Variations in the earth's electric field

Whitlock, W. S.

VARIATIONS IN THE EARTH'S ELECTRIC FIELD.

by

W.S.WHITLOCK.

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ABSTRACT

The nature and causes of variations in the atmospheric electric field as measured at the earth's surface at Durham are investigated. Determinations of the horizontal velocity of travel of variations of periods less than one hour are made from simultaneous field measurements, using two rotating electrostatic fluxmeters, at two points approximately 100m apart.

In fair weather the horizontal speed of the variations is about 1.2 times that of the wind at 10m, suggesting that they are due primarily to the motion of windborne space charges contained in the first 100m of atmosphere. In general the magnitude of the field variations appears to be dependent on the vertical stability of the lower atmosphere. Certain distinctive variations are believed to originate from charged locomotive steam while others appear related to atmospheric convective motion.

Measuremnts in mist and fog support the view that the undulatory nature of the field is due to the horizontal drift of fog [redacted] of varying thickness[redacted] or density.

Frequently fields below layer clouds show wave-like variations, these are shown to be due to the horizontal motion of cloud layers which contain a periodic spatial distribution of charges. This charge distribution appears to be closely related to visible structural variations in

cloud thickness or density. Reasons are given for suggesting that, in stratus cloud, charge is separated by the Wilson process.

It is shown that the field disturbances below shower clouds are due mainly to the horizontal drift of the charge system associated with the cloud. Such systems may be complex for appreciable charges appear to exist outside the cloud bounderies. Examples are given of the modification of surface fields by space charges liberated by point discharge processes and it is shown that surface measurements may be critically dependent on the location of the measuring instruments relative to discharging points.

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PART I

GENERAL INTRODUCTION

1. THE EARTH'S ELECTRICAL SYSTEM.

In the past more time has been devoted to the measurement of the earth's electric field than to any other of the atmospheric electrical elements and as a result a great deal of literature has been published which is directly concerned with the variations of this field. In this section and in the following survey these variations and their origins are discussed generally; where work of others bears specifically on the present investigation a detailed discussion of the relevant literature is reserved to a later section.

The Rationalised System of M.K.S. Units is used throughout. Field strength is used as a direct replacement for potential gradient; a vertical positive field tends to move a positive charge downwards.

1.1 The Condenser Analogy.

When studying atmospheric electrical phenomena it is often convenient to regard the earth as a conducting sphere surrounded by a second conducting spherical region known as the Ionosphere. This arrangement forms a concentric spherical condenser system in which the medium between the conducting surfaces is the atmosphere, a dielectric with a low but finite conductivity.

It has been found that the Ionosphere is at a positive potential with respect to the earth and that an electric field links the positive charge in the upper air with a negative charge bound on the earth's surface. The total resistance between the Ionosphere and the earth is about 200 ohms and with the average potential of the upper conductor at 3.6×10^{5} volts a leakage current of about 1800amps must flow. With this transference of charge between the conductors the electric field would quickly decay unless maintained by some other process. For many years the maintenance of the fine weather field remained a mystery but it is now generally accepted that the "supply current" is generated in those regions of the world which are suffering from stormy or disturbed weather.

Problems in atmospheric electricity may now be divided into two groups; on the one hand there are those concerned with the fine weather or dissipation processes, whilst disturbed weather problems are primarily concerned with processes which lead to the generation of the supply current.

1.2 Limitations of the Condenser Analogy.

At the earth's surface the electric field strength is seldom steady, its variations are diverse both in form and origin and arise from both the dissipation and generation processes. The classification of these variations is often based on the equation

$$E_p = \frac{V}{R \lambda_p} \qquad (1.1)$$

where Ep is the field strength at a point p, R the columnar resistance, V the potential of the Ionosphere and λ_p the specific conductivity of the air at p. Variations in Ep may then be classified according to which parameter(s) in (1.1) is changing. Eq.(1.1) has limited application however, for it has been derived with the assumption that the vertical current i(= V/R) is ohmic and its density is constant with altitude. Although this appears true for the stationary state, under normal conditions the atmosphere and its electrical elements are seldom steady so that the vertical current may be complex and may vary with altitude.

Let us consider the case where a steady equilibrium field E_a suffers an abrupt change at time t=0 and then eventually settles down to a final equilibrium value E_b. The transitional field strength E is then a function of time as shown by Kasemir(1950), for

$$E = E_a e^{-\lambda t/\varepsilon_0} + E_b\left(1 - e^{-\lambda t/\varepsilon_0}\right) \tag{1.2}$$

where ε_0 is the permittivity of free space (8.854×10^{-12} C/v^{-1}/m^{-1}). The value ε_0/λ being known as the relaxation time. Taking typical values of λ Israel(1953) has shown that the transition time in which the surface field reaches 99% of its new equilibrium value is about 30 minutes. As $i = E\lambda$ and λ varies with height then the vertical current density cannot be considered constant with altitude unless the variations of the other elements occur with periods greater than about

$5\varepsilon_0/\lambda$. For these quasi-stationary conditions the condenser analogy is applicable and has been used to explain many of the long period (secular and diurnal) field variations.

When considering the short period variations the idealised condition where there is a definite upper layer of positive charge must generally be abandoned. It has been found that the field strength decreases with height, Schweidler(1929) gives the empirical relation.

$$E = 90\,e^{(-3.5\times10^{-3}z)} + 40\,e^{(-.23\times10^{-3}z)} \tag{1.3}$$

where E is in v/m and z in metres. Differentiation of (1.3) shows that the upper charge is distributed throughout the lower atmosphere and rapidly decreases with height. This mean distribution of space charge follows from the vertical motion of ions in a medium whose conductivity increases with height. As the conductivity near the surface is comparatively low, more than half the total upper charge is, in fact, concentrated in the lowest 500m. Small ions in these lower air levels have relatively large mobilities and so make the largest contribution to the total ohmic vertical current. With mobilities of about 1.5×10^{-4} m/sec/v/m these small ions move at about 2.0×10^{-2} m/sec under the action of the normal fair weather field. However, it is not uncommon to find vertical air velocities of 1m/sec even in fair weather so that the airborne ions may have velocities which are governed primarily by aerodynamic rather than electrostatic forces.

In the present investigation only the comparatively short period (less than one hour) field variations are studied so that the problems are rarely concerned with steady-state conditions or the "current-field" picture of Kasemir. As these variations generally find their origin in local meteorological phenomena the condenser analogy is no longer applicable, in its place it is convenient to picture the electrical structure of the lower atmosphere as one of a complex distribution of space charge suspended in an often fast-flowing and turbulent fluid.

2. VARIATIONS IN THE EARTH'S ELECTRIC FIELD - A SURVEY.

In the following, a brief survey is made of all the various types of field variations. These may be analysed into components of various periodic times ranging from years down to fractions of a second. Although the present investigation is only concerned with a part of this time spectrum, variations of all periods are discussed in order to illustrate the wide variety of factors involved.

2.1 Annual and Secular Variations.

At a number of observing stations throughout the world a continuous record of the vertical field strength has been maintained over many years. From the mean values of the field as recorded on "Selected Days", see Whipple(1937), Israel(1948), it is possible to plot a curve of mean field against time for each year. The result usually indicates a greater field in the local winter than in the local summer. This form of variation has been attributed to a seasonal variation in λ, Eq.(1.1), for in the winter the density of small ions is low owing to their attachment to the kernels (Aitken Nuclei) produced by various sources of pollution. In the summer the number of small ions increases owing to the lessening of the pollution and as the conductivity is primarily dependent on the small ion density, so λ suffers an annual variation. The fact that there is little or no annual variation over the oceans is understandable considering the lack of sources of pollution. A small component of the annual variation may be due to a change in the potential of the Ionosphere, V, as discussed by Whipple(1929).

So far as a secular variation is concerned there appears to be little evidence that this is anything but fortuitous. Scrase(1934) has pointed out the probable significance of part of the secular variation at Kew, whilst Bauer(1923) seems to think that there is a relation between secular variation and sunspot activity.

2.2 Diurnal Variations.

As the period of the field variation under investigation becomes smaller, so it is found that the contribution made by local influences becomes larger. This applies particularly to land stations where most of the daily variation is due to changes in the local atmosphere. In contrast, the form of the variation that occurs over the oceans and in polar regions is comparatively free from local effects, hence measurements made in these regions are of particular interest. Where such measurements have been made, they have indicated a well-marked diurnal variation and it has been shown that this variation occurs simultaneously in all parts of the world. This world-wide alteration of field strength is of fundamental importance and has been ascribed to a variation of the potential of the Ionosphere with time. If Wilson's(1920) theory that the world's thunderstorms maintain the ionospheric potential is correct, then one might expect that when the world's thunderstorm activity was at its height the potential of the Ionosphere would be at a maximum. This in fact was found by Whipple (1929), who showed that the diurnal variation of the world's thunderstorm activity follows closely the diurnal variation of the field strength as measured over the oceans.

Naturally this component of the diurnal variation exists at all stations although it is generally masked by local effects at land stations. Using suitable analytical treatment the worldwide component can often be extracted from the daily course of the field and the remaining curve is then due to purely local effects; for example see Allen(1939). The form of this curve depends to a large extent on the weather prevailing but again if only "Selected Days" are considered, then the local component has been found to vary closely with local solar-time. Just before dawn the field is at its lowest value; as the morning progresses the field increases, reaching a maximum about noon. From noon onwards the field falls through a secondary minimum to rise again to a secondary maximum at dusk, finally falling to the minimum at next sunrise. Whipple(1929) has explained this by considering changes in the local conductivity due to a combination of changes in the rate of pollution production and the effectiveness of the dispersal of this pollution by the motion of the lower air masses. Brown(1934) has enlarged on this theory and comes to the conclusion that the daily cycle of turbulence, convection and subsidence, is primarily responsible for the form of the field variation. Modification of the form of variation by weather conditions has also been found by Brown(1936)(1937); both with constant cloud cover and with increasing wind speed the amplitude of variation is reduced. This is explained by considering the modified state of the convection cycle as would exist under these conditions.

2.3 Short Period Variations.

The term short period is used here to cover those variations which have periods ranging from about one hour to a few seconds. A large proportion of these variations have their origin in the changes of conditions in the local atmosphere, therefore, it is convenient to classify them under different meteorological conditions.

a) Fine Weather.

By comparison with the variations of other periods there has been little detailed study made of the short-period fluctuations that exist in fine weather. The significance of these was not thought to be important, in any case very little detail could have been extracted from field registering instruments designed to investigate long-period variations. Such instruments had a long response time and a slow recording-chart speed.

Fundamentally all field variations are the result of a change in charge distribution but whether a particular field variation is due to a direct change or to an indirect one arising from an alteration of conductivity is generally difficult to decide, particularly if the air-earth current is not measured alongside the field.

As a large percentage of the total upper positive charge is confined to the lower atmosphere then even if the conductivity is undisturbed from its normal value and there is no direct charge generation taking place, field variations might be expected to occur if the air becomes turbulent, causing vertical motion of the existing charges.

When conductivity changes do occur, the field generally follows the anticipated inverse course and many experimental examples of this relation may be found in the literature. The sudden introduction of a mass of air whose conductivity differs from that of its surroundings would not cause rapid changes in field strength because of the relaxation effects. Under normal circumstances one would expect variations arising from pure conductivity effects to have periods greater than about five minutes. A small pocket of air whose conductivity differs from that of its environment can have little effect on the field at the surface. Even the clouds of fair weather with their internal conductivity reduced to about one third of the normal value have been found to have a negligible effect on the surface field. In general, appreciable conductivity effects must be associated with fairly large air masses, for example see Koenigsfeld(1951).

Other fine weather field variations arise from the existence of free charges which have been produced by some direct charge generation process. These processes may be natural or may arise from the activities of man. Of the first the only one likely to be encountered is that which arises from the frictional effects of dust particles. A number of instances, for example Sil(1933), have been reported when the normal positive fine weather field was decreased, often to a negative value, and the effect was associated with "dust devils". This implies a negative charge on the particles, however, this is not an infallible rule, as has been shown by Rudge(1914).

So far as man-made charges are concerned, the majority are associated with combustion processes. Muhleisen(1952) (1953) has made a thorough search for the origins of these charges and his findings are tabulated in Table 1. He finds that in some cases the life-time of the ions bearing the charges may exceed one hour and may be detected more than 10km from their source.

Table 1.

Positive.	Negative.
Exhaust Gases.	Open Fires.
Chimney Smoke.	Wood Fires.
Pulverised Coal Furnace.	Pure Water Vapour (from metal nozzle).
Steam (from Loco's and Gasworks).	

To conclude this discussion of field variations in fine weather, mention should be made of the possibility of extra-terrestrial phenomenon affecting the earth's electric field. Atmospheric electrical measurements have been made during solar eclipses and there seems to be evidence that the effects of the eclipse are felt by the electrical elements. Typical results are those of Jones and Giesecke (1949) who, like others, found a field decrease during a partial eclipse and a conductivity increase. Bauer(1923) believes that sunspot influence is also felt but neither his conclusions nor those of Cooper(1936), who found a 27-day field component, have met with much support. Broxton, Meridith and Strait(1933) have found a correlation between magnetic character, cosmic-ray intensity and field strength.

A detailed discussion of these extra-terrestrial effects may be found in papers by Israel(1947) and Koenigsfeld(1953).

b) Mist and Fog.

The presence of a wide-spread layer of mist or fog at or near the earth's surface may affect all three electrical elements. Generally the conductivity within the fog appears to be reduced to about one third of its normal value and this may lead to a reduction in the value of the air-earth current. Despite this reduced current the field generally shows an increase within the fog because of the reciprocal relation between E and λ. Inhomogeneous fog may give rise to complex space charge distributions, for if the conductivity decreases with height, negative space charge will be created and any subsequent overturning(austausch) of the fog layers may result in a very variable field at the surface. This has been discussed by Israel and Kasemir(1952).

Generally, records in fog display smooth wave-like variations of a positive field, these arise from the passage overhead of fog layers of varying density and thickness. However, on occasions, persistent negative fields have been found to occur in misty or foggy weather, Chalmers and Little (1947). Subsequent investigation by Chalmers(1952) showed that negative charge is liberated from high tension transmission cables and may drift downwind in sufficient quantities to reverse the normal field over distances of some kilometres.

c) Disturbed Weather.

While there are many general statements in the literature about the field during disturbed weather, Simpson(1949) was the first to publish an account of a detailed study of the electrical elements under these conditions. His conclusions and findings, some of which have since been verified by Sivaramakrishnan(1952), are summarised in the following paragraphs.

i) Steady Continuous Rain.

Generally, the field is negative in sign and only undergoes minor variations of comparatively long periods. Such fields are characteristic of a "quiet" atmosphere; for example, in advance of, or during the passage of, a warm front, or in a warm sector.

ii) Variable Continuous Rain.

As the active vertical instability of the atmosphere increases, so the variation of the associated field increases. At the passage of an occlusion the field may show alternate positive and negative values, whilst at the passage of a cold front these excursions may become very large and rapid. Simpson found that the intensity of the rainfall bears little or no relation to the sign or the magnitude of the field.

iii) Showers.

As showers are the result of rapid vertical movements of air masses, they are usually accompanied by very variable fields. Violent excursions of the field may occur; in one case Simpson recorded both positive and negative fields of over 10,000v/m. It is interesting to note that Simpson found no significant difference between very active showers and thunderstorms, apart from the occurrence of lightning flashes in the latter.

iv) Snow and Sleet.

The field during steady snowfall shows the same general characteristics as the field during steady rain. Two important differences appear to exist. In steady snowfall the field appears to be little removed from its normal positive fine weather value; in snow and sleet showers the fields frequently show even greater amplitudes and shorter periods than occur with rain showers. The largest field strength ever recorded by Simpson(20,000v/m) occurred during a snow shower.

v) Field Patterns.

Simpson was the first to point out some of the remarkable forms of field variation that occur during disturbed weather. Two main classes of pattern were revealed; the wave pattern and the symmetrical pattern. The former consists of a series of more or less regular waves. These range from waves which are irregular in period and amplitude, to others which resemble a series of harmonic waves of constant period and regularly varying amplitude. Such patterns are usually associated with an overcast sky in a "quiet" atmosphere, with or without precipitation.

Symmetrical patterns of many forms are described by Simpson and their form and frequency of occurrence lead him to the conclusion that such variations are not just random in nature. Many of the patterns are symmetrical either in time or about the zero field axis and appear similar to field patterns that would arise from the passage overhead of horizontally separated positive and negative charges. Simpson gives no physical explanation of either the wave or the symmetrical patterns.

d) The Thunderstorm.

Despite the fact that the electrical activity associated with thunderstorms is both obvious and easily detected, the actual process of charge separation still remains uncertain. Investigations of the electrical and physical structure of these storms has become rather a specialised task and as such storms are relatively rare in N.E.England, it was anticipated that little opportunity would arise for their study during the present work. It must be emphasised that as yet there is no concrete evidence to show that the difference between showers and thunderstorms is not just one of degree but of some fundamental difference in the electrical processes involved. Therefore, a study of shower phenomena might reveal important results which are directly applicable to the more violent thunderstorm conditions.

Much of the credit for investigations into the main structure of thunderstorms must go to Simpson and Robinson (1940) for their work with the alti-electrograph. They found that the average storm-cloud has an upper positive charge, situated in a region well below freezing point; a lower negative charge situated at about the freezing level and sometimes a third small charge, positive in sign and situated below the main negative charge. Field measurements beneath thunder clouds generally support the above findings but such fields are usually very variable and there are frequent discontinuities due to the transference of charge by lightning.

American work has added considerably to this picture, see for example Byers(1953). They have shown that the thunderstorm is essentially a dynamic phenomenon. Each storm may consist of a number of cells, each of which is defined by the vertical air currents within it. A single cell has a definite life cycle starting from a general updraft stage and dying out in a general downdraft stage. A single cell may have a life of about one hour and may extend horizontally for about one kilometre. Using a micro-network of meteorological stations the Americans have shown that strong downdrafts may be co-existent with updrafts in the one storm and that a definite sequence of meteorological disturbances can be associated with its passage.

2.4 Ultra-short Period Variations.

Dwight(1925) carried out an investigation to determine whether very short(less than one second) period variations occurred in the earth's electric field. He found that the only variations of this type were due to the transference of charge by lightning in near or distant thunderstorms and if other ultra-short variations do exist, then they must have an amplitude less than 18v/m.

The form of the field variation that occurs when charge is transferred by lightning is well described in the literature, for example Wormell(1953), and does not come under the scope of the present work.

3.1 THE OBJECT OF RESEARCH.

The aim of the present investigation is simple in statement; to determine the form and the cause of variations in the earth's electric field as they occur in both fine and disturbed weather.

Owing to the complexity of the variations to be investigated it was not possible in the early stages of the work to define particular objectives but as the investigation progressed it was hoped that specific problems would reveal themselves, so enabling subsequent work to be precisely directed. It seemed important, therefore, that the experimental techniques used should be capable of coping with a wide range of electrical and meteorological conditions.

The first task was the design and construction of a field measuring instrument of sufficient versatility to satisfy any normal requirement as might be expected when dealing with fine and disturbed weather conditions. By suitable application of this and subsidiary instruments the work could then be concentrated on finding the cause or origin of the variations.

No single experimental technique could be completely satisfactory for all ranges of field variations. Investigations which are concentrated on the long period(annual-diurnal,etc.) variations require field records covering long periods of time. As the records obtained during the present investigation only cover an hour or so, only the short period variations can be studied satisfactorily. This limitation is not altogether an unwelcome restriction, for in the past most of the correlation between field and weather has been made by comparing the field record with the synoptic weather chart occasionally supplemented by observers' notes. In this investigation, however, an attempt is made to compare minute by minute the value of the field strength and the state of the sky above.

One field measuring instrument is sufficient for the type of investigation outlined above but the addition of further instruments greatly increases the scope of the experimental technique for the following reasons. Most, if not all field variations are due to charge motion in the atmosphere. Such motion may have both horizontal and vertical components. In the case of a charge which moves in the lower atmosphere the effect of its vertical displacement is to create a field disturbance which is registered simultaneously at all points on the surface below. In contrast the horizontal component of the charge motion gives rise to a progressive disturbance which travels over the surface with the horizontal velocity of the charge. If, therefore, the field is measured at two or more separated points on the surface, it should be possible to distinguish between disturbances which are simultaneous and those which are progressive. For this reason it was intended to operate a second field measuring instrument horizontally displaced from the first.

Although in the past little experimental work has been concentrated on this problem of charge motion, most writers have assumed, and rightly so, that a great majority of field variations originate from the motion of windborne charges. Such a suggestion was first made by Lord Kelvin(1884) but subsequent measurements have shown that not only is it impossible to explain all charge motion in terms of wind velocity but that the results can be difficult to interpret and in some cases completely contradictory.

4. MEASUREMENT OF ELECTRIC FIELD.

4.1 Simultaneous Measurement at Two Sites.

From simple considerations there appears to be much to recommend a large separation between the two sites at which the field is to be measured. Kahler(1908) used separations of about a kilometre, which although desirable in many respects, are too large for the present investigation. The setting-up, calibration, synchronisation and maintenance of even two instruments separated by a kilometre or so, are not tasks easily carried out single-handed. A more convenient arrangement utilises comparatively short distances of about 100 metres.

With separations of this order, the delay times between progressive disturbances as measured at each site are small, even for windborne charges. Delay times of ten seconds or so are involved, so that it is necessary to measure relative time to at least one or two seconds. Time resolution to this accuracy presents serious synchronisation difficulties if two totally independent instruments are used. To avoid these difficulties the two field measuring instruments are arranged to record onto the same recording chart. In order to resolve one second intervals on the chart, it is necessary that the chart speed be about 5 cm/min.- an unusually high speed for field records.

Preliminary experiments were to be carried out with the two instruments, approximately 100 metres apart, on a line roughly parallel with the surface wind direction. This required portable instruments, for they were to be moved from site to site as the wind shifted. It also seemed important that the two instruments should be identical if an accurate comparison was to be made of their records.

4.2 Instrument Requirements.

In laying down the instrument requirements, an attempt was made to specify an instrument which is as versatile as possible. This versatility was stressed, for it was not known just to what purpose the instruments were to be put until specific problems had been uncovered. The following requirements formed the basis for the choice of instrument type.

a) The instrument must provide a continuous indication of the strength of the field. It must be capable of coping with large fields that accompany disturbed weather, yet have sufficient maximum sensitivity to enable fair weather variations to be studied in detail.

b) It must indicate the sign of the field.

c) It must have a good short-period stability and a response time of less than one second. This was essential for studies of the fair weather variations and for the faithful reproduction of the rapid changes that occur in disturbed weather.

d) The instrument must operate satisfactorily in all normal weather conditions.

e) Its presence must cause as little disturbance as possible to the natural electrical state of the atmosphere. Also it must not interfere with any other atmospheric electrical measurements made in the vicinity.

f) It must be portable. The position of the instrument would be governed by wind direction. In addition, it would be an advantage if the equipment was independent of mains supplies for the occasion might arise when it was required to be operated away from buildings.

g) The instrument must be remote indicating. The outputs from two instruments were to be recorded on one camera. It was considered very desirable that the information being recorded was also available in some visual form. This proviso was added because it was felt that an immediate and continuous direct comparison of field and weather might prove valuable.

4.3 Choice of Instrument Type.

Two main methods are available for the continuous measurement of the earth's electric field. The first method actually gives the mean potential difference between two vertically separated points, one of which is generally the earth's surface. If the probe or wire is to acquire the potential of its neighbouring air in a reasonably short time, some provision must be made for the transfer of charge to the probe. This charge transfer may be carried out for example by water drops, Kelvin(1855). Considerable advance in the water-dropper has been made since Kelvin's day but although a portable instrument of this type has been made by Lecolazet (1946), it was considered far too cumbersome for the present work. A more common form of collector utilises the ionisation produced by a radio-active source. In this case the probe reaches the required potential by virtue of the increased conductivity of the air in the vicinity of the probe. Although the radio-active collector provides the simplest method of measuring the field it suffers from one fundamental disadvantage. It is thought that the violation of requirement e),(the collector, by the very nature of its purpose, must create charge) would lead to difficulties when interpreting the recorded fine structure variations of small fields. Muhleisen(1951)(1953) has shown this criticism is justified, for not only may the potential of the probe depend to some extent on both wind speed and direction but also many of the fine structure variations in its potential are probably due to the irregular motions of the ions produced by the collector itself. There are other difficulties associated with the measurement of potential, such as the provision of a wide range of sensitivities, the necessity for high insulation and the provision of a short response time. The arrangements used by Kasemir(1952) and Brewer(1953) have overcome some of these difficulties.

The other main method of field measurement is an indirect one in that the density of bound charge is measured and the field strength deduced, using $\varepsilon_0 E = \sigma$. Here the energy required for the transfer of charge is derived from some mechanical source, hence the name of mechanical collectors. These mechanical collectors have been developed along two lines. The first form is basically a d.c.generator. A charge proportional to the applied field strength is induced on a conducting plate, initially earthed. The earth connecter is broken and the plate moved to a position screened from the field and shares its charge with an electrometer or the charge flows through a current measuring instrument. If the plate is then returned to its original position and the above sequence of events rapidly repeated, a series of uni-directional current pulses will flow from the collector. The magnitude and sign of this current is directly related to the magnitude and sign of the applied field. The first mechanical collector built by Russelvedt(1925) was of this form.

A modern instrument of this form, named the Agrimeter, has been designed by Chalmers(1953); as a current generator it has a wide range of sensitivity, will operate in all weathers and possesses the great advantage of operating an indicating instrument directly. The output gives both magnitude and sign of the field but is directly proportional to the motor speed. It is not altogether suited to the present work however, for an Agrimeter that is sufficiently small to be portable would not satisfactorily operate an indicating instrument over large distances without the assistance of power amplification. The difficulties associated with the amplification of small d.c.signals may be considerable and once it becomes necessary to resort to amplification, the Agrimeter type loses its main advantage.

With the second form of mechanical collector the difficulties associated with signal amplification are comparatively small, for the instrument is an a.c.generator. Here a fixed or moving conducting plate is alternatively exposed to and screened from the field and the resulting charge that flows to and from the plate provides a means for the determination of the magnitude of the field. If the plate is connected to earth by an impedance then the amplitude of the alternating voltage developed across this impedance is directly proportional to the field strength. The power available is usually too small for direct application but the addition of a conventional a.c.amplifier usually presents little difficulty. By suitable design the output from the instrument can be made virtually independent of the motor speed and also the necessity for high insulation can be avoided; two important properties so far as the present demands were concerned. Theoretically this form of instrument would appear to satisfy all the requirements as outlined in the previous section. Practically the instrument may prove unreliable, for it is comparatively complicated and the necessity for providing an extra unit for the determination of the sign of the field will add to the possible sources of mechanical and electronic failure. Despite these forseen difficulties it was thought that the Field Mill, the name by which this form of collector is popularly known, offers the best method for measurement of field over wide ranges and under all weather conditions, yet be small in size and have very little effect on the natural state of the atmosphere.

PART II

APPARATUS AND EXPERIMENTAL METHODS.

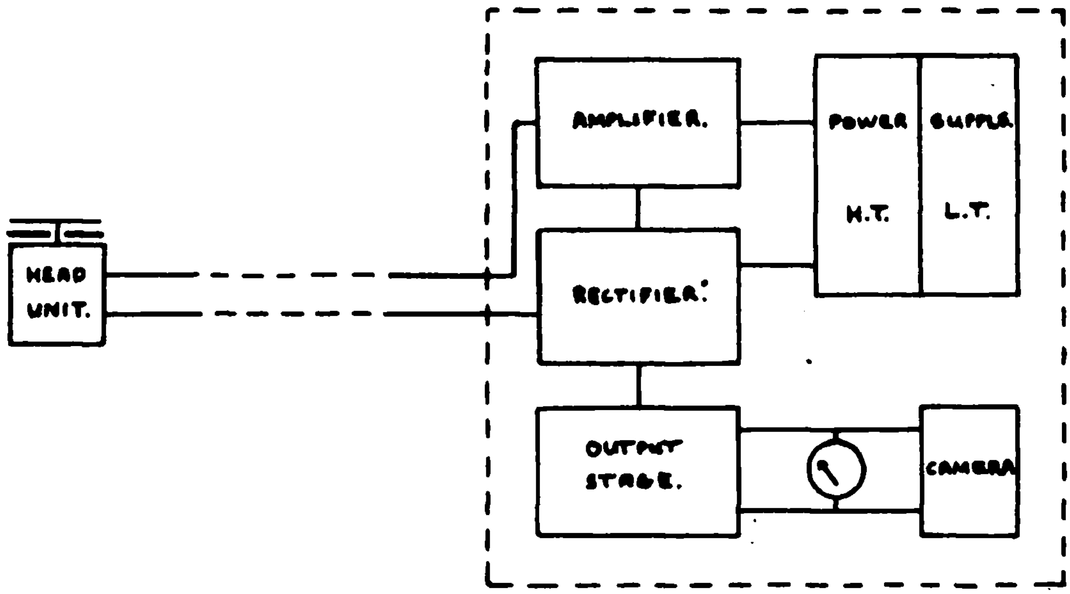


Fig. 1 Mill Units — Block Schematic.

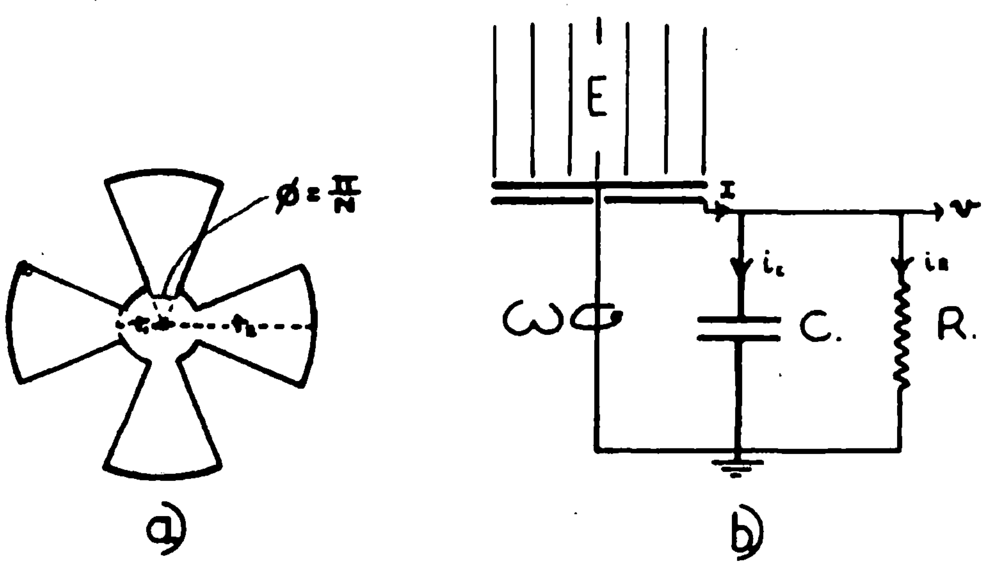


Fig. 2 Rotor-stator Assembly.

5. THE FIELD MILL - DESIGN.

5.1 General Plan.

In the previous sections reasons have been given for the construction of two identical field mills to be used for the simultaneous measurement of the earth's electric field at two points on the surface about 100m apart. It was proposed to connect the instruments by cable to a central control room but, because of the frequent changes in mill position, it was necessary to keep the external equipment to a minimum and the cable weight low.

The mill proper is contained in a small light box called the Head Unit, see Fig.1 , which was placed at the actual site where field measurements were to be made. Within the Head Unit the signal and reference voltages are generated and then transmitted by 60m of cable to the control room.

Within the control room was the signal amplifier, power supplies and the recording system. Both mills can be operated from mains or battery supplies.

In the following sub-sections the various units of the field mills are discussed in detail.

5.2 The Rotor-Stator Assembly.

For constructional simplicity the rotor and stator vanes were cut as sectors of a circle so as to give a triangular output waveform. A more efficient method uses vanes shaped to give a sine-wave output, for example Rangs(1942), but it is felt that the constructional difficulties associated with this type of vane outweigh the advantages. Malan and Schonland's(1951) method has the merit of simplicity but lacks the efficient use of all the available rotor area.

Before discussing the theory of the design, mention must be made of a paper by Dahl(1951) which contains a survey of the design of sector-type mills. Dahl's paper was received since the following theory was developed and although some of his conclusions are repeated here the methods of deriving these conclusions are different.

Considering the vanes as sectors of a circle, then, from Fig. 2a, the area of each vane is

$$(r_2^2 - r_1^2)\phi/2 \qquad (5.1)$$

If the stator vanes are fully exposed to a perpendicular electrostatic field of magnitude E, then the total bound charge is given by

$$\varepsilon_0 E (r_2^2 - r_1^2) N\phi/2 \qquad (5.2)$$

where N is the number of vanes. Assuming that when the rotor is in its screening position the bound charge on the stator is zero, then for an intermediate position of the rotor this charge is given by

$$q = \varepsilon_0 E (r_2^2 - r_1^2) N\omega t/2 \qquad (5.3)$$

where ω is the angular velocity of the motor and t is the time measured from the screening position. Hence the stator displacement current is

$$I = \varepsilon_0 E N\omega\left(r_2^2 - r_1^2\right)/2 \tag{5.4}$$

Considering the equivalent circuit shown in Fig.2b where the stator has a total fixed capacitance C and a resistance R to earth, let the component of the displacement current in the resistor arm be i_r and that in the condenser arm i_c. Then

$$I = i_r + i_c \tag{5.5}$$

At time t the voltage across the condenser is

$$v = \frac{1}{C}\int_0^t i_c\,dt. \tag{5.6}$$

But $i_c = I - \frac{v}{R}$, therefore,

$$v = \frac{1}{C}\int_0^t \left(I - \frac{v}{R}\right)dt. \tag{5.7}$$

Integrating with the condition $v = 0$ when $t = 0$ we have

$$v = IR\left(1 - e^{-t/RC}\right) \tag{5.8}$$

Eq.(5.8) gives the instantaneous voltage across C at any time during the first half-cycle. At the end of this $t = \pi/N\omega$ and the peak(half the peak-peak) voltage is

$$v_{p1} = IR\left(1 - e^{-\frac{\pi}{N\omega RC}}\right)/2 \tag{5.9}$$

Similarly the voltage at the end of the nth. half-cycle may be derived by integrating Eq.(5.7) with the condition $v = v_{p(n-1)}$ when $t = 0$ ($v_{p(n-1)}$ being the voltage at the beginning of the nth. half-cycle). This proceedure gives

$$v_{pn} = v_{p(n-1)}\alpha + IR(1-\alpha) \quad \text{where } \alpha = e^{-\frac{\pi}{N\omega RC}} \tag{5.10}$$

If now, the appropriate value of $v_{p(n-1)}$ is substituted in Eq.(5.10) for n 1,2,3...and noting that the sign of I changes with each successive half-cycle then the following series may be derived,

$$v_{pn} = IR(-1)^{n-1}[1-\alpha][1-\alpha+\alpha^2 \ldots\ldots (-1)^{n-1}\alpha^{n-1}] \qquad (5.11)$$

If $\alpha<1$ then the series is convergent and when summed gives

$$v_{pn} = IR(-1)^{n-1}\frac{[1-\alpha]}{[1+\alpha]}[1-(-1)^n\alpha^n] \qquad (5.12)$$

Equation (5.12) reveals some interesting characteristics of the output waveform. First consider the case when $n=1$. The peak voltage at the end of the first half-cycle is

$$v_{p1} = IR[1-\alpha]/2$$

as before. If $n=\infty$ the final steady peak voltage is

$$v_{p\infty} = IR\frac{[1-\alpha]}{[1+\alpha]} \qquad (5.13)$$

Hence the ratio of the peak value of the first half-cycle to the steady peak value is

$$\frac{v_{p1}}{v_{p\infty}} = \frac{1+\alpha}{2} \qquad (5.14)$$

If the electric field is suddenly applied at $t=0$ then so long as $\alpha\approx1$, the first half-cycle has the same peak amplitude as the succeeding ones. Hence so far as the alternating component of the output voltage is concerned the response time may be made negligible for practical purposes.

Returning to Eq.(5.12) if n is expressed in terms of time where t_n is the time occupied by n half-cycles then

$$n = t_n\frac{\omega N}{\pi}$$

and

$$v_{pn} = IR(-1)^{n-1}[1-(-1)^n e^{-\frac{t_n}{RC}}] \qquad (5.15)$$

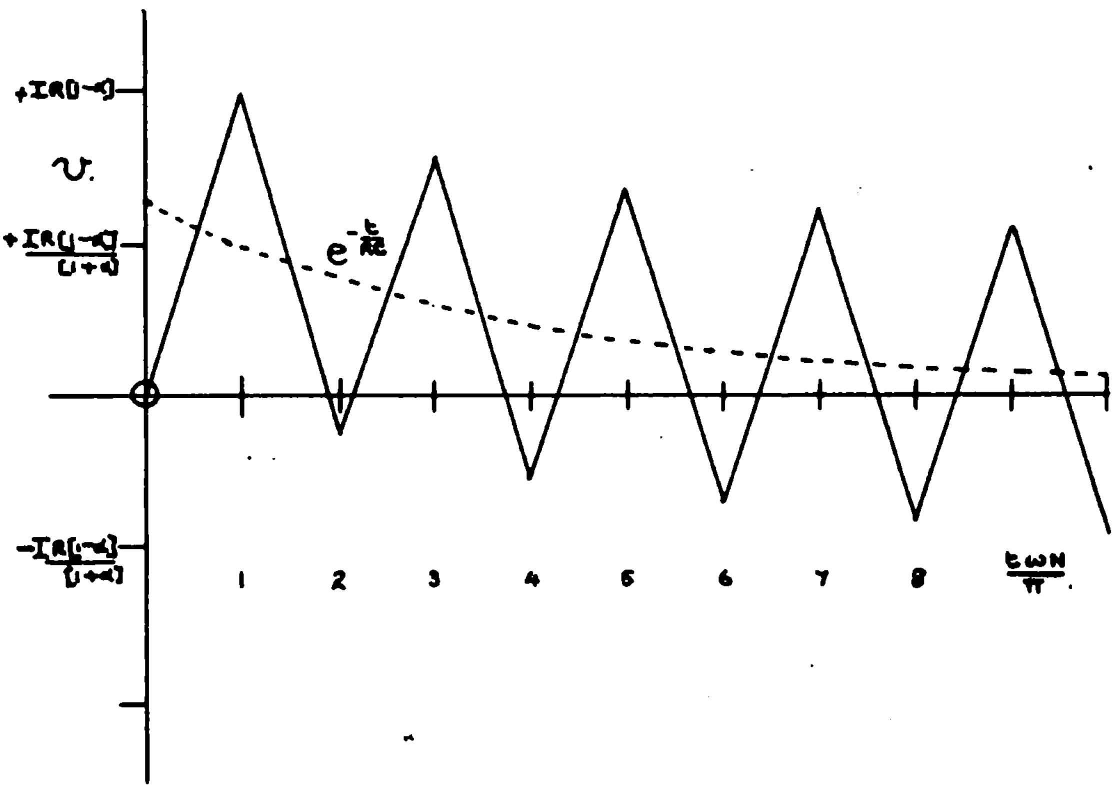


Fig. 3 Voltage Waveform across C. ($\alpha \simeq 1$).

Fig.3 illustrates the effect of the exponential term contained in Eq.(5.15) and shows that if the field is suddenly applied at t=0 then the alternating component of the output is superimposed on an exponentially decaying d.c. pulse of time constant RC seconds. The ultimate effect of this d.c. pulse depends on the characteristics of the amplifier, rectifier and recording systems and its effect will be similar to that of a charged drop which is discussed later.

Eq. (5.13) of the last section gives the output voltage from the rotor-stator assembly in terms of field strength and other parameters. This equation is now used as a guide to practical design. Substituting for I and α in (5.13) gives

$$v_{p\infty} = V = \frac{\varepsilon_0 E N \omega R}{2}\left(r_2^2 - r_1^2\right)\left[\frac{1 - e^{-\frac{\pi}{N\omega RC}}}{1 + e^{-\frac{\pi}{N\omega RC}}}\right] \qquad (5.16)$$

Now it is desirable that the steady state voltage V be linearly related to E in the manner V=PE where P is an instrument constant. Eq.(5.16) as it stands does not appear to meet this requirement for variations in motor speed and R may both have a direct influence on V. In order to make V independent of both ω and R, it is necessary that,

$$\frac{\pi}{N\omega RC} \ll 1 \qquad (5.17)$$

that is, the time constant RC must be much greater than the period of the exposure-screening cycle. Assuming $\frac{\pi}{N\omega RC}$ small then the exponential terms in (5.16) may be expanded as a series to give, $$V = \frac{\varepsilon_0 E N\omega R}{2}\left(r_2^2 - r_1^2\right)\frac{\left[1 - 1 + \frac{\pi}{N\omega RC} - \frac{1}{2}\left(\frac{\pi}{N\omega RC}\right)^2 + \frac{1}{6}\left(\frac{\pi}{N\omega RC}\right)^3\right.}{\left[1 + 1 - \frac{\pi}{N\omega RC} + \frac{1}{2}\left(\frac{\pi}{N\omega RC}\right)^2 \ldots\right.}$$

$$= \frac{\pi\varepsilon_0 E}{4C}\left(r_2^2 - r_1^2\right)\left[1 - \frac{\pi^2}{12(\omega NRC)^2} + \text{higher power terms}\right] \qquad (5.18)$$

Neglecting $\frac{\pi^2}{12(N\omega RC)^2}$ and higher power terms,

$$V = \frac{\pi\varepsilon_0 E}{4C}\left(r_2^2 - r_1^2\right) \qquad (5.19)$$

which is of the form V=PE and V is independent of both ω and R but is inversely proportional to the total capacitance of the stator.

Practical values can be assigned to the parameters in Eq.(5.19) from the following considerations. If the smallest field to be measured is 1v/m and the smallest value of V that can be successfully amplified and detected is 0.1mv, then with r_2=6.75cm and r_1=2.5cm (values appropriate to a portable instrument) Eq.(5.19) gives,

$$C \leqslant 2.8 \times 10^{-10}\,F.$$

Having fixed this limiting value of C, some of the parameters in (5.17) can now be assigned practical values.

In fixing the value of R, the most important factor is the effect of the voltage developed across this resistor by the grid current of the first valve(R being the grid-leak). If this grid current is Ig then the stator will be at a potential RIg with respect to earth and as the magnitude of Ig may vary then the stator potential may also vary. This stator potential will have a two-fold effect on the output. Firstly, the number of lines of force which terminate on the stator will depend partly on its potential; in effect, stator potential variations lead to changes in the effective exposure. Second and more important, there will exist an electrostatic field between the rotor and the stator which is indistinguishable from the external field so far as the output is concerned. An alternative approach considers the effect of changes in the stator capacitance as the rotor moves. Let the mean capacity be Co and the variable component ΔC, then the peak alternating voltage across C is given by,

$$\frac{\Delta C}{C_o} . R . I_g = V_c \qquad (5.20)$$

As ΔC varies at the same frequency as the exposure-screening cycle, then the ultimate result of the grid current is a spurious alternating voltage of the same frequency as the signal. Therefore, Ig must be as small as possible.

In the present instrument the first valve had a measured value of $I_g = 5 \times 10^{-11}$ A. If $C = 250 \mu\mu f$ and $\Delta C = 12 \mu\mu f$ (measured value), then from Eq.(5.20),

$$V_c = 2.4 \times 10^{-12} R$$

If Vc is to be smaller than the voltage due to a steady applied field of say, 5v/m, then,

$$R \leqslant 10^8 \Omega$$

With $C = 250 \mu\mu f$ and $R = 10^8 \Omega$ then Eq.(5.17) gives,

$$N\omega \gg 1200 \text{ r.p.m.}$$

So far as N is concerned, there appears to be an optimum value. The larger N, the lower the necessary speed of rotation, however, if there are a large number of narrow vanes then the effective exposure of each vane will be poor. As a compromise, four vanes are used, so that,

$$\omega \gg 280 \text{ r.p.m}$$

In practice $\omega = 5{,}000$r.p.m., so the above condition is satisfied. Inserting the final values in Eq.(5.18) gives,

$$V = 1{\cdot}1 \times 10^{-4} E \left(1 - 3 \times 10^{-4}\right) \text{ volts} \qquad (5.21)$$

Hence a 10% change in the nominal value of ω produces a .03% change in V.

5.3 Effects of Air-earth and Precipitation Currents.

Consideration must now be given to the effects of vertical atmospheric currents on the field mill.

Rarely do precipitation currents exceed 10^{-9} A/m^2 and in any case when such large currents occur they are usually accompanied by large fields so that the percentage error due to them can be kept small. If the effects of a current of 10^{-9} A/m^2 are small then no trouble should be experienced with the air-earth current, for this is usually very much less.

In the ideal case the vertically flowing current is modulated by the rotor at a frequency equal to that of the exposure-screening cycle. The resultant stator current then consists of an alternating component superimposed on a direct component. Consider first the effect of the alternating component.

During any half-cycle the total precipitation current flowing into the stator is,

$$j\left(r_2^2 - r_1^2\right)\frac{N\omega t}{2}$$

where j is the precipitation current density. Hence the total charge flowing into the stator during one half-cycle is,

$$Q = j\left(r_2^2 - r_1^2\right)\frac{N\omega}{2}\int_0^{\frac{\pi}{N\omega}} t\,.\,dt = \frac{\pi^2 j}{4N\omega}\left(r_2^2 - r_1^2\right) \qquad (5.22)$$

Assuming that only a negligible quantity of this charge leaks away during the half-cycle, then the voltage change across C is Q/C. Further, it can be shown that the peak-peak voltage of the alternating component never exceeds Q/C. Using Eq. (5.22) this voltage can be expressed in terms of an equivalent steady field Ej, where Ej is given by,

$$E_j = \frac{\pi j}{2\epsilon_0 N\omega} \qquad (5.23)$$

This result reveals yet another advantage in using a high rotor speed for the relative effect of precipitation currents is inversely proportional to ω. Substituting instrument values in Eq.(5.23) we find that a current of 10^{-9} A/m^2 produces an output which is equivalent to that produced by a field of less than 1v/m.

The steady direct current that flows through R is given by

$$I_j = \frac{\pi j}{4}\left(r_2^2 - r_1^2\right) = 3\times10^{-3}\,j$$

As the effect of this current is precisely the same as that due to the grid current of the first valve, then obviously j must reach extremely large values before its effects override those of the grid current (5×10^{-11}A).

It must be stressed at this point that the preceeding discussions probably have little application to practical conditions. The high rotor speed of the mills must cause considerable disruption of the lines of current flow in the vicinity of the stator. In fact the rotor presents an almost impenetrable barrier to the average size raindrop. This is another point in favour of high rotor speeds but on the other hand it would be very unfavourable if these high speeds resulted in the generation of charge in the vicinity of the stator when the raindrops are shattered(Lenard Effect).

As individual drops must occasionally penetrate to the stator, it is well to make some determination as to their effects. On falling onto the stator the drop will give rise to a voltage pulse of peak amplitude q/C, where q is the drop charge. This voltage will then decay with a time constant of RC(.025)secs. If this pulse is transmitted through all the units of the mill without attenuation, then the recorded pulse will have a peak amplitude, the value of which may be expressed in terms of equivalent steady field Ed, where Ed is given by,

$$E_d = \frac{4q}{\pi \varepsilon_0 (r_2^2 - r_1^2)} \qquad (5.24)$$

Under conditions of no point discharge,i.e., E<500v/m, a drop rarely carries a charge which exceeds 10^{-13}C(3×10^{-4}esu)(Chalmers and Hutchinson(1951)). If $q=10^{-13}C$, then from Eq.(5.24), Ed= 4.0v/m. In practice however, d.c. pulses are considerably attenuated by the rectifier, so this theory only represents the maximum possible errors due to individual drops.

