The electrification of raindrops

Trickett, E.

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The Electrification of Raindrops.

E. Trickett, B.Sc.

University College.

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University of Durham.

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Abstract.

The charges and masses of individual raindrops were measured in different conditions of rainfall at two different sites. An apparatus was developed to measure raindrop parameters and display their values in the form of a spot whose vertical and horizontal positions on an oscilloscope screen represent the mass and charge respectively. Photographic records, each of a number of successive spots, were made for periods of between half-a-minute and twenty-five minutes during twenty-four separate periods of rainfall which covered many meteorological conditions between thunderstorms and fine drizzle. The photographic results are analysed in terms of the weather conditions applying at the times of measurement. It is shown that stratus and cumulus clouds produce distinct charge/mass patterns on the exposures, and that these patterns can be related to known factors about the nature of the different clouds.

The methods of charge measurement by electrostatic induction, and of mass measurement by registering the impacts of drops on to a detector plate are described. Suggestions are made for future work and improvements to the equipment.

Acknowledgements.

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Edward Trickett.

Contents.

Chapter 1. The Electrification of Rain.

Chapter 2. Apparatus for Measuring Raindrops.

Chapter 3. The Rain Detector.

Chapter 4. Calibration of the Rain Detector.

Chapter 5. Measurement of Potential Gradient.

Chapter 6. Observations of Rain.

Chapter 7. Discussion of Results.

Chapter 8. Conclusion.

References.

Appendix A.

Appendix B.

Chapter 1.

The Electrification of Rain.

1.1. Introduction

This chapter is intended to describe the work that has been done in the field of Atmospheric Physics that bears directly on the present work on the Electrification of Rain. I have attempted to describe the general background and then to discuss in more detail the work of previous researchers into the same topic. Finally I have described what I see as the more important electrification theories and so the present state of knowledge.

The second and third chapters describe apparatus for measuring raindrops, Chapter 2 dealing with the equipment used by previous workers and my own early designs. Chapters 3 and 4 describe my final apparatus and its calibration.

The fifth chapter covers the measurements made of potential gradient at the Observatory site where some of the rain measurements were made.

The remaining chapters cover the results of rain measurements made and discuss them in the light of previous work. I have attempted to outline what I consider should be the next steps in research into this topic.

1.1.1. The Importance of Rain Electricity.

There is a circulation of electric current in the lower atmosphere of which the current carried by rain is a very important part. Under normal fairweather conditions there is a positive potential gradient in the lower atmosphere and a small current of positive charge arriving at the ground under the influence of this potential gradient. Correspondingly in other parts of the world positive charge must be carried up to the electrosphere or conversely negative charge carried down. Only comparatively rarely is there a negative potential gradient when rain is not either near or actually present so it seems that rain ~~is entirely or almost entirely~~ usually accompanies processes responsible for bringing negative charge to the earth's surface. It is presumably unlikely that other currents in the air during rainfall are of as great magnitude as the rain current itself and in high potential gradients the point-discharge current. I am neglecting here such "apparent" currents as the displacement current.

Apart from measurement of fine weather potential gradient and of rain current there is a good deal of evidence to suggest that the rain current, point-discharge current and lightning current maintain the balance of negative bound charge on the earth's surface. A correlation was found between the estimated number of storms raging at any one time of the day and the fair weather potential gradient over the oceans by Whipple and

Scrase (1936). They showed that the maximum of thunderstorm intensity at 14 - 20 hrs. G.M.T. due to the storms over the great land-masses of Europe and Africa, and North and South America during their respective afternoons correspond to a maximum of the fair-weather potential gradient measured on the vessels "Carnegie" and "Maud". This can be explained by assuming that a greater number of storms will bring down a greater amount of negative charge, which will require a greater positive current over the remaining parts of the earth. If the amount of air-borne ions is assumed approximately constant this can only be brought about by an increase in the potential gradient such as has been observed.

The above correlation applies particularly to thunderstorms as these are supposed to have more effect on the electricity of the atmosphere than non-thundery rain. Although the presence of lightning supports this suggestion, it is shown in this work and in previous work that it is better described as an extreme case at one end of a spectrum of rain conditions varying in the intensity of their electrical activity. Thus all rain conditions contribute to the transport of charge between atmosphere and earth, and the present single-drop measurements in addition to previous measurements both of single drops and of rain current, are designed to investigate the nature of the processes involved.

1.1.2. The Charging of Raindrops.

Raindrop charges are usually measured at ground level. All airborne measurements have been made inside clouds and so have been aimed more at measuring cloud-drop parameters. The droplet charges that are measured at the ground may have been produced within the cloud or between the cloud-base and ground-level. The nature of this charging has been neglected by comparison with work done on charge separation within clouds, but is closely connected with that. If we assume that the charging of drops takes place mainly in the cloud then the cloud-droplet charging processes are supremely important, but if below the cloud, then the processes may be similar to or completely independent ~~to~~ of those involved in the cloud.

Evidence showing a close correlation between total precipitation current and potential gradient, notably the "mirror-image" effect found by Simpson (1949) where the current and potential gradient are found to be generally opposite in sign, suggest that the charging processes affecting the charge at the ground occur below cloud level. However to a certain extent it is possible that the potential gradient is dependent on the rain charges when the potential gradient is less than 500 Vm^{-1} e.g. potential gradient changes due to rain splashing at the ground.

Simpson's results however do include high potential gradients (up to 10,000 Vm^{-1}). In the following discussion I shall assume that the significant influence on raindrop charges is below cloud-level.

Between cloud-base and ground the drops fall through a layer of air in which a quantity of small and large ions are present. The charges acquired by the drops may come from these ions under the influence of the potential gradient. The other parameters that may affect the charging of a drop are wind, fall velocity of drop, radius of drop (on which the terminal fall velocity depends), ion concentration and the chance of collision. The chance of collision between drops is probably so small as to be safely neglected. Except in the cases of sleet and snow, which are not covered by this work, and of hail, which I am neglecting for the purposes of this discussion, precipitation is not in the ice-phase below cloud base and so charging due to freezing or melting need not be considered.

Some laboratory experimental and theoretical work has been done on the nature of charging of droplets in the presence of an electric field and of charged ions. The most notable theoretical work originated with the Ion-Capture theory of Wilson (1929). This was developed by Whipple and Chalmers (1944). The results of these calculations give formulae from which the electric charge of a water drop falling through the air may be calculated given the electric field, the drop radius and the original charge carried, together with knowledge of sizes and charges of the ions present. Smith (1955) used the results of these formulae for comparison with his own single-drop measurements. The agreement in some cases is considerable, but the calculations require a much greater potential gradient, roughly one order of magnitude greater, than he measured at ground level.

Wilson's theory, therefore, seems a most promising explanation but with some adjustments to compensate for the high fields required. Generally, more observations of drop charges are required under various conditions. The details of this section are more closely examined in Section 1.3.

The potential gradient in stormy conditions is controlled by the charges in the clouds. There are several theories about the charge separation in clouds, but in temperate climates it is sufficient to say that the presence of the ice-phase in the cloud is probably the major cause of this charging. The ions in the air come from radio-active ionisation, ionisation by cosmic rays and to some extent from point-discharge in high potential gradients and some other sources.

1.1.3. Experimental Work on Rain.

The quantity of rain falling on the earth is and has been measured widely for many years with standard pieces of meteorological equipment. The standard rain-gauge and tilting-bucket rain-gauge are well known pieces of equipment. Frequently, rain-gauge measurements have been used alongside rain current measurements both to show the total rain falling at the time and, in some cases, the proportion of rain that is collected by the rain current meter. The equipment used by Scrase (1938) was particularly subject to collecting only a proportion of the rain. An electrically insulated collecting cone was mounted at the bottom of a metal cylinder which acted as an electrical screen. Unfortunately this meant that in any case when the rain was not falling vertically or nearly vertically then much rain would not be collected, also small drops would be more easily blown clear of the collector than would large ones.

The normal unshielded collector consists of a horizontally mounted plate connected to an electrometer and usually in the plane of the ground. This collects the total air-earth current including not only the rain current, but also the ionic convection and conduction currents and the displacement current, which latter is the change in the bound charge at the earth's surface due to changes in the potential gradient.

More elaborate versions of the screened collector designed to combine the advantages of total rain collection, of the unscreened version, and of cutting out the displacement current of the screened version, have been tried out at Durham by Mr. M.F. Stringfellow.

When single drops are collected the apparatus must be so selective that the integral of the charges of all drops collected in a certain time could not represent the total rain current to a certain area. A detailed description of earlier forms of single drop collectors is given in Chapter 2. Smith (1955) mounted his collector so that it might be tilted into the wind and would not discriminate against drops of small size. The single drop collectors are not subject to error as a result of displacement current and other air-earth currents, because these need d. c. amplification in the electrometer circuit, which is not necessary for single drops.

1.2. Review of Results of Previous Workers.

Several researchers have carried out work on precipitation currents, a smaller number on single-drop observations. Earlier observations of single drops were limited as to the rate of drop collection; more recent workers have been able to collect more drops per second and presumably to gain a better representative sample of the rain, by the use of more advanced techniques.

Not all measurements of drop charge were combined with simultaneous measurements of drop size. The readings of Gunn and Devin (1953) are a case in point. Failing to recognise any comprehensible pattern in their results they concluded that there was no distinguishable correlation between potential gradient and drop charge. The results of Smith, which came from measurements of charge and size, published two years later, adequately refuted this conclusion.

1.2.1. Early Observations.

Measurements of drop charge and size were first made by Gschwend (1922) who found from 1,537 drops a ratio of 1·77:1 for positive to negative drops, and a ratio of 1·5:1 for total positive charge to total negative charge brought down. This suggests that the negatively charged drops were more highly charged, a conclusion generally supported by later workers although figures for the above ratios vary; examples being those of Chalmers and Pasquill (1938) and Gunn (1949). Chalmers (1967 Ch. 10) gives details.

Gunn (1949) considered his results in terms of the electric field that exists at the surface of a rain droplet. He found all his drops had values of this field between 33 kVm^{-1} and 330 kVm^{-1}, an average value being 61·2 kVm^{-1}. As well as finding that the negatively-charged drops were more highly charged than the positive, he also found that they were more massive, and also that drops of opposite charge could fall in quick succession.

The absolute values of the charges found by these observers were of the order of 0·1pC (Gschwend) or 1pC (Chalmers and Pasquill) for quiet rain, 1pC (Gschwend, and Chalmers and Pasquill) or 2pC (Banerji and Lele) for shower rain and the higher values of 3pC (Gschwend, Chalmers and Pasquill, and Banerji and Lele) or 6pC (Gunn) for thunderstorm rain. Although this shows the greater charges that may be expected from electrically active thunderclouds the discrepancies between the results of individual workers suggest that the methods of measurement may be inconsistent with each other. The values of charges quoted are roughly average and may be explained by the fact that different pieces of equipment had differing lower levels of sensitivity.

As mentioned above, most of the researchers measured drop size; the lower limit was limited by the apparatus and at the upper limit few drops were found with diameter in excess of 3mm.

1.2.2. Airborne Observations.

A number of workers have designed and built apparatus for measuring drop charge and size that is suitable for mounting on an aircraft. Quite apart from the fact that the techniques used are interesting and valuable in themselves, the results are of interest to compare with similar observations made at the ground. The airborne operator, however, has an advantage in that he need not wait for suitable weather conditions to come to his equipment, instead he takes it at will through any convenient cloud.

Gunn (1947, 1950) was the first worker in this field, generally finding the charges were greatly in excess of charges found at the ground in similar rain conditions. For altitudes between 1 and 6km typical charges in shower rain were between 10 and 30pC, and in thunderstorm rain between 20 and 40pC. These values are an order of magnitude greater than those found at the ground. Gunn did not measure the sizes of the drops, but this was done in a later investigation by Fluegge and Pilie (1965).

Investigations of droplet charge have also been made in non-raining clouds, frequently with emphasis on drops of very small size, about 1 μm to 10 μm. Twomey (1956) photographed the tracks of small droplets passing through an a.c. field and found mostly positive drops when no ice was present. MacCready and Proudfit (1965) found that charges appeared on the drops at the melting level in the cloud, which suggests that the ice-phase is all-important in cloud electrification.

~~In general it seems that clouds contain not only~~

raindrops, but also the smaller cloud-droplets, ~~and that on the whole, particularly in a raining cloud, these are charged to a greater degree than the raindrops at the ground~~. When ice is present, charging appears to be due directly to the freezing and melting processes, and otherwise charge is collected by the absorption of airborne ions. Gunn (1957) has pointed out that the electric fields inside a thunderstorm are greater than those below, and are particularly high in the vicinity of the freezing level. In non-thundery clouds Gunn (1948) states that the field inside a cloud producing steady rain is less than 4000 Vm^{-1} and in a non-precipitating cloud it is less than 1000 Vm^{-1}, but both these values are greater than the values of potential gradient observed at the ground in the same conditions.

1.2.3. Latest Observations.

Since 1950 there have been published results of raindrop charge and size measurement by three workers. Hutchinson and Chalmers (1951) measured charge and size of drops whilst simultaneously measuring the potential gradient and, in high fields, the point discharge current through a metal point. Their results generally agree with the results found by previous workers, and could be explained by Wilson's Ion-capture theory if the potential gradient was several times higher than that measured at the ground. Smith (1955) used a technique which permitted the measurement of a much greater number of drops during any period of time. When plotted on graphs of co-ordinates representing drop charge and drop radius points with parameters corresponding to those of drops collected demonstrated clear patterns. These distributions fit the patterns theoretically predicted by Smith from Wilson's Ion-capture theory, as derived from the paper by Whipple and Chalmers (1944). Smith's readings were taken over short periods of time when it could be said that the controlling factors of potential gradient and wind would not change by more than a trivial extent. Typical times were about two or three minutes. Smith also took readings of potential gradient and of point-discharge current through an artificial point. Smith's lowest measurable charge was 0·3pC, Hutchinson and Chalmers' 0·03pC, and 0·6pC was the minimum charge measurable by Arabadji (1959). Arabadji also used a technique that would permit the collection of many drops in a short time; at the maximum rate he was collecting at a rate of 1·7 drops s^{-1}. Arabadji found that in six storms out of the ten in which he took readings the number of negatively charged drops exceeded the number of positively charged drops, and that the average charge on the negatively charged drops was greater than for the positive.

The general conclusion from all these results is that there is a fundamental asymmetric nature of the charge distribution of drops brought down. Usually this is such that drops of one sign of charge predominate on larger drops and those of the opposite sign, on smaller drops. Frequently, the negative charge is on the larger drops, although this is probably controlled by the sign of the potential gradient in the region where charging takes place. The larger drops also appear to carry a greater net charge, but this is to be expected if the field at the surface of the drop is not to be much greater for smaller drops. The explanation in terms of Wilson's Ion-capture theory will be given in section 1.3.

1.3. Theoretical Background.

Raindrops arriving at the ground formed originally by coalescence in the cloud. Falling out of the cloud they may have coalesced with more cloud droplets, and in an active thundercloud or cumulo-nimbus may have been carried up and down in the updraughts and downdraughts before eventually falling. In this country, in a temperate climate, a considerable proportion of the cloud will consist of ice particles and drops normally start as snowflakes, which are clumps of ice particles and which melt to produce the drops after they have fallen to the 0°C level. In active cumulo-nimbus clouds the updraughts may carry a raindrop above the freezing level when it may freeze and form a hailstone. In clouds with a strong updraught the drops must grow to a larger size before falling if they have to fall against the updraught, than if there is no or little updraught. Small drops may fall from a different part of the same cloud, but if no large drops at all fall then it may be assumed that there is no strong updraught present. When a drop has fallen out of the cloud it will be subject to wind, possible collision with other drops, and, if large, the possibility of spontaneous break-up due to the pressure of air on its lower surface. It will fall most of the way at its terminal velocity in the air. At the ground, drops of different sizes arriving at the same time will, by virtue of their different terminal velocities and their different susceptibilities to being blown by the wind, have originated from different parts of the cloud and at different times. How much they differ in origin is a matter for speculation; the fact that drops of the same size arrive at the same time with different charge having apparently passed through the same part of the atmosphere at the same time is confusing.

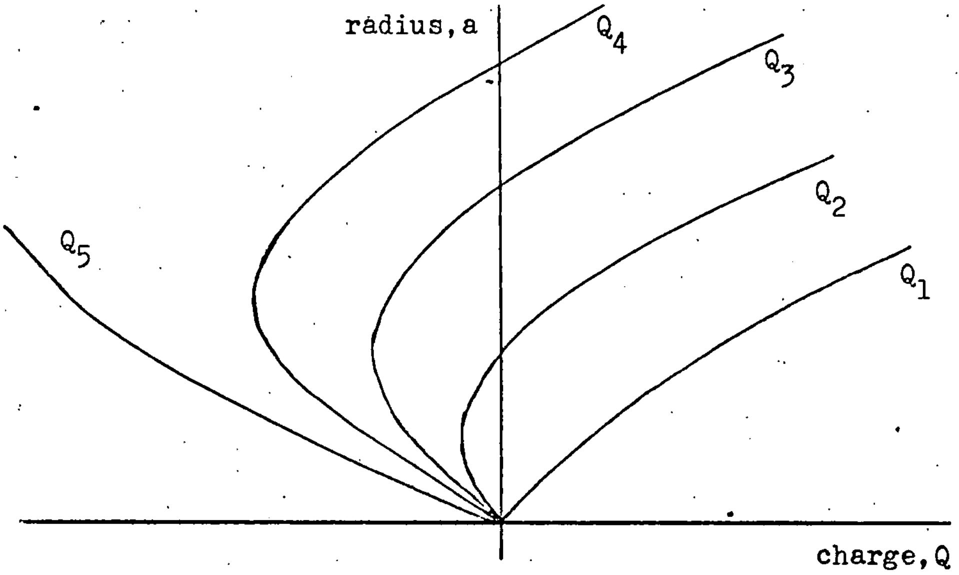
During all the period of formation and fall of a raindrop it is subject to electric fields. Charging by some mechanism is inevitable when freezing or melting takes place, and ion pairs produced by cosmic rays and radioactive substances, and point discharge ions supply a considerable quantity of ions that may be picked up. Any explanation of the charging observed must take into account all the conditions the drop falls through and also explain the near-random distribution of charge amongst the drops.

The charges on drops inside clouds have been observed to be much greater than on the drops measured at the ground. It has already been mentioned that potential gradients inside clouds are greater than those below at ground level. A typical quiet non-raining cloud has a potential gradient less than 1000 Vm^{-1}, but a thundercloud has typically a potential gradient of about 100 kVm^{-1}, a value exceeded by a factor of 2 or 3 immediately before a lightning flash. Correspondingly there are high potential gradients at the ground below thunderstorms, but except when a lightning flash to ground is imminent in the immediate vicinity of the point of measurement, these are an order of magnitude less than those measured in the cloud.

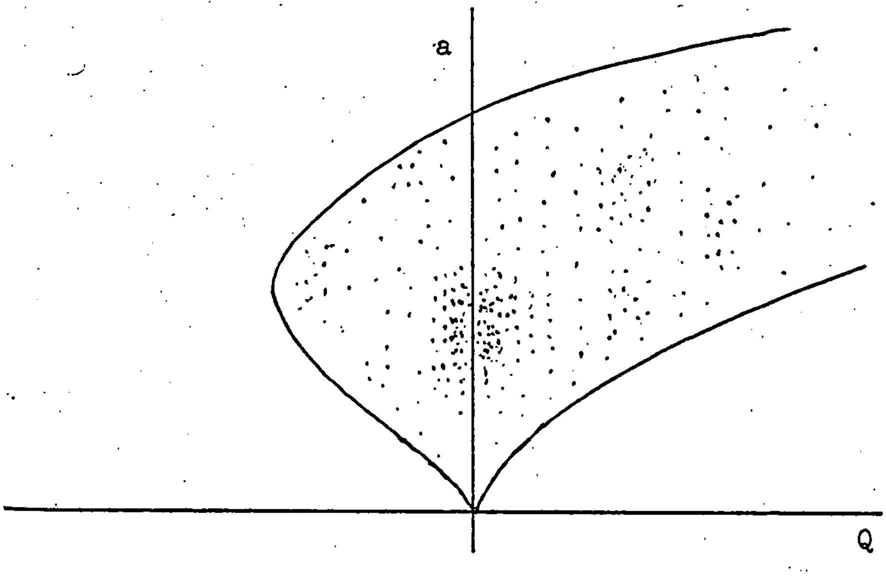
The situation given is thus: a cloud contains charged precipitation particles in both ice and water phase. There is a potential gradient caused by the separation of charges within the cloud, and this potential gradient is generally greater than that existing outside the cloud. Separated charge causes the potential gradient, and it is certain that the potential gradient is involved in the separation of charge. It is not important to decide which must come first as all clouds build up gradually and the processes which go on inside must also build up in intensity. The melting of ice and freezing of water appear to give rise to considerable charging even though the processes concerned are not fully understood, and will not be described here. Charge separation occurs also in clouds that do not include the ice-phase by processes that presumably take place in all clouds. The most satisfactory description of charge separation involving falling drops, ions in the air and an existing potential gradient is that suggested by Wilson (1929) and developed by Whipple and Chalmers (1944) and Chalmers(1947).

Wilson's theory refers to a drop of radius a falling under the influence of a vertical potential gradient X in an atmosphere containing ions of either or both signs of charge. The potential gradient polarises the drop, whether or not it has an initial charge. The polarised charges on the drop attract ions of opposite charge from the air, but whether these ions actually touch the drop and so affect the charge depend not only on the potential gradient but also the speed of fall of the drop. When negative ions are present the final charge on the drop is $-12\pi\varepsilon_0 X a^2$ where a = drop radius, and -x = vertical potential gradient, but if the conductivities due to the ions of each sign are equal then the final charge is $-2{\cdot}06\pi\varepsilon_0 X a^2$. This suggests that the final charge at the ground is fixed by the dimensions of the drop and the potential gradient that it has experienced. Even if the potential gradient was constant between cloud-base and ground this would be an over-simplification.

Smith (1955) plotted the results he obtained for charge



Theoretical loci of parameters of drops falling and obeying Wilson's Ion-capture theory.
(Q_1-Q_5 refer to various initial charges)



Typical experimental distribution of drop parameters as found by Smith, with envelope curves.

