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"CONDUCTIVITY MEASUREMENTS NEAR THE GROUND"

by

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ABSTRACT

Conductivity measurements in the lowest few metres of the atmosphere have been the subject of investigation of relatively few workers. Their results appear to be confusing especially where the electrode effect is concerned. The present work was undertaken as a further contribution to the understanding of conduction in the lowest metre of the atmosphere.

Simultaneous measurements of the polar conductivities of opposite sign at ground level as well as conductivities of either sign at 20 cm. and 100 cm. above the ground were made together with the potential gradient at ground level. A mean value for the wind speed, and the wind direction during a period of recording could be obtained from the records of the Durham University Observatory where the work was undertaken. The conductivities were measured using two cylindrical condensers of the Gerdien type housed in a pit underground with their intakes flush with the surface. Air from the required height was drawn through a cardboard tube of that height slipped over the outer tube of the Gerdien condenser. To minimise the distortion to the lines of force resulting from the introduction of the cardboard tube in this manner, the intake of the cardboard tube was surrounded by a narrow aluminium band continuously maintained at the right potential of the surroundings, by utilising the output of the field mill at ground and a "continuous balance circuit" of a Honeywell Brown recorder.

Results have shown that both positive and negative conductivities decrease with height in the lowest metre from ground, due to the effect of the radioactivity of the soil. The variation of the radioactive emanation in the air is directly affected by the role which the wind plays in the mixing of the air. It is suggested that in most conditions overland these factors combine against the enhancement of the electrode effect.

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CHAPTER I

INTRODUCTION

IONS IN THE ATMOSPHERE

The general result of investigations on the ions in the atmosphere shows that they can be classified into three classes depending on their mobility. Those which have mobilities between 1×10^{-4} and 2×10^{-4} $m.sec.^{-1}$ for a potential gradient of $1\ V.m.^{-1}$ are known as the small ions. The actual value of a mobility being dependent, among other things, on humidity, impurities and pressure. This and the fact that under identical conditions negative ions have mobilities which are rather greater than positive ions, suggests that a small ion is more complex than merely a single molecule with a single electron in excess or deficit. It has in fact been established that a small ion consists of a single ionised molecule with other molecules clustered round it, and kept together by the charge.

The second class of ions - known as large ions - are those which have mobilities between 3×10^{-8} and 8×10^{-7} $m.^2v.^{-1}sec.^{-1}$ These are produced whenever a small ion is captured by the uncharged particles found in the atmosphere known as condensation or Aitken nuclei. Large ions are considerably larger than the small ions which are not much larger than molecular size.

The difference in mobility between the small and large ions is not the only distinction between them. It is to be noted that the aggregate of molecules which constitute the small ion is held together by the charge. As soon as the charge is lost the aggregate falls apart and the small ion no longer exists. The large ion, however, can lose its charge and still exist, as an uncharged nucleus and can readily acquire another charge, of either sign.

The third class of ions - known as intermediate ions - are the ones which have mobilities between those of the small and large ions. Pollock (1915) first discovered such a group of ions with mobilities between 10^{-5} and 10^{-6} $m.^{2}v.^{-1}sec.^{-1}$ to exist only under conditions of low humidity. The existence of these ions was later confirmed by Wait (1935) but he did not find the same effect of humidity. Hogg (1939a) found definite groups of ions with mobilities from 2×10^{-5} to 1×10^{-7} $m.^{2}v.^{-1}sec.^{-1}$ He interpreted them as particles of sulphuric acid having volumes which are integral multiples (up to 15) of a unit size (radius 3.6×10^{-9}m.) comprising some 2000 molecules. He did not find the effect of humidity which Pollock found, nor did he put forward any theory to account for the unit size. However, if his interpretation is correct, these ions can only be found where industrial processes produce sulphuric acid. On the whole, while some workers found ions in the atmosphere to exist into separate groups, each group comprising a different range of mobilities, with no ions with intervening values of mobility, others could only find a continuous range of mobilities. Intermediate ions are generally neglected in discussions of atmospheric electricity.

PRODUCTION AND DESTRUCTION OF IONS

Various processes can act as ionisers of the atmosphere. In the high atmosphere, from an altitude of about 80 km. and upward, ultraviolet light from the sun is doubtless the chief ioniser. Ionisation by collision takes place in lightning flashes and in the process of point discharge, but these occur only in limited regions of the air and for a limited time in stormy weather. In some special circumstances ions may be formed when light, even of visible wavelength, strikes certain photosensitive substances. However, substances of the required sensitivity are so small a part of the constituents of the earth that this is undoubtedly an insignificant ioniser in the atmosphere. Ultraviolet light of sufficiently short wavelength directly to ionise the air is apparently all absorbed high in the atmosphere.

Large and intermediate ions as well as numerous nuclei which serve for the later formation of large ions are at times introduced into the atmosphere by some chemical and a few mechanical processes; for example domestic and industrial furnaces, bush and forest fires, etc. Chalmers (1952) has found negative potential gradients in mist and fog, ascribed to negative ions produced at high tension cables. Other similar effects were also reported by Muhleisen (1953).