5.4 The Phase-sensitive Rectifier.

a) The Schuster Circuit.

In the last section it is shown that the mill proper generates an alternating voltage, the amplitude of which is proportional to the magnitude of the applied field. In this section the phase-sensitive rectifier is described and this unit determines the sign of the field.

In the past, other workers have used one of three main methods for this sign determination. The most popular method has been that of mechanical rectification, using either cam operated switches or a commutator like that of Kirkpatrick and Miyake(1932). In view of the fact that the motor speed is over 5,000r.p.m. it was felt that mechanical rectification might prove unreliable if applied to the present mills. Phase discrimination may also be obtained by the algebraic addition of the signal voltage to a reference voltage of fixed amplitude, Rangs(1942). However, this method involves the difficulties associated with building a reference generator with the necessary voltage stability and under certain conditions may give an output that is ambiguous in sign.

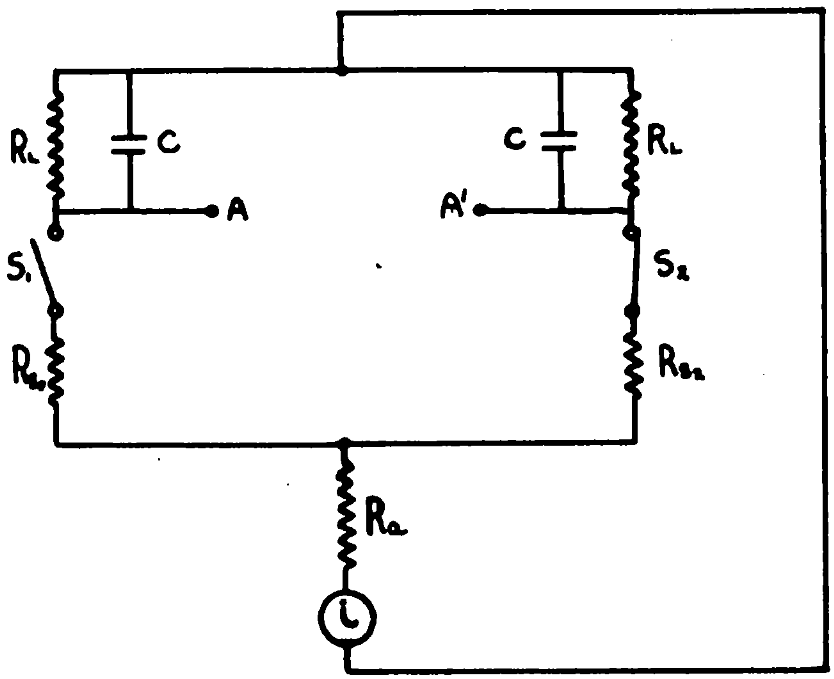


Fig.4 The Schuster Circuit - Equiv. Diagram.

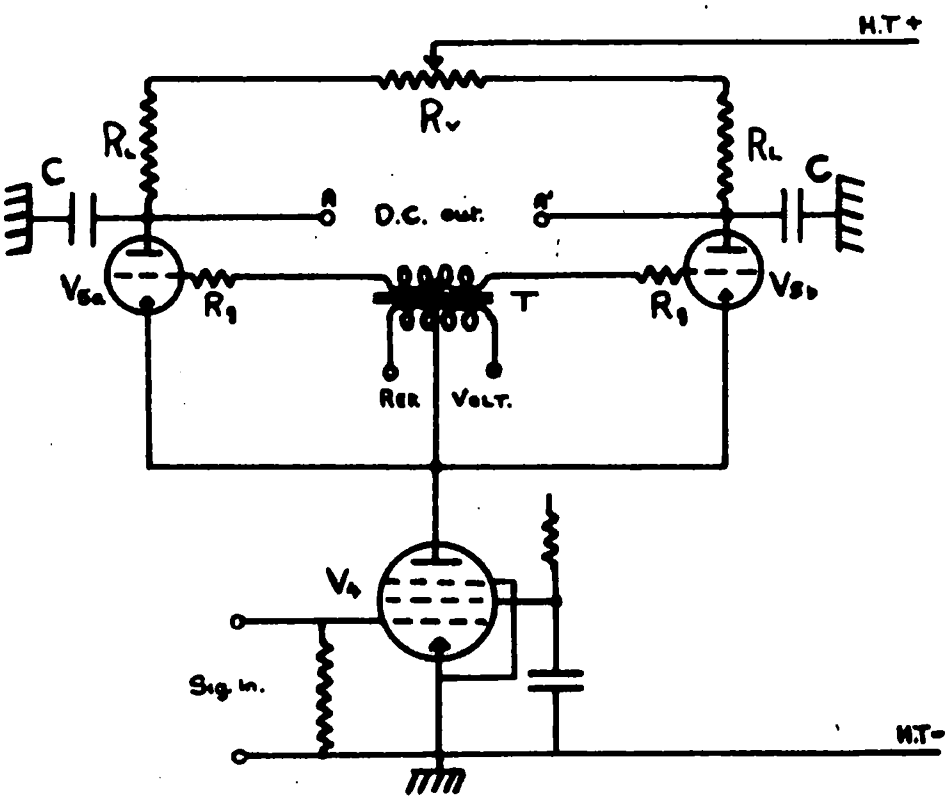


Fig.5 The Schuster Circuit - A Practical Form.

The third method involves electronic switching and this is the system used in the present case.

The application of electronic phase-sensitive rectification to field mills appears to have been initiated by Mapleson(1953) and it is felt that this technique is worthy of further development. From the many published phase-sensitive rectifier circuits the one that appears best suited to the present needs is that of Schuster(1951). All the "push-pull" circuits considered contained some form of "twin-section", for example, the circuit at some point divided into two similar arms. Generally differences between the electrical characteristics of these circuit arms lead to errors in the form of non-linearity or zero-drift. However, the Schuster circuit has been designed so as to keep these errors small.

Fig.4 gives the equivalent circuit of the Schuster rectifier and its mode of operation is as follows. Let i be the output current from the mill amplifier, where i varies periodically with an amplitude proportional to field strength. When in the closed position the two switches S_1 and S_2 have a resistance Rs_1 and Rs_2 respectively. When the mill stator is fully exposed to the field, S_2 is open while S_1 is closed. When the stator is fully screened the switch positions are reversed. For a positive electric field let i be at a maximum value when the stator is exposed so that with the stator screened, i is at a minimum. Hence, as the rotor rotates, positive half-cycles of current flow up the lefthand arm and negative half-cycles down the righthand arm. If this sequence of events is rapidly repeated and the smoothing adequate, then a steady current will flow up one arm and down the other. Hence the potential difference that will exist between points A and A' is directly proportional to i(hence field strength) and the sign of this p.d. will change with a change in sign of the field.

Alterations in the value of the switch resistance Rs might give rise to non-linearity or zero-drift. This danger has been avoided by Schuster by introducing a common series resistor Ra, where $Ra \gg Rs$, so that the current in the switching arms depends primarily on Ra and only to a small extent on Rs.

Fig.5 shows a practical form of the rectifier. V_4 is a high impedance pentode(ra=1MΩ) and replaces Ra of Fig.4 , V_{5a} and V_{5b} are the switching triodes(ra=7KΩ). The reference voltage is fed to the primary of the switching transformer T, the secondary of which is arranged so that when one triode is cut-off the other is conducting. R_L are the fixed components of the anode load, whilst Rv permits the adjustment of the d.c. output level. Grid currents, limited by Rg , flow in closed loops so do not affect the output. Similarly, normal changes in H.T. voltage are balanced out within the circuit. An additional advantage of this type of rectifier

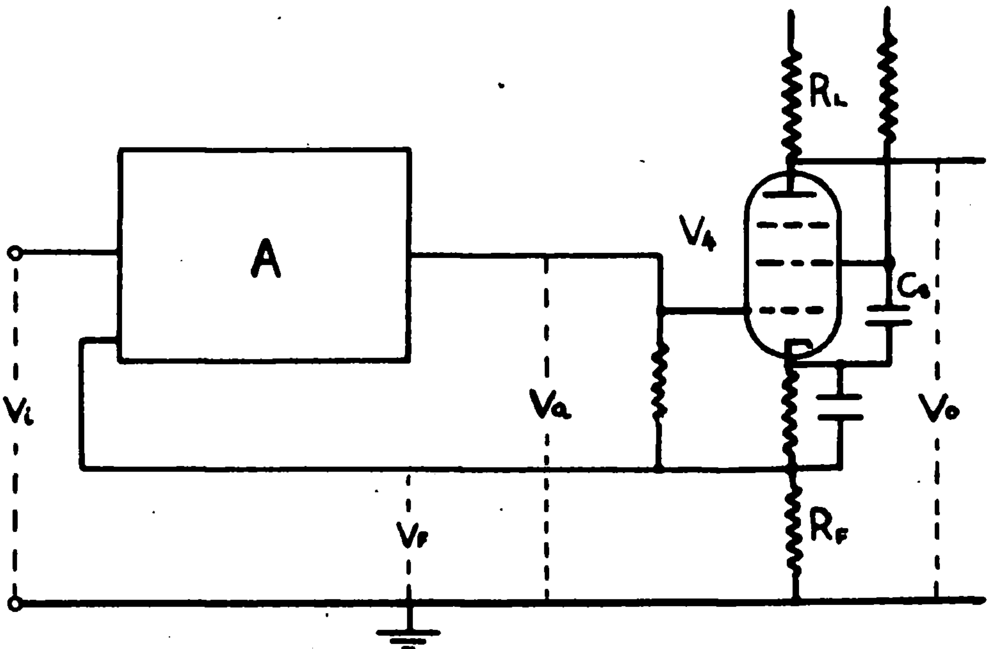


Fig.6 <u>The Inclusion of the Schuster Circuit into a Feedback Loop.</u>

is that the signal is amplified in the process of rectification.

b) The Modified Schuster Circuit.

As the output from the mill proper requires amplification before the signal can be fed to the rectifier, then if only for reasons of gain stability, a negative feedback amplifier is called for. The primary purpose of the feedback system is to stabilise the signal current in the anode circuit of V_4 against both changes in the properties of the amplifier and in the characteristics of V_4 itself. Hence, the feedback voltage V_f must be proportional to the signal current in V_4. The simplest way of deriving this voltage is to insert an undecoupled resistor in the cathode lead. As the alternating component of the cathode current in V_4 consists of both anode and screen currents, it is desirable that the screen current should not flow through the feedback resistor. To avoid this difficulty a screen decoupling capacitor Cs is inserted as shown in Fig.6.

The inclusion of part of the rectifier into a feedback network improves its performance as may be shown in the following manner.

Let there be an amplifier of gain A coupled to the rectifier as shown in Fig.6. Also let,

V_i = Applied Input Voltage.

V_a = Amplifier Output Voltage.

Vo = Final Output Voltage.

Vf = Feedback Voltage.

If $V_f = -\beta V_o$, then β is the fraction of the output voltage that is fed back to the input in reverse phase. Fig.6 gives the equivalent circuit of the V_4 stage and the stage gain may be written directly as,

$$\frac{V_o}{V_a} = \frac{\mu R_L}{R_a + R_s + R_L + R_f(1+\mu)} \qquad (5.25)$$

where μ and Ra are the amplification factor and the anode impedance of V_4, respectively. The effective input voltage to the amplifier is,

$$(V_i + V_f) = (V_i - \beta V_o)$$

Hence, $$V_a = A(V_i + V_f) = A(V_i - \beta V_o) \qquad (5.26)$$

Combining Eqs.(5.25) and (5.26) the overall gain with feedback is given by,

$$G_f = \frac{V_o}{V_i} = \frac{A\mu R_L}{R_a + R_L + R_s + R_f(1+\mu(1+A))} \qquad (5.27)$$

As mentioned previously, the advantages of the Schuster circuit result from the introduction of a common series resistor of magnitude much greater than that of the switch resistance Rs. Before the inclusion of the rectifier into the feedback loop, this common resistor had a value Ra. Having included the rectifier into the loop, Eq.(5.27) shows that this series resistor has been supplemented by the extra term $R_f(1+\mu(1+A))$. With $A = 10^3$, $\mu = 10^3$ and $R_f = 10\Omega$, this new impedance has a value of about $10^7\Omega$ so that the effect of changes in the impedance of the switching valves(Rs) on the rectifier are further reduced by the feedback arrangement.

5.5 The Reference Generator.

The ideal reference voltage generator for the Schuster rectifier should provide a square-wave output of about 10-20v peak. This output must be synchronised with the signal voltage of the mill, with provision for varying the phase relation between signal and reference voltages.

Two types of generator were considered, the electromagnetic type and the electrostatic. There is little doubt that the electromagnetic type would have proved the more reliable but owing to the restricted space available in the Head Unit, its construction may have proved difficult. On the other hand, the choice of an electrostatic type facilitated easy design and construction. Previously, Schwenkhagen(1943), electrostatic generators have been built in the form of a small field mill operating in a fixed field. However, if the main mill and the reference mill are on the same shaft and share the same earthing brush, there is the danger of electrical interaction occurring between the two mills. To avoid this, the present generator is designed so that it is electrically isolated from the motor and does not require an earthing brush.

Fig.7 shows the principle of operation of the generator. If q is the charge on the condenser at time t, then,

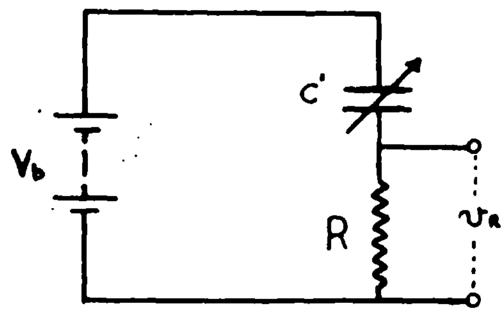


Fig.7 The Reference Generator - Equiv. Circuit.

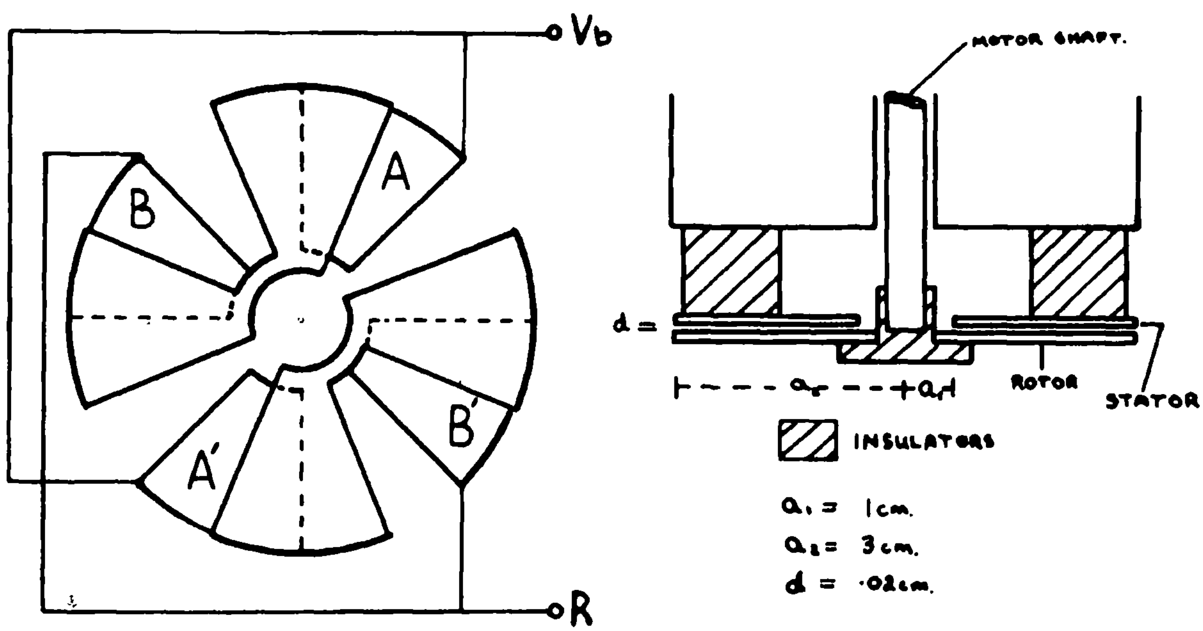


Fig.8 The Reference Generator - Construction.

$$V_b = \frac{q}{c'} + R\frac{dq}{dt}$$

Let c' increase linearly with time such that c'=Ct, then,

$$V_b = \frac{q}{Ct} + R\frac{dq}{dt}$$

The solution of which is,

$$q = \frac{V_b Ct}{1+RC} + \text{Const.}$$

Hence,

$$i = \frac{V_b C}{1+RC}$$

and (5.28)

$$v_R = V_b.C.R. \quad \text{if} \quad RC \ll 1$$

A practical arrangement based on the above principle is shown in Fig.8 . Vanes AA' and BB' form the generator stator. Vanes AA' are connected to the positive H.T. supply, whilst vanes BB' are connected to the negative line(earth) by the resistance R. The rotor consists of four vanes similar to those of the stator, except that adjacent vanes are connected to form two electrically isolated pairs. Any change in the capacitative linkage between the A and B vanes of the stator will result in a current through R. Such linkage changes occur when the rotor rotates. The capacitance between the A and B vanes is represented by c' in Fig.7 and as c' increases and decreases four times for every revolution of the motor shaft, there appears across R an alternating voltage which is in synchronism with the signal voltage.

As,

$$C = \frac{\epsilon_0 N \omega}{2d}\left(a_2^2 - a_1^2\right) \qquad (5.29)$$

then from the dimensions given in Fig.8 ,

$$C = 4 \times 10^{-9} \text{ farads/sec.}$$

With $R = 3M\Omega$ and $V_b = 260v$, then from Eq.(5.28), $V_R = 3v$ and $RC = 1.2 \times 10^{-2}$ secs. As this voltage is rather too small to be applied directly to the grids of the switching valves, a switching transformer is used which has a turns ratio of 1:3, so that the actual voltage applied to the grids of V_{5a+b} is about 10v.

The phase relation between V_R and the signal voltage depends on the relative angular position on the motor shaft of the reference and main rotors. If the main rotor is screwed firmly to the motor shaft, then the correct phase relation can be established, merely by adjusting the position of the reference rotor.

5.6 The Amplifier.

The most suitable form of recording instrument for the field mills would be a multi-channel penrecorder but although this was not available for the present work, the amplifier is designed to drive such an instrument. A comparatively large power output has other advantages, for example, the rectifier is more reliable at large signal voltages and the output can be monitored with a robust moving-coil meter.

The amplifier gain with feedback is given by Eq.(5.27), which may be written in the form,

$$G_f = \frac{R_L}{R_f}\left(1 - \frac{R_a + R_s + R_L}{A.\mu.R_f}\right) \qquad (5.30)$$

$$\text{if} \quad \frac{R_a + R_s + R_L}{A\mu R_f} \ll 1$$

It will be noticed that as $A \to \infty$ so $G_f \to \frac{R_L}{R_f} = \frac{1}{\beta}$. This result satisfies the general equation of the effect of negative feedback on an amplifier, for under certain limiting conditions the gain becomes dependent solely on the values of certain resistors and virtually independent of the valve or supply characteristics.

To achieve the requisite gain stability it is necessary that,

$$\frac{R_a + R_s + R_L}{A\mu R_f} \simeq \frac{1}{A g_m R_f} < 5 \times 10^{-2}$$

This ensures that changes in A or g_m have only a negligible effect on the overall gain. Knowing the value of R_L/R_f from the choice of gain and the value of g_m, the value of A(gain without feedback) can be determined. This was found to be not less than 700, a value easily achieved by using two valve stages prior to the rectifier.

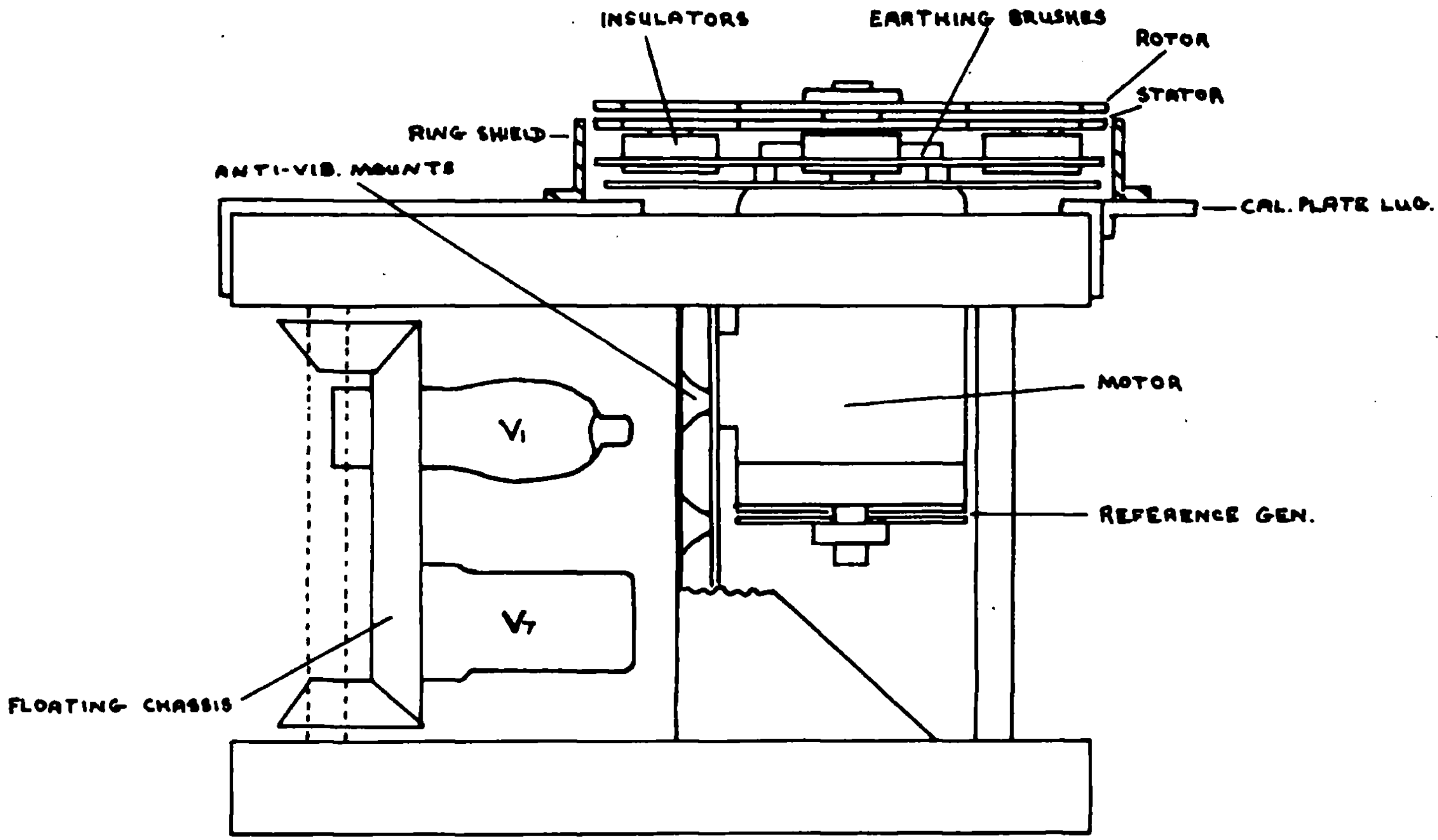
No mention has yet been made of the required frequency response of the amplifier. The Fourier series for a triangular wave may be represented by,

$$y = \frac{8K}{\pi^2}\left(\cos x + \frac{1}{9}\cos 3x + \frac{1}{25}\cos 5x \ldots\ldots\right)$$

From the values of the co-efficients it is obvious that only the fundamental and first harmonic are of primary importance, hence a flat frequency response between 300 and 1000cps should be adequate. It was thought that the large feedback factor employed would ensure this response.

In designing the circuit details of the amplifier special consideration was paid to the value of both gain and phase-shift at all frequencies, for it is important that at all frequencies $|A||\beta| < +1$ (Nyquist Criterion) otherwise positive feedback occurs and the circuit becomes oscillatary.

Fig.9 The Head Unit and Calibrating Plate.



HALF ACTUAL SIZE

Fig.10 The Head Unit.

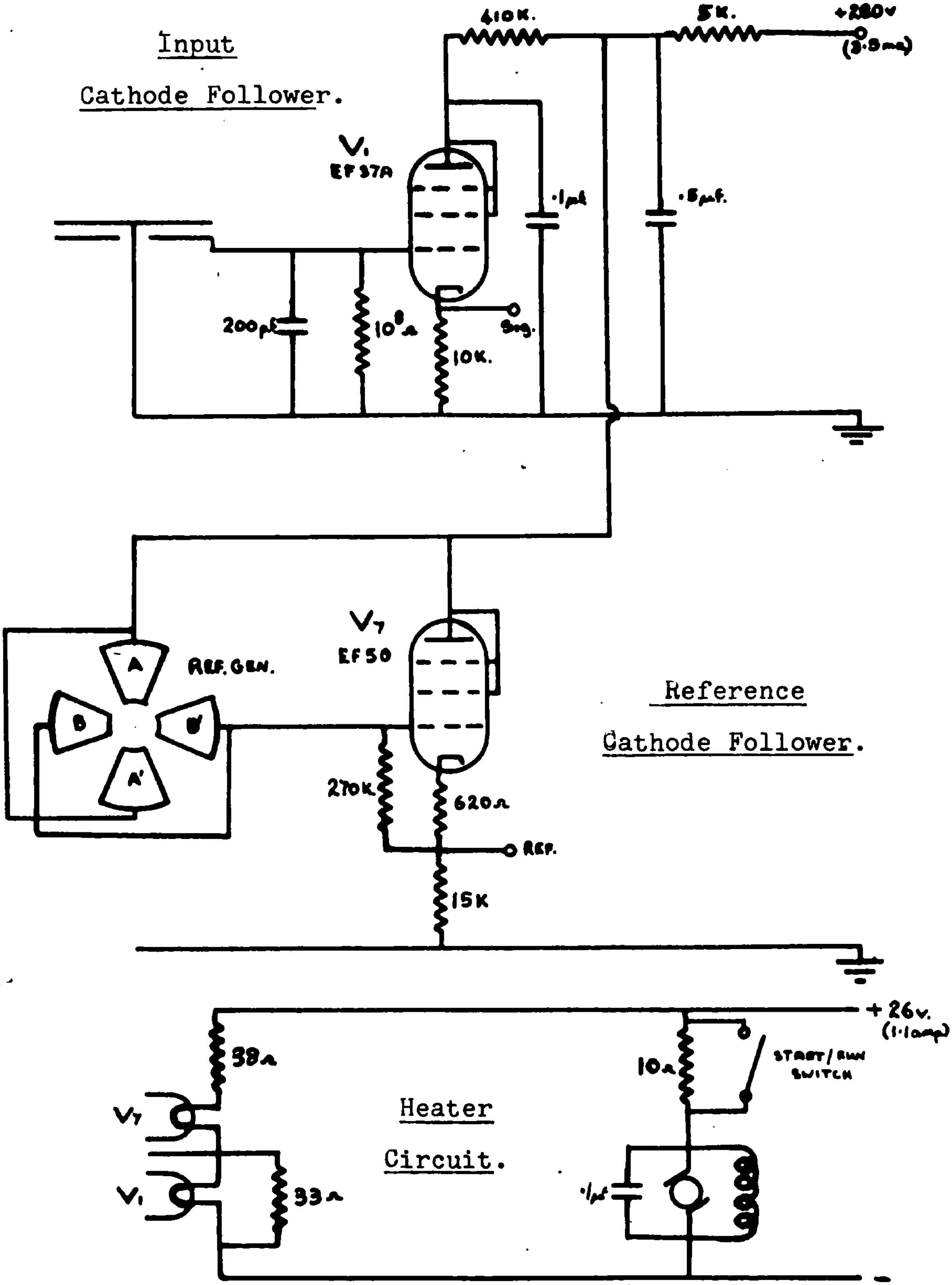
6. THE FIELD MILL - CONSTRUCTIONAL DETAILS AND PERFORMANCE.

6.1 The Head Unit.

When choosing a suitable motor for the Mill it was felt that in the long run it would be better to use a low voltage d.c. motor which would operate from batteries and hence avoid the danger of 50 cps pick-up by the stator. A suitable motor was found in a Government surplus 27v. shunt-wound motor, its double ended shaft giving a 1.7oz/in. tourque at 5,700 r.p.m.

Figs.9 and 10 show the salient feature of the Head Unit. A steel cradle serves both to hold the motor in a vertical position and to act as an electromagnetic screen between the valves and the motor. To reduce the effect of motor vibrations on the adjoining valves, it is mounted on four anti-vibration mounts. The upper shaft of the motor carries the main rotor, the lower shaft the reference generator rotor. Both the main rotor and stator are made from 16g. chromium-plated brass sheet. The stator is mounted on four polystyrene insulators shaped so that their surface leakage path is large. All four insulators are protected from driving rain by an aluminium ring-shield, whilst additional protection is provided by surrounding each insulator by a short polystyrene tube.

Two spring-loaded carbon brushes bearing onto a copper collar screwed to the motor shaft form the earthing device. One brush was found to be inadequate because of slight



Input
Cathode Follower.
410K.
5K.
+280v
V1
EF37A
·1μf
·5μf.
200pf
10K.
Sig.
V7
EF50
REF. GEN.
A
B
B'
A'
Reference
Cathode Follower.
270K
620Ω
REF.
15K
+26v.
(1·1amp)
33Ω
10Ω
START/RUN
SWITCH
V7
V1
Heater
Circuit.
33Ω
·1μf

Fig.11

eccentricities in the shaft.

Additional anti-vibration precautions are taken by mounting the two valves contained within the Head Unit on a small floating chassis suspended within the main framework by four light springs.

Each side of the main framework is covered by a detachable panel in order to facilitate easy maintenance. When assembled, the Unit forms a rectangular box of 25x15x15cm.

6.2 The Input and Reference Cathode Followers.

By virtue of its good anti-microphonic properties, the Mullard E.F.37A was chosen for the input cathode follower. Operated as a triode at reduced heater and anode potentials, the grid current may be reduced to a sufficiently low value.

Using the values of the various circuit elements as given in Fig. 11, the stage gain is approximately 0.8, with an output impedance of 2,000Ω. The 60m. of co-axial cable connecting the Head Unit to the amplifier presents a reactive load to the cathode follower of 120KΩ at 300 cps. A 10% change in motor speed produces a corresponding change in load impedance and hence a 0.2% change in signal voltage amplitude. The purpose of the cathode follower is, of course, to isolate the stator from the cable capacity.

In order to keep the cable weight low, the 27v. supply line to the Head Unit supplies both the motor and the valve

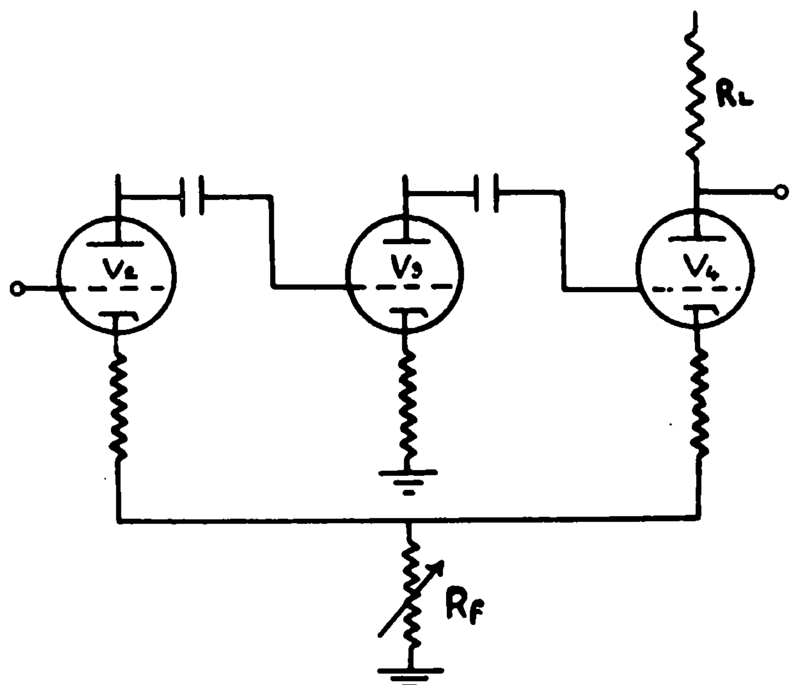


Fig. 12 The Amplifier - Simplified Circuit.

heaters. This method has the additional advantages that no 50 cps supplies are fed to the Unit. As the reference generator has a very high output impedance, it is necessary to isolate the generator from the load presented by the connecting cable. Fig.11 shows the conventional cathode follower circuit used. The effective resistance of R is about 3MΩ due to its inclusion into the negative feedback loop of the valve.

6.3 The Amplifier.

Fig.12 shows a simplified circuit of the three stage negative feedback amplifier, the negative feedback is applied by introducing a common cathode load Rf into the cathode leads of V_2 and V_4. As the gain with feedback is approximately inversely proportional to the value of Rf, the different values of gain are obtained simply by the alteration of this resistor.

Fig.13 shows the amplifier circuit in detail. The amplitude of the signal voltage fed to the amplifier is controlled by an input potentiometer which selects various fractions (1/1, 1/2, 1/6, 1/10, 1/∞, (earthed)) of the signal voltage that is developed by the Head Unit. In general the circuit is conventional for an audio frequency amplifier. To combat oscillation the first stage is designed so that its band pass is wide, whereas the second stage has a comparatively narrow band pass, Terman(1943). S_2 is the gain selector

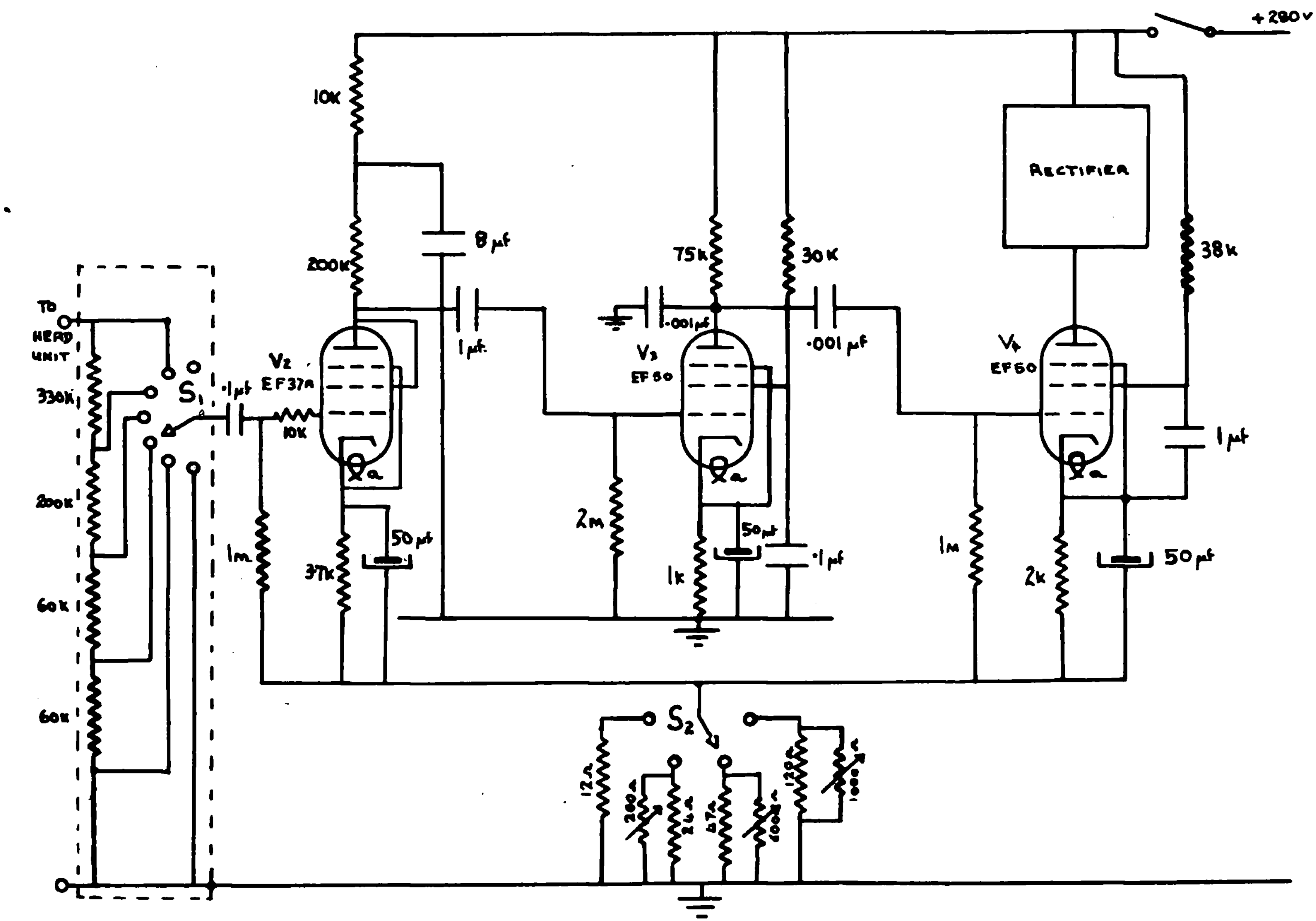


Fig.13 The Field Mill Amplifier.

and for the values of Rf given in Fig.13 the d.c. output from the rectifier is approximately ±30v for applied fields of ±50, ±100, ±200, ±500v/m respectively. The '50' gain position was seldom used because it is not reliable. If the gain control is set at the '500' position and if the fraction of the signal fed to the amplifier is selected by means of the input potentiometer, the full scale meter deflection can be obtained for fields of ±500, ±1000, ±3000, ±5000v/m. By combining the two selector switches, a large degree of sensitivity control is available, so ensuring the maximum possible deflection for a wide range of field strengths and hence a greater accuracy in the measurement of time delays.

Two identical amplifiers are built onto the one chassis and share the same power supplies. There appears to be no appreciable interaction between the two circuits.

6.4 The Phase-sensitive Rectifier.

This has been discussed in principle in 5.4 and the transformation from paper to practice was quite straightforward. Some care had to be exercised in choosing a valve suitable for the switching duties, for particular characteristics are called for. It is important that the differential characteristics between the two triodes remain as small as possible and each triode must have a low anode impedance. Possible differential characteristics are minimised by using

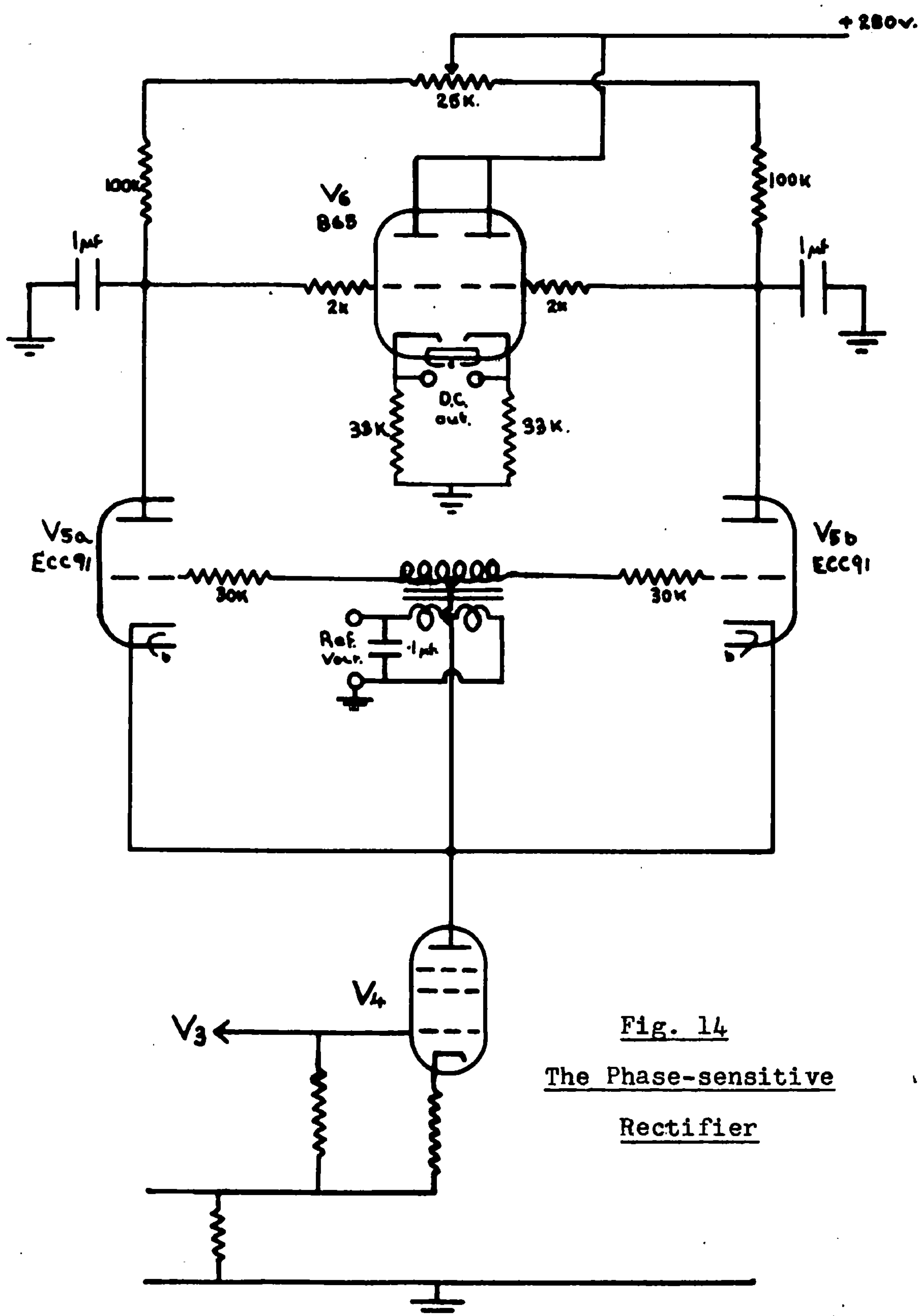


Fig. 14

The Phase-sensitive Rectifier

a double triode valve with a common cathode as found in the Mullard ECC 91(ra•7KΩ).

The switching transformer was picked from stock and operates with its primary tuned to 300cps in order to attenuate the unwanted frequencies produced by the reference generator.

On the output side of the rectifier the ripple is filtered off by the condensers which shunt the anode loads. The time constant of the field mill as a whole is primarily dependent on the values of these capacitors and the anode load resistors and with the values given in Fig.14 the response time is about 0.1sec.

As the output impedance of the rectifier is too great to operate a robust meter directly, an output cathode follower stage had to be added, giving a final maximum output voltage of 25v into 2,000Ω.

6.5 Power Supplies.

A modified ex-R.A.F. power unit is used to supply the H.T. and heater currents. Modifications to the unit consisted of replacing the original power transformer with one of larger secondary output voltage and a voltage stabiliser was added. After modification, the unit supplied H.T. current at 280v±5v for the current range of 0-50ma.

Fig.15 gives the circuit details of a specially

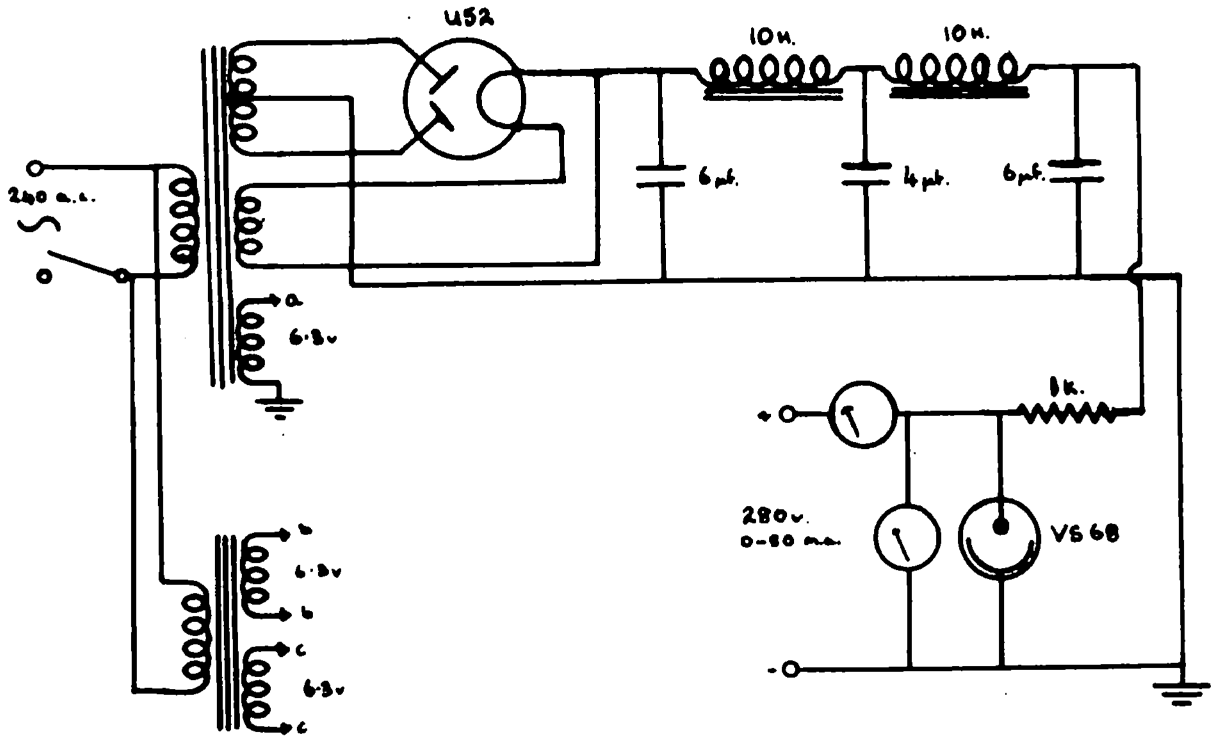
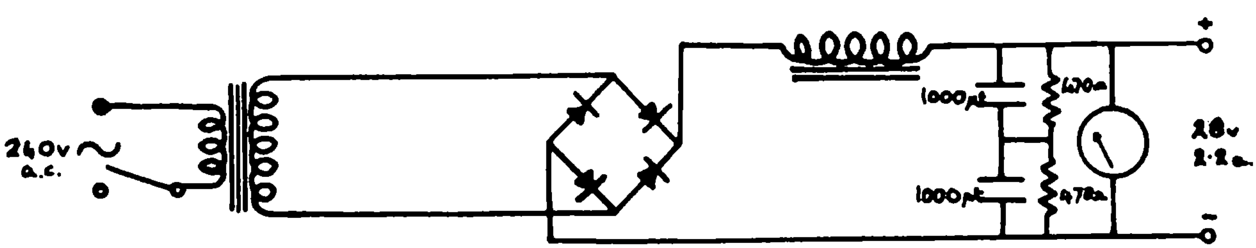


Fig. 15 The Power Supplies



constructed low voltage d.c. power unit which supplies the Head Units. The circuit shows the orthodox arrangement of a power transformer and metal rectifier to give 28v, 2.2A unstabilised output.

In the event of the instruments being required to operate away from mains supplies, the two power units may be replaced by a 28v battery supply. By rewiring the valve heaters in a series-parallel arrangement they may be connected direct to the 28v supply and the H.T. voltage may be derived from a 28v Dynamotor.

