ion concentration, etc., is insufficient to estimate the rate of recombination." An attempt to make such an estimate in the present case led to a similar conclusion since, although a considerable reduction in F_S could be obtained by this procedure the values were still much higher than those found in practice.

(c) Conclusions.

From the foregoing the difficulty of arriving at a reliable estimate of the field due to point space charge is abundantly apparent but it is also clear that the probability of its being considerable is too great for it to be ignored.

Although the point space charge field will reduce the charge on the cable somewhat no reliable estimate can be made of the effect on the field due to the cable charge.

3.4. IMPLICATIONS OF POINT SPACE CHARGE AND CABLE CHARGE EFFECTS.

Although there is considerable doubt over the values of F_S and some uncertainty in the values of F_W it seems highly probable that close to the flying cable, and particularly to leeward of it, F_S and F_W will represent appreciable fractions of the undisturbed field. Therefore if the field at the ground were measured near the base of the cable and taken as a measure of the undisturbed field there would be a grave danger that any relation established between field and current would be invalid as would also any relations between current and the other parameters which made use of the current-field relation.

It is therefore clear that, in order to obtain significant results, whatever measure is taken of electric field must approximate as closely as possible to the undistrubed field.

3.5. METHODS OF DETERMINING THE UNDISTURBED FIELD.

(a) Measuring the field remote from the flying cable.

The most obvious method of obtaining a measure of the undisturbed field would be to measure the field at the ground to windward of the flying cable and far enough away from it for F_S and F_W to be negligible. There are two limitations to this method.

Firstly: as the distance between the cable and the place of measurement is increased so the correlation between the field to which the discharge responds and the measured field will decrease. This is not a very serious limitation since it seems unlikely that, for any practical separation, a systematic deviation would occur between the two fields but a certain amount of extra scatter would be introduced into the results and therefore a greater number of observations would be needed in order to obtain significant results. However, the work of Dupérier and Collado (25) suggests that the separation could be as great as a few hundred metres without introducing any great scatter into the results.

Secondly: the practical difficulties and inconvenience of measuring the field at a great distance from the cable are considerable, particularly since the apparatus would have to be moved when the wind direction changed. Further, the nature of the site of the present investigation (see Figs. 9 - 15), with a wood, a cornfield and private allotments nearby, placed serious limitations on the separation of the cable and the place of measurement.

On balance it appeared that in the present investigation the optimum separation for this procedure would be about 50m: practical considerations prevent it being any greater, and to make it any smaller would increase the errors due to F_W and F_S. A glance at Table I will show that, provided ϕ is not less than $\pi/2$ (i.e the place of measurement is not more than $\pi/2$ off windward) the errors due to F_W will not exceed 10 per cent. The errors due to F_S are likely to be somewhat greater when the discharge point is high, and perhaps when the wind speed is low, but the uncertainty over the values of F_S makes it impossible to assess the errors accurately.

The conclusion to be drawn then, is that this method should, in general, give satisfactory results although caution must be observed in low winds and when the point is high, particular note being taken of the change of field during the ascent and descent of the point under these conditions.

(b) Indirect Estimation of the Undisturbed Field.

Despite the doubt over the calculated values of F_S it may be possible to use what is known of the point space charge effect and cable charge effect to obtain an estimate of the undisturbed field. It would obviously be quite unjustifiable to apply corrections, for F_S at any rate, directly to the measured field but an indirect method is available which, under certain circumstances, considerably reduces the effects of the errors in F_S.

Consider a discharge point set up in a field of undisturbed value F_u. Then the value of the field at the ground at two positions near the point will be given by

$$f' = F_u - F_S' - F_W'$$

$$f'' = F_u - F_S'' - F_W''$$

where F_S' and F_S'' are the fields due to the point space charge and F_W' and F_W'' the fields due to the cable charge. Now assume that the point space charge drifts downwind in a horizontal line of infinite extent and constant density; but do not assume that this density is given by I/v.

Then $F_S' =$ say Dp'

$F_S'' =$ say Dp''

where p' and p" are given by equation (3.10) if I/v is replaced by D.

Let $F_W' = k'F_u$ and $F_W'' = k''F_u$ (as in Table I)

Then $f' = F_u(1 - k') - Dp'$

$f'' = F_u(1 - k'') - Dp''$

Whence $F_c = \dfrac{p'f'' - p''f'}{(1 - k'')p' - (1 - k')p''}$

(where F_c is the calculated value of F_u)

and $D = \dfrac{f''(1 - k') - f'(1 - k'')}{p'(1 - k'') - p''(1 - k')}$

This provides a method of calculating F_u which does not assume any particular value for the point space charge density but merely that it is constant and extends to infinity. It also ignores any reduction of the cable charge effect by the point space charge.

As to the first assumption; it is to be expected that errors in F_c will be greatest in low wind speeds and will become small for wind speeds above some critical value which, it is to be hoped, will be small.

As to the second assumption: the values of k' and k" will be somewhat reduced by a dense space charge but the extent is difficult to estimate.

The extent to which errors due to these assumptions may be neglected can be gauged by comparing D with I/v. Over the range of values of the various variables for which D is equal, or at any rate proportional, to I/v the values of F_c should be a close approximation to F_u.

In assessing the value of this method of estimating the undisturbed field the following factors must be borne in mind.

1.) It involves the use of two field measuring instruments.

2.) It is laborious.

3.) In the formulae for F_c and D the denominators and numerators both consist of the differences between two quantities so that errors in the measured values of field and in the calculated values of p' and p" will produce large errors in F_c and K.

4.) Its accuracy can only be judged by applying it in particular instances and comparing D with I/v and comparing values of F_c immediately after an ascent or before a descent with the measured values of field immediately before an ascent or after a descent respectively.

(c) Method Finally Adopted.

In the early experiments, before the cable charge and point space charge effects had been fully investigated, use was made of the Agrimeter of Dr. Chalmers (14) for measurement of field. This was situated about 8m from the base of the current wire and the magnitude of the cable charge and point space charge effects soon became apparent. A spur to adopt the second, indirect, method of estimating the undisturbed field came from an apparent agreement between the actual changes of field during ascent and descent and those predicted by the point space charge effect. This later turned out to be a pure coincidence arising from an overestimation of wind speed, but since the Agrimeter could not be moved a second field measuring apparatus had to be built whichever method was adopted. Further, its optimum position was the same for both methods.

Thus for the later experiments the field measurements of both the Agrimeter and the newly constructed "Field Mill" were recorded and either method could be applied to the interpretation of the results.

<u>CHAPTER 4. THE FIELD MILL</u>

As the Field Mill was the most complex single piece of apparatus used and occupied a considerable amount of time in its design and development it will be well to allot it a chapter of its own. The remainder of the apparatus will be described in Chapter 5.

4.1. REQUIREMENTS.

The apparatus for measuring the electric field 50m to windward of the flying cable must fulfil the following requirements.

1.) In view of the fairly rapid fluctuations of electric field the apparatus must provide a <u>continuous automatic record</u> in order that average values may be taken over short periods.

2.) Since the position of the apparatus is partly determined by wind direction it must be <u>transportable</u> -- the alternative of providing a number of similar instruments in fixed positions would be too costly.

3.) For convenience in comparing the field with point discharge current the indicating instrument must be in the same room as the point discharge galvanometer. Therefore the apparatus must be <u>remote indicating</u> -- over a distance of about 50m.

4.) The apparatus must cause <u>no interference</u> with other atmospheric electricity measurements in the vicinity.

5.) In view of the restriction placed by the weather on balloon flying a range of measurement from +500 v/m to -250 v/m will be ample and a range from +250 v/m to 0 will be sufficient for most occasions.

6.) In view of the large degree of scatter in the results obtained in point discharge work an accuracy of ± 2.5 v/m up to 250 v/m and ± 5 v/m up to 500 v/m will be ample.

7.) The response time should be not greater than say 5 seconds.

8.) A variable sensitivity must be provided to allow for the different exposure factors of the positions in which the apparatus is to be operated.

9.) There will be no need for the apparatus to work in adverse weather conditions although it would be an advantage for it to work in mist and light drizzle.

4.2. TYPE OF APPARATUS.

A wide variety of methods have been devised for the measurement of the earth's electric field one of the simplest and most common being the radioactive collector. Although this could be made to fulfil most of the requirements in the present case the fourth and seventh are mutually exclusive to a large extent although it is interesting to note that Mühleisen (63) has recently largely overcome this difficulty by a cathode follower technique.

As no other simple apparatus satisfied all the requirements it was decided that some form of "mechanical collector" must be used.

4.3. PRINCIPLE OF OPERATION OF MECHANICAL COLLECTOR.

The mechanical collector is essentially a development of Wilson's (94) test plate apparatus. Wilson measured the charge flowing to a conductor or "test plate" when it was suddenly exposed to an electric field. Since the induced charge is proportional to the electric field this provided a measure of the field. The mechanical collector,which elaborates Wilson's method into a continuous measurement of induced charge, has been developed in two main forms.

In the first form the test plate is first earthed and exposed to the field to be measured. The earth connection is broken and the then charged test plate is moved to some screened position where it is connected to an electrometer with which it shares its charge. The test plate is then returned to its original position and the procedure repeated continuously and rapidly so that the electrometer receives a sequence of unidirectional current pulses and eventually reaches a steady potential which is proportional to the electric field. This appears to have been the first form of mechanical collector built since when the Norwegian Russeltvedt (71) reported it in 1926 it had then been in use for some years. This form has been further developed by Workman and Holzer (97) and, in the form of the Agrimeter, by Chalmers (14). In the Agrimeter it is customary to measure the current due to the sequence of pulses instead of the potential built up on an electrometer. Since the repetition frequency of the pulses is kept constant, the current is proportional to the field.

In the second form, devised by the German Matthias (61) in 1926, two test plates are used forming the two halves of a cylinder, split along its axis. The cylinder is exposed and rotated about its axis which lies perpendicular to the field. The charges induced on the two semi-cylinders have a sine wave form with respect to time, the two sine waves being π radians out of phase. The sine wave current between the two semi cylinders, or the sine wave voltage developed by it across some impedance, then provides a measure of the electric field.

Later variations of this form have usually had a fixed test plate connected to earth through a high impedance and regularly exposed to and screened from the electric field. A charge, varying between some value and 0 is therefore induced on the test plate and an alternating voltage, proportional to the field, is developed across the impedance.

This form has proved exceedingly popular being used both for atmospheric electric field measurements -- Macky (57), Rangs (70), Lueder (53), Kasemir (42), Waddel (84), von Kilinski (83) and Malan and Schonland (58) -- and for indirect measurement of voltage in high tension laboratories -- Kirkpatrick and Miyake (43), Harnwell and Van Voorhis (36), Henderson, Goss and Rose (37), van Atta, Northrup, van Atta and van de Graff (82), Feldenkrais (26), Thomas (79), Neubert (65), Gohlke and Neubert (30,31) and Schwenkhagen (72).

Some mention must also be made of the "Portable Electrometer" devised by the American Ross Gunn (33). The American literature frequently seems to imply that this instrument was the beginning of the mechanical collector but since the paper was not published until 1932 this claim is clearly invalid. Furthermore it was not a mechanical collector as such but an electrometer for the measurement of charge, which relied on very high insulation to prevent the charge leaking away. It consisted essentially of a pair of rotating semi-cylinders as in the second form of mechanical collector, surrounded by two concentric fixed semi-cylinders one of which was earthed while the other, which carried the unknown charge, was highly insulated. Thus it was not suitable for continuous measurement of electric field unless the fixed outer semi-cylinders were removed, thereby reducing it to the form used by Matthias some six years earlier.

In selecting the form of the mechanical collector most suitable for the present task the first form was rejected as, at that time, the Agrimeter of Dr. Chalmers did not fulfil the requirement of accuracy although the later improvements made it quite satisfactory.

Thus it was decided that a mechanical collector of the second form must be built. Collectors of this form have been variously named generating voltmeter, valve electrometer, electric field meter, vibrating voltmeter, electrostatic induction voltmeter, field measurement machine, rotating voltmeter and electrostatic fluxmeter. Here the term "Field Mill" -- Rangs (70), "Feldmühle"; Kasemir (42) and Lueder (53),"Feldstärkenmühle" -- is used on the grounds that its undoubted brevity outweighs the merits of the more descriptive nature of the other somewhat cumbersome terms.

4.4. MODES OF OPERATION USED BY PREVIOUS WORKERS.

In the arrangement used by Macky (57), Waddel (84) and von Kilinski (83) the test plate consisted of a number of equal sectors of a circle, separated from one another by sectors of equal size. A similar set of earthed sectors rotated over them. The output waveform was therefore approximately triangular. Van Atta <u>et al</u> (82) and Bangs (70) used a similar arrangement but shaped their rotating earthed screening plate to give a sine wave output. Lueder (53) used a circular test plate with a fixed perforated earthed plate over it and rotated a similar perforated plate between the two. Harnwell and Van Voorhis (36) used a similar arrangement but instead of earthing the fixed perforated plate they applied a variable known potential to it thereby providing a null method of measurement. Malan and Schonland (58) used a set of 18 studs arranged in a circle as their test plate and rotated over them a plate with 18 corresponding holes. Originally Gohlke and Neubert (30) varied the exposure of their test plate by vibrating it up and down through a corresponding hole in a flat earthed plate but in a later model (31) they used a number of parallel strips as their test plate and vibrated them to and fro below an earthed plate containing the same number of corresponding slits. Schwenkhagen (72) developed a number of models using many of the methods already described. Kirkpatrick and Miyake (43), Henderson, Goss and Rose (37), Thomas (79), Feldenkrais (26), Neubert (65) and Kasemir (42) used the original cylindrical arrangement of Matthias (61).

In order to determine the direction of the field Matthias, van Atta et al, Macky, Gohlke and Neubert, Lueder and Kasemir used quite independent methods; Kirkpatrick and Miyake, Henderson Goss and Rose, Thomas, Feldenkrais, Waddel and von Kilinski rectified the alternating current by a commutator synchronised with the current; Rangs, Schwenkhagen and von Kilinski used an auxiliary synchronous generator which was added to the output of the Mill and so displaced the zero. Harnwell and Van Voorhis, of course, could determine the sign of the field from the sign of the voltage to be applied to the fixed plate for zero output. Malan and Schonland, who displayed their output on a C. R. O. , used a most ingenious method. In addition to their 18 main studs they had two subsidiary studs mounted somewhat closer to the axis but on the same radii as two of the main studs. Corresponding holes were made in the rotating earthed screening plate so that every ninth peak or trough of the waveform was slightly pronounced thereby identifying the peaks or the troughs with the moment when the studs were exposed and hence, taking into account any inversion which occured in the circuit, the sign of the field was determined.

In almost all cases some degree of amplification of the alternating current was necessary prior to rectification or C. R. O. display.

4.5. MODE OF OPERATION ADOPTED.

Most of the designs described above could readily be adapted to the present requirements; the final selection of a design essentially similar to that of Malan and Schonland (58) being determined by the following considerations.

In view of the smallness of the fields to be measured some amplification would undoubtledly be necessary. Therefore an operating frequency of a few hundred cycles per second would be advantageous both in order to keep down the size of coupling and by-pass condensers and in order to facilitate discrimination against 50 c/s mains pick up. A high operating frequency was desirable also, as will be shown in section 4.7.(a), in order to obtain maximum output and keep it independent of frequency. This being so the cylindrical type of Mill could be discarded since an inconveniently high rotor speed would have been necessary (operating frequency being equal to rotor speed). Finally, the sector plate type of Mill was discarded in favour of the Malan and Schonland type because the construction of the latter was so simple: the studs can be screw heads and the rotating plate a circular plate with circular holes drilled in it. The disadvantage of the small area of the studs in this design is not serious since it can easily be compensated for by increased amplification; the effect of the principal source of error (contact potential between studs and rotating plate) being reduced in proportion to the area of the studs in approximately the same way as the output.

It might have been possible to have relied on the output of the Agrimeter for the determination of the direction of the field but this would have led to some ambiguity when the field was near zero. It was therefore decided that the Mill must provide its own indication of sign. This could have been done by displacing the zero, either by adding the output of an auxiliary synchronised generator to the output of the Mill or by applying an artificial field to part of the face of the Mill. While this would probably have been satisfactory so far as the present requirements were concerned, it was felt that the apparatus would be of more general use -- for any projects which the Department might undertake after the completion of the present work -- if phase sensitive detection were used. Also, this method has the additional advantage that a very high noise level can be tolerated. This has frequently been done in the past by the use of a mechanical commutator mounted on the same shaft as the screening plate. However, it was felt that, at the comparatively high frequency at which the apparatus was to operate, electronic phase sensitive detection would be more reliable -- a technique which, it is believed, has not previously been applied to the Field Mill although Lueder (54) has recently used it in an instrument for the measurement of charge due to riming of supercooled water droplets.

Thus the apparatus was to be essentially similar to that of Malan and Schonland but with electronic phase sensitive detection of the amplified output.

It must be emphasised that although some reasons have been given for the choice of the mode of operation they are somewhat insubstantial and probably largely a matter of personal preference; it is probable that almost any of the existing designs could have been used to produce an equally suitable instrument.

4.6. GENERAL DESIGN CONSIDERATIONS.

Since phase sensitive detection was to be used a reference voltage had to be generated. The most convenient way of doing this seemed to be to use a motor alternator and build the Field Mill onto the end of its shaft so that the frequency of Mill and alternator outputs would be perfectly synchronised. A coarse adjustment of relative phase could then be obtained by the relative orientations on the shaft of the screening plate and alternator rotor, but for a fine adjustment it was decided to build a variable phase shift network.

In accordance with the requirements, the indicating instrument had to be in the recording room and the Field Mill proper about 50m away. In between these two the amplifier, phase sensitive dêtector and phase shifter were required. It was desirable to have these in the recording room rather than at the Field Mill for a variety of reasons:

1.) Convenient protection from weather,

2.) Reduction of temperature variation,

3.) Isolation from Field Mill vibration,

4.) Gain, balance and phase shift controls could be adjusted while watching the effect on the indicating instrument.

It was, however, desirable, as will be shown in section 4.7(a), to have one stage of amplification at the Field Mill proper in order to isolate the cable capacity from the Mill. It was thought best to make this stage a cathode follower in order to provide a high ratio of i/p to o/p impedance and ensure stability of gain.

Since photographic recording was employed and in order to reduce the gain required of the amplifier a mirror galvanometer was the most suitable indicating instrument.

Originally it was intended to use a.c. heaters for the valves and the electronic apparatus was designed on that assumption. However, when a suitable motor alternator was eventually obtained it was found to require a direct current to excite the alternator field coil. The obvious course was then to use d.c. for the cathode follower heater so that the same pair of wires could be used to supply cathode follower heater and field coil. Since the interconnections of the supply system had also been constructed by that time it became convenient to supply d.c. to the amplifier and detector heaters as well.

4.7. THE FIELD MILL PROPER.

(a) Electrical Design.

The principle of operation of the Field Mill must now be considered quantitatively.

Let the studs have a capacity C and a resistance R to earth due either to actual components or to strays.

Let the electric field be F and the effective area of the studs, at any moment, be a with maximum value A. Then the charge induced on the studs will be given by:

$q = Fa/4\pi$ or $q_{max} = Q$, say, $= FA/4\pi$

If a varies sinusoidally $a = \frac{A}{2} + \frac{A}{2}\sin pt$ and

hence $q = \frac{Q}{2} + \frac{Q}{2}\sin pt$ where p = angular frequency

of exposure-screening cycle and t = time. Now this charge must flow through C and R. Therefore the instantaneous value of the current through C and R is given by

$$i = \frac{dq}{dt} = \frac{pQ}{2}\cos pt$$

and the peak value of i is given by

$$I = pQ/2 = pFA/8\pi$$

The impedance of C and R in parallel is given by

$$Z = \frac{R}{(p^2C^2R^2 + 1)^{1/2}}$$

Therefore the peak voltage across C and R is given by

$$V = IZ = \frac{pRFA}{8\pi(p^2C^2R^2 + 1)^{1/2}}$$

$$\text{or } V = \frac{FA}{8\pi(C^2 + 1/p^2R^2)^{1/2}}$$

This relationship will be falsified by the facts that the waveform is not a pure sinewave and that C varies slightly in synchronism with q; the studs have different capacitances to the rotating plate when they are screened to when they are exposed. However, examination of the wave form on a C. R. O. showed that it was not far removed from a pure sine wave and a rough measurement of capacity variation showed it to be about 8pF in 70pF so that the error in the relationship is small and probably does not affect its nature.

From the relationship it is clear that for maximum V, pR must be large and C must be small, and that if $pCR \gg 1$ the relationship simplifies to $V = FA/8\pi C$ which is independent of rotor speed. This condition is clearly desirable since, even if a synchronous motor is used, it will, with the current practice of load shedding, be subject to some speed variation.

Little can be done to decrease C without decreasing A except, of course, building the cathode follower close to the Mill proper in order to isolate it from the large capacity of the cable which feeds the signal to the indicator in the recording room. With the constructional arrangement used C was about 70pF. 10 studs were used with a synchronous motor driving the screening plate at 3000 r.p.m. so that p was 1000π. It is unwise to make R too high or grid current in the first valve will build up an appreciable potential on the studs and hence produce an output which will vary with grid current, due to the variation of capacity as the screening plate rotates. A value of 50M was finally selected for R.

With these values V was 0.4 percent below the maximum value for the given F, A and C, and a 6 per cent fall in mains frequency, believed to be the maximum change to be encountered, would produce a 0.04 per cent fall in V. Thus the requirements of maximum and constant output were more than adequately fulfilled.

The total area of the studs was 7.86 sq.cm. so that if the exposure were perfect the output should be 12.4mv peak (8.5mv r.m.s.) for a field of 250 v/m or about 50μv peak (35μv r.m.s.) per v/m.

If a sudden change of field occurs the a.c. output of the Mill, being nearly a pure sine wave, will respond virtually instantaneously. In addition there will be a d.c. "kick" which will decay in say 5CR = 18 msec., and be somewhat attenuated, relative to the a.c., in passing through the amplifier. Thus the response time of the Mill proper is well within the required value.

The air-earth current may be represented by $j = \frac{J}{2} + \frac{J}{2}\sin pt$ where j is the instantaneous value and J the value when the studs are fully exposed. The voltage across C and R due to this will therefore be given by

$$v = \frac{JZ}{2}\sin pt + \frac{JR}{2}$$

Taking 10^{-15} amps/sq.cm. as a generous figure for the current $J = 7.86 \times 10^{-15}$ amps and

$$v = 2.3 \times 10^{-9}\sin pt + 2.5 \times 10^{-8} \text{ volts.}$$

Thus both the steady and the alternating effects are negligible.

The same considerations may be applied for the average rain current. Chalmers (10 p113) gives 10^{-14} amps/sq.cm. as an upper limit for steady rain. Since this is only 10 times the air-earth current it would be negligible. Individual drops, however, may well produce a noticeable effect. Taking a value of 10^{-3} e.s.u. for the charge on a drop (Hutchinson and Chalmers (39)) this would give an instantaneous voltage across the 70pF condenser of about 0.5mv which is equal to the peak value of the alternating voltage due to a field of 10 v/m. This sudden kick would be somewhat attenuated, relative to the a.c., in passing through the amplifier and the individual drop charges in drizzle would be much smaller, so that it is doubtful whether rain will have any appreciable effect, in this sense.

(b) Mechanical Design. (see Figs 1 - 3)

This was considerably influenced by the motor alternator used which was a second-hand four-frequency instrument originally manufactured for Standard Telephones and Cables. While it satisfied the theoretical demands and had the advantage of a synchronous motor it was inconveniently bulky and heavy. However, it was the most suitable instrument readily available, the delivery time of new motor alternators being about nine months.

The casing was cylindrical 6" in diameter and 18" long. The total weight was estimated to approach half a

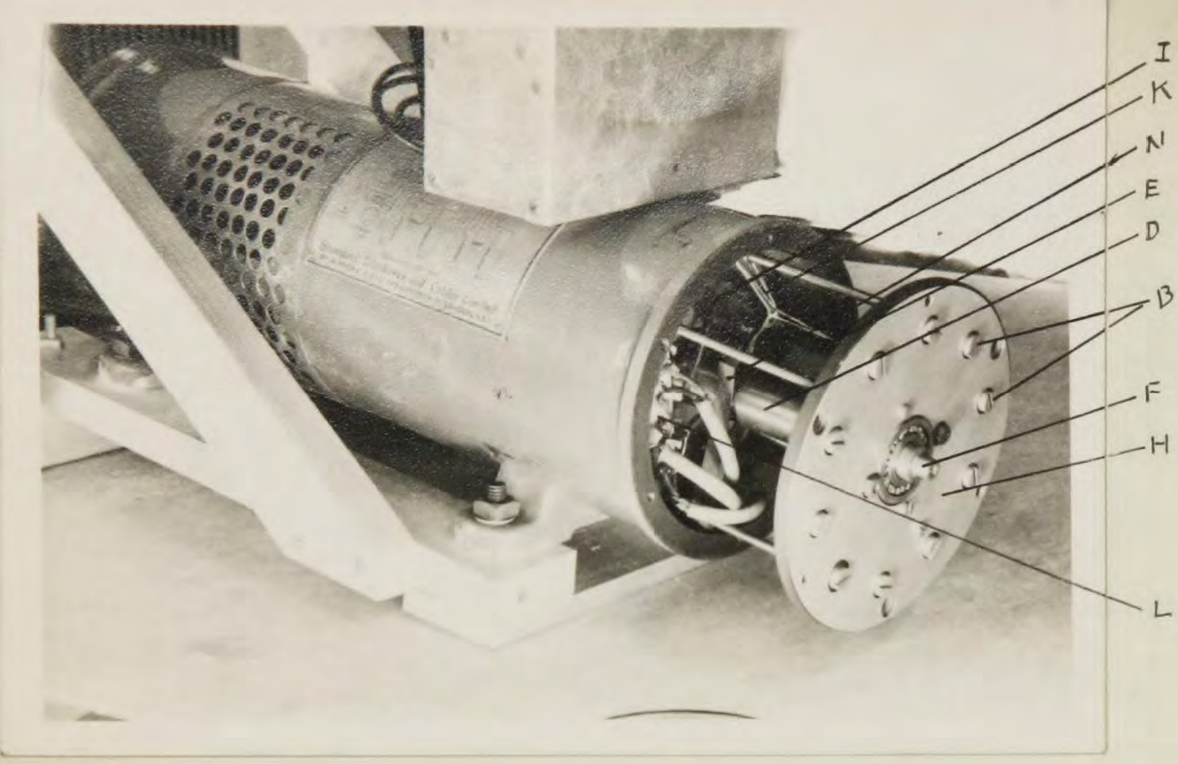
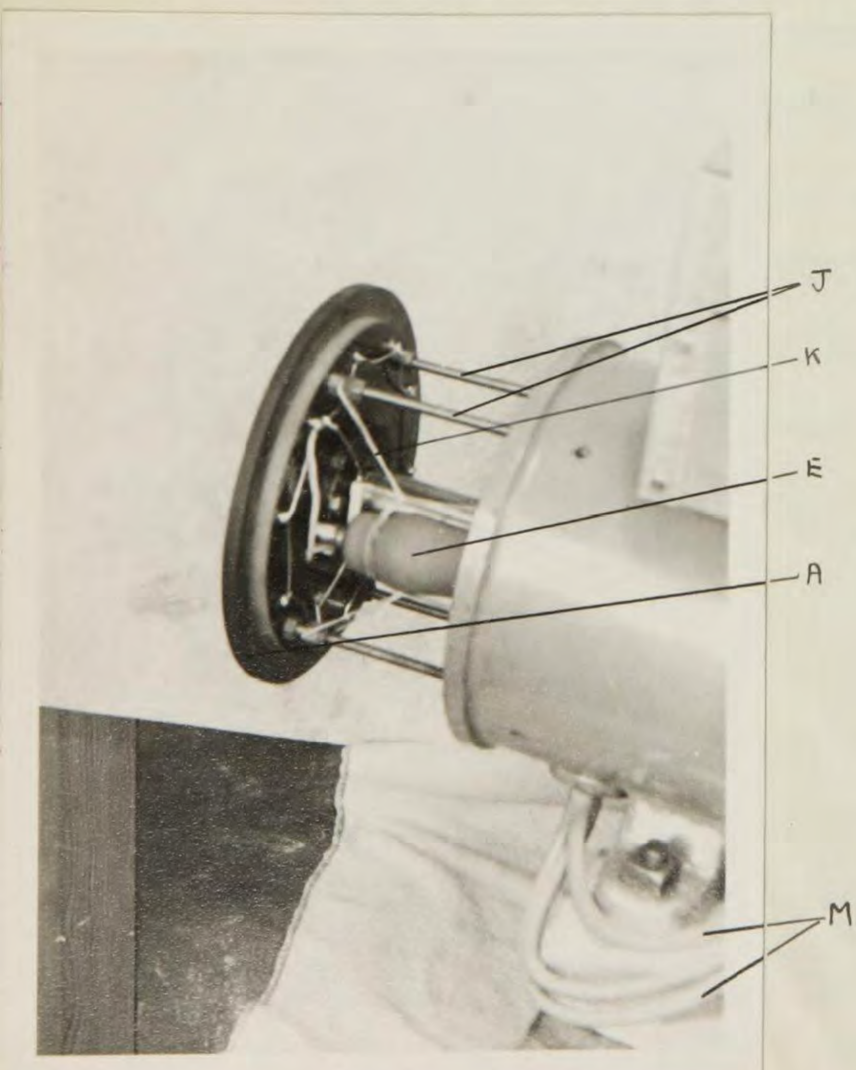


Fig. 1 THE FIELD MILL (PARTLY DISMANTLED).