Small and large ions are reported to be formed when a surface of water is suddenly disrupted. In pure water the small droplets carry a negative charge into the surrounding air whereas the larger ones with a positive charge settle to earth. If the water contains small amounts of certain impurities, the sign of the charges may be reversed. This process can only be of importance in the immediate neighbourhood of waterfalls or perhaps by the sea shore.

Ions are also said to be formed by drifting dust or snow. At such times abnormally intense electric fields become manifest in limited areas and for short periods, resulting presumably in the production of ions.

All the several possible processes mentioned by which ions may be formed in the atmosphere are not sufficiently widespread and effective to be dominant factors in the ionisation of the atmosphere during fine weather. However, three other processes qualify as dominant factors. These are: ionisation due to radioactive substances in the earth's crust, ionisation due to radioactive matter present in the air itself and ionisation due to cosmic rays.

Uranium, thorium and their products are widely distributed through the earth's crust, whose surface layers therefore emit α, β, or γ rays into the air. α rays, having the least power of penetration, cause a very small ionisation mainly in the first few centimeters of the air above the surface. β rays and γ rays can come from greater depths and penetrate much further into the atmosphere thus causing very appreciable ionisation. The γ ray activity of potassium introduces another source of ionisation because the potassium content of the earth's crust is considerable.

Radioactive gases arise from the decay of radium and thorium within the earth and escape into the atmosphere by diffusion, thermal convection and decreases in the external atmospheric pressure. The ionisation produced in this case is largely due to the α rays from the emanations themselves as well as their successive products since here there is no absorbing layer between the disintegrating atom and the air.

Cosmic rays come to the earth's surface from above and suffer a partial absorption in the atmosphere. Their penetrating power is much greater than that of the most penetrating γ rays from radioactive bodies. The ionisation produced by the cosmic radiation increases rapidly with height above sea level, rising ten fold in the first 10 km. The amount of ionisation shows some change with geomagnetic latitude, being less at the magnetic equator than at higher magnetic latitudes.

In order to understand the relative importance of the three major ionising processes mentioned, it is convenient to use the unit, q , to represent the number of pairs of ions produced in the air per c.c. per second. In air at N.T.P. and at sea level cosmic rays produce ions amounting to 1.8 q at latitudes over 50° and 1.5 q near the geomagnetic equator. The effect of the radioactivity of the earth is subject to considerable fluctuations with local conditions but on average is found to be 4 q over land and is insignificant over the sea. The effect of the radioactivity in the air averages about 5 q over land and is negligible over the sea. Thus, on average, the total effect over land is nearly 11 q and that over the sea is 1.8 q falling to 1.5 q near the equator.

The number of ions produced by the processes mentioned does not increase indefinitely with time because certain processes are at work removing them. Small ions are mainly removed by combination with uncharged nuclei to form large ions and by combination with large ions of opposite sign to form neutral Aitken nuclei. They are removed to a very small extent by recombination, the same being true for large ions. The ion population in a given space increases or decreases until there is a balance between the rate of formation and the rate of destruction.

CHAPTER II

THE ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE

HISTORICAL

That the air is not a perfect insulator and that electric charge may be dissipated through it was first discovered by Coulomb (1785) who showed that a metallic conductor, placed in air, gradually loses its charge in a manner to be ascribed not only to faulty insulation, but also, to some extent, to the conduction of electricity away from the body into the air. Coulomb assumed that particles suspended in the surrounding air - e.g. dust, water vapour - first become charged by contact with the electrified body and then carry away its charge. The discovery of Coulomb, however, received little attention until Linss (1887) reported his determinations of the dissipation coefficient, made twice each day at Darmstadt, Germany, during two years. The values varied from a maximum in summer to a minimum in winter. Then in the last decade of the Century Elster and Geitel perfected the method of measuring electrical dissipation from charged bodies and made numerous measurements in the outside air, from which they concluded that the dissipation of charge is greatest in pure air and that fog, smoke, or other factors which reduce the visibility, also reduce the dissipation, sometimes to values as low as one tenth that for very clear air. Although it was therefore believed that the moisture in the air helped to discharge a body, Elster and Geitel concluded that in pure air the dissipation decreases when the air becomes nearly saturated with water vapour. They found that in the pure air of the mountains electrical charges are dissipated more rapidly than elsewhere. But their observations on mountains disclosed another interesting part of this picture puzzle. Although in the lowlands electricity was dissipated from a charged body exposed in the outside air at about the same rate whether the charge was positive or negative, yet it was found that on exposed mountain peaks during clear weather a negative charge was dissipated much more rapidly than one of positive sign.

Thus it became evident that the air of the atmosphere has the property of conducting electricity to a very slight yet a sufficient degree for this property to play an important role in the electrical phenomena of the atmosphere. It was the conception of ions in gases developed at this time, chiefly by J. J. Thompson and his collaborators, which enabled, almost simultaneously, Elster and Geitel (1899) and Wilson (1900) to give a satisfactory explanation for the dissipation of an electric charge as being due to the neutralisation by ions of opposite sign drawn to the surface of the body by electrostatic attraction.