Figure 1.1

and radius of drops collected in the presence of point-discharge current (from a metal point) as a distribution on a graph, plotting charge against radius for each drop measured in a short period of time. In some, but not all, cases a clear pattern appeared such that the drops could be contained in an envelope of two curves. When this appeared, larger drops would be predominantly of one sign and smaller drops of the opposite sign. In his discussion, Smith made calculations using the formulae for rate of charging in the paper by Whipple and Chalmers. After integration these formulae gave the final charge at the ground in terms of the thickness of air through which the drops had fallen as well as in terms of the initial charge carried, the potential gradient and the vertical conduction current. Smith assumed a negative potential gradient and a conduction current of negative ions produced only by point discharge from the ground. The results when sketched on a distribution graph (See fig. 1.1.) compare very closely with Smith's experimental results. They differ from the figure calculated by Whipple and Chalmers because that is a final limiting value of charge, and Smith's figures state that the charging process is not complete when the drop reaches the ground. In theory if the initial charges on the drops were zero then they would all lie on one curve, but the distribution bounded by two curves is explained in terms of the variation in initial charges.

Not all Smith's results followed this pattern; some appeared to have an almost random distribution, probably due to the variation in vertical potential gradient while the drops were falling or variations in other effective parameters. Smith's explanation of his results is limited to conditions where negative ions predominate, and point-discharge, due to high negative potential gradients is the cause. It also explains results in terms of positive ions and high positive potential gradients, but does not take into account conditions where point-discharge is not taking place.

1.4. Present Situation.

If an explanation has been made for the charging of raindrops in high-field conditions, this leaves open the whole range of rainfall at times when point-discharge is absent. Rain may fall as drizzle from blanketing stratus clouds or as heavy thunderstorm drops from towering cumulo-nimbus, and indeed in any form over the whole spectrum between these two extremes. In general electrical activity increases with cloud turbulence activity, such that cumulus clouds show a more pronounced electrical nature, with corresponding higher potential gradients than do stratus clouds. Results of rain measurements are needed in steady rain and non-thundery shower rain, and, in general, in all conditions where high potential gradients are not present and point-discharge unlikely. More information about the nature of point-discharge is also required, so that we can estimate the nature and quantity of the ions under clouds.

~~Smith's discussion includes ions of one sign only, and in theory if ions of both signs are present in equal numbers then no net charging will occur. This should be experimentally tested. In general many more readings in all types of rainfall are needed.~~

The object of the present work is to attempt to make measurements of raindrop charge and size in all rain conditions encountered, together with measurements of the earth's vertical potential gradient at the same time. Facilities available at the sites of observations, Durham University Observatory and the Lanehead Field Centre also allow wind speed and direction readings to be taken.

Chapter 2.

Apparatus for Measuring Raindrops.

2.1. Introduction.

An apparatus was designed which could be placed out of doors to receive raindrops as they fell and to measure their respective electric charges and sizes by electronic means. The publications of previous workers in this field were studied so that they might act as a guide to this design and a number of new ideas were tried out to see if they would be useful. Several versions of the apparatus, from now on to be referred to as the "Rain Detector", were produced in turn, each version being an improvement on its predecessors until an acceptable design had been evolved.

2.2. Techniques used by Previous Workers.

2.2.1. Measurement of Charge.

The earliest measurement of charge was by Gschwend (1922) using a string electrometer. Chalmers and Pasquill (1938) were the first to use valve amplification, and this was also used by Gunn (1949), Hutchinson and Chalmers(1951), Smith (1955), Arabadji (1959) and all recent workers. In some cases the charge flowed directly into the amplifying circuit from a collecting can, but more usually the drop has been allowed to fall through an induction ring connected to the amplifier. This has the advantage of leaving the drop intact so that other measurements may be made upon it.

2.2.2. Measurement of Size.

There have been several different techniques used for measuring the sizes of raindrops. Gschwend (1922) and Hütchinson and Chalmers (1951) allowed the drops to be absorbed in filter paper dusted with a dyestuff powder and then measured the size of the stain resulting. Gunn (1949) and Smith (1955) measured the time interval between the two pulses produced as each drop fell through two spaced induction rings. This time would give the terminal velocity of each drop, which will give the size of the drop when compared with tables of terminal velocity, for example those of Best (1950). The terminal velocities of drops of diameter greater than 6mm diameter vary by only 2% and so Smith used another technique for larger drops. He let the drops fall between two plates which acted as a capacitor controlling the frequency of a high frequency oscillator. The drop falling between the plates altered the capacity, and therefore the frequency of the oscillator. When this change of frequency was measured, it could be used to indicate the size of the drop falling through the apparatus.

Arabadji (1959) measured the size of his drops by measuring the impulse caused as the drops hit a small plate. He gives few details in his paper, but does say that a piezo-electric crystal was used to receive the impulse and give a voltage pulse related to the magnitude of the impact.

Using an apparatus mounted on an aircraft for within-cloud observations of water drops, Fluegge and Pilie (1965) measured the sizes of drops by an optical method. The drops passed through a collimated beam of light and the amount of light to be scattered was measured.

2.3. Comparison of Previous Techniques.

All previous workers have used basically similar methods of charge measurement, differing only in the type of electrometer used. The methods used for measuring size are very varied and show wide differences in speed and convenience. The early technique of absorbing the drops and measuring the stain produced is slow as the operator cannot measure more than one of two drops at a time, and the recording of results cannot be automated. All the other techniques allow the size of the drop to be converted into an electric signal which may be used in an automatic recording system. The optical method is sufficiently accurate, but in a ground-based system would need large lenses, leading not only to considerable expense but also to a difficult physical set-up. The fall velocity and capacitance techniques need a complex electronic circuit when compared with the simpler alternative of using a plate or diaphragm with a piezo-electric sensing device.

2.4. Preliminary Design Attempts.

2.4.1. Charge Measurement.

A suggestion by the late Professor J.A. Chalmers for using an electromagnetic method for measuring charge was investigated. The idea was that the charged raindrop should pass through a ring of ferromagnetic material which carried a toroidal winding. The charged drop would then act as the primary of a transformer, and the toroidal winding would act as the secondary. The output of this would then be related to the charge on the drop and also to the drop velocity relative to the ring. However, the output signal would be too small to amplify even with a core of the maximum available permeability, the maximum number of windings and the maximum attainable relative velocity between drop and ring, for all drops of usual magnitude of charge. The electromagnetic method could not be adopted and therefore the electrostatic induction method was chosen.

2.4.2. Size Measurement.

A variation of Arabadji's impact plate technique was chosen after consideration of its fundamental simplicity as discussed in Section 2.2. The first idea was to use a loudspeaker as the detector. A droplet hitting the cone would cause a fluctuation, and the loudspeaker coil acting in the same manner as the coil of a moving-coil microphone would produce an electrical signal. Although this would have solved all problems of mounting the impact diaphragm, once the loudspeaker chassis had been fixed, the paper cone would have been very vulnerable to rainwater and difficult to protect. After the loudspeaker idea had been rejected, a paper diaphragm cemented to a piezo-electric ceramic element at the centre and supported on sponge rubber round the edge was tried. If this had been successful the paper would have been replaced by a water-repellant material. It was however too big at 600 mm diameter to be sensitive to small raindrops and the scale of the whole apparatus had to be severely reduced. The piezo-electric ceramic element was effective as a mechanical sensing device and so was retained. A mica disc of 60mm diameter was tried as the receiving plate. The ceramic element was cemented to the centre of this and the result seemed successful. The only fault that remained for practical measurement was that the electrical pulse output from the ceramic element varied for drops of the same size falling on different parts of the disc. This was apparently due to a twist imparted to the ceramic element when the drops fell away from the centre of the plate. To eliminate this the plate was mounted on a hinged wire (see fig. 3.4.) and thus only rested on the ceramic element instead of being cemented to it. No twist could then be transmitted to the ceramic element, and it was found that the electric output was consistent for drops of the same size, irrespective of what part of the impact plate they hit.

Fig. 3.2. shows that the maximum aperture of the apparatus to receive drops is controlled by the maximum plate size. The aperture eventually chosen was 4·7cm diameter. A smaller diameter was tried but found to be too small to receive much rain.

Figure 3.1 The head-unit in the field

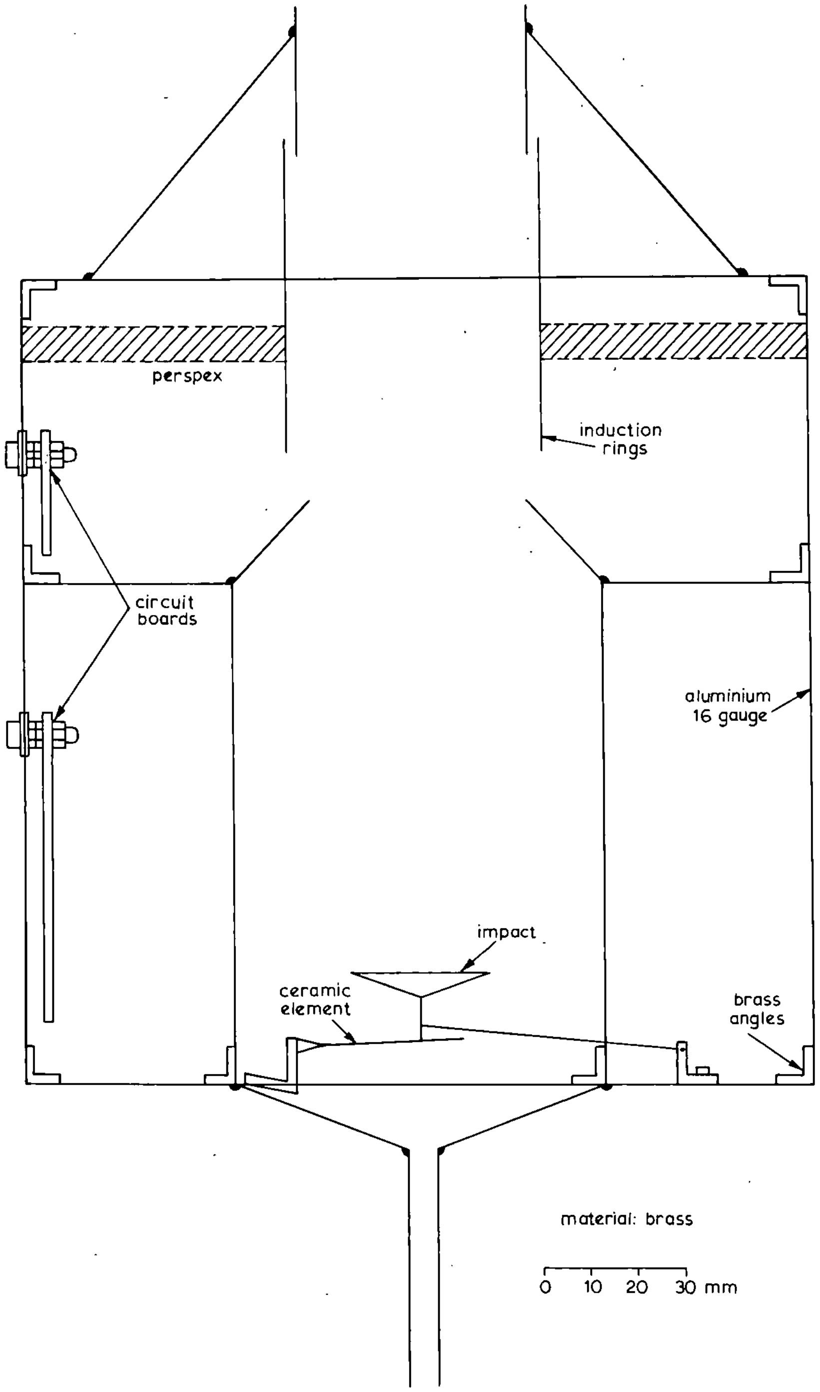


Fig. 3.2. Mechanical design of head-unit

Chapter 3.

The Rain Detector.

3.1. Introduction.

The previous chapter describes the preliminary work leading up to the final design of the rain detector. In its complete form this consists of a head unit which stands outside in the field and receives the raindrops, and which is connected by cable to a recording unit in the laboratory. The electronic circuits in the head unit transmit pulses corresponding to the two parameters, charge and size, of each raindrop detected along the cables to the recording unit which then converts these pulses into a visible display on an oscilloscope. Each drop collected has two parameters to be measured: size and electric charge. It is convenient to plot these as co-ordinates on a graph and this can be done automatically producing a two-dimensional display of spots on an oscilloscope screen. Each spot then corresponds to one raindrop and the co-ordinates of its position on the screen correspond to the two measured parameters. A camera is fitted to the oscilloscope to make a permanent record of the spots, one frame of film being exposed for every two or three minutes of rain. I am indebted to Dr. I. M. Stromberg for this idea.

3.2. Mechanical Construction.

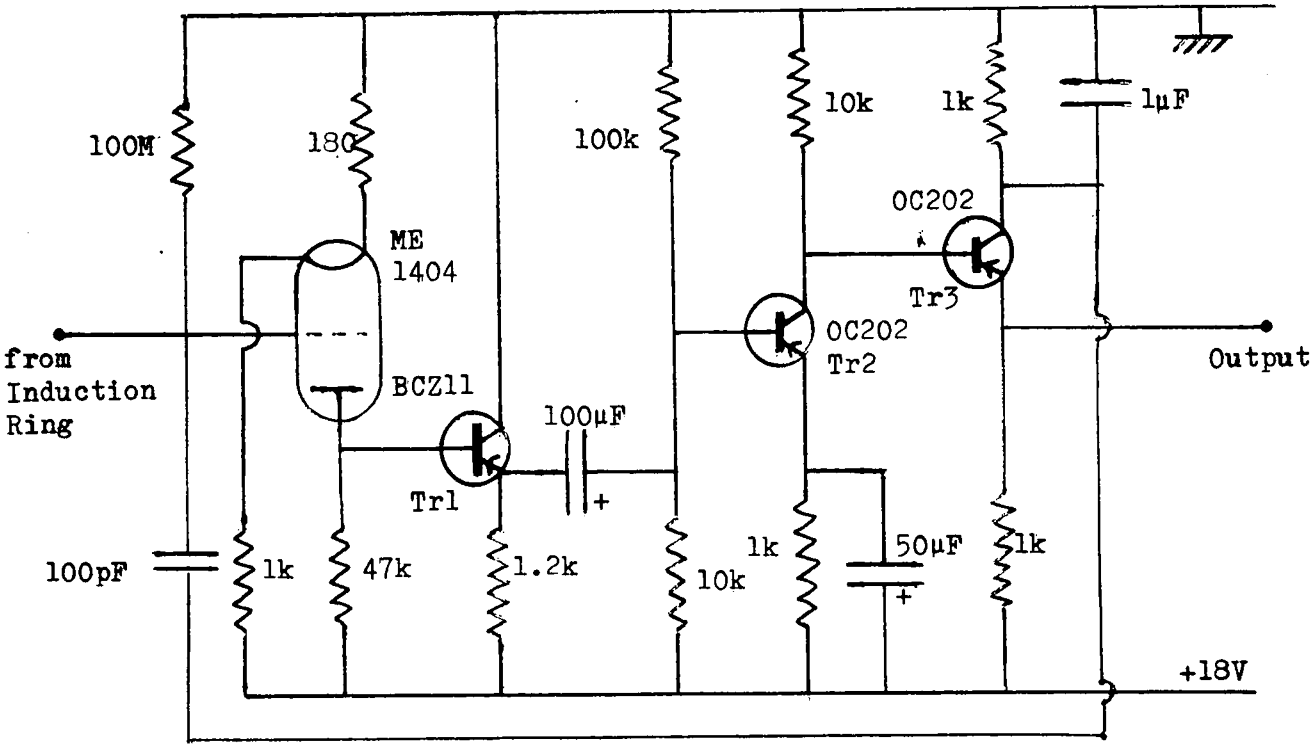
Figure 3.2. shows the mechanical lay-out of the head-unit.

Figure 3.3 Head-unit opened to show interior.

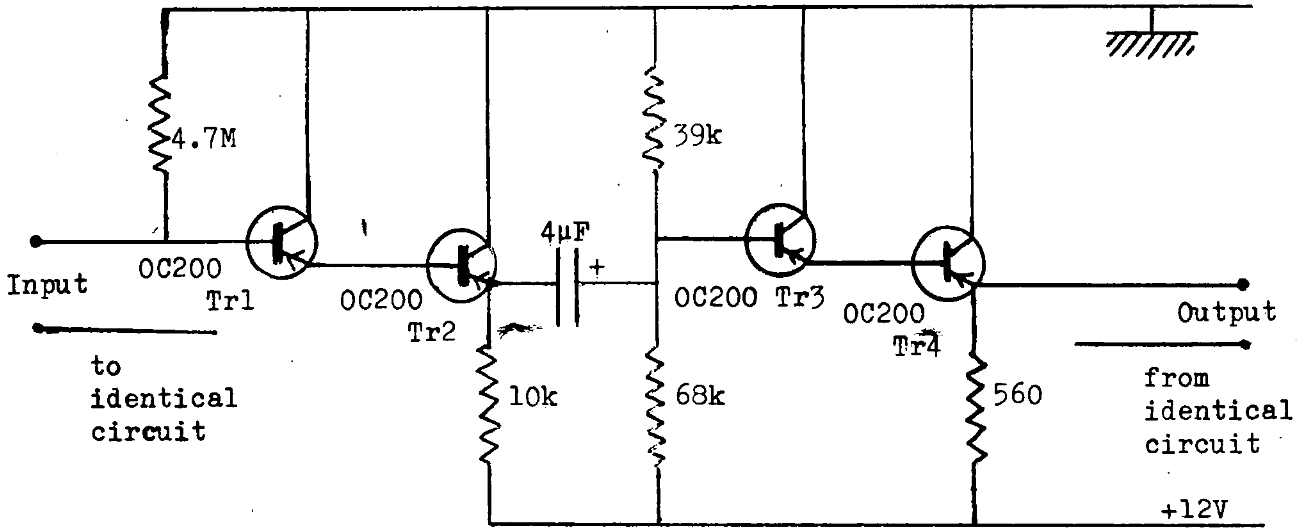
The frame of the unit is built of angle-section brass, the remainder of the construction being of brass and aluminium sheet. Drops of rain falling into the apparatus pass first through the induction cylinder, which is of brass supported by perspex, and then into the bottom of the unit to strike the impact plate. Raindrops hitting the head-unit and not entering splash on the cone. The angle of the cone helps to prevent any droplets from the splash from entering the unit. The inner cone prevents drops that hit the induction cylinder from dropping on to the impact plate. Water drains out of the apparatus through the tube at the bottom. The electronic circuits in the head-unit are fastened to one of the side-panels where they are safely protected from the rain-water (see figure 3.3).

Figure 3.4 shows the impact plate which receives the raindrops at the bottom of the apparatus. A mica disc of 30mm diameter is cemented to a shallow cone of expanded polystyrene of the same diameter and 5mm depth. The plate produced is cemented to a wire coupled to a hinge 30mm away from the centre of the plate and bent so as to present a flat piece which rests on a ceramic element mounted separately. This arrangement ensures that the vertical impulse received by the plate is transmitted directly to the ceramic element. The ceramic element is covered with two layers of plastic insulating tape in order to protect it from the rainwater and to increase the natural damping. The wire cemented to the plate is protected from the

Figure 3.4 The impact plate.



(a) Charge Amplifier.



(b) Impact Amplifier.

Fig.3.5. Head Unit Amplifiers

water by a thin coating of vaseline. The electrical connections to the ceramic element are made at the mounted end.

The whole unit is fixed in a gimballed mounting so that it may be swung in any direction to face the rain (see figure 3.1.).

3.3. Electronic Design of the Head-Unit.

The charge amplifier shown in figure 3.5. (a) amplifies the charge induced on the induction ring. The high-impedance input needed by the induction ring is supplied by an electrometer valve with 100MΩ resistor. The output of this is fed into an emitter follower (Tr1) which supplies a high-gain stage (Tr2). The last transistor (Tr3) is connected as another emitter follower, giving an output impedance for the whole circuit of about 1KΩ. From the collector of the last transistor a negative feedback loop is connected to the 100pF input capacitor. The 1μF capacitor between this connection and earth is to filter out high frequency noise. The effect of this feedback loop is to give a long time constant to the whole circuit thus:

$$T = kRC$$

where T = time constant
k = overall gain = 200
R = input resistance = $10^{8}\Omega$
C = input capacitor = 10^{-10}F

thus $T = 2$s

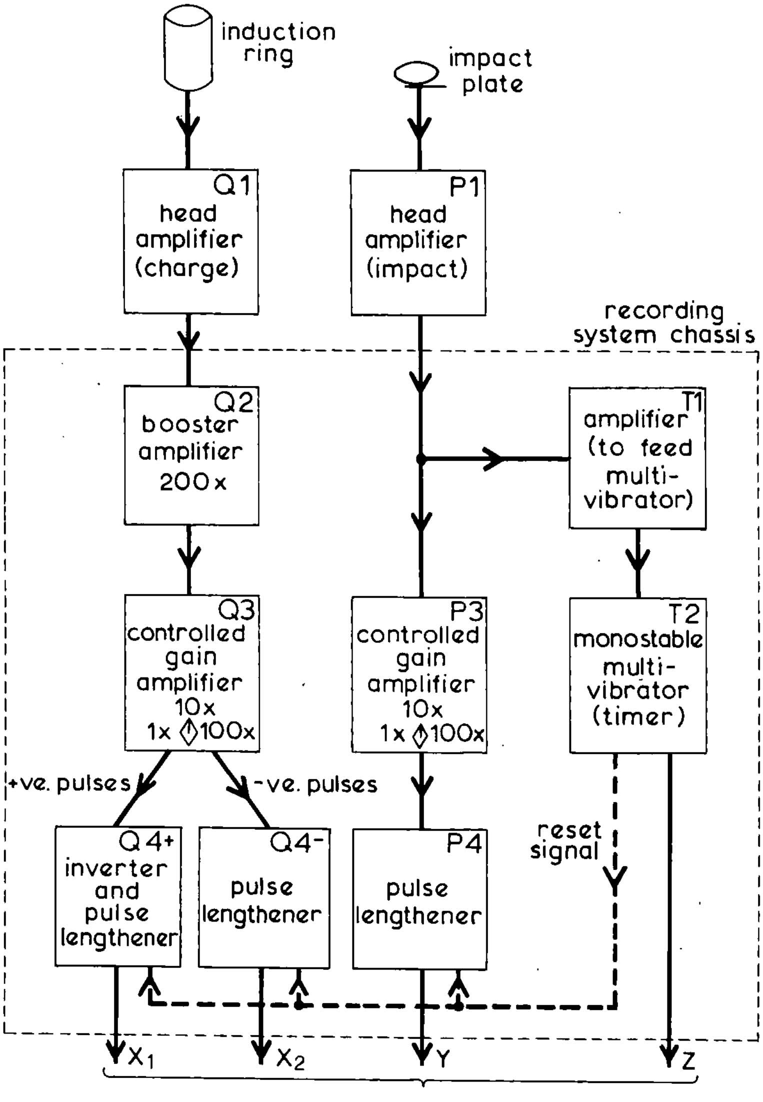


Fig. 3.6. Block diagram of recording system

The output voltage is given by:

$$V = \frac{Q}{C}\left(1 + \frac{1}{k}\right)^{-1}$$

where V = output voltage
Q = charge induced on the ring
C, k as above

The amplifier for the impact circuit is shown in figure 3.5 (b). This is simply two Darlington pair circuits capacitor-coupled acting as a current amplifier. The overall voltage amplification is one. On its own this circuit interferes badly with the charge circuit and it was necessary to put in a duplicate circuit acting out of phase with the first to cancel out the interference. The output from the ceramic element is humdingered across the two 4.7MΩ input resistors to the amplifying circuits. The final output is taken from only one of the circuits, giving an output impedance of about 500Ω.