Fig. 2 THE FIELD MILL (PARTLY DISMANTLED).



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hundredweight. The motor had separate "start" and "run" windings and drew about 1.2 amps on "run". There were four alternators providing outputs of 500, 600, 750 and 900 c/s at 20v when the field coils were energised by 24v.

By removing the three unwanted alternators and replacing one end plate by a Tufnol disc (A) it was found possible to build the studs (BB) into the Tufnol, fix the screening plate (C) on the end of the shaft (D) and build the cathode follower (E) inside the casing.

The 10 studs, which consisted of 0 B.A. screws, whose heads projected through the Tufnol, were mounted at equal intervals on a circle of 5.9cm radius. They were connected together and to the grid of the cathode follower and through the 50M grid leak to earth, inside the casing.

The screening plate was 15.2cm in diameter, about 1.5mm thick and about 1 mm away from the surface of the studs. 10 3/4" diameter holes were drilled in it in positions corresponding to the studs. The last quarter inch (F) of the shaft was turned down to 3/8" diameter, thereby providing a shoulder against which the screening plate was placed. The end of the shaft was then covered with a "thimble" (G) and a 2B.A. screw screwed through the thimble into the end of the shaft thereby clamping the screening plate. Thus rough adjustment of the phase relation between Mill o/p and alternator o/p could readily be made by slackening the retaining screw, rotating the screening plate on the shaft and retightening the screw.

An earthed aluminium sheet (H) was placed over the surface of the Tufnol, a clearance of about 1 mm being allowed around each stud. This served to screen the cathode follower from any pick-up from outside the casing and also, what was not realised at the time but later proved to be most important, to screen the insulating Tufnol from the screening plate; stray charges on insulators being believed to be a major source of zero drift.

An aluminium disk(I) between the cathode follower and the alternator was supported on the ends of four lengths of 2 B.A. studding, (J) extending from the Tufnol end plate and held steady by strips of phosphor bronze pressing against the inside of the casing. The studding served to support the cathode follower valve and the aluminium disk served to provide some screening from the motor alternator. Soft iron or mumetal would, of course, have been a much more appropriate material but the amount of pick-up was not a major cause of zero error.

The valve was suspended between two lengths of studding by rubber bands (K), as recommended by Malan and Schonland, to reduce microphony, and originally the leads to the base went directly through a hole in the side of the casing. However, it was found that they thereby provided a rather stiff support and if their position outside the casing was altered the valve might be brought into firm contact with some part of the motor alternator leading to a large amount of 50 c/s pick-up. When this effect was discovered the valve was connected by specially flexible leads to a tag strip (L) rigidly mounted inside the casing, and from there to the outside with ordinary leads (M).

The whole arrangement was such that the Tufnol end plate, the valve and its supports and the shaft could be withdrawn a few inches from the casing without disconnecting any leads -- as shown in figs 1 and 2. This greatly facilitated inspection and maintenance.

As has been found by most investigators the earthing of the shaft,and hence of the screening plate, through the bearings was quite inadequate and accordingly a good earthing contact was provided by two strips of phosphor bronze (N) "pinching" the shaft. This proved quite satisfactory in practice and did not seem to give rise to any noticeable contact potential.

All the leads from the motor alternator and Mill were brought out to a connector-switching box fixed to the

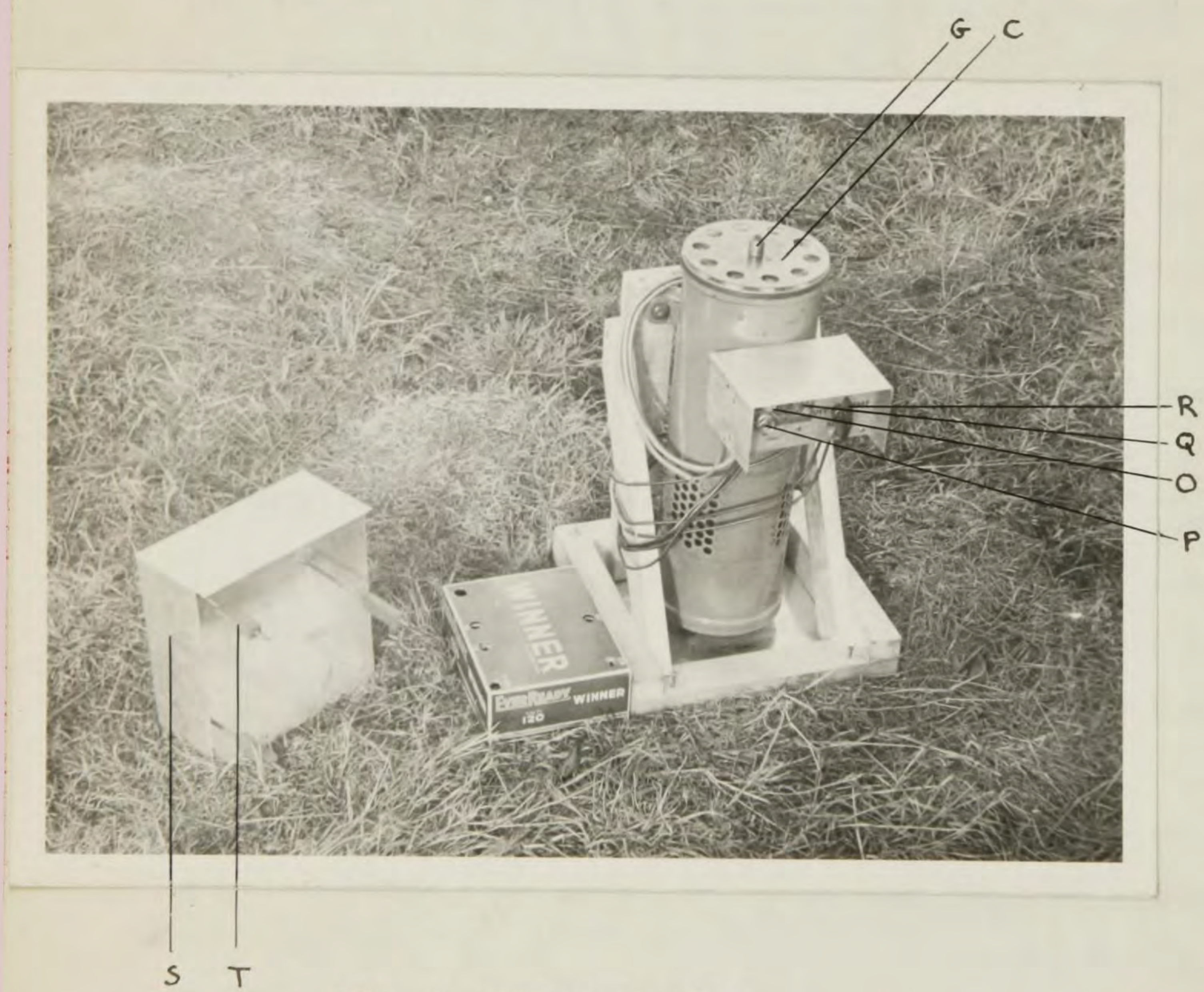
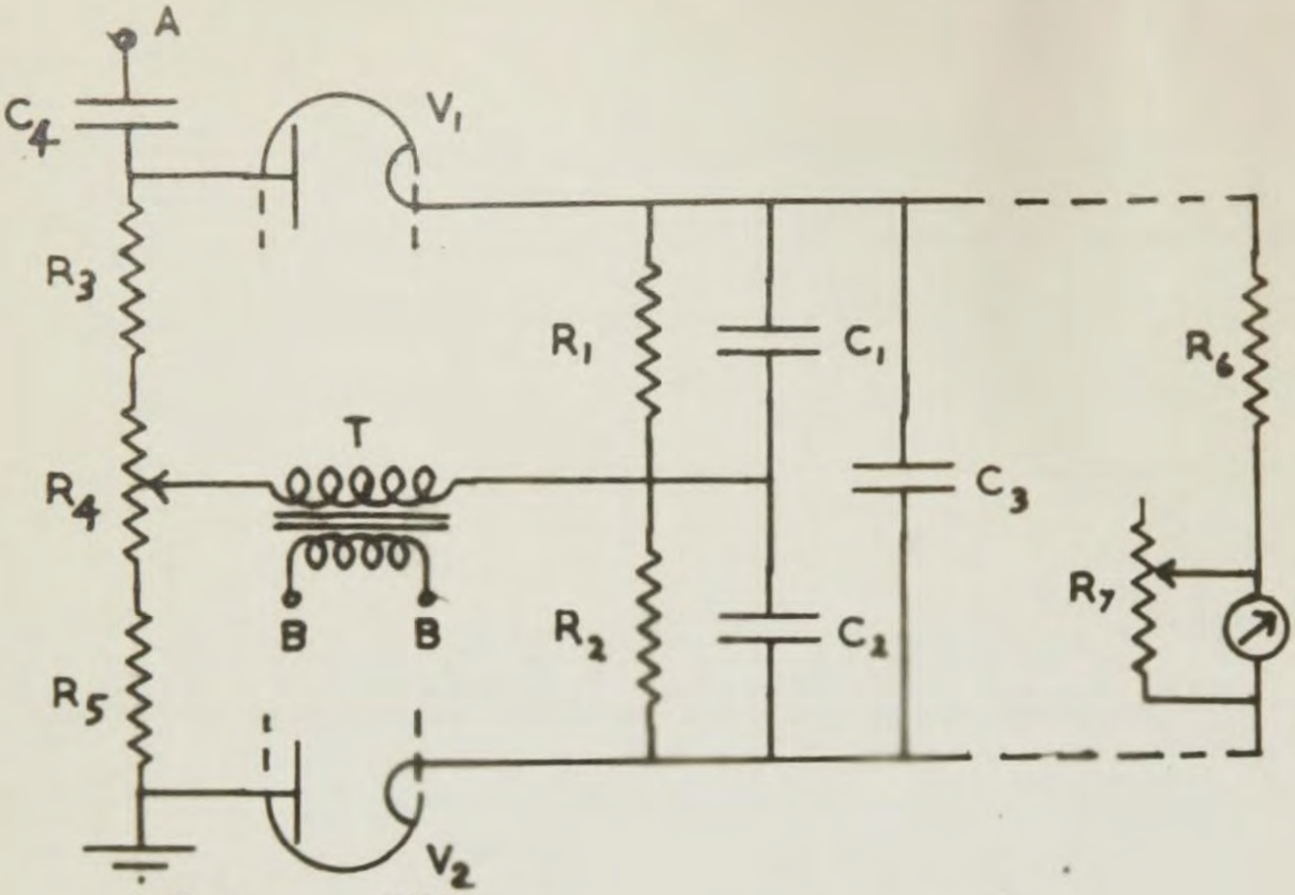


FIG. 3 THE FIELD MILL

(The calibrating box (S) is shown here for the purpose of illustration. Normally, when not in use, it was placed two or three metres away from the Mill to prevent it producing any variable field distortion at the Mill.)

outside of the casing. Here the signal and reference voltages were connected to Pye plugs (O,P) and all the supply voltages to a 10-pin Belling and Lee socket (Q). A four position, heavy duty, switch (R) was mounted in the box. It would have been slightly more convenient to have had this in the recording room but that would have meant the use of an extra 50m lead. The box also contained a dropping resistor so that the valve heater could be fed from the same supply as the alternator field coil. The top and sides of the box were extended over the plug and switch panel to provide some protection from rain. Of the leads from inside the casing to the box those carrying the motor and alternator field coil supplies and alternator o/p were unscreened, but separate screened leads were used for the H.T. Heater and signal voltages.

The whole instrument was mounted on a wooden framework so that it could be stood upright; the screening plate was then horizontal and about 45cm above the base of the framework. The framework was coated tith aluminium paint to prevent stray charges collecting on it and producing variable field distortion.



R_7	20K	$C_1\ C_2\ C_3$	0·1 μF
$R_1\ R_2$	1 M	C_4	2 μF
$R_3\ R_4\ R_5$	100K	T	3:1 step up
R_6	50 M		
$V_1\ V_2$	2 halves VR 54		
A	Signal i/p from amp.		
BB	Reference i/p from phase shifter		

FIG 4 PHASE SENSITIVE DETECTOR AND GALVANOMETER

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4.8. THE PHASE-SENSITIVE DETECTOR (Fig 4)

(a) Design.

The circuit adopted is a modification of one quoted by James, Nichols and Phillips(41). Although it appears to be very simple its precise mode of operation is somewhat complex and it has not been found possible to develop a mathematical theory of it -- chiefly because of the complex shapes of the waveforms and the characteristics of the diodes. It was, however, found just possible to obtain the requisite performance.

Its mode of operation may be explained roughly as follows. When the left hand end of the secondary of T is driven positive by the reference voltage the diodes will conduct charging C_1 and C_2. When the left hand end is negative the diodes will be cut off and C_1 and C_2 will discharge slowly through R_1 and R_2. Thus the diodes will conduct for rather less than half of each cycle of the reference voltage (because of the voltage developed across C_1 and C_2). During the period that they are conducting the circuit to their right will, so far as the signal voltage is concerned, be in parallel with R_3, R_4 and R_5, provided that the diode current due to the signal is less than that due to the reference voltage. Thus, if the signal and referenne voltages are in phase, i.e. signal positive when left of T is positive, C_3 and

C_1 and C_2 in series, will build up a positive charge. If the signal and reference voltages are π out of phase a negative charge will build up on C_3 etc. Thus since, when the sign of the field changes, the phase of the Mill o/p is reversed with respect to the reference voltage, the d.c. output of the detector will be reversed.

In designing the circuit the following requirements were borne in mind.

For good linearity the valve current due to the signal should be small compared to that due to the reference voltage -- because of the curvature of the diode characteristics.

For good zero stability the current due to the signal should be large -- in order to minimise relative changes in the characteristics of the two halves of the valve.

Since T forms part of a phase shifter, which depends on low loading of T for its satisfactory operation the current drawn from it must be small.

The combination of C_1, C_2, C_3, R_1 and R_2 should have a time constant long enough to give peak detection but short enough to give a response time less than 5 sec.

The last requirement was easily fulfilled. The values chosen gave a time constant of 0.3 seconds. The measured response was about 0.9 of the peak signal i/p and would clearly be reached in less than 5 seconds.

The first three requirements were more difficult to fulfil being mutually contradictory to a considerable extent. A reasonable compromise was arrived at by making the output of T equal 9v r.m.s. (13v peak) and making the range of signal input 0 to 1.15v r.m.s. (0 to 1.6v peak). Component values were as shown in Fig.4. Then in order to meet the requirements of measurement range and accuracy it was decided to use two ranges: - 250 v/m, 0, + 250 v/m and - 500 v/m, 0, + 500 v/m; each corresponding to a range of signal input 1.15v, 0, 1.15v r.m.s. and a range of output of -1.5v, 0, + 1.5v. Then on both ranges the Field Mill had to have an overall accuracy of ± 1 per cent of full scale (positive or negative) output.

A double diode is clearly preferable to two single diodes since temperature and heater voltage variations will have less effect on the balance. A batch of VR54's was available, four of which were tested the one giving the best linearity being selected.

(b) Performance.

For the final arrangement the following performance figures may be quoted.

The combined effect of a 10 per cent fall of heater volts and a 20 percent fall of reference voltage and frequency produced a 0.5 per cent fall in output.

Most of the fall was due to the fall in frequency and could not be explained quantitatively. Since the maximum change of frequency in a synchronous motor is a 6 per cent fall this effect will be very small.

A noise level of about 250mv r.m.s was needed to reduce the full scale output by 1 per cent. For small outputs the effect was less. Again no explanation could be found but as the total noise level was fairly steady at about 200mv the error introduced was very small.

If the signal and reference voltages were slightly out of phase the output of the circuit was somewhat diminished but its performance in other respects was substantially unimpaired.

The linearity of the response for positive and negative outputs was such that the error at half full scale was about 0.5 per cent of the full scale output.

The sensitivity for negative output was about 7 per cent higher than for positive output. In view of the output of the Mill proper for zero field this presented a serious problem. If the zero error was compensated by displacing the galvanometer zero a marked change of sensitivity would occur as the actual output of the detector passed through zero i.e. at some value of field between zero and full scale. Therefore if the calibration were checked at zero and

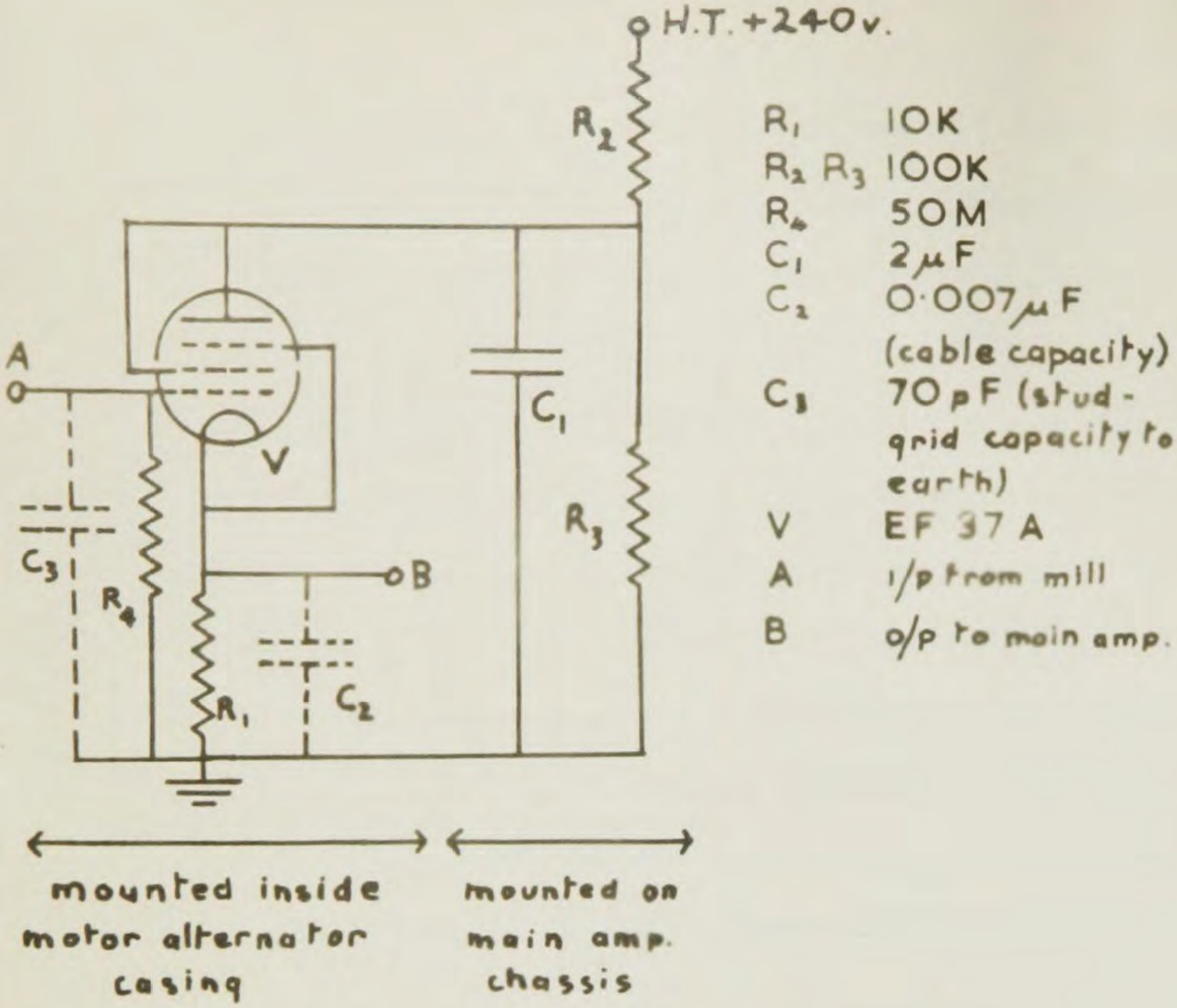

FIG 5 CATHODE-FOLLOWER

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full scale serious non-linearity errors would be introduced for either positive or negative outputs. In view of this it was decided to use the balance control R_4 to supply an input to the detector from the reference voltage which was equal and opposite to the signal input for zero field so that the change of sensitivity occured at zero field. This meant, of course, that the output depended in large measure on the reference voltage but as this was derived from a synchronous motor alternator with the field energizing voltage derived from accumulators the errors introduced could be kept small by maintaining the accumulators in good order.

Drift of sensitivity and zero were just small to enough to obtain the requisite accuracy if calibrations were made at the beginning and end of each hour.

4.9. THE CATHODE FOLLOWER (Fig 5)

This had the primary task of matching the high output impedance of the Mill proper to the low impedance of the cable. The output impedance of the Mill was 70pF in parallel with 50M and the cable capacity was 0.007μF (70m at 1pF per cm.) -- a reactance of 45K at 500c/s.

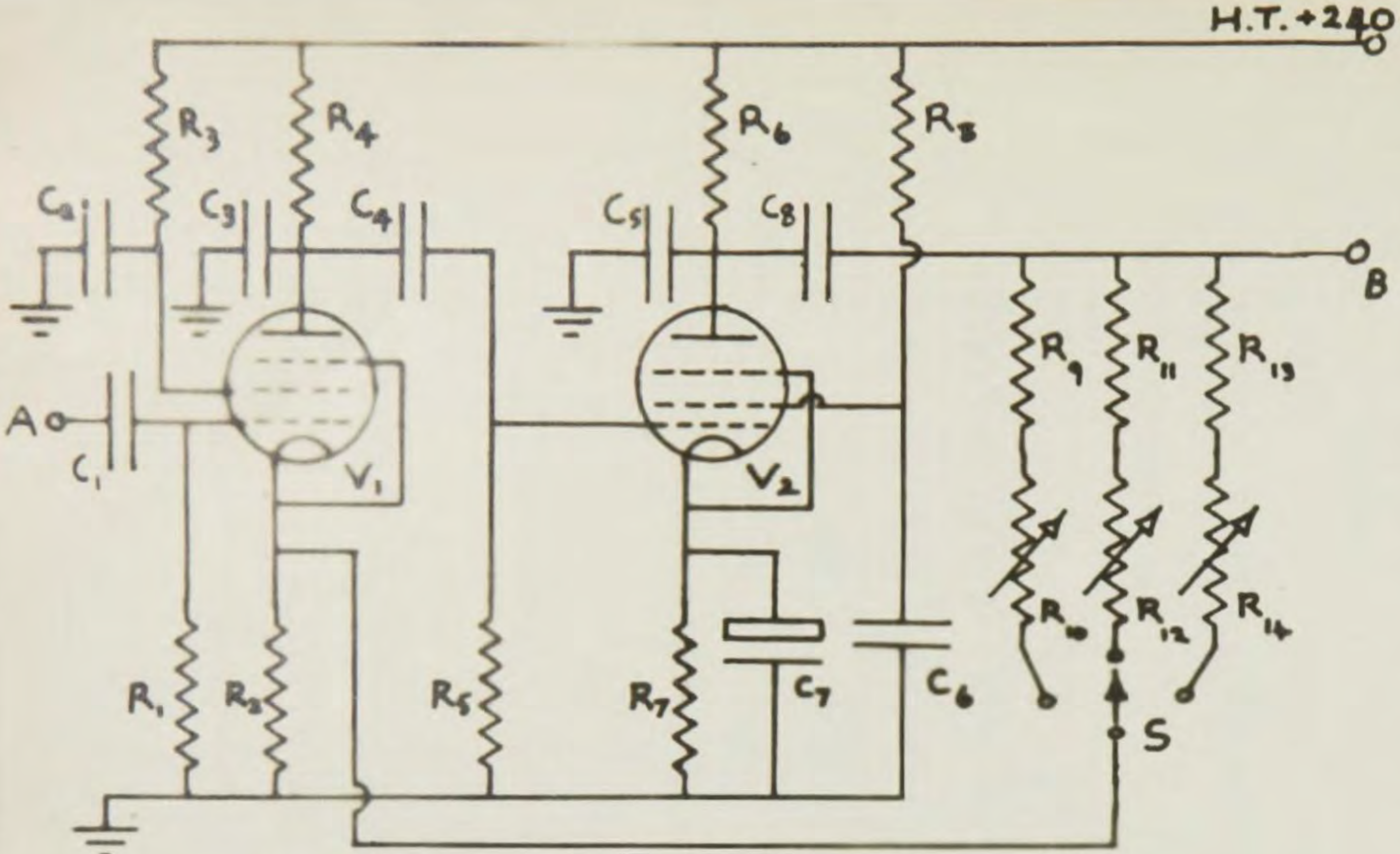
The valve used must have low microphony and as it was originally intended to use a.c. heaters the Mullard EF37A, a low hum, low microphony, H.F. pentode, was chosen. It was strapped as a triode and operated at reduced anode and heater voltages. 4.5v were obtained for the heater from the 6v alternator field coil supply by means of a 10 ohm series resistor. 100v for the anode were obtained from a bleeder across the main H.T. supply. With a 10K cathode load the valve passed 0.4 ma and had a mutual conductance of about 0.7 ma/v.