The explanation of the observation that on mountain peaks a negatively charged body loses its charge much faster than does one that is charged positively is as follows: the surface of the earth is charged negatively during fair weather and that surface charge is greatest on protruding portions such as mountain peaks; hence, negative ions drift away from the earth while positive ions in the air above drift toward it. Negative ions are therefore somewhat less abundant near the earth's surface, especially over mountain peaks, than are ions of positive sign, although at distances further from the earth ions of each sign are about equally abundant. Thus in air near the earth's surface, the number of negative ions available being less, a positively charged body loses its charge more slowly than does one which is negatively charged.

SATURATION CURRENT

Let us consider two electrodes separated by air, which, as we know, is always feebly ionised. On applying a potential difference between the electrodes the ions begin to move towards one or other of the electrodes according to their sign. On reaching the electrodes the ions give up their charges and so a small current begins to flow.

If n_1 and n_2 are the numbers of small positive and negative ions per unit volume, e is the charge on an ion, k_1 and k_2 the mobilities of the two kinds of ion, respectively, and F the potential gradient, then the current density, i , is given by:

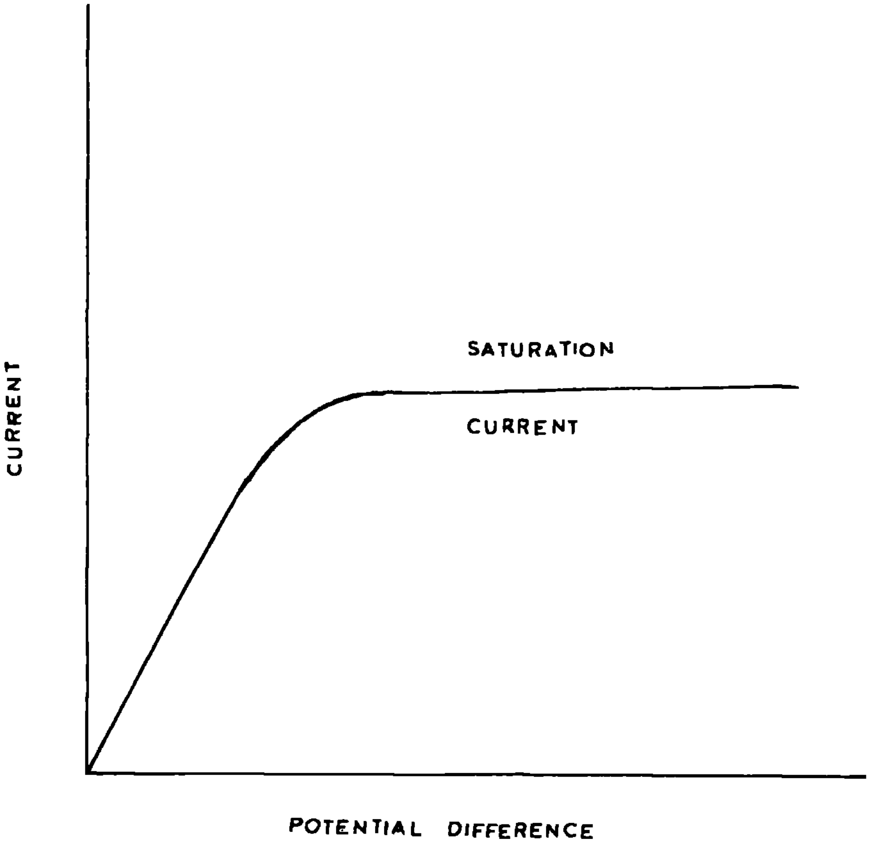


FIG. 1. IONIC AND SATURATION CURRENT

$$i = e(n_1k_1 + n_2k_2)F \ldots\ldots\ldots\ldots \quad (1)$$

The expression

$$\lambda = e(n_1k_1 + n_2k_2) \ldots\ldots\ldots\ldots \quad (2)$$

is called the specific conductivity or the total conductivity of the air. The quantity λ may also be considered as consisting of two terms, λ_1 and λ_2, such that

$$\lambda = \lambda_1 + \lambda_2, \qquad \lambda_1 = en_1k_1, \qquad \lambda_2 = en_2k_2$$

λ_1 and λ_2 are called, respectively, the polar positive and negative conductivities.

Should the air also contain other types of ions having different mobilities, the expressions for each of the components of conductivity would contain a sum of terms like nk.

As long as (1) is fulfilled the current density is proportional to the applied potential difference; i.e. Ohm's law is obeyed. In FIG. (1) this is represented by the initial linear portion of the curve. As the potential is still further increased more and more ions will be drawn to the electrodes in unit time and a marked diminution in the ionic concentration will occur. The conductivity of the air will accordingly fall, and so the current density will no longer increase proportionally with the field strength, but more slowly. With still more potential between the electrodes a condition is finally reached in which practically all the ions produced in one second are drawn to the electrodes. The current is then known as the saturation current and is characterised by the fact that further increase in potential produces no corresponding increase of current so long as no new factors affecting the ionisation come into play.