3.4. The Recording System.

The recording system is designed to cope with the signal pulses from the head unit and to convert these data into a two-dimensional display on an oscilloscope screen. Figure 3.6 is a block diagram showing the layout of the system. In principle the heights of the pulses coming from the head unit are increased to a value between 0.1V and 5V by amplifiers with switched gain-control. The pulses are lengthened to an approximately square-wave shape whose height is the same as that of the pulse fed in. These lengthened pulses are fed to the

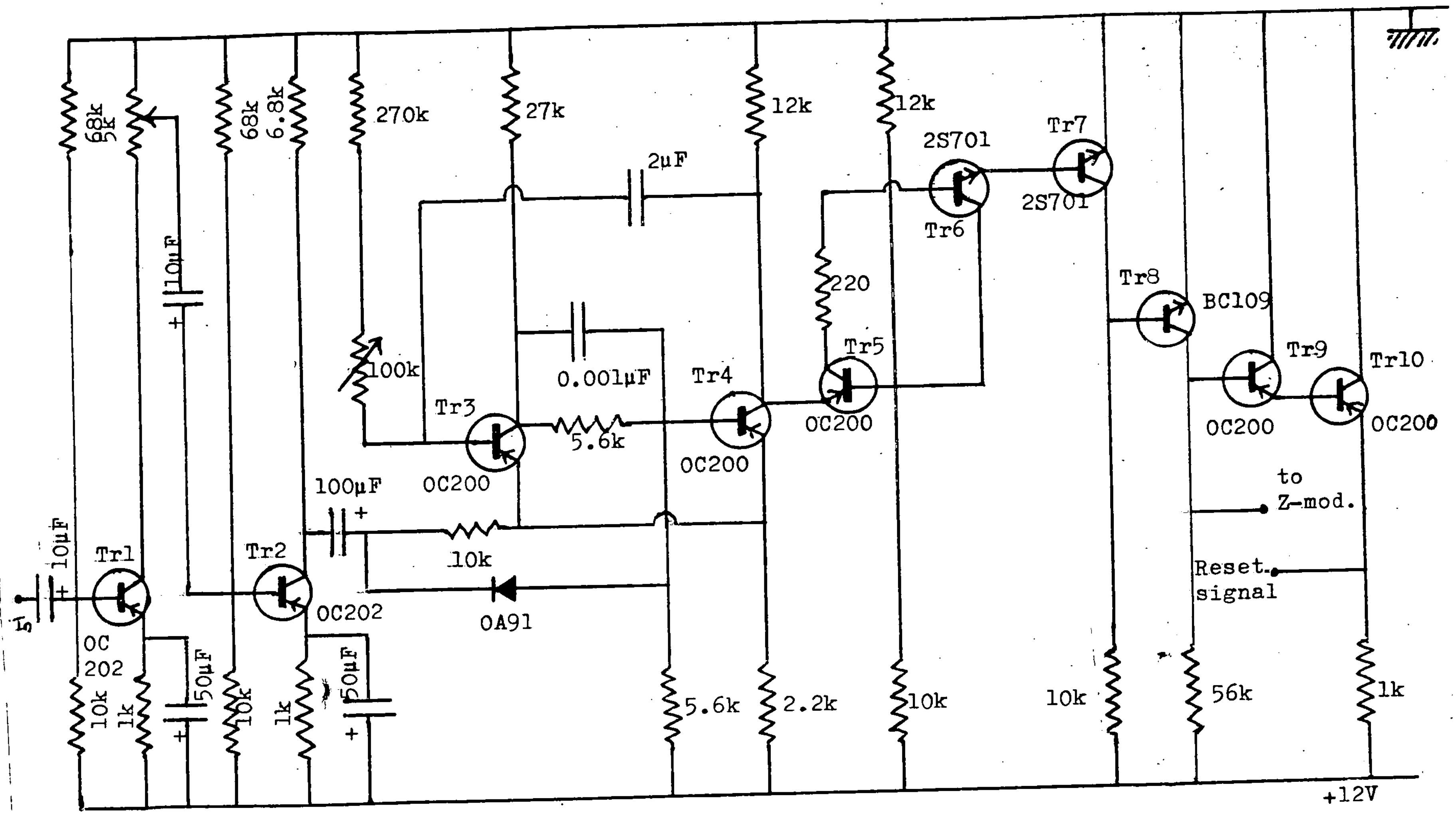


Fig.3.7. Timer with Pre-amplifier.

X- and Y- plates of the oscilloscope causing the spot to move from its neutral position to position determined by the pulse heights. At the same time the timer circuit sends another pulse to brighten the spot for 100ms at the end of which time all the circuits are re-set to be ready to receive the next pulses.

3.4.1 The Timer.

The circuit represented on the block diagram by the boxes marked T1 and T2 is shown in figure 3.7. The pre-amplifier designed to feed the multivibrator consists of two transistors, Tr1 and Tr2, acting as high-gain amplifiers capacitor-coupled with a potentiometer gain control. This part of the circuit amplifies the impact pulse received from the head unit sufficiently to trigger the multivibrator (Tr3 and Tr4), and the gain control can be adjusted so that the circuit is just sufficiently sensitive for the smallest drops that will produce a finite reading of size. It is important that the circuit should not trigger just because the head unit is subject to a breath of wind. The triggering pulse goes via the diode to set off a conventional one-shot multivibrator. The output of this is fed into a two-transistor circuit acting as a pulse squarer (Tr5 and Tr6). It is important that the square pulse should have sharp corners for supplying the reset pulse. The negative square pulse from the pulse shaper

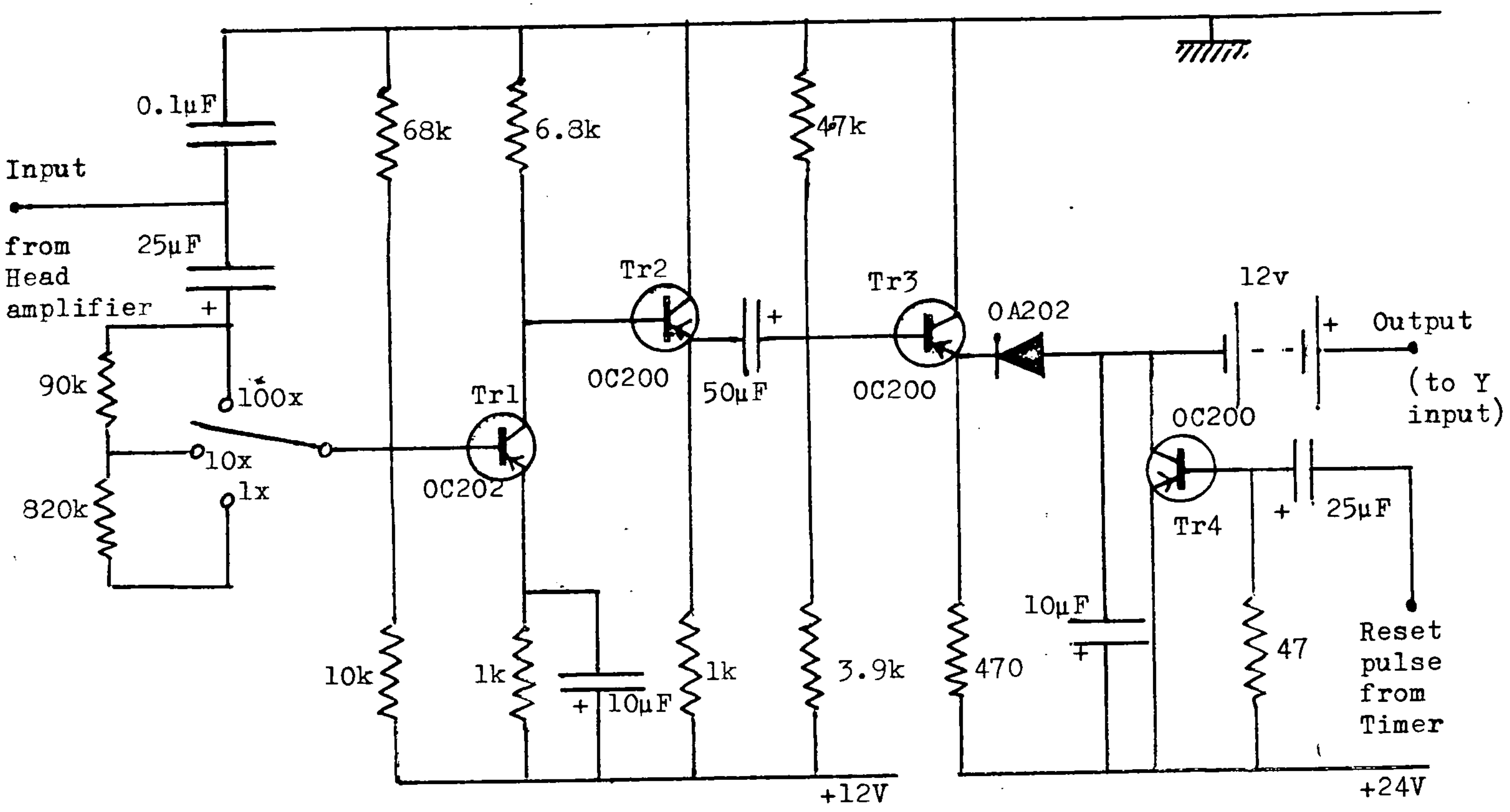


Fig.3.8. Impact Amplifier and Pulse Lengthener.

is inverted by Tr8 and the positive pulse which results is used to modulate the brightness of the oscilloscope. The same pulse is fed into a Darlington pair (Tr9 and Tr10) to produce a low impedance output suitable to feed the pulse lengtheners as a reset pulse (see section 3.4.2). The pulse is a positive square pulse of 8V height and 100ms length.

3.4.2 Impact Amplifier and Pulse Lengthener.

Figure 3.8 is a diagram of the circuit which deals with the pulses from the impact amplifier in the head unit (P3 and P4 in the block diagram). The pulses consist of a negative pulse followed by a train of decaying oscillations which die away completely within the reset time of 100ms. The pulses first pass through an attenuator for 1x, 10x and 100x and then into a single stage high-gain amplifier, Tr1. On the input an 0.1μF capacitor leaks any high frequency oscillation to earth. After the amplifying stage an emitter follower, Tr2, reduces the impedance to prepare for the pulse lengthening circuit which follows. The pulse lengthener is capacitor-coupled to the amplifier and starts with its own emitter follower, Tr3, to drop the impedance right down to about 400Ω. From the emitter the negative pulse passes through a diode to charge a 10μF capacitor. Once the capacitor is charged negatively the charge cannot easily leak back through the diode so the pulse height is held and only begins to die away very slowly. This point of the circuit is directly connected to the Y- input of the oscilloscope to produce the deflection in the vertical direction on the screen. After the spot has moved downwards it is lit by the Z-modulating pulse from the timer for 100ms. At the end of the 100ms the brightness dies and a reset pulse discharges the 10µF capacitor. The reset signal, like the brightness signal, consists of a positive square pulse of 100ms length. This passes into a differentiating circuit of 25µF against 47Ω, converting it to a positive spike followed 100ms later by a negative spike. The transistor, Tr4, is held hard off and is unaffected by the positive spike. The negative spike however sends the collector hard positive thus discharging the 10µF capacitor. The diode then leaks the excess positive charge rapidly away and the potential of the capacitor reverts to the neutral position ready for the next raindrop.

3.4.3 The Charge Amplifier and Pulse Lengtheners.

The circuits represented on the block diagram by boxes Q2, Q3, Q4+ and Q4- and shown in figure 3.9 are basically the same as the impact circuits described above. The differences allow for the fact that the pulses to be processed are smaller and also may be either positive or negative and have a much longer duration. All the charge

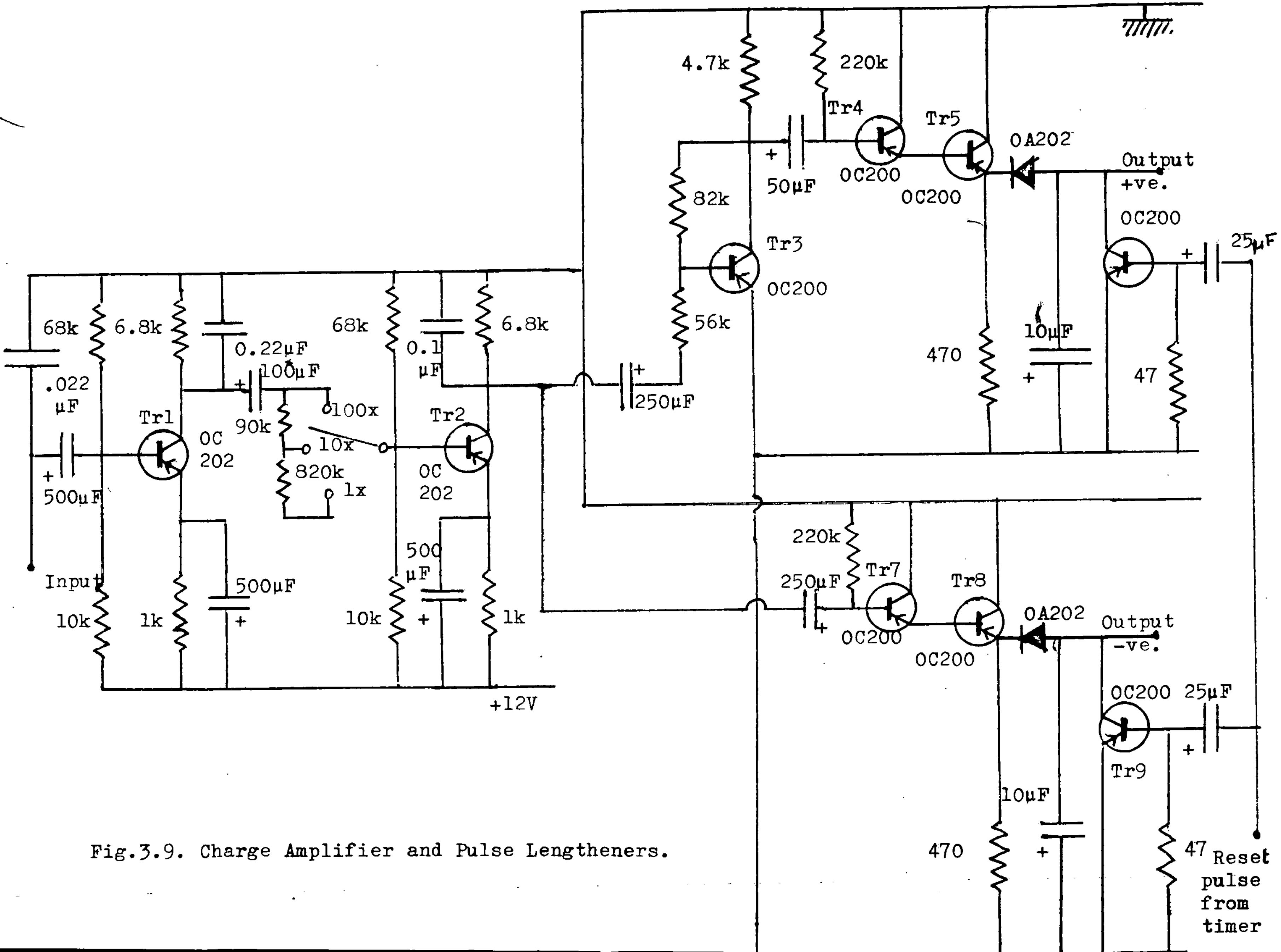


Fig.3.9. Charge Amplifier and Pulse Lengtheners.

circuits are designed to cope with a time constant of the order of 1s. An extra amplifying stage, Tr1, is put before the attenuator, and three small capacitors were connected between the input and the outputs of both amplifying stages to remove high frequency oscillation coming from the head amplifier. The pulses from the head unit are simple pulses of length determined by the time of fall of the raindrop through the induction ring, and are followed by no oscillatory train of pulses.

The simple form of pulse lengthener described in section 3.4.2 will only deal with negative pulses, so two lengtheners are used for the charge pulses, one preceded by an inverting stage (Tr3). Two separate outputs are the result of this circuit, both carrying an equal d.c. bias and both producing negative square pulses. By connecting these to opposing X- plate amplifiers, labelled X1 and X2, the outputs may be made to work against each other, such that the d.c. bias of each cancels the effect of the other, and the pulses of each move the spot in the opposite direction to the other. Positively charged raindrops will then move the spot to the right, and negatively charged drops to the left. Thus a complete plot of impact against charge can be plotted in the two lower quadrants of the graph on the oscilloscope screen.

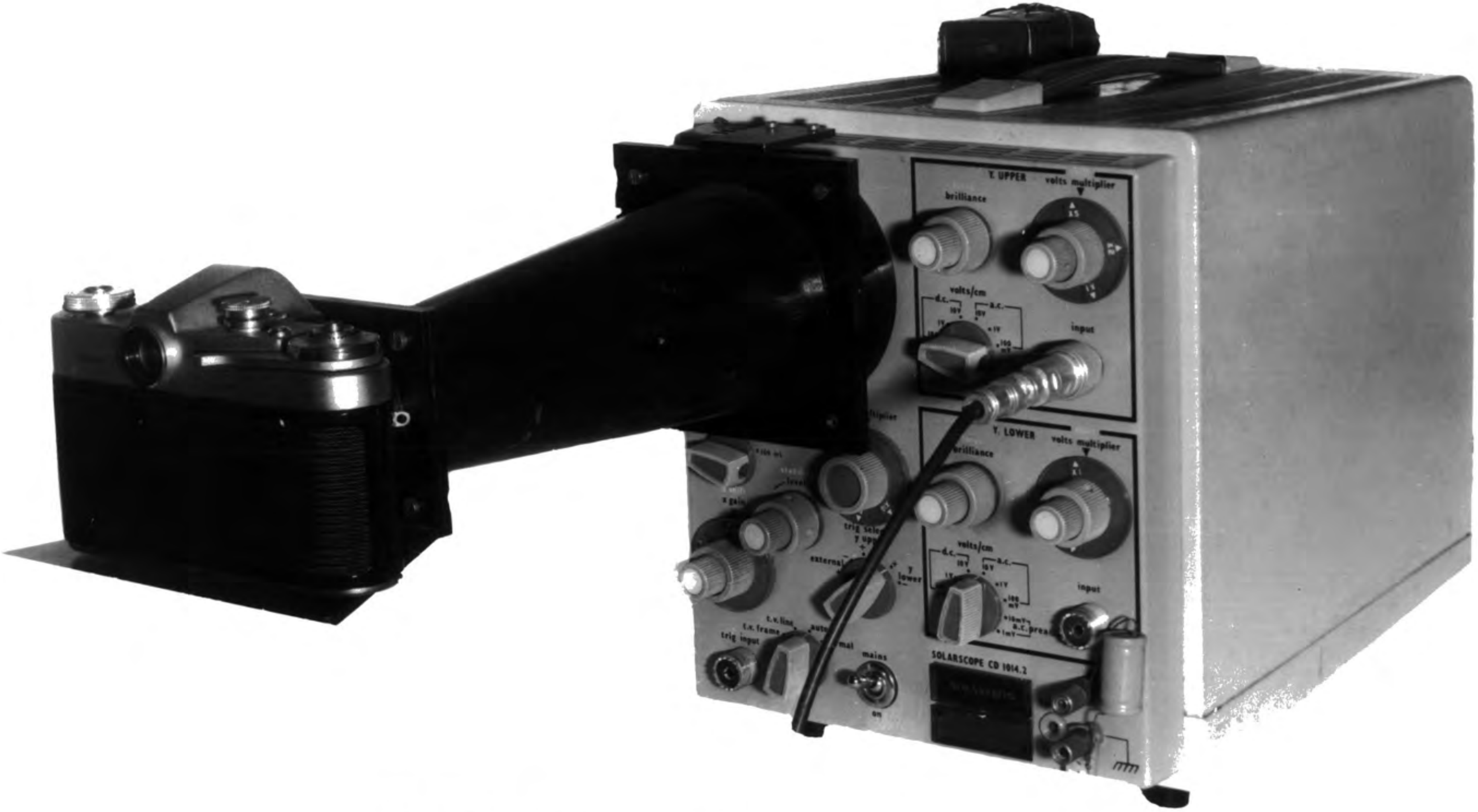


Figure 3.10 The oscilloscope and camera.