Under these conditions the gain was calculated to be 0.87. A 6 per cent fall of mutual conductance was needed to produce a 1 per cent fall of output and a 6 per cent fall of frequency produced a 0.05 per cent fall of output and a 2^{o} phase shift. Thus sensitivity variation of the cathode follower may be regarded as negligible.

4.10. THE AMPLIFIER. (Fig 6)

It was stated in section 4.8(a) that the detector required a full scale input of 1.15v and calculated in section 4.7(a) that the Field Mill provided an output of 8.5 mv for 250 v/m and hence 17 mv for 500 v/m. Therefore, taking account of the gain of the cathode follower, gains of about 160 and 80 respectively, were required of the amplifier if the exposure factor of the field mill were unity. Different exposure factors for the various operating positions of the Mill necessitated widening this range somewhat.

Gains of this order could have been achieved with a



A i/p from c/f
B o/p to phase sensitive detector
S gain selector switch

R_1	100K
R_2	1K
R_3	200K
R_4	82K
R_5	1M
R_6	47K
R_7	560Ω
R_8	47K
R_9	39K
R_{10}	20K
R_{11}	75K
R_{12}	50K
R_{13}	150K
R_{14}	100K
C_1	0·1μF
$C_2 C_6 C_8$	2μF
C_3	0·0004μF
C_4	0·003μF
C_5	0·001μF
C_7	50μF
$V_1 V_2$	SP61 (VR65)

FIG 6 AMPLIFIER

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single valve but the gain would then have been somewhat unstable. Accordingly it was decided to use two valves which provided a margin for a generous degree of negative feedback.

A plentiful supply of VR65's (Mazda SP61's), high slope H.F. pentodes, was available and these were found to be quite satisfactory in operation.

The design of the amplifier is quite straightforward and only the following points seem to call for comment. C_3 and C_5 provided some reduction of high frequency response and by making C_4 small and C_8 large some reduction in low frequency response was obtained. C_4 (Fig 4) served to isolate the cathode potential of V_1 from the phase sensitive detector.

The gain selector switch, S, combined with the potentiometers R_{10}, R_{12}, R_{14} covered the following ranges of gain: 40 - 60, 75 - 125, 150 - 250.

All the resistors in the feedback chain should, of course, have been wirewound for maximum stability, but carbon resistors, which were to hand, were installed initially and as they proved sufficiently stable they were not replaced.

The amount of feedback was such that a 50 per cent change in the gain of both stages produced a 1 per cent change of overall gain.

Only two practical difficulties were encountered once the amplifier had been properly built. One was leakage across the paxolin of the tag board on which most of the components were mounted. This was only noticeable between the anode of V_1 and the grid of V_2 which were connected to adjacent tags and was eliminated by inserting small "stand off" insulators of perspex.

The second difficulty arose from frequent small but sudden jumps in the H.T. supplied from a mains driven power pack. These did not affect the operation of the amplifier but were fed through the phase sensitive detector and produced quite large kicks on the galvanometer. Attempts to eliminate them by modifying the amplifier or the detector spoilt their performance in other respects; a brief attempt to eliminate them by stabilising the H.T. by a conventional circuit was unsuccessful in that although slow changes were largely removed these sudden jumps passed through unaffected. Accordingly it was decided to use dry batteries as the H.T. supply as a temporary measure. In point of fact no time could be found to tackle the problem fully.

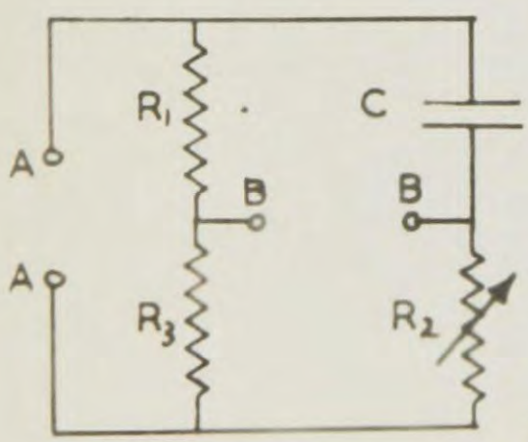
4.11. THE PHASE SHIFTER. (Fig 7)

The circuit used is one given by Terman (73)(p 949). As R_2 is varied from 0 to some value very much greater

TABLE III.

(For explanation see text, section 4.11.)

	E_i/E_o		ϕ	
	$p = 1000\pi$	$p = 940\pi$	$p = 1000\pi$	$p = 940\pi$
R_2 = 10ohm	2.00	2.00	80.6°	81.3°
R_2 = 100ohm	1.90	1.90	4.5°	8.5°
R_2 = 1000ohm	1.80	1.78	-76.3°	-75.3°



$R_1 R_3$ 50
R_2 1 K (max)
C 3μF (100Ω at 500 c/s)
AA i/p from alternator
BB o/p to transformer (T) in phase sensitive detector.
Primary inductance of T = 0·3 H (1K at 500 c/s)

FIG 7 PHASE SHIFTER

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than the reactance of C the output shifts through nearly π radians relative to the input. R_1 and R_3 must be large enough not to overload the alternator and the reactance of C large enough for the change of alternator load, as R_2 is varied, not to produce any great change in alternator o/p. The primary inductance of T (Fig 4) must be high enough and the secondary load light enough not to impose any appreciable load on the circuit.

If $R_1 = R_3$, L = primary inductance of T, $\beta = pCR_2$, E_i = input voltage, E_o = output voltage and the load presented by T is assumed to be entirely inductive then

$$\frac{E_i}{E_o} = \frac{R_1(1 - \beta^2) + 2R_2 - 4\beta pL + j[2\beta R_1 + 2\beta R_2 + 2pL(1-\beta^2)]}{1 + \beta^2}$$

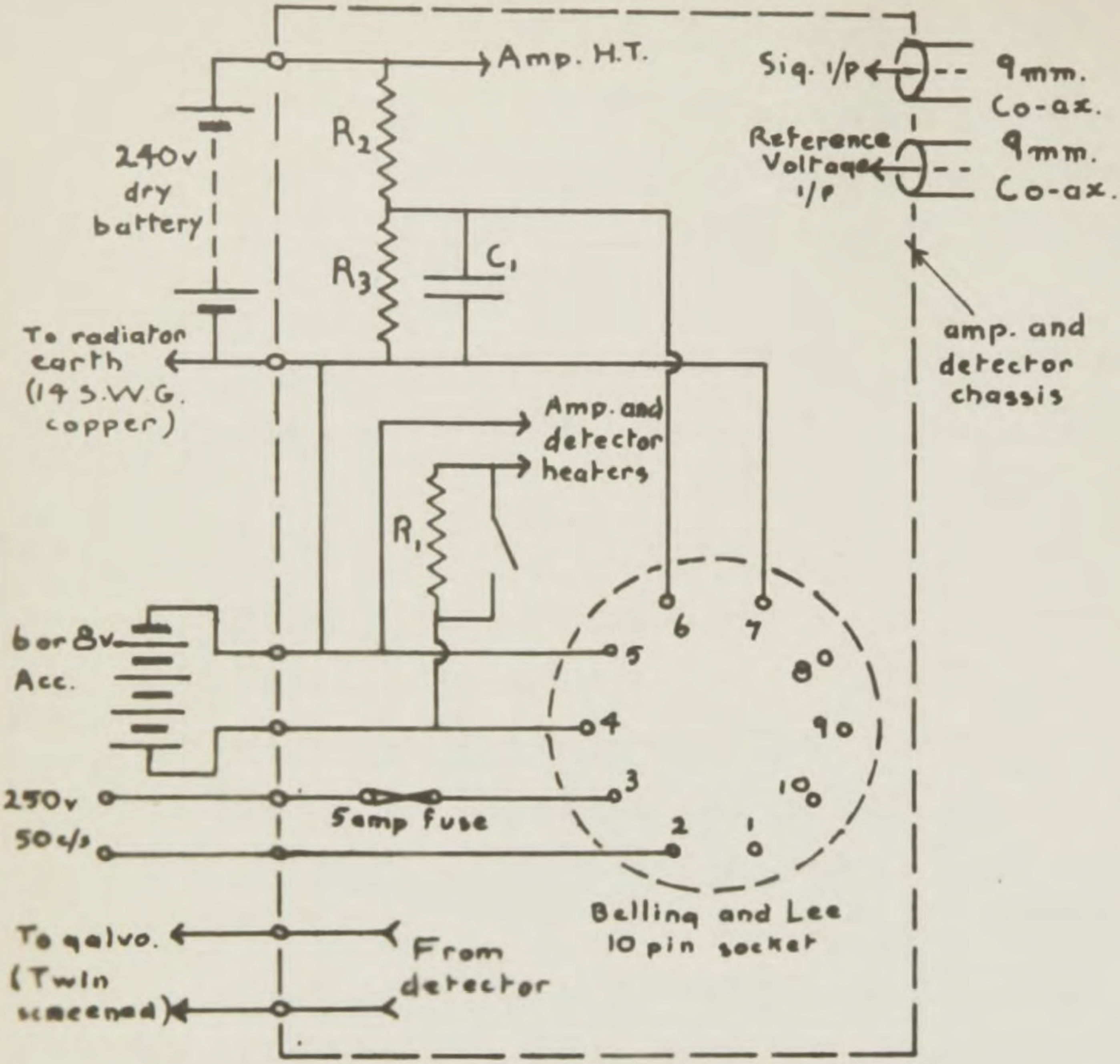
Table III which has been calculated according to this formula shows the effect on output voltage and phase (ϕ) of changes in R_2 and a 6 per cent fall in frequency. It will be seen that as R_2 is varied the output voltage remains fairly steady, assuming, as is justifiable, that the input voltage remains constant, and that once R_2 is set the output voltage is not much affected by frequency. The phase of the output covers a good range as R_2 is varied but is somewhat sensitive to frequency variation for intermediate values of R_2.

In operation very little mains frequency variation was encountered so it seems safe to disregard the phase shifter as a source of error.

4.12. THE GALVANOMETER. (Fig 4)

A Tinsley taut suspension galvanometer was immediately to hand and was used as the indicating instrument. A 20K rheostat R_7 in parallel with it was adjusted to give just under critical damping which made its response time about 1 second and its sensitivity about 1600 mm per μamp at 1m. The photographic paper used for recording was 12cm wide so it was decided to use -5, 0 +5cm as the measurement range. To make this correspond with the output voltage range of the detector (-1.5, 0, +1.5v) a 50M series resistor was used. It would, of course, have been possible to use a smaller series resistor with a less sensitive instrument had one been to hand.

The galvanometer proved reasonably satisfactory in operation. Its zero drift rarely exceeded 0.5mm in an hour. Its periodic time unfortunately approximately coincided with that of a source of violent vibration located near a boiler house about 50m away. However, this vibration rarely occured during the use of the Mill and then for only a few minutes at a time. It imposed an oscillation of about 3 mm amplitude on the trace which was otherwise unaffected. On two occasions, when it was not in use, the galvanometer behaved most erratically; the mirror tended to settle at one or other



R_1 1·7Ω $R_2 R_3$ 100K C_1 2μF

Cable connections to Belling and Lee 10pin plug:

Pins 2&3 Twin T.R.S. 23/·0076 to motor

Pins 4&5 Twin screened 14/·0076 to alternator field coil and c/f heater. (Braiding connected to pin 4.)

Pins 6&7 Twin screened 14/·0076 : c/f H.T. (Braiding connected to pin 7.)

FIG 8 SUPPLIES AND CHASSIS CONNECTIONS

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extreme of deflection even when the instrument was electrically isolated. No explanation could be found for this remarkable behaviour.

4.13. INTERCONNECTIONS AND POWER SUPPLIES.

These are shown diagrammatically in Fig 8 which is largely self explanatory.

The choice of coaxial cable for the signal and reference voltages seemed fairly obvious although after the weight of the 9mm diameter cable had been experienced for a short time it was wished that a narrower cable had been purchased even though the increased capacity would have involved some redesign of the cathode follower.

After it was decided to use d.c. for the cathode follower heater it would have been possible to use a three core screened cable for heaters and H.T. making one of the three cores a common earth return.

The connection of signal, reference and supply voltages at the Mill proper were the same as at the amplifier chassis except that the braiding of the heater and H.T. cables was not earthed there.

The main earth connection of the apparatus was made to a radiator in the recording room although other incidental low resistance earth connections would be made through the framework supporting the Mill proper and through the braiding of the heater and H.T. cables. On one occasion the effect of adding a deliberate earth at the Mill was tried but no change in the galvanometer deflection was observed.

In view of the length of the cable for the normal operating positions of the Mill (70m) a noticeable volts drop occurred along the heater cable. Under these conditions an 8v accumulator was used which gave about 6v to the alternator field coil, 4.5v to the cathode follower heater by means of the dropping resistor referred to in section 4.9. and 6v to the amplifier and detector heaters by means of the 1.7 ohm dropping resistor R_1. In the course of the absolute calibration, when the Mill was operated much nearer the recording room, only 17m of cable were used. Then a 6v accumulator was used and R_1 was shorted out.

4.14. ROUTINE CALIBRATION AND SETTING UP PROCEDURE.

For the purpose of routine calibration an aluminium box was constructed. It was square on a side of 23cm with a depth of 10cm. This was inverted over the face of the Field Mill and supported on three insulating "legs" (T Fig3). Two of these dropped into holes in the wooden framework and the third rested on the switch and plug box. Thus, when in place it always had the same position relative to the Mill. A short length of flex with wander plugs on one end and crocodile clips on the other enabled the box to be earthed or supplied with a known voltage from an H.T. battery nearby. It was found sufficient to check the voltage each day the Mill was used and although the surface of the battery sometimes became quite warm in the sun its voltage was not measurably affected.

In setting up the Mill 10 to 15 minutes were allowed after switching on for it to settle down. The calibrating box was then put over the Mill and earthed. With the detector balance control in about the mid position the phase shift control was adjusted for maximum deflection. (The unwanted voltage producing this deflection was found to be almost exactly in phase with the signal voltage.) If the phase shifter gave insufficient change of phase the screening plate on the Mill proper had to be rotated through a small angle relative to the shaft; this, of course, was only after the Mill had been partly dismantled for any reason. The balance control was then adjusted to return the galvanometer to its true zero. A voltage was then applied to the calibrating box, the equivalent field having been previously determined by an absolute calibration, and the gain adjusted to give the appropriate corresponding deflection. If the gain adjustment required was appreciable it was necessary to repeat the whole process in order to ensure that change from positive to negative sensitivities occurred at zero field. The apparatus was then ready for use.

4.15. ABSOLUTE CALIBRATION.

(a) "Home" Position.

The absolute calibration of the Field Mill was made by comparing the output of the Mill for a given voltage on the calibrating box with the relation between the output of the Mill for a given natural field and a direct measure of that field obtained with a stretched wire with fuse.

This was first done with the Mill in some arbitrary but precisely located position (which will be called the "home" position) in the field immediately adjoining the recording room and with the stretched wire nearby in the same field (see Fig 9). The stretched wire was about 20m long and about 70 or 80cm high at the fuse. It was insulated from its supports by polythene and connected by another stretched wire at about the same height to a length of polythene insulated coaxial cable which led to a quadrant electrometer in the recording room. A 2.5cm. diameter wire coil was slipped over the stretched wire and used as a cradle for the fuse which consisted of string impregnated with lead nitrate.

It was assumed that the potential measured by the electrometer was that at the height of the fuse. This height was taken as the average height over the length of the fuse, and was checked for each set of observations. In view of the marked non-linearity of the electrometer response it was calibrated at the beginning or the end of each set of observations, at 12v intervals. The voltages were derived from dry batteries and measured by a meter which agreed well with a sub-standard instrument. The zero and calibration deflections of the Mill were checked at about 20 minute intervals, periods during which a large change had occurred being rejected. The calibration voltage was derived and checked in the same way as the electrometer calibration voltage.

Readings of Field Mill galvanometer and quadrant electrometer were taken at half minute intervals. In view of the very slow response of the stretched wire it was not satisfactory to compare all pairs of readings. Instead only those readings were used at which the wire was believed to be at the potential of the surrounding air. To make clear what is meant by this it will be best to give an illustration.

Suppose the field, according to the Mill, is steadily rising and that the wire potential is also rising. There will then be some lag of wire potential on the potential of the air surrounding it. If, however, the field now begins to fall, the wire potential will continue to rise until it reaches the potential of the surrounding air and then begin to fall, as that potential falls, but lagging behind it. Similar considerations will apply in inverse conditions. Thus the wire may be regarded as giving a reliable value of the field at any clearly defined peak or trough.

31 such values were obtained distributed over 6 days. 15 of these gave values for the natural field equivalent to the artificial field produced by a given voltage on the calibrating box which were mutually consistent to better than 10 per cent. The remaining 16 gave much lower and widely scattered values. It seemed justifiable to disregard these as probably being due to leakage across the stretched wire insulators: a possibility which seemed to be confirmed by the fact that they were all obtained during mornings following fairly heavy dew and that where a number of values were obtained during one morning they increased systematically, probably as the insulators dried out.

The 15 values used were distributed over four days. It was decided to take the mean value for each day; since the fact that 8 values were obtained in quick succession on one day was quite fortuitous. A "best" straight line was fitted to these four means by the method of least squares giving the result that a change of 25v in the voltage applied to the calibrating box was equivalent to a change of field of 133 v/m and that 0v on the box corresponded to a field of -1 v/m. Since this zero error was rather less than the limits of accuracy of the experiment it was ignored in future use of the Mill.

It is to be noted here that McNish (62) issues a warning on the effect of space charge in determining exposure factors. However, he shows that if the space charge is uniformly distributed, the potential of the stretched wire divided by its height will give the field at half its height: about 35 to 40 cm in the present case. It seems reasonable to suppose, however, that space charge below the level of the face of the Mill (45cm) will not have much effect on it: being taller than it is wide air will tend to flow round it rather than over it. In that case the Mill should respond to the field at 45cm above the ground. Thus there should not be any great discrepancy between the two methods of measurement.

(b) Normal Operating Positions.

At about this time the Agrimeter in its final form became available; so, as calibration against a stretched wire is a long and tedious process, it was decided to calibrate the Agrimeter against the Mill (in the Home position) and then calibrate the Mill, in each of its standard operating positions (see Fig 9) against the Agrimeter.

The "North" position had a good exposure and the Mill was placed directly on the ground. The other three positions, however, were somewhat sheltered and in order to obtain a good exposure the Mill was stood on a stool so that its face was 1.07m from the ground. The four positions were marked so that they could accurately be reproduced: the Mill was always placed "facing" the base of the flying cable (the switch and plug box being regarded as the front); in the North position the centre of the back of the Mill was placed against a stake in the ground, in the South-East position a small arrow was painted on a kerbstone, marked "15 inches to centre" (of Mill), the South-South-West position (on the flat roof of the boiler house) and the West position (on a manhole cover) were marked by outlining the positions of the legs of the stool in paint. (The Home position was determined by placing the Mill, facing East, with the centre of its back against a stake in the ground.)

Simultaneous recordings were taken of both Agrimeter and Mill and mean values of deflection (as a percentage of the deflection for a given calibration voltage) were taken at one minute intervals, at least 80 such observations being obtained for each position of the Mill. The results generally showed a very close correlation even with 50m between the two instruments. On a few occasions a wide scatter was observed and these results were disregarded. The slope of the line relating Mill reading to Agrimeter reading showed very little variation from day to day for any one position but the zero discrepancy varied over a range of about 8 v/m and on one occasion in the West position was nearly 30 v/m.

This effect was first attributed to space charge but when a check was made by operating the Mill and Agrimeter close together with their collecting surfaces both in the plane of the ground the variation of zero discrepancy was found to be about the same. It was therefore attributed to variation of contact potential between the collecting surfaces and the calibrating box or plate surfaces of the two instruments. This check could not, of course, give any information on the way in which the variation was shared between the two instruments, but, since the Agrimeter and its calibrating plate were continuously exposed to the weather whereas the Mill and its calibrating box were rarely so exposed, it seemed safe to assume that less than half the variation arose in the Mill. Thus, in general, the zero error of the Mill due to this effect was which his work has contributed to the advancement of knowledge. He shall make a specific recommendation that the thesis be accepted or rejected. Where the recommendation is for rejection he may in exceptional circumstances recommend that the candidate be permitted to submit the thesis in a revised form. Any such further recommendation shall be accompanied by a full statement of reasons.

4. The examiner's report should be made on the appropriate form, which will be supplied by the Registrar.

5. The reports and recommendations of the examiners must be sent to the Registrar of the University who will lay them before the Dean of the Faculty concerned. If the examiners are agreed without qualification that the degree be awarded or not, the Dean may authorise the Registrar to publish the result or inform the candidate of his failure. If the examiners recommend that the thesis be submitted in a revised form, the Dean may authorise the re-submission to the same examiners, or may bring the matter before the Board of the Faculty. If there is doubt or disagreement, he shall bring the matter before the Board of the Faculty at its next meeting, and the Board after considering the reports, shall either recommend to Senate the appointment of a third Examiner or take such other action as it may deem appropriate. In all cases, the examiners' reports and recommendations shall be communicated to the Board of the Faculty concerned.

NOTE: With the concurrence of the Dean of the Faculty concerned the Oral Examination of a candidate for the degree of Ph.D. may be held elsewhere than at Durham or Newcastle. The expenses incurred by both Internal and External examiners in attending such an Oral Examination will be refunded by the University at the usual rates, if claimed from the Registrar. If the circumstances require it, the candidate's expenses will be refunded as well as the examiners'.

October, 1949

UNIVERSITY OF DURHAM

INSTRUCTIONS TO EXAMINERS FOR THE DEGREE OF PH.D.

One External Examiner and one Internal Examiner are ordinarily appointed for each candidate in the first instance.

1. In making their recommendations in regard to the award of the Ph.D. Degree, examiners should take into consideration both the extent and merit of the work submitted, together with the manner of its presentation. As to extent, the examiners should satisfy themselves that the candidate's work shows evidence of industry and application over a period of not less than six terms. As to merit, the candidate is expected to show distinct ability in conducting original investigations and in testing ideas whether his own or those of others. He is also expected to show understanding of the relationship of his special theme to a wider field of knowledge. His results should contribute a definite addition to knowledge, worthy of publication, although the thesis itself need not be submitted in a form suitable for publication. In the case of work done jointly or under direction, it is important that the extent of the candidate's own contribution shall be ascertained.

2. An oral examination of the candidate on the subject of his thesis and subjects related thereto will normally be held ; in exceptional circumstances the examiners may recommend that this be dispensed with. The grounds for this recommendation must be stated. The Examiners may, in addition, require the candidate to submit himself for a written examination.

3. Having considered all the evidence at his disposal each examiner shall present a written statement of his opinion concerning the candidate's performance and the manner in

probably quite small. However, had it been discovered earlier than just before the completion of the observations, it would have been worth using a nickel plated calibrating box.

In most cases it was evident that the change of zero discrepancy over the period of observations for any one position of the Mill was negligible. In the West position, however, different sets of observations were fairly widely separated in time and it was evident that there was some change of zero discrepancy between the sets. Accordingly these sets were treated separately: the "best" straight line relating Agrimeter reading to Mill reading, was determined by the method of least squares for each set and the mean slope taken as the true value. A similar procedure was followed for the other positions of the Mill except that all the observations for each position were treated together.

The calibration figures obtained are listed below:

North	position:	49v	on	cal.	box	corresponds	to	234v/m
S.E.	"	36v	"	"	"	"	"	258v/m
S.S.W.	"	10v	"	"	"	"	"	234v/m
West	"	36v	"	"	"	"	"	247v/m

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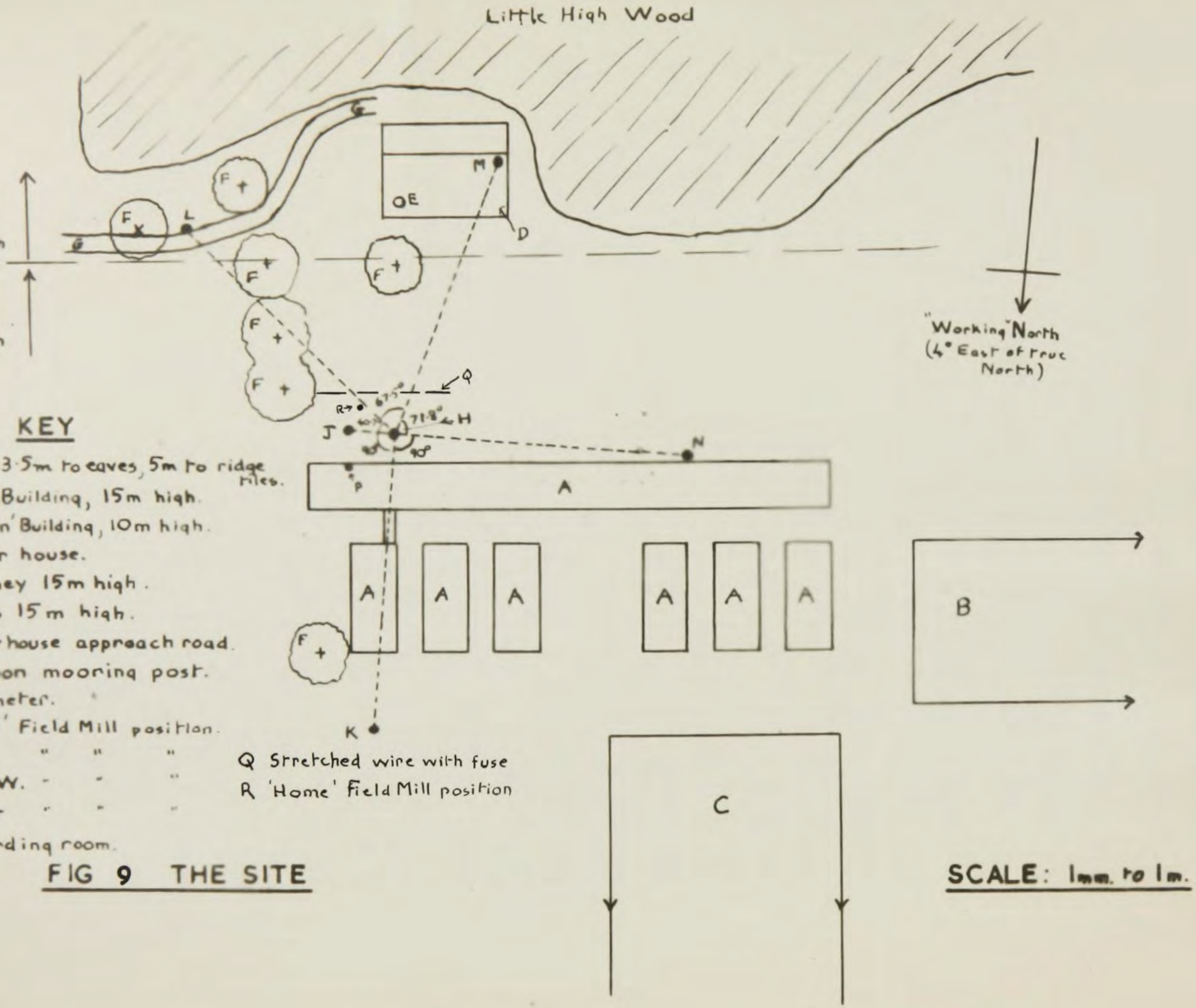

KEY

A Huts, 3·5m to eaves, 5m to ridge tiles.
B 'West' Building, 15m high.
C 'Dawson' Building, 10m high.
D Boiler house.
E Chimney 15m high.
F Trees 15m high.
GG Boilerhouse approach road.
H Balloon mooring post.
J Agrimeter.
K 'North' Field Mill position.
L S.E. " " "
M S.S.W. " " "
N West " " "
Recording room.

