Observations of the variation of precipitation electricity with height

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ABSTRACT

Previous workers have found evidence of negative space charge in continuous rain and that the precipitation current is greater at a height of 30 m than at ground level.

An investigation into these effects was carried out by making measurements of the precipitation current and potential gradient at the top of a mast and simultaneously at ground level. Unfortunately the investigation was brought to a premature end and the potential gradient measurements were rendered ambiguous through difficulties encountered when calibrating the instrument to be used on the mast. It was possible however to detect the presence of some space charge. The current at the top of the mast was found to be several times greater than that at the ground and their variations did not correspond exactly, suggesting that some charging process was operating in the lower 30 m of the atmosphere.

Observations of the Variation of Precipitation Electricity with Height

by

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PREFACE

The work described here was carried out as a joint research project by I.A. Raisbeck and the author. As a result much of the work was shared by them although Raisbeck was responsible for the design and construction of the agrimeter, rate of rainfall recorder and recording system. The author's main contributions were the construction of field mills and the development of the sign discrimination system. He also carried out the statistical analysis of the records.

The rationalised M.K.S. system of units has been used for all formulae except those derived experimentally where more practical units of charge and current ($\mu\mu$C and $\mu\mu$A) have been employed.

ABSTRACT

Previous workers have found evidence of negative space charge in continuous rain and that the precipitation current was greater at a height of 30 m than at ground level.

An investigation into these effects was carried out by making measurements of the precipitation current and potential gradient at the top of a mast and simultaneously at ground level. Unfortunately the investigation was brought to a premature end and the potential gradient measurements were rendered ambiguous through difficulties encountered when calibrating the instrument to be on the mast. It was possible however to detect the presence of some space charge. The current at the top of the mast was found to be several times greater than that at the ground and their variations did not correspond exactly, suggesting that some charging process was operating in the lower 30 m of the atmosphere.

CONTENTS

Chapter I INTRODUCTION

Interest was first aroused in precipitation electricity by its possible importance in bringing down negative charge to maintain the charge on the earth's surface which is being neutralised by the charge brought down by the fair weather conduction current. It is also generally accepted that the origin of the charge is closely related to the charge separation processes occuring in clouds so that information gained about the charge carried by the rain would help to throw light on these processes.

Kelvin (1860) had suggested that the electricity of precipitation should be investigated, but Elster and Geitel (1888) were the first to make observations of it. They used a collecting vessel which was shielded electrostaticly to avoid the displacement currents produced by changes in the bound charge accompanying potential gradient changes. They measured the charge reaching their collector in an interval of time with an electrometer. This method was used by a number of later investigators, notably Simpson (1909 and 1949). Other workers including Scrase (1938) found the charge carried by a known quantity of water by allowing the rain to run into a bucket which tipped up when full and simultaneously earthed the electrometer.

The main disadvantage of these methods is that the electrostatic shield might exclude a portion of the rain and the collecting vessel might only receive a few of the smaller drops, especially if there is a strong wind. This might be important if a significant part of the total charge is carried by small drops, as suggested by Smith (1955). Also the conduction current and any charging due to splashing in the potential gradient are excluded. Wilson (1916) made a few observations with an exposed receiver fitted with a guard ring so that charges lost from the receiver by water splashing off it would be balanced by splashes falling onto it. Schonland (1928) and Chalmers and Little (1940 and 1947) used a similar method and more recently Chalmers (1956), Adamson (1958) and Ramsay (1959) made observations with an exposed receiver and corrected for displacement currents.

Some of the earlier workers found a tendency for the precipitation current to be opposite in sign to the potential gradient, but not all later workers found this correspondance. However the results of Simpson (1949) dispelled all doubt of the existance of this inverse relation between the precipitation current and potential gradient. Later work has confirmed that the current is usually proportional to the potential gradient and of opposite sign to it. Similar results have been found for individual raindrops, although Smith (1955) found that the sign of a drop's charge depended on its size. With single drops the divergence from the average was found to be very great with drops of the same size and falling together having charges that differed in magnitude or even in sign.

The inverse relation can be explained by a charge separation in the cloud giving charge of one sign to the rain and leaving the other in the cloud to give rise to the potential gradient. Another explanation is the capture of point discharge ions by the raindrops (Wilson 1929) giving them a charge of opposite sign to the potential gradient. Point discharge does not usually occur except during thunderstorms, and in nimbostratus conditions this process is unlikely to be of primary importance. No satisfactory interpretation has been made of the results for nimbostratus rain although by considering that rain is formed in the same way as snow Chalmers (1958) has been able to draw some conclusions about the positions of charge separation processes.

In addition to the inverse relation many workers have observed that the potential gradient and precipitation current changed sign either simultaneously or with a short time lag, either the potential gradient or current leading. This has been named the mirror image effect and is an instantaneous relation whereas the inverse relation is a statistical one. It is possible to consider it to be due to the movement overhead of the charges in the clouds as the clouds are blown past. If the wind is of uniform strength between the cloud and ground the rain is always directly below the part of the cloud where it originated. The time lags sometimes observed can be explained if the wind strength varies. On the other hand the effect may be explained by the rain gaining its charge by some process which operates near the ground.

Most workers have only made their observations at ground level although Gunn (1950) measured the charges on precipitation inside a thunderstorm. However, Kelvin (1860) and Chauveau (1900) measured the potential gradient, but not the precipitation currents, at the ground and simultaneously at the top of a tower. They both found that during steady rain the potential gradient was usually negative but occasionally the potential gradient at the top became positive while that at the bottom remained negative. Chauveau also observed that changes in potential gradient at the top were less pronounced than the corresponding changes at the bottom and that sometimes a change of sign at the bottom was only accompanied by a diminution of the potential gradient at the top.

The difference in sign of the potential gradient at the top and bottom indicates the presence of a negative space charge and if its density varied the potential gradient at the bottom would also vary and if the space charge were confined to the lower layers of the atmosphere so that most of it was below the top of the tower the changes would be smaller at the top.

Several suggestions have been made to account for the production of this charge. Lenard (1892) found that when drops splashed a negative charge was given to the air which could lead to a negative space charge near the ground. Recently however Gill and Alfrey (1952) have questioned the existence of any charging by this process. It has also been found that when drops are shattered by air blasts a negative space charge is produced, but drops of the size of ordinary rain drops are very stable and it is improbable that the gusts of wind near the ground are strong enough to shatter them. Adkins (1959a) suggested that the precipitation was in fact snow at the top of the tower and that this melted before reaching the ground, the melting being accompanied by a charge separation process. However Chauveau reported that the effect occurred quite frequently and it is unlikely that he would not have observed any snow that fell.

Merry (1959) continued the work of Kelvin and Chauveau by making simultaneous measurements of the potential gradient and precipitation currents at the top and bottom of a mast, but was only able to make recordings on two occasions. He did not report differences in the sign of the potential gradient at the top and bottom of his mast, but he did observe, at both places, the inverse relation between potential gradient and precipitation current and the mirror image effect which are well known for observations at the ground. His most interesting observation however was that the current at the top was several times larger than that at the bottom.

The present work was to be conducted on the site used by Merry as a continuation of his work. It was hoped that it would be possible to take a large number of results which would enable an explanation to be found of the 'Kelvin-Chauveau' effect and that some information might be gained about the origin of the charges on the precipitation. It was in fact only possible to make a few recordings before October 1962 but these showed some interesting features and it is intended to continue the work.

Chapter II THE EQUIPMENT

The Equipment Required

As the problem was to investigate the rain currents and potential gradients at the top and bottom of the mast, the basic equipment had to consist of two potential gradient measuring devices and two rain collectors. A further potential gradient measuring device was required to provide a standard by comparison with which the others could be calibrated. As the rain current was known to be considerably effected by the rate of rainfall, a rate of rainfall recorder was also required.

Previous workers (Ramsay 1959, Merry 1959) had used rain collectors of similar design to that of Scrase (1938), collecting the rain in a shielded receiver and allowing the charge carried by it to flow to earth through a Vibrating Reed Electrometer. Ramsay had compared the currents registered by shielded and unshielded receivers and had found little difference between them. The shielded type had the advantage that displacement currents and conduction currents were eliminated. This was important as at the top of the mast the potential gradient was exaggerated giving an increased conduction current. As it was simple to construct and the VRE's were available the design was adopted.

The simplest potential gradient measuring devices were the field mill and the agrimeter. The latter was simple in construction and gave the sign of the potential gradient without trouble, but would only operate in high potential gradients unless of large size. The field mill gave a large output even in small potential gradients, and which could easily be amplified as it was in the form of an AC voltage. However, with this instrument the determination of sign gave considerable trouble. Thus an agrimeter seemed suitable for use at the top of the mast where the potential gradient was very high, while field mills would be necessary at the ground. The one at the bottom of the mast would have to have sign discrimination, but the other would not as it would only be used when conditions were uniform.

It was desirable that the rate of rainfall recorder should be direct reading and be sensitive to rates as low as 0.15 mm/hr. Conventional recording rain gauges gave the rate of rainfall from the slope of the record and their sensitivity was low. A more sensitive model had been developed by Ramsay, but the rate was again given by the slope of the record. However an electronic type developed by Adkins (1959c) gave a direct reading and it was decided to use this method.

The Site and Mast

The mast, situated in a field about 100 yds west of Durham

Observatory was a three pole structure 90ft high and was held up by guylines. As no ladder was fitted and there was no platform on it previous workers had experienced trouble servicing equipment that had developed faults, it usually being necessary to remove the equipment completely. In order to simplify this problem it was decided to fit all the equipment which would be used at the top, to a platform which could be raised to the top with ropes and brought down again if any faults arose. All repairs could then be carried out in comparative comfort on the ground.

To this end a rectangular frame was constructed which projected over one side of the top of the mast. Ropes coming up from the movable platform on which the equipment was mounted passed through this and then down the inside of the mast so that the platform could be hoisted up to the top with the assistance of a counterweight moving inside the mast. More ropes on the outside of the mast facilitated lowering it.

Boxes containing the power supplies for the equipment and the VRE indicator units were situated near the base of the mast. Cables connecting the equipment to the Observatory were carried across the field on short 'T' shaped posts so that they would not get overgrown or accidently cut when the field was mown and at the same time would not be high enough above the ground to cause any serious distortion of the

Fig 1

potential gradient, especially in the region of the calibrating pit.

The calibrating pit (Fig. 1) was about 100 ft from the mast and as far as possible from the nearby trees and fences in order that the potential gradient near it would be as little distorted as possible. The pit was covered with a metal plate level with the ground so that a field mill facing up through a hole in the middle would measure the 'natural' potential gradient under the same conditions as when it was calibrated.

Unfortunately, before all the equipment was ready for use the guys of the mast became slack and it became slightly twisted. As the firm who originally supplied it had gone out of business, experts from other firms were consulted and they declared that although the mast could be repaired they would be unable to do the work as it was a type of mast they were not used to and its fittings were not standard. However the Electricity Board offered to supply a tower such as they used for power lines and which had no guys. This was normally only 35 ft high but could be fitted with a 40 ft extension to bring it up to 75 ft.

In due course this was erected on the site of the old mast (Fig. 2). Unfortunately it proved difficult to climb,

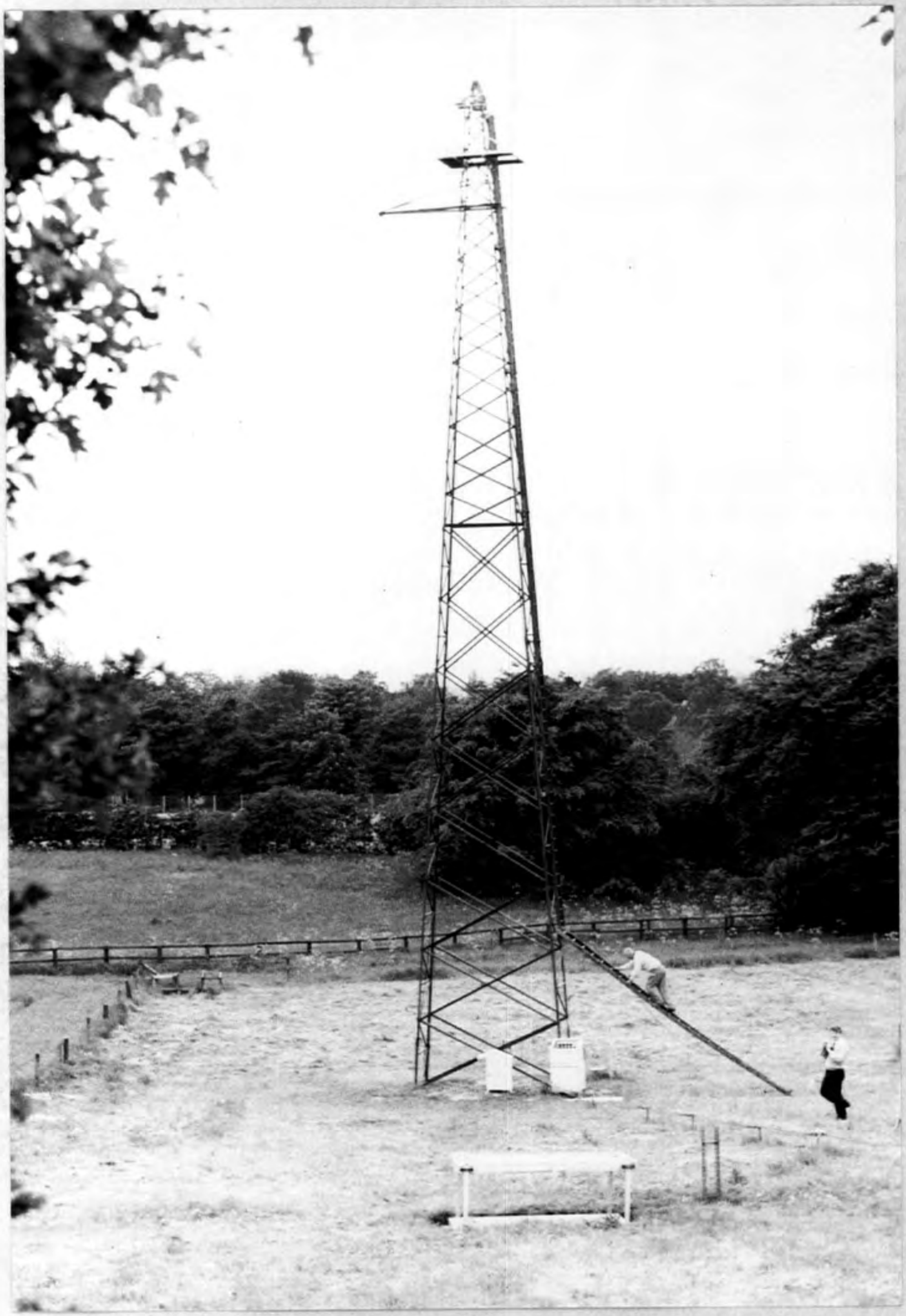


Fig 2

but a special ladder was ordered and pending its arrival a temporary one was fitted. A platform was also constructed to facilitate work at the top. This was a robust structure 4 ft. square with the top 5 ft of the tower projecting through it. In view of the comparative ease of working that this provided it was decided not to construct another pulley system but to fasten the equipment directly to the tower.

All the equipment was then installed except for the rate of rainfall collector which was still incomplete. The agrimeter had previously been calibrated in the pit to avoid hoisting it up and down more than was necessary.

Unluckily, only six weeks after recordings were started the tower was blown down in a gale, the gusts apparently responsible had speeds of over 85 mph. Some equipment was damaged, but in the main only superficially, although the tower was badly battered. Fortunately it was possible to salvage most of it and the Electricity Board very soon began reconstructing it, but when it was 15 ft above ground work stopped through lack of skilled men and was not recommenced until it was too late to do any further recording.