PREVIOUS MEASUREMENTS

Measurements of atmospheric conductivity at ground level and at one metre above have been made at Kew by Watson, Scrase and Hogg and at Glencree by P. J. Nolan. Watson (1929) used two Wilson universal electrometers one flush with the ground and the other 130 cm. above. His results showed the conductivity at ground level to be, on average, about 25% more than at one metre. Scrase (1934) with more improvements on Watson's method obtained approximately the same results. He attributed the lower value of conductivity at the one metre level to defects in his experimental procedure, and expressed the belief that the conductivity at the two levels should be the same. Both Watson and Scrase measured the positive unipolar conductivity only. Hogg (1939b) made simultaneous measurements of both polar conductivities at three heights between ground and one metre as well as the positive unipolar conductivity at ground measured with the Wilson apparatus. To investigate the variation of conductivity with height he used an aspiration apparatus of the Gerdien type housed in the Kew underground laboratory. Air from the desired height was drawn through a vertical cardboard tube slipped over the outer electrode. To reduce the disturbance of the earth's field due to the introduction of the cardboard tube, the latter was surrounded at its entry point by a metal ring charged to a potential appropriate to its height as determined by the Wilson apparatus just before a conductivity observation. His results show that:

(a) the positive conductivity, decreases with height, the decrease being relatively rapid in the lowest 25 cm., reaching about half its initial value at a height of one metre.

(b) the negative conductivity, increases with height rising from zero at the surface to about equal to the positive conductivity at one metre.

(c) the total conductivity remains approximately constant over the whole range of height considered, being equal to the positive conductivity at ground level measured with the Wilson apparatus.

Nolan (1940) measured the positive conductivity at ground level using Wilson's apparatus as well as the total conductivity at one metre using an adaption of Gerdien's method. Air at the one metre level was drawn through a hole in the wall of the building. Nolan found the total conductivity at one metre to exceed that measured at the ground by the Wilson method by about 12%. To account for this difference he postulated an upward positive convection current due to turbulence, the magnitude of which varies, but which, on average, is 12% of the air earth current.

O'Donnel (1952) using a portable apparatus of the Gerdien type measured both polar conductivities at ground and at one metre above it from within New York city to 100 miles of it. With the Gerdien apparatus horizontal, he arranged a right angled elbow of galvanised iron with a long arm to fit over the end of the outer cylinder. For observations at the one metre level the elbow was turned about the cylinder axis to a horizontal position with the intake one metre above ground. O'Donnel, however, specifically mentions that the apparatus was always set up under the branches of large trees as a protection from the field. His measurements show that:

(a) the total conductivities at ground level and at one metre above are not equal, the latter being generally greater by day, and less at night.

(b) the ratios of polar conductivities of one sign at ground level to the corresponding values at one metre are not constant and the ratio of the total conductivity at ground to that at one metre is not constant.

More recently Law (1963) working in Cambridge used an Ebert Counter to measure the small ion concentration at three heights between ground and 150 cm. above it. He also made simultaneous measurements of space charge and potential gradient at one metre. Air was drawn from the required height through a flexible tube. His results show that the conductivity decreases with height under most conditions. He concluded that this is incompatible with a conduction current constant with height and so he implied the existence of a convection current comperable with the conduction current.

THE ELECTRODE EFFECT

Consider a vertical cylinder of perfectly still air of unit cross section extending from the ground to one metre above it. Let F and F_g be the potential gradients, λ_1 and λ_{1g} be the positive conductivities, λ_2 and λ_{2g} be the negative conductivities at the top and bottom, respectively, of this cylinder. In the normal fine weather positive potential gradient in the atmosphere, positive ions move downwards in the field while negative ions move upwards. At the ground there can be no conduction current due to negative ions unless these come out of the ground itself. The ionic conduction current across the top of the column will be $F\lambda_1$ downwards, and $F\lambda_2$ upwards, i.e. each second, a positive charge $F\lambda_1$ enters the column and a negative charge $F\lambda_2$ leaves it. At the ground there is only a downward flow of positive ions, carrying away a postive charge $F_g\lambda_{1g}$. The cylinder as a whole thus loses a positive charge $(F_g\lambda_{1g} - F\lambda_1)$ per second, and a negative charge $F\lambda_2$ per second. This is equivalent to a development of a positive space charge at a rate per second of

$$F\lambda_2 - (F_g\lambda_{1g} - F\lambda_1) = F(\lambda_1 + \lambda_2) - F_g\lambda_{1g}$$

This is known as the "electrode effect". The existence of this space charge should decrease F and should cease only when F has such a value that as many negative as positive ions leave the cylinder in each second, i.e. when

$$F(\lambda_1 + \lambda_2) = F_g\lambda_{1g} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Measurements on Lake Constance made by Muhleisen (1961) have shown that the potential gradient was greater on the surface of the lake and kept decreasing up to a height of about 10 metres, as would be expected from the electrode effect.