6.6 Performance and Calibration.

In general, laboratory tests on each unit of the field mill showed their performance to be satisfactory. It is proposed therefore, to discuss only the short-comings of the instrument and factors in its behaviour which were unexpected.

Fig.16 shows a typical graph relating output voltage and applied field strength. Some non-linearity is evident but this is reduced at lower sensitivities, for when the applied field is small, the signal waveform is distorted. From Fig.16 it is seen that when the applied field is zero the output corresponds to a field of about -20v/m(all field strengths are given for the mill operated flush with a large conducting surface). This spurious output is probably due to a contact

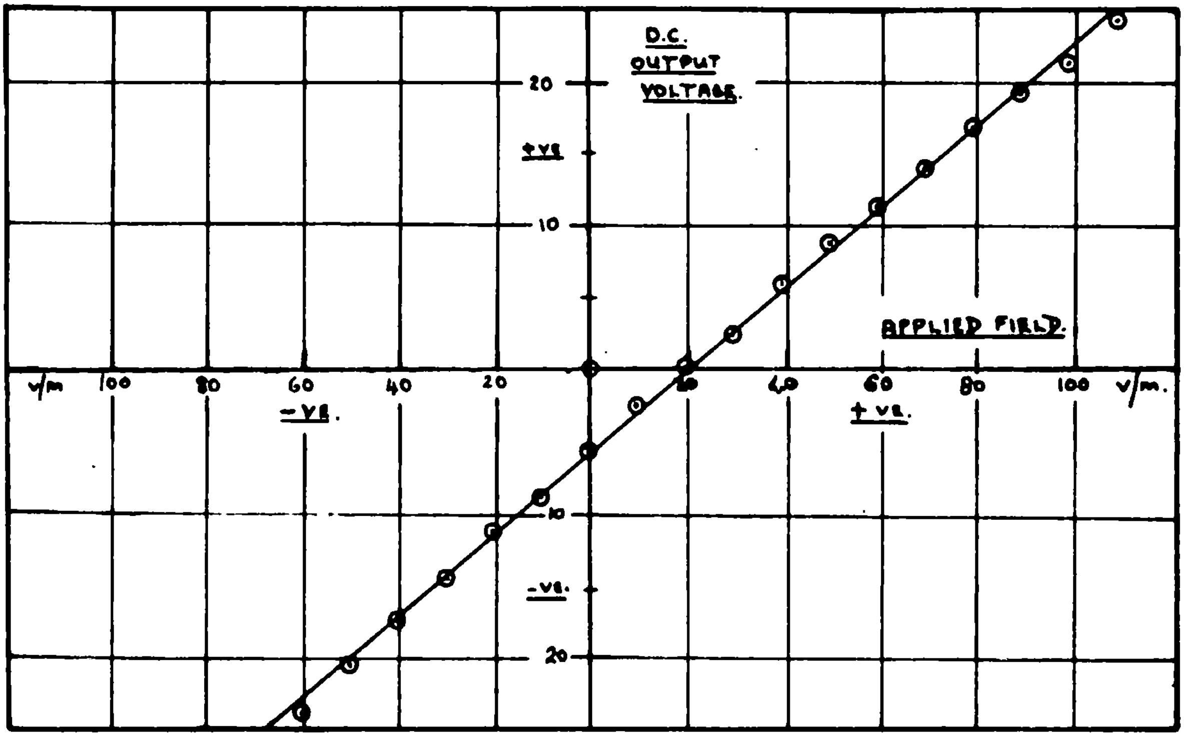
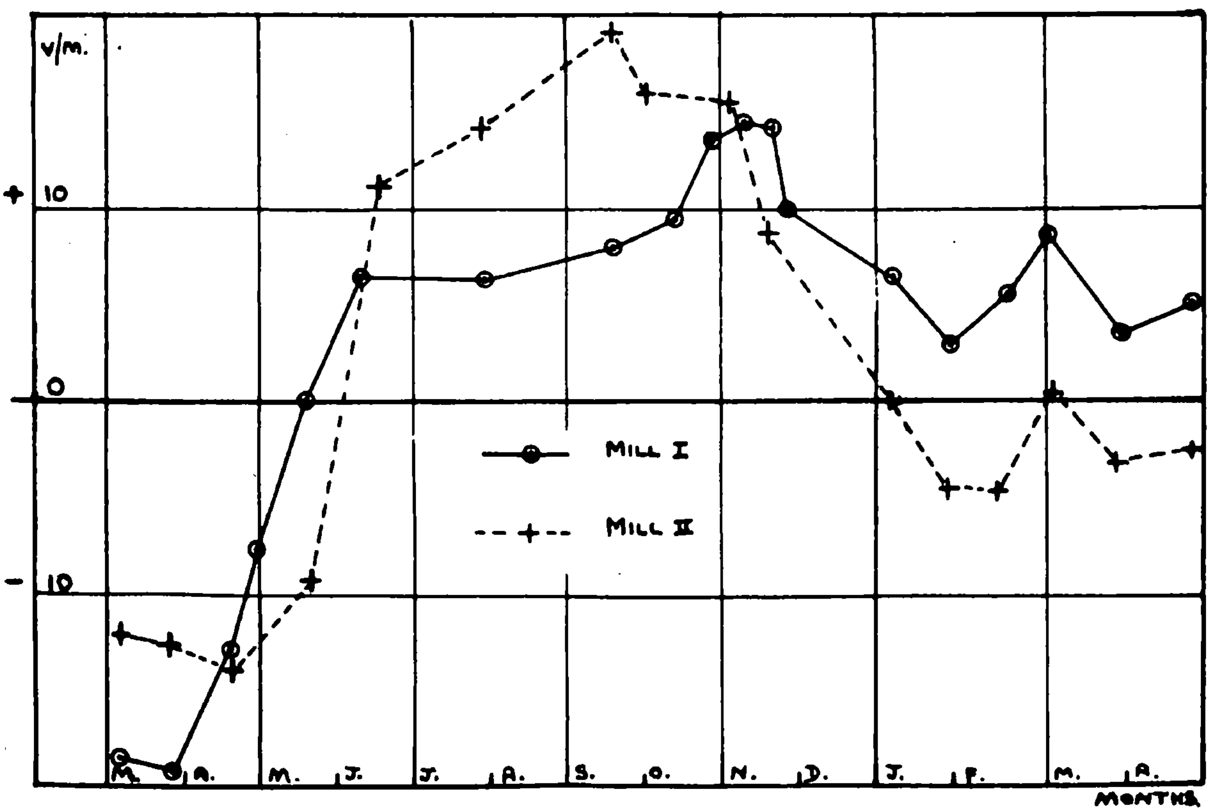


Fig.16 A Mill Calibration Curve.

Fig.17 Variation of Spurious Output with Time.



potential difference between the surfaces of the rotor and stator vanes and existed despite the fact that both sets of vanes were chromium plated, following the practice of Lueder (1943). Known fields may be applied to the mills by means of a calibrating plate which fits into lugs built onto the Head Unit. This plate was also plated with chromium and when earthed the field between it and the stator was <1v/m.

At about fortnightly intervals the spurious output was measured and Fig.17 shows the interesting variation of this output with time. Presumably the variations are due to changes in the surface properties of the plating. No short-term effects could be attributed to rain contaminating the plating and no change in the output occurred when alternate earthing methods were tried.

Although the amplifier proved satisfactory, the performance of the rectifier failed to live up to all the design expectations. It had been anticipated that the output voltage would be virtually independent of reference generator voltage but in practice it was found that the output varied by about 10% at full scale deflection for a 20% change in V_R. This defect is probably due to two causes; the amplitude of reference voltage is too small, and the two halves of the secondary winding of the switching transformer are not capacitatively balanced with respect to earth, resulting in grid waveforms which are not quite in quadrature. Fortunately the reference generator is fed from a stabilised H.T. source so that variations in its output are small. Occasionally the reference voltage would fluctuate violently and the trouble was traced to particles of dirt between the generator vanes. This trouble was easily identified and remedied by cleaning.

Both mills operated satisfactorily in all weather conditions except those of heavy thunderstorm rain, when the insulation generally broke down. During very heavy rain the output appears"grassy" due to the effect of drop charges and the momentary bridging of the main rotor and stator by raindrops. The above defects were not serious and if future work requires the mills to be used in heavy rain they may be operated in the inverted position.

The main performance characteristics of the mills may be summed up as follows:- Noise level in the frequency range 10 - 0.1cps is 0.5v/m. Drift $\simeq$ 2% in the first hour. For an applied field of 50v/m the maximum d.c. output available is 26v which corresponds to a galvo. deflection of 10cms. Linearity better than 2% at mid-scale.

There seemed to be no better test of the mill's performance than to watch their behaviour under actual operating conditions. The two mills, separated by over 100m, generally indicated field variations which agreed to within a few percent, yet were displaced in time by an amount which depended on the wind velocity.

Although the nature of the present investigation does not call for an accurate measurement of the absolute value of the earth's electric field, it is necessary to know approximate values. In fact, only approximate values were available because each mill was operated at any one of five different sites at which the exposure factor averaged about 0.8 and varied by about ±15% as the seasons passed.

A rough calibration at one site was made by comparing the field strength as indicated by a mill with the potential gradient as measured by a potential-equaliser method. In order to measure the potential of the wire an electronic electrometer, similar to that of Brewer(1953), was constructed. Both the wire and the mill were set-up at the one site and the outputs from the mill and the electrometer were simultaneously recorded on the mill camera. Hence it was a simple matter to express mill output voltage in terms of absolute potential gradient. In view of the variability of the exposure factors of the various sites, the field strength quoted in the subsequent sections may be in error by 20%, compared with true absolute values.

The potential equaliser used was a glowing fuse of string which had previously been soaked in Lead Nitrate

Amplifier.

Field Monitoring
Meters.

Head Unit.

Fig. 18 The Field Mill Units.

and dried. It is interesting to note that such an equaliser is not very suitable for investigations aimed at studying the fine structure of small fields, for it was found that as smoke-puffs left the fuse the potential of the wire might change by as much as three volts.

7. OTHER APPARATUS AND EXPERIMENTAL ARRANGEMENTS.

7.1 The Dines Anemometer.

As the measurement of wind speed played an important part in the present investigation, a brief description of the anemometer is given and its errors are discussed.

The Dines Pressure-tube Anemometer formed part of the meteorological equipment of the University Observatory and was used continuously to supply information for the Meteorological Office Climatalogical Reports, consequently the present work had to be carried out without interrupting its normal duties or without altering its exposure.

a) Principle of the Instrument.

A freely swinging wind vane carries in its nose an open-ended tube in which the pressure increases when air impinges on the tube opening. Below the pressure head is a fixed perforated pipe in which there is a pressure reduction due to the air flow past the pipe. The pressure difference between the air in the pressure head and the air in the suction head is measured by means of a sensitive water and float manometer. If ΔP is the pressure difference then,

$$\Delta P = \frac{1}{2}(1+k)\rho V^2$$

where V is the velocity of the air flowing past the heads, ρ the air density and k a non-dimensional constant($\simeq 0.5$) which governs the contribution to ΔP made by the suction head. The shape of the float is so designed that its vertical

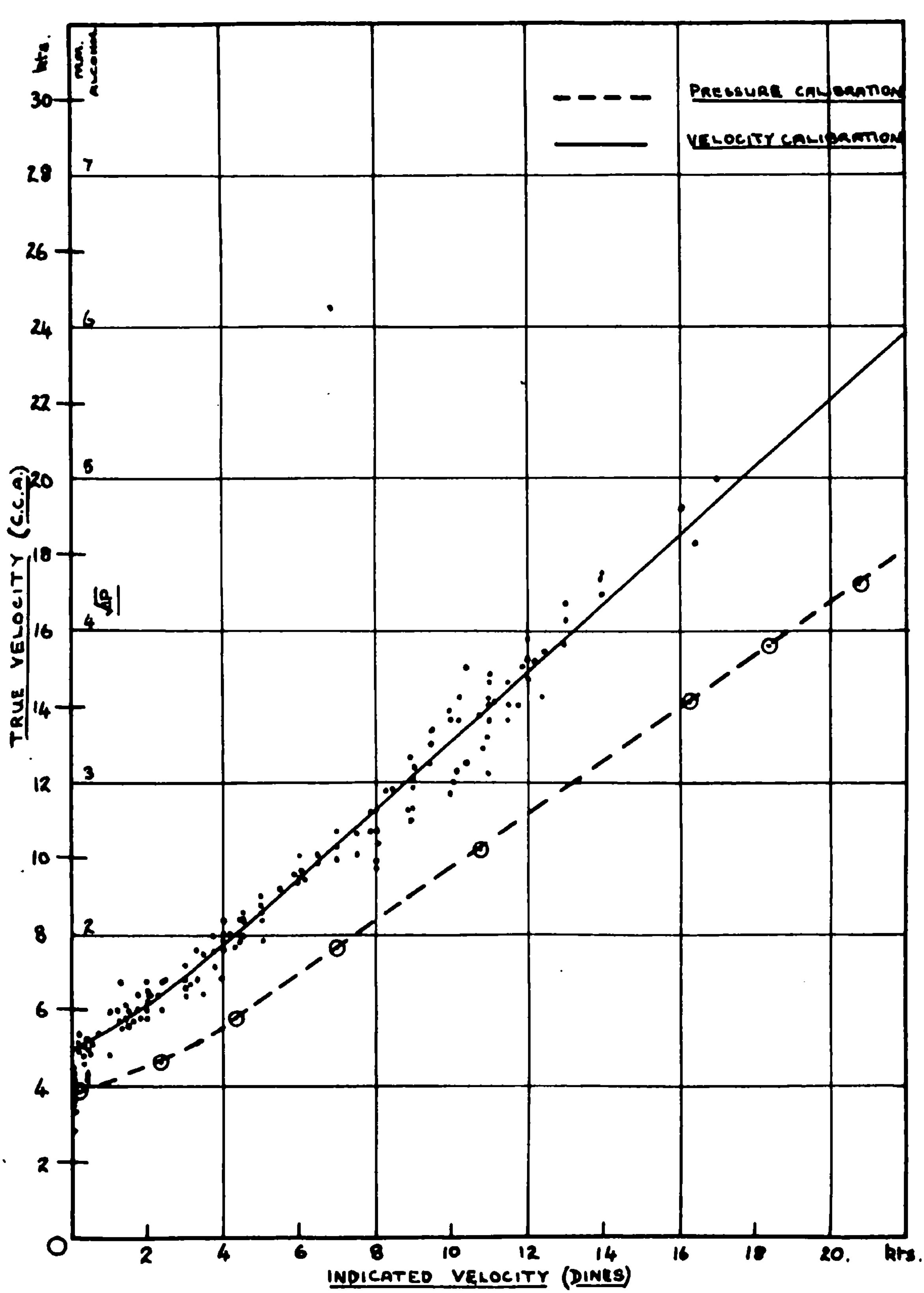


Fig. 19 The Dines Calibration.

displacement is proportional to $\sqrt{\Delta P}$, hence proportional to V. Float displacement is recorded by pen on a paper chart, the scale being 1.3cm=10kts and 1.5cm=1hr. For a more detailed description of the instrument see the Met. Office Observer's Handbook(1952).

The Observatory instrument was 18.5m(56ft) above ground level but its effective height, according to the Met. Office, was 10m(33ft). In general, the exposure of the anemometer was good, for the vane dominated all other objects for many kilometres around.

b) Calibration.

As the investigation progressed it became increasingly obvious that certain anomalies in the results could be removed if the anemometer was assumed to have a zero error of about 2m/sec. It was therefore desirable that an accurate calibration be made, for if the anemometer readings were taken uncorrected a wrong interpretation might be made as to the location of the electric charges.

The first calibration was one of float displacement against pressure, Fig.19 , and this showed that a zero error did in fact exist. As a further check a direct calibration in terms of true airspeed was carried out by comparing the velocity as indicated by the Dines with that given by an anemometer of known calibration. A sensitive cup-contact anemometer, Sheppard(1940) pattern, was mounted alongside

Fig.20 The Mast Assembly.

the vane of the Dines, see Fig.20. Recordings of the number of contacts per minute from the C.C.A. were made on the field mill camera and subsequently converted to true airspeed from the anemometer calibration chart provided with the instrument by the Meteorological Office. The Dines indicated velocity has been plotted against true velocity in Fig.19 ,(note that the vertical scales are not equivalent) and again there appears to be a zero error such that the Dines does not respond to wind speeds less than 2.5m/sec(5kts) and above this value the indicated speeds are about 2.0m/sec low. It is known that cup anemometers tend to over-estimate the mean speed in fluctuating winds but it appears that the small moment of inertia of the Sheppard type anemometer ensures that this over-estimation is normally negligible; this is discussed by Sheppard(1940) and Deacon(1951).

The full curve of Fig.19 was used to convert all the anemographs to true wind velocity. Although no alteration was made to the calibration of the Dines, it is possible that the zero error slowly changed over the fifteen months of the investigation. This error was primarily due to sticking of the float rod and as the above calibration was made at the end of the fifteen month period, it is likely that the error was somewhat less at the beginning. Consequently the values of the wind velocity at ten metres, as used in the analysis of records, may be about 1m/sec too high on some occasions.

7.2 The Point Discharger.

Point discharge currents may play a vital role in determining the form of the field variations at the surface, therefore it was necessary to measure the current which flowed through at least one point at or near the site.

A stainless steel point, connected to earth through a recording galvanometer, was erected on an insulated mast. The stub mast supporting the point was mounted on the anemometer mast some 1.2m from the vane centre, with the actual point about 10cm above the vane tail, see Fig.20.

Such an arrangement left much to be desired, yet it seemed the best compromise between a number of conflicting factors. As the anemometer vane was the highest object for many kilometres, it was obvious that point discharge current might flow from the vane at a time when the field strengths at other points were still too low to initiate breakdown. Consequently, it was necessary that the point be higher than the vane if the current through the point was to be unique even for a small range of field strengths. It was not easy, however, to erect a point over 18m above the surface without utilising the anemometer mast in such a way as not to alter the exposure of the Dines or run the risk of the point fouling the vane.

Whipple and Scrase(1936) obtained an empirical expression for the relationship between the point discharge current

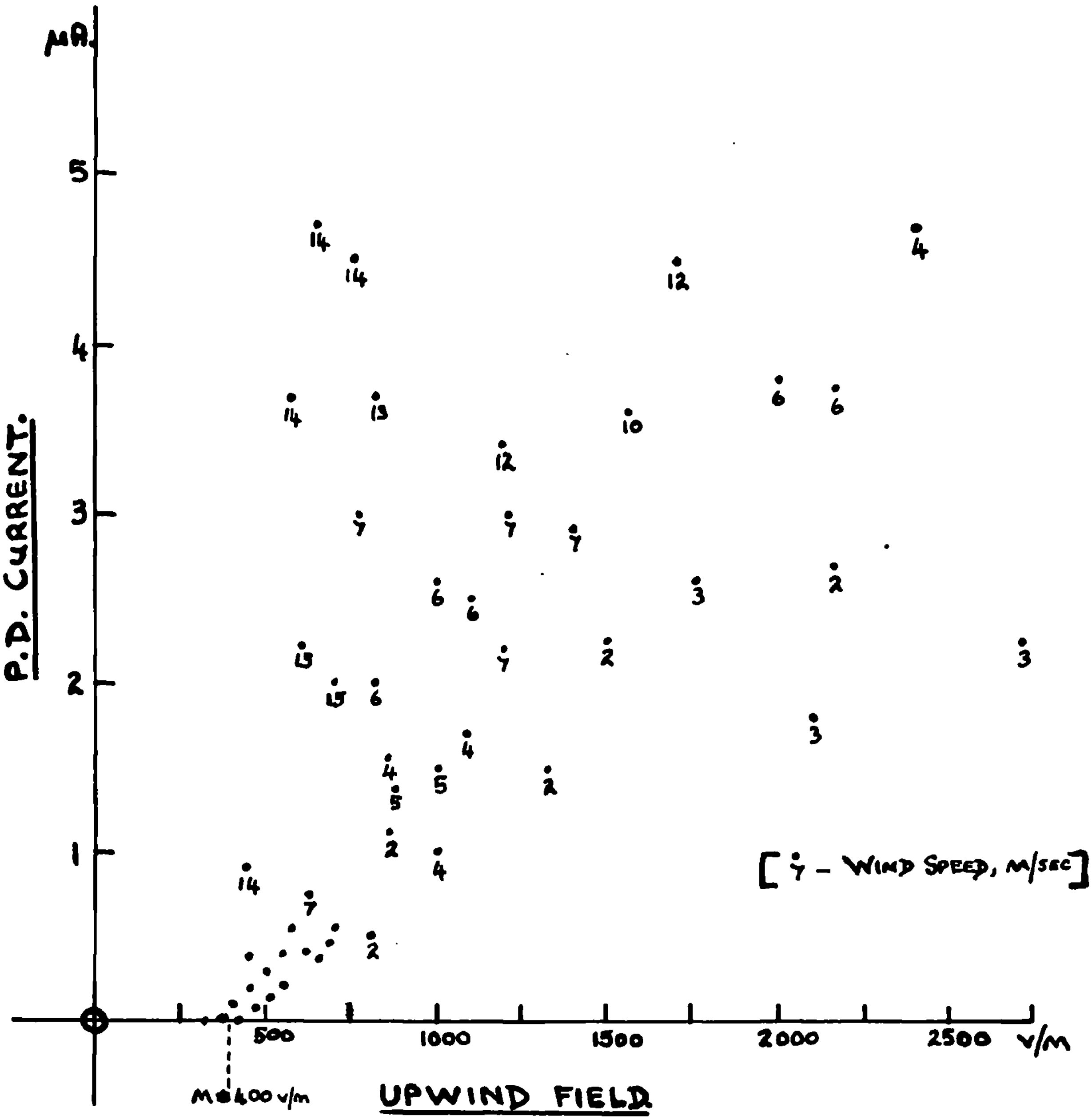


Fig. 21 Variation of Point Discharge Current with Field and Wind Speed.

through a comparatively low point surrounded by similar points and the surface field strength, under steady conditions. They suggested that,

$$i = a(E^2 - M^2)$$

where i is the current, 'a' a constant, E the surface field strength and M the value of the surface field below which the current is zero. Subsequent work, for example Chalmers and Mapleson(1954), has shown that the relationship between i and E is not as simple, at least for a high isolated point, as suggested by Whipple and Scrase, for in the first instance i depends on wind speed. Although the present work is not aimed at relating i with other parameters, it is interesting to plot a few values of p.d. current against field over a wide range of wind speeds. A few randomly selected points have been plotted in Fig.21 and the result gives the impression that, for a given field, i increases nearly linearly with wind speed. There are of course, too few points to give anything but a general impression.

For fields between 380-1000v/m there is little doubt that the only point discharge currents flowing in the neighbourhood of the Observatory originated from the erected point. For reasons which are given later, it is believed that the M value for the vane was about 1,500v/m, whilst in greater fields discharge probably occurred from trees and projections on the Observatory roof. Hence for $E > 1000$v/m, unmeasured

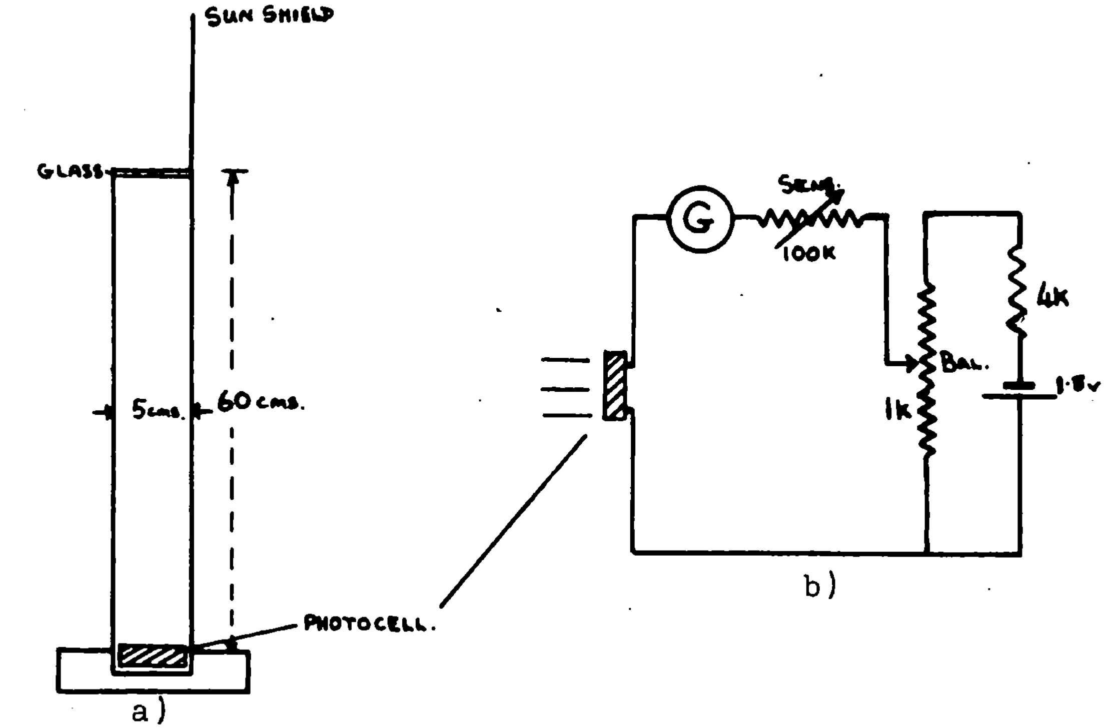
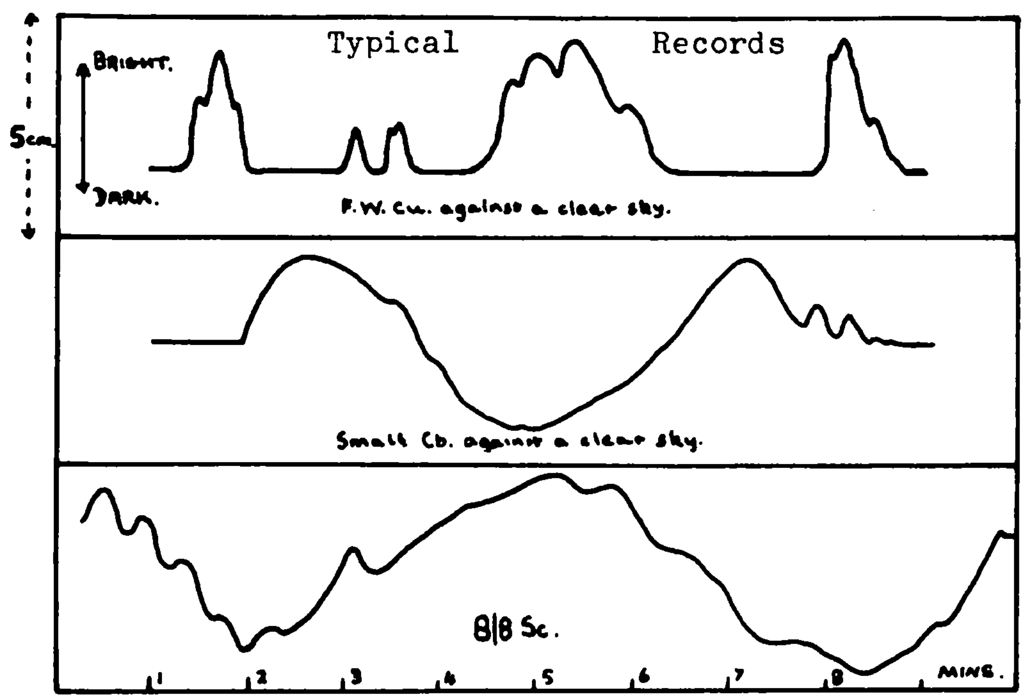


Fig.22 The Sky Photometer.



c)

point discharge current flowed into the air and it seems likely that under these conditions the current through the point was only a small fraction of the total current flow in the area.

7.3 The Sky Photometer.

One could not watch the field monitoring meters for long without being impressed by the obvious connection between field and the state of the overhead sky. Although this relationship was obvious to the observer, some instrument was required which would record "state of overhead sky" so that permanent records could be used to verify and add further to the observer's impressions. In an attempt to record this rather nebulous quantity "state of overhead sky", the Sky Photometer was developed. The main virtue of the instrument is its simplicity, yet it did provide information which, whilst of little quantitative value, was very helpful in locating the source of certain field variations.

Basically the instrument consists of a 45mm dia. barrier-layer photocell mounted at the bottom of a vertical tube, see Fig.22a. When placed in the open, the photocell "sees" a small area of the sky immediately overhead. The output from the cell due to the ambient light of the sky is balanced off by means of a simple potentiometer circuit shown in Fig.22b. Any out-of-balance current is then recorded, via a mirror galvanometer, on the field mill camera.

When field measurements were being made the Photometer was mounted roughly halfway between the two mills. The balance control was adjusted until the current through the galvanometer was about zero, any subsequent change in sky or cloud brightness resulted in an increase or decrease of cell output and a corresponding change in galvanometer defection.

In the first instance the Photometer was of great value in helping to fix, at any given instant, the position of individual clouds relative to the site. This was useful when studying the effects of Fair Weather Cu. on the surface field. Fig.22c illustrates a typical record produced by Fair Weather Cu. If the clouds were of the Cb. type the Photometer record was more difficult to interpret unless the clouds were situated against a clear sky. When the sky was overcast with St.,Ns., or Sc., the Photometer proved of great value. Any periodic structural variations in the cloud layer were usually manifest in the Photometer output, as in Fig.22c. On many occasions the Photometer record was incomprehensible, for example, under a chaotic sky with cloud at all levels. Fortunately the electrical conditions associated with such a sky do not suggest a close connection with individual clouds, so no vital information was lost.

7.4 The Quick-response Air Thermometer.

At one period during the investigation it was thought that a measurement of the micro-structure of the air temperature near the surface might offer a clue as to the origin of certain field variations. A series of cursory experiments were carried out using the following instrument.

Arranged round the top of a vertical ebonite tube are six copper-iron thermo-couples, each couple is of fine wire and protected from rain, but exposed to horizontally flowing air. The six corresponding "cold" juctions are embedded in a thermally insulated block of paraffin wax mounted about 15cm below the "hot" junctions. Paraffin wax was used because the factor MassxSp.Heat/Thermal Cond. is large, therefore temperature changes at the centre of the block tend to be slow. Hence the upper thermo-couples had a short thermal response time to the air temperature, whilst the lower 'couples had a long response time. With the 'couples connected in series, the p.d. across the free ends was about 200μV/$^\circ$C. The thermometer output was fed to a recording galvanometer and temperature changes of 0.1°C could be measured with ease.

When exposed to the free air near the surface the thermometer measured the micro-variations of the air temperature about some mean value. It will be stated now that the temperature records failed to be of any value except that they showed the existence of a cold air mass preceeding many shower clouds.

7.5 The Recording System.

Recordings of the field were made on 145mm photographic paper which, whilst passing continuously through a drum camera, was exposed to the light beams reflected from two Tinsley Mirror Galvanometers(No.4500m, periodic time 0.2sec). When constructing the camera provision was made for a large paper capacity(100ft) and a variable paper speed(0.5-10cm/min, in three ranges). The variable speed was included mainly for reasons of paper economy. In order to maintain the correct level of exposure of the photographic paper over the three speed ranges, the brightness of the galvanometer lamps was made to vary with selection of speed range.

The passage of time was recorded on the paper by means of "time marking". At known intervals the galvo, lamps and fogging lamp(which projected a background scale on the record) were switched off for two seconds, so leaving lateral white lines on the developed record. The time interval between the lines was 10secs for the higher camera speeds and one minute for the lower. The actual timing mechanism consisted of a mains-operated clock motor which operated a series of cams and relays. Selection of time interval was automatic with selection of camera speed.

The camera and all its associated equipment were

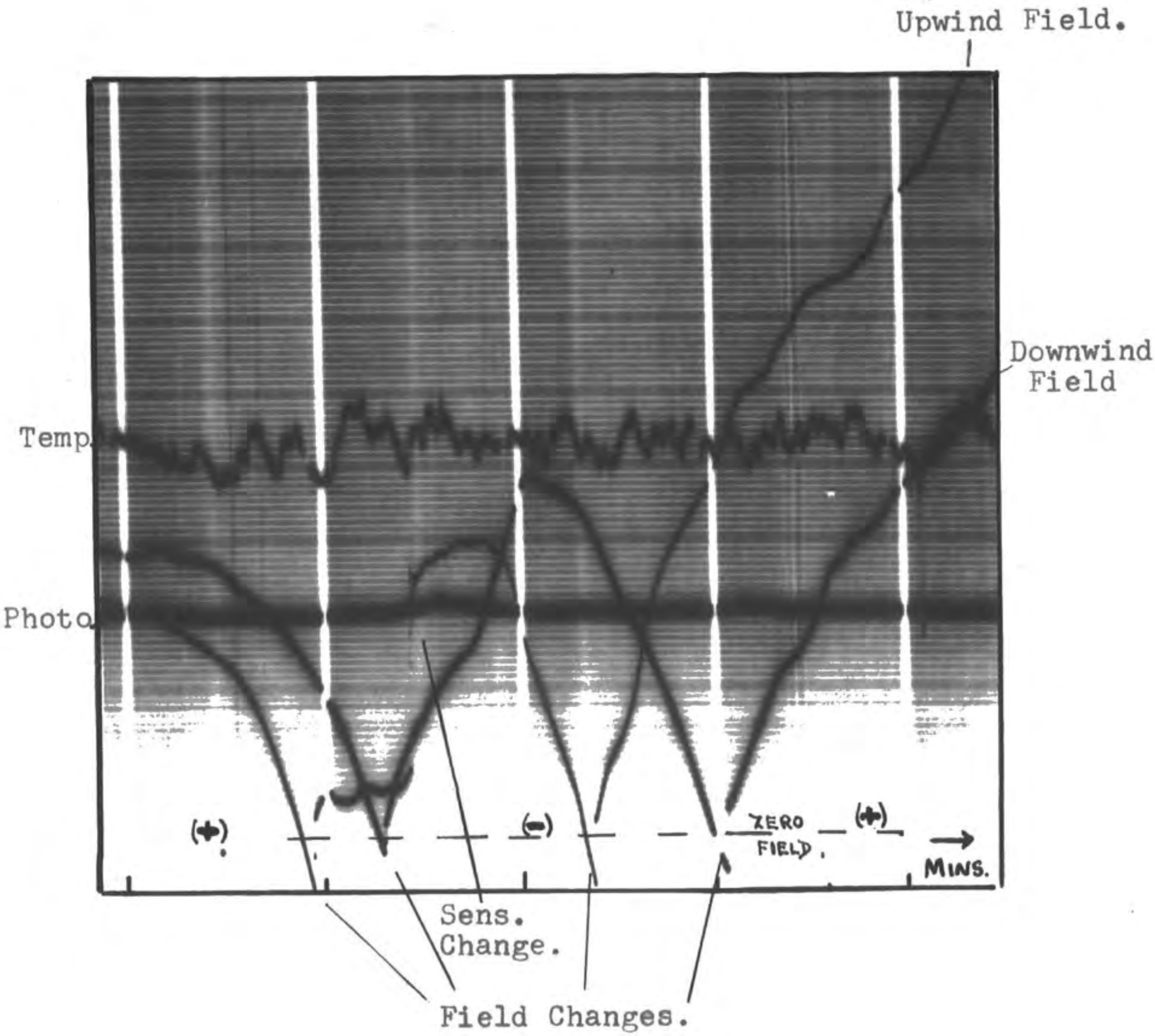


Fig. 23 Facsimile of Typical Record.

contained in a dark room away from the observer but all the equipment could be switched on by means of a master switch if the information appearing on the field monitoring meters required recording.

Visual monitoring of the field variations was made on two large dial 100μA meters which were connected in parallel with the recording galvanometers. The light spots from the field galvanometers were arranged so that they fell onto the edge of the photographic paper when the field was zero. For a positive field increase the spots would move across the paper, whereas for a negative field the spots tended to move off the paper. Two switches mounted on the monitoring meters could be used to reverse the leads from the amplifier to the recording galvanometers and the meters. Hence, whenever the field changed sign the switches were thrown so as to keep the needles on the monitor meter dials and therefore the spots remained on the paper. So long as the needles were on the dials the sign of the field could be determined from the position of the switches(they having been calibrated previously). The whole point of this arrangement is that it effectively doubles the width of the recording paper as compared with the centre zero method. With the amplifier on its most sensitive range a field change of +50 to -50v/m caused the galvanometer spot to scan the paper twice, so that the total deflection was 20cm. Fig.23 is a facsimile of part of a

Fig. 25 The Observatory.

Looking S.W.

Fig. 24 <u>The Observatory Environs.</u>

Looking E.

typical record.

7.6 The Site.

Originally it was planned that a site at the University Science Laboratories should be used for the investigation but some preliminary runs with the mills revealed a number of disturbing factors which rendered the site unsuitable.

Durham University Observatory stands on a hill 120m above sea level and about one kilometre to the west of Durham City. The Observatory building is surrounded, for the most part, by agricultural land and is well away from large sources of atmospheric pollution. Such a site seemed to offer many advantages over that at the Laboratories, for a useful range of meteorological instruments was maintained and the site was ideal for the investigation of certain problems. The main disadvantage lay in the state of the building, for it was in a very dilapidated condition.

Fig.24 gives an idea as to the type of country overlooked by the building, whilst Fig.25 shows how the building and the anemometer mast dominated the surrounding trees. A general plan is given in Fig.26, this shows how the eight mill sites lay roughly on a circle of 100m diameter, at the centre of which stood the Observatory building. One site was only available during part of the year, when the particular field was crop-free.

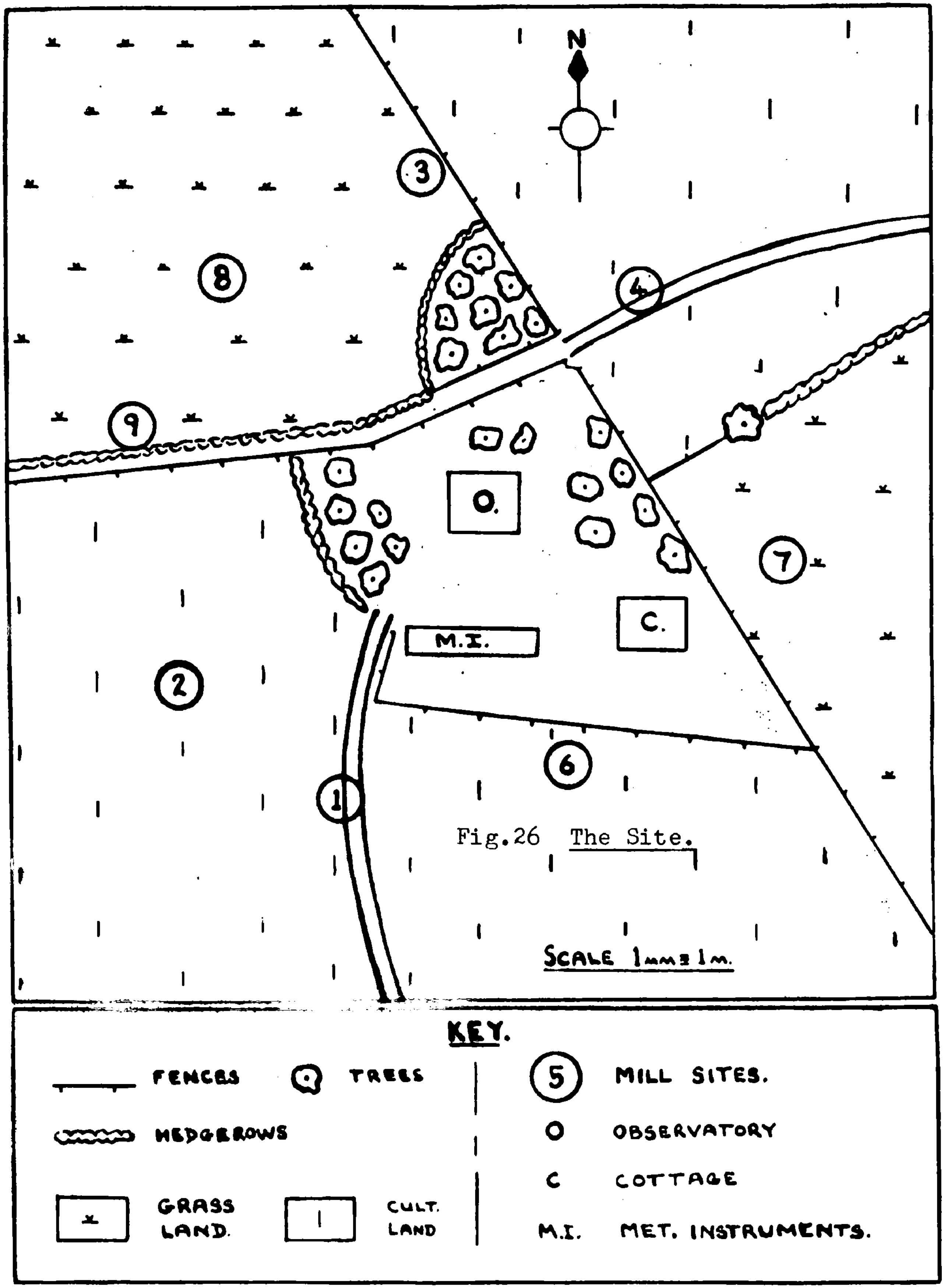
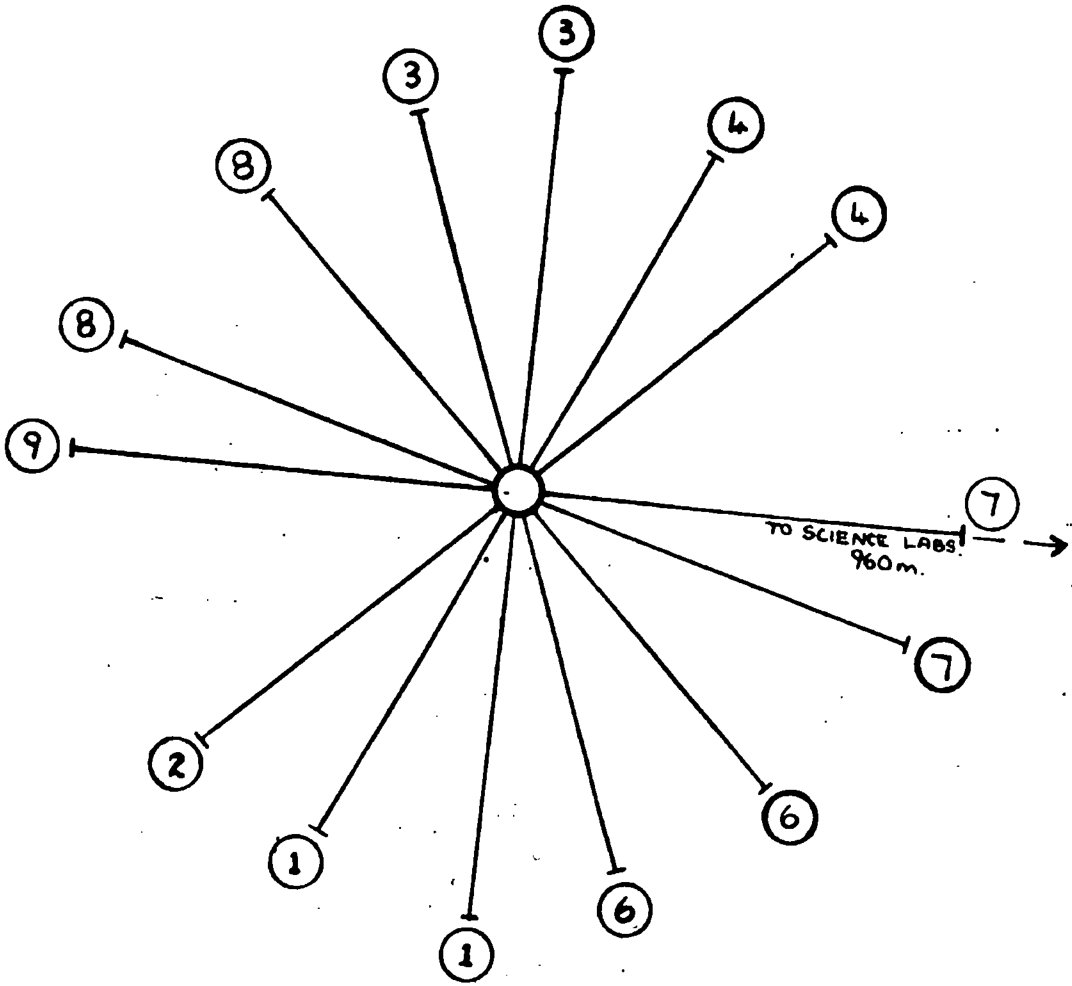


Fig.26 The Site.



SCALE - 1mm. = 1m.

Fig.27 The Mill Lines.

Fig.27 shows how seven different mill line directions were obtained by choosing suitable mill site pairs. Whatever the wind direction, two sites could be picked such that the line joining them was within 25° of the wind direction without reducing the mill separation below 100m. A further advantage of using the Observatory site was that when combined with the Laboratories site, simultaneous field recordings could be made at two points 960m apart on a bearing of 096° which was also the bearing of one of the mill lines. An agrimeter was in continuous operation at the Laboratories and so provided field records for comparison with those obtained at the Observatory. The agrimeter records were usually supplemented by field mill and point discharge current records also made at the Laboratories.

Time synchronisation between the Observatory and the Laboratories was achieved by making simultaneous marks on the two records on receipt of a pre-arranged telephone signal. Signals were sent about every 30mins, between signals the records were time marked by their independent time marking systems. Generally, any time mark on one record would agree with its contemporary to within ±5secs.

PART III

RESULTS AND DISCUSSIONS.

8. ANALYSIS AND INTERPRETATION OF RECORDS.

8.1 Analysis.

In the early stages of the investigation field recordings were made on every possible occasion irrespective of weather conditions. Later the work was concentrated on disturbed weather phenomena, for the problems here are more numerous. Because the records were made at random they should show a fairly representative cross-section of all the various types of short-period field variations. Except for the very few occasions on which instrument defects spoilt the record, all have been included in the analysis.

During a recording a detailed log was kept. This gave details of past and present weather, mill sites, sign of field, sensitivity of amplifier, in fact any observed event which might have some influence on the information being recorded. During disturbed weather an entry in the log was often made about every 15secs but on many occasions vital information was lost because the logging could not be kept abreast with events.

Altogether 480 feet of record have been analysed, covering a total of 220 hours and made up of 173 different periods. In classifying the records a system based on the immediate weather is used, in particular, records are grouped under different cloud types. Occasionally it was obvious that the field was varying in a manner which suggested that the weather was not directly responsible; these cases are dealt with separately. The weather symbols used are taken from the Meteorological Office Observer's Handbook,1952. Most of the weather details in the tables and diagrams came from the log book, occasionally these have been supplemented by information obtained from the Daily Weather Report and the Daily Aerological Report. Many of the figures contain diagrammatic representations of clouds. These have been drawn from the Photometer records and notes in the log book. The horizontal extent of the cloud is drawn in correct relationship to the time scale used but the height and detailed structure are only figurative.