The Rain Collectors

These were constructed on the same lines as those of Scrase (1938) but without the tipping bucket arrangement (Fig. 3). The inner cone was electrostatically shielded as well

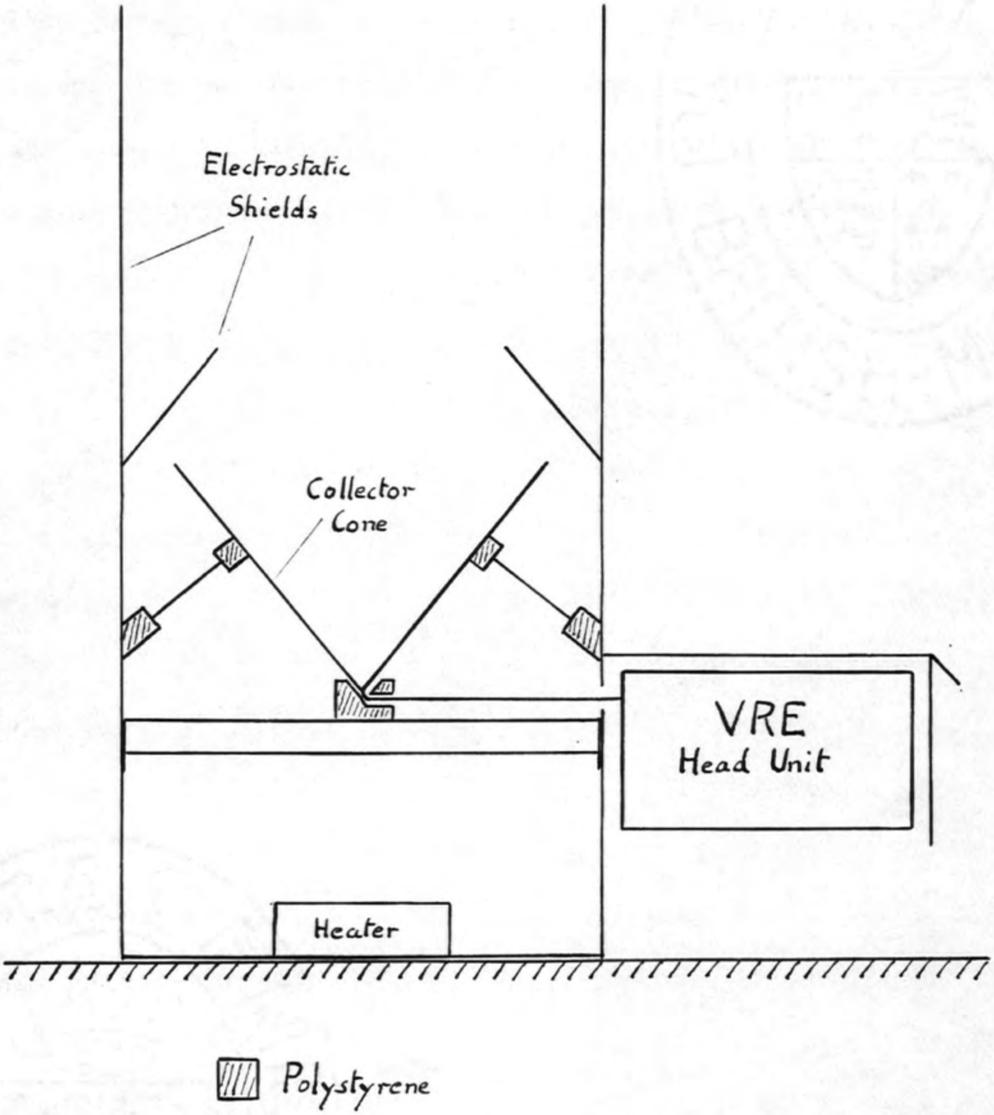

Electrostatic Shields
Collector Cone
VRE Head Unit
Heater
▨ Polystyrene

Fig 3

as possible to reduce the potential gradient at its surface in order to eliminate displacement currents and to reduce the spurious charges produced by drops splashing in a potential gradient. This cone which was to catch the rain was constructed of zinc sheet so that the joints could be soldered to make them waterproof. The cable from it to the VRE Head-Unit was clamped firmly to a supporting girder to prevent any microphonics.

The insulators were kept dry by sealing the joints in the conical shield with Araldite to prevent water running onto them, and by providing heaters to evaporate condensation. These consisted of two 100 w light bulbs wired in series to lengthen their lives and enclosed in earthed aluminium boxes to eliminate mains pick-up.

The VRE's used by previous workers were in good condition and after a few minor repairs worked well. They were used with the rain collectors as DC amplifiers measuring the voltage generated across a high resistance by the rain current as it flowed to earth through it. The Indicator Units were housed in a specially designed box at the foot of the mast as they could not be separated from the Head Units by more than 200 ft, and their outputs were taken to the Observatory along shielded cables.

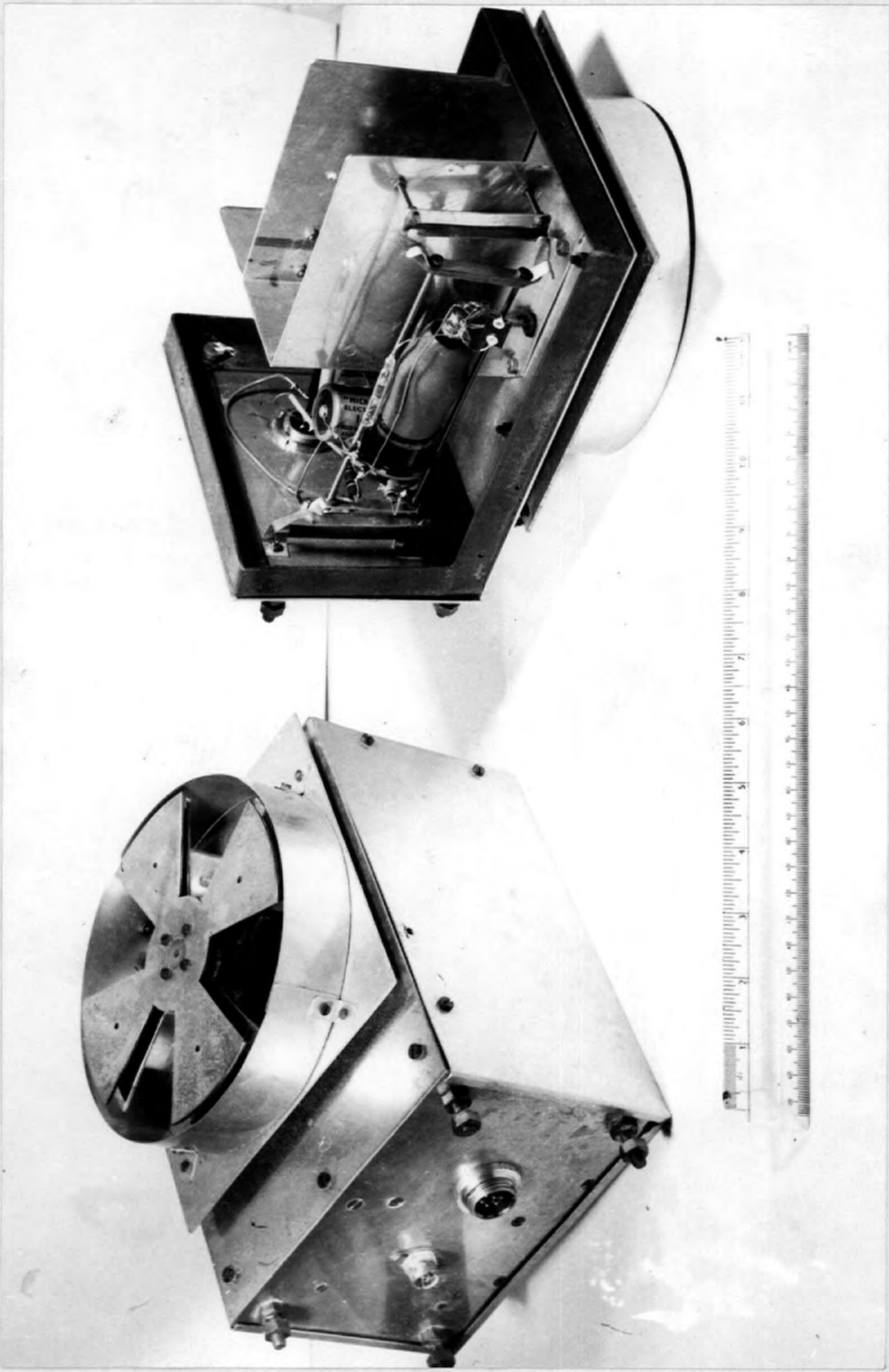


Fig 4

The Field Mills

Two of these were needed, one with sign discrimination for actual observations and another for use as a standard so that the exposure factors could be determined. As already noticed this one did not need any means of sign discrimination. The type developed by Whitlock (1935) appeared the most suitable and the group was experienced in its use. It consisted of cross shaped collector plate and rotor and incorporated an electrostatic generator operating synchronously with the rotor and rectification was effected by a phase sensitive detector (Schuster 1951).

The vanes and motors were taken over from machines used by a previous worker. They were mounted on a plate which was supported by anti-vibration mounts on the main chassis. The chassis was constructed of steel angle and designed to make the interior as accessible as possible. The motor was shielded to prevent pickup and the cathode followers (Fig. 5a) mounted in elastic bands on one side of the shield and a small power pack on the other (Fig. 4).

The amplifier was adapted from a design used by Milner (1961) (Fig. 6). The Schuster circuit was included in the feedback loop in the manner of Whitlock. For the 'calibrating mill' only Milner's circuit was used.

Previous workers had experienced some difficulty with

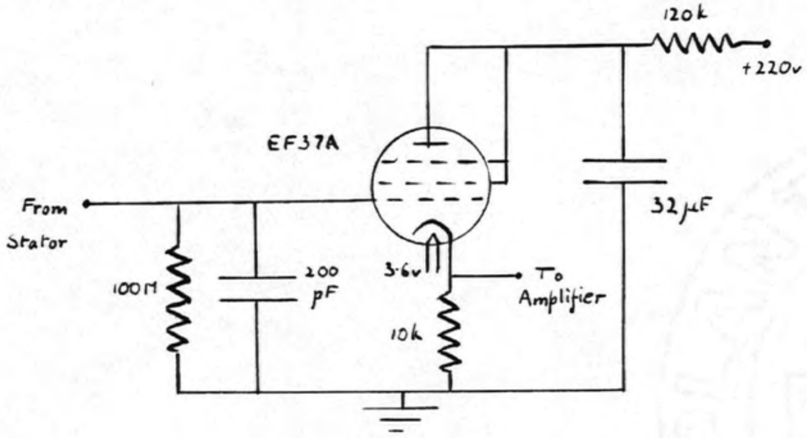

120k
+220v
EF37A
From
Stator
100M
200
pF
3·6v
To
Amplifier
10k
32µF

Fig 5a

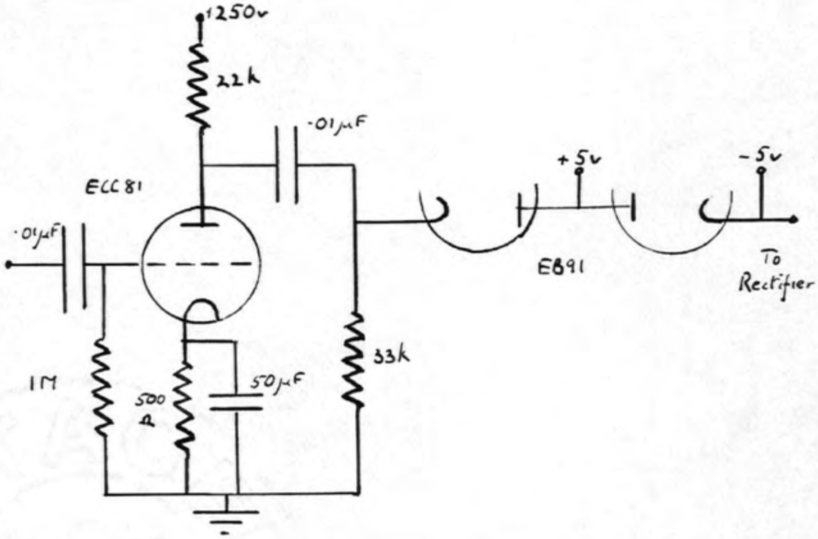

+250v
22k
·01µF
ECC81
·01µF
+5v
-5v
EB91
To
Rectifier
1M
500
Ω
50µF
33k

Fig 5b

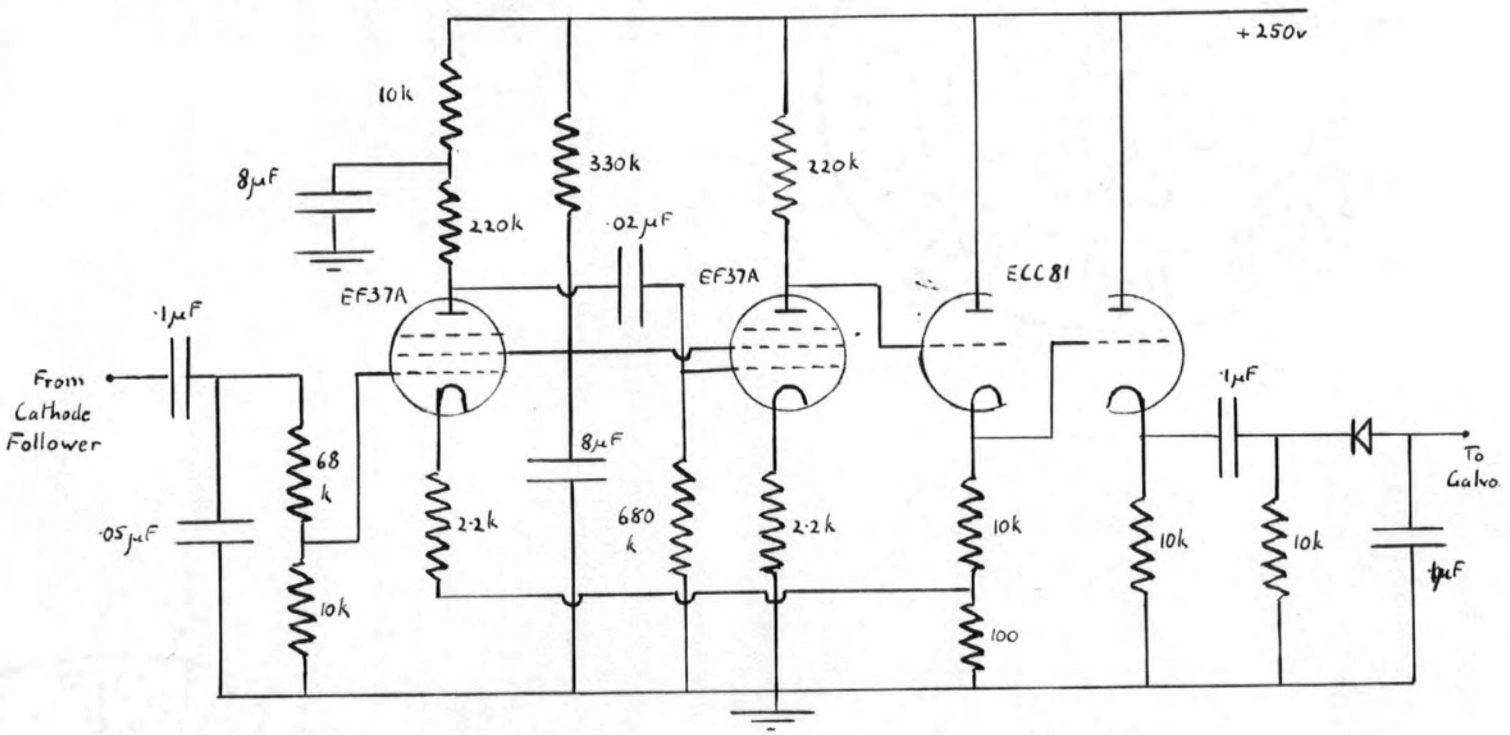

+250v
10k
8µF
220k
330k
·02µF
220k
EF37A
EF37A
ECC81
From
Cathode
Follower
·1µF
·05µF
68
k
10k
2·2k
8µF
680
k
2·2k
10k
100
10k
·1µF
10k
To
Galvo.
·1µF

Fig 6

the rectifier since fluctuations in the size of the reference signal had a considerable effect on the amplification and also caused zero drift. It appeared that humidity had some effect on the size of the signal, but as no means could be discovered to keep it constant it was decided to shape it electronically. This was done by amplifying it to about 40v and then 'limiting' it by passing it through two diodes which were biassed to cut off at +5v and -5v (Fig. 5b). However this did not operate very satisfactorily, probably because the diodes were operating at the intermediate part of their characteristics so that they were acting as variable resistors. Despite this some improvement was made on Whitlock's instrument for which he gave the drift to be 10% of full scale for a 20% change of reference signal amplitude.

Following this rather unsuccessful attempt other methods of sign discrimination were considered. The simplest appeared to be that of shifting the zero by means of a synchronous auxillary generator which gave a 'zero signal' of constant size and phase, but much larger than the maximum expected output of the mill so that for positive potential gradients the signals would add and for negative potential gradients where the mill signal changed phase they would subtract. This meant that the resultant never went down to zero. The greatest difficulty with this method would have been that the auxilliary signal would have had to have been constant to within very narrow limits, for if the mill was to measure potential gradients between only +1000v/m and -1000v/m and was expected to have an accuracy of 5% in the range ±50v/m the magnitude of the auxilliary signal would have to be constant to better than 0.3%. If a more versatile instrument had been required which would have measured the high potential gradients occurring in very disturbed weather an even greater accuracy would have been required. In addition it would have been necessary for the auxilliary signal to have been as closely as possible the same shape as the mill signal, for, in an extreme case, if the auxilliary signal had been a square wave and the mill signal in the form of sharp pulses the signal would have added satisfactorily, but the difference would have had the same amplitude as the auxilliary signal and so any negative potential gradients would have been recorded as zero.

This indicated that difficulty might be experienced with an electromagnetic generator. An electrostatic generator of the same design as the rotor-stator assembly could have been used, or the rotor-stator assembly itself would have given a zero signal if a voltage had been applied to the rotor. In either method variations of the voltage or of the rotor-stator separation would have caused fluctuations in the signal amplitude. Although it would have been possible to stabilise the voltage by using a conventional stabilising circuit, the inevitable slackness of the motor bearings would have caused variations of the rotor-stator separation. It seemed probable that this would have given rise to quite short term fluctuations which it would not have been possible to follow even by quite frequent zero checks.

The most accurate instrument of the field mill type would have been one consisting of only the rotor-stator assembly, amplifier, simple rectifier and recording system. Additional equipment to determine sign would have introduced inaccuracies in the form of zero drift and amplification changes. Although it might have been possible to take account of these by frequent use of a 'test plate' to cover the mill and produce a known potential gradient, such a process would have wasted recording time and either imposed a considerable burden on the experimenter or required a quantity of automatic equipment.