3.4.4 The Oscilloscope and Camera.

The electronic circuits of the recording system that have been described above are housed in a rack on a frame along with the amplifiers and meters operating from the field-mills (see chapter 5). The oscilloscope and camera (figure 3.10) stand on an adjoining bench. The oscilloscope, a Solartron CD.1014 is a double-beam oscilloscope of which only one Y- input is used for this experiment. The X- inputs are via sockets on the back of the chassis and these sockets may be linked to the internal time-base and X-shift controls, but in this case are directly connected to the recording system outputs. There is a similar socket for the brightness or Z- modulation of the spot, but as this is connected to the cathode ray tube grid by a 0.03μF capacitor the time constant is rather shorter than 100ms. The brightness pulse from the timer has therefore been connected to the grid via a 0.5μF capacitor strapped to the outside of the oscilloscope chassis.

The camera used is a single lens reflex zenith with a f/3.5, 50mm Industar lens. A supplementary lens was added so that the camera would focus down to about 200mm. An oscilloscope camera cone was designed and built to fit the particular oscilloscope and camera. It allows for the cone to be removed from the oscilloscope by the removal of four screws.

3.4.5 Power Supplies.

Three different d.c. voltage supplies are required for the various circuits: 24V for the pulse lengtheners, 18V for the charge head amplifier and 12V for the remainder. The field-mill circuits require the same voltages. The 24V is supplied by a Farnell L30 regulated power supply, and the 18V required by the inverted field-mill is supplied by a Farnell MSU regulated power supply. The 18V for the charge head amplifier is supplied by a battery of Flag dry cells, since the circuit will tolerate no mains noise such as would come from a mains power supply. The 12V is supplied by two lead-acid batteries, one of which may be recharged while the other is in use.

When in use at the Lanehead Field Centre the 12V batteries were replaced by a d.c. power supply built and lent for the purpose by Mr. M.F. Stringfellow, a fellow student. The 18V supply for the charge circuit consisted of two 9V transistor radio batteries connected in series.

Chapter 4.

Calibration of the Rain Detector.

4.1. Introduction.

During the design process the various parts of the rain detector were tested to show whether they would be suitable for the sizes and charges of raindrops that were expected. The earliest alterations of the design were to ensure that the impact plate would be sensitive to raindrops, and one of the last alterations was to ensure that results would be independent of the position on the impact plate which the drop strikes. Similarly the charge amplifier was designed with the help of tests using drops charged in the laboratory. These tests were not conclusive so a switched gain control was added to the recording system amplifiers so that the equipment could deal with a much wider range of drop sizes and charges than was expected.

4.2. Charge Calibration.

A device for producing artificially charged drops was needed. This was built following closely a design used by Hutchinson (1949) which consisted of a cylindrical earthed outer body of brass wholly containing a cylindrical glass vessel into which was fitted a narrowed tube to act as a water dropper. The water flow was controlled by a tap on a tube fitted into the top of the glass cylinder. An electrical connection was made to the water in the cylinder. A drop appearing on the end of the dropper was then in an electric field between it and the earthed outer body causing it to acquire a charge which it carried out of the device.

The charge so formed on the drop would be affected by the potential difference between the water and the earthed container, and the size of the drops. The same glass dropping tube was used throughout the work and the pressure of the water at the tip of the dropper was always atmospheric, varying by only small degrees, so it has been assumed that all the drops were of the same size. The charge on the drop is then proportional to the field it encounters immediately before dropping, and this in turn is proportional to the potential difference between the water and the earthed container. The drop charges are then proportional to the voltage applied to the water.

The dropper was itself calibrated by allowing a known number of charged drops to fall from it into a conducting container connected to earth via a 0.5µF capacitor. When about a thousand drops had been collected the capacitor was discharged through a ballistic galvanometer. This was repeated a number of times, with voltages up to 670V applied to the dropper, and then the container was charged directly to 1.5V when holding water, and discharged after various time intervals to estimate the degree of leakage resistance, and the absolute charge on each drop. The average charge per drop per volt applied to the dropper was found to be 0.24pC.

4.3. Impact Calibration.

It was assumed that all drops received by the apparatus would be falling at their terminal velocity. Assuming that all drops are spherical the only independent variables that can affect the impact are mass and velocity. By the first assumption the velocity is determined by the radius of the drop, which in its turn is dependent on the mass. Therefore, the impact is wholly dependent on the radius or mass of the drop.

For calibration it was possible to produce a small number of different sizes of drop in the laboratory, but to drop them only through a short distance so that they could not reach terminal velocity. The droppers used consisted of glass tubes of 15mm diameter and 50mm long sealed to short lengths of narrow tubing. Each piece of tubing was drawn into a narrow spout which was ground down to give a small aperture through which the droplets could fall. The radius of droplets falling from these tubes was controlled by the wetted area of the glass surrounding the aperture. This could be reduced by wiping on to the nozzle a thin layer of petroleum jelly. By these means two tubes were prepared and selected which would supply droplets of the largest and smallest size that it was possible to produce. The droplets were measured by counting a hundred off into previously weighed containers and weighing the result.

The tubes were then set up in turn above the rain-collecting equipment. The distance from the impact plate to the tip of the nozzle was varied over the range 50 to 600mm and droplets were allowed to fall on to the plate. The voltage pulse from the impact plate was noted on an oscilloscope for each size of droplet and distance of fall. In passing, it was noticed that the voltage pulse height was the same for consecutive droplets falling from the same height within the error of personal observation. The results are shown on figure 4.1.

The calibration curves of voltage pulse against height from which the drop falls show curves for heights up to 300mm and thereafter a linear section. The linear section implies an impact pulse proportional to the energy of drops of equal mass, i.e.

$$V = \tfrac{1}{2}\,mv_1^{2} \times \text{constant}$$

$$\text{or } V \propto v_1^{2} \qquad - (1)$$

where V = voltage pulse from impact

V_1 = velocity of drop before impact

m = mass of drop.

Considering the impact plate and ceramic support as a system set into damped oscillation by the impulse of the drop, and assuming the period of oscillation to be much greater than the total time in which the impact takes place, then, by conservation of momentum:

$$mv_1 = Mv_2 \qquad - (2)$$

where M = effective mass of impact plate

v_2 = velocity of plate immediately after impact.

By conservation of energy

$$\tfrac{1}{2}Mv_2^{\,2} = \tfrac{1}{2}kx \qquad - (3)$$

where x = maximum displacement of impact plate

k = constant (assuming force is proportional to displacement)

From formulae ~~(1)~~,(2) and (3) it follows that

$$v_1^{\,2} \propto x \qquad - (4)$$

and, given that the piezo-electric element gives a voltage proportional to its displacement,

$$v_1^{\,2} \propto V \qquad - (1)$$

as suggested by the calibration curves for constant m.

If it is assumed that the energy equation $V = \frac{1}{2}mv^2 +$ constant applies for differing values of m,

then as

$$m \propto r^3$$

where r = radius of drop, then

$$V \propto v^2 r^3 \qquad - (5)$$

To test this the values of v^2r^3 were calculated for all the heights and sizes of drops used in the calibration, and these values were plotted against the voltage pulses which drops had produced. The result is shown in figure 4.2. In the case of each drop size two different straight lines appear, representing two different types of impact on the plate. The gradients of the lines appear to be the same for each drop, if each mode of impact is considered separately. The lines with greater gradient are almost coincident and appear to pass nearly through the origin, but the others, although parallel, are not coincident, and, if produced, do not pass through the origin.

The lines of the graph in figure 4.2 for values of V less than 1.5V can be represented by the equation

$$V = k_1 v^2 r^3 \qquad - (5)$$

where k_1 is a constant.

The extension of the plot in figure 4.2 representing droplets falling from the greater heights can be represented by

$$V = k_2 v^2 r^3 + f(r) \qquad - (6)$$

where k_2 is a constant, and f(r) is a function of the radius r.

4.4. Relation of Calibration to the Oscilloscope Records.

The readings were taken by photographing the oscilloscope screen as described in Chapter 3. The maximum vertical displacement of the spot on the screen was 40mm downwards only. The maximum horizontal displacement was 20mm right and 20mm left. These displacements represent pulse heights of 2V for the Y- input and 2V for each of the X- inputs. When drops charged to 30V in the dropper described in Section 4.2 were allowed to fall into the apparatus, the spot on the screen moved with a horizontal component of 13mm. From the calibration described in Section 4.2 these drops carried a charge of 0.72pC. The charge per unit displacement is then:

$$5.54 \times 10^{-2}\,\mathrm{pCmm}^{-1}$$

Or, in practical terms, a maximum displacement of ± 20mm will be produced by drops of ± 1.1pC charge. All drops that have greater charge than this value will cause the same displacement of ± 20mm. Drops of smaller charge cause a proportionally smaller displacement of the spot. A difference of charge of 0.05pC will be barely distinguishable because that charge is represented by 1mm on the screen, which is of the order of the size of the luminous spot. For the same reason drops of charge less than 0.05pC will appear to have no charge.

The maximum Y- displacement represents 2.0V, which, due to attenuation in the circuit, represents 3.0V output from the impact plate. Taking $V \propto v^2r^3$ as a rough guide for the relationship between drop size and voltage pulse, and using Best's (1950) tables for terminal velocity with respect to radius, then the relationship between Y- displacement and drop size is thus:-

Y- displacement (mm)	Impact pulse (V)	v^2r^3 ($m^5s^{-2}x10^{-7}$)	Radius (mm)
0	0	0	$\leq$0.5
5	0.37	0.1	0.7
10	0.75	0.25	0.9
15	1.13	0.4	0.95
20	1.50	0.6	1.0
25	1.88	1.0	1.1
30	2.25	1.4	1.3
35	2.63	1.7	1.4
40	3.00	2.0	$\geq$1.5

This is a working table. Appendix B gives a complete derivation of values of v^2r^3 from Best's tables. The important features are that all drops that overload the apparatus, and give full-scale Y- deflections are of 3mm diameter or more, and those giving no apparent deflection are less than 1mm diameter. Values of sizes of drops between the limits of 0.5mm and 1.5mm radius are approximate only, and should only be treated as accurate to within ±10%. This has been considered when deriving conclusions from the experimental results.

Chapter 5.

Measurement of Potential Gradient.

5.1. Necessity for Potential Gradient Measurements.

The various theories about raindrop charging have been discussed in Chapter 1. All processes of electrification take into account the electric field acting in the region concerned, and in the case of the theory of Wilson (1929) as applied by Smith (1955) the region is that between cloud and ground. The potential gradient in this region is therefore of paramount importance in any discussion of rain electricity. Although it was not possible to measure the potential gradient at different heights with the simple apparatus available, measurements were made at the ground to be used as a guide to the conditions at higher levels. In some cases the measurements may only suggest the general strength of the field, but often they will give the sign and a more accurate measure of the field strength. This is confirmed by observation of a ground based field-mill when single clouds pass over the site of observation. A symmetrical pattern occurs in which the potential gradient first rises to a high value, then reverses the sign to a high field of the first sign followed by a relaxation to the original low potential gradient characteristics of fair-weather conditions. This simple pattern is dependent on the sign or polarity of the cloud and clearly demonstrates that the potential gradient requires the presence of the cloud to reach high values, of at least an order

Figure 5.1 The field-mill.

of magnitude greater than field strengths caused by space charge in clear air. Therefore, I have assumed that the potential gradient is generally consistent in the region between cloud-base and ground, that is that high values at one height suggest high values at another, and similarly for low values. Notes were taken of the potential gradient that applied for every exposure made with the rain detector.

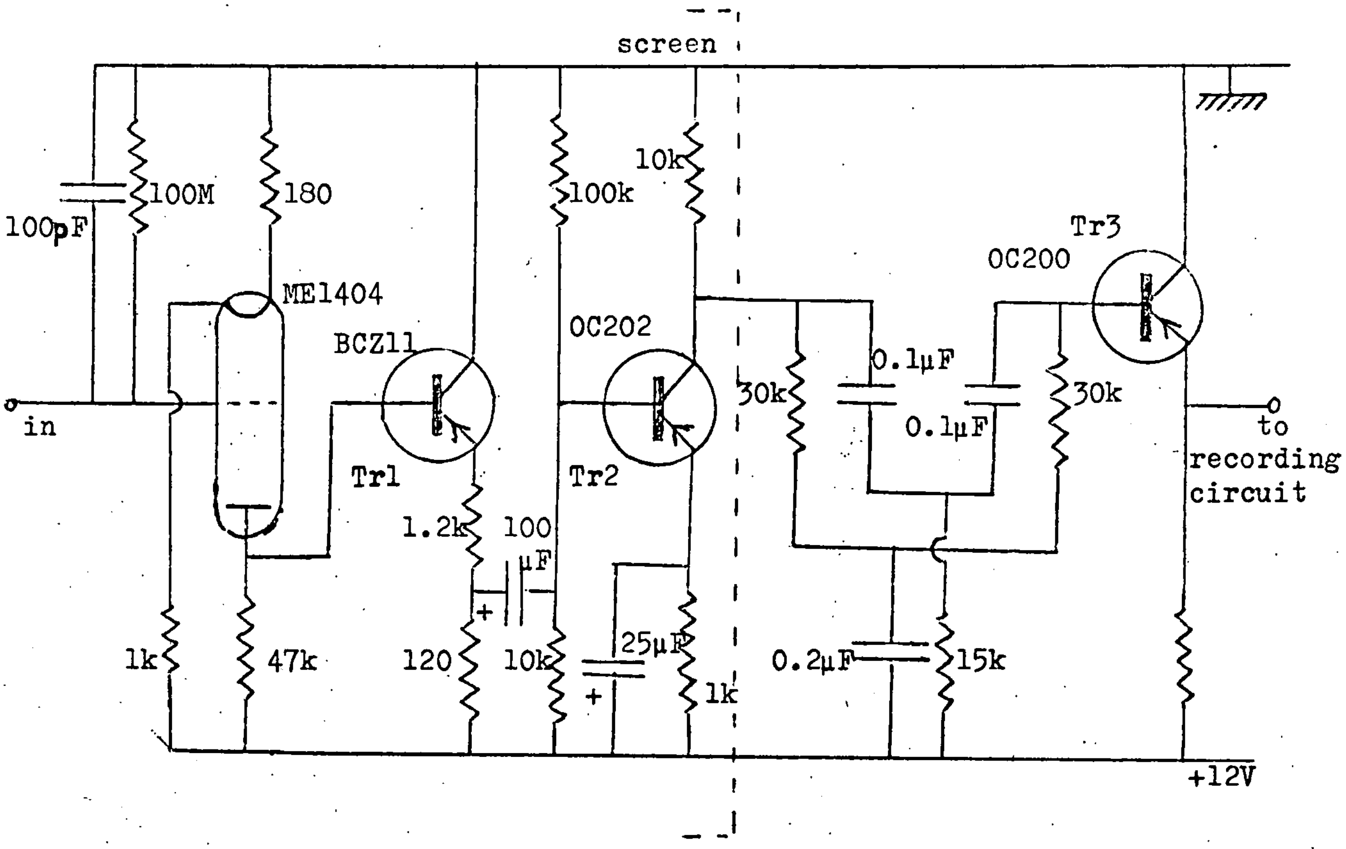
What follows is a description of the field-mill used at the Observatory. At Lanehead a similar instrument was used.

5.2. The Field-Mill.

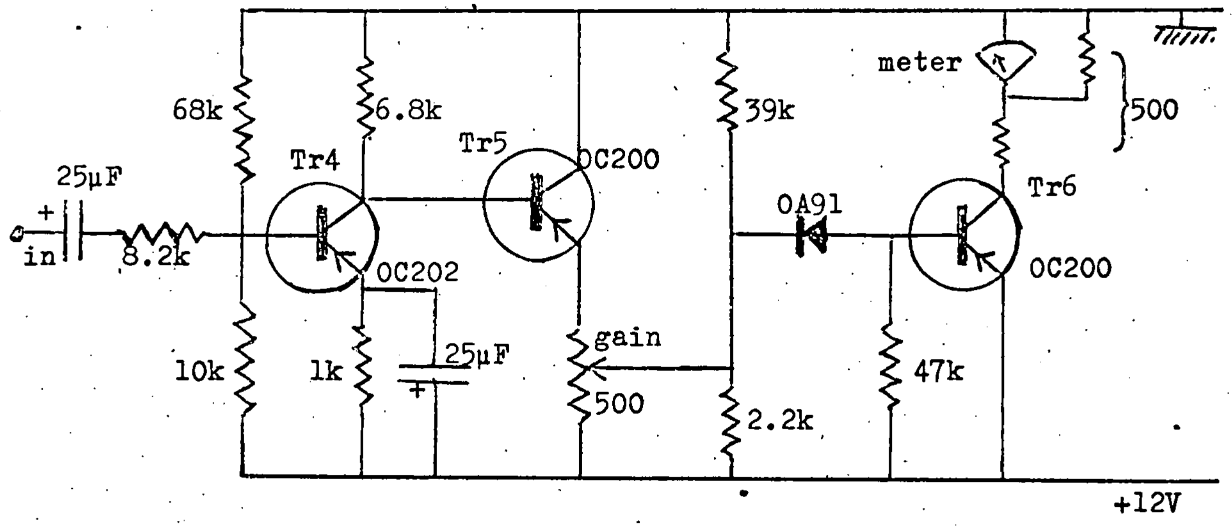
5.2.1. Physical Description.

The field-mill has been used by the majority of research workers in the Atmospheric Electricity Group at Durham, and requires no detailed description here. The field-mill used was powered by an a.c. synchronous motor rotating at 2700 revolutions per minute. It had a four-vaned rotor in the form of a Maltese cross, a similar stator mounted above the rotor when the mill is upright, and a complete disc below the rotor acted as the detector plate. The upper stator was then used as a bias plate. The signal frequency for this mill was therefore 180Hz.

The mill was mounted in an inverted position, that is with the rotor-stator assembly facing downwards, slightly less than two metres above the ground on a Handy-Angle frame as shown in figure 5.1. The box of the mill containing the



(a) Head amplifier.



(b) Recording amplifier.

Figure 5.2. Field-Mill Amplifiers

head amplifier and the motor was shrouded by an aluminium hood open only on the bottom. A second piece of aluminium was shaped so that it could be slid easily on to the hood to close the bottom face completely. When this was done the bias of the mill could be set to give the zero reading. The hood also protected the equipment from precipitation.

5.2.2. Electronic Description.

The circuit used for the field-mill is shown in figure 5.2. Part of the head amplifier was enclosed in a metal box inside the field-mill unit so that it would be screened electrostatically from the motor. The first three stages of the circuit are similar to those used in the charge circuit of the rain detector. It is not in fact necessary to use an electrometer valve for this application as a circuit of sufficiently high input impedance using transistors has been devised since this arrangement was put to use.

The valve gives a high-impedance input for receiving the 180Hz signal from the detector plate. The first transistor stage, Tr1, an emitter-follower, feeds an attenuator whose value was adjusted during testing to find the most suitable overall gain. The transistor Tr2 is in a voltage gain stage feeding into a parallel-T filter of 10kΩ impedance adjusted to cut out the mains interference frequency of 50Hz. Another emitter-follower, Tr3, feeds the line carrying the signal to the laboratory. The circuit

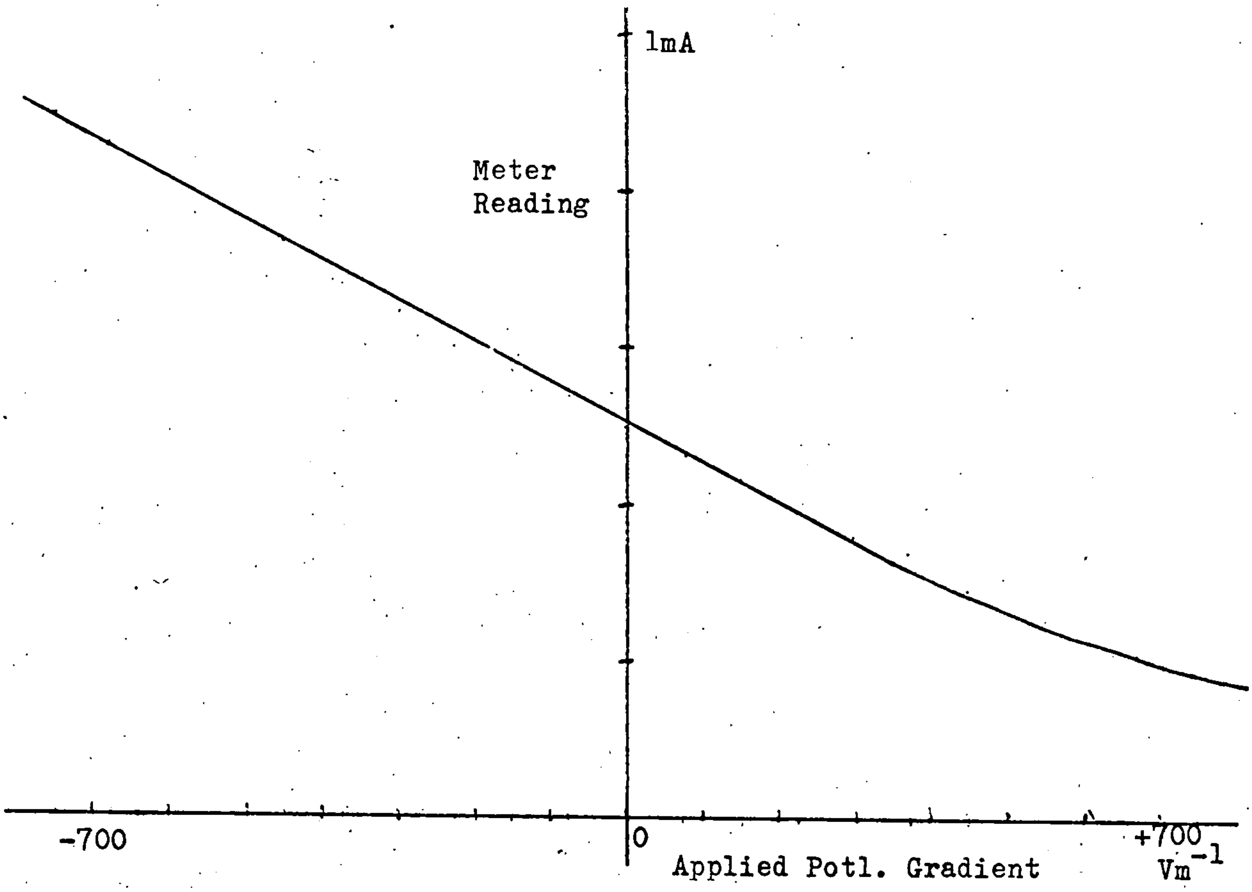


Figure 5.3

Calibration graph of Field-Mill

(upright mounting)

in the laboratory is designed to feed a 0-1mA milliammeter or a similar recording milliammeter. The transistor Tr4 is a voltage gain stage, Tr5 an emitter-follower feeding the rectifying circuit. The transistor Tr6 is a d.c. stage with the meter in the collector circuit. The total resistance in the collector circuit has to be about 500Ω, the maximum current being 5mA. The resistances are adjusted to suit whichever meter is in use at the time.