As previously mentioned, the field variations measured at two sites appeared as two traces on the recording paper. If field variations are due mainly to the vertical transfer of charge in the atmosphere, then we should expect the corresponding maximum and minimum values on the two traces to be mainly simultaneous in time. If however, horizontal charge motion is responsible for the variations, then we might expect the two traces to appear displaced relative to each other. This displacement can be expressed as a delay time, the magnitude and sign of this delay time will depend on the mill separation distance and the value of the component of the charge velocity resolved along the line of mills. Now it seems likely that many of the surface field variations owe their origin to the motion of windborne charges. Therefore, it was assumed that the direction of charge motion was parallel to the surface wind direction. Having made this assumption, a charge speed Vc can be calculated from,

$$V_c = \frac{D \cos \phi}{t_d}$$

where D is the mill separation distance, ϕ the angle between the mill line and the surface wind and t_d the delay time as obtained from the recording. For each record an arithmetic mean delay time was calculated and hence a mean Vc. If the mean surface wind speed is Vs and there exists no relationship between charge motion and wind velocity, then we should expect the ratio Vc/Vs, denoted by R, to take any value between $+\infty$ and $-\infty$. In fact, R varies between +0.7 and +2.0 for all records, so that it seems justifiable to assume that charge motion is closely related to air motion in the lower atmosphere. Errors in the determination of ϕ do not seem to be of any great importance in the present work, for ϕ rarely exceeded 20° so that Cos ϕ was generally between 0.95 and 1.0.

On the average about 25 delay times were measured on each record, so that the total number of field variations involved in the analysis is over 4,000. On any one record the delay times showed considerable scatter; Fig.47 is typical of many in this respect. Part of this scatter must be due to measurement errors, for the two traces were not always identical in form, and part must be real for charge velocity is probably a very variable quantity. Not all the relevant information could be included on the diagrams so each has been drawn to include what is hoped the most important details. No distinction is made between the two mills except to call them "upwind" and "downwind", for the instruments can be considered identical for most purposes.

As mentioned in section 1.2 the electrical phenomena we are to study are best pictured in terms of space charge distributed throughout the lower atmosphere, with charge motion governed primarily by atmospheric motion. Therefore, it seems appropriate at this stage to remind the reader of some of the characteristics of wind structure in the lower troposphere, for these characteristics play a large part in the interpretation of the results.

8.2 Wind Structure in the Lower Atmosphere.

At a height of 400-600m, above the disturbing effects of the surface, the wind vector is mainly dependent on the horizontal pressure gradient and the effects of the earth's rotation. This geostrophic wind is comparatively steady and may be estimated from a knowledge of the pressure distribution.

Below 300m the air motion suffers from the frictional effects of the surface and at low levels may be complex and variable in structure. The vertical velocity profile in the first few hundred metres cannot, as yet, be expressed in precise mathematical terms but an approximate relationship between mean wind speed V, and height Z, is given by,

$$V = V_o \left(\frac{Z}{Z_o}\right)^p$$

where Vo is the known velocity at the reference height Zo. The value of p has been found to depend on the vertical temperature gradient. Frost(1947) gives p=0.8 for steep inversion conditions, p=0.3 for a zero temperature gradient and in superadiabatic conditions p=0.14. Therefore, under normal lapse rate conditions one would expect the geostrophic wind speed to be roughly 1.5 to 2.0 times the speed of the wind at 10m.

In addition to the vertical speed gradient there is normally a change in wind direction with height. Generally, the geostrophic wind differs by about 30° from the wind at 10m, the direction veering with height.

The above discussion of wind profiles applies particularly to the case where the surface features are uniform over a large area. In the vicinity of trees and buildings the air flow lines are considerably distorted so that the direct application of profile equations to the wind structure near the Observatory does not seem appropriate.

Up to this point we have been concerned with the mean wind but a close study of a typical anemometer record reveals considerable fluctuation about this mean value. It is found that not only are there velocity fluctuations along the direction of the mean wind but that there are eddy velocity components at right angles to the general direction of travel. In addition, a particular form of wind fine-structure may be short-lived, for Giblett(1932) has shown that the structure as measured at two sites directly in line with the surface wind and only 200m apart, may differ considerably in detail.

Wind structure in the lower troposphere is critically dependent on the atmosphere's susceptibility to turbulent motion. In a stable atmosphere wind eddies tend to be damped out and the vertical transportation of momentum is small. In an unstable atmosphere the converse is true and turbulent conditions may extend from the surface to the geostrophic level. The main criterion of stability is the value of the vertical temperature gradient in the lower atmosphere. When the lapse rate is super-adiabatic the air is unstable, so we may expect turbulence to be large, whereas in the stable conditions associated with inversions the converse holds and the air flow is more laminar.

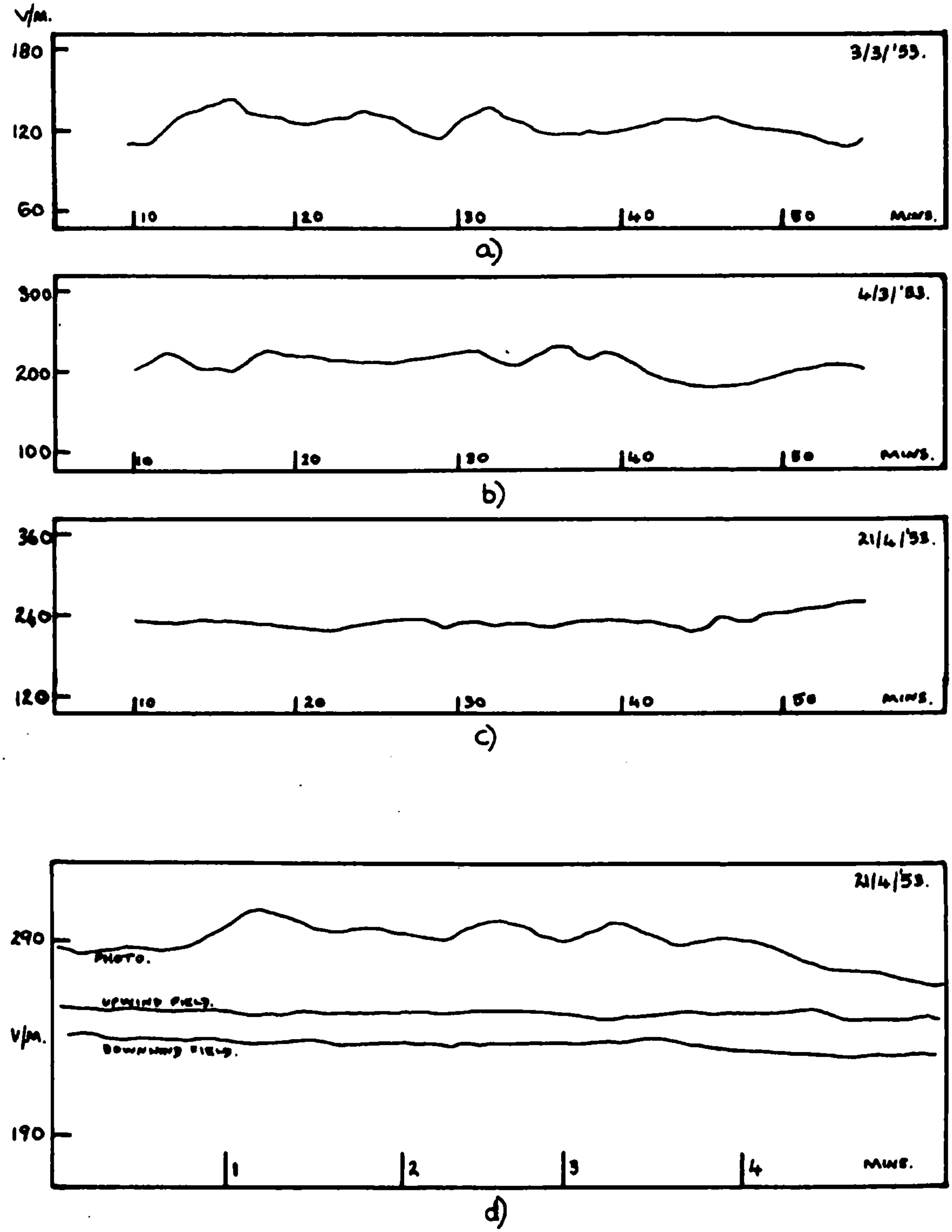


Fig.28 Fields during Fine Weather.

9. GENERAL FAIR WEATHER CONDITIONS.

A recording made when the weather conditions were such that the cloud amount was $<7/8$, the visibility >1km and with no indication of rain-bearing clouds in the vicinity, is classified under the above heading. A further sub-division is made as follows.

9.1 Fine Weather.

The term Fine Weather is used hereafter with particular definition; no cloud, visibility >1km and the field must at all times be positive.

Altogether seven records were made under strictly Fine Weather conditions and three of these are reproduced in Fig. 28. An outstanding characteristic of these fields is their remarkable steadiness, although small, smooth, random variations appear from time to time. Fig.28d is a direct copy of part of a record and even with an open time scale there is still very little evidence of any field fine-structure. What small fluctuations do exist are not always reproduced at the second mill, which suggests that they are either due to instrument noise or are of very local origin.

Table 2 gives a summary of the conditions appropriate to the seven Fine Weather periods. Also included are three periods during which there was a slight amount of Ci. cloud, for it is assumed that these clouds have no direct effect on

1. Date & Time	2. Weather	3. Mean Field v/m.	4. U_1 %	5. U_2 %	6. V_s °/m/sec.	7. V_c m/sec	8. R
3/3/53 15:04	Anticyclonic. Cloud - 0/8 Temp. 47°	120	2.9	1.2	180/2 210/1.8	1.7 1.5	0.8 0.9
4/3/53 11:26	Anticyclonic. Cloud - 1/8 Ci. Temp. 46°	225	2.5	0.9	315/1.5	1.8	1.2
4/3/53 15:43	Anticyclonic. Cloud - 1/8 Ci. Temp. 44°	240	3.9	1.1	350/3.8	4.8	1.3
6/3/53 10:26	Ridge. Cloud - 0/8 Temp. 43°	177	5.7	3.9	200/3.9 190/3.9	4.4 5.4	1.1 1.4
24/3/53 15:45	Anticyclonic. Cloud - 0/8 Temp. 61°	51	6.7	4.3	045/2.6 067/2	3.1 2.8	1.2 1.4
9/3/53 10:30	Anticyclonic. Cloud - 1/8 Ci. Temp. 51°	330	1.6	0.8	040/1.6	1.7	1.1
20/4/53 15:31	Ridge. Cloud - 0/8 Temp. 49°	104	1.8	0.7	085/4	4.9	1.2
21/4/53 10:24	Anticyclonic. Cloud - 0/8 Temp. 47°	240	1.6	0.8	120/1.5	1.5	1.0
9/6/53 14:58	Ridge. Cloud - 0/8 Temp. 57°	160	2.4	0.8	190/4.1	3.1	0.8
29/10/53 15:26	Ridge. Cloud - 0/8 Temp. 48°	170	3.8	1.7	190/3.7	4.9	1.3

Av. 1.13

Table 2 Fine Weather Conditions.

the surface field. As is to be expected, all periods occurred during general anti-cyclonic conditions but there is no consistency in surface wind velocity(surface wind is used for the wind at 10m), temperature or mean field. Col.3 contains the arithmetic mean field over the period of recording($\simeq$60 mins) and there is no indication of any relationship between the meteorological factors and the value of the mean fields, except perhaps on 24/3/54 when the falling afternoon temperature might have increased the humidity to such an extent that negative charges were liberated from high tension cables in small quantities(this is discussed later).

Cols.4&5 have been included in order to give some indication of the magnitude of the field "unrest". From the records the mean field was tabulated for each minute interval. This procedure tended to smooth out any variations of less than one minute period but as these were small they can be neglected anyway. From the minute means, the changes in field every minute, irrespective of sign, were obtained and from these values a mean change per minute for the whole record was calculated. This mean change is expressed as a percentage of the mean field in Col.4 and is denoted by U_1. Taking 3/3/53 as an example we see that during the 60mins of recording, the field changed, on the average, by 2.9% every minute. Extending this method, the mean field for every eight minute interval was obtained and hence the change in field every

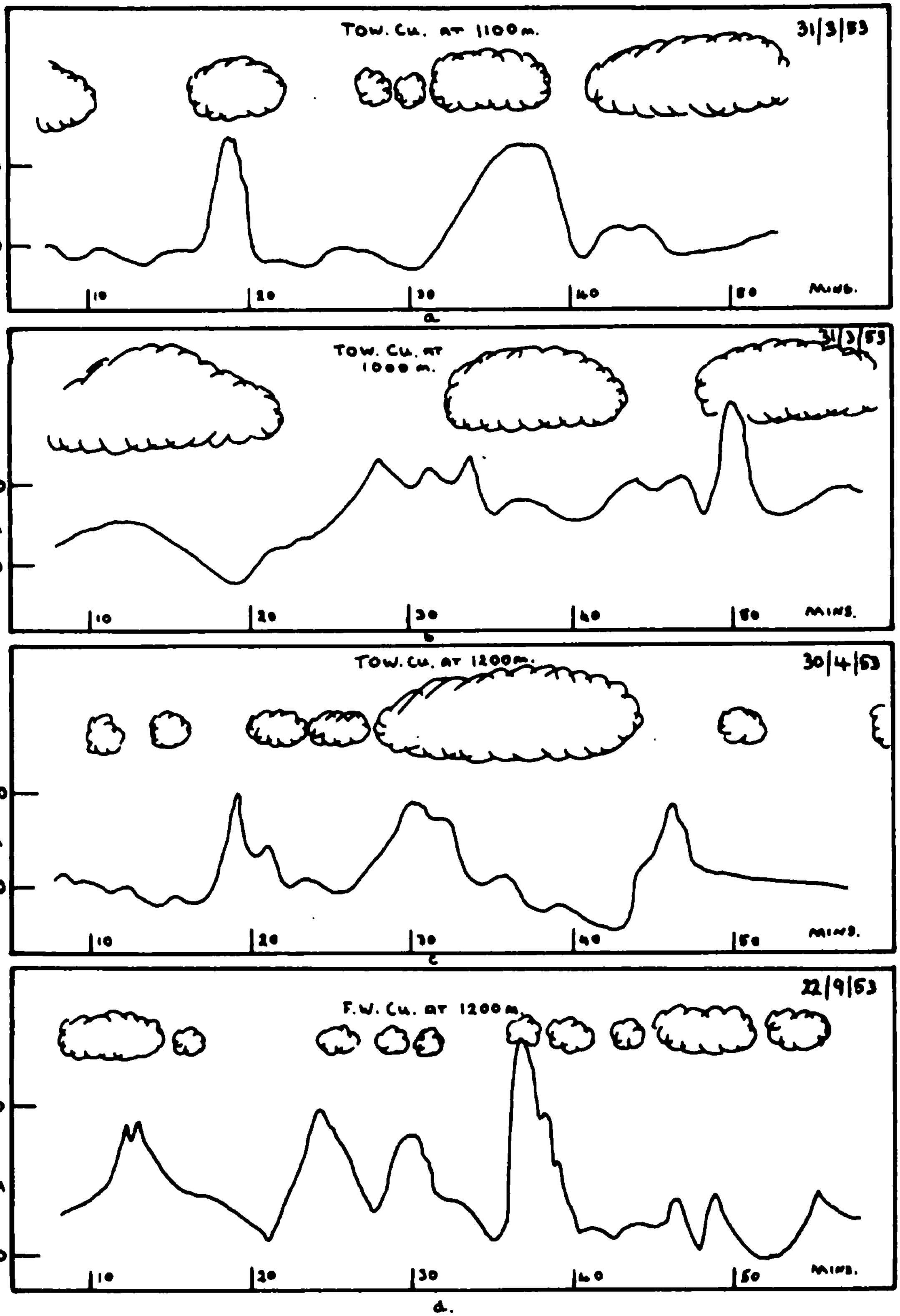


Fig.29 Fields during Fair Weather.

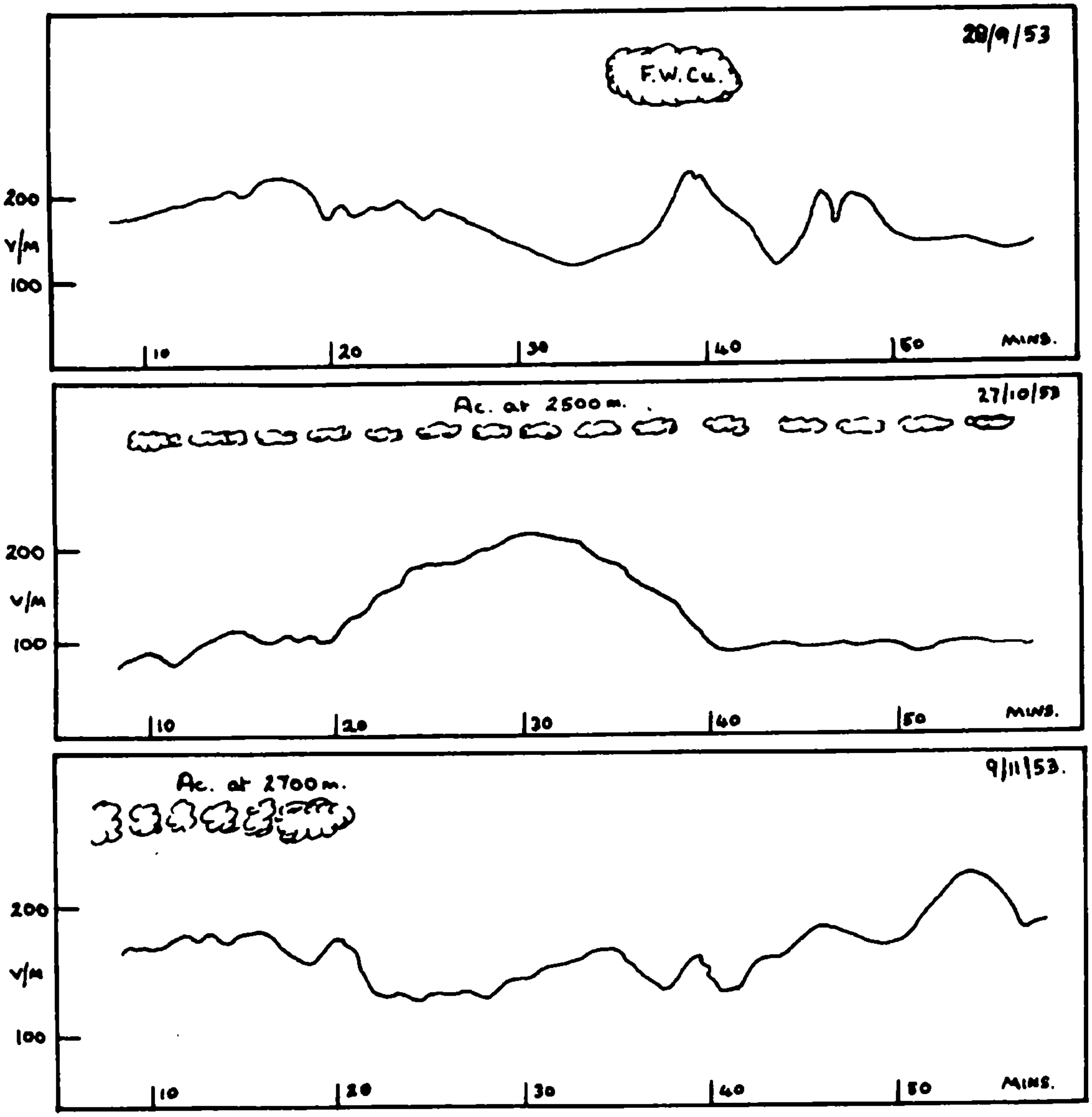


Fig.30 Fields during Fair Weather.

eight minutes. From these values of the eight minute change in field strength a mean eight minute change was calculated and finally expressed as a percentage change per minute, denoted by U_8 in Col.5. The value of U_8 then gives some indication as to the contribution made to U_1 by the long period(>8mins) field changes and by drift.

Col.6 gives the mean surface wind velocity, whilst Col.7 gives the apparent charge speed resolved along the surface wind direction. The ratio V_c/V_s is given under R in Col.8. Owing to the field variations being so small it was often difficult to measure the delay times, coupled with the fact that the anemometer did not respond to winds below 2m/sec the errors involved in the values given in Cols.7&8 may be large. The fact that the mean value of R for Fine Weather field variations is about 1.13 seems to leave little doubt that these variations find their origin in the motion of windborne charges whose mean height is between 10-50m above the surface.

Returning to Fig.28d, the third trace is that of the Photometer output showing typical variations in the sky brightness which were never apparent to the eye nor did they appear to be related to the field variations.

9.2 Fair Weather.

Fair Weather conditions are defined as those in which the cloud amount is between 7/8 and 1/8, vis.>1km, no precip-

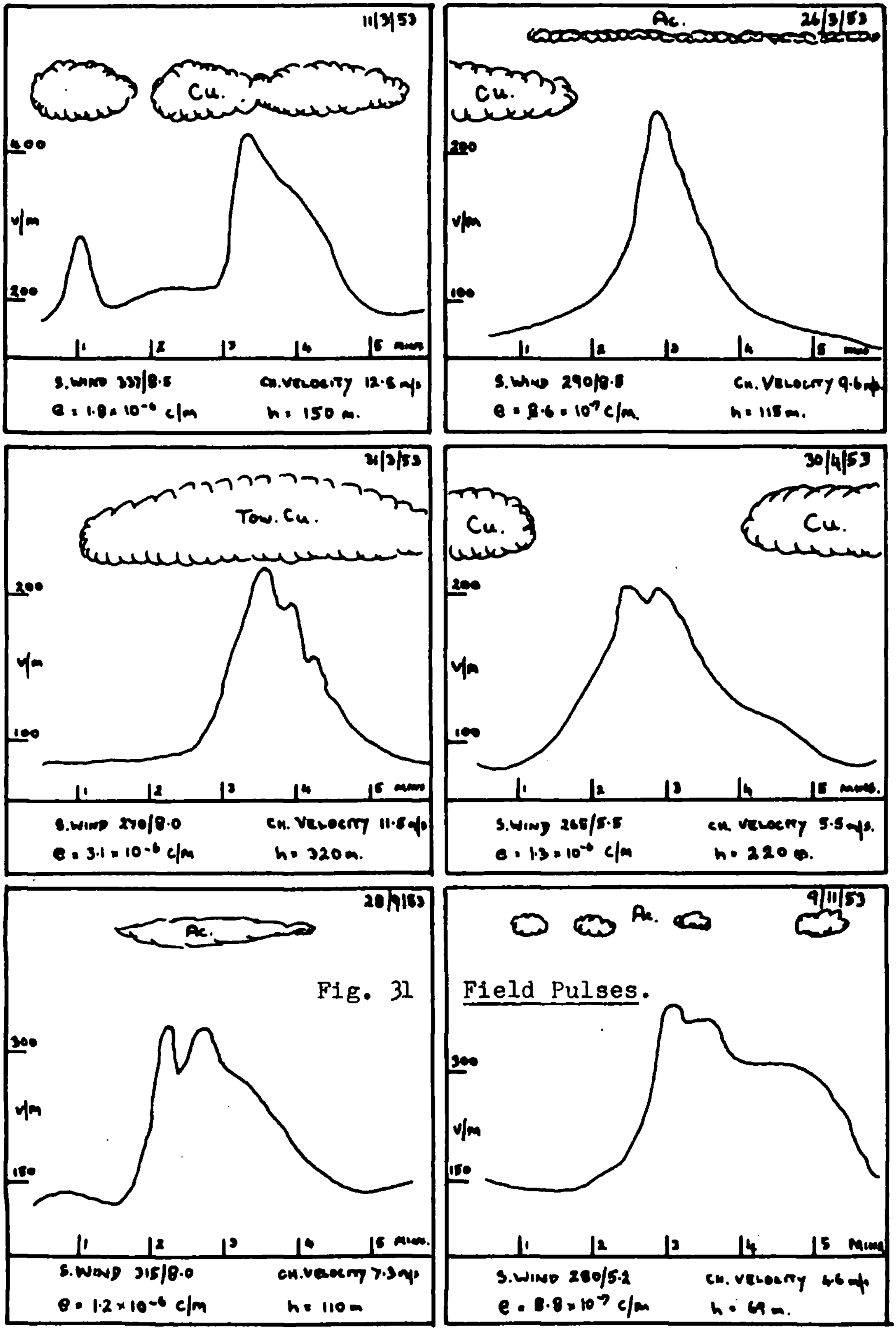


Fig. 31 Field Pulses.

itating clouds in the neighbourhood and the electric field must at all times be positive.

From the 22 hours of recording made during Fair Weather the most striking feature is that the field under these conditions is much more active than the Fine Weather field. Figs.29 and 30 show some typical records made under Cu. or Ac. skies but before going on to discuss the more general features of the Fair Weather field, attention should be drawn to the occurrence of certain well-defined variations that are believed to be of local origin.

Quite frequently the field would suddenly undergo a temporary excursion to about twice its normal value. Some of these Field Pulses, as they will be called, occur in Fig.29, whilst Fig.31 shows a number of the pulses in detail. From these figures it is obvious that the origin of the pulses is not to be found in the clouds and this was borne out by many eye observations. In fact nothing could be seen which might have accounted for the origin of the pulses and only on a very few occasions did the Photometer show a small simultaneous disturbance. Time delays generally showed that the responsible charges travelled at a speed slightly greater than that of the surface wind, actual values are given in Fig.31. In most cases the form of the pulse was unappreciably altered during its passage from one mill to the other, which suggests that the charges passed above the tree tops.

Date & Time.	Weather.	Mean Field v/m	U_1 %	U_2 %	V_s °/m/sec.	V_c m/sec.	R
11/3/53 10.36.	5/8 Cu. Temp. 49° Vis. 6km.	172	8.1	1.2	337/8.3	9.5	1.14
31/3/53 10.24	4/8 Cu. Showers later. Temp. 46° Vis. 15km.	82	21.0	1.0	270/8.7 265/7.6	9.7 8.6	1.11 1.13
26/3/53 12.12	4/8 Cu. Temp. 49° Vis. 15km.	188	10.6	5.3	290/8.5 290/10.3 310/8.3	9.4 11.0 10.0	1.10 1.07 1.20
30/4/53 11.00	5/8 Cu. Temp. 50° Vis. 10km.	90	20.0	3.6	260/5.3	6.0	1.13
22/7/53 3.04	5/8 Cu. Temp. 68° Vis. 15km.	152	7.5	3.6	240/7.7	7.3	0.95
23/7/53 11.29	5/8 Cu. 4/8 Ac. Temp. 64° Vis. 15km.	80	10.2	1.9	265/8.3	10.7	1.27
23/7/53 3.13	5/8 Cu. Ac.&Ci. Showers later. Temp. 67° Vis. 10km.	80	19.0	4.2	280/8.4	10.8	1.28
27/7/53 11.55	6/8 Cu. Prev. showers. Temp. 60° Vis. 10km.	80	8.4	3.3	215/7.4	8.1	1.09
22/9/53 11.32	3/8 Cu. Cloud developing Temp. 61° Vis. 10km.	82	14.8	1.5	270/9.3	13.7	1.48
22/9/53 3.01	4/8 Cu. Cloud dispersing Temp. 65° Vis. 10km.	117	8.7	0.6	245/7.8	10.5	1.35

Av. 1.18

Table 3 Fair Weather Conditions.

Field pulses were not mentioned in the previous sub-section on Fine Weather because they were never detected during such conditions.

In an attempt to study the more general properties of the Fair Weather field, particularly the fields under Cu. skies, Table 3 has been constructed on the same lines as Table 2. The field pulses have been eliminated so far as possible in the calculation of U_1 and U_8. In general there appears to be little connection between the electrical and meteorological details during any period of recording. Compared with the mean fields of Fine Weather the mean fields of Fair Weather show much less variation. As is to be expected from a study of the record reproductions of Figs.29 and 30 the values of U_1 are, however, very much greater because of the increased unrest. The mean value of R is 1.18 in this case, again the value to be expected if the variations are due to charges moving with the wind in the region of 10-100m.

From Fig.29 it is obvious that either the clouds contain randomly distributed positive and negative charges, or that they have no appreciable effect on the surface field and that any apparent direct relationship between cloud and field is merely fortuitous. A detailed investigation involving more than thirty isolated F.W. and Towering Cu. showed that the second hypothesis is the more likely, for the field variations beneath the clear intervals between the clouds showed no

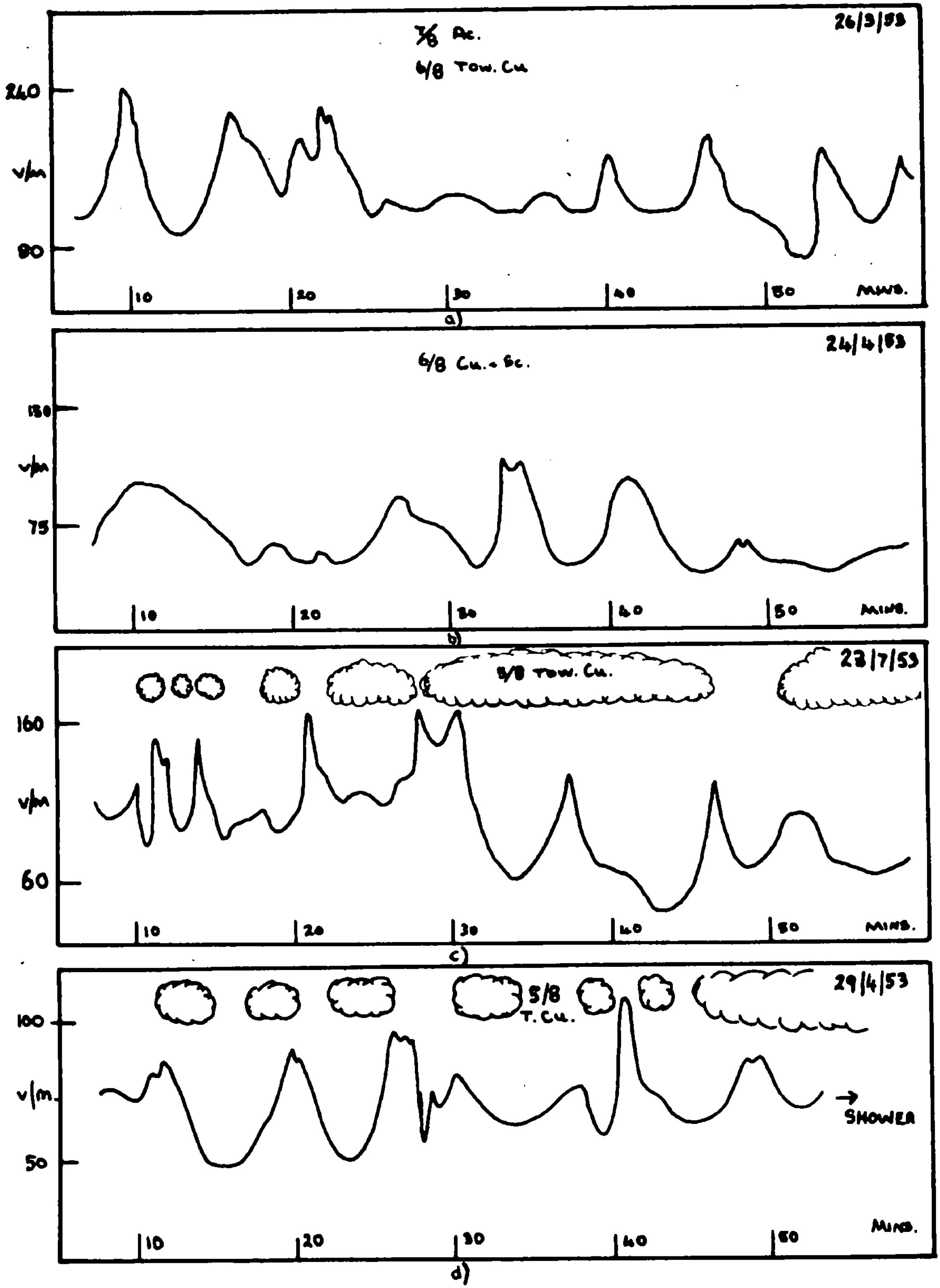


Fig.32 Field Patterns of Fair Weather.

appreciable difference from the variations which occurred beneath the clouds. From these results it is concluded that the Cu. clouds of Fair Weather(and probably all F.W. clouds) do not appreciably affect the surface field, i.e., there can be little free net charge in these clouds. However, under Cu. skies the field is much more variable than under clear skies.

On looking through the records of the Fair Weather fields one is impressed by the frequent occurrence of distinctive patterns of the form illustrated in Fig.32. Occasional examples of these "cusp-like" variations were found on almost every record made under Cu. skies but those illustrated are the most outstanding examples. In many cases the pattern elements were repeated a few times then died out, only to reappear some time later. This effect is shown in Fig.32. Although the "cusp-like" variations only appeared to occur with Cu. clouds, no direct connection could be established between individual clouds and the state of the field. A comparison of the fields as recorded at the two mill sites showed the patterns were due to a charge array in space moving with a horizontal speed which was a little greater than that of the surface wind.

As already stated, most of the Fair Weather recordings were made under Cu. skies. Those made under other cloud types showed little that was of interest. There were no patterns;

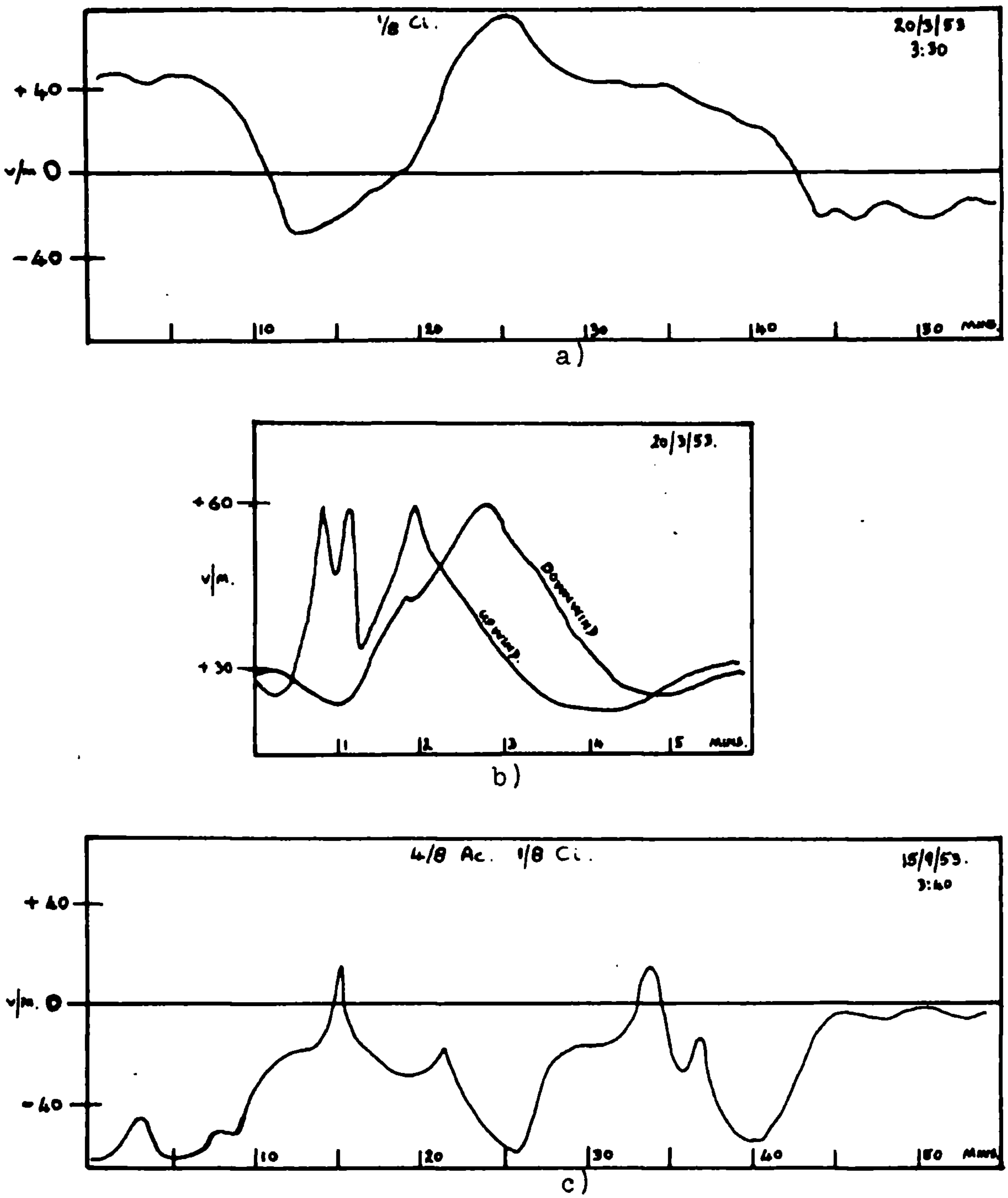


Fig. 33 Negative Fields in Fair Weather.

occasionally there was a field pulse but in general the variations were just of a random nature. The general unrest was somewhat greater than that in Fine Weather but rarely were the variations as great as those under Cu. skies.

A few of the recordings were supplemented by records made at the Laboratories. A comparison of the two records revealed that many of the fine-structure variations were not transmitted from the Observatory to the Laboratories, even when the surface wind was blowing directly along the connecting line. The time delays over 960m were difficult to measure because of the lack of similarity between the two records but although most of the delays measured gave R values between 0.8 and 1.5, some of the long period(>30mins) variations appeared to travel at speeds much greater than that of the surface wind.

9.3 Negative Fields in Fair Weather.

On three occasions negative fields occurred during periods that were meteorologically Fair or Fine. Fig.33 gives details of the field variations on two of these occasions. The way in which the field often varies about zero suggests the passage overhead of positive and negative charge pockets. This is borne out by velocity measurements which give R values of about unity, although on occasions it was obvious that the charges were moving slower than the air at

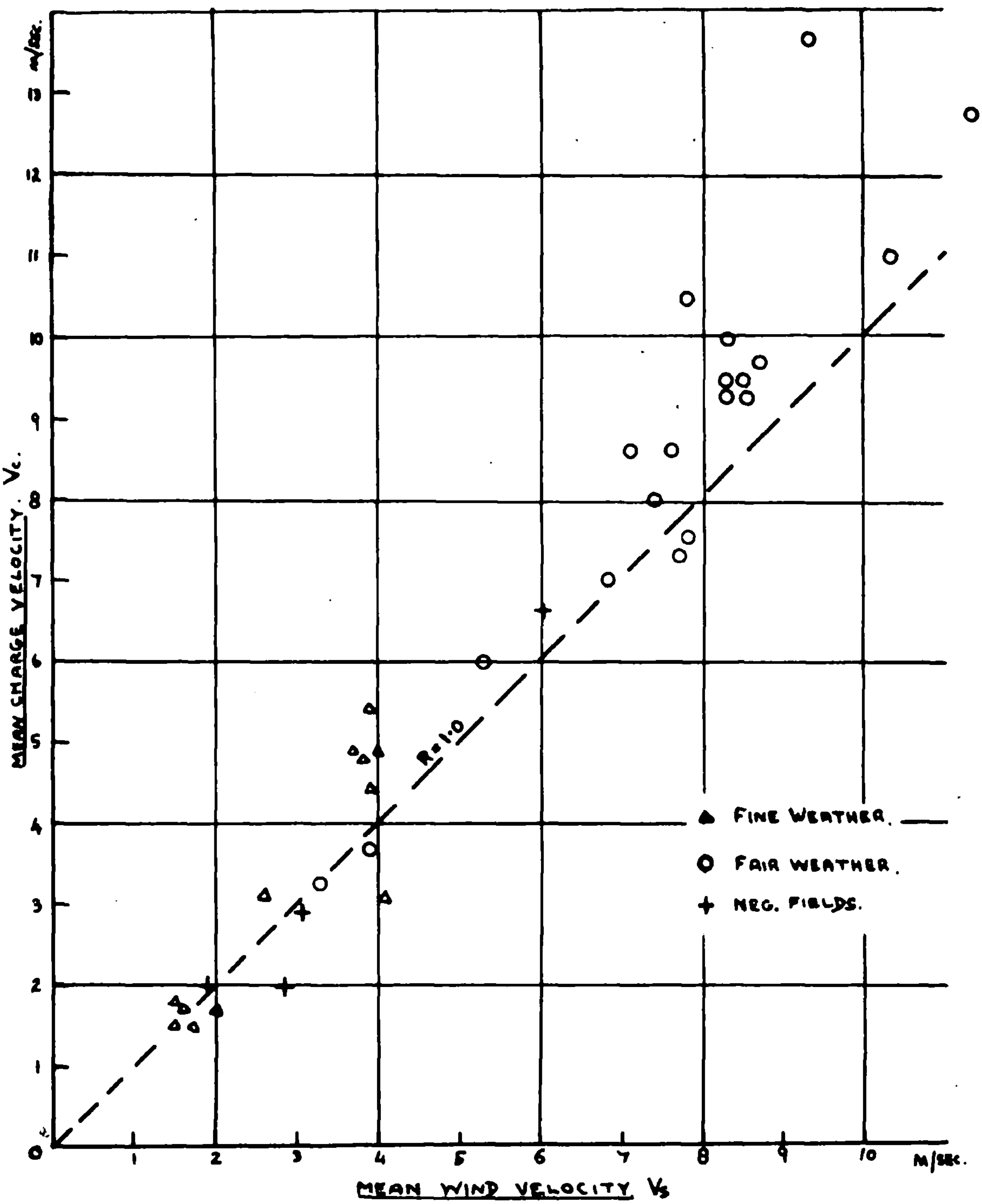


Fig.34 Variation of Charge Velocity with Surface Wind Velocity.

anemometer level and on these occasions the charge distribution must have been modified during its passage through the trees situated between the two mills. An example of this modification is shown in Fig.33b. Such differences between the two mill records are rare and can be accounted for if it is assumed that on certain occasions the charges tend to concentrate in the lowest air layers.

Eye observations revealed nothing that could account for the presence of negative charge. However, all three occasions had certain meteorological factors in common; the wind direction lay between ENE-SE and the falling afternoon temperature had caused an increase in humidity to the point where visibility had started to decrease.

There seems little doubt that on these occasions the conditions were such that negative charge was liberated from high tension cables in small quantities. In fact they probably represent the early stages of the establishment of continuous negative fields in mist and fog(see Section 10.1).

All the values of Vc obtained in both Fine and Fair Weather have been plotted against surface wind speed in Fig. 34. The result seems to indicate conclusively that most, if not all of the field variations of periods <30mins are due to the motion of windborne charges. In General Fair Weather conditions the average value of the ratio of mean charge velocity to mean wind velocity at 10m is about 1.15.

This suggests that the mean height of the charges responsible for the variations is about 50m. There is a tendency for R to increase with increasing wind speed.

9.4 Discussion.

Here the results given in the previous sub-sections are discussed and some attempt is made to account for the presence or absence of certain field variations found in Fair or Fine Weather.

a) The Field Pulses.

The rapidity with which the field changes during the passage of a pulse suggests that the charge is fairly concentrated. Small charge concentrations could not exist for long in a turbulent atmosphere for the dispersion processes will be quite rapid. Both the measurements of charge velocity and the fact that the pulse form is unaltered during its passage from one mill to the other suggests that the charge pocket is above tree-top level. All these clues tempt us to look for some fairly local source of positive charge which finds itself about 50m above the Observatory shortly after being liberated.

Some time was spent in trying to identify this source, at one time it was thought that a local chimney(½km to the NW) was the culprit but even when the smoke was blowing directly over the Observatory there was no indication that this pollution was charge bearing. As all but one pulse appeared to

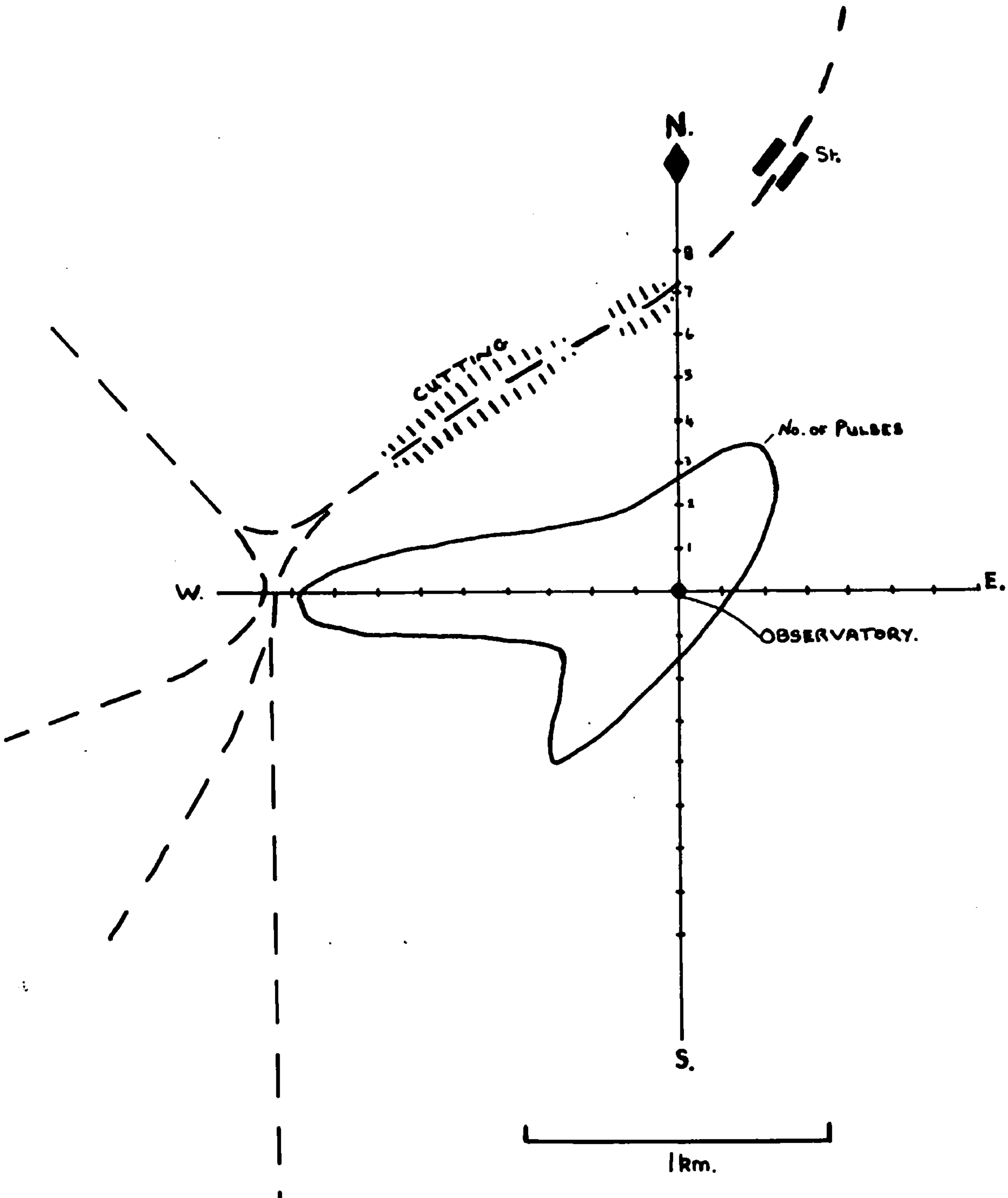


Fig. 35.

originate from the westerly quadrant, attention was concentrated in this general direction.