It proved possible to develop an instrument which operated as well as a simple one without sign discrimination, but which nevertheless gave the sign of the potential gradient by means of an 'indicator' similar to that used by Malan and Schonland (1950) who increased the area of their collector and thus increased the output at the beginning of every ninth covering operation. This enlarged the peak or trough of the corresponding wave, depending on whether the potential gradient was positive or negative. They recorded by photographing an oscilloscope trace since they were interested in very short term fluctuations. As such an indicator would have had a frequency of about 50c/s it would have been recorded on a film moving at 1cm/min merely as a zero deflection. In order to obtain an indicator with a suitable time scale a different procedure was followed. This was to make the output of the mill more positive for a few seconds every half minute.

This was done with an auxilliary generator, actually the rotor and stator with a voltage applied to the rotor by connecting the earthing brushes to earth via a battery. The voltage was not sufficiently high to make all potential gradients appear to be of the same sign as in the instruments already mentioned, but only enough to give a slight shift in the positive direction. The effect of the voltage can be seen by considering the theory developed by Whitlock (1955).

When the stator is fully exposed it has a bound charge of:

$$\varepsilon_0 E \left(r_2^2 - r_1^2\right) \frac{N}{2} \phi$$

Where E is the potential gradient, N the number of vanes, r_1, r_2 the internal and external radii of the vanes, and ϕ the angle of the sector formed by one vane and gap. When the stator is fully shielded this becomes:

$$\varepsilon_0 \frac{V}{d}\left(r_2^2 - r_1^2\right)\frac{N}{2}\phi$$

Where V is the voltage on the stator and d is the rotor-stator separation. V/d corresponds to the artificial potential gradient applied to the stator by the charged rotor. At an intermediate position the bound charge is:

$$\varepsilon_0 E\left(r_2^2-r_1^2\right)\frac{N}{2}wt + \varepsilon_0\frac{V}{d}\left(r_2^2-r_1^2\right)\frac{N}{2}\left(\phi - wt\right) = \varepsilon_0\left(r_2^2-r_1^2\right)\frac{N}{2}\left(Ewt + \frac{V}{d}\phi - \frac{V}{d}wt\right)$$

w/N is the angular velocity of the rotor and t is the time from the beginning of the shielding. This gives a current of:

$$\varepsilon_0\left(r_2^2-r_1^2\right)\frac{N}{2}w\left(E-\frac{V}{d}\right)$$

If the stator has a resistance R and capacitance C to earth, Whitlock shows that when a steady state has been reached the peak voltage across R is:

$$\varepsilon_0 wR\frac{N}{2}\left(r_2^2-r_1^2\right)\left(E-\frac{V}{d}\right)\frac{1-e^{-\pi/NwRC}}{1+e^{-\pi/NwRC}}$$

Since R is made very large this approximates to:

$$\frac{\pi\varepsilon_0}{4C}\left(r_2^2-r_1^2\right)\left(E-\frac{V}{d}\right) = V_R$$

Thus $V_R \propto E-V/d$

As the value of V_R corresponds to the amplitude of the output signal and the sign only effects the phase the amplifier

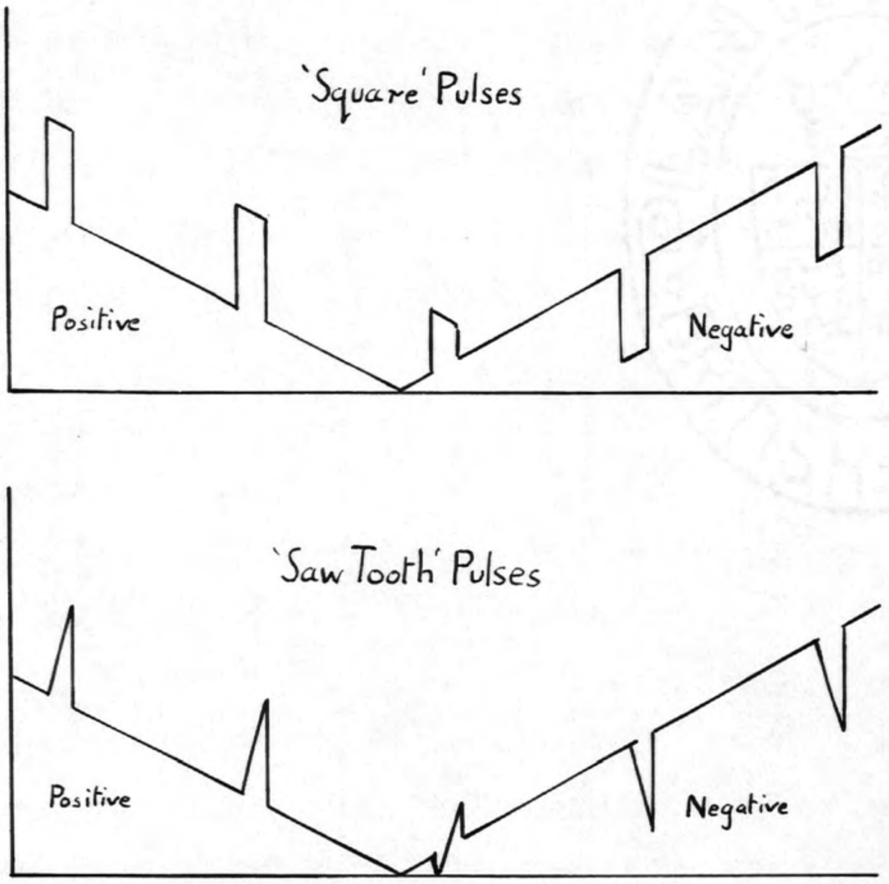

'Square' Pulses
Positive
Negative
'Saw Tooth' Pulses
Positive
Negative

Fig 7a

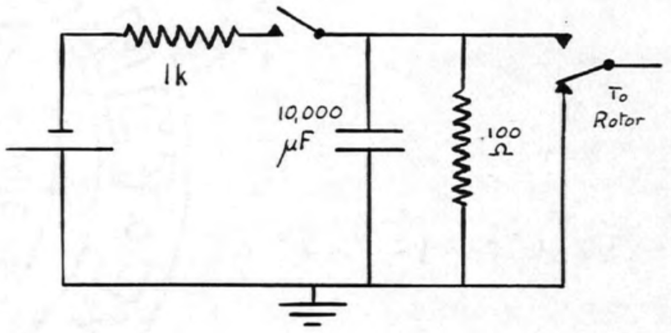

1k
10,000
μF
.100
Ω
To
Rotor

Fig 7b

output gives the modulus of V_R i.e. $|E-V/d|$. V/d is usually much smaller than E so that for positive E $|E-V/d| > |E|$ and for negative E $|E-V/d| < |E|$. If the voltage supply is only connected in for a few seconds at a time then normally $|E|$ is recorded, during the short interval when $|E-V/d|$ is recorded it shows as a pulse either above or below the line corresponding to $|E|$ depending on the sign of E.

The pulse was made to be of short duration so that the record of $|E|$ was effectively continuous and during most of the tim e the instrument was operating in its simplest condition so that its performance was as reliable as possible. The voltage for the pulses was taken from a potential divider across a 1.5v cell. The values of the resistors used had to be quite low as if the resistance of the rotor to earth was more than a few hundred ohms stray charges from frictional or other effects were not removed rapidly enough and the signal became 'grassy'. The pulses were produced by a change-over switch operated by a synchronous motor. The switch was of the 'make-before-break' type to avoid isolating the rotor from earth for any part of the pulse (Fig. 7b). The pulses produced by this means were approximately square which was suitable for all but small negative potential gradients. For if the potential gradient was negative and less than the pulse height then the application of a pulse

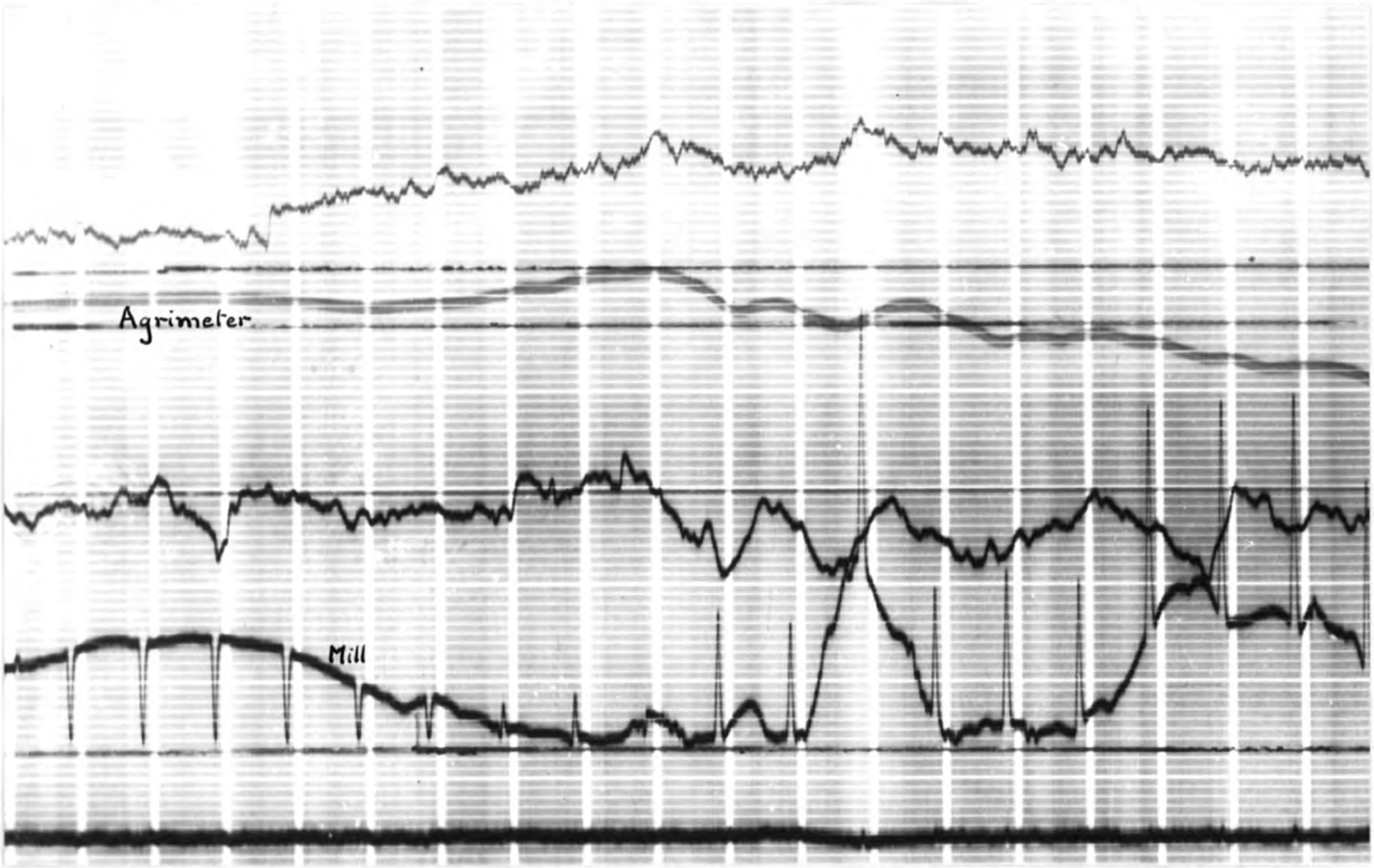


Fig 8

made the resultant apparent potential gradient positive and possibly greater than the original negative potential gradient. This gave a small positive pulse which could have caused ambiguity of sign. As the pulses had a finite rise time the apparent potential gradient fell to zero before rising to give the positive pulse and this would have got over the ambiguity if the recording system had had a sufficiently short response time. As it had not, it was necessary to lengthen the pulses' rise time by giving it a saw-tooth shape by adding a large condenser across the resistor in the potential divider, so that the voltage across it rose slowly when the cell was connected (Figs. 7a, 8). It was found that a time constant of about 1 sec was needed before the recording system showed the change in direction of the pulse. The pulse unit was housed in the box at the bottom of the mast together with the 25v DC supply for the motors and these were connected to the mills by six core cables.

Some trouble was experienced with pickup from the mill motors. It was at first intended to use the motor DC supply for the valve heaters but during trial runs a large amount of sparking was apparent on the output, and apparently originated on the commutator. Some of this was found to be transmitted via the valve heaters but some appeared at the input to the valve. This seemed to be due to imperfect earthing of the motor case which had been isolated from the chassis of the mill and earthed through the rotor brushes. This was simpler than isolating the rotor from the shaft which would otherwise have been necessary for the application of pulses. Pick-up from the commutator was being conducted to the rotor and there inducing a signal onto the stator. This was reduced considerabl by insulating the rotor from the shaft with a specially made bush and the slight residual removed by putting a small condenser across the cathode resistor of the cathode follower. The mills were mounted on stands so that they faced downwards to prevent the accumulation of rain on the vanes, and guard rings were attached round the vanes to prevent it getting on the insulation.

The Agrimeter and the Rate of Rainfall Recorder

Both these instruments were constructed by Raisbeck and he gives a full account of them in his thesis, but for completeness they will be briefly described here. The agrimeter, (Chalmers, 1953), operated by exposing an earthed plate to the potential gradient which induced a bound charge onto it. The plate was then disconnected from earth and shielded from the potential gradient and its charge allowed to flow to earth through a galvanometer. This sequence was repeated rapidly so that a current flowed through the galvanom eter, its magnitude indicating the strength of the potential gradient. The instrument was made considerably smaller than Chalmers' since it was to be used at the top of the tower where the potential gradient was considerably distorted. After suitable adjustment of the motor speed and protection of the signal plugs from the rain it gave little trouble.

The rate of rainfall recorder was developed by Adkins (1959c) and consisted of a funnel into which the rain fell and from which it emerged as a train of equal sized drops, the frequency of which gave the rate of rainfall. The drops were made to form an electrical contact between two wires to give voltage pulses, the frequency of which was measured electronically.

The Recording System

The best means of recording available was to use galvanometers and a camera with a moving film. Suitable instruments were found and set up and after considerable adjustment were made to give traces which were as fine as possible but which also had different intensities so that it was possible to recognise the records of different instruments. The lens of the camera had a scale scratched on it so that when the whole film was darkened by means of a 'fogging lamp' a series of lines was produced to give a means of measuring deflections across the paper. A time scale was produced by switching off the 'fogging lamp' for a few seconds at


COLLECTOR A
COLLECTOR B
MILL A
RECORD
MONITOR
IN
OUT
MONITOR
OUT
IN
ACRIMETER

Fig 9

half minute intervals. This was done by a switch operated by a asynchronous clock motor.

This equipment was set up in a recording room at the Observatory that could be kept permanently dark. The galvanometers were mounted on a pillar with independent foundations so that vibrations caused by movement in the room would not effect them. The sensitivities of the galvanometers were adjusted by means of Ayrton shunts. The values of the shunting resistors could be varied with a selector switch to give a series of sensitivities. These proved adequate for all recordings that were made and it was not necessary to alter the gain of the amplifiers. The switches were mounted on a monitoring panel, on a rack together with the amplifiers and other electronics (Figs. 9). Also on the monitoring panel were microammeters to show the outputs of the instruments, so that suitable sensitivities could be chosen. As the output from the agrimeter was too small to register on a microammeter its output was shown on a high sensitivity 'Scalamp', however even on this it only gave a deflection of 1 cm for a potential gradient equivalent to 2000v/m at the ground. Nevertheless, this was adequate for the selection of sensitivities.

The rack holding the electronic equipment was situated in the corner of the laboratory where the cables were led in from the field to minimise the length of cable used, and so that a good view could be obtained of the weather conditions in the field while monitoring the equipment.