Q Stretched wire with fuse
R 'Home' Field Mill position

FIG 9 THE SITE

SCALE: 1mm. to 1m.

FIG. 10 (left) THE SITE, LOOKING SSW.

Second neck (with discharge point attached - not distinguishable in this photograph)

FIG. 11 (below) THE SITE, LOOKING WEST.

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FIG. 12 (left) THE SITE, LOOKING NW.

FIG. 13 (right) THE SITE, LOOKING NNE.

Second neck
(without discharge
point.)

Cup anemometer

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FIG. 14 (above) THE SITE, LOOKING NORTH-EAST.

FIG. 15 (below) THE SITE, LOOKING EAST-SOUTH-EAST.

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4.16. OVERALL PERFORMANCE.

The combined effect of zero drift in the Mill proper, the detector and the galvanometer rendered it necessary to make zero and calibration checks every half hour. Then the zero and sensitivity rarely changed by more than 2.5 v/m between checks (for fields up to 250 v/m) so that in that sense the accuracy requirements were fulfilled. There may, however, have been some systematic error in the calibration since the stretched wire with fuse which was used as a standard was not very well exposed; its exposure can be judged from the plan and photographs of the site, Figs 9 - 15. It seems possible, therefore, that all the measurements of field were a few per cent low and this must be borne in mind in interpreting the results.

While the Mill operated quite satisfactorily in damp conditions or during light drizzle, light rain soon broke down the insulation between the studs and the aluminium plate which covered the Tufnol end plate. However, only on one occasion was this the main factor militating against a balloon ascent.

The high exposure factor for the home, North and South-East positions necessitated the use of the lowest gain range of the amplifier for fields up to 250 v/m so that to cover fields up to 500 v/m a lower gain range was needed. However, fields greater than 250 v/m were not encountered during the use of the Mill and the necessary modification was never actually carried out.

Apart from the limitations just noted the Mill fulfilled all its requirements.

CHAPTER 5. OTHER APPARATUS.

5.1. APPARATUS FOR SUPPORTING THE POINT.

(a) The Balloons.

At the start of the work a number of spherical rubber balloons of an obsolete pattern were available and use was naturally made of them. They weighed 1200gm and had two necks. It was clear that in order to permit their use in as high a wind speed as possible they should be inflated as fully as possible -- lift being proportional to the cube of the diameter and drag to the square. Initial tests suggested that a diameter of 9 feet would be satisfactory but when the limited life of this type of balloon was discovered it was decided to restrict the diameter to about 7 feet.

It was unfortunate that this feature of limited life was not discovered sooner as most of the original supply of balloons was damaged through careless storage and handling. In fact almost any attempt at "testing" a rubber balloon is sure to reduce its life considerably.

For the later work new balloons were purchased, weighing 700 grams and provided with two necks. Great care was taken in their storage and handling: on receipt of a consignment the box was opened to check the quantity but the individual cellophane wrappings were left untouched; if none of the balloons was required immediately the box was resealed with cellulose tape and in any event they were stored in a small dark room to protect them from air and light as far as possible.

Amongst the first two orders for the new balloons some orange coloured specimens were included. Although they were about twice the price of "natural" coloured balloons the manufacturers estimated that they would have about four times the life (8 hours instead of 2). In practice, however, it was found that both types had a life of about 2 hours in warm weather with sunshine, although some of the natural balloons which were used in cold cloudy weather lasted as long as 20 or 30 hours.

The use of a rubber balloon leaves much to be desired, of course, because of the possibility of considerable charges accumulating on the rubber. However, it did not seem possible to avoid this effect: if a conducting paint were applied to the balloon before inflation it would crack off as the balloon expanded; if it were applied after inflation valuable balloon life would be wasted and in either case the oil in the paint would probably hasten the decay of the rubber. If a cloth cover, sprayed with conducting paint, were used it would reduce the lift and probably abrade the surface of the balloon running the risk of reducing the life and possibly even setting fire to it.

Hydrogen was the obvious choice for the filling gas, coal gas being cheap but too heavy and helium too expensive. One standard (165 cu. ft.) cylinder was used for each balloon giving a diameter of approximately 2 metres and a gross lift of about 5.2Kg.

(b) Method of Attaching Point to Balloon.

It is desirable for the discharge point to be fixed above the balloon rather than below and in order to achieve this a string cage was made. However it was very difficult to get this into position during inflation and the method was abandoned in favour of clamping the point to the second neck of the balloon, which was suitably stiffened by the insertion of a cardboard tube stopped up with a rubber bung. This was rarely diametrically opposite to the holding neck because, on inflation, one side of the balloon invariably expanded more than the other, but the point was nearly always somewhere between horizontal and pointing vertically upwards. Some idea of the arrangement can be obtained from Figs. 10 and 13.

The current carrying wire was originally allowed to hang direct from the second neck of the balloon but on one occasion (3/7/52) this led to the discharge point being pulled over and puncturing the balloon while it was still on the ground. Consequently, for subsequent experiments, the current wire was also tied to the lower neck of the balloon to take most of its weight there. As an additional protection a guard plate (A Fig. 16) was constructed to prevent the upper neck bending over. This consisted of a tin plate disk about 20 cm in diameter with the edge bent over slightly. A hole was broken through the centre of the disk and the flaps so produced soldered to the inside of a short brass tube. The whole was then slipped over the neck of the balloon below the clamp for the point.

(c) The Flying Cable.

Cord was chosen for the flying cable in preference to wire rope as it could be handled more easily and obviated the necessity for a winch.

A few samples of whipcord and fishing line were tested, a "heavy" whipcord being finally selected. (In passing it is interesting to muse on the implications of the discovery that some of the fishing line samples broke at appreciably less than the stated breaking strain!)

The heavy whipcord had a weight of 3.1gm/m dry and 5.3gm/m wet, Its electrical resistance was 4000M/m dry and 5M/m wet, and its breaking strain was about 35Kg. Thus the weight was moderate, it could be regarded as an electrical insulator and, since the net lift of the balloon was about 4Kg, the breaking strain provided a reasonable safety factor. The cable did break on two occasions, one while the balloon was unattended and the other at a sudden jerk when the cable was at about 70° to the vertical.

At one time the use of three flying cables, brought down to an equilateral triangular base, was favoured in view of the greater stability it would give to the balloon. It was soon realised, however, that with the small base dictated by the restricted nature of the site, the advantage would be limited to very low wind speeds. Accordingly a single cable was finally used. This had the additional advantage that its declination provided a convenient measure of wind speed.

In the early part of the work, when the balloon was flying, the flying cable was tied to a metal rod secured to the sandbags to which the balloon was tethered during inflation and when not in use. This provided a certain "springiness" in the bottom fixing of the flying cable which reduced the impulse strain to which it was subjected on sudden changes of wind; on the other hand it made measurement of the declination of the cable difficult because the lower end was continually jumping about. When the extent of the cable charge effect was realised and it became desirable to get the flying cable and current wire close together the flying cable was tied to a cleat screwed to the post which carried the current wire drum.

The surplus cable was stored by coiling it roughly round a post fixed in the middle of a wooden tray. This usually avoided any tangling of the cable and was much easier to make than a winch. Certainly a winch would have made operation somewhat easier but no great difficulty was experienced in handling the cable direct and this method had the advantage that if a high wind sprang up while the balloon was flying it could be "played" as it was hauled in, thereby reducing the danger of breaking the cable.

5.2. THE DISCHARGE POINT AND ITS CONNECTION TO EARTH.

(a) Construction of Single Point.

The single discharge point consisted of about 40 cm of 12 gauge copper wire with a piece of 0.25 mm diameter platinum wire soldered into the end so that it projected about 2mm beyond the end of the copper. The base of the copper wire was soldered into a brass block which was clamped to the upper neck of the balloon. No special attention was paid to the exact shape of the point although some very sharp corners arose naturally in cutting the platinum wire.

On the two occasions when the balloon broke away new points had to be constructed, of course, but these followed the design of the original point as closely as

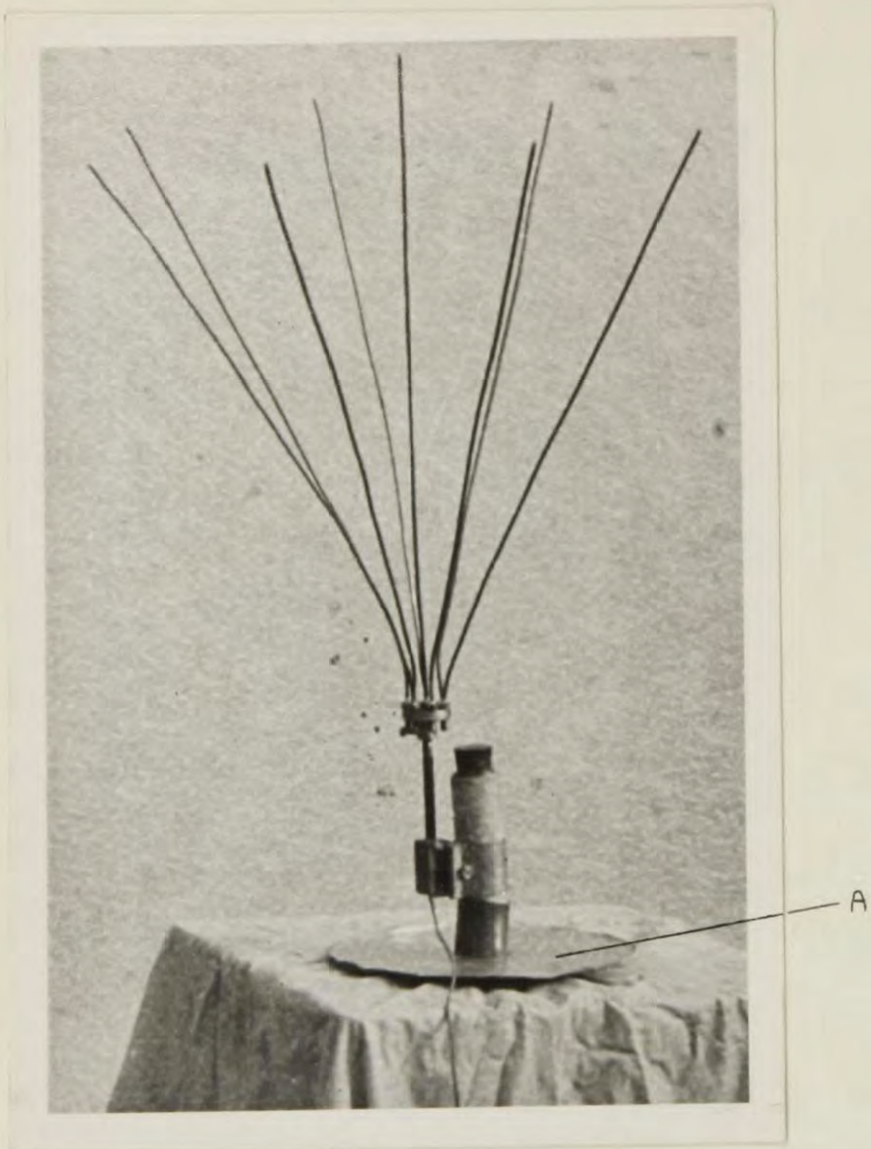

FIG. 16 THE MULTIPLE DISCHARGER.

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possible. Since the platinum wire was always of the same diameter and always cut with a pair of wire cutters it seems unlikely that any serious differences existed between one point and another and the results showed no discrepancy that could be attributed to any change in the nature of the point.

(b) Construction of Multiple Point. (Fig 16)

The individual points in the multiple array were essentially similar except that the bottom of each copper wire was soldered into a 2 B A screw. They could then be quickly screwed into tapped holes in a small brass disk clamped to the upper neck of the balloon. Provision was made for the use of up to 8 points. When all 8 were used they were arranged so that the tips of 7 of them formed an approximately regular polygon of side 15 cm with the eighth point in the centre about 17 cm from each of the others.

(c) The Current Carrying Wire and its Control. (Fig 17)

The current carrying wire usually consisted mainly of 26 gauge copper wire either cotton or enamel insulated. (No significance is to be attached to the type of insulation or even to its presence it was merely a case of using wire which was readily available and to which there seemed to be no objection.) 28 gauge wire was used in the first few ascents but this frequently broke. No trouble with breaking was experienced with the 26 gauge wire. The top three metres of so consisted of 14/.0076

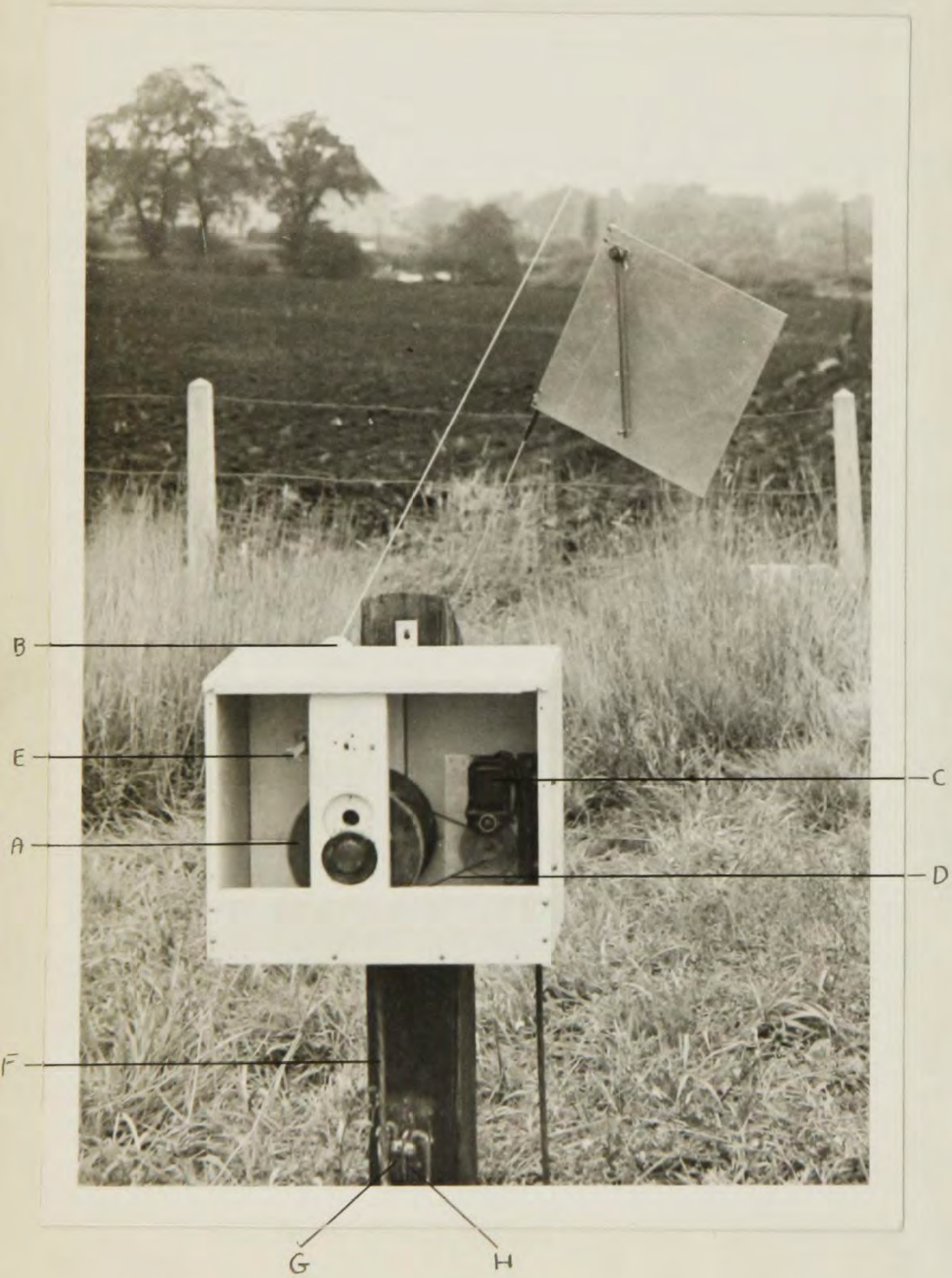

FIG. 17 WIRE DRUM CONTROL AND PROTRACTOR.

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rubber covered flexible. This satisfactorily prevented breaking at the place where it was fixed to the point clamp and also reduced the risk of the wire cutting into the balloon.

The wire was stored on a 7lb wire reel (A) mounted on an axle in a box which could be clipped onto a post securely embedded in the ground just outside the laboratory. It was fed out through a perspex insulator (B) in the top of the box so that as the flying cable was paid out the wire unwound itself from the drum. To haul in the wire during the descent of the balloon a small 12v motor (C) was coupled to the drum by a slack rubber belt drive (D) so that it could not put too much tension on the wire. A perspex guide was provided inside the box, which could be pushed to and fro by a brass rod (E) in order to wind the wire evenly onto the drum. The drum was insulated from its axle by ebonite. The end of the current wire was soldered to a copper slip ring on the side of the drum. The sliding contact of phosphor bronze which pressed on this was insulated from the box by ebonite and connected to a short length of rubber covered flexible (F) terminating in a commercial 5 amp 2 pin plug. A 5 amp 2 pin socket (G) was mounted on the post supporting the box and connected by underground armoured lead covered cable to the recording room where it was connected through the galvanometer to earth. The power supply to the motor was provided in a similar fashion: lead covered cable going from the laboratory to the post where it terminated in a second two pin 5 amp socket (H). Both these were protected from the weather by inverting a tin can over them (not shown in Fig. 17) and from insects by liberally dusting them and the inside of the can with "D.D.T."

The operation of this system was most satisfactory although a useful refinement would have been to arrange for the motor to impart a reciprocating motion to the wire guide so that it would have been fully automatic. The leakage resistance to earth was periodically checked and was always found to be much greater than the galvanometer resistance.

5.3. MEASUREMENT OF POINT DISCHARGE CURRENT.

The mirror galvanometer used for the measurement of point discharge current was a simple robust instrument which was critically damped by a shunt resistance of 120 ohms. Two sensitivities were obtained by applying the point discharge current between one terminal of the galvanometer and two different positions on the shunt. "High" sensitivity gave a deflection of about 1 cm per μa at 1 m and "low" sensitivity about 3 mm per μa at 1m.

The galvanometer was calibrated by connecting it in series with a 1.5v cell and a 900K resistor. In general the sensitivity was found to be extremely stable, but for a short time the behaviour became somewhat erratic. This fault, which was traced to a dry joint in the shunting network, necessitated the rejection of a few periods of recording in which there was a wide variation of sensitivity between successive calibration checks.

The stability of the galvanometer zero was good, never changing by more than 0.5 mm between successive checks. In some of the early experiments there was a small steady deflection when the galvanometer was connected to the point with the balloon on the ground and this was taken as the current zero in these cases. This effect did not occur in any of the later records.

Thus with one or two minor exceptions the point discharge current could be measured to the nearest 0.05μa on "high" sensitivity and 0.15μa on "low" sensitivity.

5.4. MEASUREMENT OF ELECTRIC FIELD.

As has already been explained (section 3.5(c)), the Agrimeter of Dr. Chalmers was used as one of the field measuring instruments (that near the base of the flying cable) in the later experiments and in the earlier experiments it provided an exclusive measure of field. Since it is to be fully described in a paper by Dr.

Chalmers (14) it will be sufficient here to note its performance in so far as that concerned the present investigation.

The Agrimeter underwent a number of modifications during the period covered by the experiments. The final arrangement, which was in use for the expeiments in which two field measuring instruments were operated, was most satisfactory. The instrument had a sensitivity of about 0.5 mm per v/m and the zero and sensitivity were, with one or two minor exceptions, sufficiently stable for measurement of field to be accurate to the nearest 2 v/m. The absolute calibration was subject to the same errors as that of the Field Mill.

The actual figures for calibration were: 12.2v on the calibrating plate corresponded to a field of 167v/m, and later, after a slight rearrangement 133 v/m.

The earlier arrangements of the Agrimeter were rather less satisfactory. The sensitivity was much lower, slightly less than 0.1mm per v/m, and drift of zero and sensitivity were sometimes considerable. The measurement of field was usually calculated to the nearest 5 v/m but random errors of 5 or 10 v/m were often probable due to these causes. In addition, since the absolute calibration of these earlier arrangements was not done so thoroughly as in the case of the final arrangement, systematic errors of 10 per cent, or even more, are quite probable. These errors will have to be borne in mind in interpreting the results of the earlier experiments.

The Mill, which was used for field measurement remote from the base of the flying cable has already been described in detail in Chapter 4.

5.5. MEASUREMENT OF WIND SPEED.

(a) Method.

The most reliable method of measuring wind speed at the balloon would be to attach an anemometer just below it and connect it to some indicating device on the ground but to do this while the discharge point and its wire were being supported by the balloon would involve a serious loss in lift.

An alternative method would be to measure the declination of the flying cable and determine the relation between declination and wind speed at the balloon. This method has the merit that in use it will not interfere with the balloon at all and that the measurement of the declination of the balloon can be used in determining its height from moment to moment when the length of the flying cable is known. The difficulty lies in determining the relation between declination and wind speed, and a source of error lies in the fact that different specimens of the same type of balloon have different drags: the Meteorological Office find that the rate of ascent of balloons inflated to give the same free lift may vary by ± 15 per cent for different specimens.

A further source of error lies in the fact that no special precautions were taken to ensure that every balloon had the same lift. However, although the filling in each case was simply "one cylinder of hydrogen", the internal volume can hardly be expected to vary much from cylinder to cylinder and the pressure when full was found to vary over a range of less than 10 per cent. Now since lift will vary with the cube of the diameter of the balloon while drag will vary with the square the overall variation of lift/drag ratio probably did not exceed 3 per cent.

On balance the latter method seemed preferable since it would be simpler in operation and its low accuracy would not be a serious defect.

An attempt to calculate the declination-wind speed relation from relationships and experimental results quoted by Goldstein (32) gave values of the declination for a given wind speed which were obviously much too low -- by a factor of 2 or 3. Why this was so is by no means clear but it had to be accepted and the relation determined experimentally.

This was done by making a balloon ascent especially for the purpose, without the discharge point but with a very light cup anemometer attached about 3m below the balloon (see Fig. 13). Simultaneous recordings were taken of declination and wind speed according to the anemometer and the relationship determined by comparing the two sets of readings.

(b) Calibration of Cup Anemometer.

The anemometer used was actually a "wind mill" from a radio-sonde. Since it is normally used merely to drive a rotary switch it has not been calibrated as an anemometer. This necessary preliminary task was carried out at Durham University Observatory.

The cup anemometer was clamped to the mast supporting the Dines pressure tube anemometer, about 2m below the top and its centre stood about 40cm clear of the centre of the mast so that its exposure approximated to that of the Dines instrument.

The anemometer operates a switch, opening and closing it once every 20 revolutions. this was connected by twin flex to a battery and relay situated in the room containing the Dines chart. The noise of the relay opening and closing served as an indicator of the motion of the cup anemometer. The time of each contact, and the simultaneous reading of the Dines instrument were noted over a period of three and a half hours covering a range from 2 to 30 km/hr. The number of contacts per minute was calculated for each minute and plotted against mean wind speed for the same periods. There was a fair degree of scatter in the results but no suggestion of anything other than a linear relation. As this is normal for cup anemometers the"best"straight line was determined by the method of least squares and gave the relationship:

$$V = 2.76N - 3.86$$

where V = wind velocity in km/hr.

N = number of contacts per minute.

Standard errors were not calculated but they may safely be assumed to be small.

The zero discrepancy is a little surprising and may be explained either by a sudden drop in cup anemometer response below 2 km/hr(the points on the graph were still fairly evenly distributed about the straight line at this lowest recorded wind speed) or that there is a zero error in the Dines anemometer. The latter explanation is most improbable since the zero error is checked each day as part of the routine procedure. Accordingly the formula quoted above was assumed to be correct.

(c) Calibration of Cable Angle in terms of Wind Speed.

An essentially similar procedure was adopted for this calibration. The anemometer was fixed to the cable, about 3m below the balloon, by means of a light balsa wood framework so that its axis of rotation was at about 15^{o} to the cable, thereby approximately minimising errors due to the axis of rotation not being perpendicular to the wind direction. The normal discharge current carrying wire, supplemented by a second, cotton covered, wire of 28 S.W.G., served to connect the anemometer switch to the ground.

For the measurement of cable angle a protractor was constructed from a sheet of aluminium about 20cm square, which clipped onto the flying cable and carried a freely swinging pointer (see Fig 17). The weight of the protractor was such that when the balloon was vertically overhead -- a condition which was made evident by the way the protractor as a whole idled in the horizontal plane -- the protractor reading was 4^{o}. At all declinations, at least up to 40^{o}, it was found, by sighting along the protractor arm, the protractor overestimated the declination of the balloon by about 4^{o}. In the calibration processes, however, as in all normal point discharge experiments, the protractor reading was noted, due account being taken where necessary of this 4^{o} error.

The experiment was performed twice, using different balloons. In the first experiment the procedure was as follows.