The d.c. bias to the stator was supplied from a separate potentiometer off the +24V supply. The bias was adjusted to give 50% full scale reading for zero potential gradient. Positive potential gradients then reduced the current through the meter, whilst negative potential gradients increased the reading.

5.2.3. Calibration of the Field-Mill.

The field-mill was calibrated in the laboratory to check the linearity of the response. The mill was placed on a bench facing upwards, and a metal plate with a circular hole cut just large enough to accommodate the stator-rotor assembly was placed approximately in the plane of the stator. Another plate, similar to the first except for the hole, was fixed parallel to it and a few cm above it. The lower plate being earthed, potentials were applied to the upper plate to give potential gradients up to ± $1000Vm^{-1}$ and a graph made of potential gradient against the reading of the instrument (see figure 5.3.).

5.3. Performance of the Field-Mill.

The field-mill was run at the Observatory for a continuous period of seven months between January and July 1968 monitoring the potential gradient. In general it was noticed that the periods of high or fluctuating potential gradients, as registered by the recording ammeter, corresponded to the periods of rainfall as noted by the electrical rain-gauge at the Observatory. The potential gradient remained at low levels for most of the time, this being the fair-weather gradient. This was found to be not more than about 200Vm^{-1} and usually positive. For 15 days of the month of January the value of potential gradient was read off the recorded chart for every hour during the fair-weather conditions. The average potential gradient for each of the 24 hours of the clock was taken and plotted against the time of day to show if there was a noticeable diurnal variation. Even over this short period a clear curve appeared with a maximum between 14 and 16 hours G.M.T. and a smaller one at about 24 hours. Minima appear at 3 hours and 21 hours. It is curious that this roughly corresponds to the diurnal variation observed on the vessels "Carnegie" and "Maud" as mentioned by Whipple and Scrase (1936). More recent work is described by Sharpless (1968). In this case the work was done at the Lanehead Field Centre which had been selected for its general lack of air-pollution, and where the results deserve more serious consideration. In my case the results were obtained at the Observatory, which is within the boundary of the City of Durham and must be subject to atmospheric pollution due to domestic coal fires and so, indirectly, to the regular habits of the human population. Results taken over a short period cannot be treated with the same consideration as an extended survey.

Although the fair-weather potential gradient was generally steady, the record of the gradient was far from steady during wet weather. When the precipitation was fine rain or drizzle falling from stratus clouds the gradient did not reach high values, and sometimes could not be distinguished from the fair-weather trace. Cumulus clouds were the cause of high fields and frequent reversal of the field. The potential gradients even under some non-raining clouds and under most raining cumulus clouds were of the order of four or more times greater than the fair-weather gradients. Thunderstorms showed similar effects to the non-thundery cumulus clouds except that the fields were greater and the reversals more frequent. There might be five or ten field reversals per minute under non-thundery showery conditions, but this would increase by an order of magnitude when a thunderstorm was present. By observing the meter showing the potential gradient, it was possible to observe field reversals taking place extremely quickly immediately after nearby flashes of lightning. These reversals were more rapid than the instrument could show. Theoretically the field change is simultaneous with the flash, but in practice the field-mill is limited by the time-constant of its amplifier, and by the mechanical inertia of its meter.

Figure 6.1 The Observatory.

Chapter 6.

Observations of Rain.

6.1. Sites at which Observations were made.

The site originally planned for making observations was Durham University Observatory which is situated within the boundary of the City of Durham, about 1km south-west of the centre. It was designed as an astronomical observatory and was built on the top of a small hill at a height of 100m above sea-level. It has a well-appointed laboratory which has been in use by the Atmospheric Physics Group of the Department of Physics for some years. Some observations were made here during the summer of 1968. For a short period in September and October 1968 the equipment for measuring raindrops was installed at the Lanehead Field Centre of the Department of Geography. This is a converted school in upper Weardale some 56km west of Durham. At a height of 434m above sea-level the atmospheric pollution at this Centre is so small that it can only be measured with difficulty. Since 1966 the Centre has also been in use by the Atmospheric Physics Group as a Field Centre. Equipment already set up supplied measures of potential gradient and wind speed and direction, and also of space charge, conductivity and rain current levels.

The Lanehead site was chosen for a few late readings of single drops after a fairly dry summer in Durham which had afforded little opportunity for obtaining results. Lanehead receives

Figure 6.2 The Lanehead Field Centre.

the greater mean annual rainfall of 1500mm compared with about 650mm at the Observatory, and that suggested a greater chance of rain in a given time. The Lanehead Field Centre allows the observer to reside in the same building as the equipment and so there need be little delay between the commencement of precipitation and the start of observations. Much of the rainfall at Lanehead was associated with high winds which made readings difficult. For that reason only half the time that rain was falling was useful for readings.

6.2. Taking Readings.

The apparatus has been described in detail in Chapter 3. The film used in the camera was Ilford HP4 35mm miniature film, bought in bulk and cut up and loaded in cassettes for the present work. It was developed in "Acuspeed " developer, and fixed using "Amfix" fixer. The darkroom at the Observatory was used for all the photographic work.

The 24V power supply and the 12V supply were generally left on continuously, but the 18V battery was only connected up when precipitation had started or appeared imminent. A second oscilloscope was used at Lanehead to monitor the output of the impact circuit in the head unit. This showed that a high frequency oscillation was produced by this circuit for about a minute or so after plugging in the 18V battery, and it was necessary to wait until the circuit had settled before attempting to take readings. This oscilloscope was useful in giving a clear indication of when drops were falling on to the impact plate by showing the rapidly decaying oscillatory waveform which is characteristic of the drop impact. The mechanical system of the impact plate has its own resonant frequency at which it vibrates in any condition of wind. If the wind is sufficiently great the recording system may trigger, depending on where the sensitivity level is set (see Section 3.4.1.). The monitoring oscilloscope showed whether raindrops or wind caused the system to trigger at any one time.

Observation shows that rain generally falls in approximately parallel lines. The head unit must be aimed into the rain to collect the maximum possible number of drops and, if the wind direction or strength varies, then the angle and direction of the head unit must be adjusted accordingly. Fortunately once set the head unit rarely needed adjustment as the rain fell steadily from one direction on most occasions.

When the head unit had been aimed into the rain the oscilloscope was set so that the neutral position of the spot was at the top of the screen and in the centre. Sometimes it was necessary to use dry battery cells to supply a d.c. bias to assist in this adjustment. The spot brightness was then reduced to a level below visibility so that the Z-modulation pulses just brought the spot into visibility. As the camera is a reflex model all this adjusting could be done with the camera in place whilst observing the screen through the view-finder.

This was a check on the focusing of the camera. The camera was always set on maximum aperture and exposures were made on the "B" or brief exposure setting, the shutter being held open by a screw clamp on the cable release. Exposures were made for any length of time between 30s and 10 minutes or more, and usually with the least possible time delay between them.

The length of time for each exposure was varied to discover what times were most suitable. Too small a number of drops would be registered when very short exposures were made but conditions in the atmosphere would vary considerably during a long exposure, and as any drop pattern would be expected to depend on these atmospheric parameters, no pattern would be likely to emerge from a long exposure. In practice exposures were changed when the potential gradient was reversed or showed a sudden change, but otherwise readings would be taken for consecutive periods of one, two or five minutes. In the thunderstorms of July 1st and 2nd the conditions varied very rapidly, with the potential gradient changing sign more than once each minute. It was inevitable that each exposure should cover a range of atmospheric conditions. By comparison several periods of steady rain were encountered when the potential gradient and other conditions did not apparently vary for up to 30 minutes. Other showers and periods of rain ranged between these two extremes of activity.

The recording system allows for considerable variation of gain for both the impact and charge amplifiers, but in practice in the present work the same settings were used for all the readings taken. As marked on the circuit diagrams, figures 3.8 and 3.9, the gain on the impact circuit was 100x and on the charge circuit 10x. The sensitivity of the oscilloscope as set was $100 \mathrm{mVmm}^{-1}$ in the X- direction and $50 \mathrm{mVmm}^{-1}$ in the Y-direction.

When readings had been taken the film could be developed. Unfortunately this meant inevitable delay, particularly when readings were being taken at Lanehead, and it was a long time before the lessons learnt from one set of negatives could be applied to the taking of the next film.

6.3. General Classification of Cloud Types.

It was not the purpose of this work to limit observations to conditions when clouds were electrically active, but to measure the parameters of raindrops in every period of rainfall encountered. Rain was expected particularly from nimbo-stratus and cumulo-nimbus clouds but also from cumulus and, in the form of drizzle, from stratus clouds.

The broad heavy nimbo-stratus clouds were responsible for steady rainfall over long periods. During these times the potential gradient as measured by the field-mill varied only slowly and generally registered values that were not in excess of $1000 \mathrm{Vm}^{-1}$ and were more often negative than positive. The lighter stratus clouds were similarly responsible for low and generally negative potential gradients, but the rain would come either as drizzle, or, in the presence of a gusty wind, in intervals of slanting rain interrupted by dry spells. This latter condition was frequently observed at Lanehead, and may be more prevalent in hilly areas.

Cumulus clouds were the cause of much greater fluctuations in the potential gradient than were stratus. The rain which fell from them was usually only for short periods of a few minutes, but could be for longer periods if the clouds were collected into large banks. The condition usually described as "showery" was almost always the result of banks of cumulus, responsible for steady rainfall interspersed with very heavy short periods of rain and, in some cases, thunder. The two earliest sets of results were taken during active thunderstorms. The potential gradient was off-scale on the meter, that is in excess of $1000 Vm^{-1}$, for most of the time in these conditions, and reversed very frequently, in some cases up to four or five times in a minute. The rate of rainfall was the greatest experienced: typically 10mm fell in 10 minutes. Much has been written about thunderclouds; Chalmers (1967) gives a good summary in Chapter 12 of his book.

6.4. Weather Conditions at Time of Measurement.

Appendix A includes a summary of the weather conditions at the time of each exposure. I have classified the condition into four general groups, two based on cumulus clouds and two on stratus.

Group A includes all conditions of stratus clouds and light winds in which light rain or drizzle is falling. This includes rain periods 22. and 24.

Group B includes all conditions of stratus and nimbo-stratus clouds and brisk winds in which the rain is continuous, cold and frequently wind-blown. The potential gradient may be low, but is usually high and varies in magnitude and sign. This includes periods 18. - 21. and 23.

Group C includes all conditions of cumulus or cumulo-nimbus cloud in which thunder can not be heard. The rain falls in showers, the wind is light and the potential gradient generally variable in magnitude and sign. This includes periods 11. - 17.

Group D includes conditions of cumulo-nimbus in which thunder is heard. This includes periods 1. - 3.

The exposures have been analysed in terms of the above group classification although the boundaries between the groups cannot be precisely defined.

6.5. Description of Exposures made in Rainfall.

The 182 useful exposures made are displayed in Appendix A. Each exposure consists of a pattern of dots, each the result of the measurement of one raindrop. The parameters represented by the position of each spot are represented in figure 6.3. Each exposure shows a distinct pattern of drops, and it can be seen how consistently these patterns are repeated during the periods of rainfall. In each period exposures were made up to the time

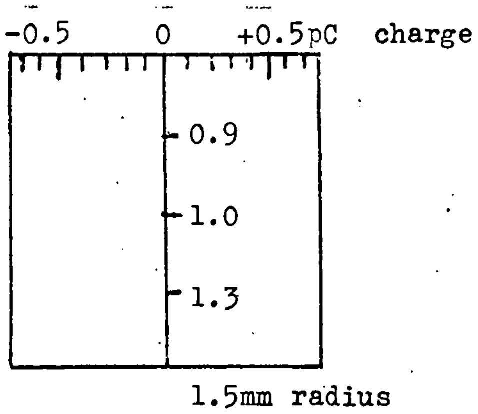
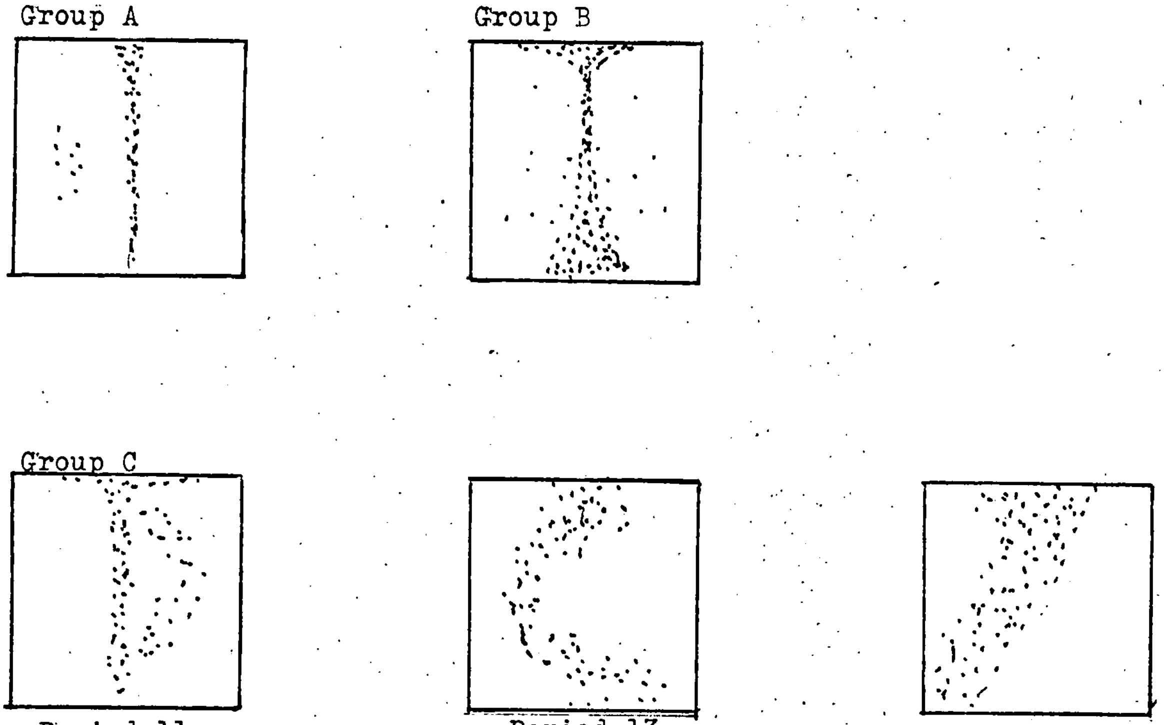
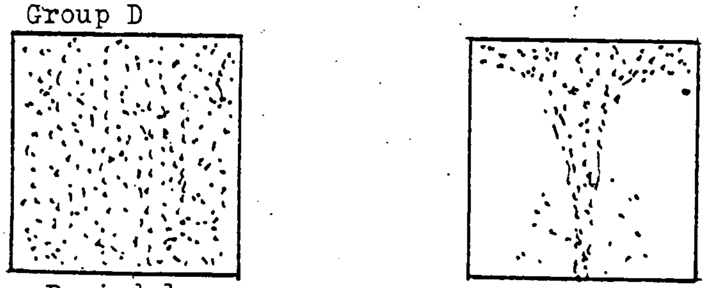


Diagram to show calibration of the oscilloscope screen in terms of drop parameters.



Period 11. Period 13.

These exposures can be found with the charges reversed.



Period 1. Period 2.

Figure 6.3 Typical exposures from the various rain periods making up the classified groups A-D.

when the rainfall finally ceased.

6.5.1. Exposures in light rain from stratus. (Group A)

The exposures show that raindrops of Group A may be negatively charged or have little charge. The negative charge is of the same sign as the potential gradient in almost all of the exposures. A similar pattern was observed on all of the exposures, showing that the conditions were steady throughout the period of measurement. A typical exposure is sketched in figure 6.3.

6.5.2. Exposures in continuous or spitting rain from nimbo-stratus and stratus. (Group B)

The last eleven exposures of period 23. have more spots than the remainder of the group and this corresponds to the lighter winds and heavier rain present at the time of these exposures. In general exposures of this group have drops of all sizes within the range, but the charges they carry are little or negative up to and possibly exceeding -1pC. Very few positively charged drops are found, and these only with a low charge. There seems to be a tendency for spots to be grouped about the vertical axis representing little charge for in no case is this grouping absent, but in some cases there are spots in no other place on the exposure. Exposures from Group A are admissible as exposures of Group B made in conditions with smaller and fewer droplets. As in

Group A the potential gradient for almost all of the exposures was negative, matching the sign of the charge carried on the majority of charged drops. A typical exposure is drawn in figure 6.3.

6.5.3. Exposures in showery rain from cumulus or cumulo-nimbus in the absence of thunder. (Group C)

These exposures are better treated in terms of each rain period because of the differences in each set of results.

The first set of fifteen exposures from period 11 shows a strong preponderance of drops with little or no charge. A few of the exposures show drops with positive charge of up to 0.5pC but apparently no case of drops with negative charge greater than about 0.1pC. This rainfall came after the conclusion of thunder and lightning in a thunderstorm, when the potential gradient measured at the ground had already returned to the fair-weather value.

By contrast period 12 was showery rainfall. For the first eight exposures the potential gradient varied between high negative and high positive values. The exposures show large drops of both negative and positive charge and not as many medium size drops. Most drops are therefore 3mm in diameter or greater with charges up to and exceeding $|1|$ pC. The spots apparently representing drops of no size but some charge should be disregarded as they are probably false results. During the last twelve exposures of this period the potential gradient had relaxed to the fair-weather value, and the exposures generally show drops of the same size distribution as before but charges not exceeding $|0.5|$ pC. The three exceptions have charges up to $|1|$ pC as before, and, except that they be long exposures of 10, 15 and 10 minutes respectively, there is no obvious explanation of this. The previous exposures were of 5 minutes except during the early part of the rainfall when the short exposure of 2½ minutes was used. It is apparent that the number of drops per minute falling into the apparatus gradually lessened as time passed.

Rainfall period 13 was similar to 11 and the later part of 12 in that the rain was light, and the potential gradient was low and positive, similar to the fair-weather value. The exposures were all about 10 minutes long but the rain was very light and not many spots appear on the film. These show many drops within the charge limits of ± 0.5pC and some outside these limits. Three examples from this period, nos. 2,4 and 6 show a curve such as might be expected from Smith's (1956) calculations described in Chapter 1.

During period 14 the potential gradient had a value between 500 and $100\mathrm{Vm}^{-1}$ approximately and alternated in sign between negative and positive. Commencing with the third exposure the rain was very heavy. Most of the exposures were fairly long, none of them being for less than 5 minutes.

Those exposures made in heavy rain show a completely filled rectangle on the film. In the lighter rain at the beginning and towards the end of the rainfall the exposures are similar to those for period <u>11</u> with several drops of all sizes and little charge and some drops of medium or perhaps large size (2 - 3mm in diameter) and negative charge of up to -1pC.

Rain period <u>15</u> had a potential gradient varying between 0 and -1000Vm^{-1}. These exposures show many drops of all sizes with little or no charge. A consistent pattern on all the exposures shows drops of negative charge of -1pC or greater and of 1 to 3mm in diameter. Any positively charged drops only had a small charge. All the drops of charge greater than 0.5 pC had charge of the same sign as the potential gradient.

The seven exposures in periods <u>16</u> and <u>17</u> are nearly symmetrical between positive and negatively charged drops. There is perhaps a slight preponderance of negative drops. Although the first period was a shower and the second a period of steadier rain the potential gradient fluctuated between positive and negative in both cases. The steady rain period appears to have contained larger droplets than the shower, and also to have higher maximum charges on its drops, but this would correspond to the greater values of potential gradient during that period.

Figure 6.3. illustrates some of the typical exposures to be found in Group C, including the height of a shower and the quieter period after a thunderstorm.

6.5.4. Exposures in thundery rain. (Group D)

Some of these photographs were incorrectly exposed as they were the first results to be obtained. No.19 onwards in period 1 were exposed with the gain of the Y- amplifier attenuated to half its usual value. The thundery exposures show a much greater variety of patterns than the other results from cumulus. Generally the exposures made in thundery conditions were of shorter duration, between 30s and 5 minutes, than for the other cumulus conditions. The exposures show an almost general preponderance of negatively charged drops over positive drops. There does not appear to be a great correlation between the potential gradient at the time of the exposure and the pattern on the film, but a more detailed discussion of the exposures of period 1 is made in Section 7.3.

The exposures of period 2, when the most violent thunderstorm was raging, were mostly made for 2 minutes each, but have fewer spots per exposure than those of period 1. Also most of the drops were small but highly charged, with the exception of nos. 7,8 and 9 at the start of the violent part of the storm when the drops were of all sizes and comparatively plentiful. In period 3 few drops reached the apparatus in the first one minute exposure, only the second and last exposures, made for 3 and 9 minutes respectively, show a reasonable pattern of spots.

Figure 6.3. shows typical exposures from each of the thunderstorms in periods 1 and 2, but the variety of possible patterns can be seen in full in Appendix A.

6.5.5. Summary.

In most of the result exposures made there appeared to be a numerical preponderance of drops with large negative charges over drops with large positive charges. This applies equally to rain from cumulus and stratus clouds. The largest drops fell from cumulo-nimbus clouds, the smallest measured were from stratus clouds in drizzle-like conditions. Cumulo-nimbus clouds produced drops up to and apparently greater than the measurable limit in charge, but so also did nimbo-stratus clouds. The cumulo-nimbus clouds only failed to produce drops of high charge when the potential gradient had reverted to a fair-weather level towards the end of a shower, whereas the stratus and nimbo-stratus clouds produced drops the magnitude of whose charge have some relation to the magnitude of the potential gradient existing, and to the physical magnitude of the drops themselves. Curved patterns that could possibly be compared with Smith's (1955) patterns were only found in the rainfall from cumulus and cumulo-nimbus clouds but even there they are rather vague and it is difficult to suggest a definite conclusion.