Seventy years ago Lord Kelvin suggested that the large quantities of positive charge emitted with locomotive steam might play a part in the production of atmospheric electrical disturbances. Kelvin's idea has since been supported by many workers, for example Rudge(1914) has detected the effects of positive charge liberated by locomotives, some 200m downwind of the engine. Muhleisen(1953) and Chalmers(1952) both report field increases of over 200v/m near locomotives. With this possibility in mind Fig.35 was drawn. Here the number of field pulses is plotted on a polar diagram against direction from which they appeared to come. Superimposed on the polar diagram is a scale map of the main railway lines round the Observatory. Although it was not possible to associate any particular pulse with a particular train, because the line was not visible from the Observatory, Fig.35 does seem to support the hypothesis that the field pulses are due to pockets of positive charge left behind after locomotive steam has evaporated. However, to a certain extent the polar diagram also represents a frequency diagram of wind direction.

Assuming that locomotive steam is responsible for the pulses then it seems probable that the evaporated steam will leave a line charge in the air. The field below an infinite line charge of density e C/m and of height h above the surface is given by,

$$E = \frac{eh}{\varepsilon_0 \pi [h^2 + x^2]} \text{ v/m}$$

where x is measured at right angles to the line and from a point immediately below. If V is the lateral velocity of the line and $t = 0$ when $x = 0$ then,

$$E = \frac{eh}{\varepsilon_0 \pi [h^2 + V^2 t^2]} \quad \text{and} \quad E_{max} = \frac{e}{\varepsilon_0 \pi h}$$

Let $t = t'$ when $E = E_{max}/2$, then,

$$h = Vt' \quad \text{and} \quad e = \varepsilon_0 \pi E_{max} V t'$$

V, Emax and t' are all measurable quantities so that e and h may be calculated for each pulse. Values of e and h calculated this way are given in Fig.31 and appear reasonable, although the calculated heights are greater than expected, but then the line charge will hardly be infinite in extent nor uniform in density.

In the analysis of records it was a simple matter to identify the main field pulses but many of the smaller field variations might have originated from locomotive charge but it does not appear possible to distinguish these from the "natural" variations.

b) Field Patterns and Convection Currents.

We now turn to a discussion of the "cusp-like" variations of the Fair Weather field. Some details of the most marked of these variations are given in Table 4. The mean

1. Date	2. Cloud	3. Mean Period. mins	4. Vc m/sec	5. R	6. Mean Size. m.	7. Ht. of Inversion. m.
26/3/53	4/8 Cu.	6.0	9.2	1.08	3310	2700
26/3/53	6/8 Cu.	6.5	10.0	1.20	3900	2700
28/3/53	5/8 Cu.	8.0 1.5	12.7 12.7	1.12 1.12	6100 1150	Lapse
24/4/53	6/8 Cu./ Sc.	7.5	4.7	1.14	2100	1700
30/4/53	5/8 Cu.	4.2	6.0	1.10	1450	?
6/5/53	7/8 Cu./ Sc.	5.8	4.7	0.94	1670	1000
23/5/53	7/8 Cu./ Sc.	9.0	7.0	1.13	3770	1200
23/7/53	6/8 Cu.	4.6	10.6	1.27	2900	2500
23/7/53	6/8 Cu.	6.3	10.4	1.23	4200	2500
22/9/53	3/8/Cu.	6.2	13.7	1.47	5100	Lapse.
22/9/53	1/8 Cu.	9.0	10.5	1.35	5700	Lapse.
		Av.- 6.2mins.			Av.-3400m.	

Table 4 Details of Fair Weather Patterns.

period(Col.3) gives the average time interval between successive positive peaks. Knowing the horizontal speed of the charges involved it is possible to calculate the horizontal extension of the pattern elements, these calculated sizes are given in Col.6. From this table and from the results previously given the following characteristics may be ascribed to the patterns;

i) There appears to be some form of charge distribution which repeats itself at about six minute intervals and occupies about 3.5km in the horizontal plane.

ii) Although no direct relationship was found between the patterns and individual clouds, the patterns were only found under Cu. skies.

iii) The charges responsible for the patterns appears to be drifting with the wind at a mean height of 10-300m.

iv) The patterns are transitory, they often appear and die-out at regular intervals.

The most important clue as to the origin of these patterns seems to be the fact that they are co-existent with Cu. clouds yet do not appear to be due to charges within the clouds. Whatever atmospheric process is responsible for the Cu. clouds of fair weather might therefore be responsible for the distribution of charge in space which gives rise to these patterns. An obvious possibility is that the patterns are connected with convection, for the thermals of fair weather are known to occur often in the form of regularly repeated vertical air currents.

If a relation is to be established between the "cusp-like" variations and convection currents, then it would be an advantage if the exact form of the latter was known. Unfortunately there does not appear to be a generally accepted picture of convective motion. Early workers suggested a cell-like structure based on the ideas of Benard, where the unit cell consists of a downdraft surrounded by an annular updraft. Brunt(1939) suggests that if the Benard process occurs in the lower atmosphere then the cells should be about 1-3km in diameter. Blamford(1929) from observations made on the flight paths of thousands of pilot balloons comes to the conclusion that convective motion may be in the form of long, horizontal, cylindrical rolls about 1-2km in diameter. A detailed survey of wind structure over level country was made by Giblett(1932) and he explained certain periodic variations in wind speed by assuming a basic cell structure 1-3km wide. Rainey(1947), from sailplane measurements, found convection cells 3-4km wide in the downwind cross-section. Durst(1948) found evidence of eddies or "air-parcels" from 3-16km in diameter at heights above 1km.

A more recent picture of convective motion is that of Scorer and Ludlam(1953). Here a bubble of warm air breaks away from its source on the surface and rises up along a curved path through the wind gradient to about the inversion level. Aircraft observations have detected these bubbles and James(1953) tentatively suggests that they are 0.1-2.5km in diameter, Yates(1953) believes one will be found in each square kilometre.

From the examples quoted there seems little doubt that there exists in the atmosphere a form of convective motion in which the basic "cell" is about 2km wide; a value not far removed from the separation distances involved in our charge pattern. As individual clouds need not bear any close relationship to the convection currents beneath them, there is no need to anticipate a close connection between cloud and field. Convective patterns are known to continually break-down and reform, a characteristic also displayed by the field patterns. It has been suggested that the size of the "cells" might bear a simple relationship to the height of the inversion layer. Approximate heights of this layer(obtained from the Daily Aerological Report) are given in Table 4 for the days on which the patterns occurred, but no simple relationship appears to exist in these cases.

Assuming that field patterns and convection currents are closely related, what is the actual mechanism involved? This problem would be less difficult to answer if more were known about the form of the currents. For the present one can only suggest a number of possible mechanisms, any one of which might fit the observed facts. For example, if we assume the bubble picture, then a rising bubble might carry up a volume charge of density appropriate to the height of its formation. As such a bubble passes overhead, the field displacement would have a "cusp-like" form. If typical values of bubble size, bubble height and space charge density near the surface are used, then the bubble picture gives field displacements of about the right order.

During the investigation an attempt was made to correlate air temperature variations and wind velocity fluctuations with the field patterns in order to test the convection current theory. So far as temperature was concerned there was no marked variation with a period of six minutes or so. This is to be expected, for the thermometer was below tree-top level and therefore in air which had been mixed by turbulence. Wind velocity fluctuations showed more promise for they frequently contained a large six minute component but there did not appear to be any fixed connection between the field patterns and the velocity variations. Again this might be explained by assuming that the form of the surface wind disturbance depends to a great extent on the height of the bubble whereas the form of the field pattern does not.

c) Influence of Atmospheric Vertical Stability.

If certain field variations in Fair Weather derive from convective motion, then it is possible that a more general law exists relating field unrest and atmospheric vertical stability. As mentioned in section 8.2, the lower atmosphere is generally stable, neutral, or unstable, if the vertical temperature gradient is algebraically greater than, equal to, or less than, the adiabatic lapse rate.

Now the Fair Weather results indicate considerable field unrest under Cu. skies; such clouds are normally associated with large lapse rates and hence a high degree of turbulence. This turbulent motion of the air ensures a thorough mixing of the positive charge in the first few hundred metres so that the mean field in these conditions would tend to vary little from period to period. Superimposed on this mean field will be large short-period fluctuations due to small-scale density variations in the charge distribution.

Turning now to the problem of the very steady field in Fine Weather we are tempted to look for a stabilising temperature gradient. Unfortunately the vertical temperature gradient is not measured at Durham, so any attempt to correlate unrest and gradient must be very approximate. The Met. Office Daily Aerological Reports contain upper air measurements made at various stations in the British Isles. The three nearest stations to Durham are Liverpool(Lancs.), Leuchars(Fife) and Hemsby(Norfolk). From the measurements made at these three stations it was possible to determine whether the temperature gradient over N. England was negative

Fine Weather.

Date.	U, %	Ht. of Inversion m.
3/3/53	2.9	447
4/3/53	2.9	340
4/3/53	3.9	513
6/3/53	5.7	485
9/3/53	1.6	1320
24/3/53	6.7	390
20/4/53	1.8	1220
21/4/53	1.6	313
9/6/53	2.4	1040
29/10/53	3.8	Lapse/Isoth.

Fair Weather.

Date	U, %	Ht. of Inversion m.
11/3/53	8.1	1450
26/3/53	10.6	2760
31/3/53	21.0	4900
30/4/53	20.0	Lapse/Isoth.
22/7/53	7.5	Lapse.
23/7/53	10.2	Lapse.
23/7/53	19.0	Lapse.
27/7/53	8.4	2900
22/9/53	14.8	2800
28/9/53	12.7	Isothermal at 2000m.

Table 5 Field Unrest and Inversion Heights.

at all heights, or if not, the approximate height of the inversion level. Table 5 contains these very approximate inversion heights for both Fine and Fair Weather periods. If the inversion level is within the first few hundred metres then it is probable that the mean temperature gradient will at least be algebraically greater than the adiabatic lapse rate, hence turbulence will be slight in this region. Table 5 suggests that the Fine Weather recordings were in fact made during conditions when it was possible for the lower atmosphere to be in a fairly stable state. Of course, the general meteorological conditions of Fine days are those normally associated with a stable atmosphere.

A point previously mentioned is that field pulses were not detected on Fine days. Their absence might be accounted for in terms of a stabilising gradient for under these conditions the steam would not rise very far above the surface and the charges would be drawn quickly into the ground by electrostatic forces.

To sum up this discussion it is suggested that the degree of field variation during general fair weather conditions is dependent on the vertical temperature gradient in the lower atmosphere. With a super-adiabatic lapse rate there is vertical instability, large turbulence and hence a very variable field. In inversion conditions the atmosphere is usually stable, turbulence slight and the corresponding field steady.

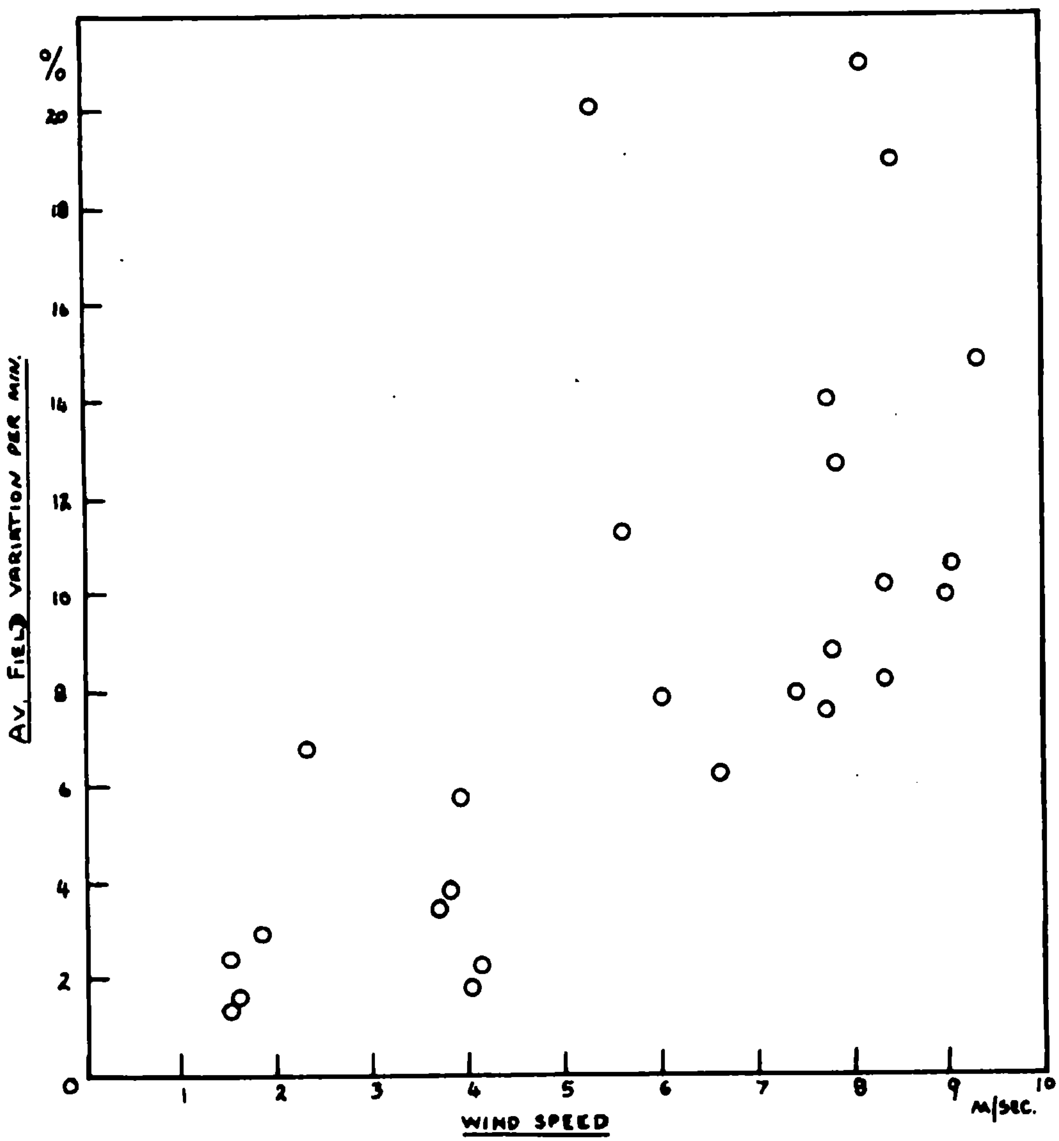


Fig.36 Variation of Field Unrest with Wind Speed.

This conclusion is complementary to that of Simpson(1949) who, for disturbed weather conditions, found that the most variable fields occur under conditions of greatest vertical instability.

d) General.

Dupier and Collardo(1933) found that there is a striking parallelism between the fields as measured at points 1500m apart, variations of 1 or 2v/m are duplicated. They claim that the variations are apparently simultaneous, irrespective of wind direction. The present findings are not in agreement with these results. In the present case it was found that over distances of about 1000m the fields differed considerably in detail. Over separation distances of 100m the differences in fine structure increased as the angle between the field measuring instruments and the surface wind increased. The present conclusions are more in agreement with those of Muhleisen(1953).

Israel(1943) from records obtained from a field variograph(which measures dE/dt) finds an increasing field unrest with an increasing wind speed. A similar result is suggested by Fig.36. This is to be expected if the field variations are primarily due to the motion of windborne charges, although the fact that greater turbulence is often associated with high wind speeds is a factor not to be ignored.

An interesting result is that of Lecolazet(1948) who finds that the conductivity below the inversion level is often only about one tenth of the conductivity above. Here is direct evidence of the effect of a stabilising temperature gradient, for the inversion limits the extent of the dispersion of pollution from the surface. Above the level the air is comparatively clean so that the conductivity is high.

Although Lecolazet(1946) claimed to have found an effect of F.W.Cu. on the surface field, the present investigation certainly found no evidence of net charge in such clouds nor could it identify any effects due to the cloud's conductivity. The magnitude of the surface field distortion due to a poorly conducting cloud passing overhead in a uniform current field has been theoretically investigated by Kasemir(1952). Without going into the details of such a theory it can be stated that in order for a spherical cloud to have an appreciable effect on the surface field its diameter must be greater than one kilometre, i.e., much bigger than the average F.W.Cu. A more realistic theoretical approach has been made by Lecolazet and Pluvinage(1948) who considered a typical cloud imbedded in the boundary of two media of different conductivities, i.e., a cloud situated at the inversion level. Both the theory and actual measurements in and around clouds showed that the distortion of the primary large-scale field is small and would hardly be felt at the surface. One of the main difficulties involved in trying to detect the surface effects of F.W.Cu. is that any small effect the cloud might have will be eclipsed by the motion of space charges between the cloud and the surface.

Date & Time	Weather	Mean Field v/m	V_s °/m/s	V_c m/s	R.
5/3/53 17:45	Fog. Vis. 100m Decreasing.	-30	214/5.1	6.0	1.18
21/3/53 09:56	Fog. Vis. 550m Increasing.	+120	284/3.2	3.1	0.97
17/4/53 15:53	Fog. Vis. 400m (Low cloud)	-200	030/4.1	5.0	1.22
23/4/53 10:12	High Mist. Vis. 1km Increasing.	+120	190/5.5	4.8	0.87
24/10/53 10:04	High Mist. Vis. 1km. Increasing.	+80	195/5.5	7.9	1.40
7/12/53 14:19	Fog. Vis. 600m Increasing.	-160	098/3.5	4.2	1.20
16/12/53 10:14	Fog. Vis. 60m. Decreasing	+400	300/1.0	1.0	1.00

Av. 1·12

Table 6 Mist and Fog Conditions.

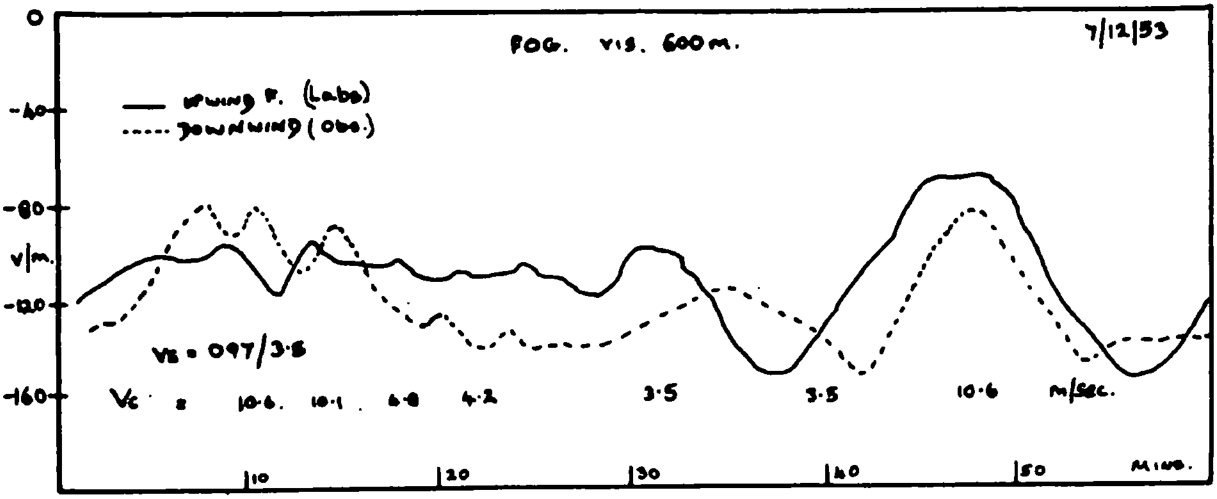
10. MIST, FOG AND THE OVERCAST SKY.

10.1 Mist and Fog.

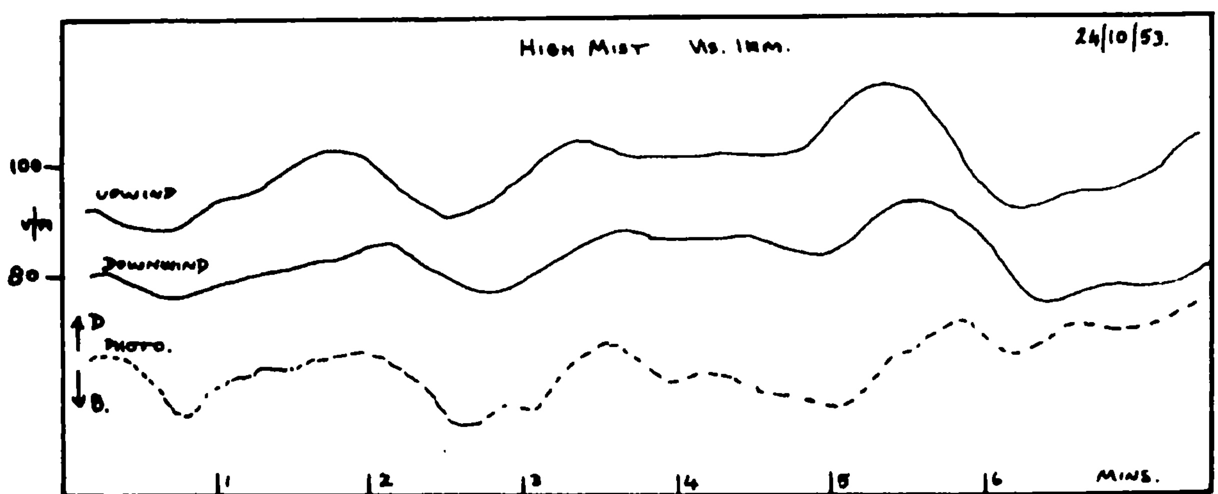
In mist and fog the fields at Durham are very variable both in magnitude and sign. Damp conditions are favourable for the emission of negative charge from high tension cables (or their supporting insulators) which pass on the easterly side of the City, hence the sign of the field depends largely on the surface wind direction, as shown by Chalmers(1952). In fact, negative fields generally occur when the wind blows from any direction between N.-S. via E., as shown by Table 6. Only on one occasion was the field large and positive, a characteristic normally associated with conditions of reduced conductivity. During this period the field was often 200v/m greater than the M value for the point discharger, yet no current flowed, presumably because the field fell away rapidly with height as suggested by Wormell(1927).

Values of Vs, Vc and R are also given in Table 6 and again windborne charges appear to be the prime cause of the field variations.

Fig.37a illustrates a result that is typical not only of foggy conditions but of many others as well. The two curves represent the fields at two points 960m apart during a period when the surface wind was blowing from the Laboratories to the Observatory, even so the variations are often so dissimilar that delay times are impossible to measure. Where these



a)



b)

Fig,37 Fields in Mist and Fog.

times have been measured they show considerable variation and are difficult to interpret.

The wave-like variations of the field during mist and fog are well known and a comparison of the Photometer output with these variations, Fig.37b, verifies the fact that they are due to undulations in either the fog depth or density. In both positive and negative fields it was found that the darker patches of fog were associated with the greatest field strength; a possible interpretation is that in the case of the positive field the denser fog had the smaller conductivity whilst in a negative field the denser fog patches contained the most negative charge. Naturally when the fields fluctuated about zero the records were more difficult to interpret.

10.2 The Overcast Sky.

This sub-section is concerned with the periods during which the sky was virtually overcast. Although on all the occasions discussed no precipitation actually reached the ground, on some occasions rain appeared imminent.

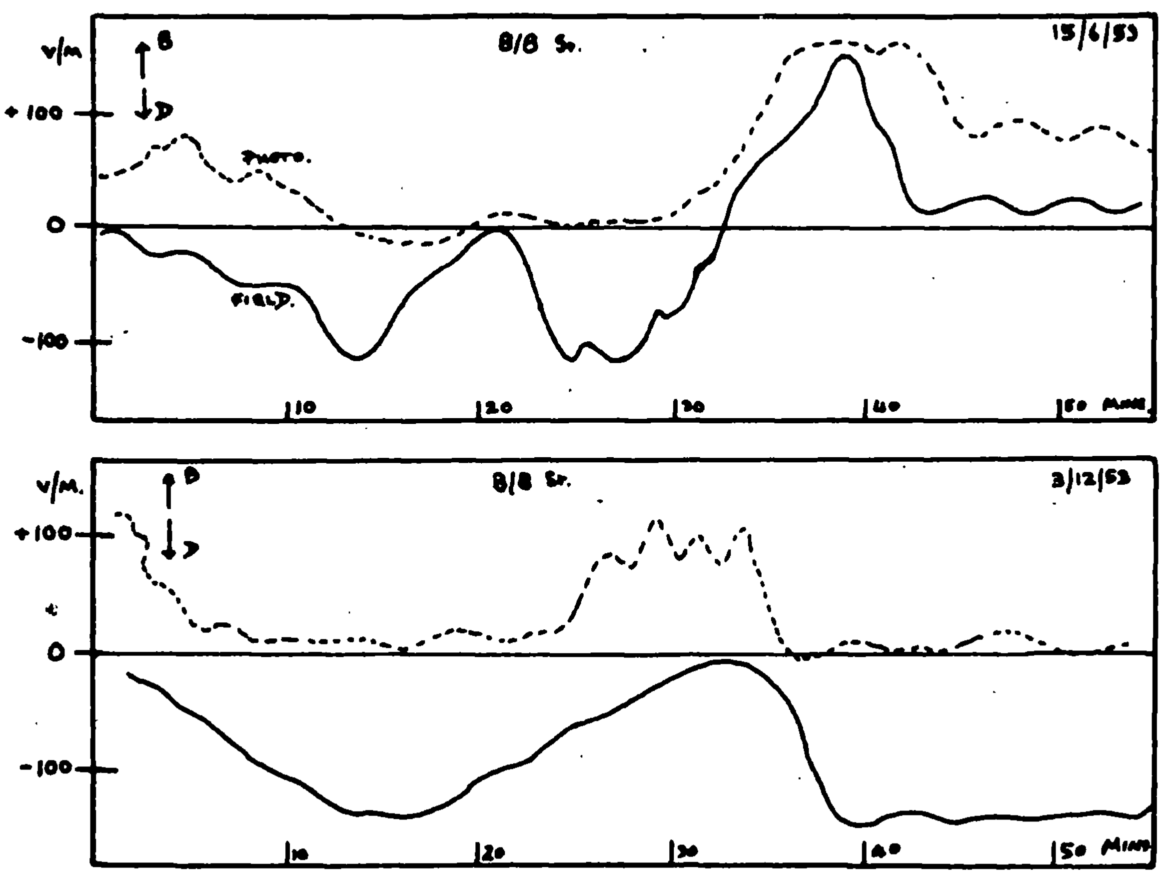
Naturally many of the field characteristics which appear in Fine, Fair or Foggy Weather may also occur in the more meteorologically disturbed conditions so that we must expect the origins of the field variations to become more diverse as we progress.

Under overcast skies a new source of field disturbance is

Date & Time	Weather.	Mean Field.	V_s	V_c	R
10/3/53 11.24	8/8 Ac. Dir.-270° Vis. 3km.	+50	225°/6,2	6.2	1.0
20/3/53 10.30	8/8 St. Dir.-180° Vis. 2km.	+90	135°/1.5	1.4	.93
15/6/53 14.40	8/8 St. Dir.-005° Vis. 1km. Drizzle followed.	-10	022°/3.1	3.1 (3.2)	1.0
3/12/53 10.20	8/8 St. Dir.-190° Vis. 1.5 km. Very dark cloud.	-60	182°/4.9	7.6 (7.6)	1.55

Table 7 Overcast Sky Conditions

Fig. 38 Fields under Overcast Skies.



introduced, i.e., charges on clouds. Table 7 contains details of four typical overcast days and shows how the mean field may be either positive or negative. The existence of negative fields during periods when the visibility was quite good ruled out the possibility of the charges originating from high tension cables, so a new problem was posed. It was this problem of negative fields under overcast skies that first called for an instrument of the form of the Sky Photometer for it was apparent to the observer that the gentle undulations of the field were following similar undulations in cloud structure.

Fig.38 shows how the field varied with Photometer output on two occasions. The relationship between the two outputs suggests that the lighter portions of the cloud contain a net positive charge whilst the denser or thicker parts contain a net negative charge. Measurements of delay times gave velocities along the direction of cloud motion which were generally greater than the surface wind velocity and in some cases approached the geostrophic value. A typical anomalous case is that of 15/6/53, when the charge velocity was almost equal to that of the surface wind, yet all other factors pointed to the charges being in the cloud. Subsequent checks on the Daily Aerological Report showed that on this particular day the wind velocity was almost constant with altitude.

On the 18/3/53 the Photometer was used for the first time

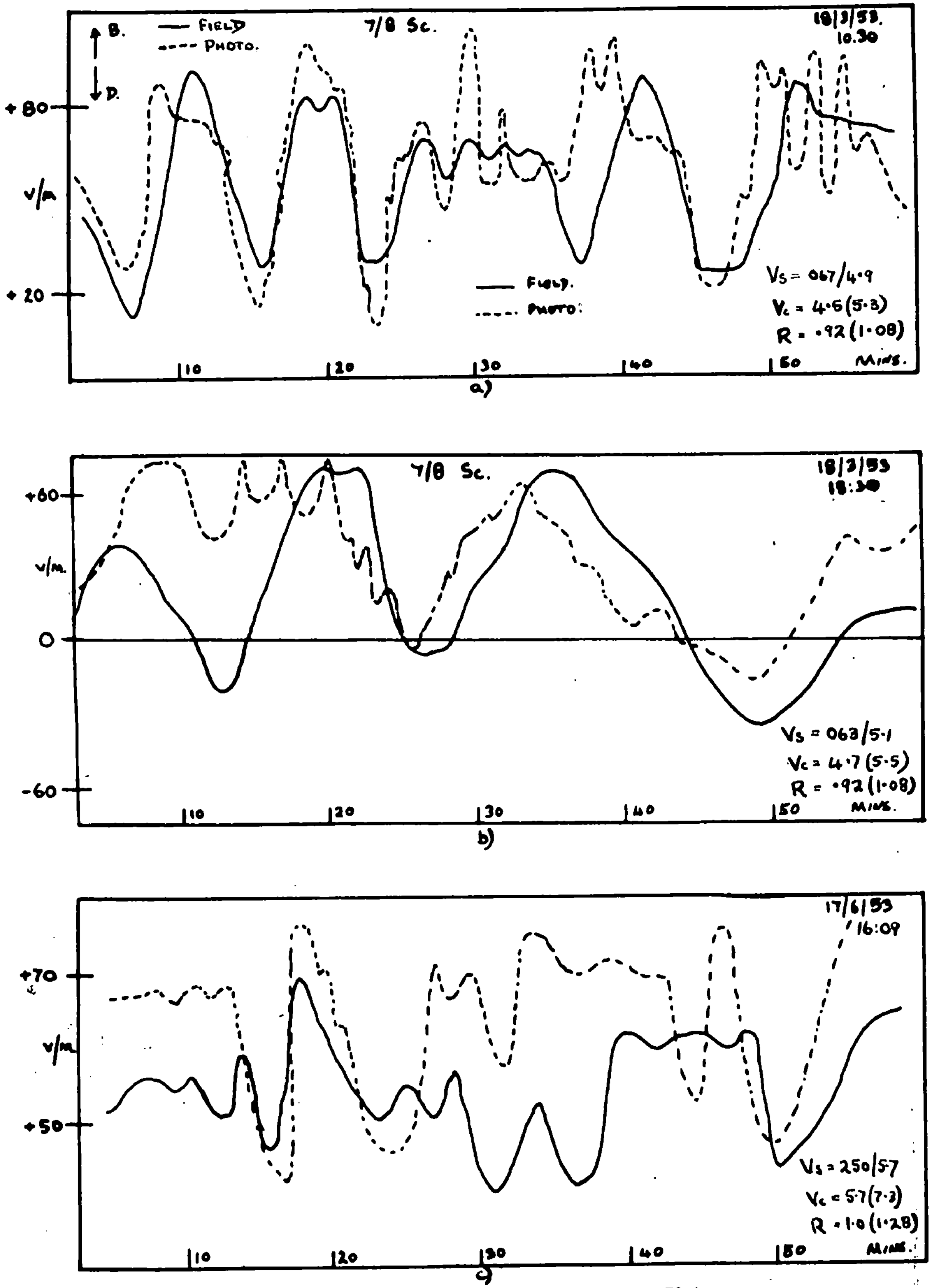


Fig.39 <u>Fields under Overcast Skies.</u>

and on that day one of the most interesting records of the whole investigation was obtained. Fig.39a shows the morning record made under thick Sc. The marked correlation between Photometer and field leaves little doubt that the wave-like variations of the latter were due to the passage overhead of a charge structure which varied periodically in space in almost the same manner as the cloud structure. Eye observations indicated some roll structure oblique to the direction in which the cloud was travelling. The time delays were very clear-cut and were consistent with charges travelling at cloud base level. Later in the day the Sc. thickened still more and negative fields occurred spasmodically, Fig.39b, indicating the presence of negative charges. Upper air reports indicated a freezing level at about 1600m, the cloud base was at 800m. Fig.39c shows a more typical record made under Sc. skies.

Figs.39a & 39b are very similar to some of Simpson's wave-like field patterns and occurred under the same conditions of low cloud and no precipitation. Whereas Simpson's patterns were usually symmetrical about zero and had amplitudes of about 500v/m, the waves illustrated here are assymmetrical and have much smaller amplitudes. However, there seems no reason to doubt that the same process is responsible for all such waves.

10.3 Discussion.

The field variations in mist and fog are well understood and the present investigation appears to have added little to the existing knowledge. A profitable line of investigation would be to mount two mills so that one was upwind and the other downwind, of a high tension line. This was actually tried, using the present mills as battery-operated portable instruments but on this first and only occasion the mist cleared whilst the mills were being set up and nothing of interest was detected. New high tension cables are being built round Durham City and eventually will encircle the Observatory and future field investigations will therefore be further complicated.

Turning now to a discussion of the wave-like variations of the field under overcast skies we may make one or two remarks before going into the problem in detail in the light of further evidence given later.

One explanation of these field patterns might be that periodic variations in the air-earth current are caused by variations in the total vertical resistance of the cloud which in turn is due to cloud thickness variations. Without going into a quantitative discussion of this hypothesis two facts suggest that such a process is very unlikely. In the first case it seems most unlikely that the lines of current flow could extend from the cloud to the ground yet retain a periodic structure in the horizontal cross-section. Long before the current flow lines reach the surface they would merge into an almost uniform current-field. From the records illustrated the field disturbances involved are about 80v/m in amplitude and simple calculations show that either the cloud thickness must be exceptionally great or that the internal conductivity must be very small if conductivity effects are responsible for the wave-like patterns. However, one factor above all appears to rule out conductivity effects as a major process; the occurrence of negative fields must be associated with negative charge and no pure conductivity effects at cloud level could possibly produce free negative charge in sufficient quantities to reverse the normal positive field.

The negative charge might have originated from high tension cables for in the case of 18/3/53 the wind was easterly. The nearest cables to the east of the Observatory are 4km away, therefore, for the charges to have reached the cloud base(800m) in a horizontal distance of 4km, their vertical velocity must have been 0.8/4 times the wind velocity. On the occasion under discussion the charges must have climbed at over 1m/sec in order to reach the cloud base by the time the cloud reached the Observatory. Such a rate of climb seems most unlikely. Of course, the charges might have originated further downwind but then one would expect them to be distributed between the cloud and the ground and not just in or near cloud base.

A hypothesis which seems to account for the observations is one which attributes the field patterns to alternate positive and negative line charges in the cloud base. The patterns of 18/3/53 can be explained in terms of lines charges drifting overhead with the wind. The problem remaining is to account for the presence of these charges. Are they left in the cloud long after precipitation has ceased or can charge be generated and separated in layer clouds without the necessity of precipitation reaching the surface? This problem is discussed later in the light of further evidence.

A fact that might have some bearing on the origin of undulating charge structures is that radar echoes reflected from layer clouds have been found, Browne(1952), to vary in intensity in such a manner as to suggest a striated cloud structure or a striated pattern of rainfall <u>within</u> the cloud.

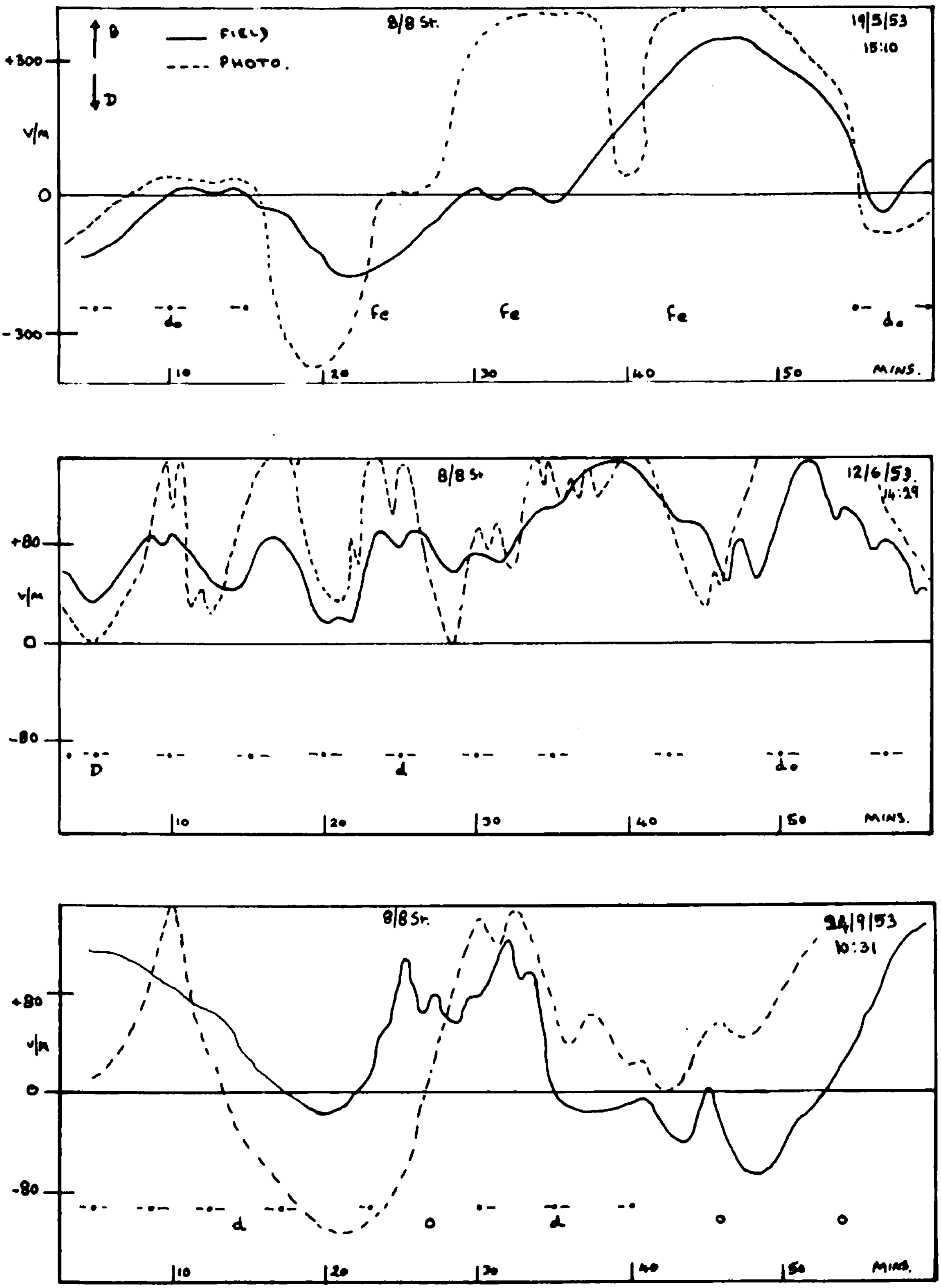


Fig.40 <u>Fields during Precipitation from St.</u>

1 Date & Time.	2 Weather.	3. Peak Fields	4. Vs.	5. Vc.	6. R.
14/5/53 10:26	8/8 St. Temp. 47° $r_o dd_o$O. Vis.5km Cl.Ht.450m.Fr.2000m	+10 -220	070/7.0	7.5 (8.4)	1.07
19/5/53 10:09	8/8 St. Temp.49° DD. Vis.1km Cl.Ht.160m.Fr.3000m	0 -250	042/7.2	7.5 (7.6)	1.04
19/5/53 15:10	8/8 St. Temp.49° $d_o f_e f_e d_o$ Vis.300m Cl.Ht.0m.Fr.3000m	+340 -180	020/3.3	3.0	0.91
12/6/53 10:04	8/8 St. Temp.57° dd. Vis.1km Cl.Ht.300m.Fr.3000m	+40 -90	022/3.9	4.2 (4.4)	1.08
12/6/53 14:29	8/8 St. Temp.58° Ddd_o. Vis.800m Cl.Ht.300m.Fr.3000m	+150 +20	042/2.7	2.7 (2.7)	1.00
24/9/53 10:31	8/8 St. Temp.58° dOdO. Vis.4km. Cl.Ht.600m.Fr.2000m	+160 -70	300/3.2	4.3 (4.3)	1.35
24/11/53 14:44	8/8 St. Temp.44° dDd_oO. Vis.1km. Cl.Ht.450.Fr.2000m.	+190 +30	196/5.2	6.1 (6.2)	1.17
27/11/53 10:22	8/8 St. Temp.50° r_oOdr_o Vis.6km. Cl.Ht.700.Fr.2000m.	+40 -160	187/7.3	9.9 (10.6)	1.35
4/12/53 10:20	8/8 St. Temp.46° d_oOd_o. Vis.1km. Cl.Ht.800.Fr.1600m.	+80 -320	355/3.3	4.2 (4.3)	1.27
4/12/53 14:50	8/8 St. Temp.48° $d_o d_o$. Vis.1km. Cl.Ht.700.Fr.1600m.	+60 -420	355/3.2	4.4 (4.5)	1.37
10/12/54 15:00	8/8 St. Temp.33.5° $d_o d_o$. Vis.5km. Cl.Ht.300.Fr.500m.	+5 -145	128/4.3	4.3 (5.1)	1.00

Av. 1.16

Table 8 Conditions in Precipitating St.

11. PRECIPITATION FROM LAYER CLOUDS.

11.1 Rain and Drizzle.

In general the fields beneath precipitating Stratus cloud exhibit smooth variations of a hundred or so v/m about a small mean negative field. Table 8 gives the details of all the stratus periods covered by the investigation. Col.2 gives the usual details plus an abbreviated weather sequence and an approximate cloud height and freezing level. Instead of the usual mean field, Col.3 gives the peak fields which occurred during the recording. From Col.6 we see that the R values average to 1.16 and that the charge speeds when resolved along the cloud direction* are much greater than the surface wind speed. Such speeds are appropriate if the average charge height is about halfway between the surface and the geostrophic level. From the values of cloud height and freezing level it appears that the temperature of the cloud base was well above freezing on most occasions.

Fig.40 shows some typical records and again there is often a good correlation between field and Photometer output. In general there appears to be little to distinguish the fields under precipitating St. from those under non-precipitating St., except that the field strengths are usually greater in the former. The arrival of precipitation at the surface does not seem to influence the field to any appreciable extent. Field disturbances appear to be dependent on the cloud charges

(* These speeds are given in brackets under Vc.)

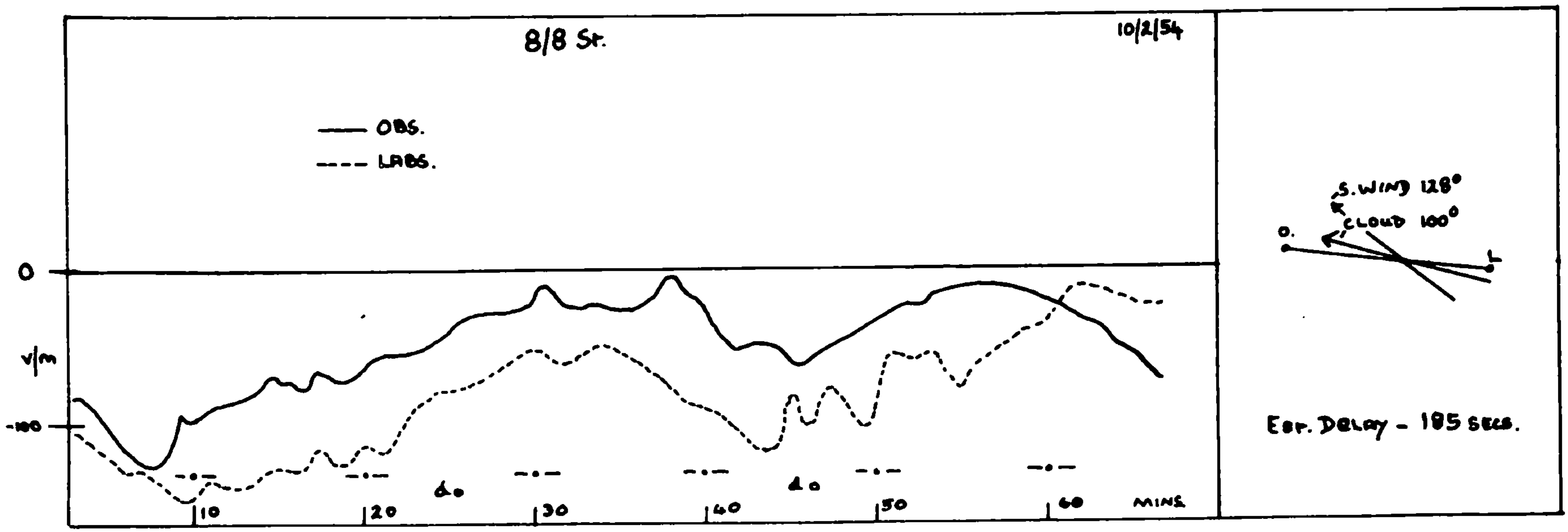


Fig. 41 Comparison of Fields over 960m.

1 Date & Time.	2. Weather.	3 Peak Fields	4. Vs.	5. Vc.	6. R.
27/4/53 10:48	8/8 Ns. Temp.45° Or$_o$r$_o$r. Vis.11km Cl.Ht.900.Fr. ?	-10 -780	075/8.0	8.9 (9.0)	1.11
12/5/53 10:14	8/8 Ns. Temp. 48° OOr$_o$O. Vis.11km Cl.Ht.800.Fr.2000	+145 -75	022/2.9	2.8 (2.3)	0.97
24/7/53 10:19	8/8 Ns. Temp.62° OrRr$_o$O. Vis.5km Cl.Ht.500.Fr.3600	+115 -70	190/5.2	7.1 (7.8)	1.38
24/9/53 15:11	8/8 Ns. Temp.52° Od$_o$r$_o$O. Vis.8km Cl.Ht.600.Fr.2200	+365 -300	356/3.2	4.2 (4.2)	1.31
30/10/53 10:11	8/8 Ns. Temp.48° r$_o$ror$_o$O. Vis.3km Cl.Ht.500.Fr.2000	+990 -1100	195/6.2	Too difficult to measure. (Pt.Space Ch.)	
30/10/53 14:33	8/8 Ns. Temp.47° r$_o$OO. Vis.6km Cl.Ht.700.Fr.1200	+170 +65	278/3.6	4.8 (4.8)	1.33
2/11/53 10:14	8/8 Ns. Temp.46° r$_o$r$_o$rO. Vis.10km Cl.Ht.1200.Fr.1000	+100 -150	233/5.9	8.6 (10.2)	1.46
12/11/53 15:26	7/8 Ns. Temp.52° Or$_o$r$_o$. Vis.9km Cl.Ht.600.Fr.1700	+155 +90	228/7.1	9.7 (9.5)	1.37
6/1/54 10:22	8/8 Ns. Temp.35° r$_o$r$_o$. Vis.4km Cl.Ht.600.Fr.500	+300 -245	345/6.0	8.3 (8.1)	1.38
24/2/54 15:09	7/8 Sc. Temp.44° r$_o$r$_o$. Vis.5km Cl.Ht.1000.Fr.700	+170 +80	212/7.6	7.9 (7.8)	1.04
14/5/54 14:39	8/8 Ns. Temp. 48° r$_o$r$_o$. Vis.3km Cl.Ht.300.Fr.2000	+640 -780	023/4.4	5.1 (5.1)	1.16

Av. 1.25

Table 9 Rain from Layer Clouds.