The balloon was flown from a 50m length of cable the total load being 1.25Kg and the net lift therefore 3.95Kg. Audible indication of the making and breaking of the anemometer switch contact was given by connecting it in series with a relay and d.c. supply.

The time of each anemometer contact and the protractor reading at the time of each contact were noted over a period of two hours covering a range of protractor reading from 4° to 40°. The average wind speed (deduced from the number of conacts per minute) for each minute was plotted against average protractor reading for the same periods.

There was a considerable degree of scatter in the results but, surprisingly enough, no clear suggestion of curvature. In making a statistical analysis of the results it was decided to neglect readings for protractor readings of less than 12°. This was necessitated by clear evidence of overestimation of cable angle below this value due to the fact that the slight gustiness of the wind increased the chance of a contact occuring when the protractor reading was high. In view of this it was decided to make the calculated curve pass through the origin: zero wind speed; 4° protractor reading. It was decided to work with tan(protractor reading - 4°) i.e. drag/lift, rather than protractor reading, as drag is clearly a more fundamental parameter. By this means it was hoped that extrapolation beyond 40^{o} would be less subject to error.

First and second order curves were fitted giving

$y = 0.0328x$

and $y = 0.0282x + 0.00034x^2$

where $y = \tan$ (protractor reading - 4^{o})

x = wind speed in km/hr (derived from cup anemometer calibration).

Standard errors were not calculated but they can safely be assumed to be small.

In the second experiment the procedure was similar except for the following particulars. The balloon was flown from a 100m length of cable, the total load being 1.62Kg and the net lift therefore 3.58Kg. An a.c. supply and headphones were used to indicate the movement of the anemometer. A second observer was available so while one noted the time of each anemometer contact the other noted quarter minute averages of protractor reading thereby eliminating the overestimation of small protractor readings which occured in the first experiment.

Observations covering a range of protractor readings from 4^{o} to 27^{o} were made for a period of 45 minutes soon after the balloon had been inflated. About two hours later observations were made for a further 8 minutes, immediately before the balloon burst, covering a range of protractor reading from 11^{o} to 16^{o}.

In view of the small range covered by these results it was decided to fit to them a curve of the form $y = a(x + cx^2)$ where c (= 0.00034/0.0282) was derived from the results of the previous calibration. This procedure was adopted because it was considered that the previous calibration gave the most reliable value for the degree of curvature of the "best" line and that by fitting a curve of this form to the two new sets of data any change in the general slope of the line would become apparent.

The equations obtained from the second experiment were: $y = a''(x + cx^2)$ where $a''=0.0258$ for the first set of observations,

and $y = a'''(x + cx^2)$ where $a'''=0.0314$ for the second set of observations,

to be compared with the equation

$y = a'(x + cx^2)$ where $a'=0.0310$ for the first experiment after correcting it to the reduced lift of the second experiment.

As before $y = \tan(\text{protractor reading} - 4^{o})$

x = wind speed in km/hr

On testing the significances of the differences $a''-a'$ and $a'''-a'$ it was found that the value a'', derived from 44 observations, would arise by chance from a true value a' only once in a thousand times, but that a'''

derived from 8 observations, would arise nine times out of ten. Thus there is a significant difference between a" and a' but not between a"' and a'.

Now the value of a" was obtained from the second experiment when the balloon was of "good" shape -- very nearly a true sphere -- while a"' was obtained when the balloon was of "poor" shape -- considerably distorted from a true sphere. Further, the balloon used in the first experiment, when the value a' was obtained, was of "poor" shape for the whole of its life. Thus it appears that the drag of the balloon increases as its shape deviates from a true sphere. Since notes were kept of the shape of each balloon used in the point discharge ascents it would have been possible to estimate a correction to the mean drag but it was felt that such a correction would be small and not very reliable and hence the complication introduced would not be justified.

It was finally decided to adopt a value of a of 0.0284 (the mean of a" and a') so that the observed values were within 10 per cent of the adopted value. The fact that the Meteorological Office find a variation of 30 per cent in drag suggests that in exceptional cases there may be a deviation of 20 per cent in one direction from the adopted value though it seems more likely that the errors will be more evenly balanced giving a maximum

TABLE IV

Nominal height of balloon (m)	Net lift (Kg)	Equation
50	3.92	$y = 0.0259(x + 0.0121x^2)$
100	3.69	$y = 0.0275(x + 0.0121x^2)$
150	3.46	$y = 0.0293(x + 0.0121x^2)$
200	3.23	$y = 0.0314(x + 0.0121x^2)$

$y = \tan(\text{protractor reading} - 4^\circ)$

x = wind speed in km/hr.

When the 8 point discharger is used the lift is reduced by 0.29 Kg which is approximately the same as raising the balloon by 50m.

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deviation of not much more than 15 per cent in either direction. There will also be asmall error due to variation in the lift of the balloon as explained in section 5.5(a).

The adopted value of a was then corrected for the net lift of the balloon under normal operating conditions giving the equations shown in Table IV. From these equations the values given in Table V were calculated.

5.6. MEASUREMENT OF HEIGHT OF POINT.

The height of the point was very easily determined by making the flying cable into a sort of tape measure. Before it had been used it was put under a small but constant tension and marked off in one metre lengths by blobs of ink. Bands of colour were then painted round the cable adjacent to each ink mark using one band for each digit in the number of the metre length and allotting the colours the same significance as used in the resistor colour code. The effect of various tensions on a few sections was tested and it was found that over the range 4 to 8 Kg (corresponding to declinations of about 0^o to 60^o) the length of each "metre" section was fairly constant at 105cm. In use, then, the length according to the colour coding was increased by 5 per cent before noting it down, and a further 3m were added to allow for

TABLE V

Protractor reading (degrees)	Nominal Ht:- 50m		Nominal Ht:- 100m		Nominal Ht:- 150m		Nominal Ht:- 200m	
	Wind speed (km/hr)	Ht. (m)	Wind speed (km/hr)	Ht. (m)	Wind speed (km/hr)	Ht. (m)	Wind speed (km/hr)	Ht. (m)
4	0.0	52.5	0.0	105	0.0	157.5	0.0	210
5	0.5	52.5	0.5	105	0.5	157.5	0.5	210
6	1.5	52.5	1.0	105	1.0	157.5	1.0	210
7	2.0	52.5	2.0	105	2.0	157.5	1.5	210
8	2.5	52.5	2.5	105	2.5	157.5	2.0	210
9	3.0	52.5	3.0	105	3.0	157.5	2.5	210
10	4.0	52.0	3.5	104	3.5	156.0	3.0	208
11	4.5	52.0	4.0	104	4.0	156.0	3.5	208
12	5.0	52.0	5.0	104	4.5	156.0	4.0	208
13	5.5	52.0	5.5	104	5.0	156.0	4.5	208
14	6.5	51.5	6.0	103	5.5	154.5	5.0	206
15	7.0	51.5	6.5	103	6.0	154.5	5.5	206
16	7.5	51.5	7.0	103	6.5	154.5	6.0	206
17	8.0	51.0	7.5	102	7.0	153.0	6.5	204
18	8.5	51.0	8.0	102	8.0	153.0	7.0	204
19	9.5	50.5	9.0	101	8.5	151.5	8.0	202
20	10.0	50.5	9.5	101	9.0	151.5	8.5	202
21	10.5	50.0	10.0	100	9.5	150.0	9.0	200
22	11.0	50.0	10.5	100	10.0	150.0	9.5	200
23	11.5	49.5	11.0	99	10.5	148.5	10.0	198
24	12.0	49.5	11.5	99	11.0	148.5	10.0	198
25	13.0	49.0	12.0	98	11.5	147.0	10.5	196
26	13.5	48.5	13.0	97	12.0	145.5	11.0	194
27	14.0	48.5	13.5	97	12.5	145.5	11.5	194
28	14.5	48.0	14.0	96	13.0	144.0	12.0	192
29	15.0	47.5	14.5	95	13.5	142.5	13.0	190
30	16.0	47.0	15.0	94	14.0	141.0	13.5	188
31	16.5	46.5	15.5	93	14.5	139.5	14.0	186
32	17.0	46.5	16.0	93	15.5	139.5	14.5	186
33	17.5	46.0	16.5	92	16.0	138.0	15.0	184
34	18.5	45.5	17.5	91	16.5	136.5	15.5	182
35	19.0	45.0	18.0	90	17.0	135.0	16.0	180
36	19.5	44.5	18.5	89	17.5	133.5	16.5	178
37	20.0	44.0	19.0	88	18.0	132.0	17.0	176
38	21.0	43.5	19.5	87	18.5	130.5	17.5	174
39	21.5	43.0	20.5	86	19.5	129.0	18.0	172
40	22.0	42.5	21.0	85	20.0	127.5	19.0	170
41	23.0	42.0	21.5	84	20.5	126.0	19.5	168
42	23.5	41.5	22.0	83	21.0	124.5	20.0	166
43	24.0	41.0	23.0	82	22.0	123.0	20.5	164
44	25.0	40.5	23.5	81	22.5	121.5	21.0	162
45	25.5	39.5	24.5	79	23.0	118.5	22.0	158

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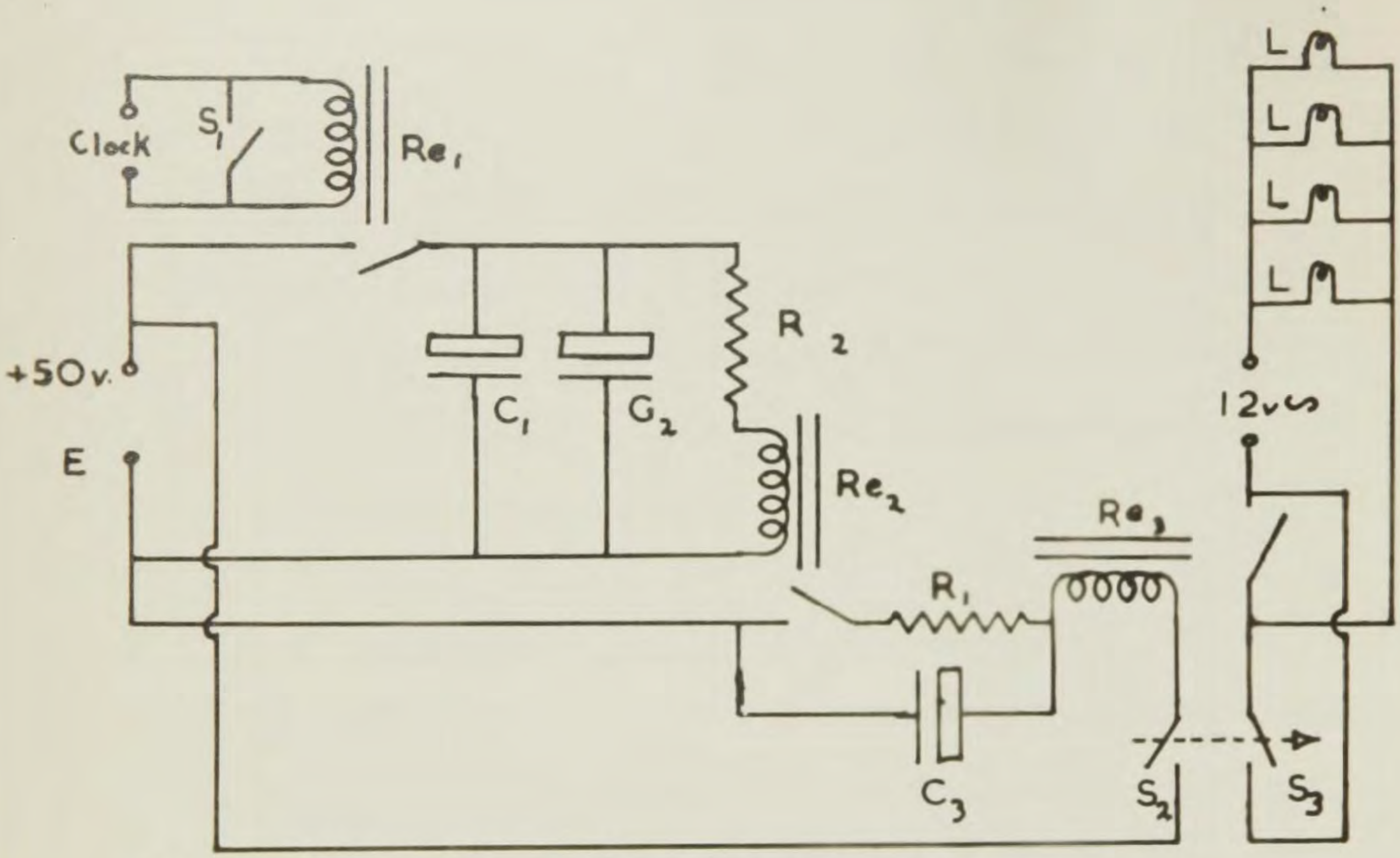
the height of the point above the top of the cable and the height of the tying point of the bottom of the cable above the ground.

The height was then obtained by multiplying the distance between ground and point so determined by the cosine of the declination (protractor reading - 4^o) of the balloon. The values are shown in Table V.

5.7. THE RECORDING SYSTEM.

Point discharge current and the outputs of the Field Mill and Agrimeter were all passed through mirror galvanometers and recorded photographically. All three galvanometers were mounted on a pillar with independent foundation in the recording room. The galvanometers and lamps were adjusted to feed all three beams onto one camera. This was electrically driven with a paper speed of about 2.5 cm per minute. The cylindrical lens had a millimetre and centimetre scale etched on it which, by means of a fogging lamp was reproduced on the record greatly facilitating measurement of deflections. In order to facilitate measurement of time the supply to the galvanometer and fogging lamps was interrupted for about 2 secs every half minute by means of a relay system (Fig. 18) worked from the laboratory electric pulse clock system. This enabled the three traces to be accurately



R_1	100 Ω	Re_1	4 Ω	C_1	60 μF
R_2	4·7 K	Re_2	2 K	C_2	32 μF
L	Galvo. lamps	Re_3	100 Ω	C_3	32 μF

FIG 18 TIME MARKER SYSTEM

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synchronised with each other and with visual observations of cable angle and wind direction.

The camera worked reasonably satisfactorily except that the paper sometimes drifted well to one side of the rollers so that part of the trace was lost, and sometimes the "used" spool tended to drag the paper through the driving rollers and produce unequal speeds. However, once the time marking system was in operation this was no serious fault.

In the earliest records a clockwork driven drum camera was used which had neither of these disadvantages -- but none of the more useful refinements of the electrically driven instrument.

5.8. THE SITE AND DISTRIBUTION OF APPARATUS.

Some deprecatory remarks have been made about the site in previous sections and its nature will be apparent from the photographs of Figures 10 - 15 and the plan of Figure 9. It will be noted that the various positions in which the Field Mill was operated were by no means all at the same height and this must be borne in mind in interpreting the results if the indirect method of determining the undisturbed field is used.

CHAPTER 6. EXPERIMENTAL PROCEDURE

6.1. SPECIAL ACKNOWLEDGEMENT.

Special mention must be made at the start of this chapter of the very great help given in the experimental work by the author's supervisor, Dr. J. A. Chalmers. He normally attended to the Agrimeter, the point discharge galvanometer, the camera and the development and fixing of the records, together with a great deal of help in various minor details. In addition to the obvious benefits of this assistance it helped greatly in making the best use of the limited life of the balloons.

6.2. DECISION TO MAKE A BALLOON ASCENT.

A necessary preliminary to the flying of captive balloons is to obtain the permission of the Ministry of Civil Aviation. Initially this was freely given for periods of three months at a time (for flying up to 200m), except in "storm and tempest" or poor visibility. Permission was also granted for flying up to 100m in fog. Later, however, the condition was imposed that for flying at heights greater then 100m 24 hours notice had to be given to Air Traffic Control, Preston (Civil Aeronautical Information Services Department).

Once permission to fly had been obtained the chief restriction, assuming that all the apparatus was serviceable, lay in wind speed. It was found from experience that if the declination exceeded about 40^{o} (equivalent wind 20 km/hr) there was a danger of the flying cable breaking. It was usually found that if the surface wind did not exceed about 10 km/hr (6 knots) by 10 a.m. the wind speed at the height of the balloon would not exceed 20 km/hr during the day. Exceptions did occur, of course; sometimes an ascent had to be abandoned just before the balloon was filled, once the balloon was grounded for a time as a safety measure, and on two occasions the balloon broke away. In general, however, a low wind speed up to about 10 a.m. was an adequate guide to the suitability of the day for an ascent.

Although the Daily Weather Report of the Meteorological Office was taken the latest information it contained was 24 hours old when it was received and therefore not very useful.

Unless the meteorological conditions were markedly anticyclonic it was not found possible to predict wind speed 24 hours ahead from local observation or from weather forecasts transmitted by the B.B.C. In the later work, therefore, when it was desired to operate above 100m, recourse was had to the Meteorological Section of Royal Air Force, Middleton St. George. Their 24 hour forecasts of wind speed were very helpful and usually quite accurate. In fact, when their usefulness was fully appreciated, it became customary to ask them for a six hour forecast on any morning which appeared to promise suitable conditions for an ascent.

6.3. PREPARATION FOR AN ASCENT.

Once it had been decided to make an ascent the first thing to determine was where to operate the Mill. This, of course, had to be to windward of the balloon and it was found that the best guide to wind direction at the height of the balloon was the direction of movement of low cloud. If there was no low cloud it was necessary to rely on surface wind or a forecast from Middleton St. George. Placing the Field Mill in the right position was most important; if it was more than $\pi/2$ off windward its readings were seriously affected by cable charge and point space charge effects; if its position was changed after the balloon had been inflated about half an hour of valuable balloon life was wasted.

Having decided on the position, the Field Mill was set out and the cables connected. These were normally left in the position last used, with a piece of balloon rubber wrapped over the plugs. Battery voltages were checked and the batteries were replaced if necessary; the apparatus was switched on and allowed to settle down while the other preparations were completed. Any adjustments of phase shift, balance and gain controls that were necessary were made just before inflation of the balloon. Sometime during the day the voltage of the battery supplying the calibration field was measured and noted.

The other preparations consisted in setting out in their appropriate positions the box containing the wire drum, the flying cable, protractor, sand bags, some sheets of used balloon rubber to protect the balloon from the ground, hydrogen cylinder, reducing valve, etc., and in preparing the balloon itself. For this a cardboard tube was inserted in each neck; a holding loop of tape being bound onto the lower one and the guard plate and discharge point being clamped to the upper one which was also bound with string and firmly stoppered. The balloon was then firmly tethered to the sandbags by rope and the flying cable and current wire attached, both being left slack.

The balloon was inflated to about one third full and then examined for leaks. On the two occasions when a leak was found the balloon was deflated and another hastily prepared, but in view of the satisfactoriness of an attempt at subsequent patching of the second of these balloons it was decided that it would be quite practical to repair a leak, with rubber solution and a piece of old balloon rubber, on the partly inflated balloon. Inflation was continued until a full cylinder had been emptied into the balloon, the total time of inflation, excluding any delay over leaks, being kept at the recommended 8 to 10 minutes. The filling tube was disconnected and replaced by a rubber bung while a colleague pinched the upper part of the neck to prevent the excape of gas. The balloon was then ready for the ascent.

6.4. CHOICE OF HEIGHT.

The balloon was usually flown at one of four "standard" heights. These were nominally 50, 100, 150 and 200m. More precisely: the distance between the discharge point and the base of the mooring post was made to be 52.5, 105, 157.5 or 210m. Thus variation of declination with wind speed, up to moderate values, distributed the heights of the point roughly evenly about the nominal values. On two occasions in the early work the balloon was raised to 200m in steps of 20m, about three minutes being allowed at each step. This was in an attempt to determine directly the relation between current and height, but it was unsatisfactory because of the variation of field during ascent and accordingly the procedure was abandoned.

The choice of height on any occasion depended mainly on whether permission had been obtained to fly over 100m, whether the field was high enough to produce discharge at a given height and on what height was most likely to yield information of immediate interest.

6.5. THE ASCENT AND DESCENT.

Having decided on the operating height the flying cable was paid out (see Figs. 10, 12, 13 -- which were not all taken with the same balloon) and made off at the appropriate point. The current carrying wire unwound automatically. A note was usually made of the time of start and finish of the ascent and then the protractor clipped onto the flying cable (see Fig. 17). All was then ready for full scale observations.

Since the Ministry of Civil Aviation required that the balloon should not be left unattended it had to be hauled down at the end of each morning and afternoon if it had not previously burst. The procedure for the descent was essentially the reverse of that for the ascent except that the motor driving the wire drum was energised and the guide rocked slowly to and fro, usually by a colleague.

If the balloon burst while it was flying there followed the tedious operation of recovery, sometimes from roofs or tree tops, but this was not regretted because of the excellent indication afforded of point space charge and cable charge effects: a controlled ascent or descent took some minutes during which the field might vary considerably due to other causes, but since the descent of a burst balloon took only a few seconds a comparison of the fields immediately before and after gave a good measure of cable charge effect and the following minute or so showed the effect of the point space charge clearing away.

6.6. PROCEDURE DURING FLYING.

Photographic records were taken of the Mill, Agrimeter and point discharge current while the balloon was flying and also during its ascent and descent. Each record was normally allowed to run for about an hour with zero and calibration marks on all three traces at beginning, middle and end.

Visual observations were made of the protractor reading and wind direction, the latter being estimated to the nearest 22.5^{o} from the lie of the protractor as a whole. The mean value of both these quantities was noted for each half minute. Wind direction was recorded according to a "working" compass which deviated about 4^{o} from true directions (see "working" North on site plan Fig. 9). This was merely in order to fit in with the bearings of the Field Mill positions to minimise the labour involved in the calculations of the indirect method of determining the undisturbed field.

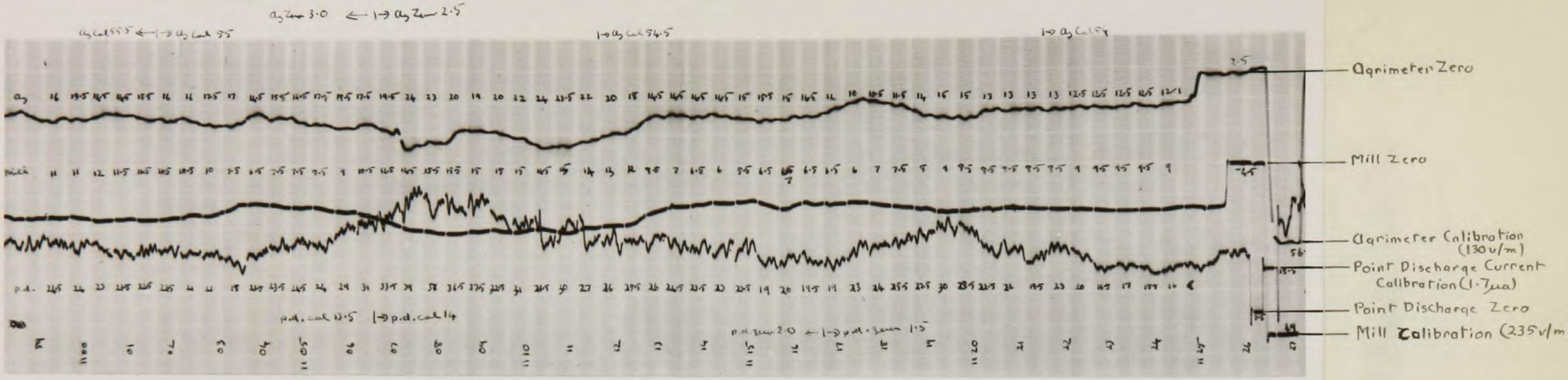

FIG. 19 PART OF A TYPICAL RECORDING (No. 48).
(Approximately half full size.)

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In order to synchronise the visual observations with those on the photographic record the following technique was used. Before observations were started the second hand of the observer's wrist watch was synchronised with the pulses of the laboratory clock system so that the beginning and end of each half minute over which the visual observations were averaged coincided with the breaks in the photographic traces. Correspondence between the two sets of observations was then obtained from notes of the times of application of the calibrating field to the Mill. By this means any drift between the observer's wrist watch and the clock system showed up in the relation between calibration deflections and time markers on the photographic record. The drift never exceeded 5 seconds.

6.7. INTERPRETATION OF RECORDS.

The technique adopted for the measurement of point discharge records, an example of which is shown in Fig. 19 was as follows:

1.) The corresponding time was written alongside every alternate time mark.

2.) The deviation in millimetres of each zero and calibration mark from a convenient arbitrary zero was written alongside it, the arbitrary zero chosen for each trace normally being the centimetre mark nearest its zero.

3.) The average deviation from the appropriate arbitrary zero for each half minute of each trace was written on the record. Periods not covered by the visual observations were not measured.

4.) Deviations were usually measured to the nearest half millimetre although if the point discharge trace was subject to violent fluctuations the nearest millimetre was noted.

5.) If the zero or calibration of any trace varied between two successive checks the change was assumed to be linear. The values of the zero and calibration deviations appropriate to each section of each trace were written on the record together with arrows to indicate the extent of the section to which they applied.

6.) The actual values of field and current were then readily calculated from the known conversion factors. Point discharge current was always calculated to the nearest 0.05μa except when the galvanometer was on low sensitivity when the nearest 0·1μa was used. Treatment of field was not so consistent in the first instance but before the final analysis all values were calculated to the nearest 5 v/m.

7.) Estimates of the magnitudes of the point space charge and cable charge effects at ascent and descent were made where possible.

8.) The notes of protractor readings were used to calculate height to 1 per cent of the nominal value, and to determine wind speed to the nearest 0.5 km/hr.

6.8. TABULATION OF OBSERVATIONS.

As such a considerable number of parameters were recorded and as there were a large number of operations to be performed on some of them if the indirect method of estimating the true field were to be employed it was found that they could best be recorded in a multi-column account book. One line was allotted to each half minute period and one or more columns to each parameter or operation.

6.9. INITIAL ANALYSIS OF RESULTS.

Once the values of the various parameters had been calculated graphs were plotted for each recording, of current against field for both the Mill and the Agrimeter. Various other graphs were plotted from time to time and occasionally some brief statistical treatments were applied. These were often very useful in guiding the course of the research but a full statistical analysis was not undertaken until all the results had been obtained.

6.10. PROCEDURE IN THE EARLY EXPERIMENTS.

The procedure described so far in this chapter applies strictly only to Recording No. 33 (6/6/52) and onwards, but the procedure in the earlier recordings was essentially similar except that fewer parameters were measured and others were measured in less detail. The extent to which this was so will be shown in chapter 7. The only important difference of technique was that parameter values were averaged over periods of one minute instead of half a minute.

CHAPTER 7. RESULTS

7.1. STATISTICAL TECHNIQUES.

It will be convenient to note at the outset that the statistical techniques used in the analysis were taken from Yule and Kendall (100a) and Kendall (42a). Where a value is given as y ± x it is to be taken as meaning that the probability that the value lies outside the limits y + x and y - x is 1 in 20. Unless otherwise stated a result is regarded as significant if the probability that it would arise by chance is not more than 1 in 20.