Chapter 7.

Discussion of Results.

7.1. Comparison with Results of Previous Workers.

A general discussion of the results of previous workers is in Chapter 1. The present results confirm previous conclusions that rain falling from cumulus and electrically active clouds is much more highly charged than that falling from stratus clouds. In general previous workers mostly found a greater number of positively charged drops, but that the most highly charged carried negative charge. The present results confirm that from cumulus and cumulo-nimbus clouds the more highly charged drops are mostly negative, but also suggest that on most of the occasions there is a majority of negatively charged drops. This last observation is not conclusive as the lower limit of sensitivity of the equipment to electrical charge would prevent many drops of charge less than $|0.05|$ pC from registering a finite value of charge.

The present results do give a broader picture than was previously available as they describe the amount of variation of charge and size distributions that occurs in different conditions of rainfall. For example it is made apparent why the figures of many previous workers for the positive/negative total charge ratio and the ratio of numbers of drops carrying each sign of charge are in considerable disagreement. The amount of charge is closely dependent on the prevailing conditions, and these conditions vary rapidly. It is unlikely that the observations of any one previous worker would have been taken in the same conditions as those of another. In some of the earlier cases the conditions must have varied considerably during the period of each observation.

The results of Smith (1955) are an exception to the above generalisations. Smith's conclusions were that the drops could have acquired their charge by the mechanism theoretically devised from Wilson's ion-capture theory. To agree with Smith the present results would have to show that the larger drops had charges of the same sign as the potential gradient and the smaller drops had charges of the opposite sign. In these results it is not usually easy to tell what are the exact charges of the smaller drops, but for the larger it is more obvious. During the thunder rain periods and considering only those exposures which show a definite positive or negative charge on most of the larger drops about twelve are in agreement with Smith's predictions and about nine are not. In the cumulus rain where no thunder was heard the majority of those exposures showing a definite pattern are in agreement with Smith's predictions, although most of these are in conditions of negative potential gradient. The less consistent results from the thunder rain could be explained by the rapid change in conditions at the times of measurement. In two cases (<u>1</u>.15 and <u>1</u>.25) results apparently inconsistent with Smith came shortly after a flash of lightning and a rapid reversal of the potential gradient. Had the raindrops begun falling before the flash in the previous conditions then these results also would have been consistent. None of the result exposures show a pattern as clearly defined as that in fig. 1.1 so, further than what has been described, the present results do not support Smith's results.

7.2. New Information Discovered.

The major difference between the present results and those published before is that these exposures made in quick succession show the development and alteration of the conditions during each period of rainfall.

7.2.1. The size of raindrops.

Clouds are made up of ice crystals or water droplets or both. These are formed by condensation of water vapour on to nuclei in the atmosphere, or by the freezing of water droplets. When both the ice phase and the water phase are present in a cloud the freezing level is that above which most of the ice crystals are found. According to the Bergeron theory of raindrop formation ice crystals in or near the freezing level grow at the expense of water droplets in the same region and, becoming too massive to stay at that height, fall to the ground, probably coalescing with other droplets on the way. According to the coalescence theory of the initiation of precipitation, an accidental process of coalescence between droplets takes place within the cloud and some larger drops are formed which themselves fall and may collect other droplets on the way.

If raindrops are considered which fall from clouds in which there are no significant updraughts or downdraughts, for example, stratus and nimbo-stratus clouds, then drops which begin their fall near the top of the cloud are likely to have more opportunity for coalescence with other drops and so to be larger when they eventually reach the ground than raindrops which fall from a lesser height. In clouds where there are updraughts and downdraughts a droplet falling against an updraught will effectively fall through a much greater depth of cloud than it otherwise would and conversely, drops in downdraughts would pass through a relatively thin layer of cloud. In rain from cumulus and cumulo-nimbus clouds, which have strong vertical currents, a wider range of drop size than from stratus clouds is to be expected, as drops falling against updraughts will have grown more by coalescence and those in downdraughts less.

During the times of making measurements the appearance of the raindrops was observed. The largest drops observed fell during the thunderstorms, and the rainfall which was responsible for the smallest maximum size of drop was the fine drizzle from low-lying stratus clouds at Lanehead. Non-thundery cumulus clouds never produced drizzle, the raindrops always contained some larger drops if rain fell at all. Nimbo-stratus clouds were capable of fairly large drops, but never as large as those from cumulo-nimbus.

To some extent the photographic results agree with these observations, but droplets greater than the maximum size of 3mm diameter are all registered as the same size. All clouds with the exception of those stratus clouds producing fine drizzle, showed some droplets up to this size, but the cumulus clouds appear to have produced more drops in excess of this size in proportion to the total number than do the stratus clouds. The minimum size that would register with the apparatus will also have limited the photographic results as the large proportion of very small droplets, less than 0.5mm in diameter, in the stratus drizzle could not be recorded.

7.2.2. The charge of raindrops.

Cumulus clouds were supposed to be more electrically active than stratus and so to produce raindrops with greater charge in proportion to their size. With the exception of the thunderstorms the results do not bear this out. Some cumulus clouds produced rain with little charge, while some stratus clouds produced raindrops with charges up to the maximum measurable with the equipment.

Cumulus clouds give the impression of electrical activity because of the fluctuation of potential gradient for which they are responsible, and also because of their near relationship to cumulo-nimbus clouds. Stratus clouds are essentially steady and unvarying, both in the rain that they produce, and the potential gradient for which they are responsible. But the stratus clouds which produced the rain at Lanehead in September 1968 were 500m above sea-level at base and most likely contained a fair proportion of ice crystals. It was observed in the work carried out by Workman and Reynolds (1950) that large potentials are created when water freezes, and this could account for the charges on the rain from some of the stratus clouds. The cumulus clouds exist in a whole family from thunderclouds down to small non-precipitating clouds in an otherwise clear sky. The electrical activity of these clouds is in a parallel scale, at a maximum in the thunderstorms and at a minimum where precipitation cannot or can only just take place. Some cumulus clouds then will produce drops which are relatively little charged when compared with the average for cumulus.

7.3. The Sequence of Rain Exposures.

The exposures made during the periods of rainfall are set out in chronological order in Appendix A. For each period of rainfall the length of time between consecutive exposures was as short as possible, being the time to wind on the film and open the shutter. The only exceptions to this rule occur where the film in the camera had to be changed or rain had temporarily ceased.

The sequence of each set of exposures should then show the history of each period of rainfall measured. It would seem likely from observation of potential gradient that the cumulus and cumulo-nimbus clouds would be responsible for more variation in the patterns of the spots on the exposures than would the stratus and nimbo-stratus clouds.

In the periods of light rain from stratus clouds (Group A, nos. 22 and 24) the pattern appears consistent throughout. There are only two exposures in period 22 but the seven in period 24 show only a general slackening off of the amount of rain falling without much change in the pattern of spots caused by the raindrops.

The other periods of rain from stratus and nimbo-stratus clouds (Group B, nos. 18 - 21 and 23) show more variation. Of these nos. 20 and 23 have a significant number of exposures. The results from period 20 show basically the same pattern being repeated with fewer and fewer drops as the rain petered out, whilst in period 23 the patterns show more highly charged drops with the size and charge of the drops varying from exposure to exposure. This observation matches the steady potential gradient apparent during period 20 and the varying conditions operating during period 23.

Group C includes the rainfall from cumulus clouds when thunder was not heard, periods 11 - 17. The fifteen exposures of period 11 show almost no change in the nature of the rainfall apart from a gradual increase and decrease in the quantity of rain falling. This corresponds to the steady potential gradient which kept to a fair-weather condition throughout. Periods 12 and 14 show similar sequence patterns to each other. In each case they commenced with a high and fluctuating value for measured potential gradient and ended with a low, steady, positive value. The drop size distribution remains wide throughout the rainfall, but the drop charge distribution contracts slowly as the activity of the potential gradient lessens. It should be noticed that some of the later exposures in each period were made for a longer duration than the earlier ones. The other periods of rainfall have not produced exposures which show a marked lessening of the rainfall. With the exception of those in period 11 all the series of exposures show significant variation with time of the predominant charge on the drops. In some cases the change of the predominant charge corresponds to a change in the measured potential gradient. In rain period 12 the potential gradient sign changed from positive to negative between exposures 2 and 3. The sign of the predominant drop charge also changed from positive to negative in these exposures. The difference between periods of steady and fluctuating potential gradient is shown in period 15. Exposures 4 - 7 have a narrower distribution of charge than those preceding and succeeding, and were taken at a time when the potential gradient was comparatively steady. The difference between rainfall in conditions of high and low potential gradient is seen between periods 16 and 17 where the exposures of period 17 show drops of considerably greater charge than those of 16. In period 12 the conditions of high and fluctuating potential gradient were succeeded by conditions of low and steady potential gradient during exposures 5,6,7 and 8. These same exposures show a clear reduction in the maximum charge on the drops measured.

The exposures taken during the thunderstorms (periods 1 and 2) show more variation between successive exposures than those in any of the other rain periods. This corresponds to the fluctuating potential gradients that were present at all times during the thunderstorms, but it is difficult to match the changes in distribution to the observed changes in potential gradient. However the sequence during period 1 is fairly distinctive:-

1 - 4 Preponderance of positive charged drops changes to an overall distribution of charges.

5 - 8 Overall distribution reduces to small drops.

9 - 13 Negative charge preponderance changes to positive charge preponderance.

14 - 17 Drops with small charges gradually change to a marked curve of smaller drops with negative charges and larger drops with positive charges.

18 - 25 Positive charge preponderance changes to overall charge distribution.

26 - 31 Curve in opposite sense to no.17 followed by negative preponderance and development to full charge distribution.

32 & 33 Short exposures with few but relatively highly charged drops.

34 Long exposure probably like the preceding.

35 - 42 Cessation of rainfall followed by generally full distribution. No.39 shows the rough outline of a curve in the same sense as in no.17.

Three curves appeared in the exposures such as might be expected from Smith's calculations. In three separate and distinct occasions a preponderance of drops of one charge gave way to an overall distribution. This seemed to be followed by a cessation or partial cessation of rainfall, before a repetition of the process.

The exposures from period 2 show rainfall of a quite different character. Most drops are small except for four exposures nos.7-12 where a small proportion of larger drops were also measured. Rain period 3 is unfortunately too short to show a distinct sequence.

7.4. Summary.

The general conclusions to be drawn from the photographic results are that the comparative level of electrical activity between cumulus and stratus clouds is reflected in the charge and size range of raindrops falling from them. It is not always possible to correlate the sign of the measured potential gradient with the sign of the predominant charge on the raindrops. The sequence of exposures in thunderstorms does appear to show the development and decline of individual thundercloud cells as they move over the site of measurement.

Chapter 8.

Conclusion.

8.1. The Apparatus.

Throughout the experimental period when results were taken the equipment broke down only once when it failed to register charge and a number of results were lost. Otherwise it behaved very reliably in conditions of wind and rain. The danger of insulation break-down was the greatest worry but apparently no rain entered the compartments where the electronic circuits were housed or managed to short-circuit the electrostatic induction ring to earth. Once the recording system, which was housed in the laboratory, had been set up with all the experimental work that was involved it was reliable during the period of taking observations.

The criticisms of the apparatus are entirely criticisms of of design. My suggestions for better designs are discussed in Section 8.3.

8.2. The degree of success of the results.

The apparatus was used successfully in a wide range of rain conditions. It is possible, therefore, to describe the typical charge/size pattern which may be expected from particular clouds in particular conditions as shown in figure 6.3. The stratus clouds give consistent narrow patterns with drops of low charge, with little variation between successive exposures. The cumulus clouds give a variety of patterns varying probably with the state of the cloud from which the drops have fallen. This does not necessarily suggest that the charge on the drops is decided before it leaves the cloud-base, but it does imply that possibility.

The thunderclouds were alone in supplying results which appeared to reinforce Smith's results, but this only occurred in three exposures. The regular pattern shown by the sequence of thunderstorm exposures suggests a definite correlation with the movement of cloud cells overhead or with the rise and decline of the cloud cell. The approximate period of the pattern is about 30 to 40 minutes which suggests correlation with the movement of clouds overhead, as the cloud life cycle is generally considered to last about 1 or 2 hours.

8.3. Possible Improvements in the Apparatus.

Although the equipment operated reliably in the field its basic principles were simple and the ranges of drop sizes and charges which it could measure were limited. A new apparatus should be capable of recording a greater range of both charge and size of raindrops. This would require more sophisticated electronic circuits both in the head unit and in the recording system. The circuits developed for the present equipment are very crude and a considerable amount of improvement is possible, particularly in the induction ring charge circuit and the recording circuits. The range of drop sizes measurable could be increased by using a second more sensitive type of mass detector in combination with the present impact plate.

The present induction ring circuit uses an electrometer valve for the first stage in order to give a high input impedance. This could be replaced by a Field Effect Transistor and there would be less risk of failure over a long period.

I would alter the recording system fundamentally by introducing a clock circuit. This would be a multivibrator running at a frequency of 100Hz which is much greater than the maximum possible rate of collection of drops. The outputs of the charge and mass detectors would be respectively sampled at this frequency. The output of the system would be pulses or trains of pulses which could be recorded magnetically, or stored on paper tape along with information about the wind velocity, the potential gradient, the temperature, the nature of the cloud, and the time of the measurement. These figures would be analysed by a computer programme designed to show any possible correlation between the mass/charge patterns and the prevailing weather conditions.

In the head unit better arrangements for measuring the mass and charge of small drops is required. The present arrangement needs little adaptation to cope with the largest masses and charges found, but was not sufficiently sensitive for the smallest. Smith's (1955) arrangement for the smaller masses of measuring the time of fall between two induction rings could be incorporated. Alternatively, the impact plate could be moved so as to increase artificially the impact effect of the smaller drops. For example, if the plate were mounted vertically and moved horizontally at a constant speed the impact signals would be directly proportional to the mass of the drops, i.e. r^3 instead of to v^2r^3 as at present.

Even if the impact plate mechanism was not so drastically altered some improvements could be made to eliminate the effect of wind on the mass measuring equipment. A large baffle round the apparatus would help to reduce the wind driving on to the impact plate and so producing false readings.

Keeping the head unit aimed into the direction of the rainfall is another problem which could be automated. Servo-motors could be arranged to aim the head unit for both direction and inclination as controlled by a wind-vane and anemometer.

I have suggested that readings could be taken down on paper tape, but if the photographic system of recording were to be used then Polaroid cameras would give results which could be seen shortly after the exposure and so guide the making of the following exposures.

The whole apparatus, head-unit and control circuits, could be made in a form that is easy to carry and could be run by dry batteries. The use of Integrated Circuits would reduce the size of the recording system so that it could easily be used in the field and carried from place to place.

A method of protecting the head unit from the wind would help to avoid the spurious results caused by gusts of wind over the top of the apparatus. A longer head-unit might be less prone to wind effects at the impact plate which would be further from the aperture.

8.4. Future work on measurements of raindrops.

The results which have been described were all produced on one set of apparatus mounted at ground level. Most of the results came from one period of six weeks in the autumn of 1968.

The next step would be to increase the period for which observations are taken. Results from all the rain that fell in one or more periods of twelve months would give a more comprehensive view of all possible rainfall conditions. Two or more sets of equipment working simultaneously in different places, and if possible at different heights from the ground would demonstrate the variation of the results with horizontal and vertical distances. It would be interesting to have results from various sets of equipment placed in all different parts of, say, this country for one year.

8.5. The Next Step.

At the time of writing weather forecasting in Great Britain is about to be helped by the purchase of a new computer for the Meteorological Office at Bracknell. The need for this is due to the short time in which a large quantity of data has to be processed for a forecast to be published. In a similar way a large quantity of data will be needed to describe more completely the processes occurring within and around rain clouds. A large number of ground-level and elevated measuring devices working simultaneously over a defined area during various conditions of precipitation and fine weather could supply this data. The instruments would include devices for measuring potential gradient, wind velocity, temperature, air-earth current, drop charges and sizes and ionic conductivity.

Using this equipment it would be interesting to plot the complete life cycles of a number of thundercloud cells to see how much they conform to the pattern as it is understood at present.

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Appendix A.

Photographic record of results and description of weather conditions at the time of measurement.

This appendix is a complete record of all the photographic exposures used in the thesis. Facing each page of prints is a description of the rainfall at the time the exposures were made, and details of the meteorological conditions for each exposure. The time, in Greenwich Mean Time, and duration of each exposure are also noted.

The abbreviations in the tables are thus:-

Potential Gradient, Magnitude
H = high, > 700 Vm^{-1}
L = low, < 700 Vm^{-1}

Sign
+ = positive
- = negative
+ - = both signs during exposure

Variation
fl = fluctuating
st = steady

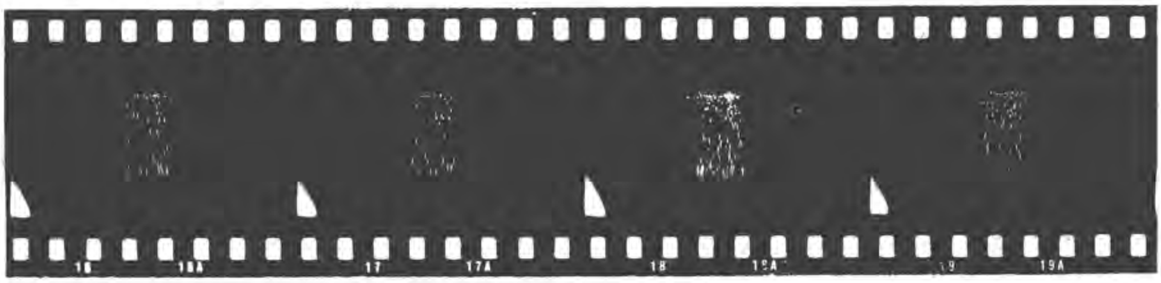
Cloud
Cn = cumulo-nimbus
Cu = cumulus
St = stratus
Ns = nimbo-stratus

Wind
L = light (<force 3)
Bl = blustery (>force 3)
Nil = calm

Rain types
Th = thundery rain
Sh = showery rain
L = light rainfall
L.Sh = light showery rain
St = steady rain
W = windblown rain
Dr = drizzle
W.Dr = windblown drizzle

The descriptions are based on personal observation at the time of measurement.

The exposures consist of a number of white spots within the bounds of a rectangle. The origin is at the centre of the top line and is generally clear because frequently there is a preponderance of spots around it. Spots further away often appear as streaks pointing away from the origin. The values of charge and size represented by spots in different places is shown in figure 6.3.



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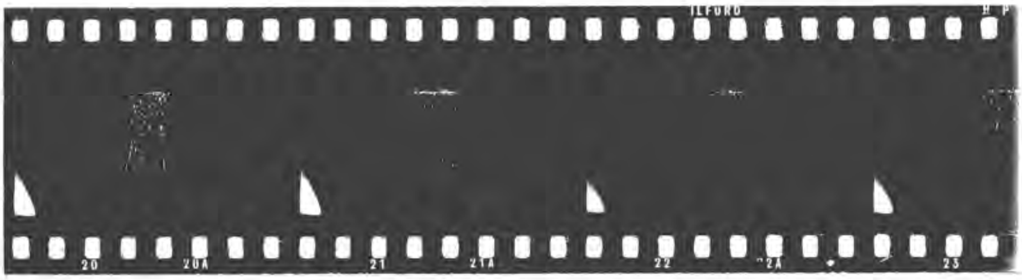

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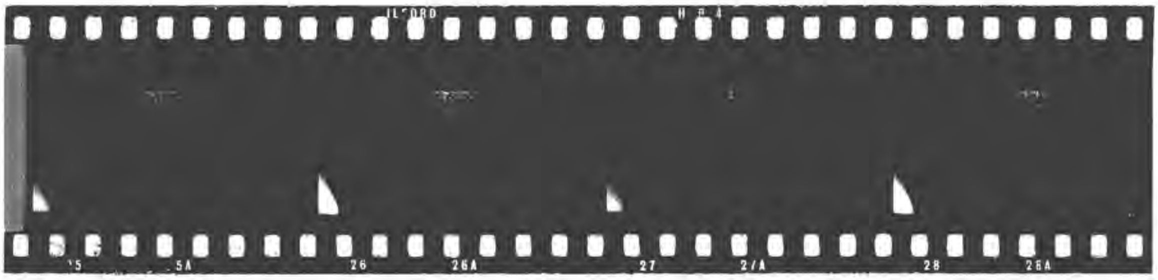

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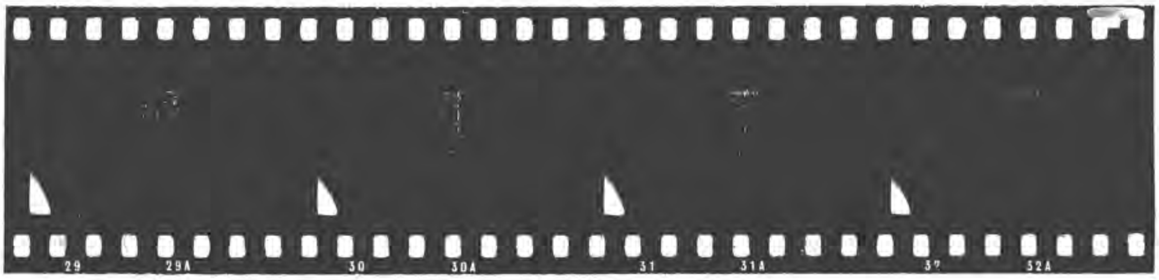

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1. July 1st., 1968.   12.09 - 14.32 hrs. G.M.T.

This was a thunderstorm lasting about three hours. No useful readings were taken in the earliest part of the storm but otherwise exposures were made up to the end of the storm. The preceding days had been unusually hot and sultry producing instability, and thunderstorms over two days in the Durham area. Rain fell continuously during the period of the storm, but varied in intensity. About six lightning flashes appeared to be close to the place of measurement; these were mostly accompanied by rapid reversal of the potential gradient and a sudden increase in the intensity of the rainfall.