Calculations have shown that due to the electrode effect the potential gradient at the ground should be about 30% greater than that at one metre. Actual measurements, e.g. Scrase (1935), have shown that the potential gradient remains practically unchanged over the first few metres above the ground. Space charge measurements near the ground show a space charge density insufficient to account for any significant variation of the potential gradient between ground and one metre above. The discrepancy seems to have been resolved by the suggestion originally put forward by Hogg and worked out in more detail by Chalmers. Hogg (1939b) has suggested that the rate of production of ions may be different at the surface and at one metre above. Chalmers (1946) assumed that the rate of ionisation at the earth's surface, due to the α and β radiations from radioactive substances in and very close to the earth's surface, is five times that at one metre. He was thus able to show that a variation of conductivity with height as found practically by Hogg can be reconciled, without the requirement of a space charge density sufficiently large to alter the potential gradient appreciably.

Ruhnke (1962) in an attempt to work under conditions where interference from too many unknown factors is negligible, resorted to Greenland ice cap. There the shielding of the natural radioactive material in the soil by a thick layer of ice and snow and the absence of condensation nuclei in the air result in a very stable conductivity in fair weather. Measurement of conductivity under these ideal conditions has shown a pronounced electrode effect near the ground. Ruhnke, however, reported that the negative polar conductivity had its minimum value in completely calm air and increased to almost the full value of the positive polar conductivity with wind speeds of 2 $m.sec.^{-1}$ or greater. No explanation was given for this.

THE PRESENT INVESTIGATION

Of the measurements mentioned those of Hogg are by far the most important. This is because the use of the underground laboratory made it possible to work under conditions which approximate very well to infinite plane conditions. Also the maintenance of the top of the cardboard tube at the approximate potential of the surroundings was a big improvement. However, as used by Hogg it still introduces a source of error because the potential gradient may vary considerably during a chosen interval.

O'Donnel's results do not confirm the findings of Hogg. Chalmers (1953) has shown that the discrepancy is due to the different conditions in which the two sets of measurements were made. Hogg by working in an exposed site measured the change in conductivity caused by the vertical potential gradient and the vertical current. O'Donnel by working under the branches of large trees rendered the potential gradient and the current to be absent. O'Donnel also pointed out that the use of the right angled elbow did not cause any loss of ions by diffusion to the walls. A preliminary investigation by the author showed that the use of a right angled elbow caused the loss of 15% to 30% of ions of either sign, depending on the rate of flow.

The object of the present investigation is to use present day techniques and highly accurate equipment to undertake a similar investigation of the variation of conductivity with height in the lowest metre of the atmosphere, as a further contribution to the understanding of the conduction in that region. To this end it is hoped to resolve such disagreements as the one which the measurements of Hogg and Law seem to bring out. The project was also embarked on with the intention of comparing simultaneous measurements of the fine weather conduction current in the lowest metre of the atmosphere made by two methods : (i) indirectly, as the product of the conductivity and the potential gradient, which the present investigation would provide (ii) directly, by measuring the positive and negative components of the current, which is now the subject of an investigation by a fellow research student working on the same site. Such a comparison can give valuable information on the part played by convection.