7.2. SUMMARY OF RECORDINGS.

A total of 61 recordings, each of about one hour's duration, were made during the period January 1951 to October 1952, covering measurement of point discharge current and various parameters.

In the first 32 recordings (January 1951 to November 1951) the only measurement of field was taken by the Agrimeter at 8m from the base of the flying cable. In some of the earliest of these recordings occasional observations were taken of cable declination and wind direction, and in the last three (Nos. 30 - 32) one minute averages of these parameters were taken consistently.

The great bulk of the remaining recordings (Nos. 33 - 61, made in the period June 1952 to October 1952) included full photographic registration of point discharge current and electric field (according to the Agrimeter at 8m from the base of the flying cable and to the Mill at 50m, approximately to windward of the flying cable) together with visual observations of "protractor reading" (balloon declination + 4^{o}) and wind direction. For recordings Nos. 45, 60 and 61 the 8-point discharger was fitted to the balloon; in all other recordings a single discharge point was used.

Thus the observations contained information on the effects on point discharge current of the following parameters: electric field, height of point, wind speed, wind direction and number of points. Unfortunately the air-earth current measuring apparatus was never in operation during the periods of recording so that no information was available on the possible effects of conductivity. Furthermore, lack of time precluded any investigation of the effect of the spacing of the points in a multiple point discharger, or of the effects of the shape of the point or the nature of the wire from point to ground.

7.3. METHOD OF DETERMINING THE UNDISTURBED FIELD.

The first problem to be solved was whether to use the direct or the indirect method of determining the undisturbed field (see section 3.5.)

As a first step the actual change of field, as recorded by the Mill and Agrimeter, at the ascent and descent of the balloon was observed, and compared where possible with the change predicted by the point space charge and cable charge effects.

The field at the Agrimeter almost always showed a marked decrease at the ascent of the balloon and increase at the descent. Two rapid descents, as a result of the balloon bursting, occurred from 50m and these showed no change of field at the Mill. Two other rapid descents occurred from 100m and these showed field increases at the Mill of 5 to 10 v/m on 90 v/m. During the slow controlled ascents and descents, which took from 3 to 10 minutes, any field changes which occurred at the Mill were usually indistinguishable from natural changes although at one ascent to 200m there was a suggestion of a decrease of 25 v/m on 70 v/m.

From the foregoing it was clear that the field at the Agrimeter was quite unsuitable as an estimate of the undisturbed field and that the field at the Mill was liable to be a bit low, particularly for the greater heights of the point.

Attention was therefore turned to the indirect method. It was found that the actual changes of field, at Mill and Agrimeter, were usually a little larger than those calculated from the cable charge effect but not nearly as much so as would be required by the calculated values of the point space charge effect.

However, in view of the fact that it was shown in section 3.5(b) that, despite this disagreement, the indirect method should be applicable if K is proportional to I/v it was decided to make a few tests of the relationship between K and I/v. This was done for 30 observations from each of recordings Nos. 42 and 44, in which the mean wind speeds were about 4 km /hr and 16 km/hr respectively. It was found that for recording No. 42 the correlation coefficient between K and I/v was 0.47 and that it would arise only 1 in 140 times by chance from an uncorrelated parent population, but that for recording No. 44 the correlation coefficient was 0.056 and would arise 1 in 4 times by chance.

Since the first of these correlations was only moderately encouraging, and the second most discouraging it was decided that the direct method would have to be used.

Accordingly the field at the Mill was taken as a measure of the undisturbed field, bearing in mind the fact that when the point was high the Mill reading was probably rather low.

7.4. SELECTION OF OBSERVATIONS FOR ANALYSIS.

In view of the unsuitability of the field at the Agrimeter as a measure of the undisturbed electric field it was evident that the first 32 recordings were of little value and could not be regarded as constituting more than a preliminary survey of the problem, showing that point discharge current increases with increase of electric field, height of point and, probably, wind speed.

Rain during recordings Nos. 46 and 47 prevented the operation of the Mill and decreased the net lift of the balloon so that the protractor reading-wind speed relationship was altered. Accordingly these recordings were rejected. Recording No. 54 was rejected because the Mill record was faulty, due to an electrical defect, and No. 45 because of instability in the point discharge galvanometer sensitivity.

In Chapter 3 tables I and II showed that, according to calculation, the space and cable charge effects did not increase greatly as the point of observation deviated up to $\pi/2$ from windward of the flying cable, but that they did so to a considerable extent as the deviation increased from $\pi/2$ to π. It was therefore felt that any observations in which the Mill was more than $\pi/2$

off windward were suspect.

On these grounds the whole of recording No. 37 had to be rejected because an error of judgement had resulted in the Mill being operated almost directly to leeward of the flying cable. Its readings were obviously very low.

In recordings Nos. 38, 39 and 40 the deviation of the Mill from the windward direction varied from 67.5° to 157.5°. Despite this fact there was no obvious depression of Mill reading and since the correlation between deviation from windward and discharge current , for a given field, was -0.18 (when a positive correlation was to be expected) all these observations were accepted. Presumably the apparent absence of point space charge effect was due to the very small currents encountered in these recordings.

In recording No. 49 a significant correlation was found, for a given field, between discharge current and deviation from windward over the range $\pi/2$ to π. Accordingly, all observations for which the deviation exceeded 112.5° were rejected. A similar rejection was made for recording No. 48.

This finally left a total of some 1620 observations representing half minute averages of point discharge current, electric field, height of point, wind speed and wind direction, distributed as follows. With a single discharge point; 430 for a nominal height of 50m, 360 for 100m, 350 for 150m and 320 for 200m; with the 8-point discharger; 160 for a nominal height of 50m. They covered fields ranging from about -10 to +250 v/m, wind speeds from 0 to about 25 km/hr and point discharge currents up to 2μa at 50m, 3.5μa at 100m and 7μa at 150 and 200m.

7.5. THE EFFECT OF WIND DIRECTION.

Observations which were thought to be seriously affected by the point space charge and cable charge effects for certain wind directions had already been eliminated; there remained, however, as remarked in section 2.4(e), the possibility that local sources of pollution and the topography of the site produced some dependence of point discharge current on wind direction. However, a careful study of the results and a few brief statistical checks failed to reveal any marked dependence so it was decided to ignore any small dependence which might exist.

7.6. RE-TABULATION OF OBSERVATIONS.

It was remarked in section 6.8 that as the observations were obtained they were tabulated in chronological order in a multi-column account book. In order to get them into a more convenient form for the final analysis some large sheets of graph paper were obtained: one for each nominal height of the point. Each column of large squares was allotted a 5 v/m range of electric field and each row a 1^{o} range of protractor reading. All the observations of point discharge current (except those obtained with the 8-point discharger) were then written in the appropriate squares. This served the dual purpose of making it easy to read off the values of current for any desired range of field, height or wind speed and also of showing at a glance for what ranges of these parameters observations of current were available.

7.7. ANALYSIS OF RESULTS.

(a) Outline of Procedure.

It was decided to attempt to represent the results by an equation of the form $I = f(W).f(H).f(F)$

where I = point discharge current

W = wind speed

H = height of point

F = "undisturbed" electric field in the vicinity.

The best way to tackle this seemed to be to determine a and f(F) in $I = a.f(F)$ for small ranges of protractor reading, and hence of wind speed and exact height, at each of the four nominal heights; then to determine b and f(H) in a = b.f(H) for each small range of protractor reading and finally to determine f(W) in b = f(W). After that a similar, though necessarily less comprehensive, treatment could be applied to the 8-point discharger.

As will be shown some slight variations of this technique became necessary as the analysis progressed but it proved broadly satisfactory.

(b) Variation of Point Discharge Current with Electric Field.

An initial problem in this first stage of the analysis lay in the distribution of the observations over the ranges of protractor reading and electric field: although for "medium" values of field a good range of protractor readings was covered, values of field which were near to the minimum necessary to produce point discharge were comparatively few and, apart from those for a nominal height of 50m, tended to be restricted to a small range of protractor reading. Now it was clear that M, the minimum field for onset of point discharge, would be an important parameter in f(F) and that for those values of height and ranges of protractor reading for which that value lay well outside the range of values of F, any straightforward method of curve fitting would make the value of M so determined subject to considerable error. Consequently it was felt that if a value of M could be allotted to each range of protractor reading at each height the values of the other parameters in f(F), which would be determined subsequently would be more reliable.

The ease with which such a set of values of M could be determined depended on whether or not M was dependent on wind speed. If it were not; then by determining M for some single range of protractor reading (which contained values of F close to M) at each of the four nominal heights it would be possible to determine the relation between M and H and so allot a value of M to each range of protractor reading at each height.

Now presumably the way in which the wind increases point discharge current is by helping to remove the limiting space charge from the vicinity of the point. If this is so it seems improbable that it will have any effect on the minimum field for the onset of point discharge since for a field just less than this minimum there will be no space charge to be removed. Before making this assumption it was decided to make what tests the results permitted.

The procedure was as follows. For a given very small current at a given nominal height the regression of field on protractor reading was calculated and the significance determined of its deviation from the coefficient which would be expected if M were inversely proportional to H -- it will be remembered that as the wind speed increases the protractor reading increases and so the exact height of the point decreases. (Clearly M will increase with decrease in H and, over the small range of H involved in each case, the assumption of inverse proportionality will not introduce any great error.) This was done for currents of 0.05μa and 0.1μa at nominal heights of 50 and 100m. In all but one case the regression coefficient deviated from the value to be expected, if M were inversely proportional to H, in a direction which indicated a decrease of field with increase of wind speed (for a given small current). However, since the significance was usually small (probabilities that the values arose by chance being 1 in 5, 1 in 50, 7 in 10 and 8 in 10), and since the test had been made with F for small I (and not M) it was concluded that the tests did not contradict the assumption that M is independent of wind speed.

The next step was to determine M for a number of values of H. The best way of doing this seemed to be first to select a range of protractor readings for each nominal height (not necessarily the same in each case) which contained a wide range of values of F, including especially values of F close to M; then to determine what function of F best represented the relation between I and F in every case, and finally, from this function, determine M in each case.

Although this method has the advantage that it uses a wide range of values of F in determining M it has the disadvantage that M occurs near one limit of the range -- since values of F when I = 0 cannot be used because they will not, in general, lie on the same curve. The values of M will therefore be subject to relatively large errors. When a number of equations were fitted to various groups of observations it was, in fact, found that the values of M given were usually absurdly small or even imaginary. Furthermore, the method failed to show any significant difference between the goodness of fit of a quadratic parabola and a straight line. It was therefore decided that M must be determined by some other method and then a fresh attempt made at determining f(F) making use of the independently determined values of M.

Two methods suggested themselves for the determination of M: (1) To use the values of field at which, in the course of a recording, the current just fell to zero or just rose above zero; (2) To use groups of observations for small values of current, and small ranges of protractor reading and fit to them the "best" straight line relating I and F, taking the value of F so determined at I = 0 to be M. The first method would give no value of M for 50m and only two for each of the other heights. It therefore appeared preferable to use the second method on the grounds that it made use of a much greater number of observations. The use of a straight line can be justified on the grounds that the range of values is small. As the object was to determine F at I = 0 it was decided to use the equation $F = mI + c$ rather than $I = mF + c$. The procedure was carried out for all heights and ranges of protractor reading which contained a reasonable number of observations with small I.

The values of M so determined were plotted against 1/H and suggested two possible relations: either $M = q/H$ or $M = q/H^2$ (It is clear that as $H \to \infty$, $M \to 0$). Both these equations were fitted to the results. $M = q/H^2$ gave a slightly better fit than $M = q/H$ but not significantly so. At the time these were the only tests applied and since it seemed reasonable to suppose that the onset of point discharge was associated with some critical voltage between the point and the surrounding air at the same height it seemed justifiable to accept the $M = q/H$ equation especially as that gave a minimum voltage in close agreement with the value found in the laboratory by Warburg (86): in the present case the minimum voltage was found to be 2860 for a 0.25mm diameter wire while Warburg obtained a figure of 2880 for a 0.235mm diameter wire. (It may be noted that the somewhat higher figures obtained by Zeleny (101,102) were for rather blunt ended wires.

When the rest of the analysis had been completed, in which frequent use was made of functions involving non-integral powers of parameters, it was realised that a more rigorous test of the relation between M and H could be made by fitting the equation $M = q/H^r$ to the results. When this was done a value of 1.87 ± 0.50 was obtained for r. This seems to make it very improbable that the true value of r is 1, but when it is remembered that the surrounding trees and buildings must distort the equipotential surfaces to a considerable extent it will be realised that the effective height of the point must have been appreciably less than the measured height, especially for small heights of the point, and this will do much to reduce the value of r. When, furthermore, the theoretical considerations of section 8.5(c) are borne in mind it seems that the assumption that $M = q/H$ was, after all, justified.

Thus the first firm relationship deduced from the observations was as follows:

$$M = V_m/H$$

where M = Minimum field for point discharge

V_m = 2860 volts = minimum voltage between point and surrounding air at the same height for point discharge

H = height of point.

The way was then clear for a fresh attempt at determining the nature of f(F) making use of the values of M obtained from the above equation. The experience of the previous attempt, together with the pictorial representation afforded by plotting I against F suggested the use of some function involving a power of F between 1 and 2. It was felt desirable to select a function which involved one multiplying constant and one power constant; the power constant could then be determined for groups of observations which showed little scatter and assumed to hold true for the groups with a large degree of scatter, for which it would then be necessary to determine only the multiplying constant.

For good measure it was decided to fit the following equations to the observations for 50m with protractor readings 18° to 24°:

$$I = a(F - M)^n \quad \ldots \ldots \quad (1)$$

$$I = aF^n(F - M) \quad \ldots \ldots \quad (2)$$

$$I = aF(F - M)^n \quad \ldots \ldots \quad (3)$$

$$I = aF^n(F - M)^n \quad \ldots \ldots \quad (4)$$

$$I = a(F^n - M^n) \quad \ldots \ldots \quad (5)$$

Equations (1) to (4) could be quite easily handled by putting them into logarithmic form: then the values of a and n which gave the best fit and the correlation coefficient, R, could be determined in each case. The only way to tackle equation (5), however, was to determine a and R for a selection of pre-determined values of n. In fitting the equations logarithmic values were used for all five cases, to ensure comparability of results, but values of I near zero were excluded on the grounds that they would have a disproportionate effect. The results are listed below.

Equation	n	R
1	1.21	0.9656
2	0.34	0.9663
3	0.55	0.9675
4	0.73	0.9670
5 (n = 1.0)	-	0.9598
5 (n = 1.25)	-	0.9651
5 (n = 1.5)	-	0.9666
5 (n = 1.75)	-	0.9643
5 (n = 2.0)	-	0.9570

To determine the best value of n for equation (5) a quadratic parabola was fitted to the values of n and R and the value of n for maximum R calculated. This gave

$$n = 1.46 \qquad R = 0.9667$$

As the correlation coefficients were all so similar in value (none of the differences was significant) it was clear that no one equation was to be preferred to any other in that respect. It was therefore decided to use equation (5) as it was of approximately the same form as that used by Whipple and Scrase (90) and derived theoretically (for a rectangular array of points) by Chalmers (12).

The probable limits of n were determined by calculating a value of R which was just significantly different from that for n = 1.46 and then, determining the corresponding value of n from the quadratic parabola relating n and R. This gave the value of n as 1.46±0.70. In view of the large uncertainty in n it was decided to fit equation (5) to all other ranges of protractor reading at 50m. This procedure gave the following results.

Range of protractor reading (degrees)	Corresponding mean wind speed (km/hr)	optimum n	R at optimum n
4-10	2.1	2.34±1.33	0.9738
11-17	6.2	1.66±0.75	0.9812
18-24	10.2	1.46±0.70	0.9667
25-31	15.0	1.97±0.82	0.9881
32-38	19.0	1.87±1.36	0.9826

As there was no significant correlation between n and protractor reading it was decided that one value of n could be used for all ranges of protractor reading. The mean n for the above results was found to be 1.86. No method could be found for determining the standard error of this value but it was clear that it would be fairly large. Thus there is quite a high probability that the true value of n is 2, but in order to allow for the fact that n may be less than 1.86, rather than more, it was decided to use $I = a(F^n - M^n)$ with n = both 1.5 and 2 for the rest of the analysis.

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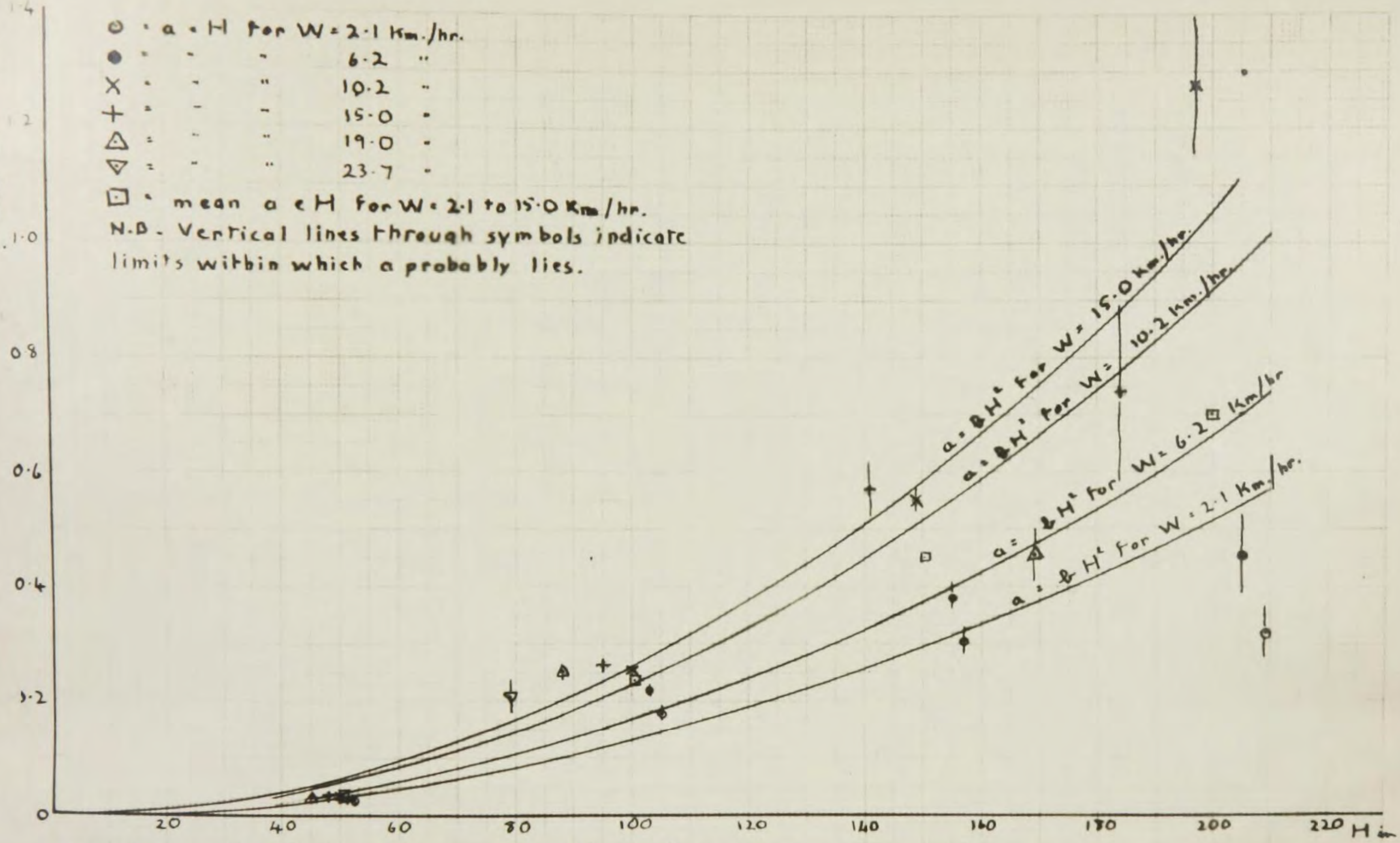

FIG. 21 H versus a (from $I = a(F^n - M^n)$) for $n = 2$

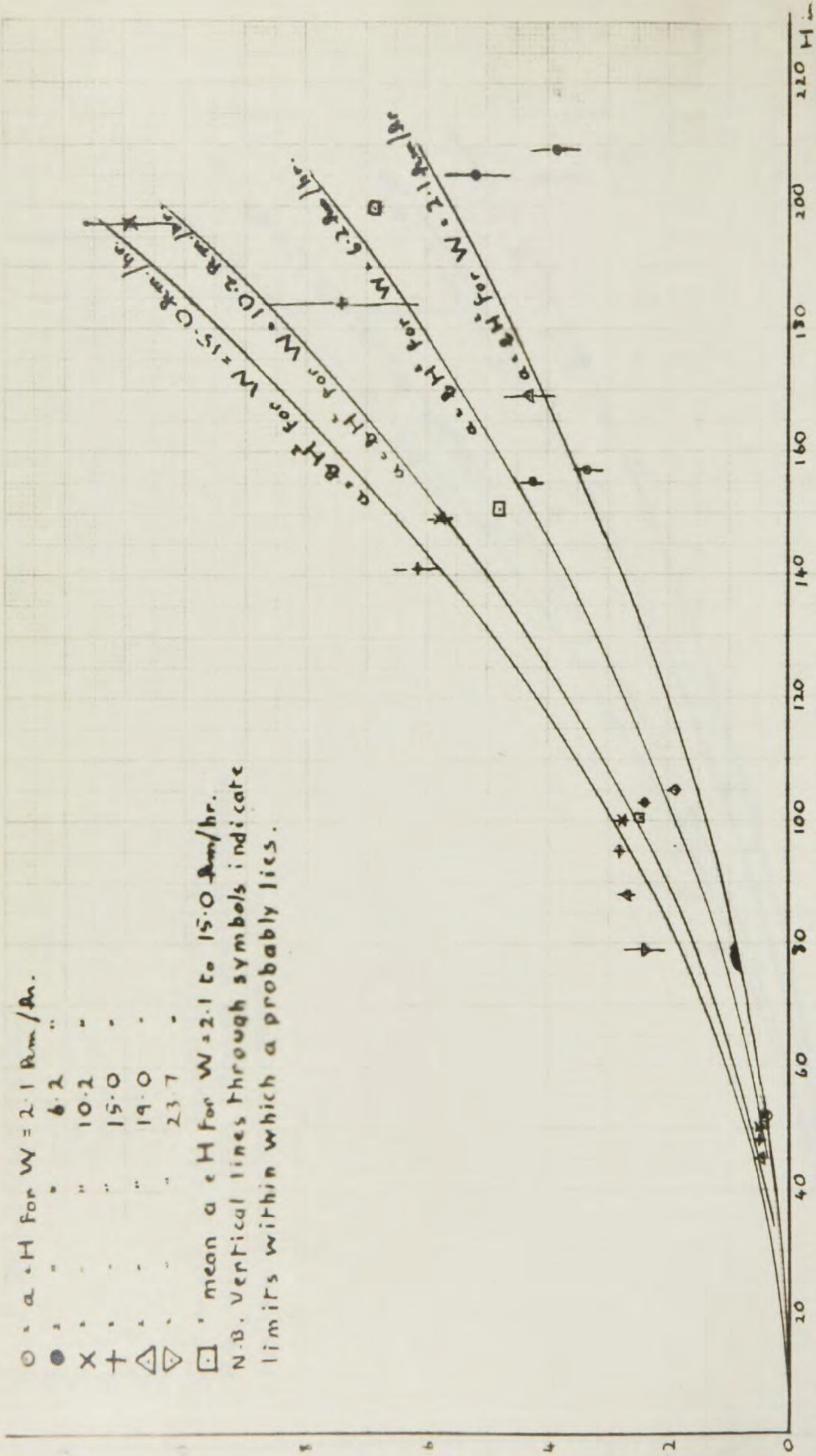

FIG. 20 H versus a (from $I = a(F^n - M^n)$) for $n = 1.5$

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TABLE VI

Values of a in $I = a(F^n - M^n)$ with n = 1.5 and 2 for various values of height of point (H) and wind speed (W). I = point discharge current in μa, F = field in v/m, M = minimum field for point discharge = V_m/h, V_m = 2860 = minimum voltage for point discharge.

Protractor readings (degrees)	H	W	Number of observations	a x 10^2 (for n = 1.5)	a x 10^3 (for n = 2.0)
4 - 10	52	2.1	0 59	0.0367±0.0028	0.0282±0.0044
11 - 17	52	6.2	115	0.0451±0.0020	0.0308±0.0012
18 - 24	50	10.2	107	0.0491±0.0020	0.0320±0.0008
25 - 31	48	15.0	75	0.0518±0.0020	0.0354±0.0012
332 - 38	45	19.0	33	0.0470±0.0036	0.0322±0.0024
4 - 11	105	2.1	37	0.188 ±0.014	0.179 ±0.014
12 - 18	103	6.2	43	0.238 ±0.010	0.221 ±0.008
19 - 25	100	10.2	31	0.275 ±0.012	0.256 ±0.010
26 - 33	95	15.0	56	0.282 ±0.010	0.266 ±0.010
34 - 40	88	19.0	27	0.271 ±0.016	0.253 ±0.017
41 - 47	79	23.7	8	0.237 ±0.034	0.211 ±0.028
4 - 11	157	2.1	70	0.325 ±0.022	0.305 ±0.023
12 - 18	155	6.2	104	0.424 ±0.018	0.382 ±0.020
19 - 26	149	10.2	88	0.577 ±0.020	0.552 ±0.020
27 - 34	141	15.0	32	0.615 ±0.042	0.568 ±0.050
4 - 12	209	2.1	46	0.386 ±0.040	0.320 ±0.044
13 - 19	205	6.2	85	0.519 ±0.058	0.453 ±0.068
20 - 28	197	10.2	85	1.088 ±0.074	1.276 ±0.120
29 - 36	184	15.0	41	0.740 ±0.124	0.738 ±0.154
37 - 44	169	19.0	34	0.431 ±0.042	0.456 ±0.046

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These two equations were then fitted to all the observations for a single point. For heights greater than 50m ranges of protractor reading were used which corresponded to the same ranges of wind speed used for 50m. The results are given in Table VI in which it should be noted that the decrease of a at large protractor reading is probably usually due to the effect of decreasing height "swamping" the effect of decreasing wind speed.

(c) Variation of Current-Field Relation with Height.

Having selected an equation which reasonably represented the relation between point discharge current and electric field and determined the values of the paramet rs involved for a number of heights and wind speeds it was then possible to study the effect of height on the current-field relation. In Figures 20 and 21 values of a (for $n = 1.5$ and $n= 2$ respectively) are plotted against H for various values of wind speed; the figures are taken from Table VI.