1 17 18 19 20

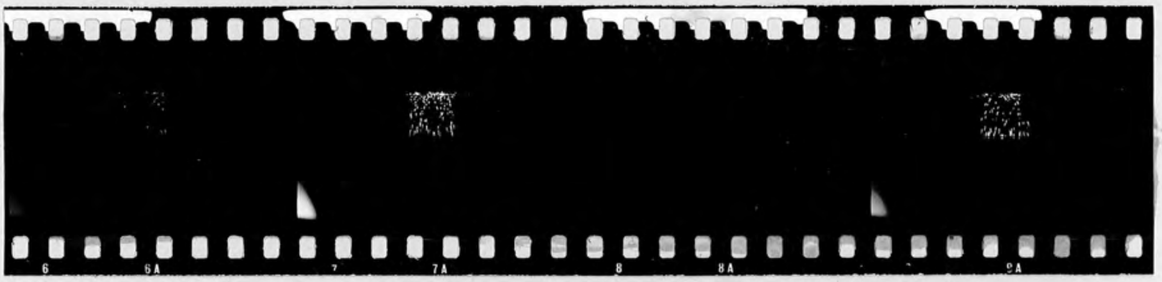
21 22 23 24

25 26 27 28

29 30 31 32

Rain period 1. (1.7.68)

	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
1	H	+–	fl	Cn	L	Th	3	12.09
2	H	–	fl	Cn	L	Th	3	.12
3	H	+	fl	Cn	L	Th	5½	.15
4	H	+	fl	Cn	L	Th	4	.21
5	H	+–	fl	Cn	L	Th	5	.25
6	H	+–	fl	Cn	L	Th	5	.30
7	H	+	fl	Cn	L	Th	2	.35
8	H	–	fl	Cn	L	Th	5	.37
9	H	–	fl	Cn	L	Th	3	.47
10	H	–	fl	Cn	L	Th	8	.50
11	H	+–	fl	Cn	L	Th	2	.58
12	H	+–	fl	Cn	L	Th	5	13.00
13	H	+–	fl	Cn	L	Th	5	.05
14	H	+	fl	Cn	L	Th	5	.10
15	H	+	fl	Cn	L	Th	5	.15
16	H	+–	fl	Cn	L	Th	4	.20
17	H	–	fl	Cn	L	Th	2	.24
18	H	+	fl	Cn	L	Th	4	.26
19	H	–	fl	Cn	L	Th	4	.31
20	H	–	fl	Cn	L	Th	5	.35
21	H	+–	fl	Cn	L	Th	2	.40
22	H	+–	fl	Cn	L	Th	½	.42
23	H	+	fl	Cn	L	Th	½	.43
24	H	–	fl	Cn	L	Th	3	.43
25	H	–	fl	Cn	L	Th	1	.46
26	H	+	fl	Cn	L	Th	½	.47
27	H	–	fl	Cn	L	Th	1½	.48
28	H	+	fl	Cn	L	Th	1½	.49
29	H	–	fl	Cn	L	Th	2½	.51
30	H	–+	fl	Cn	L	Th	½	.54
31	H	+	fl	Cn	L	Th	4	.54
32	H	+–	fl	Cn	L	Th	1	.59



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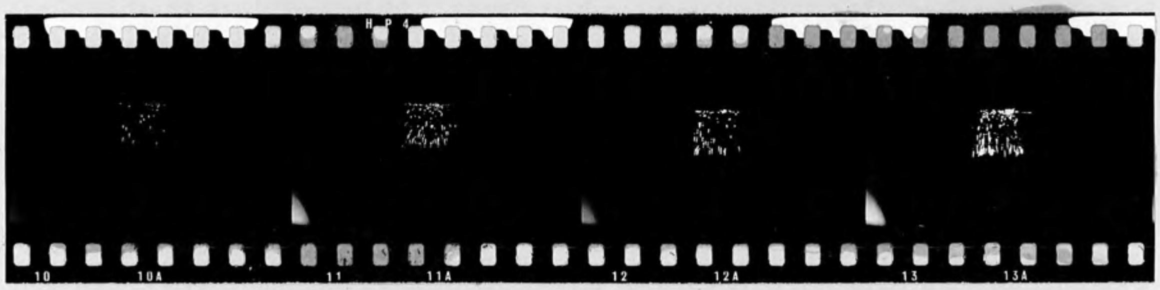

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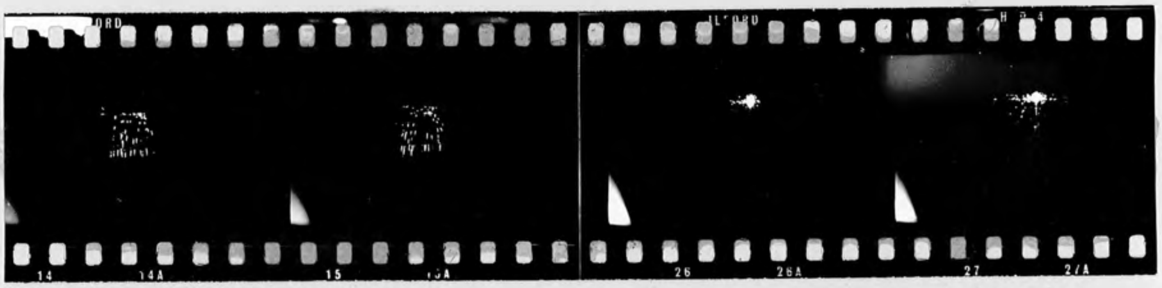

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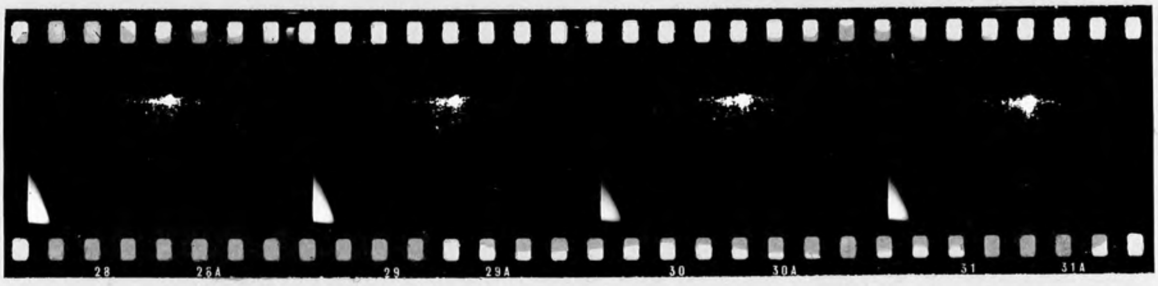


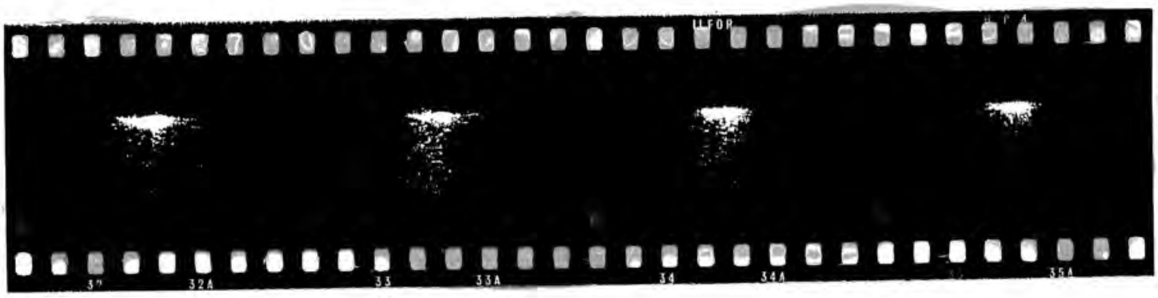
3 4 5 6

2. July 2nd., 1968. 9.47 - 12.00 hrs. G.M.T.

A period of heavy rain for the first half-hour was followed by a dry period lasting almost three-quarters of an hour. After this there was a very violent thunderstorm lasting half an hour with very frequent lightning flashes and potential gradient reversals, and almost continuous very heavy rain. The last half-hour showed less electrical activity and the rain was less heavy, finally petering out at mid-day.

3. July 2nd., 1968. 17.17 - 17.30 hrs. G.M.T.

This was a brief heavy shower later in the same day as the thunderstorm in 2. Although the clouds appeared to be cumulonimbus and the rain heavy, no lighning was observed near to the recording site.



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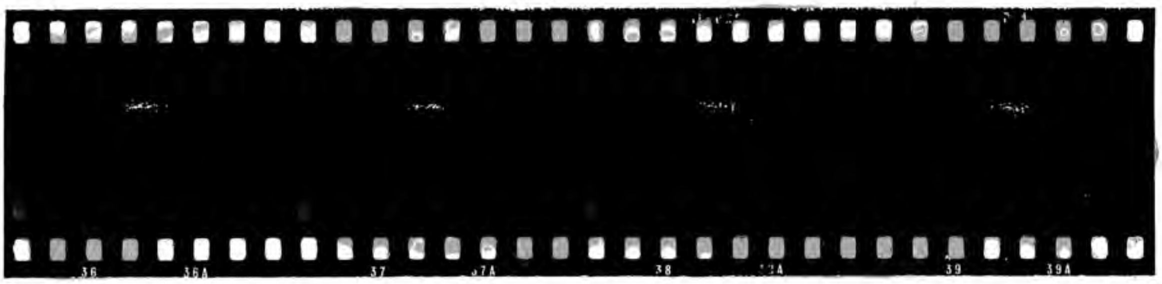

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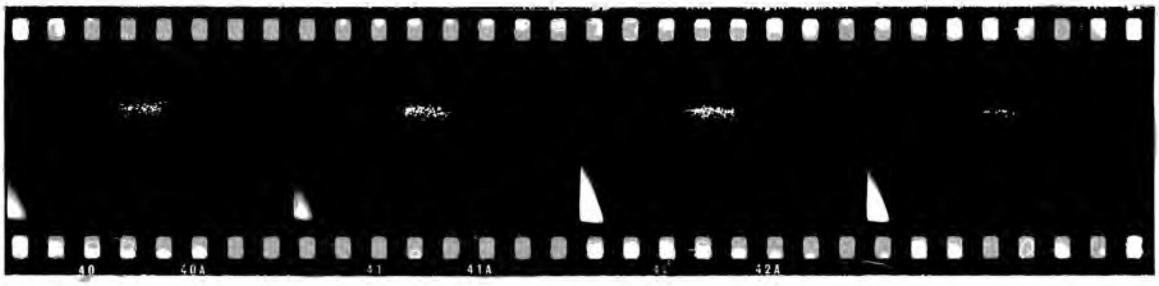

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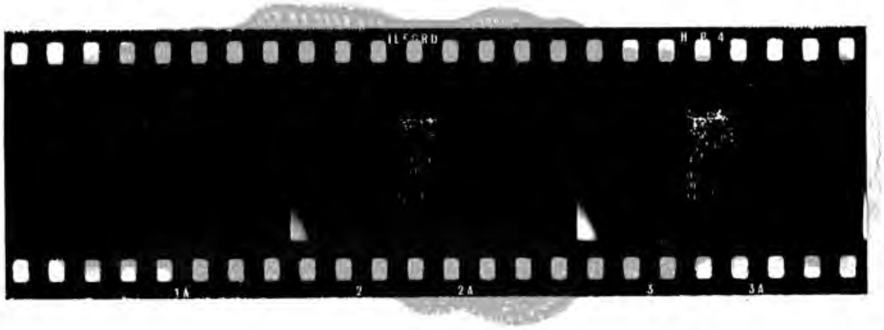


3 1 2 3

Rain period 1. (1.7.68)

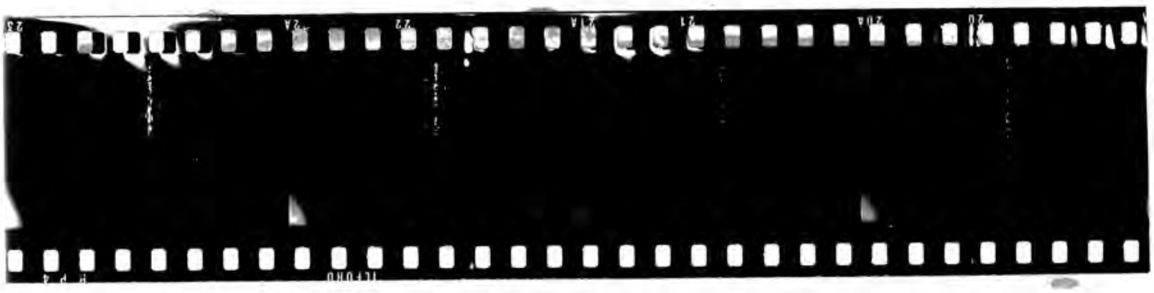
	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
33	H	-	fl	Cn	L	Th	1	14.00
34	H	+	fl	Cn	L	Th	4	.01
35	H	+-	fl	Cn	L	Th	3	.06
36	H	+	fl	Cn	L	Th	4	.09
37	H	+	fl	Cn	L	Th	1	.13
38	H	-	fl	Cn	L	Th	4	.14
39	H	+	fl	Cn	L	Th	1½	.23
40	H	-	fl	Cn	L	Th	6	.24
41	H	+-	fl	Cn	L	Th	2	.30
42	H	-	fl	Cn	L	Th	3	.32

Rain period 2. (2.7.68)

1	H	+-	fl	Cn	L	Th	8	9.47
2	H	-	fl	Cn	L	Th	5	.55
3	H	-	fl	Cn	L	Th	5	10.00
4	H	+	fl	Cn	L	Th	5	.05
5	H	+	fl	Cn	L	Th	5	.10
6	H	+	fl	Cn	L	Th	5	.15
7	H	+-	fl	Cn	L	Th	2	.58
8	H	+-	fl	Cn	L	Th	2	11.00
9	H	+-	fl	Cn	L	Th	2	.02
10	H	+-	fl	Cn	L	Th	2	.04
11	H	+-	fl	Cn	L	Th	2	.07
12	H	+-	fl	Cn	L	Th	2	.09
13	H	+-	fl	Cn	L	Th	2	.11
14	H	+-	fl	Cn	L	Th	2	.13
15	H	-	fl	Cn	L	Th	5	.15
16	H	+	fl	Cn	L	Th	5	.20
17	H	-	fl	Cn	L	Th	25	.25
18	H	-	fl	Cn	L	Th	8	.52

Rain period 3. (2.7.68)

1	H	-	fl	Cn	L	Th	1	17.17
2	H	+-	fl	Cn	L	Th	3	.18
3	H	+	fl	Cn	L	Th	9	.21



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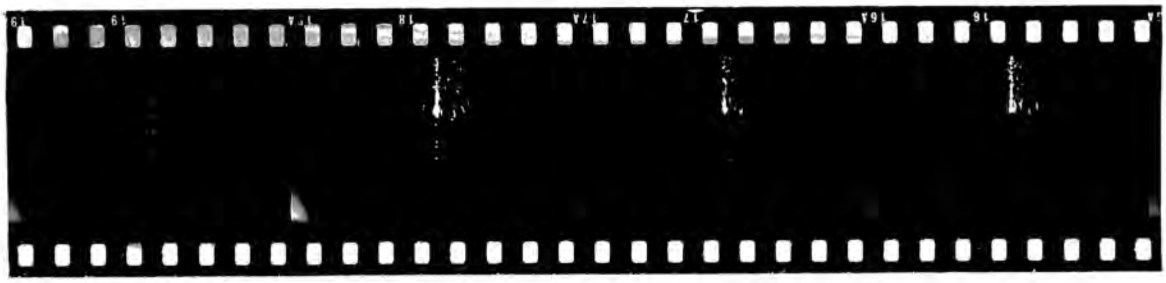

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9 10 11 12

13 14 15

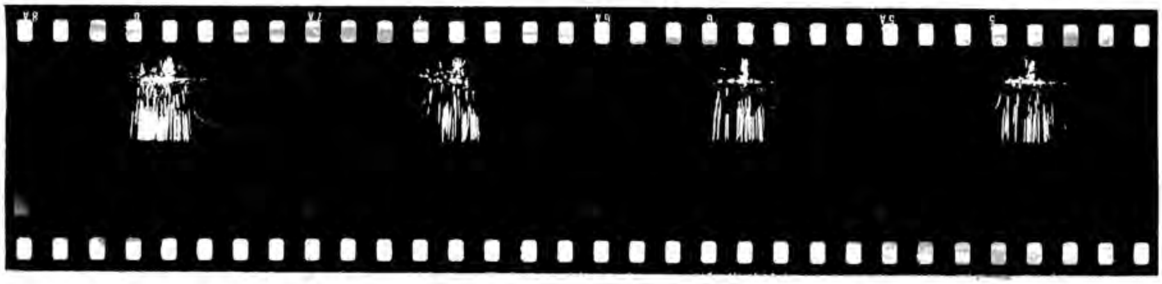
11. September 11th., 1968. 8.22 - 9.18 hrs. G.M.T.

This was light rainfall soon after a thunderstorm. After ten minutes the rain ceased but recommenced as light showery rain half-an-hour later, gradually thinning to nothing. As in the thunderstorms in July the wind was northerly or north-westerly, unlike all the other periods in which the wind came from the south or south-west.

(Soon after the above date the apparatus was moved to the Field Centre at Lanehead, where the remainder of the readings were taken)

12. September 20th., 1968. 15.10 - 17.16 hrs. G.M.T.

During the afternoon of Sept. 20th. light showery rain fell from banks of cloud which appeared to be cumulus or cumulo-nimbus with a cloud base coming down to 600m above sea-level judging by the amount to which the nearby mountain peaks were obscured. Some breeze was apparent during the rain so that the apparatus had to be tilted into the rain, but the breeze died away as the rain became very light and finally died.



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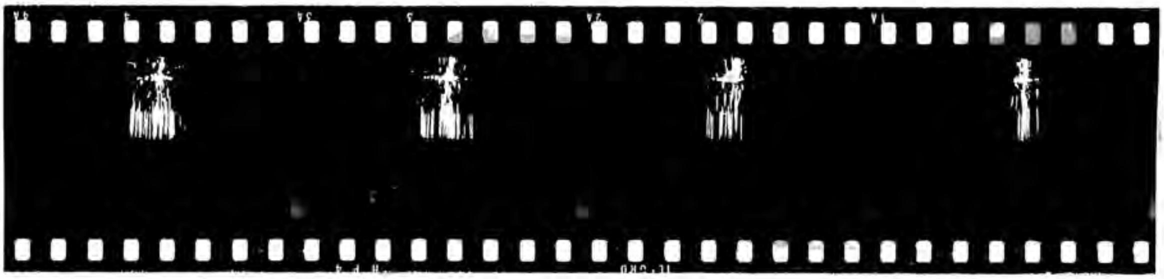


5 6 7 8

9 10 11 12

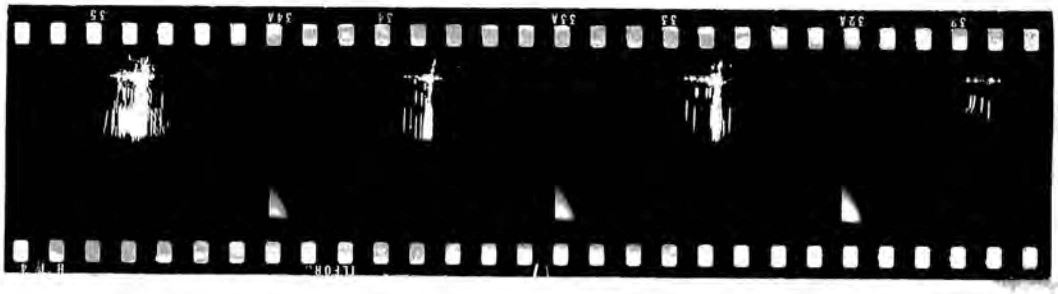
13 14 15 16

Rain period 11. (11.9.68)

	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
1	L	+	st	Cu	L	Sh	2	8.22
2	L	+	st	Cu	L	Sh	2	.24
3	L	+	st	Cu	L	Sh	1	.26
4	L	+	st	Cu	L	Sh	2	.27
5	L	+	st	Cu	L	Sh	2	.29
6	L	+	st	Cu	L	Sh	2	9.03
7	L	+	st	Cu	L	Sh	2	.05
8	L	+	st	Cu	L	Sh	1	.07
9	L	+	st	Cu	L	Sh	1	.08
10	L	+	st	Cu	L	Sh	1	.09
11	L	+	st	Cu	L	Sh	2	.10
12	L	+	st	Cu	L	Sh	1	.12
13	L	+	st	Cu	L	Sh	1½	.13
14	L	+	st	Cu	L	Sh	1½	.14
15	L	+	st	Cu	L	Sh	2	.16

Rain period 12. (20.9.68)

1	H	+	fl	Cn	L	Sh	5	15.10
2	H	+	fl	Cn	L	Sh	2½	.15
3	H	-	fl	Cn	L	Sh	2½	.17
4	H	-	fl	Cn	L	Sh	2½	.20
5	H	-	fl	Cn	L	Sh	2½	.22
6	H	-	fl	Cn	L	Sh	4	.25
7	L	+	fl	Cn	L	Sh	4	.29
8	L	+	st	Cn	L	Sh	2	.33
9	L	+	st	Cu	L	Sh	5	.35
10	L	+	st	Cu	L	Sh	5	.40
11	L	+	st	Cu	L	Sh	5	.45
12	L	+	st	Cu	L	Sh	5	.50
13	L	+	st	Cu	L	Sh	5	.55
14	L	+	st	Cu	L	Sh	5	16.00
15	L	+	st	Cu	L	Sh	10	.05
16	L	+	st	Cu	L	Sh	15	.15



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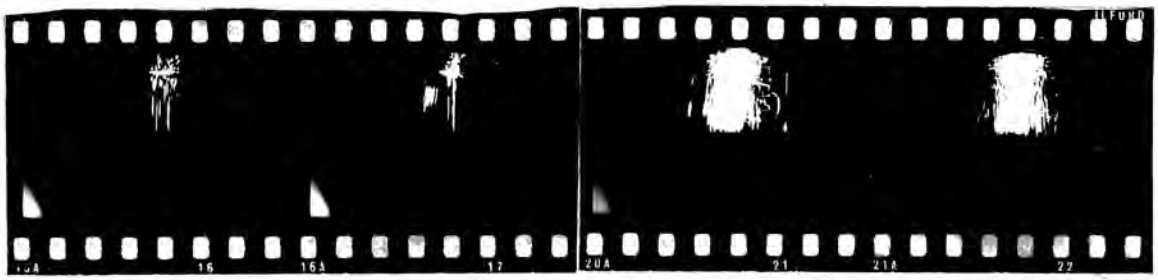
5 6



14 1 2 3 4

13. September 20th., 1968. 19.15 - 20.12 hrs. G.M.T.

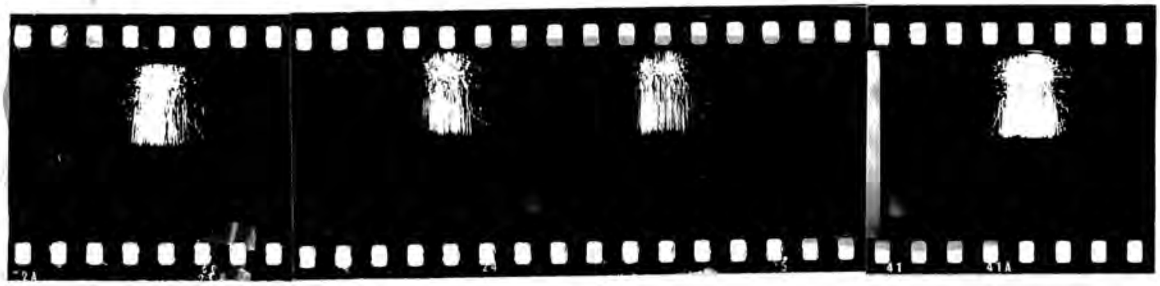
After a gap of nearly two hours on Sept. 20th. rain restarted in the early evening. It was similar to the lighter rain during the later part of the earlier period of rain but the drops were more spaced so that long exposures had to be used to record many drops.