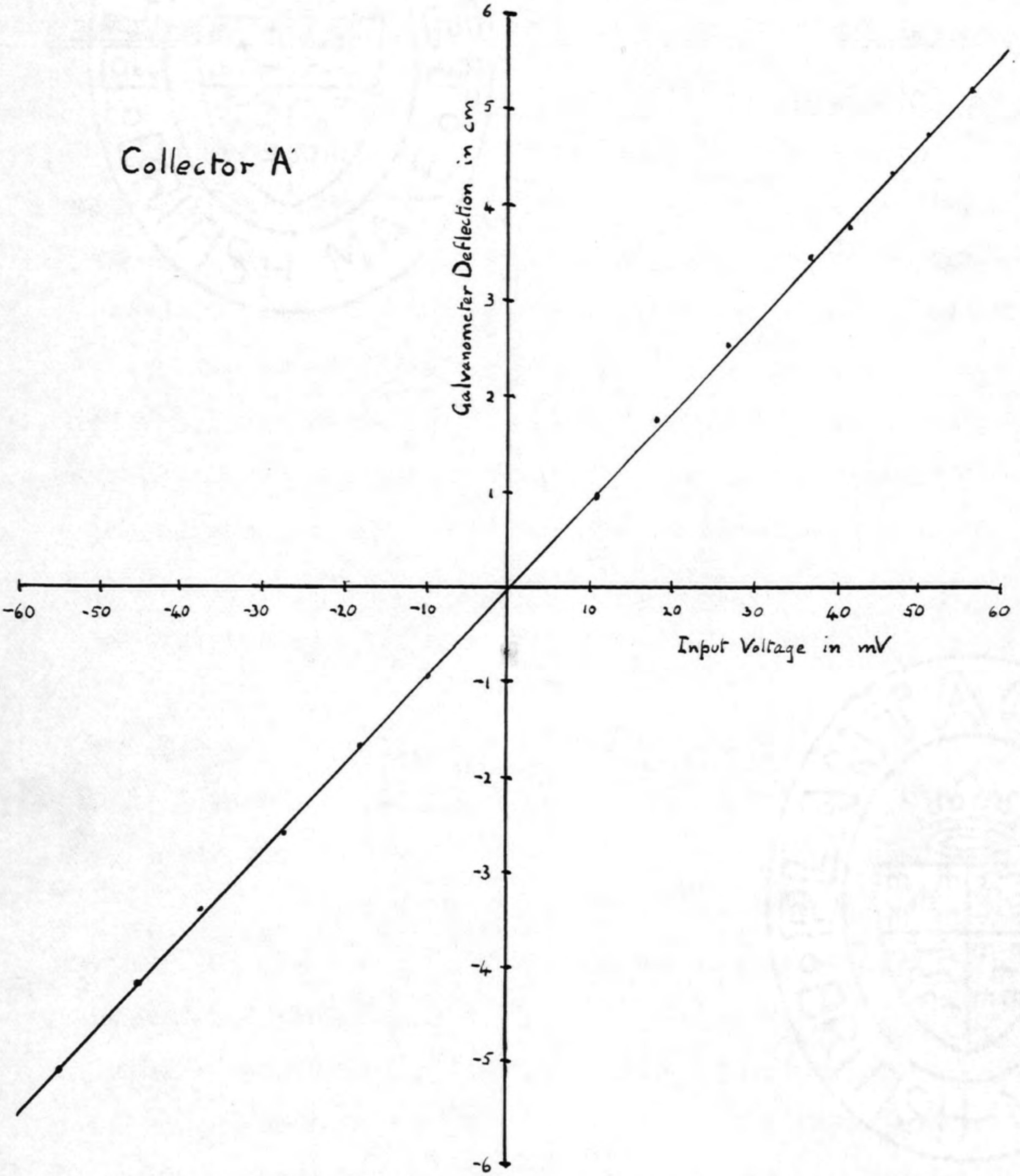

Collector 'A'
Galvanometer Deflection in cm
Input Voltage in mV
6
5
4
3
2
1
-1
-2
-3
-4
-5
-6
-60
-50
-40
-30
-20
-10
10
20
30
40
50
60

Fig 10

Chapter III CALIBRATION AND PERFORMANCE OF THE EQUIPMENT

The Rain Collectors

As the current produced by the rain was found by measuring the voltage generated by it across the high input resistor of the VRE, it was necessary to calibrate it in terms of the input voltage and also to measure the input resistor. The VRE was always operated on the 300 mv range and only exceptionally large currents would give full scale deflection, so that the amplifier would never be overloaded and it would be possible to change the sensitivity without leaving the Observatory. Frequently the output was small, but the galvanometer used was sensitive enough to record it.

The voltage calibration of the VRE was performed by shorting out the input resistor to avoid spurious signals and inserting known voltages into the feedback loop via a special calibration socket (Fig. 10).

The input resistor was carefully removed from the head unit and its value found by allowing a standard condenser to discharge through it for given times and then finding the time constant of the combination. From this, as the values of the capacitance and leakage resistance of the condenser were known, the value of the resistance could be calculated. The values of the resistors used were quoted by the makers to be $10^{10}\Omega$ ± 20%. The measured values were $1.08 \times 10^{10}\Omega$ and $1.07 \times 10^{10}\Omega$ which had an estimated error of ± 2%.

When the recording apparatus was first connected some difficulty was experienced as the output of each VRE appeared to follow the reading of the other, even if one of the VRE's was not switched on. They also gave a large zero deflection. The connections to the galvanometers were made via coaxial cables, the shields of which were connected to the chassis of the VRE's, to a plug board in the connection box near the tower and to the monitoring panel in the Observatory. Both this and the VRE chassis were earthed to the 'mains' earth pin.

These effects disappeared if the whole recording system was disconnected at the VRE outputs. It was found that when the two circuits connecting the VRE's and galvanometers were isolated from each other the VRE's ceased to follow and if they were disconnected from earth at all points except the chassis of the VRE's the zero deflections disappeared. These were apparently caused by currents flowing in the earth lines, probably generated by contact potentials at the various earthing points in the circuit.

To avoid the possibility of a similar effect occurring in any of the other equipment the 'mains' earth connection to the monitoring pannel was removed, so that the equipment was only earthed from the connection box near the tower.

These effects having eliminated, another spurious effect became apparent. A large deflection appeared which showed long term fluctuations even when there was no rain, but it was observed that it increased noticably after a heavy rain. When the heaters in the collectors were switched off the deflection slowly fell to zero and returned gradually to its original value when they were switched on again, recovery taking about a quarter of an hour. This suggested that evaporation of the water that had been collected in the cone may have caused the effect, but when the cone was emptied and dried out the deflection persisted.

This spurious deflection had only occurred since the collectors were moved to the Observatory. During trials at the Science Laboratories their performance had been satisfactory. The only difference in conditions was that at the Science Laboratories they had been standing on sheets of metal, whereas at the Observatory they stood on the grass with open bases. It was found that when they were again placed on metal sheets the deflection disappeared. The necessity of heat and grass and the dependence on rain suggested that evaporation from the grass, but not apparently from the metal, caused a charge separation which gave rise to a space charge some of which was picked up by the cone. This explanation seemed improbable as no direct evidence had ever been found that the evaporation of water gave any electrical effect. It would have been interesting to have investigated the effect, but as it was not related to the work in hand it did not appear justifiable to spend any time on it.

After these effects had been eliminated no serious trouble occurred. Some previous workers had found that the insulation was frequently shorted by spiders spinning webs inside their collectors, but spiders did not appear to favour the conditions inside the collectors used, possibly the temperature was too high for them. The heaters were of higher wattage than those used by earlier workers. Breakdown was only rarely caused by insulation getting wet, although at one stage a leak in the cone caused frequent breakdown, but this was easily remedied once the cause had been determined.

The Agrimeter and the Field Mills

Both field mills and the agrimeter were calibrated between two large plates. The lower plate had a hole cut in it, so that the vanes of the mills or the top of the agrimeter were level with the surface of the plate. Voltages were applied across the plates and knowing their separation,

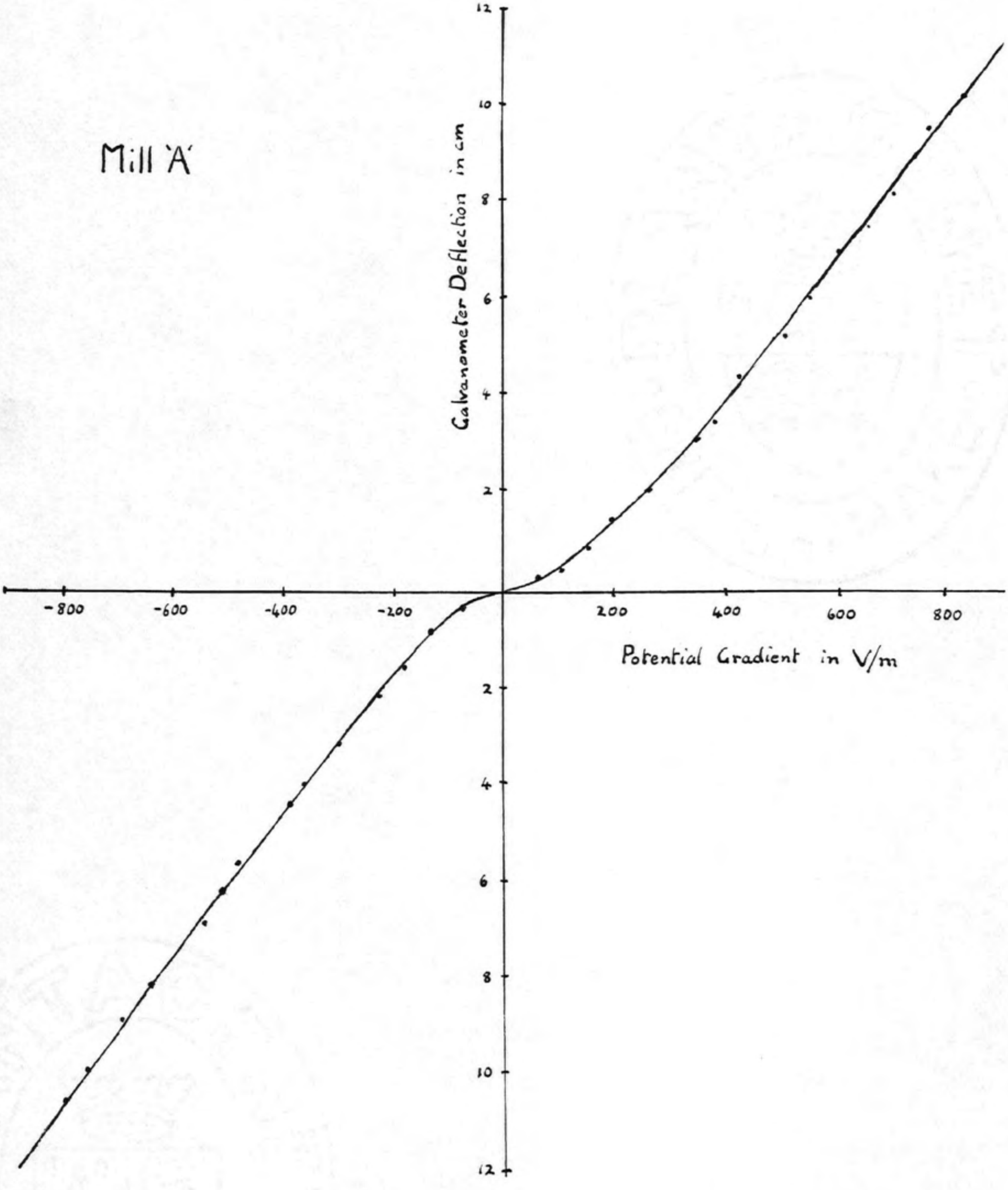
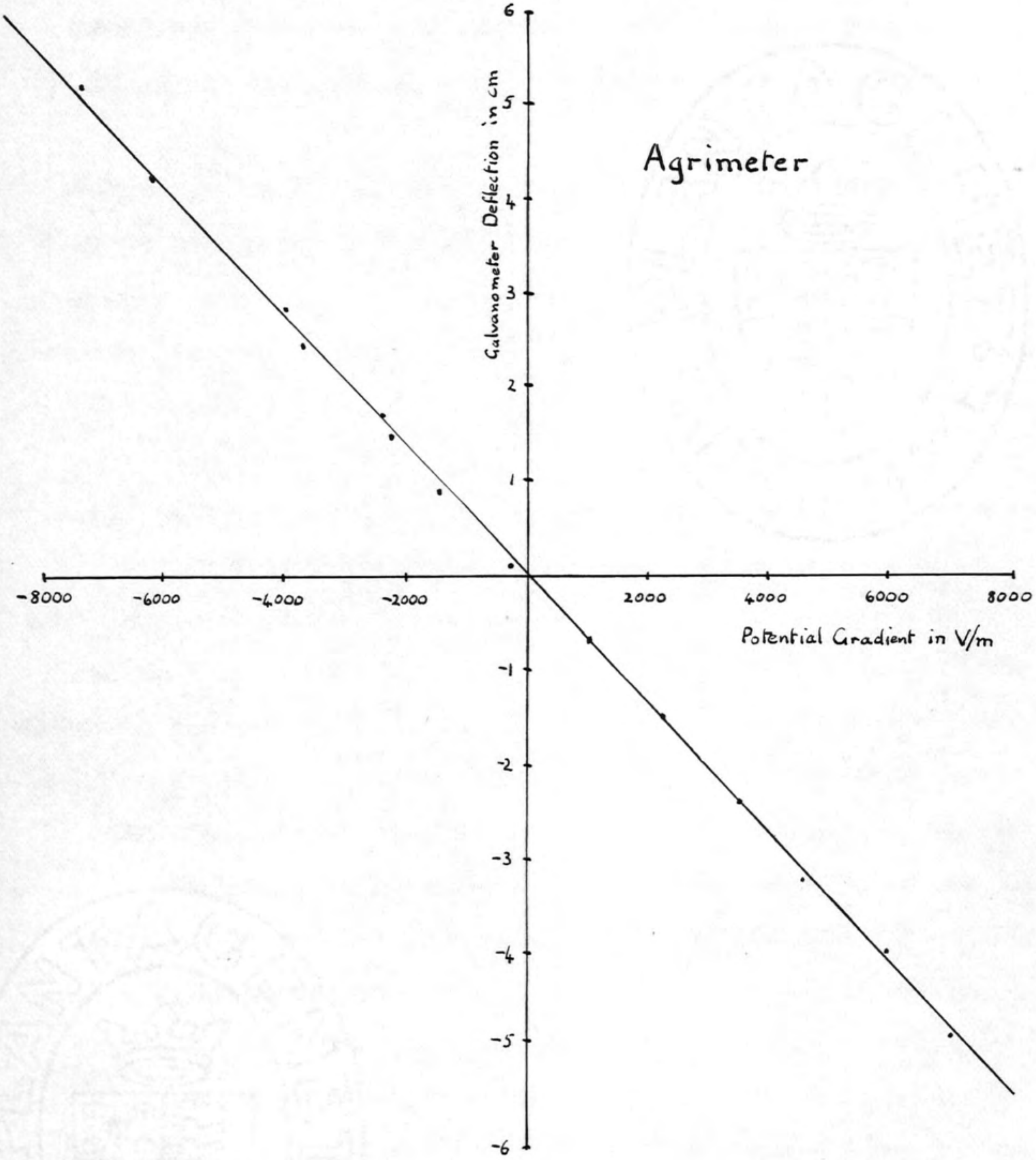

Mill 'A'
Galvanometer Deflection in cm
Potential Gradient in V/m
12
10
8
6
4
2
2
4
6
8
10
12
-800
-600
-400
-200
200
400
600
800

Fig 11



Agrimeter
Galvanometer Deflection in cm
Potential Gradient in V/m
6
5
4
3
2
1
-1
-2
-3
-4
-5
-6
-8000
-6000
-4000
-2000
2000
4000
6000
8000

Fig 12

the relation could be found between the potential gradients thus produced and the outputs of the instruments (Figs. 11 and 12).

The use of the calibration curves thus found would not in practice give the potential gradient at the ground or at 75 feet, on account of the exposure factors of the instruments, the potential gradient at the top of the tower being increased by about 100 times that at the ground. This increase was caused by the distortion of the lines of force by the tower. In order to determine these exposure factors, the 'calibrating mill' was placed underneath the lower calibrating plate with its vanes level with the surface. The calibrating plate had been sunk into the ground so that it was level with the surrounding field. The potential gradient measured by this mill would not be distorted in any way and as it was operating under the same conditions as when it was calibrated the value of the potential gradient could be found accurately from its calibration curve. The other two instruments were mounted in their operating positions and all were run simultaneously. A clear day when there was no cloud was chosen, since under such conditions no space charge would be expected, so that there would be no variation of potential gradient with height and all instruments would record the same potential gradient.

By comparing their outputs the exposure factors to be applied to each instrument was determined. These were found to be 17.5 for the agrimeter and 0.68 for the mill at the bottom of the tower, the value for the agrimeter was rather surprising as the exposure factor of a similar machine on the mast had been given by Kirkman (1956) as 125. The difference was probably produced by the geometry of the tower with its wide platform compared with that of the narrow mast, and by the position of the agrimeter, as it had been mounted close to the base of the collector which would have shielded it from the potential gradient to some extent.

Both the mills and the agrimeter proved satisfactory in use. The agrimeter gave little trouble except that when the collector near it was zeroed by putting a loosely fitting plate over it to keep out the rain the vibration in the plate caused by the agrimeter gave rise to a rather grassy output from the collector. The agrimeter's zero output was negligible and showed no variations except on one occasion when dampness in a plug connecting the instrument to its cable gave rise to a large zero drift. This was probably due to contact potentials.

Most of the difficulties with the mills appeared to originate in the motors. The sparking from the commutators has already been mentioned together with the steps taken to eliminate its effects. The motor of the calibrating mill did not operate very satisfactorily as it vibrated considerably. This was not completely absorbed by the anti-vibration mounts and, on occasions, resulted in fluctuations in the output. As this mill was not used normally to take records this was not serious and for comparison of the outputs of the different instruments for calibration any parts of the record effected could be ignored. When this mill was not in use another 'motor effect' became apparent. If the 'recording mill' was used alone with the 'calibrating mill' switched off the output of the 'recording mill' was larger for the same potential gradient than when both mills were running. This was attributed to the speeding up of the motor since the 24 V D.C. power gave a slightly higher voltage when the current taken from it was decreased. This effect was not in agreement with Whitlock's theory which showed that the output was independent of the motor speed.

These checks of zero and calibration voltage were made with a small 'test plate' that could be fastened over the vanes and to which a voltage could be applied giving a known potential gradient. On one occasion when a long zero check was made two alternating zero outputs were apparent.

One of these was the same as the galvanometer zero and each one lasted for a few minutes. When the signal was observed on an oscilloscope, the deflection was seen to be caused by 50 c/s pickup which vanished for intervals of varying length. This pick-up was present even when the mills were not working which suggested that it originated in the cables between the mills and the amplifiers. It was intended to install tuned filters to eliminate this but they were not ready for use before the tower fell down.

The system of sign discrimination worked well. The only drawback was that the cam operating the switches became worn down so that the length of the pulses changed. This was easily adjusted and caused no loss of recordings but it would clearly have been preferable to use a relay, which would not have got out of adjustment so rapidly. A relay would also not have suffered from another defect. This was that if the cam was stopped just as it was about to operate it would not start up again as the load on it was too great.