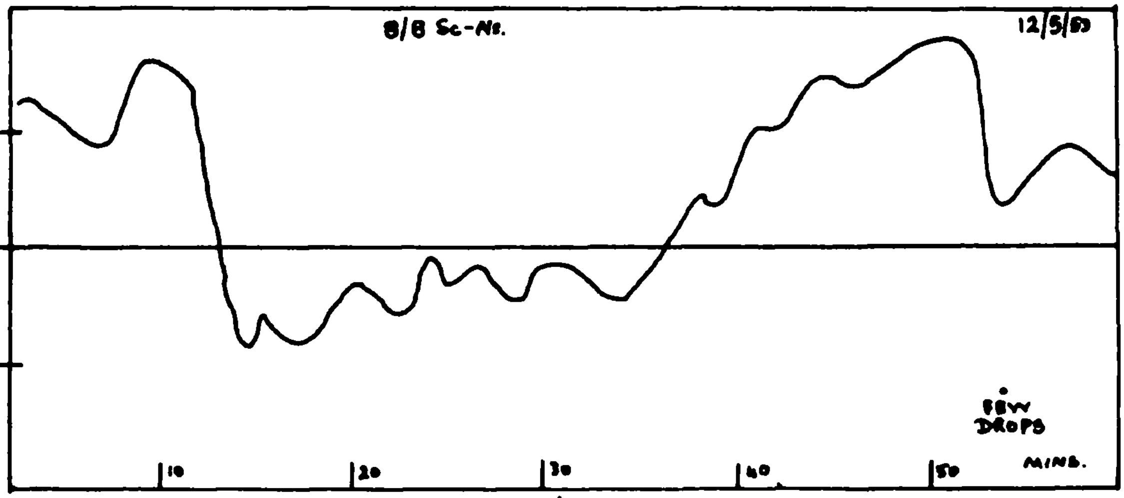
more than anything else. The thickest or more dense regions of the cloud appear to contain the most negative charge. On some occasions the field was at all times positive during precipitation, on others persistent negative fields occurred long after precipitation had ceased.

The fields at the Laboratories and the Observatory have been compared in Fig.41. As often with small fields the variations at the two sites differ so much that it is difficult to measure the time delays. The estimated delay given on Fig.41 assumes the charges moved with the surface wind.

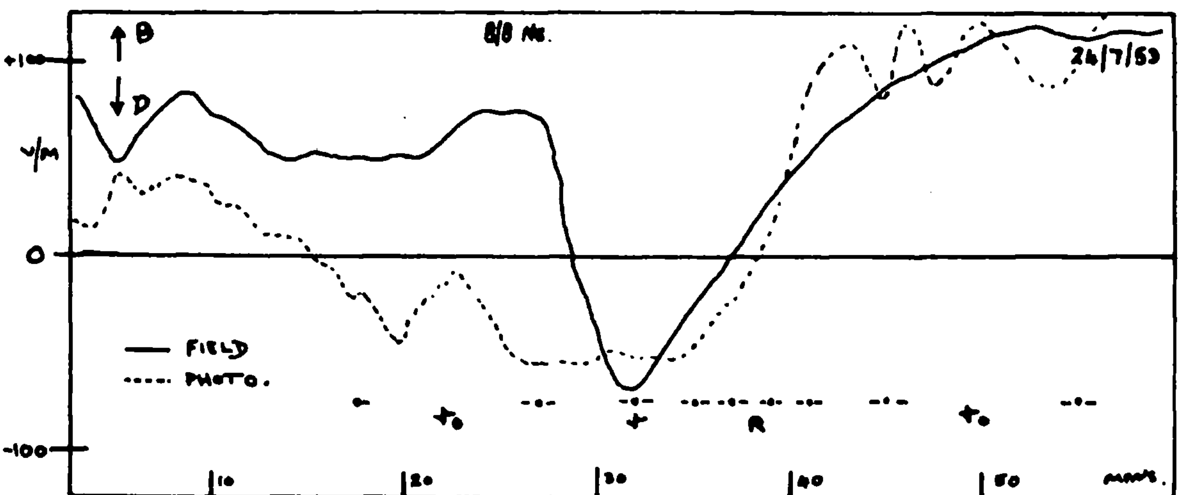
On most occasions under St. the field variations were of a wave-like nature. There is little doubt that these waves are due to the horizontal motion of charges within the cloud layer and that the charge distribution tends to be governed by the structural variations of the cloud.

Precipitation from Ns. is usually much heavier than that from St. so it is to be expected that the associated fields are also larger. This is verified by Table 9 for here the maximum fields exceed 1000v/m. In general, the fields under Ns. show variations similar to those under St. but the changes are more rapid and have greater extremes. The mean R in Table 9 is 1.25, which suggests that the main charges have a mean height which is greater than in previous cases.

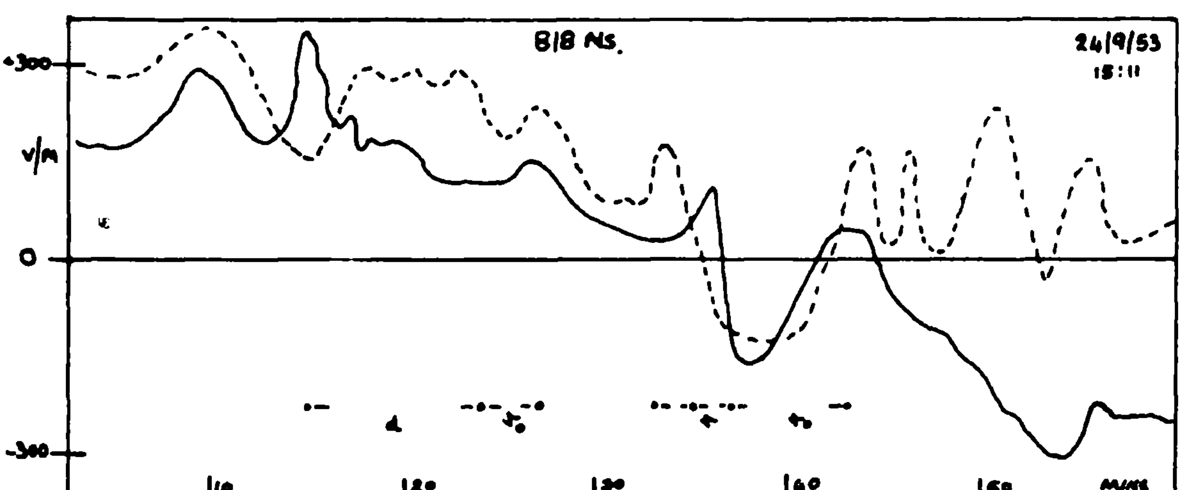
That rain is not essential for fairly rapid field changes is shown by Fig.42a, which shows field changes before rain



a)



b)



c)

Fig.42 Fields during Precipitation from Ns.

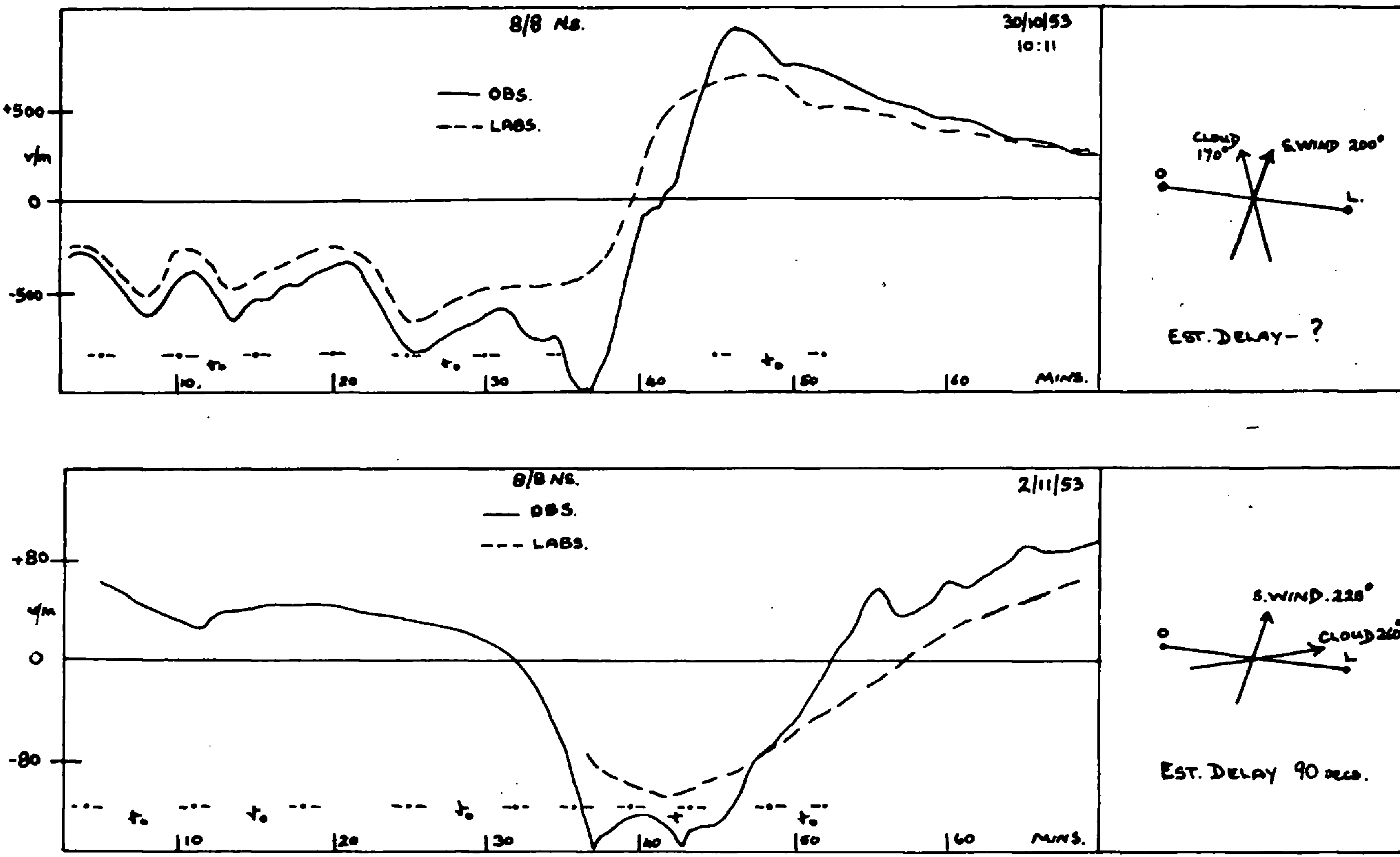


Fig.43 Comparison of Ns. Fields over 960m.

commenced. Generally the field is rapidly changing when heavy rainfall reaches the surface but the peak fields do not always occur at the time of maximum rainfall. Although the surface field appears to be dependent on cloudborne charges more than any other, there were occasions when it looked as if the charge on raindrops might account for the rapidity of the field change.

Fig.43 shows the simultaneous fields at the Laboratories and the Observatory and illustrates how charge motion is governed primarily by cloud movement. Attention is drawn to the fairly rapid field change in the absence of precipitation. Such changes cannot be explained in terms of point charges but might occur beneath the junction of sheet charges.

11.2 Snow and Sleet.

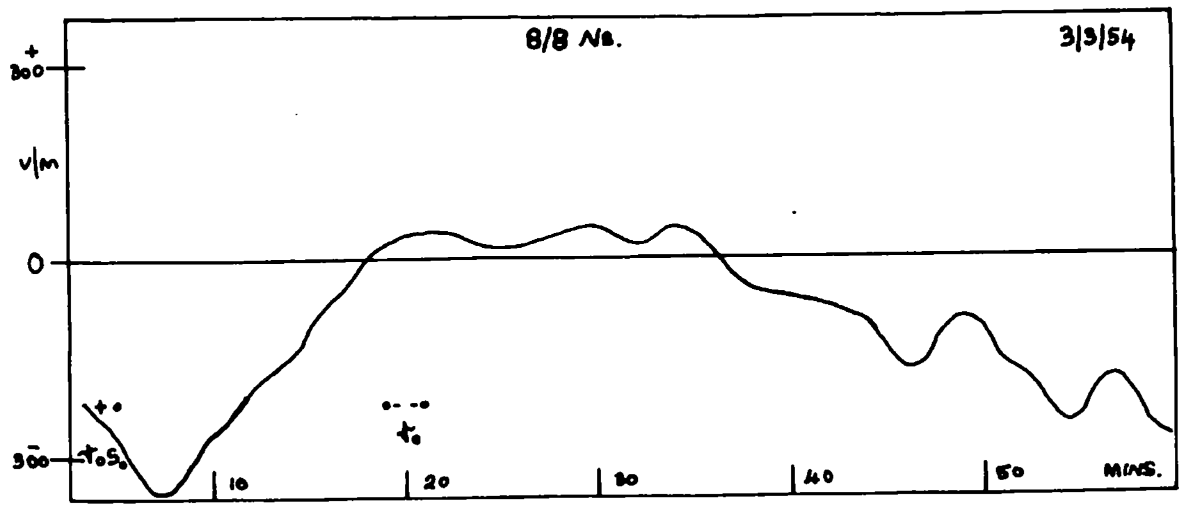
There were only six occasions during which snow or sleet fell from layer clouds(including one case of Sc.) so that the records may not be representative of normal conditions. Table 10 gives the usual details, while all six records are reproduced in Figs.44 and 45. In snow the Photometer is unreliable because the flakes tend to obstruct the aperture.

A unique feature of the fields in snow is the high frequency of occurrence of large positive fields. Fig.45 in particular shows a continuous positive field of over 400v/m.

An interesting recording is that of 4/3/54, Fig.46. For

Date & Time.	Weather.	Peak Fields	Vs.	Vc.	R.
12/2/54 15:08	8/8 Ns.Temp.35° $r_o s_o r_o s_o$.Vis.1km Cl.Ht.300.Fr.800	-100 -350	153/3.9	8.8 (8.8)	1.49
26/2/54 16:19	2/8Sc.5/8Ac.T.35° bc$r_o$sobc.Vis.5km. Cl.Ht.800.Fr.300	+700 +320	307/6.6	7.7 (8.0)	1.16
27/2/54 10:37	7/8Ns. Temp.34° 00$s_o$bc.Vis.5km Cl.Ht.1000.Fr.100	+500 -190	345/5.2	6.7 (5.5)	1.29
3/3/54 10:35	8/8 Ns. Temp.35° $r_o s_o r_o$0.Vis.7000m Cl.Ht.250.Fr.100	+25 -195	165/2.8	4.6 (4.4)	1.64
4/3/54 10:36	8/8Ns. Temp.35° $s_o r_o r_o s_o$.Vis.6km Cl.Ht.800.Fr.300	+180 -585	350/6.0	9.2 (9.1)	1.39
4/3/54 14:30	8/8 Ns. Temp.33° ss. Vis.-var. Cl.Ht.700.Fr.300	+1400 -1300	352/7.5	11.2 (11.1)	1.49
				Av.	1.41

Table 10 Snow and Sleet conditions.



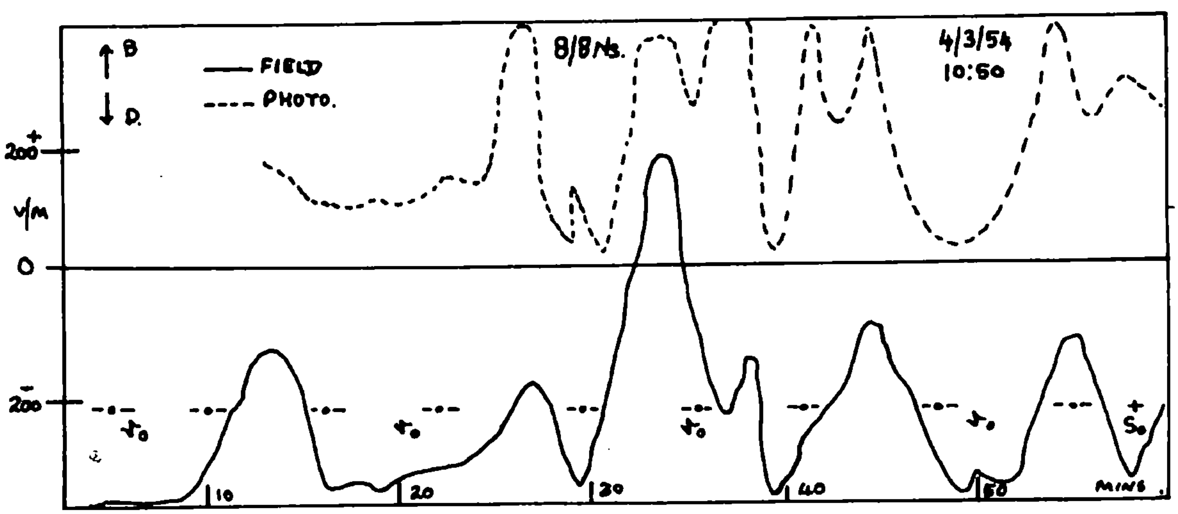


Fig.44 Fields under Ns. with sleet.

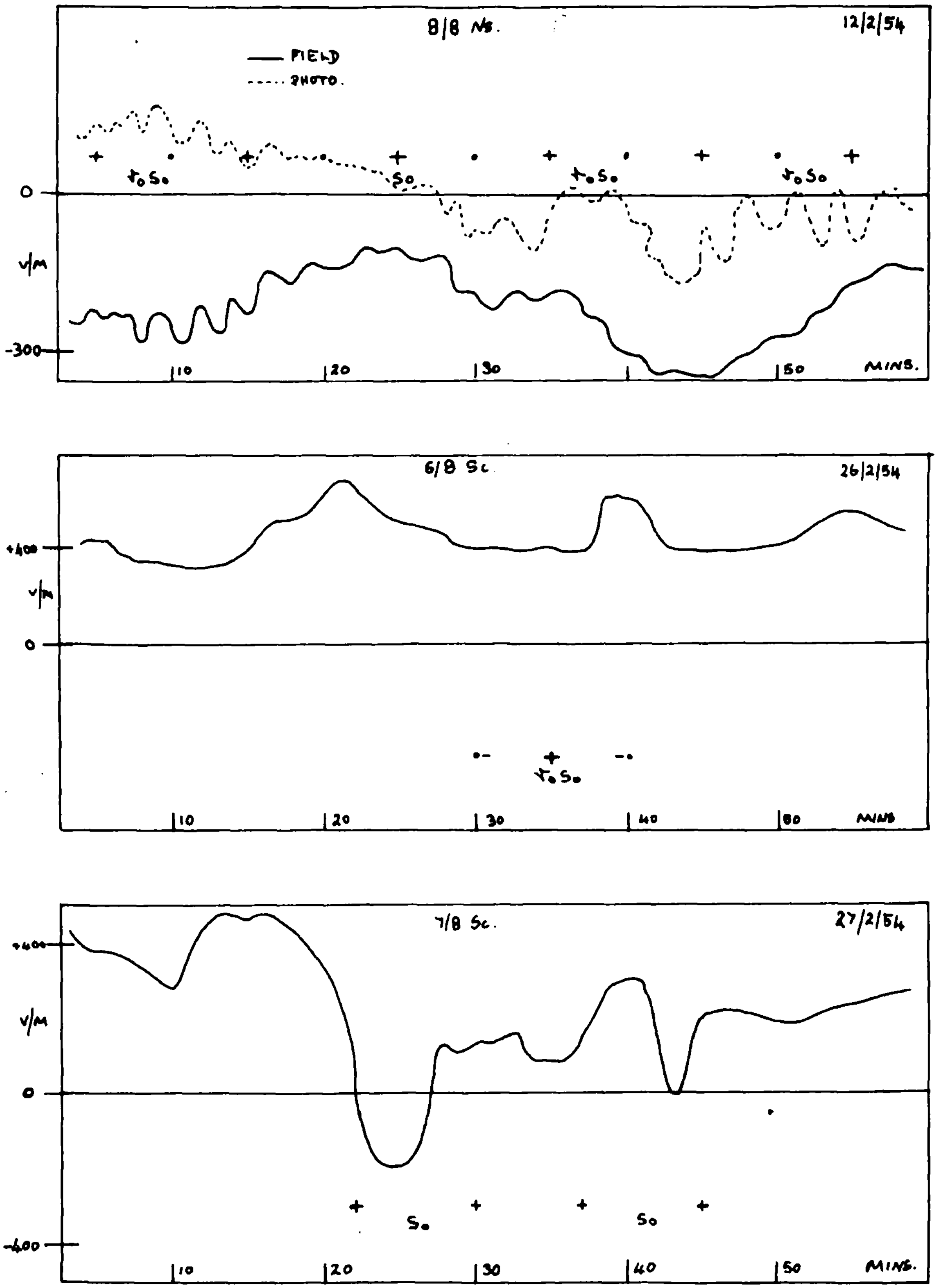


Fig. 45 Fields in sleet and snow.

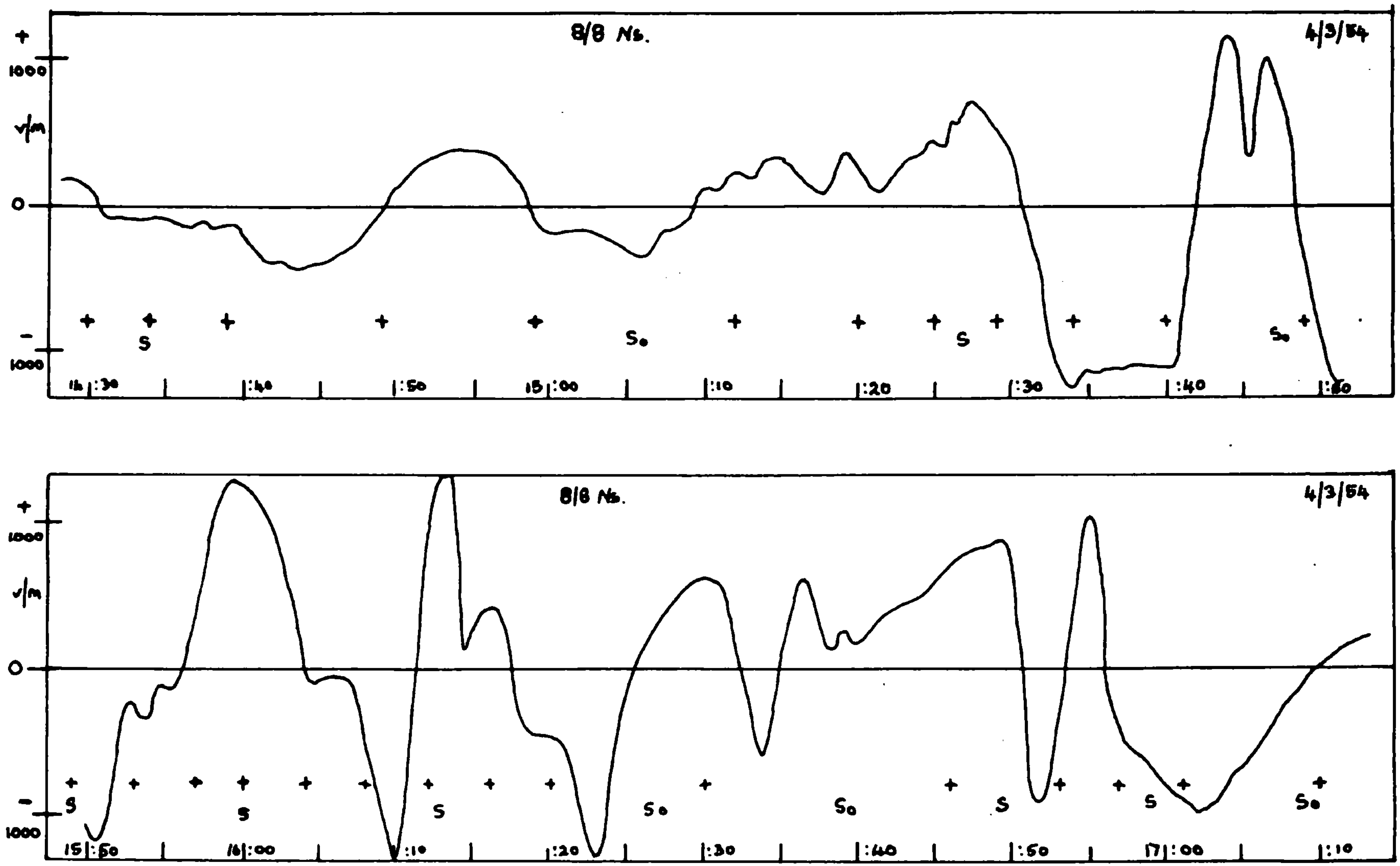


Fig.46 Fields during Continuous Snow from Ns.

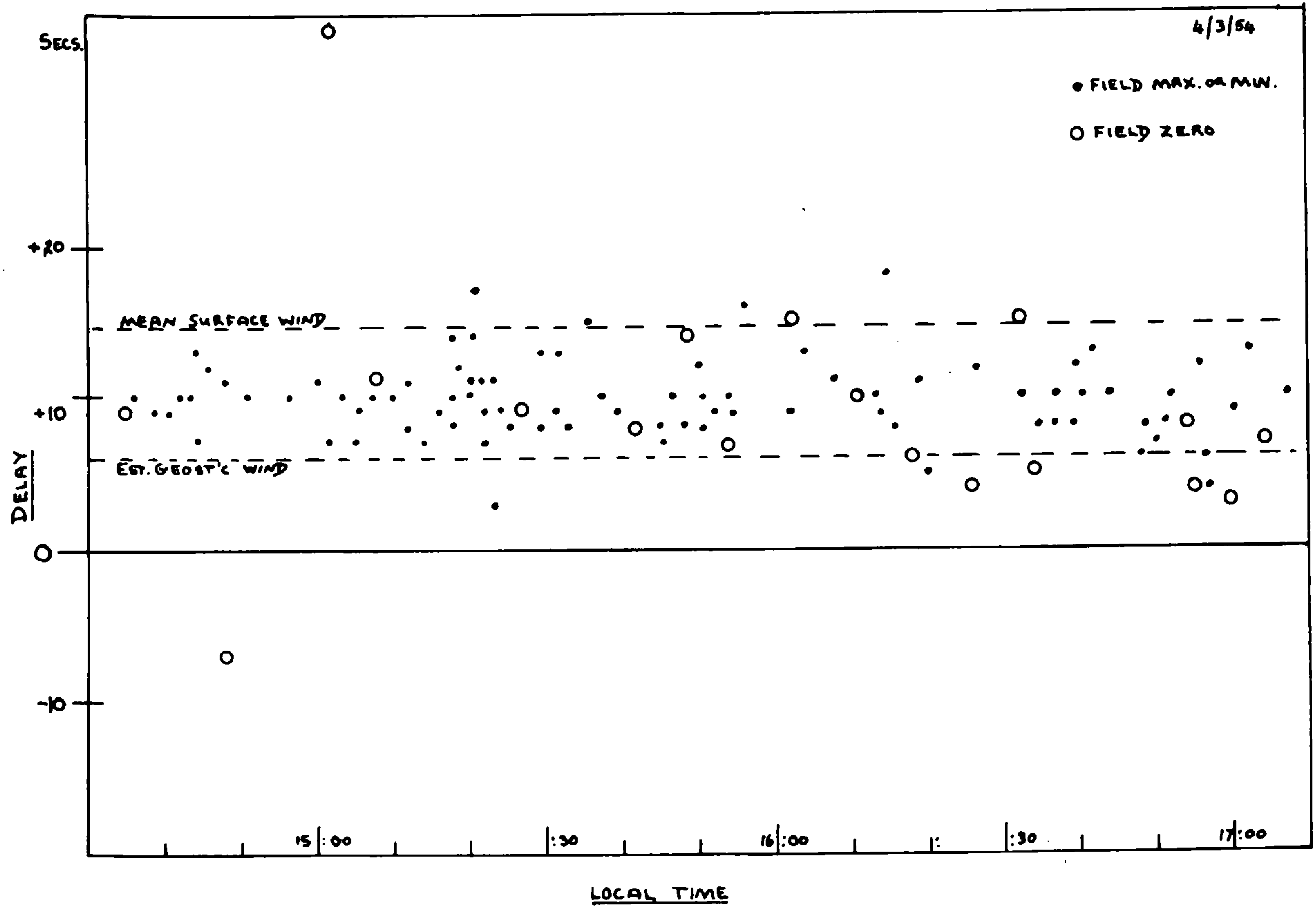


Fig. 47 Details of Delay Times from record 4/3/54.

over two hours continuous snow fell from Ns. and during this period there were eighteen field reversals. The field variations were wave-like with an amplitude that rose to a maximum and then decayed. Nothing was observed which might have accounted for these variations but then the visibility was very poor so little but snow could be seen. This type of field pattern has received considerable attention from others (discussed later) so it was thought worth while to plot every value of the measured delay times for the whole record. This has been done in Fig.47 and the result shows fairly conclusively that the patterns were caused primarily by charges moving with the wind between the surface and the geostrophic level. The dotted lines indicate the delay times expected if the charges had moved with the mean surface wind or with the geostrophic wind as calculated from the pressure distribution given on the D.W.Report.

11.3 Discussion.

It seems appropriate at this point to discuss possible charge generation processes in Stratus clouds, for this problem has received little attention in the past, yet offers conditions which are much more amenable to accurate measurement than those associated with storm clouds. It is not suggested that the same processes are responsible for the main charges in both layer and Cb. clouds but an understanding of one process should be an aid to investigators working on other charge separation problems. A distinction is made between processes in Stratus and Nimbo-stratus clouds. Such a distinction is probably justified, for the method by which precipitation is formed appears to be different in the two cloud types.

a) Charge Separation in Stratus Cloud.

From the present investigation the following impressions have been gained.

i) Generally the field is negative under continuous St. cloud. This implies a negative charge above the surface of the earth and the results suggest that this charge is on or near the cloud base. Such charge is often present on non-precipitating clouds.

ii) It appears that the thicker or denser portions of the cloud contain the more negative charge. Positive fields often occur under lighter parts of the cloud. As positive and negative charge pockets move with the wind so the surface field shows undulations in the form of waves.

iii) During the periods investigated the average height of the freezing level was 2.2km, whilst the average height of the cloud base was 450m. Therefore, it appears that the main negative charge was well below freezing level, unlike the main negative charge in thunder clouds.

iv) Precipitation itself does not seem to influence the course of the surface field to any great extent but the clouds responsible for or containing incipient precipitation carry appreciable charges which determine the main surface field variations.

Although most of these points are not new, some are worthy of further discussion. There is little doubt that the main negative charge is in or near the cloud, therefore, any suggested charge separation process which leaves the main negative charge near the surface may be ruled out. Mason and Hopworth(1952) found that drizzle frequently fell from St. under conditions which suggested that the drops were formed by a coalescence process and that ice crystals were not present. Only when the cloud-top temperature fell below -12° did the concentration of ice-forming nuclei become significant for precipitation release. The present work found negative fields under drizzling St. under conditions which suggested that the whole cloud was below freezing level. Hence it seems that the ice phase of water is not essential for separation of charge in St. cloud. If this is true, then many of the current theories of charge separation are not applicable to the St. cloud.

The two current theories which might be applicable are those of Wilson(1929) and Frenkel(1944). Consider first the applicability of the Wilson process. In the very early stages of development the field within the cloud will be about

+200v/m, assuming a straightforward flow of air-earth current through the cloud. If we assume the small ions within the cloud to have mobilities of about 10^{-4}m/sec. v/m then they will move vertically at speeds of about 2×10^{-2}m/sec. As the cloud developes the largest droplets might have diameters of about 0.1mm and so fall, relative to the surrounding air, at speeds of about 0.2m/sec. Hence the drops will fall faster relative to the downward moving positive ions. Vertical air velocities in St. are of the order of 0.1m/sec and a general uplift at this rate might be sufficient to carry the positive ions upwards yet allow the drops to continue their earthward movement. Such is the situation in which charge might be separated by the Wilson process, for the polarised drops would selectively capture negative ions and so carry negative charge to the cloud base. As the cloud developes so the rate of settlement of the larger droplets will probably increase and negative charge will tend to accumulate in the lower regions of the cloud. When sufficient negative charge has accumulated the field between the cloud base and the surface will become <u>negative</u>. Within the cloud the field is <u>positive</u> and will increase until ion velocities overcome the effects of the general uplift of air. Up to this point we have assumed that no precipitation has reached the surface, we now consider what happens when the droplets reach a size which will enable them to survive the journey to the ground. An obvious suggestion is that the Wilson process again occurs, only this time in a negative polarising field. During their fall the drops will capture positive ions and so reach the surface carrying positive charge. If, for some reason, the charge distribution in the cloud is reversed, for example, by the overturning effects of air currents within the cloud which might force positive charge to the base, then the drops will arrive at the surface carrying negative charge. Hence we should expect the "mirror-image" effect in precipitation from St., even without point discharge.

It is appreciated that the above theory has many weaknesses and that there are a number of observations which do not seem to fit the picture. Simpson(1949) could not explain his results in terms of the Wilson process. His results, however, were averaged over all quiet rain conditions and therefore included Ns. cloud which usually contains ice. In addition, his apparatus may not have responded well to the very fine rain or drizzle of St. Stockill(1955) using a more refined apparatus than that of Simpson finds that the "mirror-image" effect does in fact occur during fields which are too small to permit point discharge. Further, Stockill found that when plotting rain current against surface field, negative intercepts were more common, that is, as the current tended to zero, so the field tended to a small negative value. Simpson found that for small positive currents the field was positive, so concluded that the rain charge could not have appeared as the result of the Wilson process. Stockill also found that changes in the sign of rain current tended to lag behind the associated changes in field. Such results are to be expected if the double Wilson process is operative in layer clouds. The results of Smith(1951), although not confined to layer clouds, leave little doubt that the electrification of rain-drops may be adequately explained in terms of a selective ion-capture process.

Naturally actual measurements made in warm clouds would remove a great deal of speculation but few such measurements appear to have been made. Gunn(1952) made some measurements in warm swelling Cu. and although he found that in a particular cloud the larger droplets carried positive charges, he remarks,"The writer's impression of the measurements was that warm clouds about to precipitate carried negative charges on the larger droplets; while clouds that were more stable tend to carry positive charges on the heavier droplets". A further observation that might be relevant is the detection of negative precipitation currents in wet fog, for example, Nolan(1940) and Scrase(1933). Conditions in wet fog must be very similar to those in St. and if, as it has been found, the largest droplets carry negative charge in a positive field, then a similar transportation of charge might occur in cloud.

There seems to be no obvious reason why Frenkel's process should not operate in clouds although it would be difficult to distinguish from the Wilson process. However, the Frenkel process cannot explain the positive charge on precipitation at the surface.

Some explanation is required for the frequent good correlation between field and Photometer output. This output presumably varies with cloud thickness or density. The thicker the cloud the greater the probability of growth of the droplets by the coalescence process and hence the greater their downward migration. As the number of falling droplets increases so the rate of charge separation will be greater and hence the larger the negative field below the cloud. The fact that lighter regions of the cloud often show positive charges might be explained simply in terms of downward directed air currents which bring upper cloud charges down or perhaps it is just the effect of the Fair Weather positive space charge breaking through the thinner regions of the cloud.

There is a fundamental problem regarding the electrical structure of layer clouds, the answer to which would remove most of the speculation. Is a typical layer cloud bi-polar, i.e., is there an upper positive charge, or is the cloud uni-polar with the positive charge carried to earth on the precipitation? Simpson(1949) could not accept the bi-polar picture but it is the writer's belief that this picture is the more acceptable, for not only does it agree with the shower and storm cloud picture but most of the observed phenomena can be explained if one assumes an upper positive charge. If we assume this charge to be carried down on rain then we are faced with the difficulty of explaining negative precipitation currents in positive fields. Further, it is not easy to explain how negative charge appears on the base of non-precipitating clouds, or what happens to the positive charge on drops if they evaporate before reaching the ground. Above all there appears to be no adequate explanation as to how the drops acquire positive charge in the first place.

b) Charge Separation in Nimbo-stratus.

Generally Ns. cloud is much thicker than St. and extends far above the freezing level. Ice crystals play a vital part in precipitation processes, consequently any charge separation might involve the ice phase of water. Although the Wilson or the Frenkel process could operate in such clouds, it is very probable that some other process supplements the charges generated by the selective capture of ions by water drops.

The present investigation found little that might be of value in identifying the processes involved in Ns. but the writer's general impression throughout the whole of the investigation was that the basic processes of charge separation in <u>all</u> clouds produced similar external effects. The most influential charge is nearly always the negative charge on the cloud base and many of the electrical characteristics under layer clouds are found to occur under Cb. The magnitudes of the fields involved are, of course, very different and very large fields bring secondary processes into play which complicate the picture.

c) Fields in Snow.

The main question that arises out of the study of fields in snow is why are the fields frequently so large and positive? Snow blown up from the surface might contribute a considerable amount of positive charge to the air and it may be that this charge is superimposed on the charge system which has been generated within the clouds by the double Wilson process previously suggested.

The wave-like pattern of Fig.46 is of particular interest for Chapman(1949) and Simpson(1949) have both recorded similar patterns. Chapman used two point dischargers, separated by about 3km, to measure field and came to the conclusion that the field changes could not be due to windborne charges. The delay times between the corresponding field changes at each site were, according to Chapman, about 1/2 to 1/3 of the value expected if the surface wind was responsible for carrying the charges. Such anomalous results can be explained partly by the fact that the main charges were moving with the winds a few hundred metres above the surface and partly by assuming that Chapman's dischargers suffered from point space charge effects(discussed later) which act in such a manner as to give the impression of high horizontal charge speeds.

The cause of the patterns is not really known. A possible explanation is that vertical air currents within and below the clouds modify that basic charge distribution so as to create a horizontal arrangement of positive and negative charge centres. Many of the field variations might be due to the charges on the falling snowflakes but not all the charges can be confined to the first few hundred metres, for Chapman found field reversals up to 3,000m during steady snowfall at the surface.

12. THE CUMULO-NIMBUS CLOUD.

This section deals with the most electrically active of all clouds, that is the shower and thunder cloud. The electrical and meteorological conditions associated with such clouds are usually very complex, therefore, each cloud situation is discussed individually, beginning with the simple cases and concluding with the complex conditions under thunder clouds. In many cases only a few determinations of the delay times were possible, either because the field disturbance was relatively simple or because there was just no correlation between the upwind and downwind fields. Hence the values of Vc given on the following diagrams must be treated with some reservation. In many cases simultaneous recordings were made at both Laboratories and Observatory but in order to prevent confusion in the diagrams the Laboratories records have been reproduced only when a particular point requires illustration.

As previously discussed in Section 7.2, current flowed from the point discharger only when the field strength exceeded 400v/m. Therefore, it seems appropriate to classify the records obtained under Cb. clouds into two groups. The first containing disturbances during which the field did not exceed 400v/m, whilst the second group is concerned with conditions during which the field exceeded 400v/m, for in this case point discharge currents played an important part in determining the field at the surface.

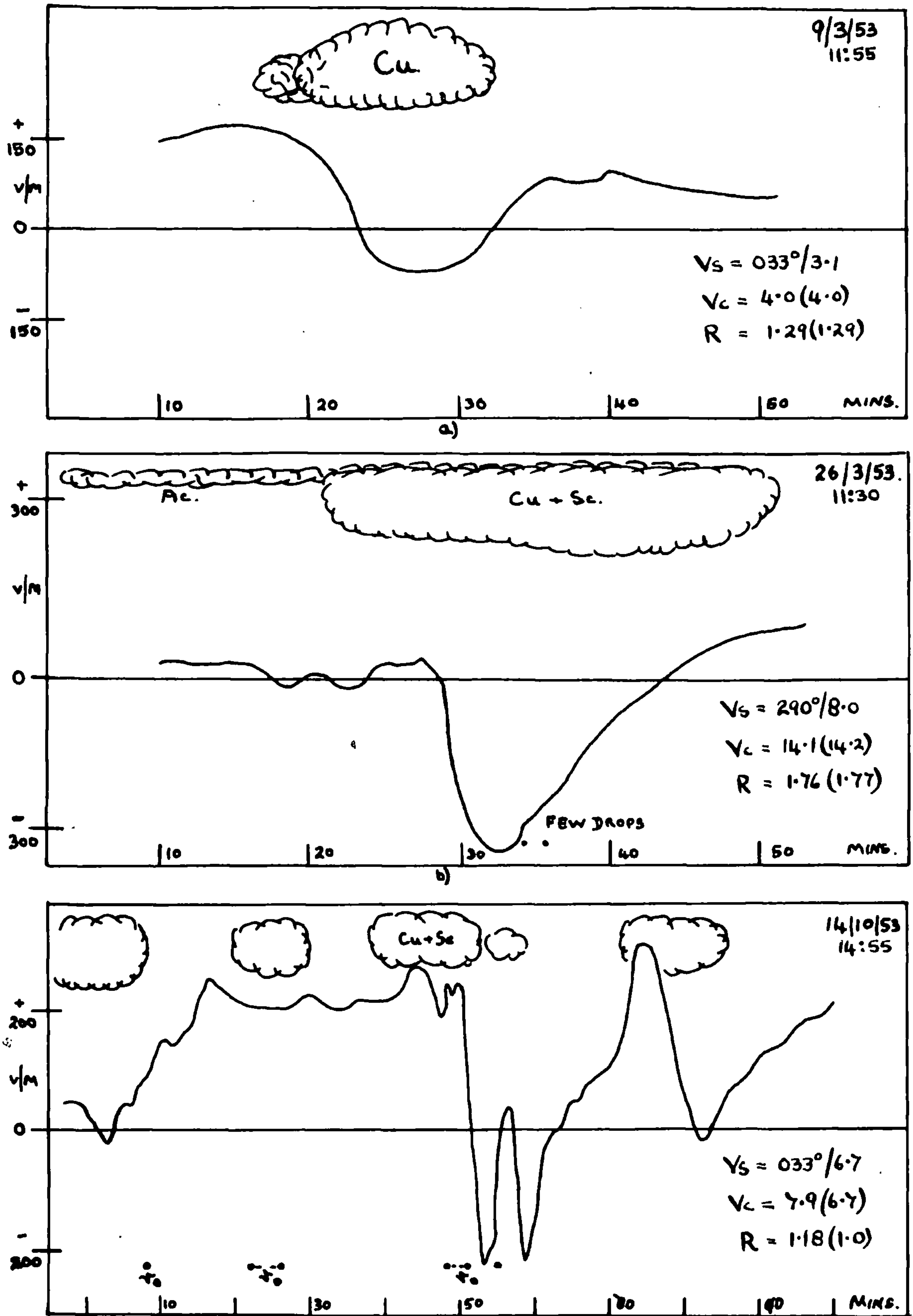


Fig.48 <u>Fields beneath Small Shower Clouds</u>.

12.1 Rain Shower Clouds, E<400v/m.

If there is a net negative charge on the base of a Cu. or Cb. cloud, then this charge will create a V-shaped disturbance at the surface as the cloud passes over. Fig.48 gives three examples of this basic pattern, with and without minor modifications. In all three cases the clouds appeared to be towering Cu. rather than Cb. for they had little vertical development and no Ci. tops.

Fig.48a illustrates an uncommon occurrence, for here the cloud produced a negative field at the surface yet no precipitation reached the Observatory. In fact no precipitation was reported anywhere in Great Britain during that particular day.

On 26/3/53, Fig.48b, the field had been very small below an extensive sheet of thick As. but, as a pack of Cu. and Sc. passed over, there occurred a sudden negative field excursion followed shortly afterwards by a few drops of rain.

On 14/10/53 a succession of large towering Cu. passed over and three distinctive patterns were recorded, Fig.48c. On one occasion a brief negative excursion was recorded without precipitation whilst the main pattern was associated with a few spots of rain and showed slight modification of the basic V form. Attention is drawn to the fact that the rain reached the surface at the time of the maximum field change.

Fig.49a illustrates a pattern very similar to that of Fig.48c. Again the rain reached the surface at the time of

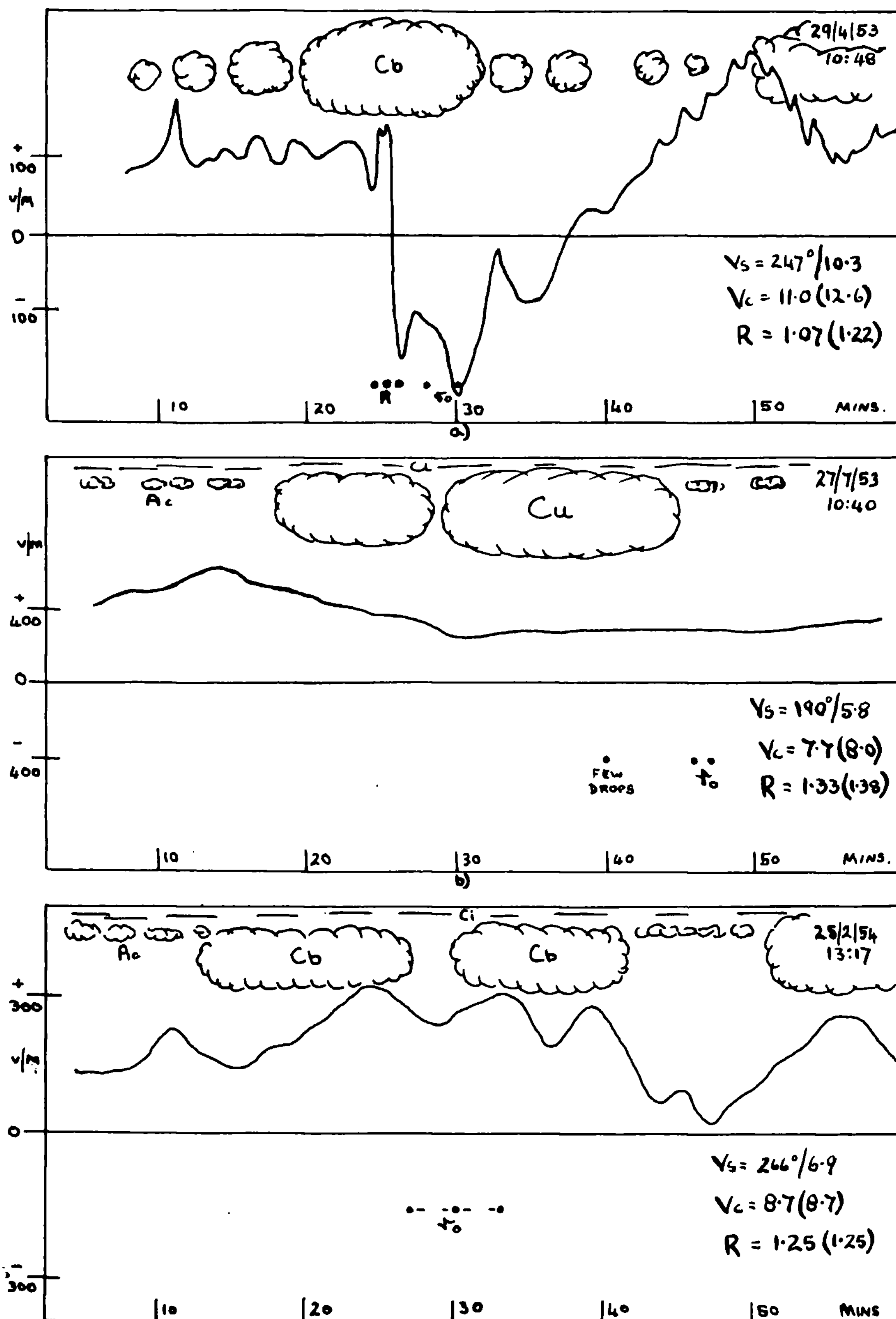


Fig.49 Fields beneath Small Shower Clouds.

maximum field change. The cloud type has been designated Cb. mainly because of the intensity of the precipitation but it had little vertical development and no Ci. top.