14. September 21st., 1968. 15.37 - 19.13 hrs. G.M.T.

The low pressure continuing from the previous days brought more rain from cumulus clouds. This again was light, well-spaced rain in a south-westerly breeze, but with the potential gradient noticeably more variable than before. Heavy drops were noticed in amongst the lighter drops but the total quantity of rain that fell was not great by comparison with other rainfall measured. There was a gap of about one hour in the rainfall about forty minutes after the commencement of readings, and three readings were lost after that due to an error in electrical connection.

15. September 22nd., 1968. 10.17 - 12.05 hrs. G.M.T.

The rainfall was lighter than on previous days, but less well spaced. The potential gradient was less active although the clouds again appeared to be cumulus rather than stratus. The wind was perceptibly gentler than on previous days.



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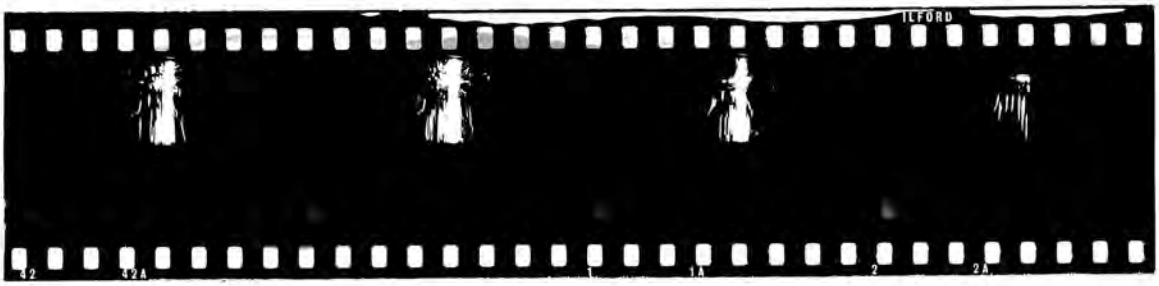


9 10 11 12

15 1 2 3 4

5 6 7 8

Rain period 12. (20.9.68)

No.	Potential Gradient Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
17	L	+	st	Cu	L	L.Sh	10	16.30
18	L	+	st	Cu	L	L.Sh	10	.40
19	L	+	st	Cu	L	L.Sh	10	.50
20	L	+	st	Cu	L	L.Sh	16	17.00

Rain period 13. (20.9.68)

No.	Potential Gradient Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
1	L	+	st	Cu	L	L	6	19.15
2	L	+	st	Cu	L	L	9	.21
3	L	+	st	Cu	L	L	10	.30
4	L	+	st	Cu	L	L	10	.40
5	L	+	st	Cu	L	L	10	.50
6	L	+	st	Cu	L	L	12	20.00

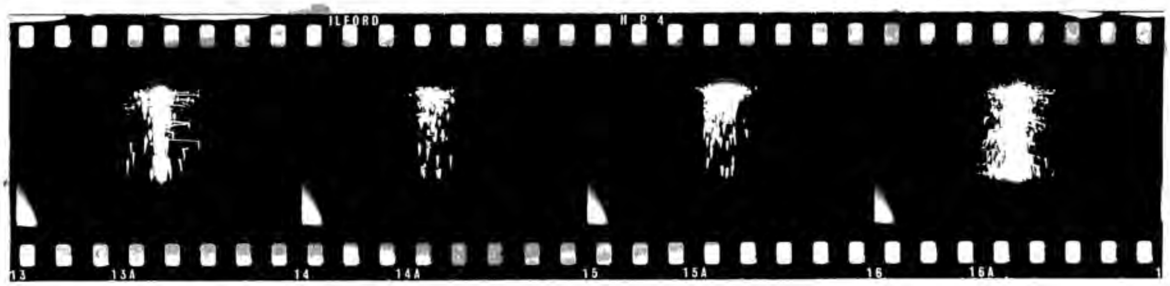
Rain period 14. (21.9.68)

No.	Potential Gradient Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
1	H	-	fl	Cu	L	L	11	15.37
2	L	-	fl	Cu	L	L	15	.48
3	L	-	st	Cu	L	L	25	17.20
4	L	-	fl	Cu	L	L	5	.45
5	L	+-	fl	Cu	L	L	5	.50
6	L	+-	fl	Cu	L	L	5	.55
7	L	+-	fl	Cu	L	L	10	18.00
8	L	+-	fl	Cu	L	L	13	.17
9	L	-	fl	Cu	L	L	5	.30
10	L	-	fl	Cu	L	L	10	.35
11	L	+	st	Cu	L	L	10	.45
12	L	+	st	Cu	L	L	18	.55

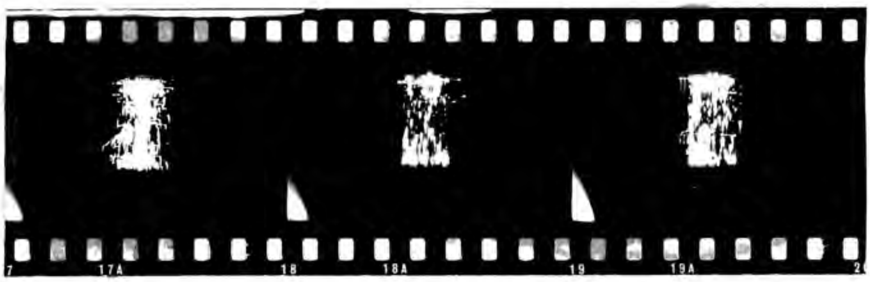
Rain period 15. (22.9.68)

No.	Potential Gradient Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
1	H	+-	fl	Cu	L	L	13	10.17
2	L	-	fl	Cu	L	L	10	.30
3	L	-	fl	Cu	L	L	20	.40
4	L	-	st	Cu	L	L	5	11.00
5	L	-	st	Cu	L	L	10	.05
6	L	-	st	Cu	L	L	10	.15
7	L	-	st	Cu	L	L	11	.25
8	L	-	fl	Cu	L	L	9	.36

15 9 10



16 1 2 3 4



17 1 2 3

18 1

16. September 22nd., 1968. 14.46 - 15.42 hrs. G.M.T.

This rain was later in the same day as period 15 and was very similar except for a brief sharp shower at 15.20 in the third exposure.

17. September 23rd., 1968. 12.39 - 13.16 hrs. G.M.T.

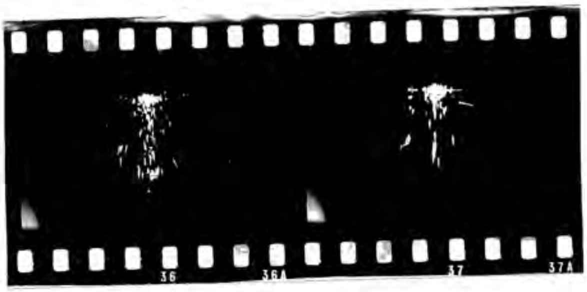
Rain fell steadily for periods of up to ten minutes from cumulus clouds. The potential gradient varied considerably during the period, suggesting that the clouds were of some considerable vertical extent, although not as great as in thunderclouds.

18. September 27th., 1968. 9.21 hrs. G.M.T.

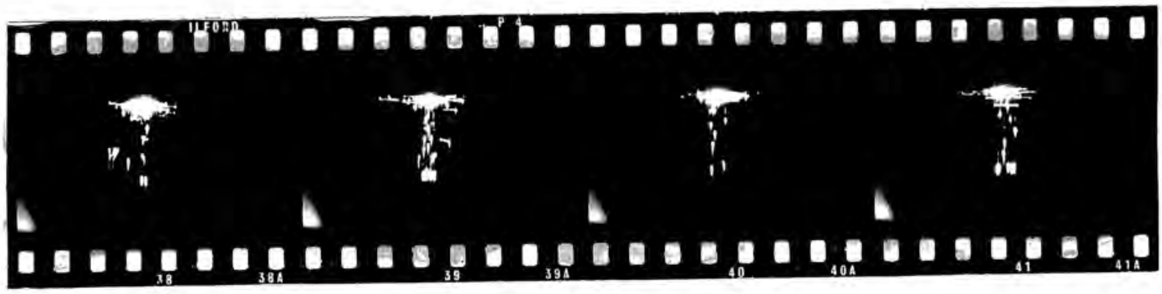
One successful exposure was made in the rain that fell in a blustery wind from the south. The rain appeared to be falling from stratus clouds although a high potential gradient was being measured by the field-mill.

19. September 30th., 1968. 9.38 - 10.00 hrs. G.M.T.

This was a cold shower in blustery conditions, the rain falling at a low angle from stratus clouds in a south-westerly wind. These conditions were frequently observed at the Lanehead Field Centre, often without any rain falling.



19 1 2



20 1 2 3 4

5 6 7 8

9 10 11 12

Rain period 15. (22.9.68)

	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
9	L	-	fl	Cu	L	L	10	11.45
10	L	-	fl	Cu	L	L	10	.55

Rain period 16. (22.9.68)

1	L	+-	fl	Cu	L	L.Sh	9	14.46
2	L	+-	fl	Cu	L	L.Sh	12	.55
3	L	+-	fl	Cu	L	Sh	10	15.19
4	L	+-	fl	Cu	L	L.Sh	12	.30

Rain period 17. (23.9.68)

1	H	-	st	Cu	L	St	11	12.39
2	H	+-	fl	Cu	L	St	4	13.00
3	H	+-	fl	Cu	L	St	12	.04

Rain period 18. (27.9.68)

1	H	-	fl	Ns	Bl	W	1½	9.21

Rain period 19. (30.9.68)

1	H	-	fl	St	Bl	W	7	9.38
2	H	-	fl	St	Bl	W	6	.54

Rain period 20. (1.10.68)

1	H	-	st	Ns	Bl	W	2	10.28
2	H	-	st	Ns	Bl	W	2½	.30
3	H	-	st	Ns	Bl	W	2½	.32
4	H	-	st	Ns	Bl	W	2½	.35
5	H	-	st	Ns	Bl	W	2½	.37
6	H	-	st	Ns	Bl	W	2	.40
7	H	-	st	Ns	Bl	W	2½	.42
8	H	-	st	Ns	Bl	W	1½	.44
9	H	-	st	Ns	Bl	W	2	.46
10	H	-	st	Ns	Bl	W	2	.48
11	L	-	st	Ns	Bl	W	2	.50
12	L	-	st	Ns	Bl	W	1½	.52

20 13 14 15 16

17 18 19 20

21

21 1

20. October 1st., 1968. 10.28 - 11.24 hrs. G.M.T.

This was another gusty day, when rain fell from stratus clouds in cold winds. The rain appeared to be hard and cold on the skin, and was very unpleasant. The cloud enveloped the nearby hill-tops appearing like mist on the upper parts of the mountains. The potential gradient in these conditions was steady, varying only slowly from about -500 to -100Vm^{-1} during the course of the rain. A gusty west wind was blowing for the whole morning. Towards the end of the rain period the rain reduced to a drizzle before finally ceasing.

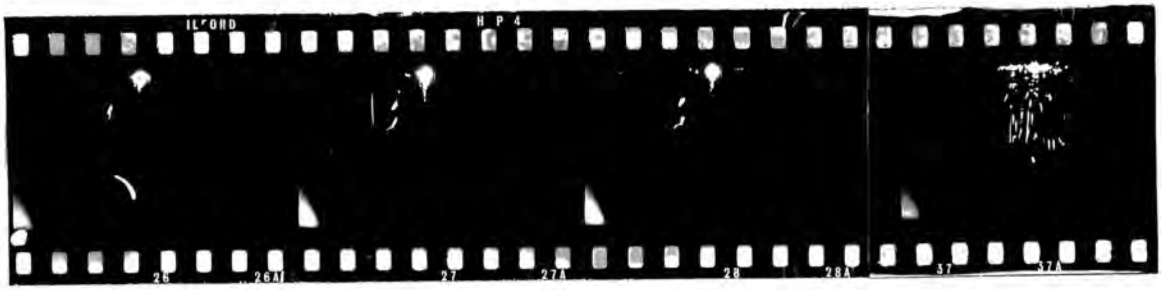
21. October 1st., 1968. 21.30 hrs. G.M.T.

One long exposure was made later in the same day as period 20. The wind was less, and some larger drops were apparent in conditions of very fine drizzle.

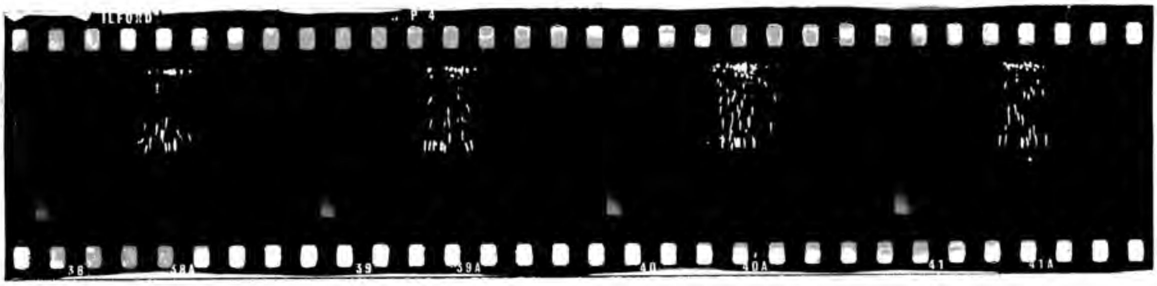
22. October 4th., 1968. 9.48 - 10.10 hrs. G.M.T.

The two exposures were made on the only day of flat calm on which rain fell sufficient for readings to be taken. The rain was very fine drizzle falling out of stratus clouds with very low cloud-base. The potential gradient was steady at the fair-weather value of about +100Vm^{-1}.

<u>22</u> 1 2



<u>23</u> 1 2 3 4



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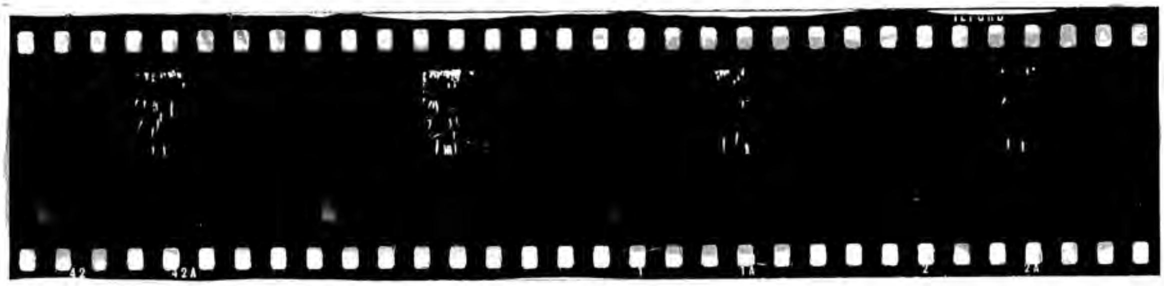


9 10 11 12

Rain period 20. (1.10.68)

	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
13	L	-	st	Ns	Bl	W	2½	10.53
14	L	-	st	Ns	Bl	W	2	.56
15	L	-	st	Ns	Bl	W	2	.58
16	L	-	st	Ns	Bl	W	2	11.00
17	L	-	st	Ns	Bl	W	2	.02
18	L	-	st	Ns	Bl	W	2	.04
19	L	-	st	Ns	Bl	W	2	.06
20	L	-	st	Ns	Bl	W	5	.08
21	L	-	st	Ns	Bl	W	7	.17

Rain period 21. (1.10.68)

1	H	+-	fl	St	L	Dr	15	21.30

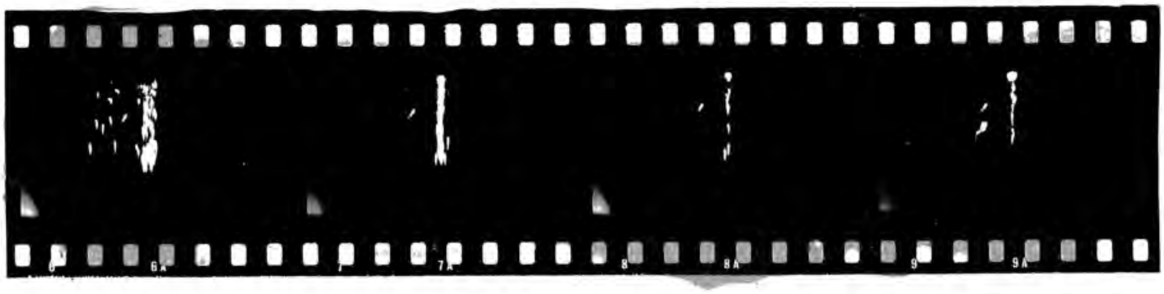
Rain period 22. (4.10.68)

1	L	+	st	St	Nil	Dr	12	9.48
2	L	+	st	St	Nil	Dr	10	10.00

Rain period 23. (10.10.68)

1	H	-	fl	Ns	Bl	W.Dr	5	20.02
2	H	-	st	Ns	Bl	W.Dr	8	.07
3	L	-	st	Ns	Bl	W.Dr	8	.16
4	L	+	fl	Ns	Bl	W.Dr	3	.27
5	H	-	fl	Ns	Bl	W.Dr	2	.30
6	H	-	fl	Ns	Bl	W.Dr	2	.32
7	H	-	fl	Ns	Bl	W.Dr	2	.34
8	H	-	fl	Ns	Bl	W.Dr	2	.36
9	H	-	fl	Ns	Bl	W.Dr	2	.38
10	H	+	fl	Ns	Bl	W.Dr	2	.40
11	H	+	fl	Ns	Bl	W.Dr	1	.42
12	H	-	fl	Ns	Bl	W.Dr	1	.43

23 13 14 15



24 1 2 3 4

5 6 7

23. October 10th., 1968. 20.02 - 20.57 hrs. G.M.T.

Rain fell from stratus clouds in blustery winds. In this set of readings the apparatus appeared to be triggered by the wind as well as by the raindrops. However, only spots of no charge and little mass could be registered by the wind. Halfway through the rain period the wind dropped to a breeze and more drops of rain began to fall. The sign of the potential gradient reversed four times during the period of the rain.

24. October 11th., 1968. 12.56 - 13.20 hrs. G.M.T.

The conditions on October 11th. were quieter than on October 10th., the wind being rather less and the rainfall steadier. Again there was stratus cloud and the distant hills were shrouded in mist. The overall rainfall was not great by comparison with October 10th.

Rain period 23. (10.10.68)

	Potential Gradient							
No.	Magnitude	Sign	Variation	Cloud	Wind	Rain	Duration (mins)	Time
13	H	-	fl	Ns	Bl	W.Dr	2	20.44
14	L	-	fl	Ns	Bl	W.Dr	4	.46
15	L	-	st	Ns	Bl	W.Dr	7	.50

Rain period 24. (11.10.68)

1	L	+	fl	Ns	L	L	4	12.56
2	L	+-	fl	Ns	L	L	3	13.00
3	L	-	fl	Ns	L	L	4	.03
4	L	-	fl	Ns	L	L	3	.07
5	L	-	st	Ns	L	L	3	.10
6	L	-	st	Ns	L	L	3	.13
7	L	-	st	Ns	L	L	4	.16

Appendix B

Values for v^2r^3 derived from Best's tables.

The values of 'r' and 'v' are derived from the tables of Best (1950) relating terminal velocity of raindrops and their diameter.

Radius r(mm)	Terminal velocity v ($\mathrm{mm\ s^{-1}}$)	v^2r^3 ($\mathrm{m^5s^{-1}}$)
0.15	1154	4.49×10^{-12}
0.25	1972	3.08×10^{-11}
0.345	2714	3.05×10^{-10}
0.385	3013	5.18×10^{-10}
0.395	3086	5.87×10^{-10}
0.50	3820	1.82×10^{-9}
0.875	5915	2.34×10^{-8}
1.145	6969	7.29×10^{-8}
1.69	8275	3.31×10^{-7}
2.035	8728	6.42×10^{-7}
2.21	8887	8.52×10^{-7}
2.465	9059	1.23×10^{-6}
2.71	9174	1.68×10^{-6}
2.975	9259	2.26×10^{-6}
3.12	9294	2.62×10^{-6}
3.185	9307	2.81×10^{-6}
3.335	9332	3.23×10^{-6}
3.625	9368	4.18×10^{-6}