The Rate of Rainfall Recorder

This was calibrated quite simply by allowing water to run into the collecting cone at a known rate and recording the output. The corresponding rate of rainfall was easily calculated from the area of the collector and the rate of supply of water.

As the instrument was never used its performance could not be tested.

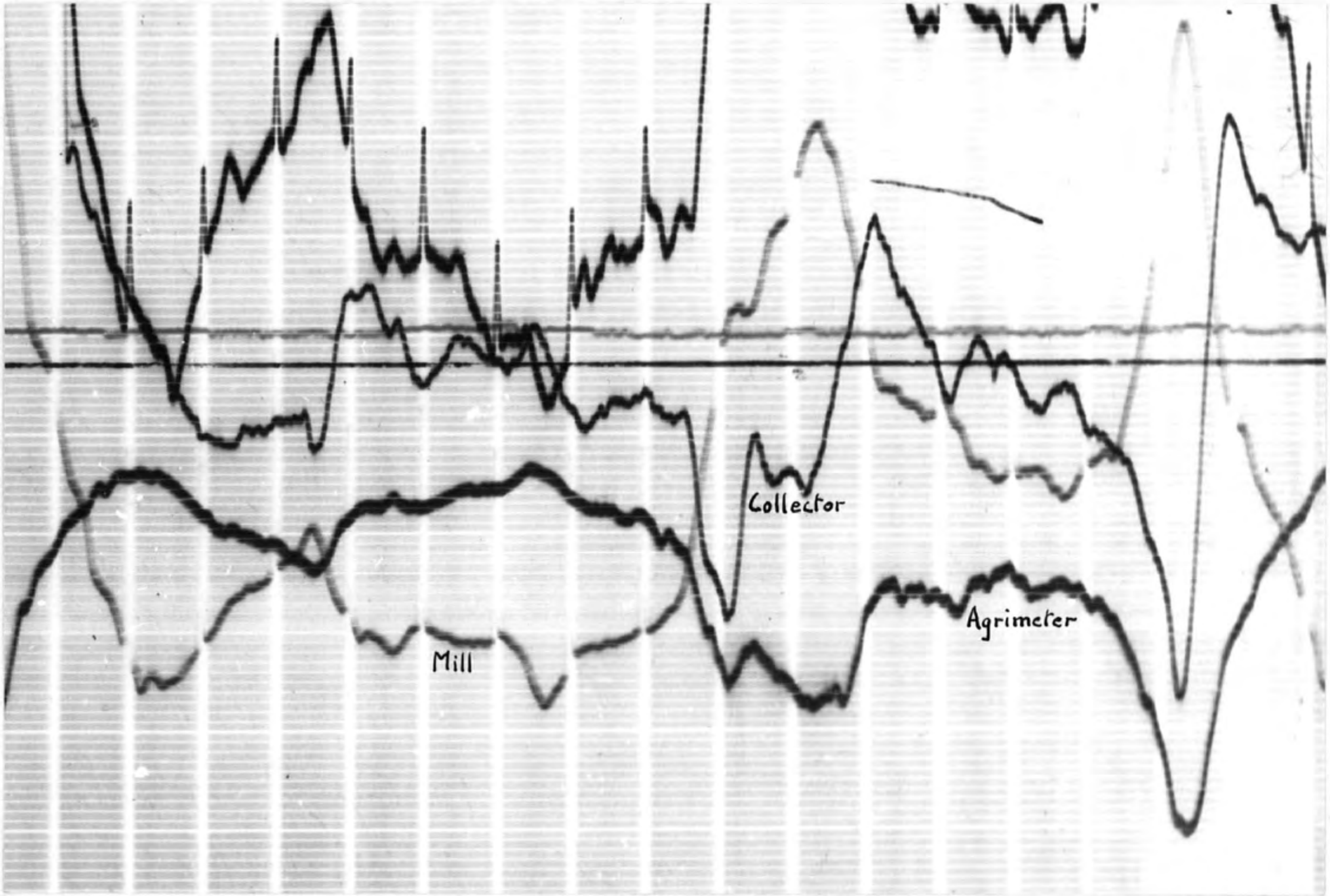


Fig 13

Chapter IV AUXILLIARY EXPERIMENTS

Compensation for Displacement Currents

The collectors had been designed to reduce the potential gradient at the inner cone in order to eliminate displacement currents and splashing effects. However the potential gradient at the top of the mast was so intense that displacement currents were clearly shown (Fig. 13) and were of a magnitude comparable with precipitation currents. As this effect could under certain conditions have masked the true precipitation current it was decided to apply a correction for this and the conduction current. This could have been done electronically using the output of the agrimeter, (Adamson, 1958), but the adjustment of such equipment would have been difficult and would probably have taken a long time as it would only have been possible in conditions when the natural potential gradient was varying rapidly. Adamson used an artificial potential gradient with a calibrating plate over the apparatus, but this was not possible on the tower. The simplest method thus appeared to be the use of a correction term calculated from the potential gradient and its rate of change.

Since the value of the potential gradient in the cone could not be determined a correction factor could not be derived theoretically so an empirical one had to be found.

For this purpose simultaneous recordings were taken of the potential gradient and current at the top of the tower on a day when there was no rain and many small cumulus clouds were overhead so that the potential gradient was varying rapidly giving displacement currents that were large and clearly defined and so could be measured accurately. The general formula relating displacement and conduction currents to the potential gradient and its rate of change could be derived theoretically and the observed values used to determine the constants involved.

The relation between the conduction current and the potential gradient is: $i_c = \lambda F$

where F is the potential gradient, i_c is the conduction current and λ is the conductivity. The relation between displacement current and potential gradient is: $i_d = \varepsilon_0 \frac{dF}{dt}$

where ε_0 is the permittivity of the air.

When interpreting the record it was usual to take values averaged over half minute intervals, and it would have been difficult to measure the slope in this way so that a value of $\frac{dF}{dt}$ would have been difficult to obtain. However an approximation was made by finding ΔF, the change in potential gradient between the beginning and end of the interval, the relation now becoming: $i_d = K \Delta F$

where K is a constant.

If we now take into account the differences in the values of the actual potential gradient at the surface of the cone and at the agrimeter the total current is given by:

$$i = i_c + i_d = AF + B\Delta F$$

Where A and B are constants and i is averaged over the interval. An equation of this type was found from the record by means of ordinary regression methods.

The equation was found to be:

$$i = (0.015\ F + 0.048\ \Delta F) \times 10^{-12}$$

This method of correction is unsatisfactory for several reasons. Since it involves applying the correction to each half minute reading the computation involved is considerable unless conditions are exceptionally steady. It is also necessary to measure ΔF in addition to the other data. More serious are inaccuracies in the correction formula. These can arise from two causes, firstly, there is evidence that the conductivity in rain would not be the same as in the fine weather when the measurements were made. The second source of inaccuracy in the method of determining the values of the constants from the recordings. This assumes that there is no error in the values of F and ΔF. Such an assumption is clearly unjustified, but there does not appear to be a

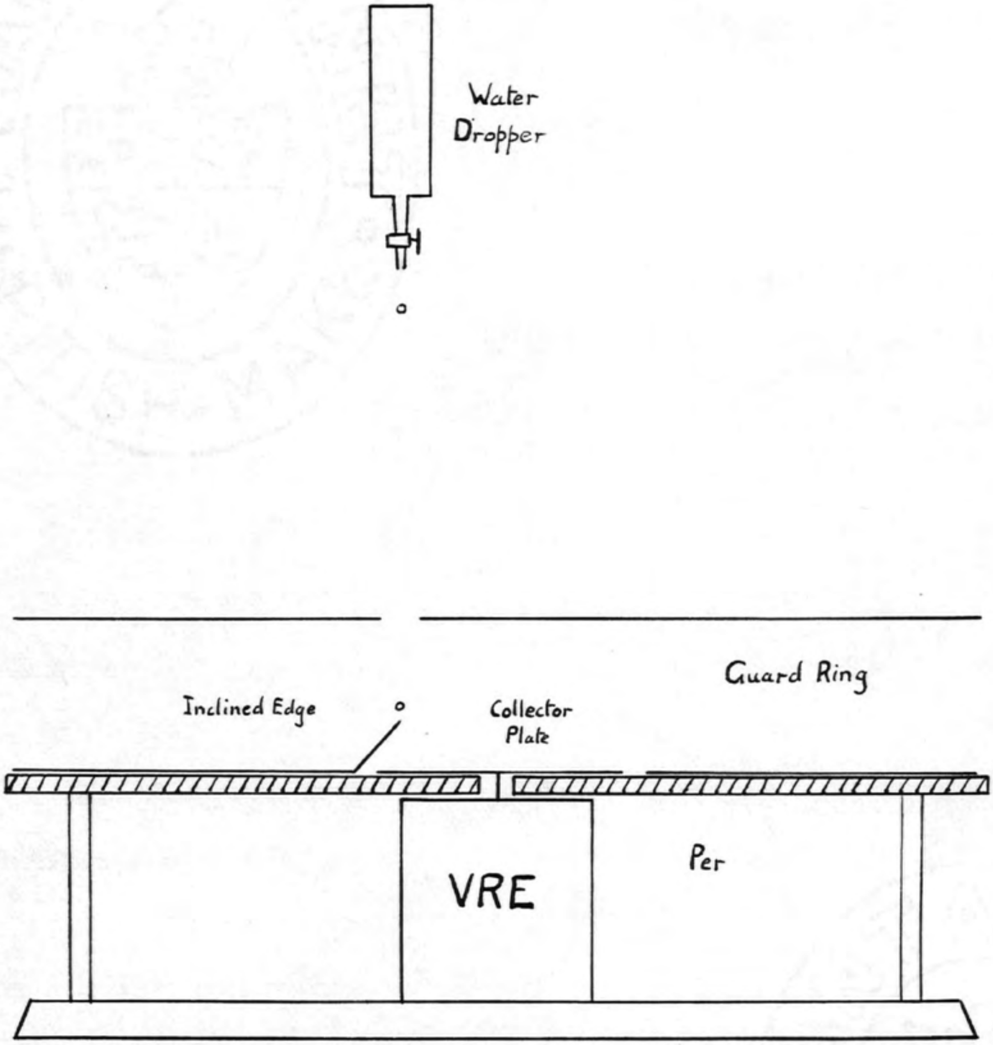

Water Dropper
Guard Ring
Inclined Edge
Collector Plate
Per
VRE

Fig 14

more suitable method of finding the constants in an equation of this type.

The Splashing of Water Drops

It had been noticed that on the record of the precipitation current at the top of the mast occasional very highly charged drops had been recorded. These were always of opposite sign to the potential gradient. It was suspected that these may have been caused by drops shattering on the edge of the collector shield. To investigate this an independent experiment was carried out to find the effects of splashing under conditions similar to those in the collector.

The equipment (Fig. 14) consisted of a small aluminium plate surrounded by an earthed guard ring above which was fixed a second plate the same size as the guard ring and having a narrow slit across it. A voltage could be applied across these plates and drops from an earthed water dropper allowed to fall through the slit onto the small plate. This plate was connected to the head unit of a VRE with which the charges could be measured. The whole was shielded to prevent stray charges being induced onto the plate, especially by the man-made fibres of the experimenters' clothes.

For the first experiment drops were allowed to fall onto a variety of surfaces, namely filter paper, water and aluminium

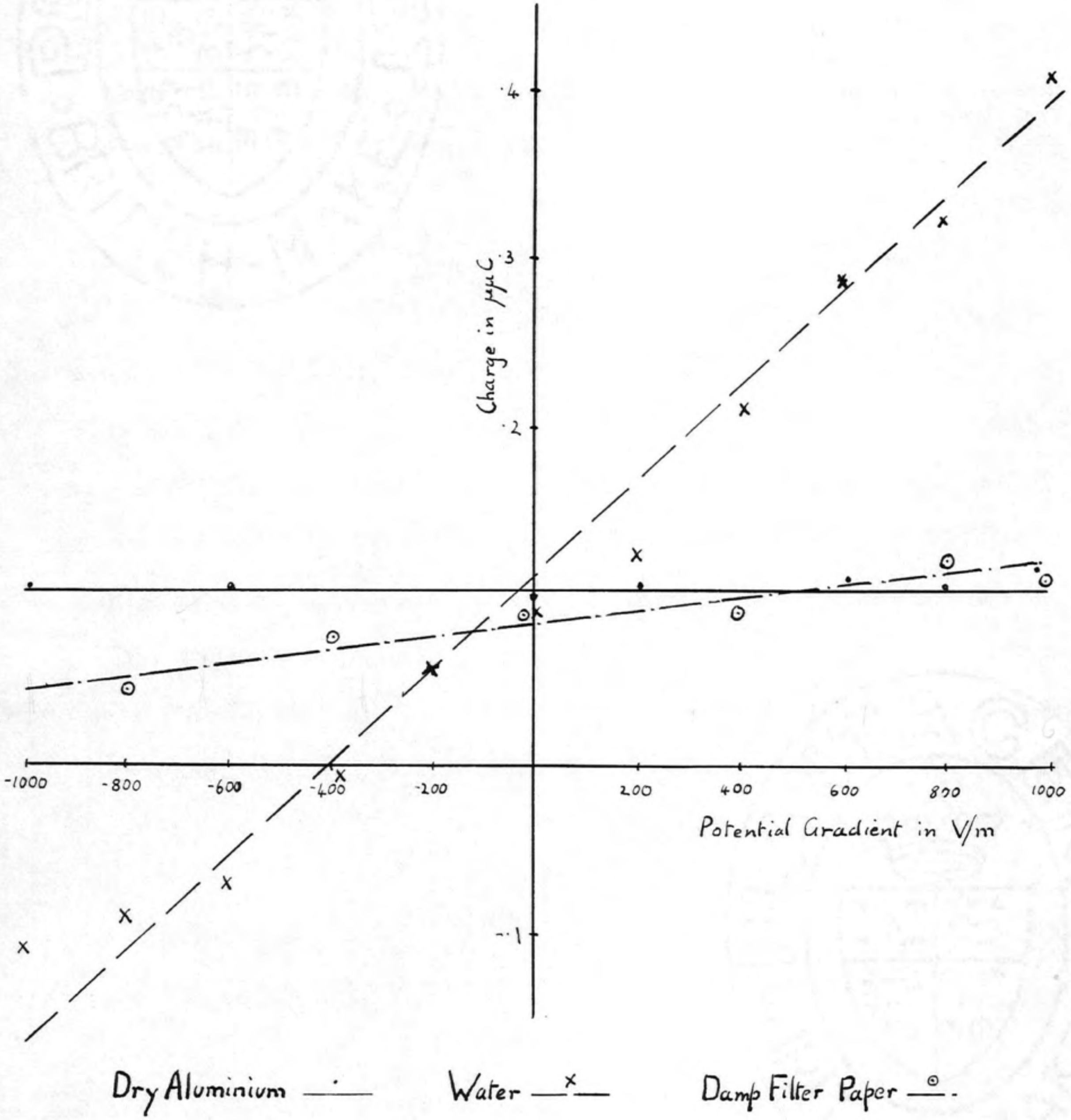
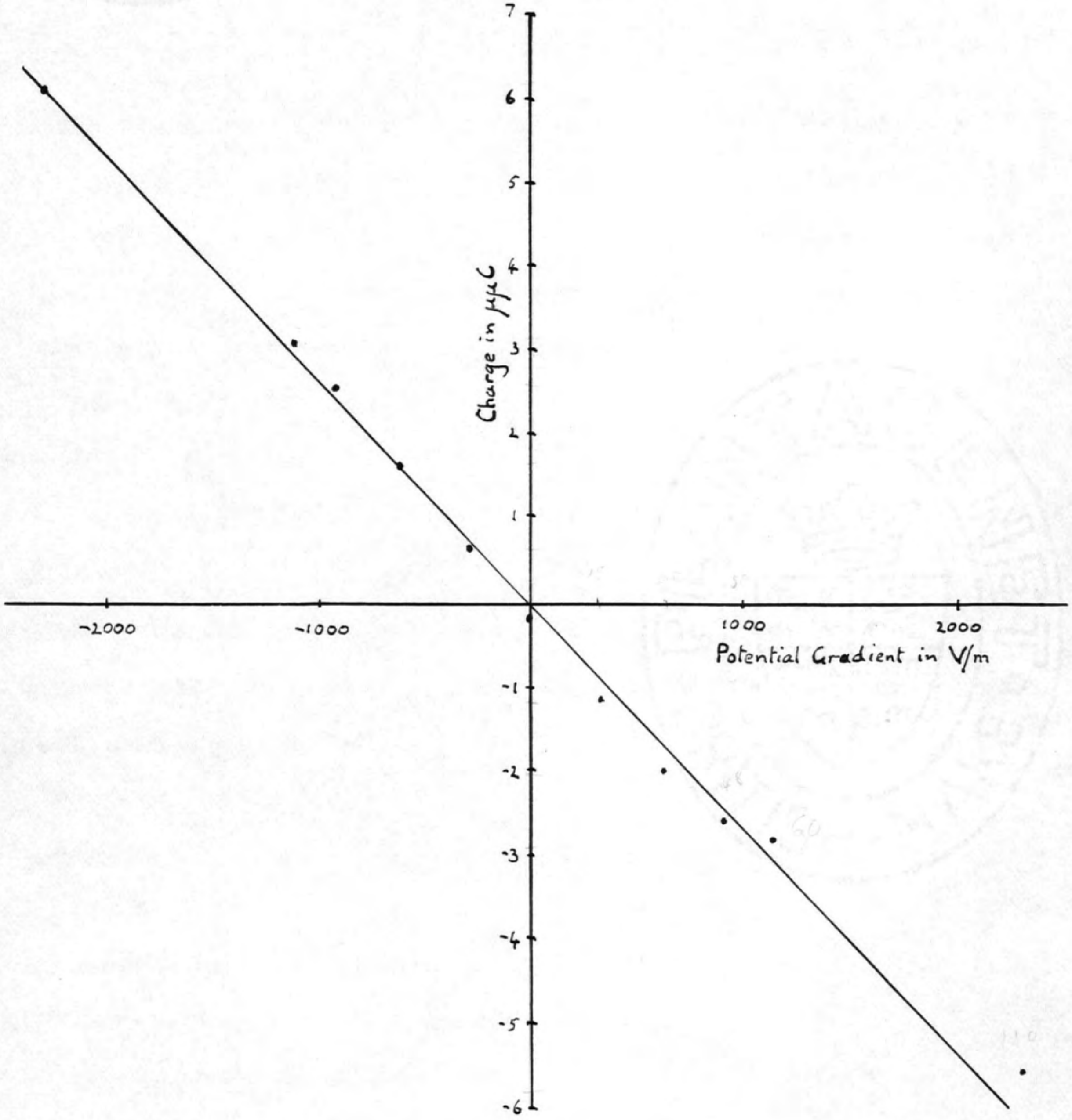

Charge in μμC
·4
·3
·2
-·1
-1000
-800
-600
-400
-200
200
400
600
800
1000
Potential Gradient in V/m
Dry Aluminium
Water
Damp Filter Paper

Fig 15

sheet. In the last case it was found necessary to dry the sheet after each drop had fallen, since otherwise a large pool of water accumulated. This effectively transformed the aluminium into a water surface.