Exceptions to the general rule are illustrated in Figs. 49b and 49c, for here the field appeared to suffer no disturbance although rain fell from well defined towering Cu. These clouds appeared to be no different from the towering Cu. which caused negative fields but there must be some factor operative in such inactive clouds which prevents the separation of appreciable charges.

A number of points arising out of Figs.48 and 49 require further discussion. It is possible for a single Cu. or Cb. cloud to produce a well defined V pattern without the necessity of precipitation reaching the site at which the field is measured. It also seems possible that Cu. clouds might carry net negative charge in their bases even though no precipitation falls from the cloud. On the other hand the fact that precipitation falls from a cloud does not guarantee the presence of appreciable net charges within the cloud. Hence it seems that the Wilson process might be operative in the early stages of Cu. development but the quantity of charge separated will probably depend critically on the vertical air currents within the cloud.

When studying Figs.48 and 49, it will have been noticed that three of the V patterns show a definite assymmetry about the peak of the V. The negative field appears to persist long after the cloud has passed and the effect gives one the impression that negative charge is trailing behind the cloud. Such a pattern might be produced if the raindrops carry negative charge on leaving the cloud base, then as they fall they will lag behind the cloud(due to the wind gradient) and if they evaporate before reaching the ground a region of negative space charge might be left in the air to hang from the cloud in the form of a tail. This lagging effect of the field is very common in Cb. conditions and further examples are given later. In general the V patterns cannot be explained in terms of a simple distribution of point charges nor by assuming a classical bipolar cloud. In many cases there was no indication of an upper positive charge but this might be due to the fact that the negative charge extends well below the cloud base and therefore screens any upper charge from an observer on the surface. In some cases the shower pattern tends towards a W form but no conclusive evidence is available which would identify the cause of the central positive peak. The general impression is that the field disturbances due to small Cb. are mainly due to the negative charge on the cloud base and partly due to charges on raindrops and space charge left in the air after the drops evaporate. Values of R also give the impression that the main charges responsible for the patterns are below the geostrophic or cloud level.

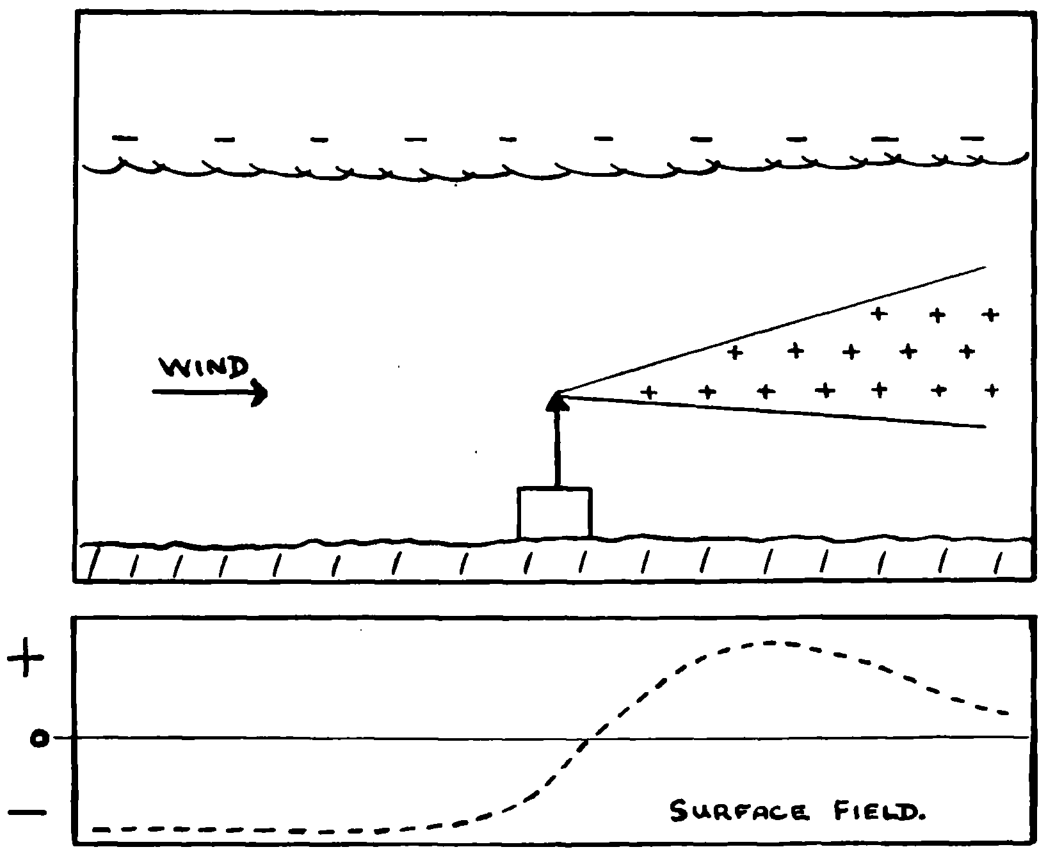


Fig.50 Illustrating the principle of the Point Space Charge Effect.

12.2 Rain Shower Clouds, $E>400$v/m.

For the moment we might assume that when current flowed from the point discharger above the Observatory the resultant space charge flowed from the point in a manner similar to that of smoke flowing from a chimney. Even if the space charge is carried on small ions then the ion motion must be determined primarily by wind motion, except in the immediate vicinity of the point where the electric field is intense. As the ions are carried downwind they will form an approximate line charge roughly parallel to the surface. Below this line charge the surface field will suffer considerable modification and this field modification will be referred to as the point space charge effect. This is discussed in more detail in Section 13 but for the moment we might assume that Fig.50 shows the principle of the cause and effect. When the field strength exceeded 1500v/m it is believed that current flowed from the anemometer mast, and for larger fields from trees, etc. Hence when the primary field was intense, considerable quantities of current flowed from the Observatory area and the effect of the space charge on the downwind field should be considerable. In order to determine whether or not the point discharger was essential for the point space charge effect the discharger was removed for a few weeks during the investigation. On the occasions when the point discharger was absent the appropriate diagrams have been marked "No Point".

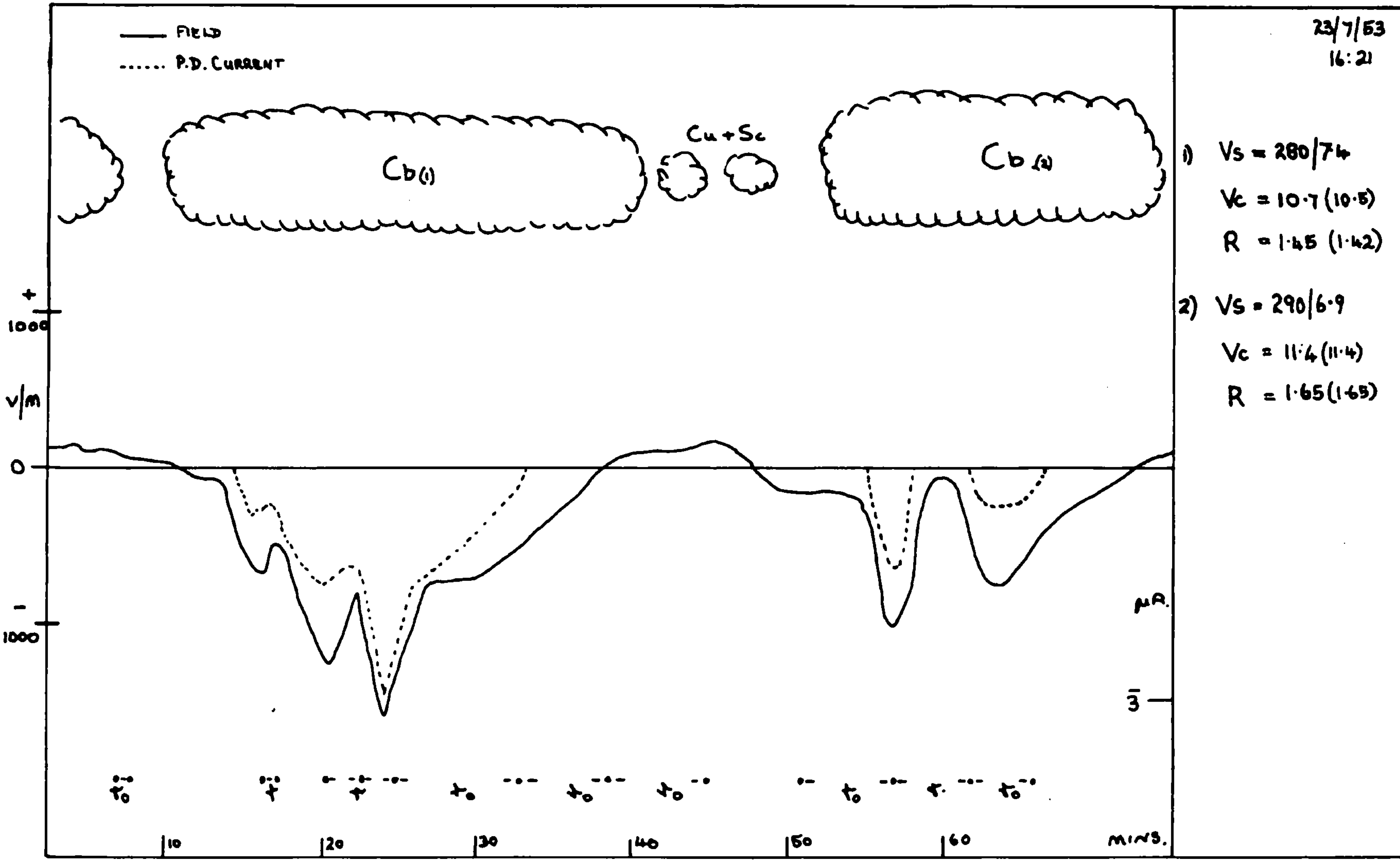


Fig.52 Field disturbances due to Shower Clouds.

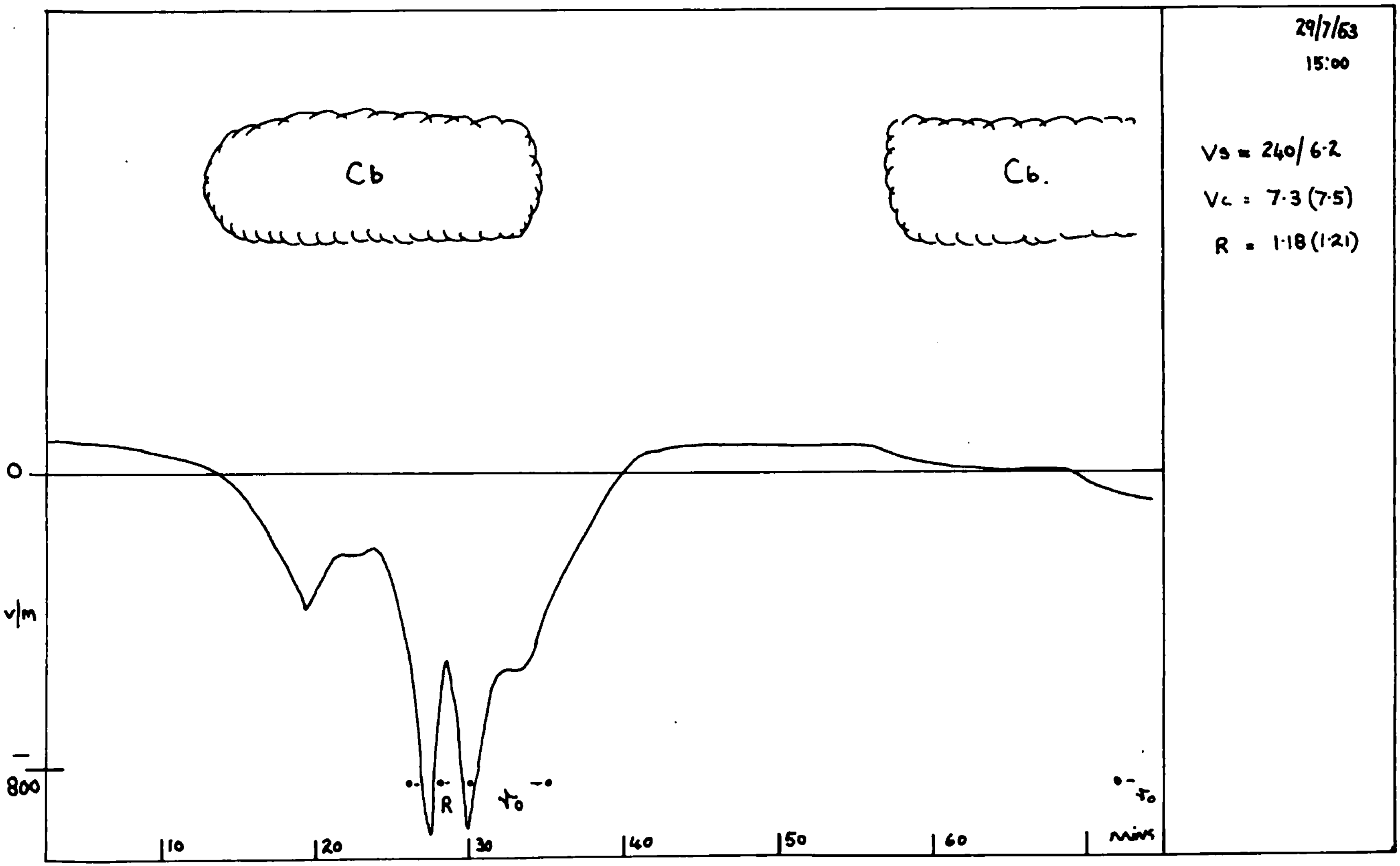


Fig.51 Field disturbance due to a Shower Cloud.

Fig.51 shows an example of a typical simple shower pattern, similar in form to those already discussed. (In the following diagrams the record is that obtained from the upwind mill at the Observatory unless otherwise stated). On the occasion of Fig.51, showers fell from small Cb. which were situated against a clear sky and had no Ci. tops. On this diagram the peak field and rain appear intimately connected and both lag behind the cloud. There is little doubt that the main field variations were due to the horizontal motion of charges associated with the clouds, or their rain, and this is supported by delay time measurements. The value of R is lower than would be expected if the main charges were entirely cloudborne. During the field disturbance the point discharge current reached a maximum value of 1.5μA. The effect of this current on the downwind field was slight and was of the form illustrated in Fig.68a, section 13.

Fig.52 shows two more simple shower cloud patterns which involved fields of just over -1000v/m. Again the clouds were isolated against a clear sky and no Ci. was visible. During the passage of both clouds the surface wind increased with the approach of the cloud, reached a maximum when the cloud was overhead, then slowly decreased as the cloud receeded. The wind direction veered during the speed increase. This type of meteorological disturbance has been associated with the passage of thunder clouds, (Byers(1953)), but no reference appears

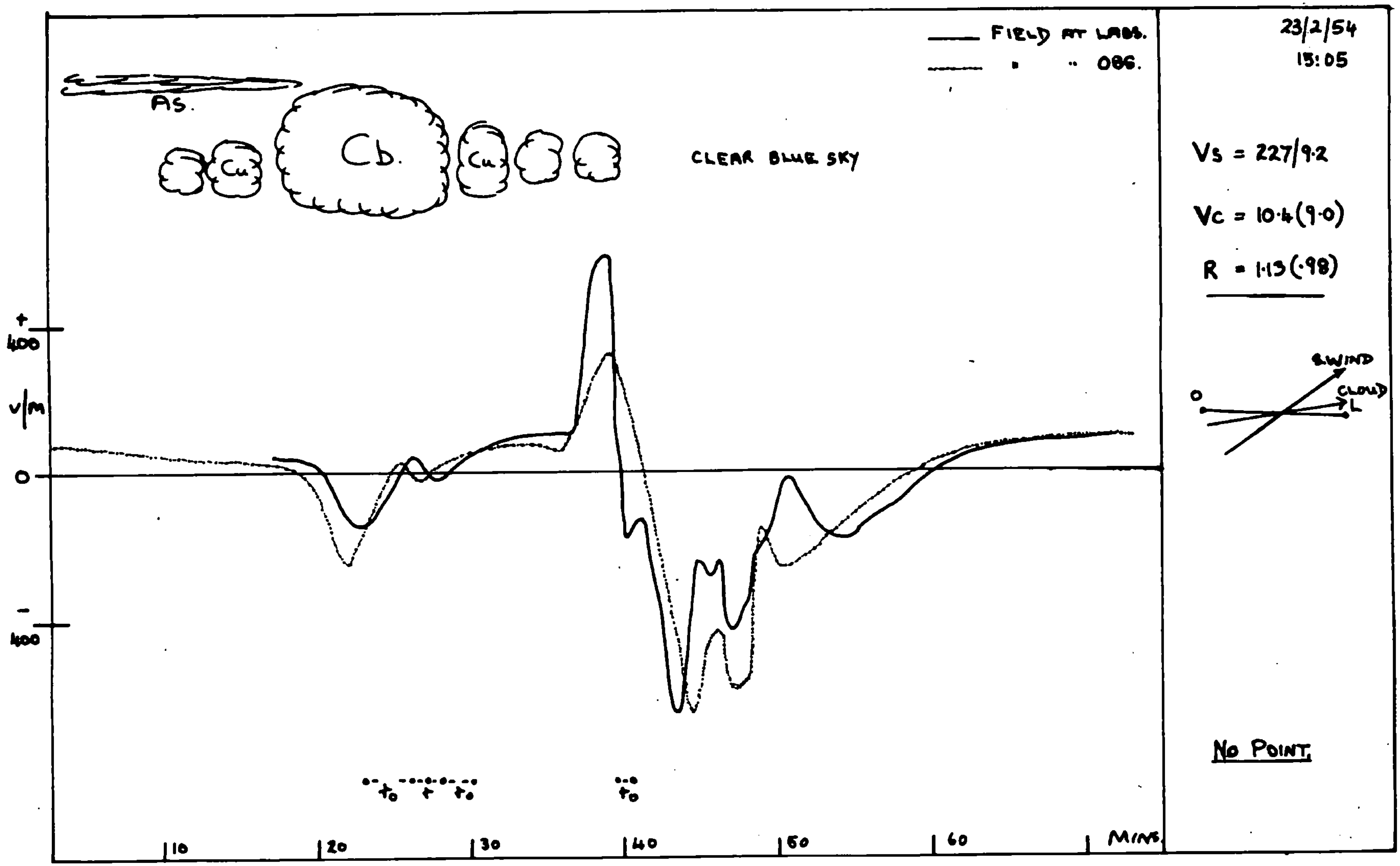


Fig.53 Anomalous field pattern due to a Shower Cloud.

to have been made associating similar disturbances with shower clouds. Another feature shown in Fig.52 is the approach to a W pattern under the second cloud. Nothing was observed which might have accounted for the distortion of the basic V pattern. About -1.3mC of charge was liberated from the point discharger during the first shower and this appeared to cause the downwind field to fail to reach the peak fields of the upwind pattern although the basic form of the pattern was the same at the two sites.

Fig.53 is an example of an anomalous field pattern. The main cloud appeared to be part of a weak cloud front and an excellent view of the cloud was obtained after it had passed, no Ci. top was visible. The remarkable feature of this pattern is that the peak fields occurred at a time when the cloud was over 10km away and with a clear sky overhead. A comparison is made on the diagram between the corresponding fields at the Laboratories and the Observatory to show how the pattern differed at the two sites. Again the results suggest that charges lag behind the cloud and that they are not confined to cloud level. It seems most unlikely that the main field variations were due to a change in cloud charge structure, i.e., a vertical motion of charge, or that any point discharge occurred in the area, for the point was not erected and the fields were not very large.

A particularly anomalous pattern is illustrated in Fig.

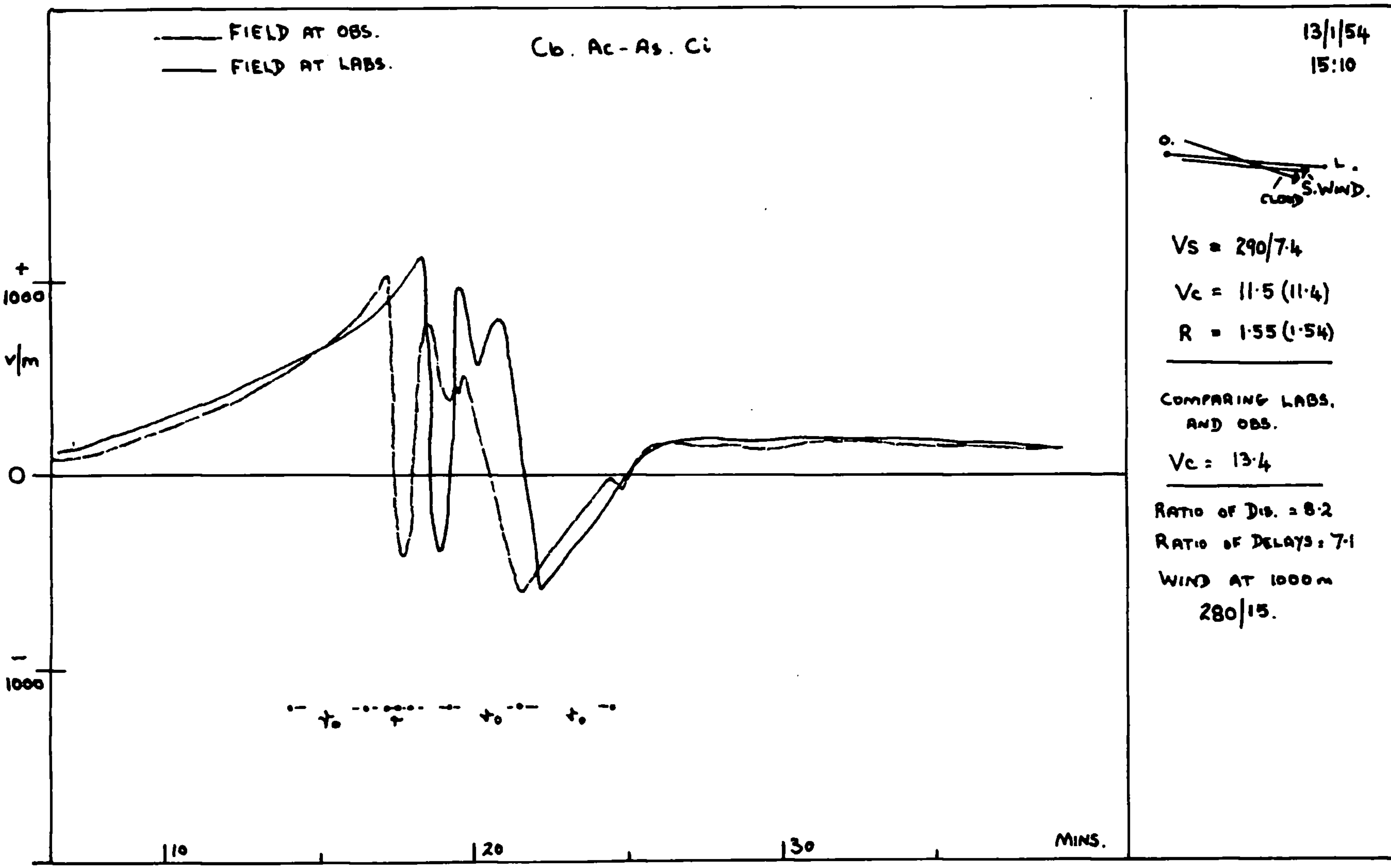


Fig. 54 Anomalous field pattern due to a Shower Cloud.

54, in this example the predominating field is positive, suggesting a positive charge on or near the cloud base. Not only was the pattern unusual but also the cloud, for it was unlike any normal shower cloud. During the shower the sky contained clouds at various levels, the rain fell from what appeared to be a thick sheet of As. and about 30mins after passing over the Observatory this cloud sheet had completely disappeared. Prior to the shower the sky had been full of moderate Cb. but one hour after the shower the sky contained only a Sc. form of degenerate Cb. It was the writer's impression that the shower cloud in question had been an active Cb. but was in the final dissipating stage by the time it had reached Durham. Hence it seems that the charge distribution in Cb. might alter considerably with cloud age. The Laboratories record showed an almost perfect reproduction of the Observatory field and the time delays were well defined. As the agrimeter and the two mills lay on a straight line then the ratio of the delay times between the two mills, and the agrimeter and one mill, should equal the ratio between the appropriate distances if the charges responsible for the pattern travelled at a constant speed. The values of these ratios are given in Fig.54 and show reasonable agreement. Note that the measured charge speed was 13.4m/sec, the wind at 1000m15m/sec and the surface wind 7.4m/sec. Current from the point reached 3.4μA and although the upwind and downwind

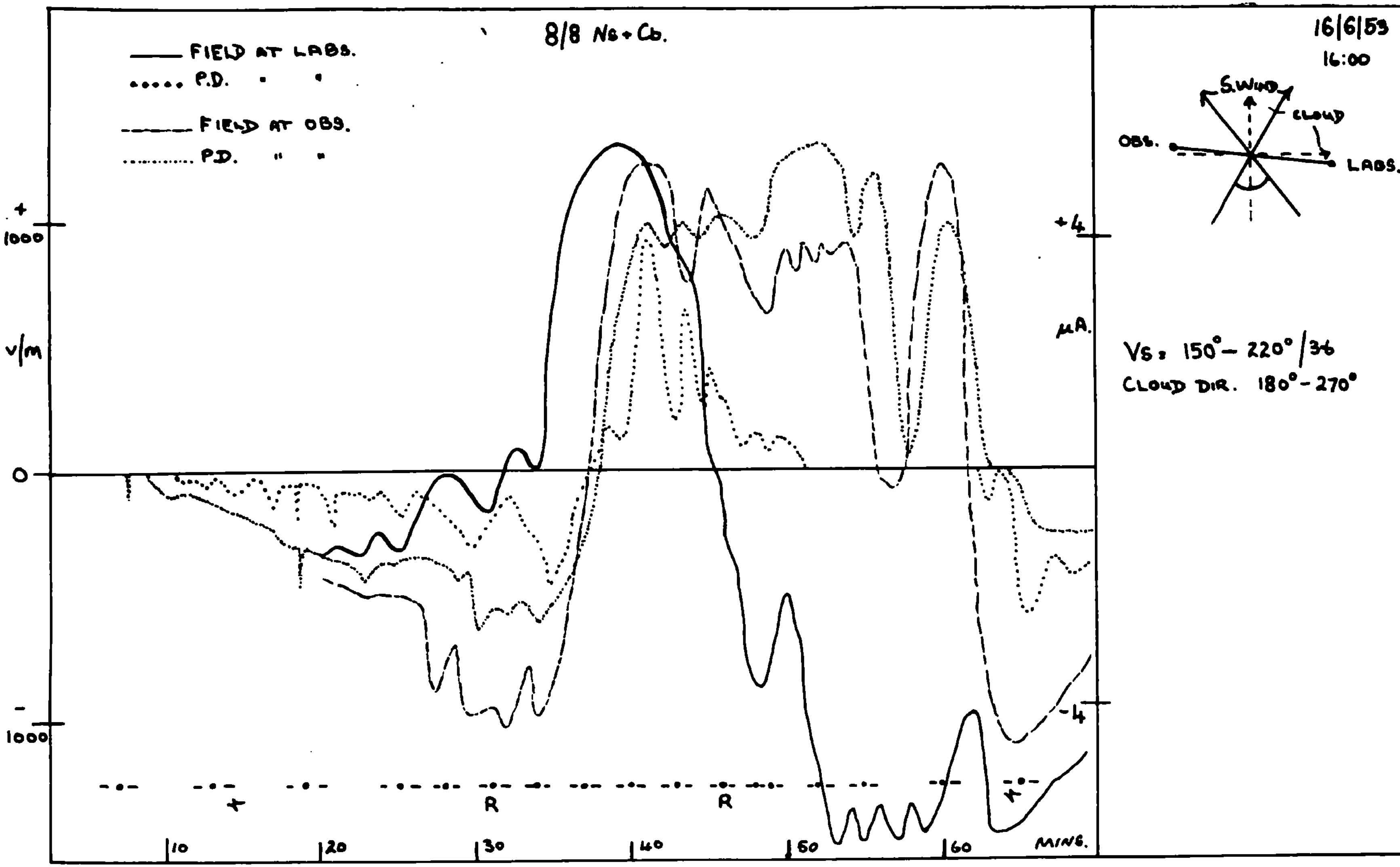


Fig.55 Simultaneous fields and p.d. currents at two sites separated by 960m.

patterns were similar, the downwind field suffered up to 30% transitory variations due to the drifting space charge. The marked central depression in the pattern cannot be explained with certainty but it is possible that it was due to the passage overhead of a column of heavily charged rain. It is doubtful whether any cloudborne charges could be responsible for such a rapid field change.

Up to this point we have been concerned with field disturbances during which the field strength did not exceed 1500v/m, for fields below this value it is believed that current flowed only from the point discharger, consequently the point space charge effect was small. In the following diagrams, which represent conditions of large surface fields, the point space charge effect was one of the main factors which determined the form of the disturbance.

Fig.55 has been included in order to illustrate the difficulties often involved when trying to interpret simultaneous field recordings. If point discharge current is taken to be a measure of field strength then Fig.55 shows how little correlation there can be between the field at the point and the field at the surface some 20m away. Note that one may find positive currents when the surface field is negative, that changes in sign of point discharge current usually lag on field changes by about 20secs(Hutchinson(1951) and others have drawn attention to this fact) and that at

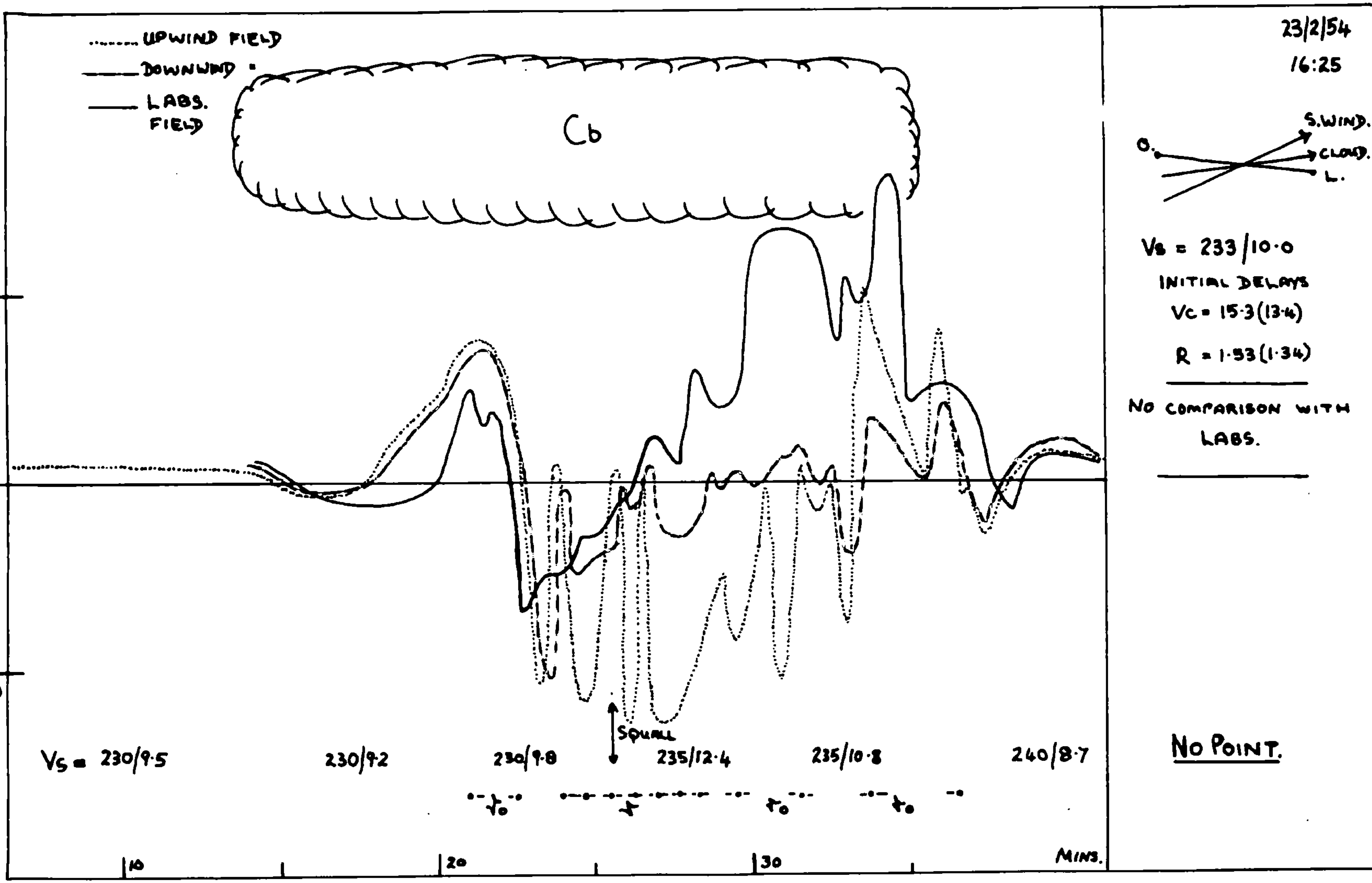


Fig.56 Fields below a Large Shower Cloud.

sites separated by 1000m the field patterns may be very different. The fields illustrated in Fig.55 occurred under an overcast Ns. sky but at the beginning of the pattern there were two small changes in field strength of a form normally associated with the transfer of charge by lightning. No thunder was heard at Durham but during that particular afternoon thunder was reported at Dishford, over 100km away. It is practically impossible to measure time delays in the diagram because of the lack of correspondence between the various traces. Some of the confusion must have been due to the fact that there was a low pressure region centred over Durham on the afternoon of the 16/6/53.

Fig.56 is believed to be one of the most revealing illustrations in the whole of this thesis. On 23/2/53 the afternoon presented a series of well defined shower clouds situated against a clear blue sky. The particular cloud illustrated passed directly over the Observatory and presented both at that site and at the Laboratories, a sequence of clear-cut disturbances. The cloud did not appear to have a Ci. top. Consider first the form of the field disturbance at the upwind site at the Observatory. The basic pattern appears to be in the form of a V but this is distorted by positive excursions at the beginning and end of the disturbance. Again the pattern lags behind the cloud. Note the way in which the basic pattern is modulated by rapid swings in the positive direction([redacted]) giving the impression that small dense pockets of positive charge moved rapidly at low heights. Turning to the downwind field at the Observatory we see that the pattern is very different, particularly so when the upwind field is large. The difference is just what would be expected if point discharge occurred from objects between the two mills. Such objects could only have been the anemometer mast or trees, for the point discharger was not erected. The point space charge effect acts in such a manner as to displace the downwind field so that its sign tends to be opposite to that of the upwind field. When this occurs the delay times have little meaning and if not interpreted correctly give the impression of exceptionally high horizontal charge speeds. In fact at one point in Fig.56 the <u>downwind</u> field crosses the zero axis about three minutes <u>before</u> the <u>upwind</u> field changes sign, yet when the fields are too small for point discharge to occur the delay times are appropriate to windborne charges. Comparing the fields at the Observatory with those at the Laboratories, some 1000m downwind, we see that the pattern has suffered further modification from point space charge with the result that the basic form of the original pattern is lost. This modification is significant, for the pattern is beginning to take on the form of a series of positive and negative excursions. If the field had been measured a further 1000m downwind of the Laboratories we might have expected the large positive excursion apparent on the Laboratories record to have drawn negative charge from points or trees and in turn this new negative space charge might have caused negative fields further still downwind. In other words, the point space charge effect, if maintained long enough, might break up the original V pattern into a series of positive and negative wave-like variations of the surface field. Hence it appears that the term "space charge blanket" which is often used with reference to conditions below thunder and shower clouds, is far from an appropriate expression, for if such a blanket exists it must be very "lumpy". Also recorded on Fig.56 are the surface wind velocities during the shower. They show a familiar sequence of variation, the increasing speed before the cloud arrives, a gust at the shower centre followed by a decreasing speed and a general wind veer. In fact, conditions under this cloud were very similar to those normally found under thunder clouds and this suggests that the difference between shower and thunder clouds is mainly one of degree and that in the former lightning does not occur because there is insufficient charge separated in the cloud to give fields large enough to cause breakdown.

The pattern illustrated in Fig.57 is even more complicated than those previously discussed. The frequent field reversals might well be explained in terms of point space

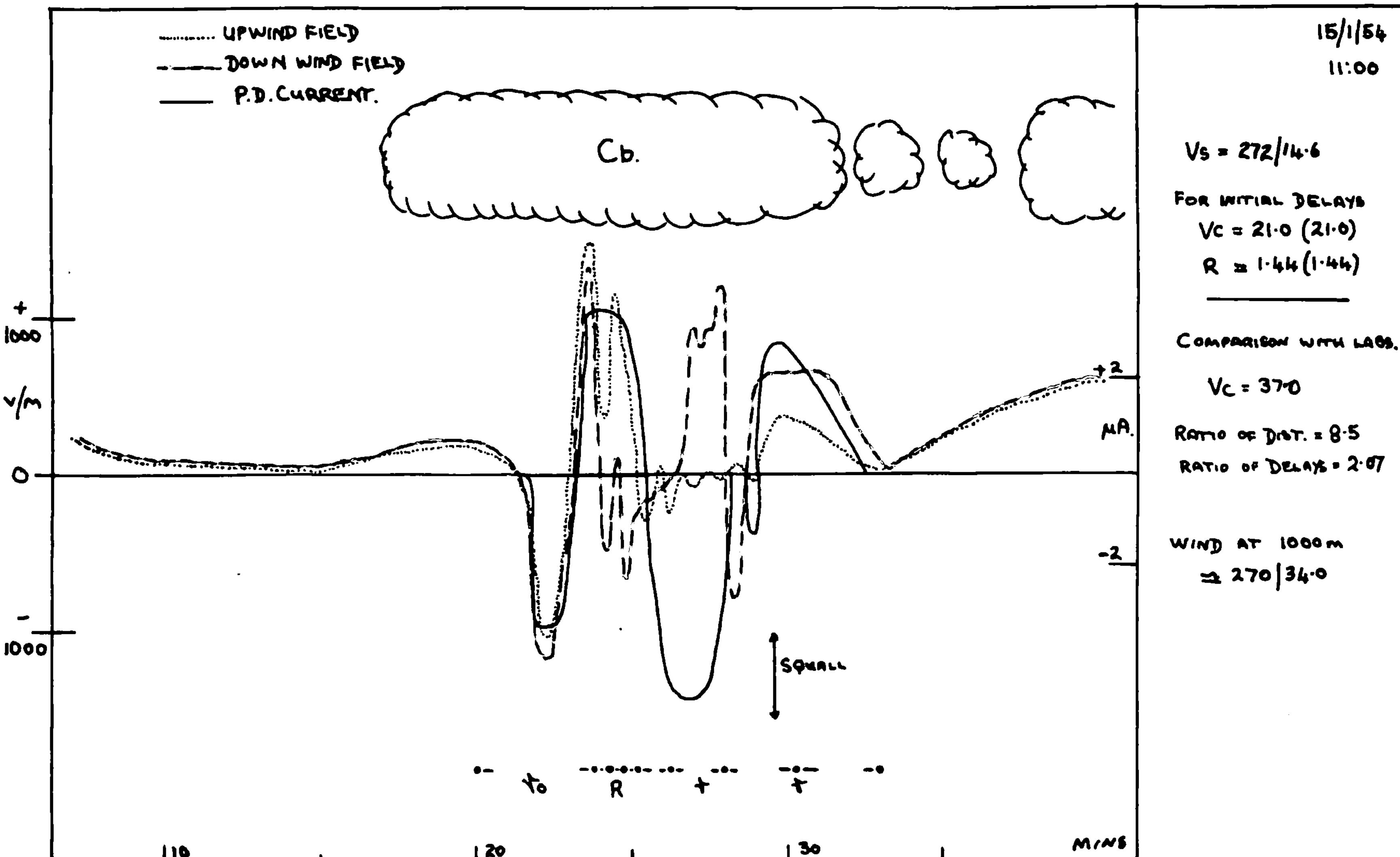


Fig.57 Fields and p.d. current below a Shower Cloud.

charge effects. At the beginning of the pattern both upwind and downwind fields and point discharge currents are all in close agreement, and give the impression that a V pattern is to follow. As the field increases all three parameters swing across the axis to show large positive values(note that this coincides with the rain core). During the next two minutes the point discharge current was reversed in sign and was appropriate to a field strength of -1500v/m, at this time the upwind field was about zero whilst the downwind field was about +1000v/m. Hence at two sites separated by only 50m the surface field may differ not only in magnitude but also in sign and the form of the field pattern recorded at the two sites may be very different. This illustration emphasizes the fact that measurements of the atmospheric electrical elements may be critically dependent on the precise spot at which they are made and that the form of field patterns recorded in disturbed weather may depend largely on the location of the measuring instruments relative to local discharging points, natural or otherwise. In this case the recorded patterns will give little indication as to the charge distribution in the clouds, such was the conclusion reached by Lutz(1941).

Further evidence is given in Fig.57 of the way in which point space charge effect advances the main changes in sign of the downwind field, so making the measurement of true delay times extremely difficult. The cloud appeared to be typical of its kind and produced the usual meteorological disturbances at the surface. The cloud top could not be seen.

Fig.58 is an example of the exceptional case. Here the fields exceeded 3000v/m yet the downwind field showed little effect from point discharge. The current through the point did not reach the peak values that one would have expected from surface field measurements. As previously a positive field was associated with the rain core. Simpson was the first to point out that many field patterns contain field changes which are almost linear with time. Fig.58 contains such an example and on the record the main field change was virtually linear with time over the range -1500 to +1500v/m. In order to explain such linear field changes one might suggest that charge is contained in an almost vertical column which moves across the surface with but below the cloud. Such a charge configuration might occur if the rain drops were charged.

Fig.59 shows another complex shower pattern. On this occasion only the downwind mill was operating. A comparison of point discharge current with downwind field shows a marked point space charge effect, for at one time the point current was appropriate to a field of about +2600v/m, whilst 50m downwind the field was -1000v/m.

Fig.60 is a plot of upwind field at the Observatory during the passage of a group of violent shower clouds. Apart

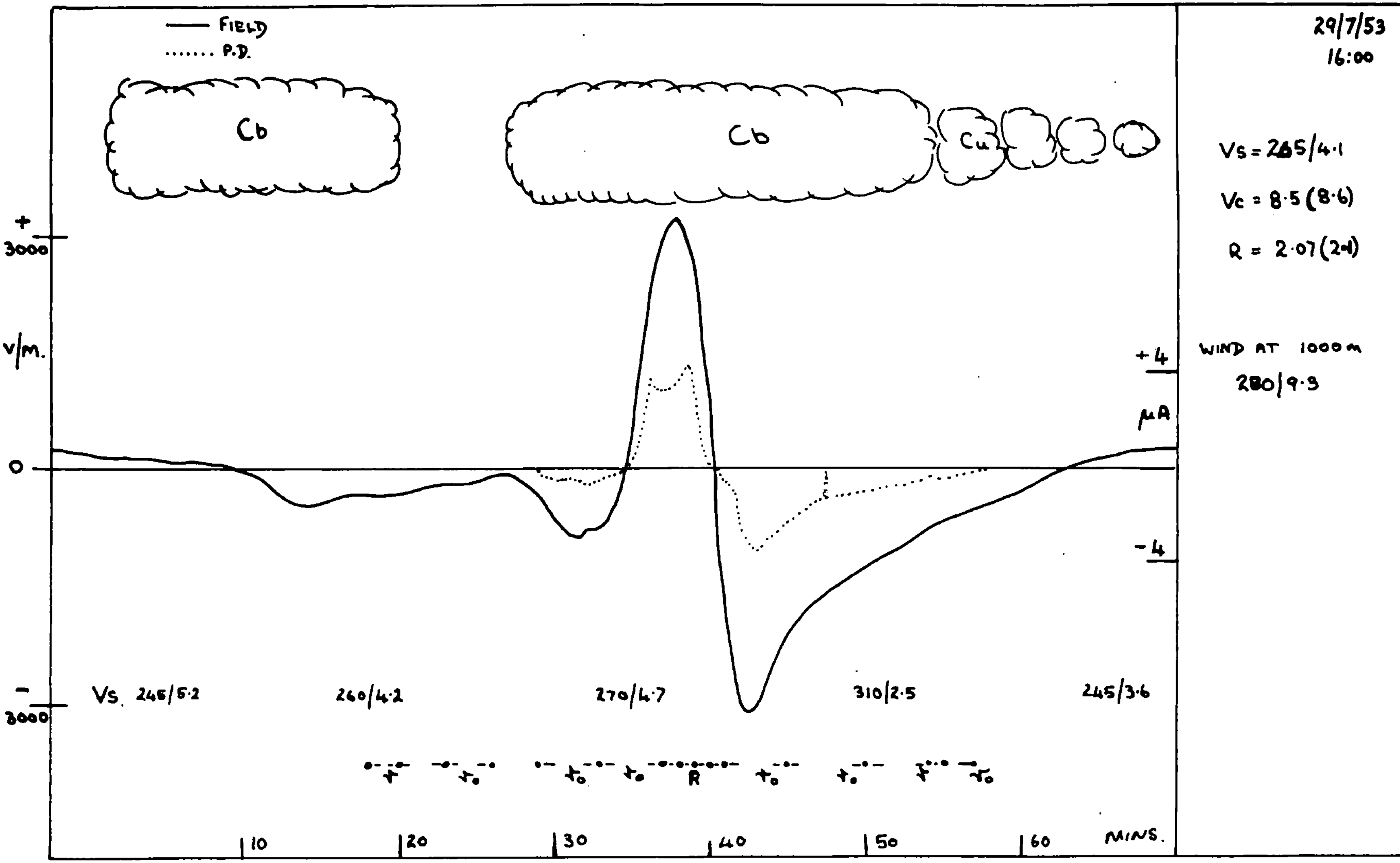


Fig. 58 Field pattern below a Shower Cloud

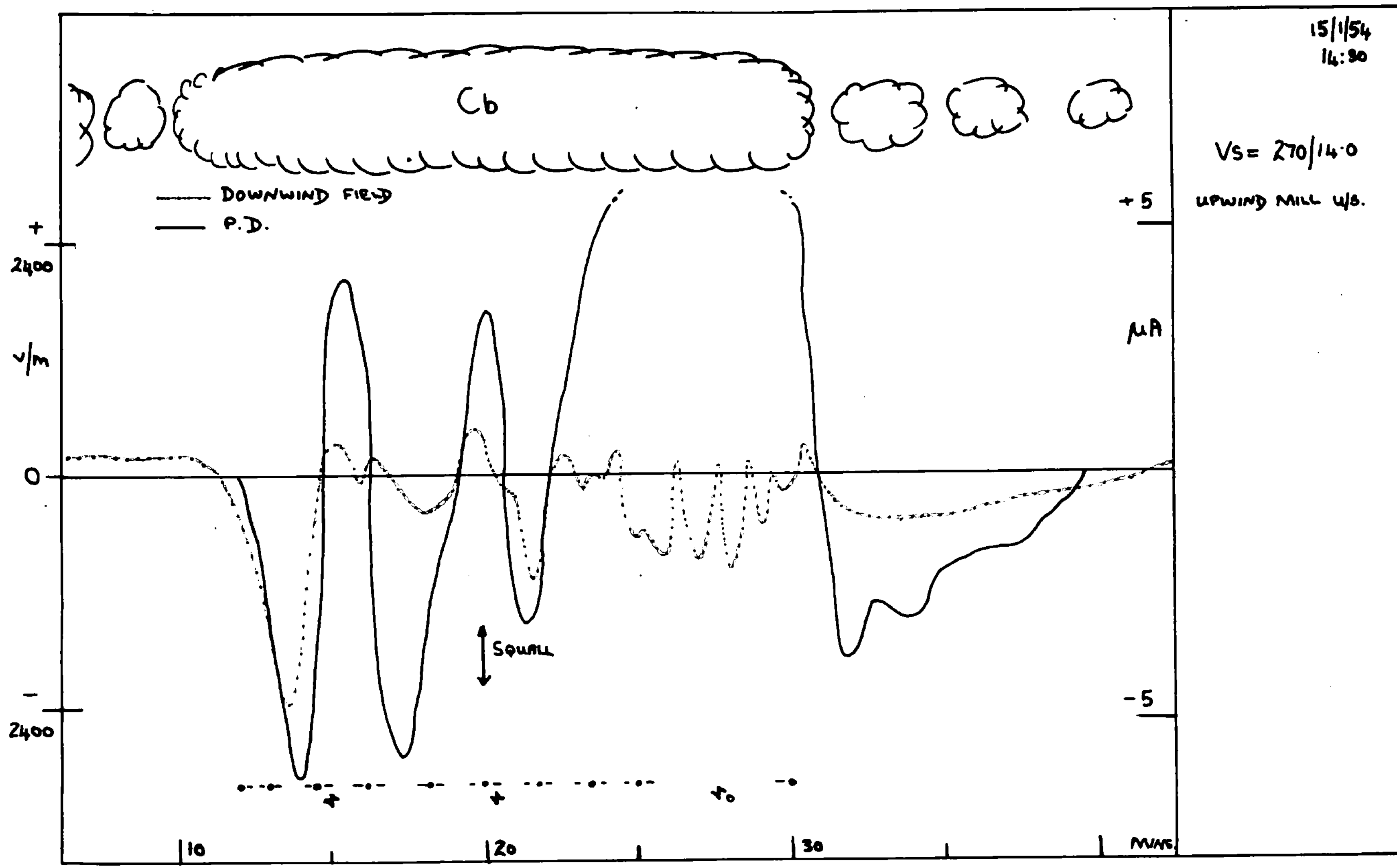


Fig.59 P.d. currents and downwind field below a very active Shower Cloud.

from the fact that no lightning effects were recorded there was nothing to distinguish this cloud group from typical thunder clouds. The cloud group appeared to consist of three "cells", two of which passed directly over the Observatory. Fine examples of Ci.(anvil) tops were observed and the usual meteorological disturbances were recorded. In addition there was a marked pressure jump of about 1mb during the heavy rain and just before the first rain fell the temperature dropped by 8 F. This pattern is so complex that very little information could be extracted from the record. Note that at the beginning of the pattern there is the usual negative field which was due probably to the negative charge on the cloud base but once space charge near the surface began to pass over, the effect of the cloud charge was lost.