Two features are outstanding: first the general increase of a with H (and with wind speed); second the somewhat anomolous distribution of a with respect to wind speed for a nominal height of 200m. Now it would appear that the second feature cannot be explained away by assuming that the true values of a deviate from the most probable values by a moderately improbable extent: the probability that the true values lie beyond the limits indicated by the vertical lines in figures 20 and 21 is only 1 in 20. However, this probability value is calculated on the assumption that the observations used in determining a were a random sample of the total possible population of observations. This assumption is by no means necessarily justified as the following considerations will show.

Figures 20 and 21 and Table VI show that the standard error of a increases with height. This is due to the greater scatter in the values of current, rather than to a smaller number of observations. This increased scatter could very reasonably be attributed to normal space charge, which would obviously have a greater effect at greater heights of the point. Further; it was found that for recordings made on different days the range of current values for any given height, field and wind speed, would often differ appreciably. This could be explained by assuming that the normal space charge changed comparatively slowly: that it tended to remain constant for the period of one recording, but might be noticeably different for another recording on another day. Thus if the observations used in obtaining a value of a were drawn mainly from only one or two recordings there is a possibility that they covered only a small range of normal space charge and hence do not represent a random sample of all possible observations. In point of fact, as the height increases each range of wind speed tends to be associated with one recording. This is due to the fact that since turbulence decreases with increase of height, the range of wind speeds encountered during one recording tends to decrease with increase of height and so, since the number of recordings taken at each height was about equal to the number of ranges of wind speed used, at 150m and especially 200m each range of wind speed tends to be associated with one particular recording.

If these deductions are justified it may be assumed (1) that the scatter in the values of I is at least partly due to normal space charge, (2) that the scatter will increase with height and (3) that the scatter, and hence the standard error of a, will tend to be artificially low at the greater heights.

It was decided to make these assumptions. The anomalous distribution of a with respect to W for a nominal height of 200m could then be disregarded. In view of this anomaly, however, and in view of the fact that the value of a for lower heights might be subject to a similar anomaly of less extent, it was decided to use the mean a and mean H (for the four lowest ranges of wind speed) for each nominal height in assessing the nature of the a - H relation. These mean values were then, of course, derived from a more nearly random sample of observations.

The mean values, which are plotted in figures 20 and 21, give a good idea of the relation between a and H but a further important guide can be gained from the following considerations. If H is decreased below 50m a cannot be negative so long as H is positive. Even when H is very small, of the order of millimetres, a will still have some positive value although M, of course, will become very large. Therefore when H = 0 a is either 0 or positive. If it is positive it must surely be extremely small. Thus within the limits of accuracy of the present investigation it may be taken that a = 0 at H = 0. The only possible objection to this assumption is that the "effective" height of the point may be less than its actual height because of the surrounding trees and buildings, where effective height is to be taken to mean that height to which a point would have to be raised at a perfectly open horizontal site in order to give the same discharge current as in the present case; all other conditions being identical. However, the distortion produced in the equipotential surfaces by trees and buildings will decrease with height so that the difference between the actual and effective heights of the point will decrease with height. In view of this it seemed unwise to attempt any correction for effective height, but to assume that $a = 0$ at $H = 0$ and accept the fact that any curve fitted to a and H would probably be rather high at $H = 50m$ and, possibly, $H = 100m$.

In the circumstances $a = bH^p$ where b and p are constants, seemed a reasonable curve to use. p could be determined by fitting the curve to the mean values of a and H and this value used for fitting the curve to various wind speed ranges. In order to give effect to the widely different standard errors of a at different heights the points were weighted in inverse proportion to their standard errors -- the standard errors of the mean values of a and H being taken as the means of the standard errors of the individual values of a and H from which the means were calculated.

By fitting $a = bH^p$ to the mean values of a and H it was found that

for $n = 1.5$ $p = 2.17 \pm 0.61$

for $n = 2.0$ $p = 2.52 \pm 0.92$

Whether the probability limits are really as large as this is uncertain, since they were calculated according to a theory which assumes that the individual points are single precise observations, whereas in point of fact they are imprecise means of large numbers of observations.

TABLE VII

Values of b in $a = bH^2$ where H = height of point in metres and a is derived from $I = a(F^n - M^n)$ (see Table VI)

Wind speed (km/hr)	$b \times 10^7$ for n = 1.5		$b \times 10^8$ for n = 2.0	
	including 200m results	excluding 200m results	including 200m results	excluding 200m results
2.1	1.27±0.49	1.40±0.48	1.17±0.54	1.32±0.52
6.2	1.74±0.60	1.88±0.65	1.57±0.65	1.67±0.89
10.2	2.63±0.37	2.58±0.61	2.47±1.05	2.29±1.42
15.0	2.68±1.08	2.94±1.74	2.49±0.96	2.60±1.71

TABLE VIII

Values of c and d in $b = cW + d$ where W = wind speed in km/hr and b is derived from $I = bH^2(F^n - M^n)$ (see Table VII)

	n = 1.5		n = 2.0	
	with 200m results included in b	with 200m results excluded from b	with 200m results included in b	with 200m results excluded from b
$c \times 10^9$	10.9±11.9	11.9± 5.7	1.04±1.18	0.97±0.53
$d \times 10^9$	116	127	10.4	11.6

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However, no statistical theory could be found which took this into account.

The figures seemed to justify the assumption that the results could be fairly represented by the equations $a = bH^2$ or $a = b\ H^{2.5}$, both for $n = 1.5$ and $n = 2.0$ but in view of the considerations in section 8.2 which show that the calculated value of p is probably rather high it was decided to use only $a = bH^2$. This equation was therefore fitted to the actual values of a and H for the four lowest ranges of wind speed. It did not seem worth while extending the work to higher ranges as no observations were available for a nominal height of 150m and only one, obviously low, value for 200m. Further, in view of the anomalous distribution of a with wind speed for a nominal height of 200m these observations were at first excluded. The curve fitting was, however, repeated with these values included and the results of both methods are shown in Table VII and Figure 22.

(d) Variation of Current-Field-Height Relation with Wind Speed.

By this stage it had been established that the results could be reasonably represented by

$I = bH^2(F^n - M^n)$ where $n = 1.5$ or 2, $M = V_m/H$ and b depends on wind speed. The final step, therefore, was to determine the relation between b and wind speed, W.

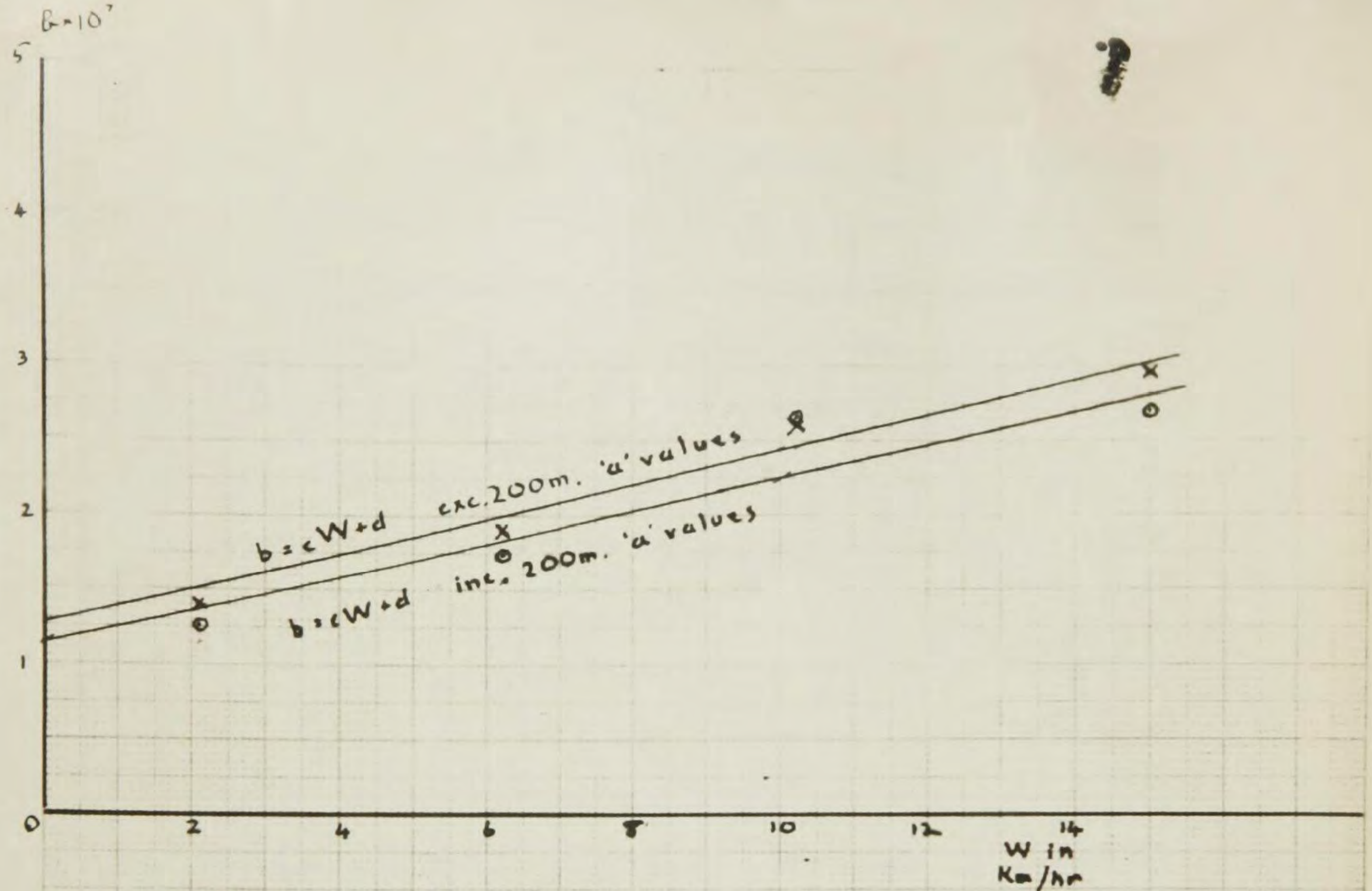
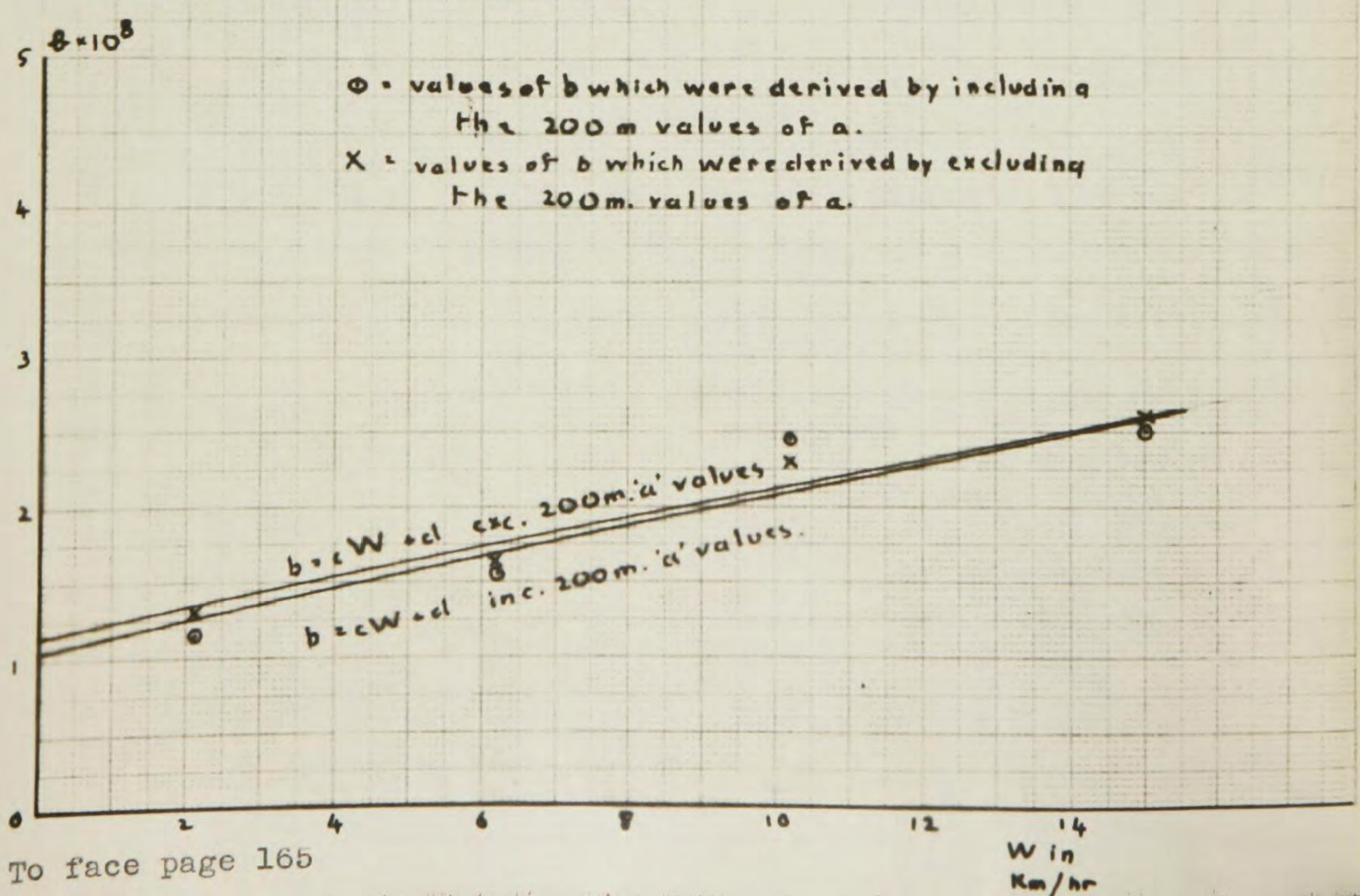


FIG 22 W versus b (from $a = bH^2$)
above: for $n = 1.5$; below: for $n = 2$.



The graphs of Figure 22 clearly suggest an equation of the form $b = cW + d$. This equation was fitted to the four sets of values of b and the results are shown in Table VIII and Figure 22. These serve to show that it makes very little difference whether or not the 200m values of a are used in determining b so, as a much lower uncertainty is obtained by excluding them it seemed best to do so.

(e) Effect of using 8-point Discharger.

The observations obtained with the 8-point discharger were somewhat limited and restricted to a nominal height of 50m. It was therefore decided to limit the treatment to the determination of a and M in $I = a(F^n - M^n)$ with n = 1.5 and 2, for the three lowest ranges of wind speed.

The first task was to determine M. By fitting straight lines to the values of I and F close to I = 0 the values of M obtained were 69, 95 and 68 v/m for protractor reading ranges $4^{\circ} - 11^{\circ}$, $12^{\circ} - 18^{\circ}$ and $19^{\circ} - 25^{\circ}$ respectively. As these results were so inconclusive a close study was made of Recording No. 60 during which the discharge current actually fell to zero. This occurred for a field at the Mill of 80 to 85 v/m and at the Agrimeter of 85 to 90 v/m. The Agrimeter reading, however, was probably reduced about 10 per cent

<u>TABLE IX</u>

Values of a in $I = a(F^n - M^n)$ for the 8-point discharger compared with values for the single point. I = point discharge current in μa, F = electric field in v/m, M = minimum field for onset of point discharge, H = height of point.

wind speed (km/hr)	a x 10^4 for 8-point discharger with M = 3640/H	a x 10^4 for 8-point discharger with M = 5200/H	a x 10^4 for single point
	with n = 1.5		
2.1	2.86±0.16	3.48±0.18	3.67±0.28
6.2	2.82±0.24	3.44±0.28	4.51±0.20
10.2	3.75±0.59	4.55±0.73	4.91±0.20
	with n = 2.0		
2.1	0.182±0.010	0.212±0.010	0.282±0.044
6.2	0.176±0.012	0.208±0.012	0.308±0.012
10.2	0.232±0.038	0.270±0.048	0.320±0.008

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by the cable charge effect so that the undisturbed field at that position was probably about 100 v/m.

In view of the uncertainty in the value of M and the importance of its effect on the value of a it was decided to analyse the results twice using an upper and lower limit value for M within which the true value was almost sure to lie. The values selected were 70 v/m and 100 v/m for a height of 52m, so that, assuming that M was inversely proportional to H, as for a single point, it followed that M = 3640/H or 5200/H where H is in metres and M in v/m. The values of a obtained by using these values of M are listed in Table IX. The ranges of protractor reading, and hence height, used for the various wind speeds are, of course, slightly different from those used with the single point because of the extra weight of the 8-point discharger. The difference in height, however, even for the highest wind speed used (10.2 km/hr) is less than 1 per cent.

From Table IX it is apparent that a is always lower with the 8-point discharger than with the single point although the significance of the difference is somewhat doubtful when the upper limit of M is used with n = 1.5. The results may be summarised by saying that the use of the 8-point discharger at a nominal height of 50m increases M by between 27 and 82 per cent and decreases a, on the average, by between 28 and 12 per cent respectively for $n = 1.5$ and between 35 and 24 per cent respectively for $n = 2$.

(f) Summary of Analysis.

The simultaneous observations of discharge current from a single point 0.25mm in diamter, from 0 to 7μa; electric field from 0 to 250 v/m; height of point from 0 to 200m and wind speed from 0 to 15 km/hr; can be reasonably well represented by the equation

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

where I = point discharge current

W = wind speed

H = height of point

F = electric field

V_m = minimum voltage between point and surrounding air at same height for onset of point discharge.

c, d, p, n = constants.

The value of n is probably between 1.5 and 2 and p is probably between 1.5 and 3. If I is expressed in μa, W in km/hr, H in metres, F in v/m and Vm in volts then V_m = 2860 and if p is taken to be 2 then with $n = 1.5$ $c = (1.19 \pm 0.57)10^{-8}$ and $d = 12.7 \times 10^{-8}$ or with $n = 2$ $c = (0.97 \pm 0.53)10^{-9}$ and $d = 11.6 \times 10^{-9}$.

If the single point is replaced by the 8-point discharger and the equation simplified to $I = a(F^n - V_m{}^n/H^n)$ then V_m is increased by between 27 and 82 per cent and a is decreased by between 28 and 12 per cent respectively with n = 1.5 and between 35 and 24 per cent with n = 2.

7.8. SYSTEMATIC ERRORS IN THE OBSERVATIONS.

The scatter of the observations,which is discussed at length in section 8.1, largely accounts for the uncertainty of the various coefficients in the final equation relating point discharge current to the various parameters. There remains, however, the important fact that the "most probable" values of the coefficients given in section 7.7(f) are, to some extent, also in error due to systematic errors in the observations. The various parameters will be considered in turn.

It was noted in section 4.16 that the values of electric field were probably all a few per cent low due to the poor exposare of the stretched wire with fuse. This effect would apply consistently to all the observations of field, the net result being to make the coefficients c and d in the final equation (section 7.7(f)) perhaps between 10 and 30 per cent high. The point space charge effect doubtless reduced the field measurements a little, especially at the greater heights and lower wind speeds. In section 7.3 it was shown that the field reduction was probably negligible for a point height of 50m, perhaps 5 or 10 v/m for 100m and possibly of the order of 25 v/m for 200m. This information is very meagre but it does suggest that the values of the coefficient a determined for the greater heights may have been noticeably high. Since the field at the Mill is claimed as an estimate of the "undisturbed" field in the vicinity it must be remembered that the work of Lecolazet (47) and Koenigsfeld and Piraux (43a) shows that the field usually decreases with height so that the Mill reading will more often than not be high especially at the greater heights. This will tend to make the values of a at the greater heights somewhat low, thereby compensating, at least to some extent, the artificial increase of a due to the point space charge effect.

Although the height of the point above the ground at the mooring post was measured with considerable accuracy it is probable that the effective height deviated appreciably from this measured value becuase of the nature of the site, and was usually somewhat less, especially at the lower heights. This would give low values of a for 50m and possibly for 100m, but this has been corrected to some extent in the final equation since, as a glance at Figures 20 and 21 will show, the fitted curves relating a and H pass above the observed values of a at 50m.

There seems no reason to suspect the measurements of wind speed of any systematic error except in so far as the "rolling" of the balloon referred to in section 8.1 may be regarded as equivalent to an increase of wind speed above the observed value.

There seems no reason to suspect the measurement of point discharge current.

It will be convenient here to consider the possibility, noted in section 2.4(j), that corona discharge occurred from the surface of the current carrying wire. This would presumably manifest itself as a steepening of the curve relating current and field. However, no such steepening was discernible at 50 or 100m, where the discharge current reached 2μa and 3.5μa respectively; and the scatter in the observations at 150 and 200m, where the current reached 7μa, was too great for any possible steepening to be noticeable.

Thus it may be concluded that in the final equation of section 7.7(f) the coefficients c and d may be between 10 and 30 per cent high, due to inaccurate absolute calibration of the Mill; and that c may be a little high if the results are applied to a rigidly supported point, because of the "rolling" of the balloon. The net effect of most of the other systematic errors is difficult to assess but probably small, and the effect of surrounding trees and buildings on the effective height of the point is probably largely taken care of by fitting the curve $a = bH^2$.

CHAPTER 8 DISCUSSION

8.1. SCATTER OF THE OBSERVATIONS.

In surveying the investigation it will, perhaps, be instructive to review the way in which the scatter of the observations was progressively reduced.

In the earliest experiments the only parameter, other than the point discharge current, which was measured in detail was the electric field at the ground some 8m from the base of the flying cable; even the height of the point was measured only to the extent of noting the length of the cable and its "average" declination over long periods. The scatter obtained when current was plotted against field, for a given cable length, was, of course, very considerable. A marked reduction in this scatter was obtained when the field was measured in a position comparatively unaffected by point space charge and cable charge effect, and some further reduction occurred when the graphs were restricted to small ranges of protractor reading -- and hence height and wind speed. It was found, however, that there was a limit to the extent to which the scatter could be reduced by taking progressively smaller ranges of protractor reading. In fact no further reduction could be obtained by working with ranges smaller than the 7 or 8 degrees used in the final analysis.

This "residual" scatter may be due either to inaccuracies in the observations or to the influence of other factors or to both. The measurements of current, field and height were reasonably precise and could account only for very little of the residual scatter. Since wind speed measurements were subject to errors of 15 to 20 per cent (see section 5.5(c)) this would account for some scatter but evidently not very much, since such scatter would be proportional to wind speed but independent of height; whereas the actual residual scatter was sensibly independent of wind speed and roughly proportional to height. Clearly, therefore, the bulk of the residual scatter must be due mainly to the influence of factors other than those used in the analysis of the results.

One factor which immediately springs to mind is that of wind direction. The effect of changing wind direction was disregarded in the analysis of the results although it doubtless contributed something to the residual scatter. However, in so far as the effect was due to local sources of pollution affecting field and current differently the scatter produced would be largely independent of the height of the point; and in so far as the effect was due to changes in the effective height of the balloon the scatter produced would tend to decrease with increasing height (as the equipotential surfaces became more nearly horizontal). Thus changes of wind direction might explain an appreciable part of the scatter when the point was at a height of 50m (although a detailed inspection of one small group of observations did not support this hypothesis to any great extent) but they could explain only smaller parts(and much smaller proportions)of the scatter when the point was at greater heights.

The cable charge and point space charge effects doubtless explained some of the residual scatter, although just how much is difficult to assess. Certainly any scatter would tend to increase with height (since the field due to the point space charge effect is roughly proportional to I/H and I increases even more rapidly than H^2) but a comparison of what values were obtained for the reduction of the field at the Mill with the graphs of I against F suggested that these effects could account for no more than half the scatter; especially since the field reduction would, to some extent, be causally related to wind speed and to current and hence, in the main, contribute to scatter only through variations of wind direction.

There are, of course, a variety of other factors which might contribute to the residual scatter but the only one which seems likely to be of major importance is normal space charge. Space charge in the atmosphere, other than the "point" space charge produced by the discharge, would have the effect of producing changes of field with height and with horizontal distance so that the field at the Mill would not always be representative of the "average" field between the point and the ground. Since point discharge current will depend on this average field rather than on the field at some particular point it is apparent that normal space charge will produce some scatter in the results. The contribution to the scatter due to variation of field with horizontal distance can be estimated from the experience of calibrating the Mill, in its various positions, against the Agrimeter: although the calibrations made in June 1952 showed little scatter, the scatter shown by one calibration which was made in September 1952 was often more than enough to explain the whole of the residual scatter when the point was at 50m. Some guide to the scatter due to the variation of field with height can be obtained from the work of Lecolazet (47) and Koenigsfeld and Piraux (43a). The former who measured field by means of a radio-active collector attached to a glider, reports one descent in which the field at 200m was 66 v/m compared with 59 v/m at the ground. The latter who used a radio-active collecter attached to a radio-sonde, found, in four ascents, decreases, by 200m of 32 v/m on 207 v/m, 10 v/m on 20 v/m, 15 v/m on 55 v/m and 0 v/m on 3 v/m. The range of variation of these observations is not very large, but since they cover only five occasions, on three of which there was no low cloud, the total possible range of variation is probably sufficient to explain the greater part of the increase of scatter with height.

Thus it seems probable that variations of normal space charge will explain a large part of the residual scatter, although an appreciable contribution may be made at the greater heights by the point space charge (and possibly cable charge) effect, at the lesser heights by the change of effective height with wind direction, and at the greater wind speeds by inaccuracies in the measurement of wind speed.

It will not be inappropriate here to make some brief mention of what might be termed the"fine structure"of the point discharge current, which appears in the sample record (Fig. 19) as fluctuations with a period of a few seconds and amplitude sometimes up to half a microampere. Although these fluctuations were too rapid to contribute appreciably to the residual scatter they may be regarded as a form of scatter and it will be interesting to attempt an explanation.

There appear to be three possible explanations.

(1) As the balloon "rolled" in turbulent air the point would tend to "escape" from the limiting space charge

in its immediate vicinity producing some general increase of current but probably also some fluctuations. This effect would probably be a small, but more or less constant, proportion of the steady discharge current, for a given degree of turbulence and would tend to decrease with decrease of turbulence and hence with increase of height and with decrease of wind speed. While it is difficult to estimate the absolute magnitude of this effect it is probably significant that the observed fluctuations agreed fairly closely with the predictions of relative magnitude. Thus it seems that the "rolling" of the balloon probably accounted for at least part of the "fine structure" of the discharge current.