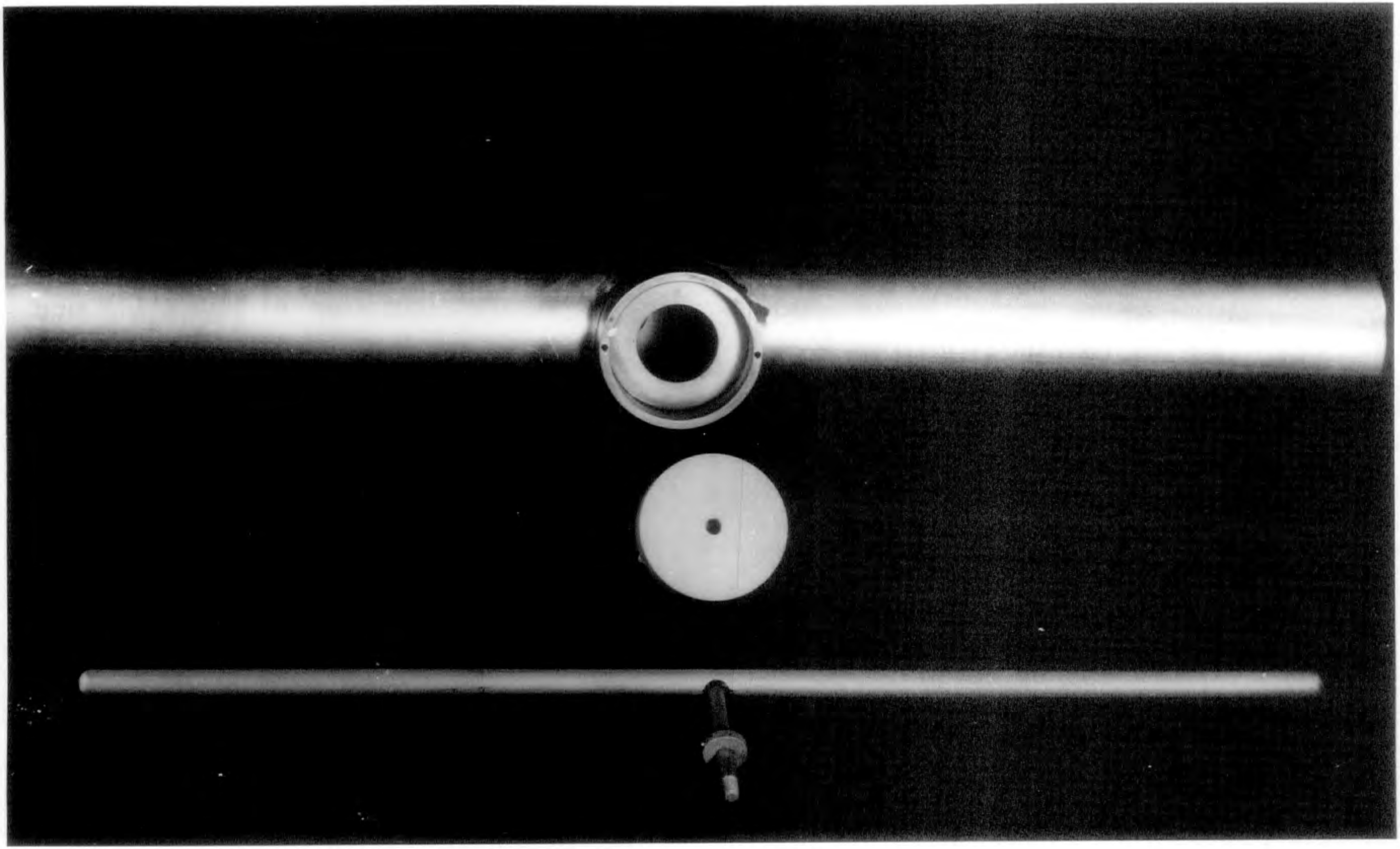


Fig. 2 The Gerdien Condenser

CHAPTER III

THE APPARATUS

THE CONDUCTIVITY CHAMBER

Atmospheric conductivity is generally measured using a modified arrangement of an instrument first used by Gerdien (1905). This consists of a cylindrical tube having inside it a small coaxial rod, thus forming an open ended cylindrical condenser. A potential difference is applied between the outer tube and the inner rod. If air is drawn through the tube, ions in the air stream will be deflected towards the inner rod or outer tube depending on their sign, under the influence of the field produced by the applied voltage. The current produced by the ions collected at the inner rod can then be measured.

For the purpose of the present investigation two conductivity chambers were required and were made to be as identical as mechanically possible. Each chamber consists of a brass tube 2⅛" (inside diameter), 14" long. The inner rod, also made of brass, is 5/16" diameter, 10" long. This is held coaxially to the tube by a supporting brass rod, 3/8" diameter which is insulated from the tube by a 1" polytetrafluoroethylene (P.T.F.E) insulator (Fig. 2). The rod, support and tube are all highly polished to avoid effects due to contact potentials. The chamber is enclosed inside an earthed aluminium box which acts as a screen.