Fig.61 is a reproduction of part of the record of the shower pattern illustrated in Fig.60. As the mills had short response times a true indication was given of the rate at which the surface field may change under violent shower clouds. The record of 30/3/54 showed that, on occasions, the field changed at a rate of over $500v/m^{-1}/sec^{-1}$ and once changed from -3000v to +3000v/m in less than 10secs. When the surface field changes as rapidly as this the horizontal component of the electric field some few metres above the surface must amount to some thousands of v/m and it seems that a very complex system of space charges may move in the first few

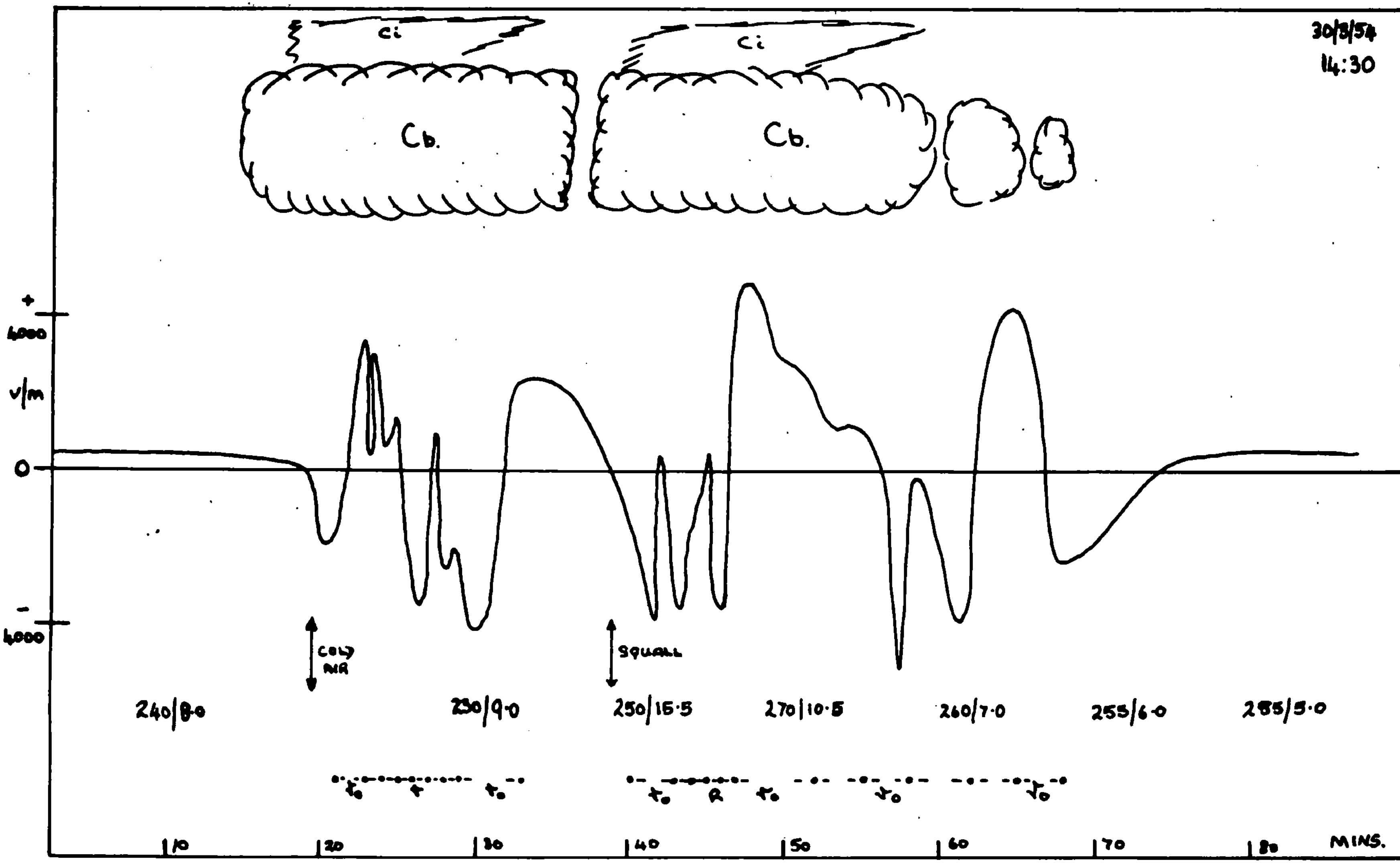


Fig.60 Field variations below a very active Shower Cloud.

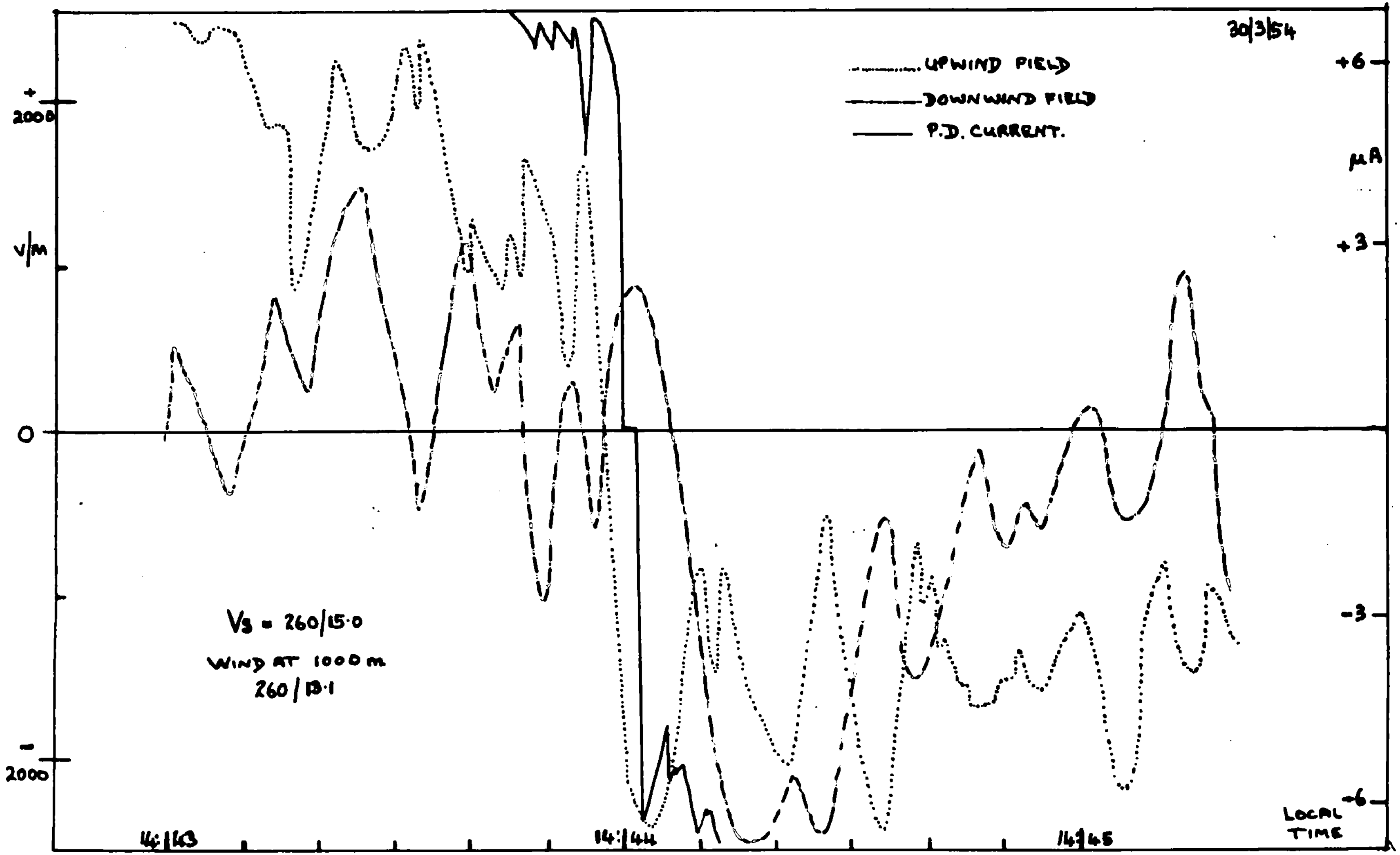


Fig.61 <u>Part of record obtained during the violent shower illustrated in Fig.60</u>.

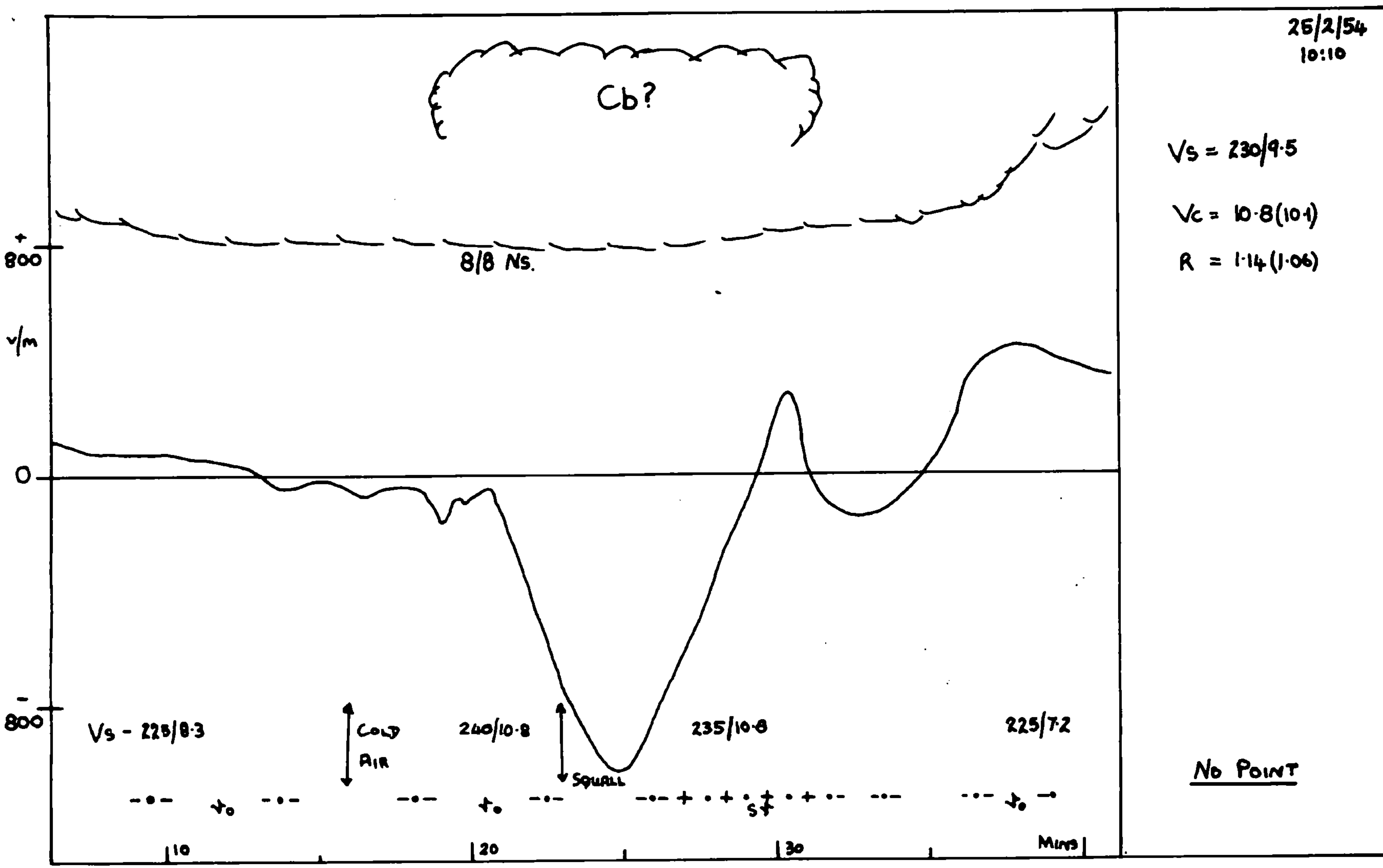


Fig.62 Field disturbance under Ns. precipitating sleet.

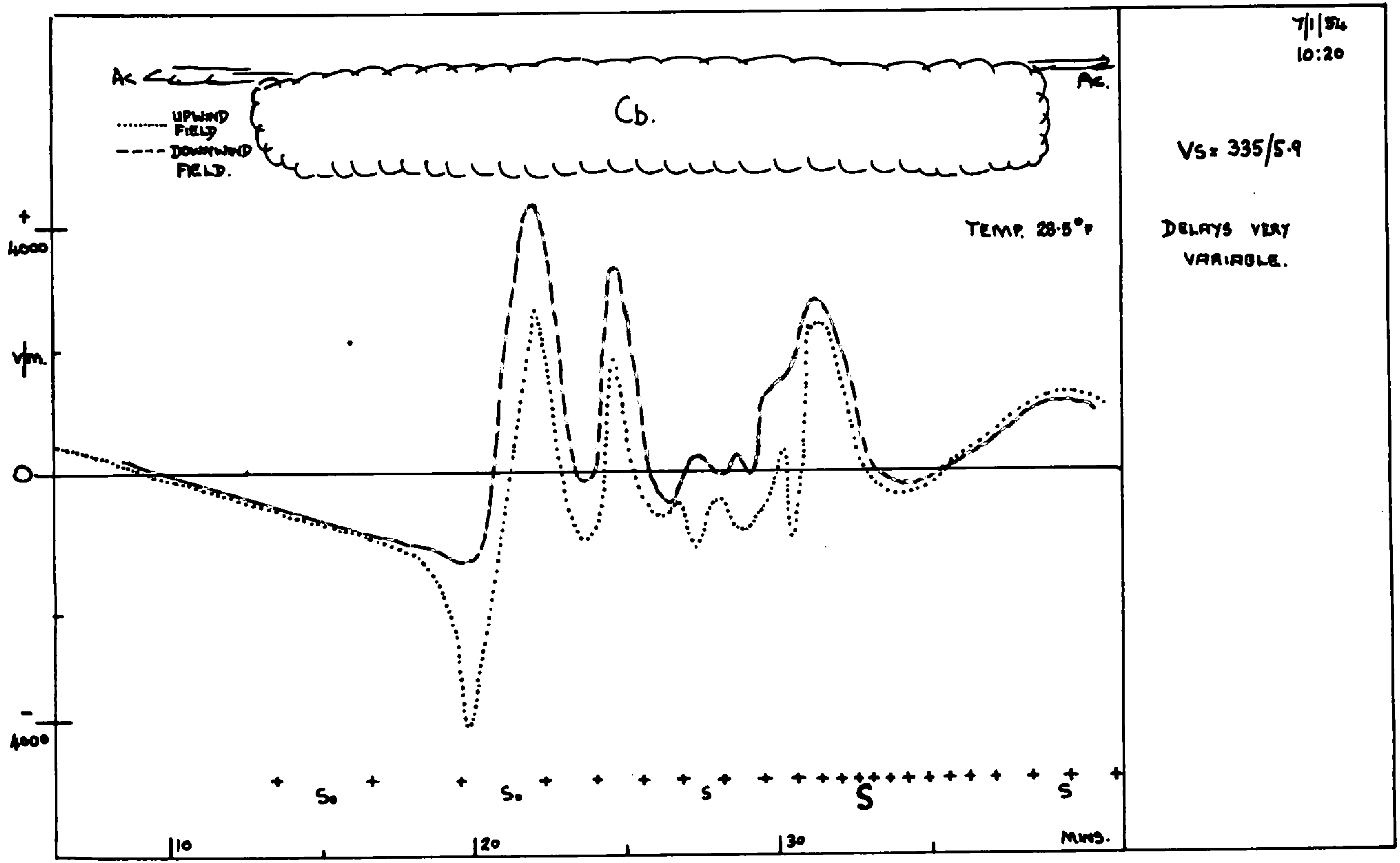


Fig.63 Fields below a Snow Shower Cloud.

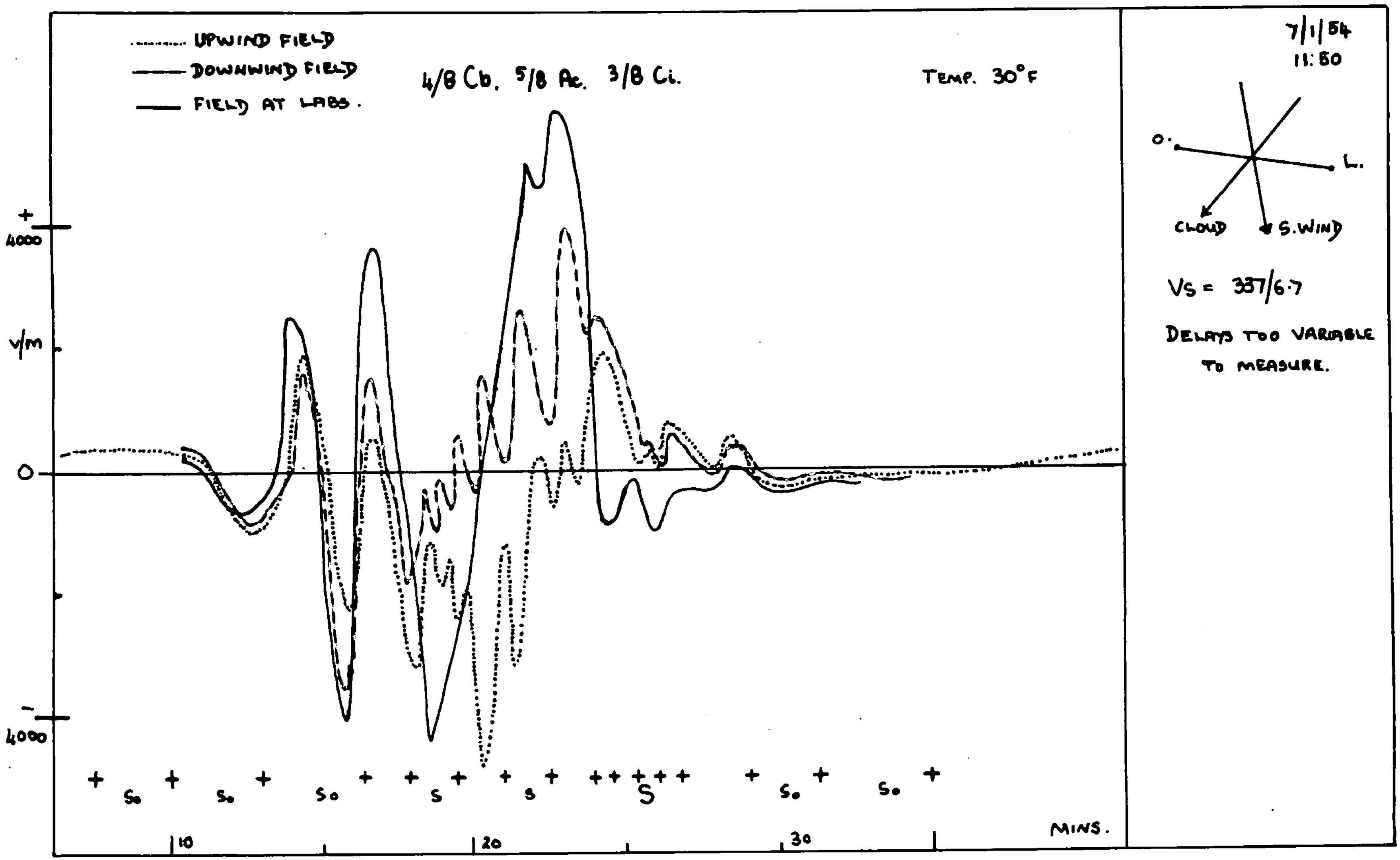


Fig.64 Fields below a Snow Shower Cloud.

hundred metres at speeds which at times may exceed 30m/sec.

12.3 Snow and Sleet Showers.

Only a few recordings were obtained during snow and sleet showers and these gave the impression that the meteorological and electrical surface disturbances below such clouds are not appreciably different from those associated with rain shower clouds.

Fig.62 shows a V pattern during sleet. Although at the time of the pattern the sky was 8/8 Ns. it is believed that the main field disturbance was due to a small Cb. imbedded in the layer cloud, later the Ns. did in fact give way to Cb. There was no evidence of point space charge effect.

Fig.63 shows a field disturbance due to the passage of a snow shower. Here the point space charge effect is very evident, particularly at the beginning of the pattern where the downwind field suffers a positive displacement as soon as the upwind field reaches about 1500v/m. Again the initial disturbance is negative.

Fig.64 is another illustration which demonstrates the way in which a field pattern may differ according to the site of measurement. The first field disturbance is negative and point space charge effects severely modify the downwind field at the Observatory. The Laboratories record also seems to have suffered from point discharge effects but different

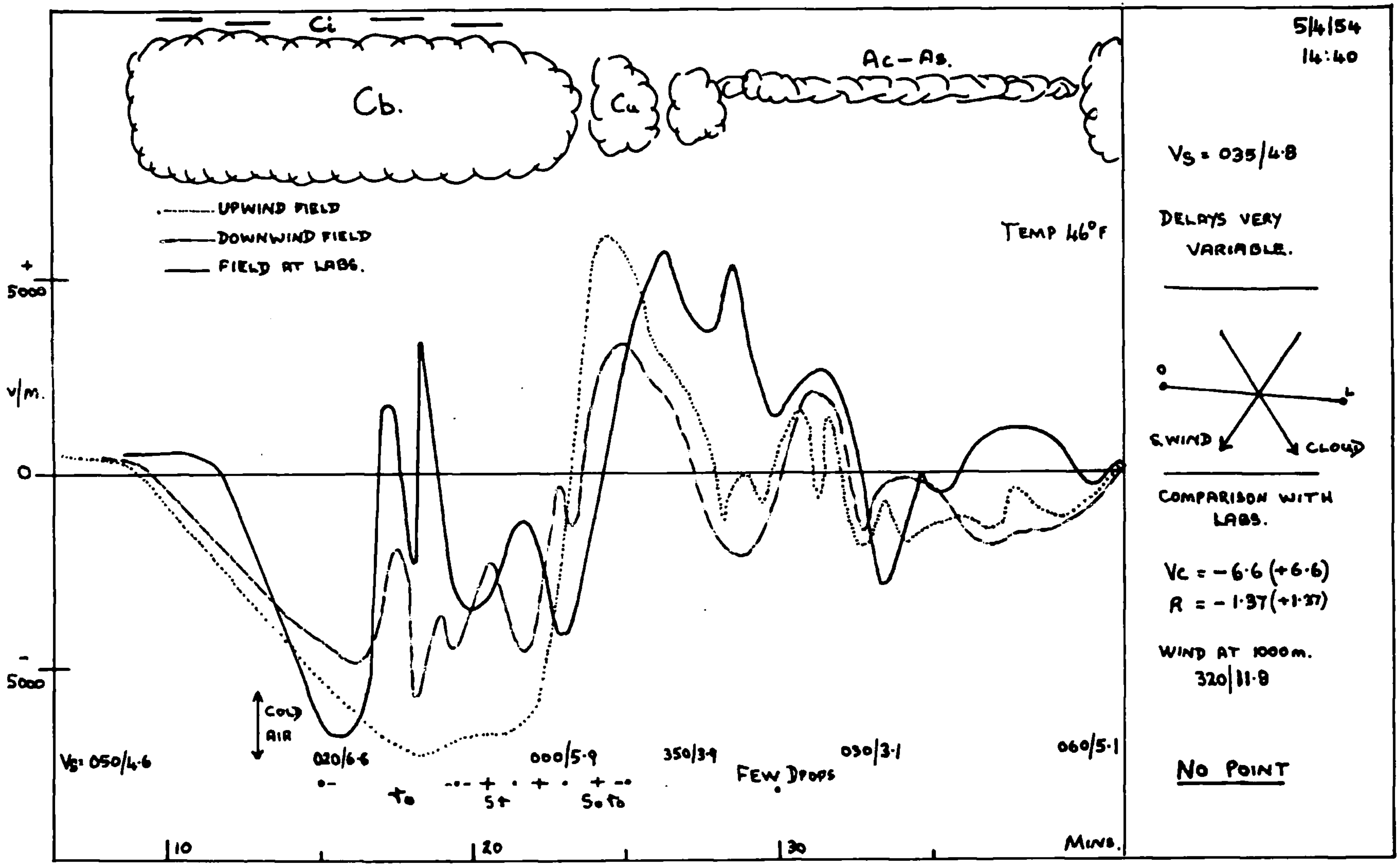


Fig.66 Fields below a very active Sleet Shower Cloud.

space charges must have been responsible for part of this pattern, for the wind and cloud direction were approximately at right angles to the Laboratories-Observatory line. There was too much snow in the air to locate the cloud boundaries accurately.

Fig.66 shows a field disturbance due to a medium sized sleet shower cloud and the peak fields were exceptionally large. Many of the previously discussed properties of shower cloud disturbances are illustrated in this one figure. The effect of point space charge, the way in which the pattern lags behind the cloud, the initial negative field, the surface wind velocity fluctuations, the way in which the delay times depend on cloud velocity when the fields are too small for point discharge to occur, the pressure jump(in this case 0.5mb) and region of cold air which flows from under the cloud. A unique feature of this particular situation was the occurrence of 15 apparently instantaneous field changes of about 10v/m. These changes were of a type normally associated with lightning flashes, yet no thunder was heard and the nearest point at which thunder was reported was Cottesmore, over 250km to the south. This was the only occasion on which so many simultaneous changes in field strength were recorded during non-thunderstorm conditions. It was the writer's impression that the changes were due to small discharges within the cloud which were not of sufficient intensity to produce audible thunder.

In the discussions on shower cloud phenomena no great significance has been attached to individual values of R. As previously mentioned, these are subject to considerable error, so that it would be unwise to attach too much importance to individual values. In general however, the values of R are slightly less than one would expect if the main field variations were caused by charges which were entirely cloudborne. This conclusion is in agreement with other evidence which points to there being appreciable space charge in the air below the cloud. Hence the general conclusion is that the main field variations associated with shower clouds derive from the horizontal motion of cloudborne and cloud associated charges.

In his memoir, Simpson(1949) gave examples of the many types of symmetrical field patterns which may occur in Cb. conditions. Although the present investigation failed to account for such patterns as the N, S and the W, it is now possible to postulate likely situations in which the effects of cloud, precipitation and point space charges combine to give distinctive field patterns at the surface as the charge system drifts with the wind.

12.4 Thunderstorm Conditions.

Some half dozen thunderstorms were included in the investigation but no serious attempt was made to decipher the complex information recorded. On most occasions the surface fields exceeded 10,000v/m and the extreme rapidity with which these fields varied made any analysis impossible. It was hoped that some indication might be obtained as to the behaviour of the point space charge immediately following a large primary field change due to lightning, but because the primary field was never constant no reliable conclusion was reached. Except when an investigation is specifically aimed at studying field changes due to lightning discharges there seems no point in using short response time instruments in thunderstorm conditions.

13. MODIFICATION OF SURFACE FIELDS BY POINT SPACE CHARGE.

This section deals with the detailed effects of point space charges on the upwind and downwind surface fields. As the problem appeared only as a result of the main work and the experimental methods were not particularly suited for its investigation, this section is intended only as an introduction and guide to future work.

13.1 The Work of Davis and Standring.

In order to arrive at a theoretical evaluation of the effects of point space charges, Davis and Standring(1947) postulated a simple physical picture of the processes involved. They assumed that the motion of ions leaving the point is governed primarily by wind, with the ions drifting downwind in the form of a line charge. Neglecting the effects of recombination this line charge will have a density which is governed by the current i from the point and the wind velocity V. Using simple electrostatic methods it is possible to express the electric field strength at any point on a conducting plane at a distance h below the line charge. If the line has a length l, then the field strength at a site immediately below the line and a horizontal distance d(measured positive downwind) downwind from the point, is given by,

$$\Delta E_D = \frac{i}{\varepsilon_0 \pi V h}\left[\frac{l-d}{(h^2+(l-d)^2)^{\frac{1}{2}}} + \frac{d}{(h^2+d^2)^{\frac{1}{2}}}\right] \qquad (13.1)$$

and the upwind field due to the line charge is given by,

$$\Delta E_u = \frac{i}{\varepsilon_0 \pi V h}\left[\frac{l+d}{(h^2+(l+d)^2)^{\frac{1}{2}}} - \frac{d}{(h^2+d^2)^{\frac{1}{2}}}\right] \qquad (13.2)$$

If the primarily large scale field is uniform then the difference between the upwind and downwind fields is given by,

$$E_D - E_u = \Delta E_D - \Delta E_u =$$

$$\frac{i}{\varepsilon_0 \pi V h}\left[\frac{2d}{(h^2+d^2)^{\frac{1}{2}}} + \frac{l-d}{(h^2+(l-d)^2)^{\frac{1}{2}}} - \frac{l+d}{(h^2+(l+d)^2)^{\frac{1}{2}}}\right] \qquad (13.3)$$

In the present investigation h=20m and d=50m. The length of the line charge is an unknown quantity but we might take 100m as a possible value(the result will not differ appreciably if it is assumed that $l=\infty$). Hence as $l+d \gg h$, then Eq.(13.3) simplifies to,

$$\Delta E_D - \Delta E_u \doteq \frac{i}{\varepsilon_0 \pi V h}\left[\frac{2d}{(h^2+d^2)^{\frac{1}{2}}} + \frac{l-d}{(h^2+(l-d)^2)^{\frac{1}{2}}} - 1\right] \qquad (13.4)$$

Substituting for l , d and h in Eq.(13.4) gives,

$$\Delta E_D - \Delta E_u = 3{\cdot}3 \times 10^3 \; i/V \quad v/m. \qquad (13.5)$$

where i is in micro-amps and V in m/sec.

The object now is to see whether the actual measured values of $E_D - E_u$ are related to i/V in the manner suggested by Eq.(13.5).

13.2 Results and Discussions.

If we are to test the applicability of Eq.(13.5) then the conditions we must look for are somewhat idealized. The best conditions are those in which the point discharge flows from a single point, where the primary field is reasonably steady, the wind speed and direction constant and no precipitation. Such situations occurred very rarely in the present investigation, for usually when current flowed from the point the primary field was far from steady, the wind velocity was varying and there was usually precipitation to complicate matters further. However, some records were made in reasonably steady conditions and few values of $E_{\flat}-E_{u}$ are available. Unfortunately only the mean wind over about 5min intervals was recorded so whereas the field measurements are practically instantaneous the wind speeds are only averages.

The values of $E_{\flat}-E_{u}$ plotted in Fig.67 have been used irrespective of wind speed and precipitation. Up to about 2μA there appears to be a roughly linear relationship between $E_{\flat}-E_{u}$ and i but above this value of current the field displacement tends to rapidly increase. Now when the current through the point reached 2μA, the primary field was about 1000v/m and above this value point discharge might be expected to occur from the anemometer mast and from trees,etc., so accounting for the sudden increase in field displacement. Two lines have been added to Fig.67 to represent Eq.(13.5) for two values of V, viz. V=2m/sec and V=14m/sec, for these are the two wind speed limits applicable to the actual

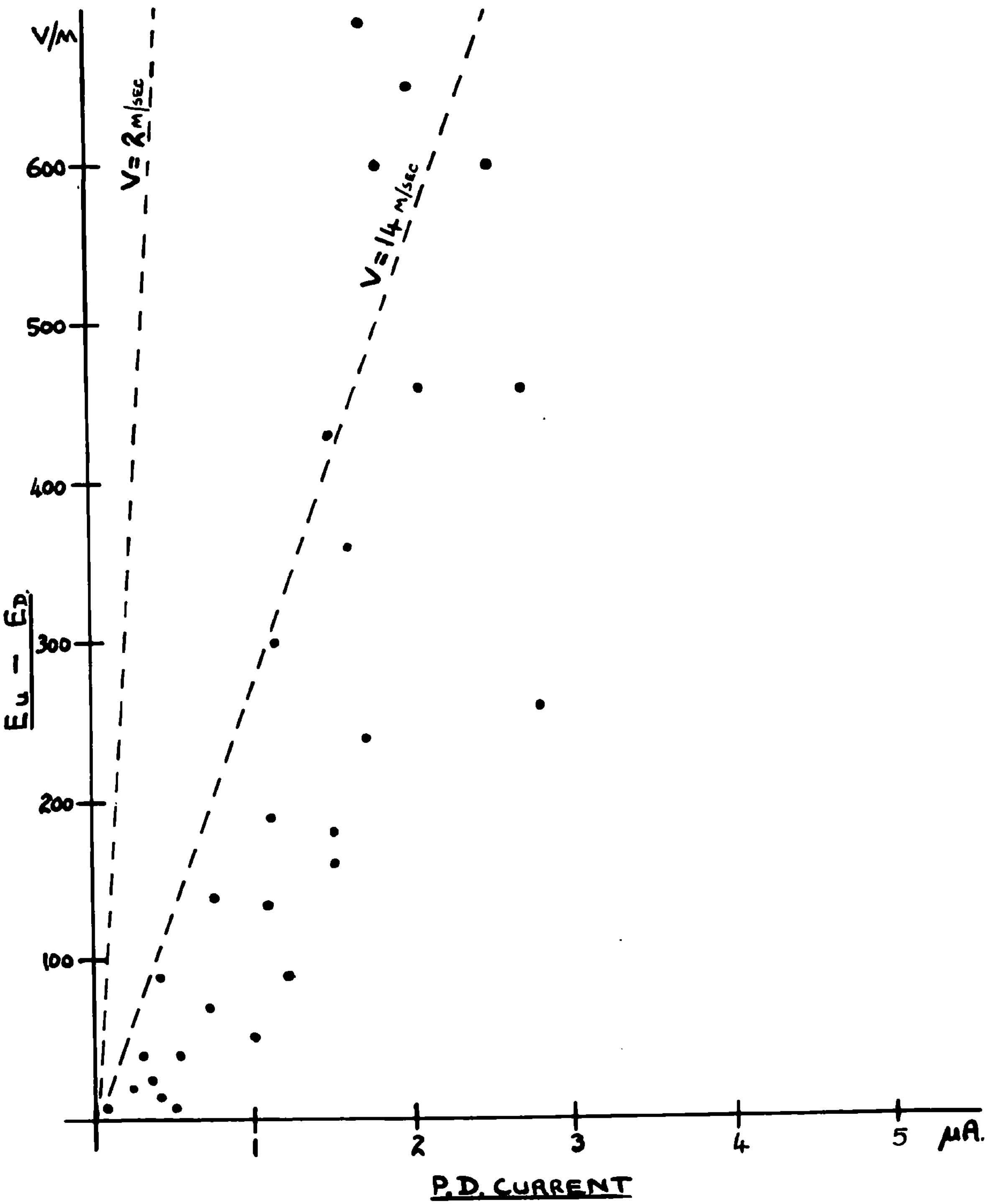


Fig.67 Variation of field displacement with p.d. current.

measured values of $E_b - E_u$. Hence from the Davis and Standring picture one would expect that for values of the field displacement obtained in conditions when the wind speed lay between 2-14m/sec, that, plotting these values against i, all the points should be contained between the two straight lines. In fact the points appear to be outside these lines, giving the impression that the actual effect of point space charge is about one third of that predicted.

There are many factors which might account for the discrepancy between actual and theoretical values. In the first instance the Davis and Standring picture is obviously over simplified. Even assuming conditions where current flows from one point only and when there is no precipitation then the point space charge must be far from a line charge. Near the point the ions will tend to follow the lines of force and so move upwards. Some metres away from the point their motion will be governed by the wind and the movements of the ions might be likened to that of smoke particles leaving a tall chimney. Such particles do not usually flow in simple manner downwind for their motion is complicated by turbulence and diffusion. Sutton(1953) has derived equations giving the ultimate distribution of matter which flows continuously from an elevated source and such equations might find some place in point discharge investigations. It appears that instead of a line charge one would expect a

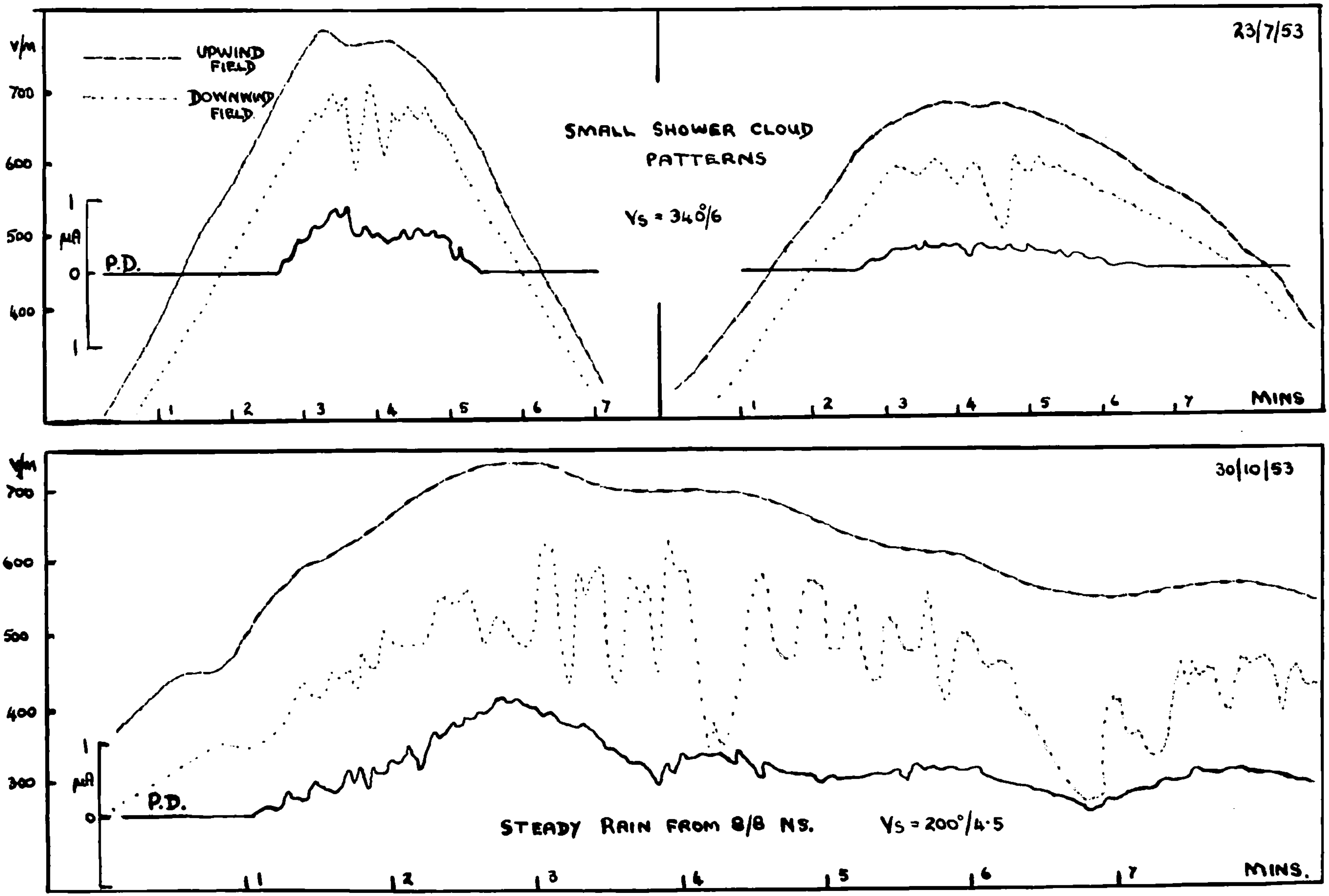


Fig.68 Some typical records showing Point Space Charge Effect.

cone-like distribution of charge with the axis of the cone tilted upwards away from the point. Within the cone the space charge distribution must be far from homogeneous because of the effects of small scale turbulence. This is supported by actual measurements of the effect of space charge on the downwind field and Fig.68 illustrates the nature of the variations of this field. Because the space charge cone is far from uniform in density and structure, accurate measurements of $E_b - E_a$ are difficult to make.

Further complications are added if the wind direction changes, for unless the field is measured immediately below the axis of the cone the effect of the charges will be reduced. Because of their screening effect local buildings, trees and the very point itself, will tend to reduce the surface field due to the point space charge.

In precipitation rain drops or snow flakes will pass through the charge cone. Within the cone the ion density will be high, as might be the conductivity. Hence despite the short time during which the precipitation particle is in the cone appreciable charges might be picked up by the Wilson process. Under these conditions the point space charge will be forced to earth and near the point the downwind field might suffer considerable displacement due to the charges residing on drops or flakes. Although it is not possible to verify this from the results of the investigation there is no evidence to suggest that the point space charge effect is lessened by heavy precipitation and there is a suggestion that the effect is enhanced in snow. Simpson(1949) has in fact shown that precipitation elements appear to carry point space charge to earth and that snow flakes are more effective as collectors than rain drops in this respect. If such a process of local Wilson capture does occur then it would be of great value to measure precipitation currents on either side of a discharging point.

14. SUGGESTIONS FOR FURTHER RESEARCH.

The following suggestions, some of which have already been made in earlier sections, are offered as possible lines for further research.

i) Fine and Fair Weather.

Future investigations might be directed towards a better understanding of the relationship between wind structure in the lower troposphere and the short period field variations. Particular attention should be paid to the effect of the vertical temperature gradient and any atmospheric convective motion on the form of these variations. Precautions would have to be taken to ensure that the field variations were due mainly to irregularities in the distribution of the normal positive space charge and not due to cloud associated or man-made charges. In order to study any connection between convection currents and field variations a profitable line of approach might be the simultaneous measurement of surface field, wind velocity and air temperature. It would be essential to measure the two meteorological elements at some well exposed site, for example at the top of a tall mast. The mast might also be used to assist in temperature gradient measurements.

Surface field measurements might be a useful tool in micro-meteorological investigations. If a known quantity of charge was liberated either instantaneously or continuously from a point source then measurements of surface field strength downwind of the point might give some indication as to the wind structure(the charge might "pick out" any convection currents) or dispersion processes.

Further work might be concentrated on the problems associated with the production of charge by "artificial" means. In particular we require to know more about the origin of net space charges associated with combustion products; what governs the sign and quantity of charges so produced, what are the properties of the combustion ions and to what degree do they affect surface field measurements in the vicinity of large towns?

ii) Mist and Fog.

The nature and origins of field variations in fog appear to be fairly well understood, although further work on the relationship between field, "precipitation" currents and droplet properties might give some indication as to the charge separation process operative in Stratus cloud.

Further work should be directed towards a better understanding of the way in which charges are liberated and carried from high tension cables in foggy weather. Preliminary experiments might be carried out using a "mock-up" transmission line a few metres in length and connected to a high voltage generator.

iii) Layer Clouds.

A fundamental difficulty associated with surface field measurements is that they give little indication as to the actual charge structure within layer clouds. Because surface measurements are limited in this respect many of the electrical properties of layer clouds can only appear as a result of a series of airborne measurements using instruments which have the same order of sensitivity as those used on the surface. Any surface measurements which give an indication as to the polarity(unipolar or bipolar) of a typical layer cloud would be invaluable.

iv) Cb. Conditions.

The results of the present investigation confirms statements made by other workers in that surface field measurements under shower and thunder clouds often give little indication as to the charge structure within the clouds. However, measurements made under <u>small</u> shower clouds generally give a much more reliable picture of the cloud charges and although conditions under such clouds are comparatively simple and clear-cut no great advantage appears to have been taken of this opportunity to study some of the processes which must occur in a much more violent form in thunder clouds. Hence it is believed that a detailed study of small shower cloud conditions will lead, indirectly, to a greater understanding of thunder cloud phenomena.

Investigations of point discharge phenomena offer considerable scope so far as surface measurements are concerned. If point discharge currents can be produced in steady conditions when the primary field is small, then the point space charge effect may be studied with ease. We need to know more about the life of the ions once they leave the point, the relative effects of air currents and electrostatic forces and the effect of precipitation on the space charge "cone". There is a great need for simultaneous measurements of precipitation currents upwind and downwind of a discharging point. Once a reasonable understanding of the point space charge effect is obtained then the field might be measured upwind and downwind of an isolated tree with a view to making indirect measurements of point discharge current from the tree. It should be possible to obtain an estimate of the M value for the tree and to investigate how this value varies with seasonal growth and whether wetting by rain affects the discharging properties.

In general it would be advisable to continue simultaneous field measurements at widely separated sites, for example at sites over 1000m apart. Ideally three sites would be required with the three instruments recording on a common recorder. Future work should concentrate on recording the micro-meteorological conditions simultaneous with visual observations of the clouds and measurements should be made of as many electrical parameters as possible.

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