It was found that using the filter paper and aluminium the potential gradient did not appreciably effect the total charge carried to the plate. In these cases little splashing occurred whereas when the water surface was used there was always splashing and a clear relation between potential gradient and charge was shown (Fig. 15). The 'zero' value of the charge was probably due to a charge on the original drop. Attempts were made to check this by allowing the drops to fall through an induction ring and measuring the induced charge as the drop approached, but the equipment was not sensitive enough to measure its charge although it could be seen that it carried one.

The results appeared to be in agreement with those of Adkins, (1959b), who found a direct relation between charge and potential gradient. The low values for the aluminium plate probably reflect the low velocity of the drop, it fell about 60 cms and did not splash greatly. Adkins had found that the drop needed to attain a 'threshold' velocity before any charging occurred.



7
6
5
4
3
2
1
-1
-2
-3
-4
-5
-6
Charge in μμC
-2000
-1000
1000
2000
Potential Gradient in V/m

Fig 16

The second part of the investigation was concerned with charging resulting from the splashing of drops when they struck the edge of the earthed shield. In the collector itself the shield was made of aluminium, so in order to reproduce the splashing as accurately as possible a sloping aluminium plate was fastened to the edge of the guard ring and projecting over the central plate. When a drop shattered on this edge some of the droplets fell onto the plate and their charge was measured with the VRE. The charge reaching the plate was found to have an inverse relation to the potential gradient between the plates and the charges were considerably higher than those recorded in the first experiment (Fig. 16.)

An attempt was made to compare the charges observed in this experiment with the peaks on the records. The heights of the peaks on part of a record taken in a fairly steady potential gradient of about 200 v/m corresponded to a mean charge of about 5.6 $\mu\mu$C. In the laboratory experiments this charge would have been produced in a potential gradient of 5000 v/m. There was no means of measuring the potential gradient inside the collector so a direct comparison could not be made, but assuming that the splashing did cause the charges the potential gradient at the edge of the inner cone would have had this value. Now the exposure factor of the agrimeter was 17.5 so that the exposure factor of the conical shield would have had to have been 25 to account for the differences in the potential gradients. The agrimeter was fairly low down beside the collector and would have been quite well shielded by it, so that the exposure factor of the collector as a whole would have been greater than 17.5, probably 50-100. This implied that the shielding of the collector reduced the potential gradient at the conical shield to $^1/_4$ of its value outside the collector. As Scrase (1938) gave the value of the potential gradient at the inner cone to be $^1/_{30}$ of its value outside this appeared a reasonable figure and suggested that the original assumption was correct.

Following this tests were carried out on various materials that were readily available with a view to finding a suitable padding for the edges which would prevent splashing.

A piece of split rubber tube placed along the edge gave even larger charges than the aluminium alone. Felt clipped round the edge made little difference, but a thick wad of tissue paper or about $^1/_4$" of foam rubber caused a considerable reduction. In the last two cases the charge released by each drop increased as more drops were allowed to fall. This was probably due to the nature of the surface changing as the material became increasingly waterlogged, and after the first few drops had been absorbed with very little

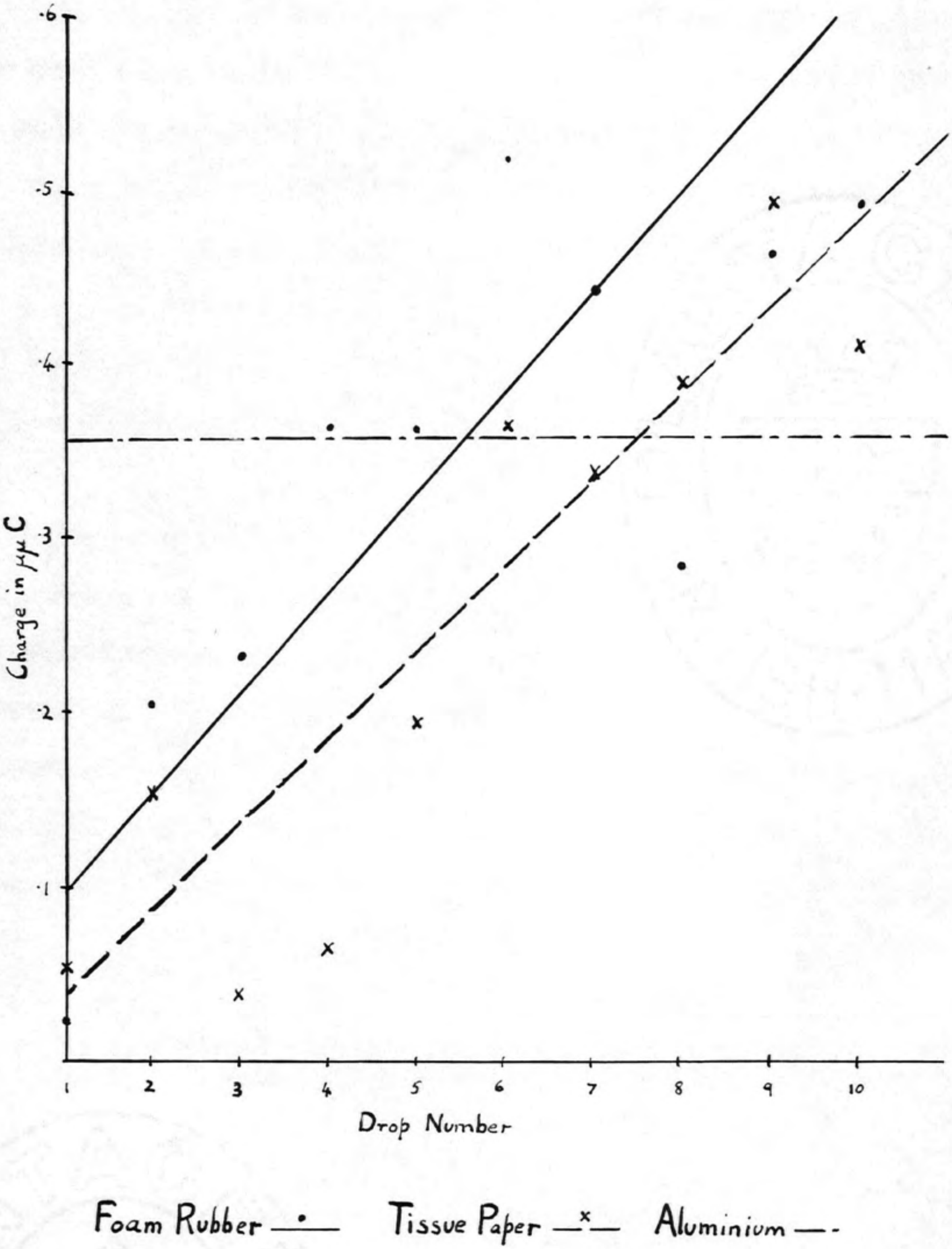

·6
·5
·4
·3
·2
·1
Charge in μμC
1
2
3
4
5
6
7
8
9
10
Drop Number
Foam Rubber —•—
Tissue Paper —×—
Aluminium —·-

Fig 17

splashing the rest struck a surface consisting largely of water and splashed badly (Fig. 17). Padding of this type would have reduced the current due to splashing on the edge in light rain, but would have become waterlogged rapidly in heavier rain and lost its effectiveness. An ideal material would have been one that was soft enough to prevent splashing and was also sufficiently porous to provide good drainage in order to avoid the accumulation of water on its surface.

These experiments were conducted after the tower was blown down, so it was impossible to make use of the findings. During the time when recordings were made neither collector had any padding on the edge of its shield. When the traces on the photographic records were measured allowance was made for splashing effects by ignoring the occasional exceptionally large deflections which were assumed to be caused by splashing on the shield.

Chapter V THE RESULTS

Introduction

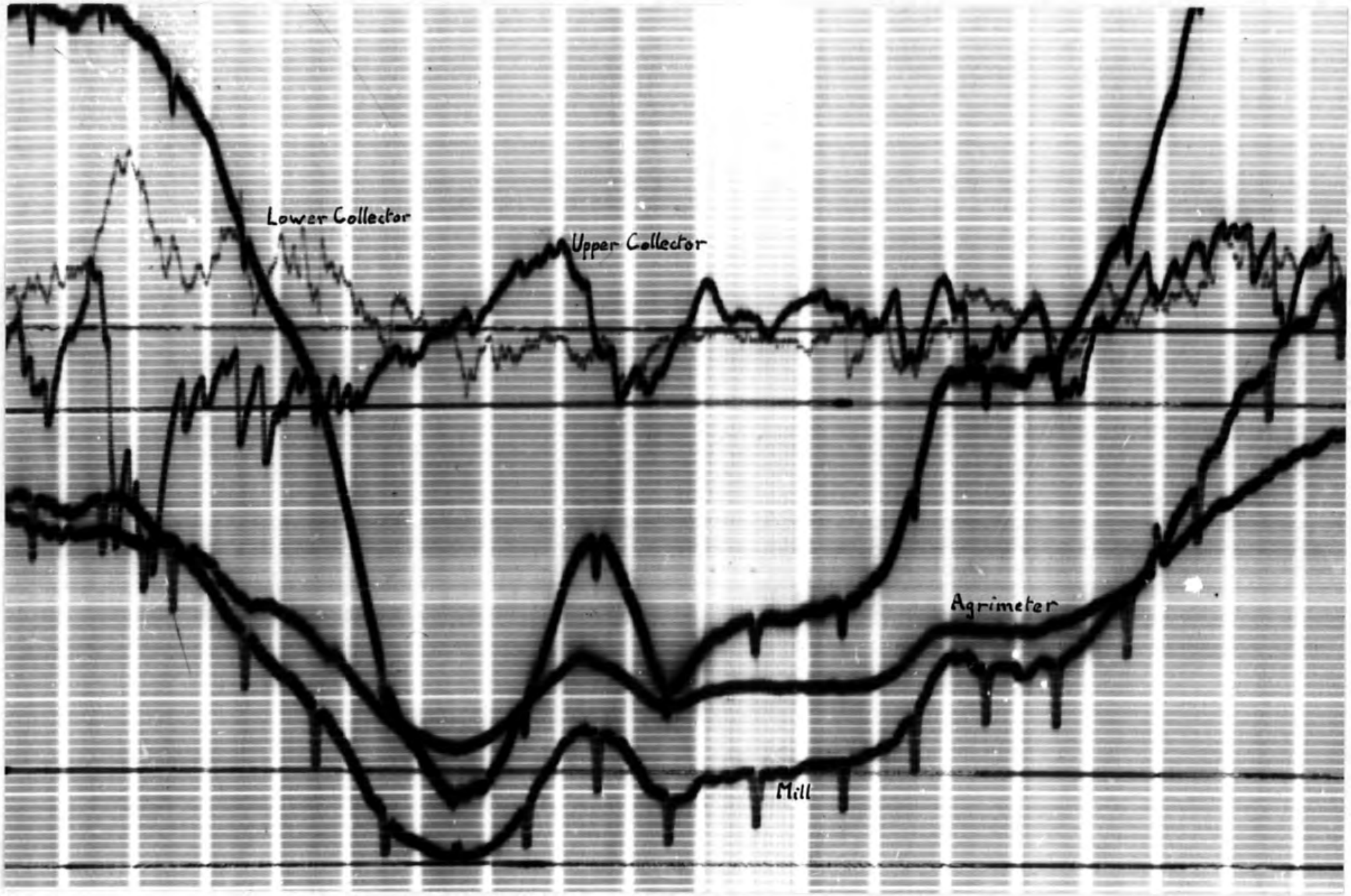
As has been mentioned several times already it was only possible to make recordings for a period of a few weeks. This consisted of the latter half of May and most of June 1962. June was in fact an unusually dry month with only 60% of its normal rainfall. However recordings were made on eight days when rain fell and on five of these some of the records were suitable for analysis. Of the remainder the rain was sometimes in the form of showers which was unsuitable or too much of the equipment was functioning unsatisfactorily. Sometimes too, rain appeared imminent but failed to materialise after recordings had been started.

No standard of duration was laid down for determining whether the rain should be classed as continuous or not, but any rain that was steady in character, rather than showery, and which came from a layer type of cloud was accepted.

After this selection only two long records and three short ones were left. These covered a total of about 15 hours of which the two long periods occupied $8\frac{1}{4}$ and $3\frac{3}{4}$. In view of this it appeared that it might be preferable to analyse the records individually since if they were all taken together the longer records would predominate so that the mean would not be very representative of average conditions. In addition any differences between the records would be masked. As the shorter records only covered a period of about three hours they were considered as a single record.

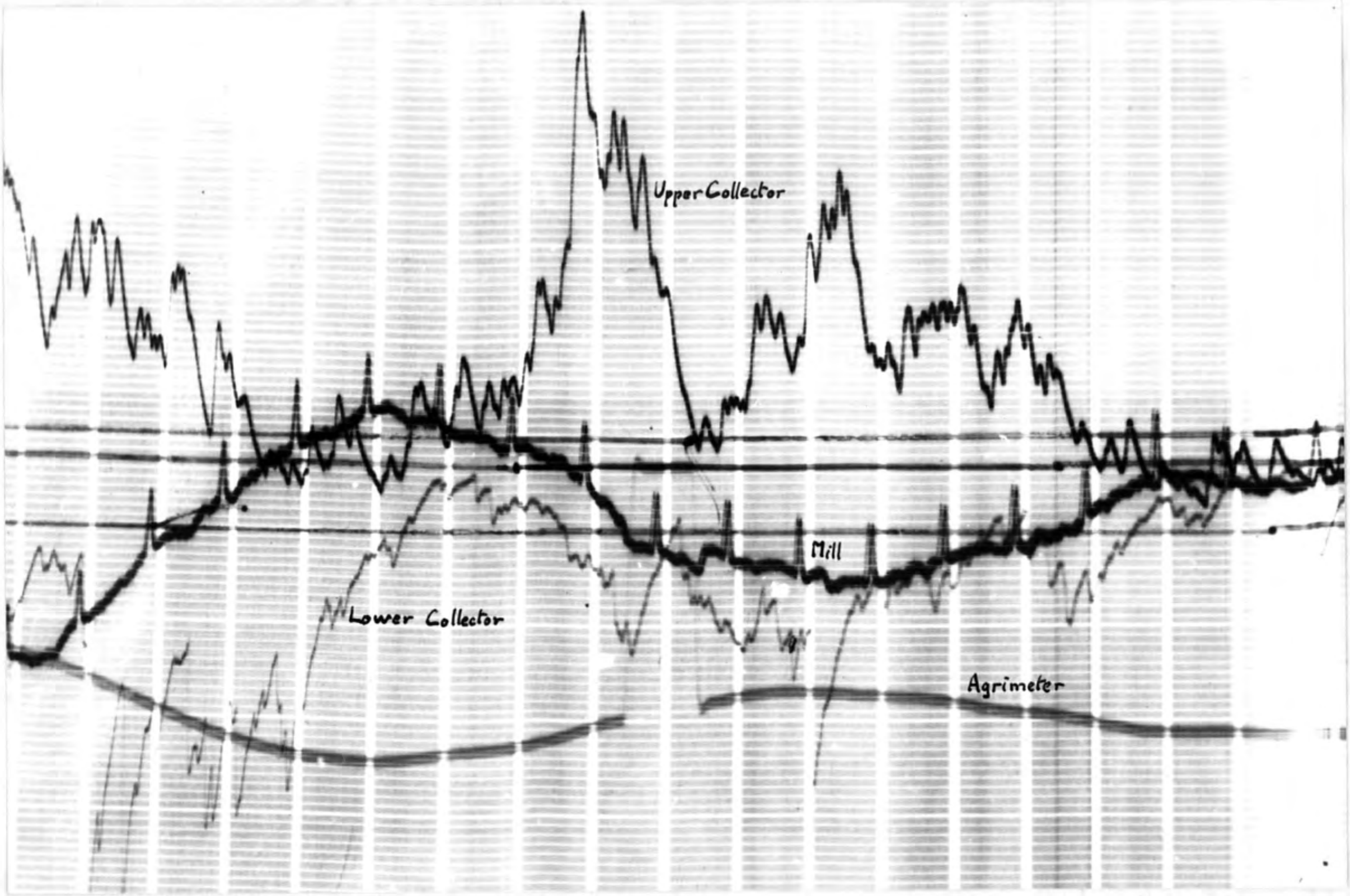
The periods for analysis were thus:

1. 19th May. This record lasted for 8¼ hours (9.30 a.m. to 5.45 p.m.) and the rain was associated with a deep depression which was moving across the South of England. The rain was not exceptionally heavy averaging 0.015 mm/min and the potential gradient was predominantly negative although at first there were some positive excursions lasting for about 20 minutes. It was at this time that some water got inside a plug in the agrimeter producing a large zero deflection. Fortunately this rapidly steadied and despite later disturbances apparently caused by the penetration of more water it was possible to keep track of the zero by frequent use of the test plate. However the accuracy of the potential gradient recorded by the agrimeter for this period must be regarded with some suspicion. During the latter part of the record, from about 2.30 p.m., the potential gradient rose to very high values so that point discharge must have taken place both from the tower and from nearby trees. This would have produced large quantities of space charge so that the conditions would have been altered. In view of this the



A Typical Record

Fig 18



A Typical Record

Fig 19

latter part of the record was not used. Also about 4.30 p.m. the upper collector sprang a leak rendering the current measurements useless.