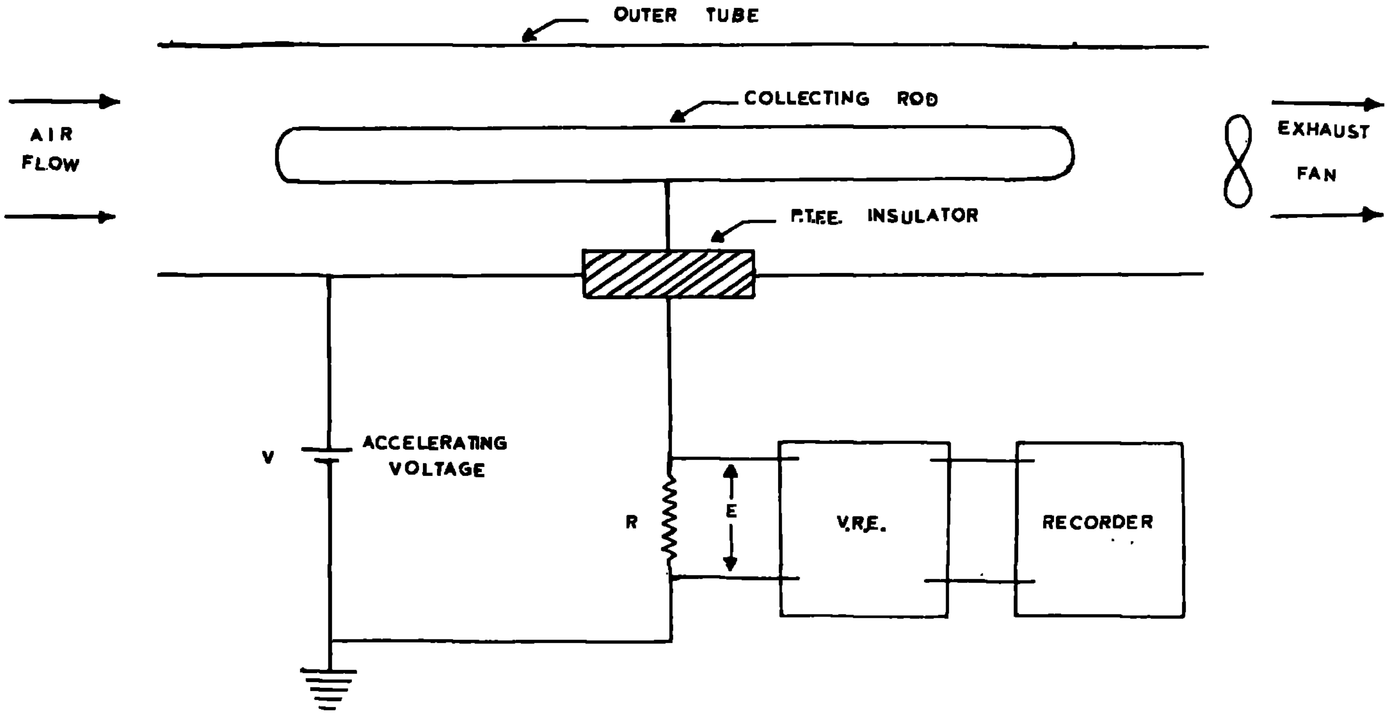


FIG. 3 THE CONDUCTIVITY SYSTEM

A potential of the required sign is applied to the outer tube while the inner rod is connected to earth through a 10^{12}ohm resistor in the head unit of an Ekco vibrating reed electrometer. The current due to the charge arriving at the central rod flows through the resistor developing a voltage signal. This voltage is converted to A.C. by means of a vibrating reed then built up to suitable strength by an A.C. amplifier. A rectifier then changes the amplified signal back to D.C. and the latter is measured on a panel meter calibrated to indicate the D.C. voltage at the input. An output current of 1 mA. corresponding to a full scale deflection on any of the four ranges provided in the electrometer, allows the use of a suitable recorder, in this case a multichannel pen recorder. Fig. (3) shows a schematic representation of the conductivity measuring arrangement. If the outer tube is maintained at a positive potential, positive ions will be accelerated to the central rod while negative ions will be forced away from the rod. Consequently, only ions of one sign are collected (in this example positive ions).

Swann (1914) has shown that the air flow through the condenser is related to the voltage E measured with the electrometer by:

$$E = \frac{RCV\lambda}{\varepsilon_0} \quad \text{volts} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where: C farads is the measured capacity of the condenser

V volts is the applied voltage

R ohms is the high resistance in series with the central rod

λ ohm^{-1}.m.$^{-1}$ is the unipolar conductivity of the air

ε farad. m.$^{-1}$ is the permittivity of the air

$$\text{or } \lambda = \frac{E\varepsilon}{RCV}$$

i.e. λ is proportional to the current $i = E/R$ through the central rod. Thus

$$\lambda = \frac{\varepsilon i}{CV} \text{ ohm}^{-1}\text{m}^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

For this equation to be applied to an instrument capable of measuring conductivity, the value of the applied voltage, V, must be less than that which produces saturation of the chamber to ensure working on the Ohmic portion of the voltage - current curve (Fig. 1). If this condition is not satisfied the instrument will function as an ion counter instead of a conductivity chamber. The saturation voltage, V_s, can be worked out by equating the current, i, to the flow of ions through the tube, thus:

$$i = Wne$$

where: n is the number of ions per cubic metre

W is the rate of flow in m.^{3}sec.$^{-1}$

Equation (5) now becomes

$$\lambda = \frac{\varepsilon Wne}{CV}$$

but $$\lambda = nek$$

where k is the mobility of the ions, of particular charge sign being collected.

$$\therefore V_s = \frac{\varepsilon_0 W}{Ck}$$

The capacity of the cylindrical condenser can be seen to be of enough importance to justify its measurement accurately. The difficulty here is presented by the fact that the supporting rod collects some of the ions and so the effective capacity of the system actually exposed to the air flow has to be determined. This is not easy to calculate. Smith (1953) has described a method for measuring this quantity. The effective capacity, C, consists of the capacity, C_1, of the fully exposed central rod and the capacity, C_2, of the partially exposed supporting rod. C_1 is determined by taking the difference between two measurements: the total capacity with and without the central rod. Under conditions of constant conductivity, two conductivity readings are then made to find the effective part of C_2. Let i_1 be the reading with the central rod and i_2 the reading without the central rod. Then the effective part of C_2 is given by

$$C_2 = \frac{C_1 \times i_2}{i_1 - i_2}$$

Hence $C = C_1 + C_2 = \dfrac{C_1 \, i_1}{i_1 - i_2}$

The capacity C_1 was measured as described above using an accurate Wayne Karr Universal Bridge and the effective capacity worked out to be 8.51 pF. The measured capacities for both chambers agreed to within 1%. Thus with a flow rate of 260 cubic feet per hour (2.04×10^{-3} m.^{3} sec.$^{-1}$), a collecting potential of 7 volts, the fastest ion completely caught would have a limiting mobility of 3×10^{-4} $m.^{2}$ $v.^{-1}$ $sec.^{-1}$

THE FIELD MILL

In order to obtain a continuous measurement of the potential gradient a field mill was decided to be used, mainly because of the considerable experience which the Durham research group has had with the instrument.