(2) As the declination of the balloon changed, with change of wind speed, the induced charge on the current carrying wire would change; the excess or deficient charge flowing through the point discharge galvanometer would produce apparent fluctuations of the point discharge current. It is possible to estimate the magnitude of this effect. In section 3.2(a) it was shown that the charge on the wire = Kx per unit length where

$$K = \frac{-E \sin\theta}{\log 4h^2/r^2 - 2}$$

where h = length of wire
r = radius of wire
θ = declination
E = electric field

The total charge, q, will be $\int_0^h Kx\,dx = Kh^2/2$

Then current, $i = dq/dt = \dfrac{-Eh^2}{2(\log 4h^2/r^2 - 2)} \dfrac{d(\sin\theta)}{dt}$

From memory it is estimated that maximum $d\theta/dt = 0.25$ radians/sec. at h = 50m. Maximum $d(\sin\theta)/dt$ will occur at $\theta = \pi/4$ and be equal to 0.18. Maximum E at 50m was 250v/m = 0.0083 e.s.u./cm; so with r= 0.023cm (26 S.W.G.) this gives

$$\text{max. } i = \frac{0.0083 \times 25 \times 10^6 \times 0.18}{2(\log 10^8/5.6 \times 10^{-4} - 2)} \text{ e.s.u.}$$

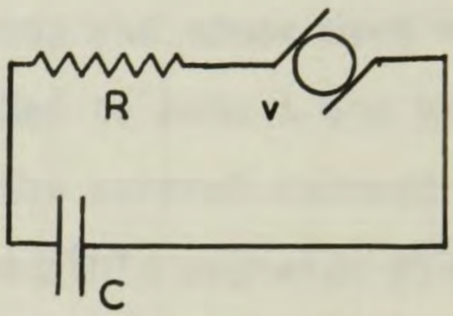
$$= 0.25\mu a.$$

At h = 200m, maximum $d\theta/dt$ was estimated as 0.06 radians/sec. and maximum E = 100 v/m giving maximum i = 0.35μa. The same effect would, of course, occur with changes of field butthe value of i would, in general be very much smaller. Thus it is apparent that this effect could also account for some of the "fine structure" of the point discharge current.

Some further evidence in support of this explanation was contained in a few of the recordings in which there were periods with no discharge current. In two cases the point discharge trace showed a slight fluctuation, symmetrical about the zero. This clearly could not have been true discharge current but might well have been due to changes in the electrostatically induced charge on the current wire.

(3) As the declination or bearing of the balloon

changed with change of wind speed or direction the current carrying wire would move in the earth's magnetic field and hence a voltage would be induced in it. An approximate equivalent circuit is given in which v represents the magnetically induced voltage, v, R represents the galvanometer and wire resistance and C the capacity of the wire to earth.



Since CR is small the voltage on C will follow changes of v very closely. The instantaneous charge q on C will therefore be given by q = Cv. The current i through R will therefore be given by $i = dq/dt = Cdv/dt = -Cd^2N/dt^2$

where N = number of lines of force cut by the wire. The area swept out by the moving wire will be $h^2\theta/2$ and therefore $N = Hh^2\theta/2$ where H is the earth's magnetic field. Therefore

$$d^2N/dt^2 = \frac{Hh^2}{2}\cdot\frac{d^2\theta}{dt^2}$$

It was assumed in the previous paragraph that at h = 50m max. $d\theta/dt = 0.25$ radians/sec. Suppose this angular velocity is reached in a tenth of a second. Then $d^2\theta/dt^2 = 2.5$ radians/sec^2.

Therefore $i = -CH \times 25 \times 10^6 \times 1.25$ e.m.u.

Taking H as 0.5 lines/sq.cm. and assuming that the wire moves in a plane perpendicular to this gives

$i = -C \times 1.6 \times 10^7$ e.m.u.

$= -1.6C \times 10^{-1}$ amps with C in farads.

Thus for a current of 0.16μa, C would have to be 1μF which is absurdly high. Since the result for a wire length of 200m is little different, and since most of the simplifying assumptions have tended to make i too big, it may safely be concluded that the current induced by the movement of the wire in the earth's magnetic field did not contribute to the "fine structure" of the point discharge current.

8.2. POSSIBLE FUNDAMENTAL IMPORTANCE OF VOLTAGE.

In the analysis of the results the effect, on point discharge current, of electric field and height of point were considered separately, and the presence of normal space charge was regarded rather as a tiresome source of scatter. It is, however, interesting to contemplate the possibility that these three parameters affect the point discharge current by virtue of the effect they have on the voltage between the point and the surrounding air at the same height, and that it is this voltage which determines the discharge current irrespective of the way in which it is made up by the three parameters. This possibility would not, of course, alter the effect of wind speed; or of any other parameters including, probably, normal space charge above the point.

The results contain no evidence on whether the effect of normal space charge below the point can be represented in this way but it is possible to consider the effects of field and height. The proposition that the onset of point discharge is associated with some critical voltage between the point and the surrounding air at the same height was considered in section 7.7(b) and although the results as they stand suggest that the probability of the truth of this proposition is rather low it becomes much higher when the effect of the surrounding trees and buildings is borne in mind. If then, this proposition is accepted the observations are satisfactorily represented by an equation of the form $I = bH^p(F^n - V_m^n/H^n)$. if $p = n$ this reduces to $I = b(V^n - V_m^n)$ where V is the voltage between the point and the surrounding air at the same height. What is the probability that $p = n$? It was shown in section 7.7(b) that n was probably between about 1.5 and 2, with a most probable value of 1.86 and in section 7.7(c) that p was probably between about 1.5 and 3 with a most probable value of 2.2 with $n = 1.5$, or 2.5 with $n = 2$. These figures show that there is quite a high probability that $n = p$, probbbly at least 1 in 3 and if some of the suspected systematic errors are taken into account the probability may be seen to be even higher as the following considerations will show. It was concluded in section 7.8 that the surrounding trees and buildings reduced the effective height of the point, especially at the lower heights. Oddly enough, because of the method used to determine V_m, this would not have much effect on the value of M used for the 50m observations, from which n was determined, and hence would not have much effect on the value of n. On the other hand it would decrease the curvature needed for the line representing the relation between a and H and hence reduce the value of p thereby bringing it closer to n.

Thus there seems to be a fairly high probability that under the conditions, and within the range of values, of this investigation the effects of field and height of point on point discharge current can be represented by the effect of the voltage they produce between the point and the surrounding air at the same height. It is almost certain that this theory would represent the results of the present investigation if some reasonable assumptions were made of the differences between the measured and effective heights of the point.

8.3. APPLICATION OF THE RESULTS TO THE BALLOON SOUNDINGS.

A single, isolated, discharge point connected to the earth, such as was used in the present investigation, is in many respects equivalent to half the length of the discharge wire used in the balloon soundings of Simpson and Scrase (76), Kreielsheimer and Belin (4, 5, 44) and Chapman (18) discussed in section 1.10. It will be remembered that Simpson and Scrase assumed the discharge current-field relation to be of the form $I = aF^2$ and found that $a = 0.03$ a/(v/cm)^2. It will be most interesting to calculate what value of a would be predicted by the results of the present investigation.

The rate of ascent of Simpson and Scrase's balloon was 5 m/sec (= 18 km/hr) and this is clearly the only "wind" to which the discharge will be subject. It is not, of course, quite the same as a cross wind of 18 km/hr but since there seems no particular reason for supposing it to be either more or less effective in increasing the discharge current it will serve to put W = 18 km/hr. Simpson and Scrase used a 20m length of wire so it will be appropriate to use H = 10m. In this case the final equation of section 7.7(f) (using n=2) reduces to $I = a(F^2 - M^2)$ with $a = 0.029$ a/(v/cm)^2 and $M = 2.9$ v/cm. The agreement with Simpson and Scrase's value is not quite so close as this suggests because of the following considerations. Since the values of c and d in the equation of section 7.7(f) are a little high a should be made a little lower; since one of the dischargers used by Simpson and Scrase consisted of six points a should be made a little lower still; and since they made M = 0 a should be made still lower. The net result of all these corrections might be to reduce a to say 0.02 $a/(v/cm)^2$ which is still of the same order as the value used by Simpson and Scrase and would merely increase their estimate of the maximum field encountered from 100v/cm to about 150 v/cm.

If n is taken equal to 1.5the present results give the formula $I = a(F^{1.5} - M^{1.5})$ with a = 0.033 $a/(v/cm)^{1.5}$ and M = 2.9 v/cm. If this is adjusted in the same proportion as before it gives $I = 0.023F^{1.5}$. Then a field of 650 v/cm with n = 1.5 would give the same current as a field of 150 v/cm with n = 2. In this case the maximum field encountered by Simpson and Scrase would be 650 v/cm. However, this is a very improbable result since (i) the probability that n is as low as 1.5 is not very high and (ii) the corresponding value of a was determined in the present investigation for currents up to only 7μa whereas Simpson and Scrase obtained currents of the order of 100μa and presumably included currents approaching this value in determining their value of a.

Thus although the present investigation suggests that the maximum field enoountered by Simpson and Scrase was probably a little larger than 100 v/cm, possibly even as large as say 300 v/cm, it does not make it comparable with the fields measured by aircraft in thunderstorms or the field just below a thundercloud predicted by Whipple and Scrase (90). It must, however, be emphasised that the present investigation does not preclude the possibility that the field estimates of the balloon soundings were seriously in error since the fields and currents encountered were comparatively small in the present case and the conditions of the discharge are not quite the same in the two cases.

8.4. APPLICATION OF THE RESULTS TO POINTS IN AN ARRAY.

It was emphasised in section 2.2(b) that results obtained for an isolated point are not, in general, applicable to one of an array of points. However, it seems fair to make a qualitative application of one of the present findings: namely that the total current through a close group of points is less than that through a single point under the same conditions. This confirms the findings of Chiplonkar (19) and makes it almost certain that the findings of Kreielsheiner (44) and Belin (4,5) in the laboratory (that discharge current is proportional to the number of points) do not hold in the atmosphere.

It therefore seems that the equivalence of a single artificial discharge point to a tree of about the same height is somewhat suspect. Whether this would lead to a reduction of the estimate of the point discharge current density below a thundercloud is, however, rather doubtful since most of the estimates are indirect and the only person to make a direct estimate, working on the number of trees per unit area and the assumption that a tree is approximately equivalent to an artificial discharge point was Wormell (99) and even he included only trees that were higher than his point. However, it is now clear that any attempt at a direct measurement of point discharge current density must either use a typical tree with typical exposure (such as a tree in a Forestry Commission plantation as suggested by Chalmers (12)) or must be preceded by a detailed study of the effect of the number of points in a discharger. (It will be remembered that Schonland's (73) estimate of current density is unreliable for the reasons stated in section 1.7.)

8.5. THEORETICAL CONSIDERATIONS.

Having established an empirical equation which reppesents the results reasonably well and considered its errors and possible applications it will be interesting to see if any theoretical justification can be found for it.

The effect on point discharge current of the various parameters will be considered in turn.

(a) Electric Field.

It was remarked in section 1.5 that point discharge current was distinguished from normal air-earth current by the ionisation by collision which occurs in the intense field close to the point leading to a current very much larger than the normal conduction current.

Chalmers (12) has considered the case of a rectangular array of points all discharging simultaneously in calm conditions. Since he has remarked in conversation that his theory can be readily adapted to the case of discharge from an isolated point in calm it will be well to give a brief outline of his theory here. He has avoided making any assumptions as to the nature of the ionisation process and assumed merely that it is confined to some small volume near the point (which will here be called the inoisation volume) where the lines of force are concentrated in sufficient density (in other words where the field is strong enough) for ionisation by collision to occur. If the field is, say positive, the positive ions produced will enter the point and the negative ions will travel upwards along the lines of force. Thus when the discharge is established some lines of force end on ions in the negative space charge instead of on the point, thereby limiting the field in the iônisation volume. A balance is thus set up whereby, for a given field, the current from the point provides just the right amount of space charge to limit the field in the ionisation volume to that appropriate to the current.

The negative space charge will move upwards and outwards through what Chalmers calls the "space charge volume", which will be bounded by the same lines of force that bound the iônisation volume. He then shows that for the space charge volume the following equation holds:

$$(XS)^2 - (X_0 S_0)^2 = 8\pi I v / w \qquad (8.1)$$

where X is the field at an equipotential surface of area S at a height x above the point and X_0 and S_0 have the same signifieance at the boundary between the space charge volume and the ionisation volume. I is the point discharge current, v is the volume of the space charge volume and w the ionic mobility. He assumes that these conditions hold up to a distance a above the point where X and S have values X_a and S_a and where the field and voltage (above earth) within the space charge volumes is equal to the field and voltage between the space charge volumes. Above this height he assumes that the space charge is rapidly diffused so that conditions are uniform in the horizontal plane. Now provided the shape and size of the space charge volumes are independent of field, the field

X_α at the height α above the point will be proportional to the field F at the ground between the points (ignoring the effect of normal space charge) so that equation(8.1) may be rewritten:

$$I = \frac{kwS_\alpha^2}{8\pi v}\left(F^2 - \frac{(X_0 S_0)^2}{kS_\alpha^2}\right) \qquad (8.2)$$

where $k = X_\alpha/F$ = constant.

If similar assumptions are made for the case of an isolated discharge point the same equation will result except that X_α will now equal F, the field at the ground remote from the point, and k will therefore equal 1.

Equation (8.2) may be rewritten:

$$I = a(F^2 - M^2) \qquad (8.3)$$

which appears to be of the same form as that used by Whipple and Scrase (90). Now k, w and S_α are clearly constants (if the shape and size of the space charge volumes are constant) and although v may vary slightly if the ionisation volume encroaches on the space charge volume this may be assumed to have a negligible effect. Thus a will be constant but M will be constant only if $X_0 S_0$ is constant. Since $X_0 S_0$ is a measure of the number of lines of force entering the ionisation volume it seems on the face of it, improbable that it will be constant. However, in order to decide whether or not it will be so it will be necessary to consider the details of the ionisation process and convenient to start by considering

Trichel's (80) theory.

For discharge from a negative point (which consists of a regular sequence of regular pulses) Trichel assumes that a pulse will occur when the field at the surface of the point is of such a value that a positive ion arriving at it will gain sufficient energy in its last free path to liberate a work function electron from the surface. This will be accelerated by the field and produce an electron avalanche. As the electrons travel away from the point into regions of lower field they will eventually slow down sufficiently to form negative ions and hence a negative space charge some little distance from the point. Meanwhile, the positive space charge left behind by the electrons will move into the point and initiate fresh avalanches until the pulse is eventually choked off by some process. Trichel assumes that this is due to the very rapid fall of field with distance from the point which occurs when the densest part of the positive space charge reaches the point so that the ions do not strike the point with sufficient velocity to liberate electrons. It then follows that when the bulk of the positive space charge has entered the point the last few positive ions will be able to liberate fresh electrons and hence start a fresh pulse. More recently, however, Loeb (51) has shown that far from producing a reduction of field the positive ions would initially produce an increase of field close to the point thereby assisting the build up of the pulse, and concludes that it is the negative space charge which is responsible for the choking off process -- because as positive ions enter the point their lines of force will not be replaced until the negative space charge is removed from the field.

If these condiderations are applied to discharge from a negative point in the atmosphere it seems that just at the end of a pulse the number of lines of force entering the ionisation volume will be at some low value and will gradually increase as negative ions either leave the space charge volume at the top or are blown out of the side by the wind. Then, when a certain critical value has been reached, a new pulse will occur and the number of lines of force entering the ionisation volume will again fall to the low value. Thus, since the pulses are all the same size, for a given point diameter, the number of lines of force entering the ionisation volume will oscillate between two fixed values and hence Chalmers' X_oS_o will on the average be a constant.

An exception to this general rule will occur if the number of lines of force entering the ionisation volumeis restored before the whole of the positive space charge has entered the point. Then, if Loeb's theory is correct, X_oS_o should fall slightly. Since Loeb quotes the duration of each pulse as about 0.5 microseconds this would occur for pulse frequencies greater than 2 Mc. and from Trichel's paper it would appear that this would correspond to a current of 200μa for a 0.25 mm diameter point.

Thus for currents up to about 200μa from a negative point in calm Chalmers' theory agrees with the empirical relation of Whipple and Scrase and is applicable both to points in a rectangular array and to isolated points. It suggests that in the present case the true value of n should be 2 and not 1.86.

The bulk of the theory is equally true for discharge from a positive point in calm although it is not possible here to assess the dependence of X_oS_o on current because of the imperfect knowledge of the ionisation process at a positive point.

(b) Wind speed.

It seems clear that the wind will contribute to an increase of current by removing charge from the side of the space charge volume in much the same way as the field removes it from the top. It has not been possible to derive theoretically any relation between wind speed and current which remotely resembled the present results but it may be remarked that whatever the relation is, some change may be expected (as in the current-field relation) when the pulse frequency from a negative point reaches 2 Mc.

It should also be noted that there seems to be no theoretical objection to the assumption made in section 7.7(b) that the minimum field for the onset of point discharge is independent of wind speed.

(c) Height of Point.

In his theory of a rectangular array of points Chalmers (12) found that by assuming specific shapes for the space charge volumes he could obtain expressions for the constant a involving h, the height of the points, and d, their spacing. The values of the powers varied widely for different shapes of the space charge volumes so, since similar results may be expected for the case of a single point it seems desirable to approach the matter in a different way.

If it can be shown theoretically that the discharge current is determined by the voltage between the point and the surrounding air at the same height, rather than by the undisturbed field and the height independently, then, when the relation between current and field for a given height is known, the effect of the height of the point is determined. For instance, suppose the current-field relation really is of the form $I = a(F^n - M^n)$

then the current-voltage relation would be of the form $I = b(V^n - V_m^n)$ and hence $I = b\left\{(\int_0^H F dH)^n - (MH)^n\right\}$ or, in the absence of normal space charge, $I = b\left\{(FH)^n - (MH)^n\right\}$

It seems that the field X close to the point could be reasonably well represented as the sum of two fields, one being a uniform field F of infinite extent (the undisturbed field), and the other, F', that due to a highly charged hemispherically capped cylinder (the discharge point and current carrying wire). This will differ somewhat from the actual configuration because the voltage of the current wire relative to the surrounding air, varies along its length. Close to the point, however, the difference should be small. The movement of the negative space charge can then be considered to be due to the sum of three effects -- the fields F and F' and the wind. Suppose that a point is set up at a height H in a given undisturbed field F and a given wind speed and that a given discharge current flows from it. Now suppose that F is, say doubled. This will double the voltage of the point and hence F'. Thus both F and F' will be doubled and a certain increase of current will result. Now suppose that instead of doubling the undisturbed field the height of the point is doubled. Then the voltage of the point, and hence F' will be doubled as before, but F will remain the same. Then, if the motion of the negative space charge is appreciably determined by F independently of the voltage of the point, doubling the height of the point will have produced a smaller increase of current than doubling the undisturbed field. Thus if the current depends on F^n and H^p p will be less than n. If, on the other hand, the undisturbed field does not influence the motion of the ions independently of the voltage of the point n will equal p and the behaviour of the current can be described in terms of point voltage without reference to the relative extent to which height and field contribute to that voltage. Now the motion of the ions of the negative space charge will be appreciably affected directly by the undisturbed field F only at and beyond the distance from the point at which F' falls to about F. At this distance the resultant field X will nowhere exceed 2F and if the velocity of the ions at this position due to their mobility, is very much smaller than their velocity due to the wind at least the bulk of them will have been swept out of the space charge volume by this distance and will no longer limit the discharge so that the undisturbed field will not directly influence the point discharge current.

Briefly then, it may be stated that if the wind speed is large compared to twice the product of the undisturbed field and the mobility of the ions, the discharge current will be determined by the voltage between the point and the surrounding air at the same height and not independently by the undisturbed field and the height of the point. If, however, the wind speed is below this value it is to be expected that the discharge current will increase more rapidly with increase of field than with increase of height. In both cases the onset of point discharge will occur at some critical point voltage since until discharge commences there is no space charge to be influenced by either of the fields or the wind.

In the present investigation the maximum undisturbed field was 2.5 v/cm so the velocity of the ions due to twice this field would be about 7.5 ~~v/cm~~ cm/sec. or 0.3 km/hr. Since the wind speed was mostly at least 10 times this it is to be expected that the present results can be represented adequately in terms of the voltage of the point -- as was found empirically in section 8.2. Unfortunately the present results do not contain sufficient observations for very low wind speeds to check the deduction that discharge current would then increase less rapidly with increase of height than with increase of field.

(d) Number of Points.

For a multiple point discharger it is clear that although the total number of lines of force ending upon it may be slightly greater than for a single point the number ending on each point will be noticeably smaller. (This, of course, does not conflict with the fundamental importance of voltage confirmed in the previous section since it requires a smaller charge to maintain a conductor at a given potential if there are other conductors nearby at the same potential.) Thus a larger undisturbed field will be required before the field at each point in a multiple discharger is high enough for the onset of discharge, thereby explaining qualitatively the observed increase in M.

Chalmers (12) has tentatively suggested that the reduced total current which Chiplonkar (19) found when he used a four-point discharger instead of a single point might be entirely explained by an increase in M. While this might well be true for calm conditions it seems that some decrease of a is to be expected in the presence of wind since some lines of force which would otherwise reach the leeward points of the discharger will end on the negative space charge of the windward points. The results quoted in section 7.7(e) certainly leave little doubt as to the reality of the reduction of a for the 8-point discharger although there is no clear evidence of the positive correlation between the magnitude of this reduction and wind speed which might be expected.

8.6. CONCLUSIONS.

An earth connected point 0.25 mm in diameter which is the only source of point discharge in the vicinity will discharge a current I given by

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

where I = point discharge current (up to 7 μa)

W = wind speed at the point (up to 15 km/hr)

H = height of point (up to 200m)

F = "undisturbed field" (the average electric field which would exist between the ground and the position of the point in its absence) (up to 250 v/m).

V_m= minimum voltage between the point and the surrounding air at the same height for the onset of point discharge.

c, d, p, n = constants.

Analysis of the observations shows that the value of n is probably a little less than 2 and that p is probably a little more than 2. If I is expressed in μa, W in km/hr, H in metres, F in v/m and V_m in volts, then $V_m = 2860$ and, if p is taken to be 2, then with n = 1.5, c = 1.19×10^{-8} and d = 12.7×10^{-8} or with n = 2.0 c = 0.97×10^{-9} and d = 11.6×10^{-9}.

Various systematic errors in the present investigation suggest that the values of c and d quoted are high by perhaps 10 to 30 per cent. They also suggest that the true value of p is a little lower than that given by the analysis and the theoretical considerations of section 8.5 suggest that n = p = 2. In this case the equation may be simplified to

$$I = (cW + d)(V^2 - V_m^2)$$

where V is the voltage between the point and the surrounding air at the same height. The effect of using a close group of 8 points is to reduce the total current by about 30 per cent.

In so far as the present results are applicable to the balloon soundings they suggest that Simpson and Scrase's (76) estimate of the maximum field they encountered should be increased from 100 v/cm to between 150 and, say, 300 v/cm.

The results confirm the findings of Chiplonkar (17), that using a number of points close together decreases the total current for a given condition, and so suggest that the current through a tree would be appreciably less than that through an artificial discharge point of the same height.

8.7. SUGGESTIONS FOR FUTURE WORK.

Although the final equation derived from the results represents the observations of the present investigation reasonably well there is considerable doubt over the true value of some of the parameters and, indeed, over the true nature of the equation. If point discharge is to form a reliable tool or if the empirically derived equation is to be an arbiter of theoretically derived equations these doubts must be reduced. It will be convenient to consider the various parameters in turn.

(a) Electric Field.

To study the nature of the current-field relation it would be best to operate with the point at quite a modest height, such that a discharge will occur in most fair weather conditions without being subject to undue scatter due to normal space charge and yet remain unique up to quite a high current. It would be a great advantage if the point could be rigidly mounted on some permanent structure rather than fixed to a balloon. The object should be to cover as wide a range of field as possible, taking note of other important parameters in order that their effects may be allowed for. In particular it would be most interesting if currents corresponding to a pulse frequency of greater than 2 Mc/s could be covered to see if any change occurs then in the current-field relation.

(b) Height of Point.

Any further study of the effect of the height of the point ideally requires a much more open site in order to eliminate the uncertainty over the effective height of the point.and a robust fabric balloon in order to limit the change of height with wind speed. In addition it would be advisable to take some measure of normal space charge, especially for heights of 200m and above, and to measure the field at two or three different distances to windward as a check on point space charge effect.

It might be possible to obtain some rather more prcise information on the effect of this parameter from the present results, if they were re-analysed using some estimate of the effective height of the point. Since the North-South cross section of the site was roughly constant for some distance to East and West of the mooring post such an estimate could be obtained from an electrolytic tank predictor.

In particular it would be interesting to obtain results at very low wind speeds and high fields to see if under these conditions point discharge current increases less rapidly with height than with field as predicted in section 8.5(c).

(c) Wind Speed.

The effect of this parameter could well be studied under the same conditions as suggested for electric field. The work could then readily be extended to much higher wind speeds to see if the current-wind speed relation remains linear.

(d) Number and Spacing of Points.

Although a study of this parameter will have little interest from the point of view of point discharge as a tool it should help towards a direct estimate of point discharge current density below a thunderstorm. There seems no great objection to making the study under the conditions suggested for (a) and (c) above so this would be preferable for the sake of getting results reasonably quickly — at least for an initial survey of the problem.

Finally, high speed oscillographic measurements of the discharge current might yield some information on the ionisation process and show whether there are any differences in that respect between laboratory and atmospheric point discharge.

Thus, if a fixed point can be set up at a height approaching, say, 50 metres, it should be possible to obtain much more detailed information on the effect of electric field, wind speed and the number and spacing of points on point discharge current. Furthermore, such a system will permit observations in disturbed weather and when discharge is occurring from lower natural points. For a better estimate of the effect of the height of the point the main requirements are a better site, a more stable and robust balloon and measurement of space charge. The oscillographic measurements should, ideally, be made with both arrangements.

THE END

SUMMARY

An isolated earth-connected discharge point 0.25 mm in diameter was raised to various heights up to 200 metres in fair weather by means of a captive balloon. Simultaneous observations of point discharge current, electric field at the ground 50 metres to windward, the height of the point and the wind speed and direction were made.

The observations can be represented by

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

where I = point discharge current in μa (up to 7)

W = wind speed in km/hr (up to 15)

H = height of point in metres (up to 200)

F = field in volts/metre (up to 250)

V_m = minimum voltage between ground and height of point for onset of discharge = 2860 volts.

c, d, p, n are constants.

The statistical analysis of the results showed that p was probably slightly greater than 2 and n slightly less than 2. However, certain suspected systematic errors in the results and some theoretical considerations suggest that both n and p have a true value of 2 and that the results can be represented by

$$I = (cW + d)(V^2 - V_m{}^2)$$

where V = voltage between ground and height of point.

Then, taking account of the suspected systematic errors, c is approximately equal to 8×10^{-10} and d is approximately equal to 9×10^{-9}

When a close group of eight discharge points was used instead of a single point the total current was reduced by about 30 per cent.

Some discussion is included on the scatter in the observations, the theoretical implications of the results and their application both to discharge from points in an array and to results obtained by other observers for balloon soundings of thunderstorms.

A detailed description is given of the apparatus used to measure the field which involved the application of electronic phase sensitive detection to the operation of the field mill.

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