2. 15th June. This marked the passage of a warm front and rain lasted from 2.30 p.m. to 6.15 p.m. and was quite heavy, at one time averaging 0.1 mm/min for nearly an hour. The overall mean rate of rainfall was 0.03 mm/min. This record also differed from the first in that the potential gradient was positive except for short intervals again in the early part. It was probably the most reliable record as it was the last one taken when all the equipment was in its best condition and most of the faults that had come to light had been remedied.

3. The remainder of the suitable records were all associated with depressions. The meteorological conditions varied and both positive and negative potential gradients were observed. They were made on the 11th 17th, and 22nd of May and in all lasted for nearly three hours. On the first two days the tower collector's VRE was not working satisfactorily and on the 22nd it also broke down halfway through the record. This meant that only three of the four parameters could be compared with the other records.

The method of analysis was fairly straightforward. After the films had been developed zero lines were drawn on them using both the zero positions recorded and in the case of the mill the cusps corresponding to a change of sign. As the record was being made notes had been taken of the times of all sensitivity charges and these could now be located and clearly marked. This often proved to be difficult in the case of the collectors on account of the rapid variations caused by the different charges on individual drops coupled with the comparatively small collecting area. The value of each of the parameters was averaged by eye over half minute intervals and measured using special rulers which had been calibrated from the instrument calibration curves. This enabled the values to be read off directly thus avoiding much of the conversion which would have been necessary otherwise. The values obtained in this way were tabulated and the correction made to the upper collector reading for displacement and conduction currents. Differences between the upper and lower currents and potential gradients were then found. Assuming that the instruments had been calibrated correctly these corresponded to the charge gained by the rain in falling from the height of the tower to the ground and to the space charg below the top of the tower.

In order to see more clearly what had been happening , the parameters were plotted against time with all the parameters on the same sheet of paper so that any relation between them was more obvious. When any interdependence between two parameters was seen they were plotted again, against each other to form a scatter diagram. It could then be decided if the relation was close enough to justify statistical analysis. In practice all the parameters appeared to be linearly dependent upon each other, and the large number of observations made the degree of statistical correlatio highly significant despite a very wide scatter.

The calculation of the 'best straight lines' through the scatter diagrams was considerably simplified by dividing the diagram into about 60 squares and treating all the points in each square as if they were all at its centre.

Initially the 'best straight lines' were found by means of the usual regression formulae, but this method is not really satisfactory since in deriving it the assumption is made that only one of the variables is subject to error. This is not often true and in the present work both had errors of about the same magnitude.

Morgan (1960) has shown that the usual method can be extended to the general case where there are errors on both variables. The use of Morgan's method is a little more complicated than the standard one but is much more accurate and considerable differences were found in some of the equations found by the two methods. In the case of the relation of the upper and lower currents the usual method gave $I_B = 0.047\ I_T$, or if the equation was found the other way about $I_T = 0.24\ I_B$ whereas Morgan's method gave $I_B = 0.36\ I_T$ which seemed far more realistic. The difference between the two equations found using the usual method is rather large although a difference is always found since for each equation a different variable is assumed to be free from error.

One disadvantage of this method is that a knowledge of the errors in the variables is necessary and it is difficult to determine these accurately. Fortunately this problem is considerably simplified in some cases as only the ratio of the errors is needed and when the variables are measurements of similar parameters, e.g. the two currents the errors are the same.

The Results

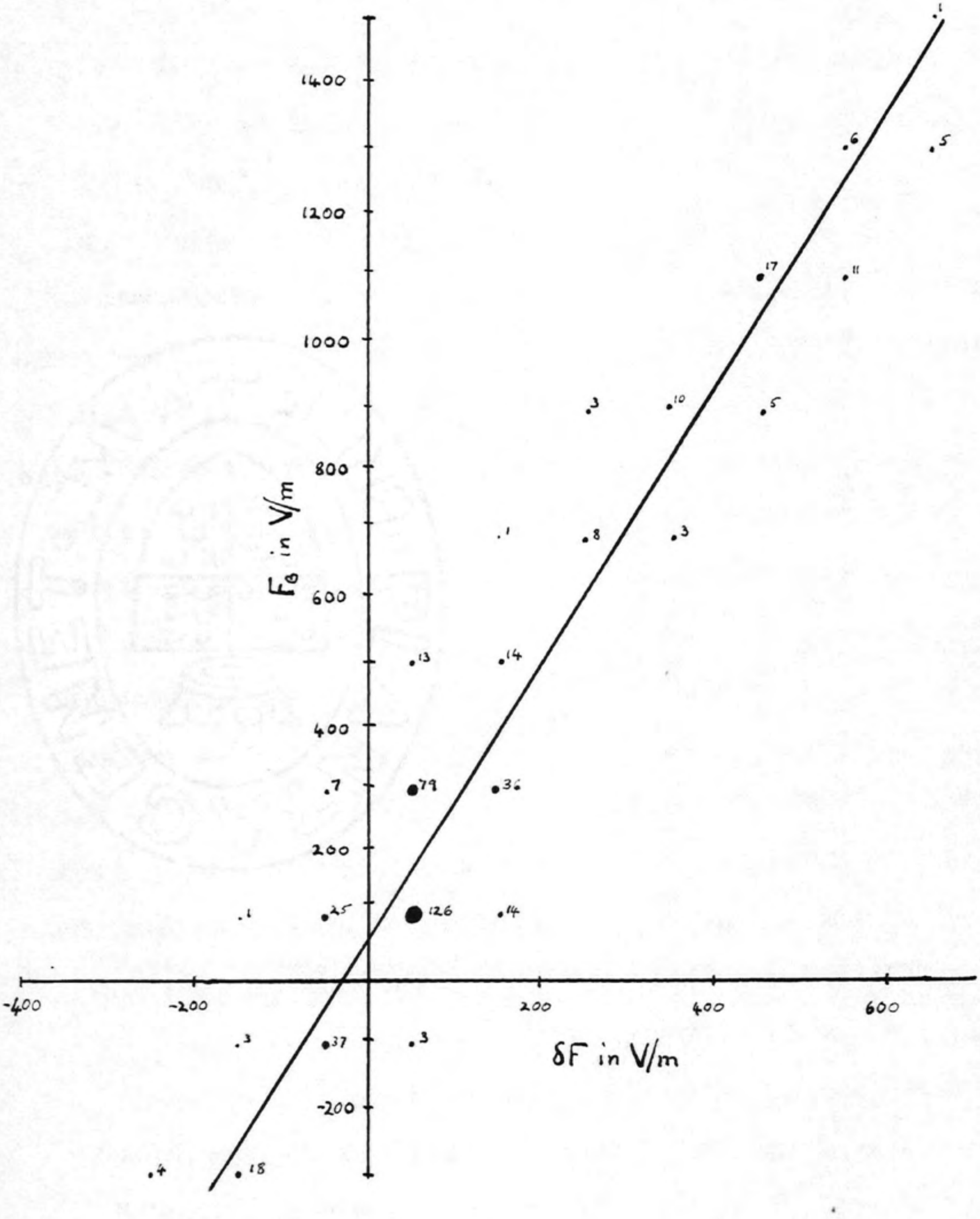
It was found convenient to refer to the records as '19' (19/5/62), '15' (15/6/62) and 'M' (Miscellaneous) and to use symbols for the parameters:

Upper potential gradient	(v/m)	F_T
Lower potential gradient	(v/m)	F_B
Upper Current	($\mu\mu A/m^2$)	I_T
Lower Current	($\mu\mu A/m^2$)	I_B

Difference in potential gradients	(v/m)	$\delta F = F_B - F_T$
Difference in currents	($\mu\mu$ A/m^2)	$\delta I = I_B - I_T$
Space charge	($\mu\mu$ C)	$\rho = \varepsilon_0 \delta F$

It was decided to make ρ the total space charge in a metre square column the height of the tower instead of the mean space charge in a cubic metre as there was no evidence that it was uniformly distributed.

From the results of earlier workers it was expected that negative space charge would be found and that I_T would be several times greater than I_B. The difference in currents was found although on examining the records it was seen to be considerably less than the sixfold one found by Merry, and there was on average a factor of 3 or 4 between the two currents although the difference was more pronounced in very high values. This relation did not always hold however. The currents were often of opposite sign, usually just before or after the potential gradient changed sign and the difference appeared to be related to the mirror image effect which was much more pronounced with I_T where there were negligible time lags while with I_B they were often of several minutes. This suggested that the rain's charge might be due in part to the local potential gradient. Since this was greatly exaggerated on the tower its effect on I_T would predominate over other influences.



1400
1200
1000
800
600
400
200
-200
F_θ in V/m
-400
-200
200
400
600
δF in V/m
1
6
5
17
11
3
10
5
1
8
3
13
14
7
79
36
1
25
126
14
3
37
3
4
18

Fig 20

When the graphs of the variations of the parameters with time were drawn it was seen that F_B and F_T followed each other but that F_T was usually less than F_B and both changed sign almost simultaneously. In this respect the 'Kelvin Chauveau' effect was never observed although one of the recordings was started at a time when F_T was almost zero, F_B nearly -150 v/m and both becoming more negative suggesting that they had been of opposite sign a few minutes previously.

The deduction from the 'Kelvin Chauveau' effect is the presence of negative space charge which would make F_B more negative than F_T so that δF would be negative. δF was found to be usually the same sign as the potential gradient and to increase with it. This dependence was very marked on '15' and when δF was plotted against F_B the scatter diagram was almost a straight line with an intercept on the F_B axis of about 50 v/m (Fig. 20). The corresponding diagrams for '19' and 'M' did not show such good linearity but the relation was still obvious.

The formulae relating F_B and δF were of the form: $F_B = a\,\delta F + b$ and this could be converted readily into $F_B = c\,\rho + b$ since $\rho = \epsilon_0\,\delta F$. The values found for 'b' were quite small (Fig. 25)so at first sight it would appear that the potential gradient was almost entirely controlled by the space charge although there was also a small 'background' potential gradient 'b'. However before drawing any conclusions from the formulae it is worth while considering the reliability of the observations.

The basic observations were those of F_B and F_T, and the validity of taking δF, F_B-F_T, as the difference in the potential gradient between an undisturbed level at the height of the tower and the ground depends on the accuracy of the calibration of the instruments and especially of the comparison of them. So far as could be determined by the use of the test plate no changes of sensitivity occurred and any inaccuracies would have originated in the initial calibrations.

All the instruments were first calibrated between plates and the errors introduced in this would be quite small. The instruments were then mounted in their operating positions and the outputs of the agrimeter on the tower and the mill at the bottom compared. The second mill was used in an attempt to find the exposure factors and any error in this would have caused a change of scale effecting both the other instruments to the same extent and so could be ignored. The comparison of the outputs is more important. It had to be assumed that at the time of the comparison the potential gradient did not change with height. A day was chosen when no space charge was expected but it was not possible to prove its absence so the potential gradient may not have been uniform.

If the potential gradient at the ground is f and at an undisturbed place the same height as the tower $f - s = F$ where s is the change of potential gradient produced by some space charge. Now it is assumed that both instruments are measuring the same potential gradients, if allowance is made for the exposure factors, and so their outputs are both equated with f. The absolute value of f is found by the calibrating mill. This means that F has been incorrectly estimated as f

$$f = F \frac{f}{F} = F \frac{f}{f-s} = F \frac{1}{1-s/f}$$

The same error will occur in all later cases when the value of the potential gradient at the height of the tower is estimated from the agrimeter output. If on one occasion the potential gradient is uniform with height and has the value F_B it is estimated as F_T and $F_T = F_B \left(\frac{1}{1-s/f}\right)$. If δF is the difference between F_B and F_T then

$$\delta F = F_B - F_T = F_B - \frac{F_B}{1-s/f} = F_B \left(\frac{1}{1-f/s}\right)$$

This gives $F_B = \delta F(1-f/s)$ which is similar to the relation actually found. A more general case is when there is space charge present. If this gives rise to a difference of potential gradient X then the potential gradient at the height of the tower is $F_B - X$ if F_B is its value at the ground. $F_B - X$

is now estimated as $\frac{F_B - X}{1-s/f} = F_T$.

Thus $\delta F = F_B - F_T = F_B - \frac{F_B - X}{1-s/f} = \frac{F_B}{1-f/s} + \frac{X}{1-s/f}$

so that $F_B = \delta F\,(1-f/s) - X\,\left(\frac{1-f/s}{1-s/f} \right)$

Here the space charge is given by the intercept on the F_B axis and is opposite in sign to it.

The values corresponding to $1-f/s$ in the regression equations are about 2 so that $f/s \doteqdot -1$ and $\frac{1-f/s}{1-s/f} \doteqdot 1$. To give rise to a slope of this order $s \doteqdot -f$ and when the comparison was made f was about + 200 v/m so that the space charge corresponding to s would have been about $-80\ \mu\mu C/m^3$ which is not impossible but is rather high for a day when little or no space charge was expected. Also if space charge was present when the comparison was made the intercepts of the $F_B/\delta F$ regression lines must be taken as being the mean space charge. These are about 70 v/m which corresponds to only about $-30\ \mu\mu C/m^3$ if it is uniformly distributed. Although if it were all contained within the first metre of the atmosphere it would amount to $630\ \mu\mu C/m^3$ which is similar to that found by Adkins (1959b).

It appears then that the results for space charge are ambiguous and there does not seem to be any way of choosing between the alternative interpretations. If the intercept represents the space charge it is usually negative, the

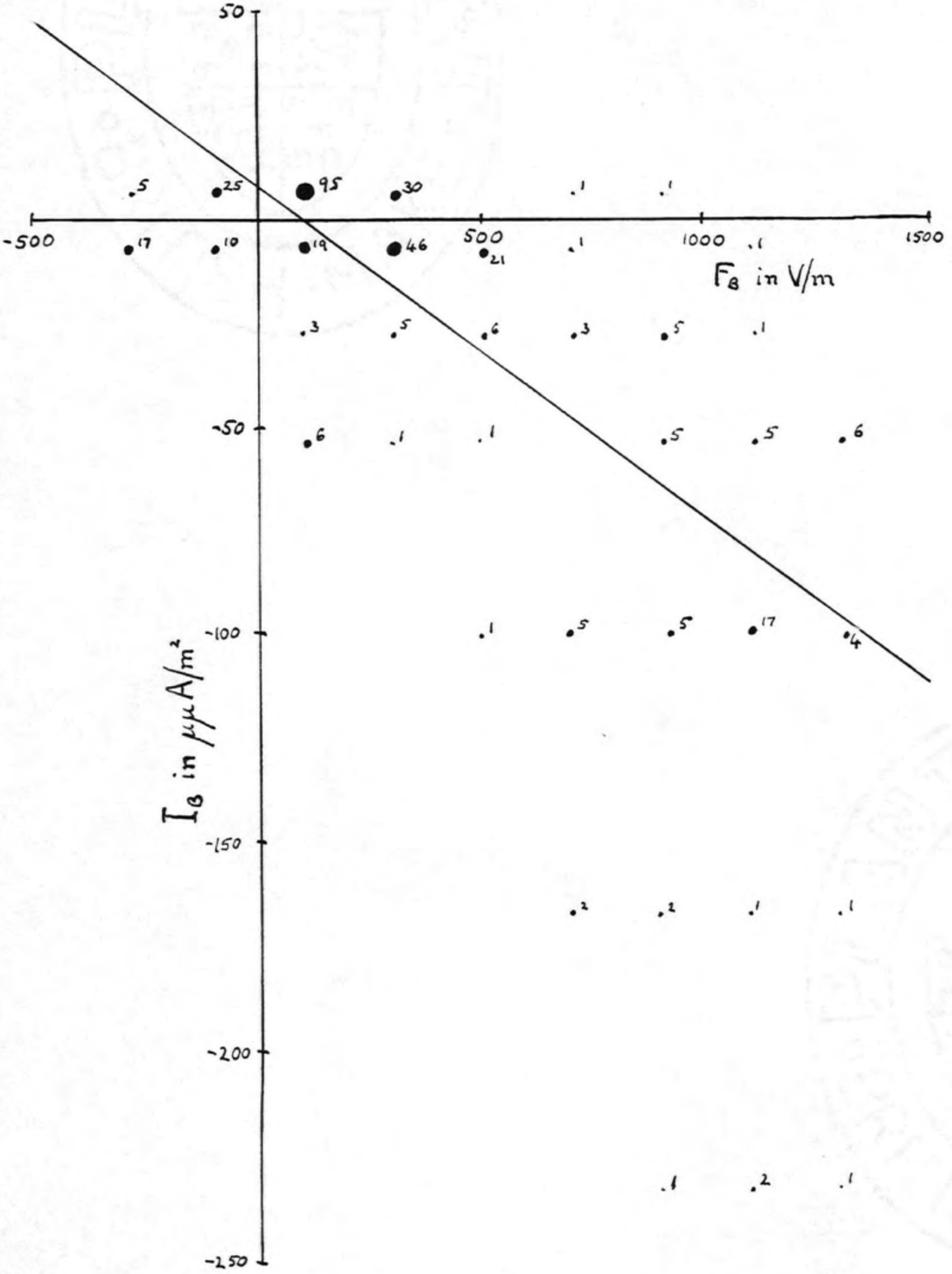

50
-500
500
1000
1500
F_B in V/m
-50
-100
-150
-200
-250
I_B in μμA/m²
5
25
95
30
1
1
17
10
19
46
21
1
1
3
5
6
3
5
1
6
1
1
5
5
6
1
5
5
17
4
2
2
1
1
1
2
1

Fig 21

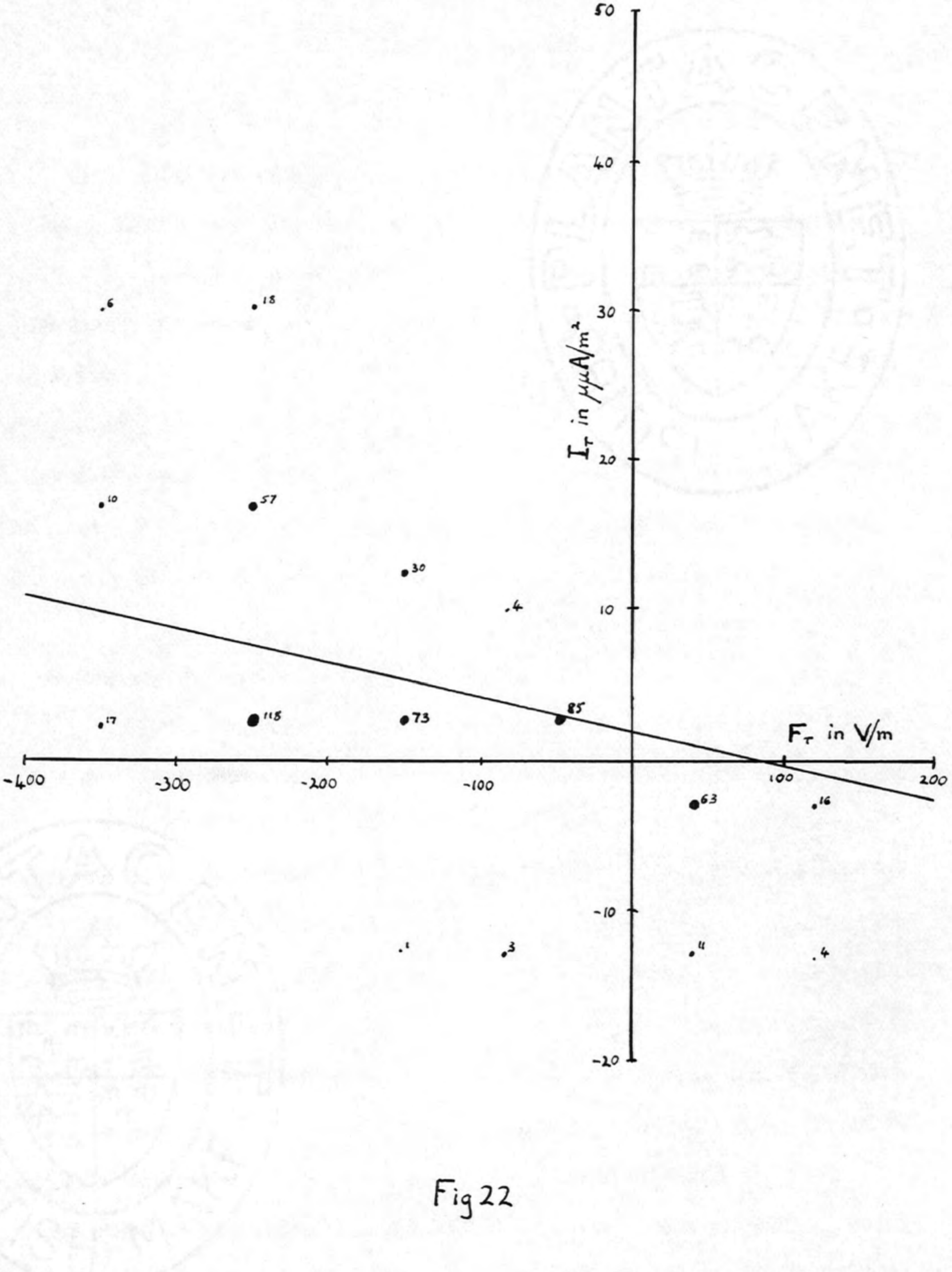

50
40
30
20
10
-10
-20
-400
-300
-200
-100
100
200
I_T in $\mu\mu A/m^2$
F_T in V/m
6
18
10
57
30
4
17
118
73
85
63
16
1
3
11
4

Fig 22

negative intercept on '19' is so small as to be not appreciably different from zero. This agrees with the observations of Kelvin and Chauveau but on the other hand the value of the space charge is very low. Also while plotting the scatter diagrams it was noticed that the points moved up and down lines which had the same gradient but different intercepts and that the sign of the intercept often appeared to follow that of the potential gradient so that the space charge might only have been negative when the potential gradient was positive. The evidence for this is inconclusive however.

The current measurements showed the inverse relation clearly (Figs. 21, 22) and regression equations were calculated relating them to the potential gradients at the same place. These are shown in Fig. 25 together with the equations found by Ramsay (1959) for the corresponding rates of rainfall. These show quite good agreement when it is remembered that the rates of rainfall are means over long periods rather than the minute by minute values used by Ramsay and that his later results gave slopes that were sometimes even of the opposite sign.

If δF is taken as a valid measure of the space charge then it appears to be more fundamental than the potential gradient so it might be expected that the currents would be

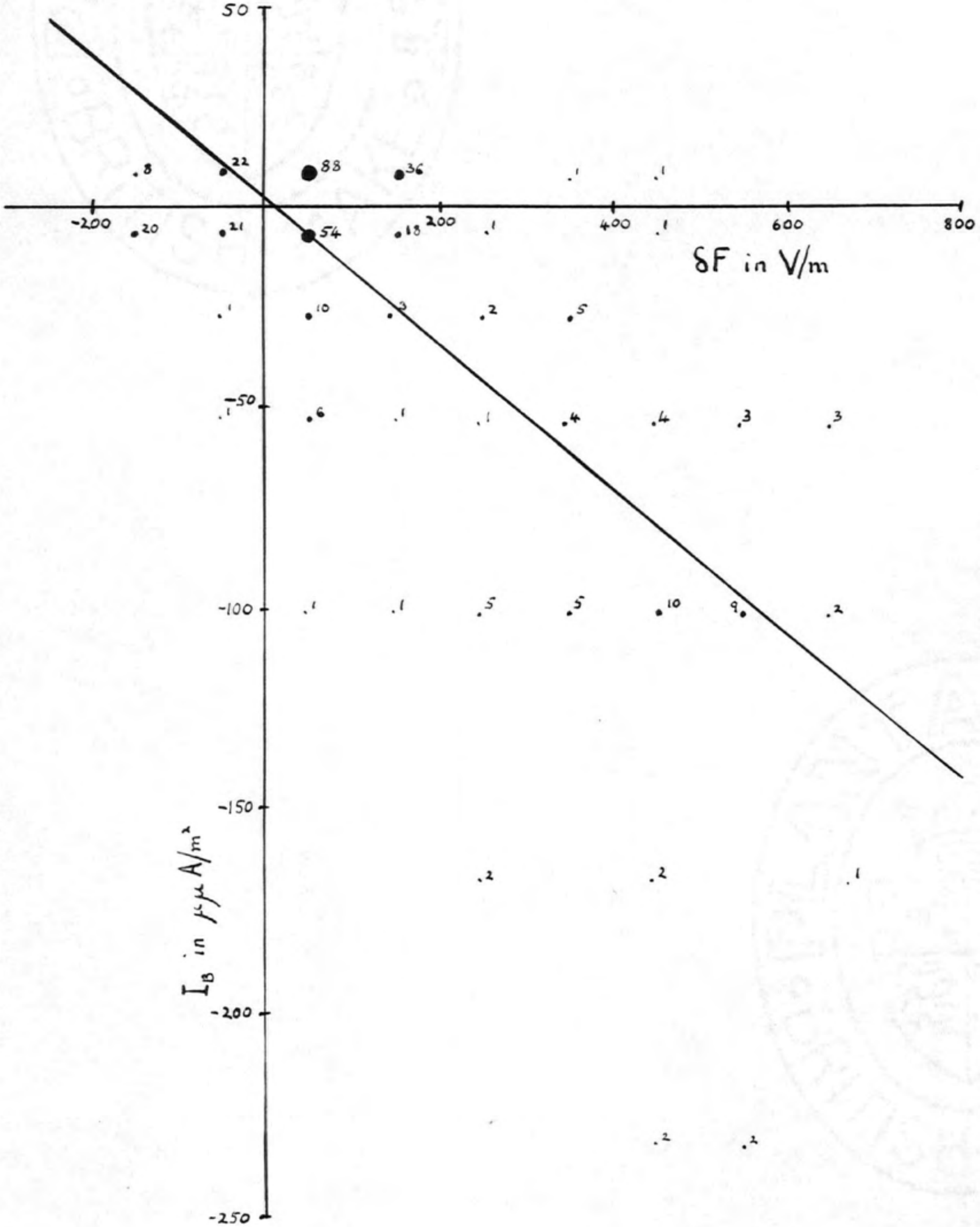
50
-50
-100
-150
-200
-250
-200
200
400
600
800
δF in V/m
I_B in $\mu\mu A/m^2$
8
22
88
36
1
1
20
21
54
18
1
1
1
10
3
2
5
1
6
1
1
4
4
3
3
1
1
5
5
10
9
2
2
2
1
2
2

Fig 23

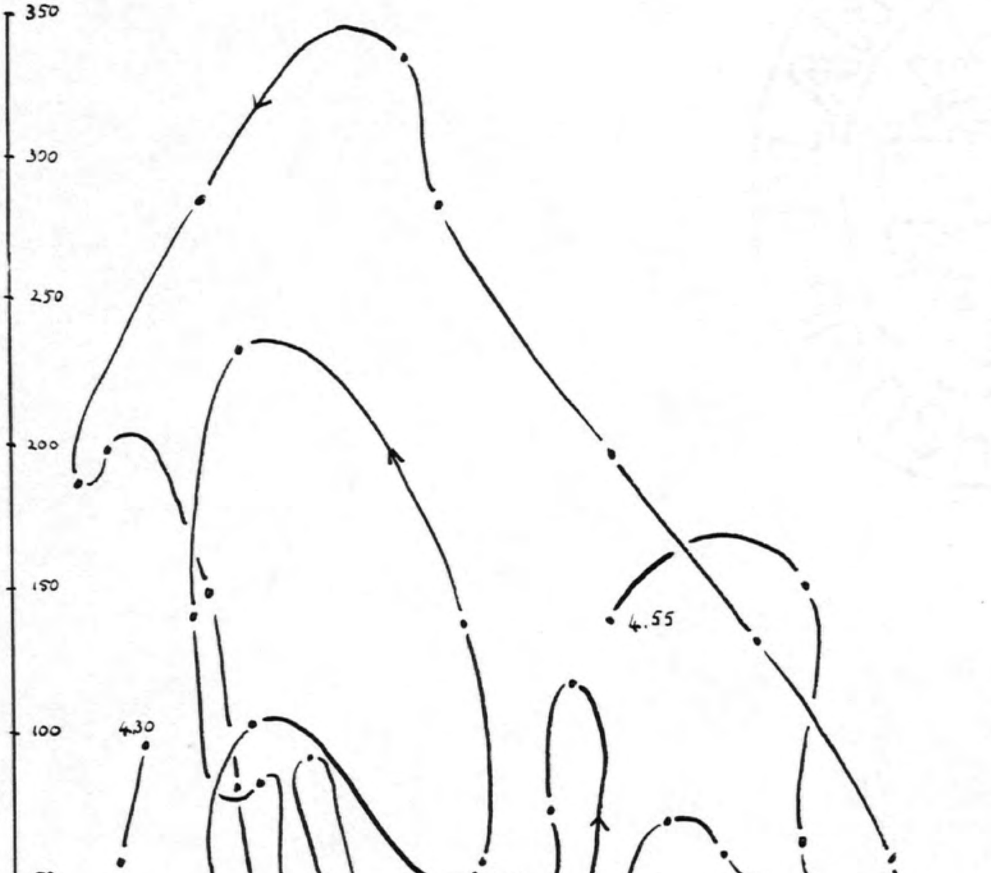

350
300
250
200
150
100
50
-50
-100
-150
300
400
500
600
700
δF in V/m
δI in μμA/m²
4.30
4.55

Fig 24

	19	15	M
F_B & δF	$F_B = 3.5\,\delta F - 9.4$	$F_B = 2.3\,\delta F + 59$	$F_B = 4.0\,\delta F + 110$
F_B & ρ	$F_B = 0.39\rho - 9.4$	$F_B = 0.26\rho + 59$	$F_B = 0.45\rho + 110$
I_T & F_T	$I_T = -0.046(F_T - 78)$	$I_T = -0.32(F_T - 87)$	$I_T = -0.051(F_T - 310)$
I_B & F_B	$I_B = -0.0047(F_B - 92)$	$I_B = -0.081(F_B - 83)$	
I & F (Ramsay)	$I = -0.04(F - 100)$	$I = -0.052(F - 96)$	
Mean Rate of Rainfall mm/min	0.015	0.03	0.006
I_B & δF	$I_B = -0.15(\delta F + 18)$	$I_B = -0.25(\delta F + 73)$	
I_T & δF	$I_T = -0.17(\delta F + 21)$	$I_T = -0.45(\delta F - 30)$	$I_T = -0.86(\delta F + 61)$

Fig 25

more closely related to it. The regression equations relating I and δF did have much smaller intercepts than those for I and F (Fig. 23) but when the correlation coefficients between I and F, and I and δF were compared there was no significant difference between them.

Another relationship with δF was the difference between the upper and lower currents. This showed very pronounced 'ellipses' indicating that when δI was large δF tended to decrease and to increase again if δI become small and especially if it became negative (Fig. 24). These 'ellipses' are similar to those found by Ramsay when investigating the mirror image effect and since δI, $I_B - I_T$, is largely determined by its greater component I_T they may nothing more. Alternatively if δF represents the space charge and δI is the charge gathered by the rain while falling through the height of the tower the rain can be considered to be washing out the space charge giving the current difference and at the same time reducing δF. The problem of a mechanism for the collection of charge now arises. Calculations based on the ion capture theory put forward by Wilson (1929) and worked out in detail by Whipple and Chalmers (1944) showed that this process would give values of δI that would have been to small to measure. If the space charge consisted of charged droplets a coalescense process might have operated, but this could not have given a sufficiently large value for δI either.

It might be possible to explain the large value of I_T as being a localised effect caused by the exaggerated potential gradient near the top of the tower, but occasionally there were pulses on the record of I_T which were not duplicated by I_B and these were accompanied by an 'ellipse' effect associated with not only F_T and F_B but also the potential gradient at some distances from the tower. Unless the 'ellipse' effect is fortuitous here, and it was observed on several occasions, this suggests that not all of I_T can be a local effect and that in at least some cases the rain looses charge between the top and bottom of the tower.

Conclusions

In view of the doubtful meaning of the $F_B/\delta F$ equations it is impossible to draw any firm conclusions about space charge except to say that some does exist and that it may be related in some way to the potential gradient.

The relation between precipitation current and potential gradient at the bottom of the tower is similar to that found by Ramsay and indicates that the presence of the tower had no appreciable influence at ground level. The difference between the currents at the two levels does indicate that some charging process does operate near the ground and even if this only produces an unnaturally large charge in the exaggerated potential gradient at the top of the tower it probably operates on a smaller scale under natural conditions.

What this work has shown most effectively is the difficulty involved in determining the exposure factor of an instrument when it is a considerable distance from the standard one. When any further work is done in this field special attention must be paid to this problem and either a check made that there is no space charge present when the calibration is made or perhaps the exposure factor could be found by some other method, possibly by experiments on a scale model.

A better method of dealing with displacement currents in the upper collector should also be found and steps taken to eliminate the effects of splashing. If the problem of exposure factor can be overcome the distribution of the space charge could be determined by measuring the potential gradient at intermediate levels or preferably measuring it directly. It might be possible to find out more about the way in which the rain's charge is altered by measuring individual drop charges at the two levels, and if the intensification of the potential gradient could be changed by changing the geometry of the tower any charging dependent on the intensification could be distinguished.

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