In the field mill a fixed vane - called the stator - is alternately exposed to and shielded from the lines of force by an identical earthed rotating vane - called the rotor - . The highly insulated stator is connected to earth through a high resistance. As a result of the alternate covering and uncovering of the stator a charge proportional to the potential gradient is alternately bound and released on it, giving rise to an alternating current through the high resistance. In the case of the quadrant type of vane usually used, the alternating potential has a triangular wave form and a frequency four times that of the rotation of the rotor. This can be amplified, rectified and measured. However, the alternating nature of the field mill output makes it impossible to ascertain the sign of the potential gradient measured. For the determination of this various methods have been used.

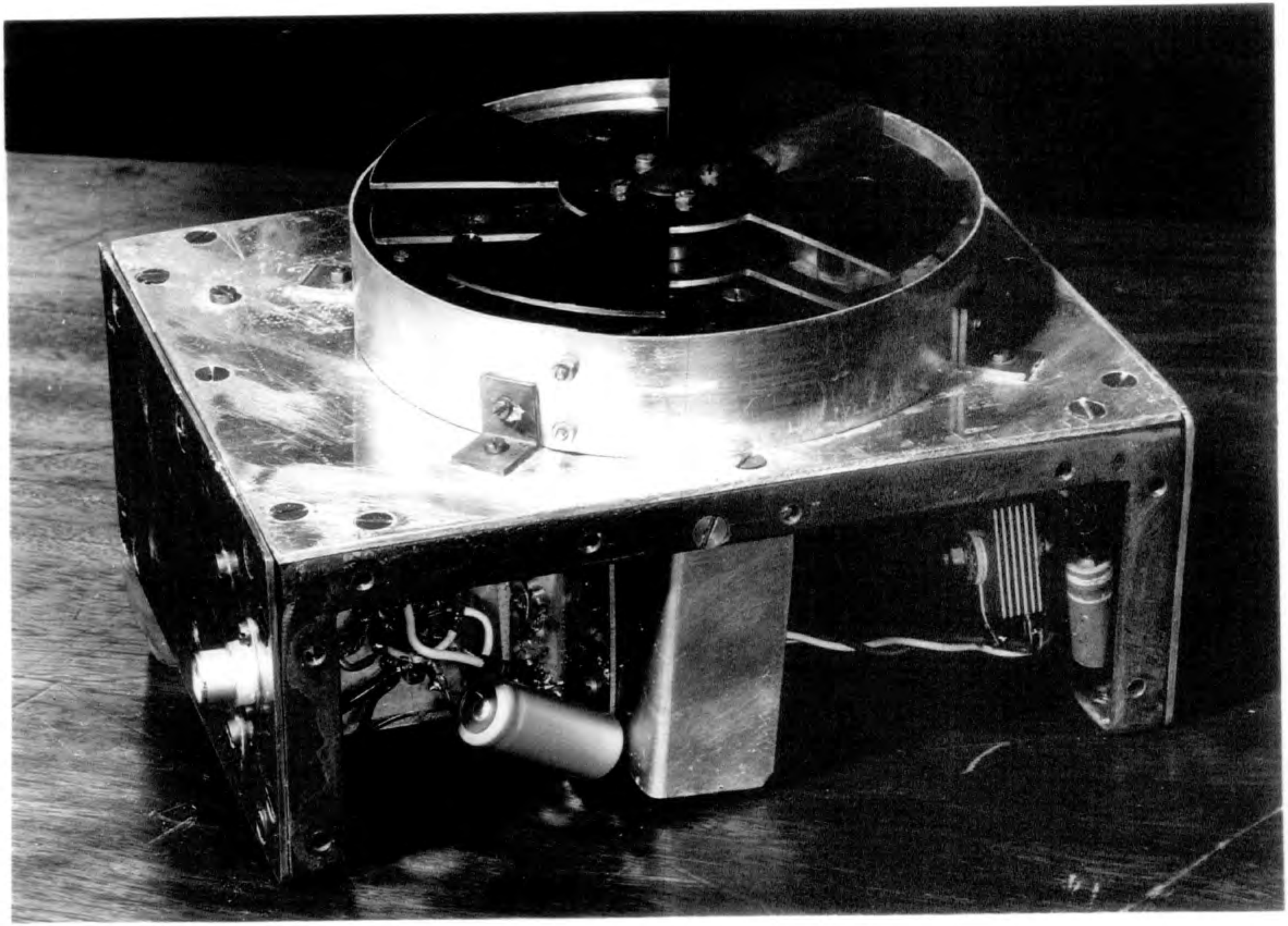


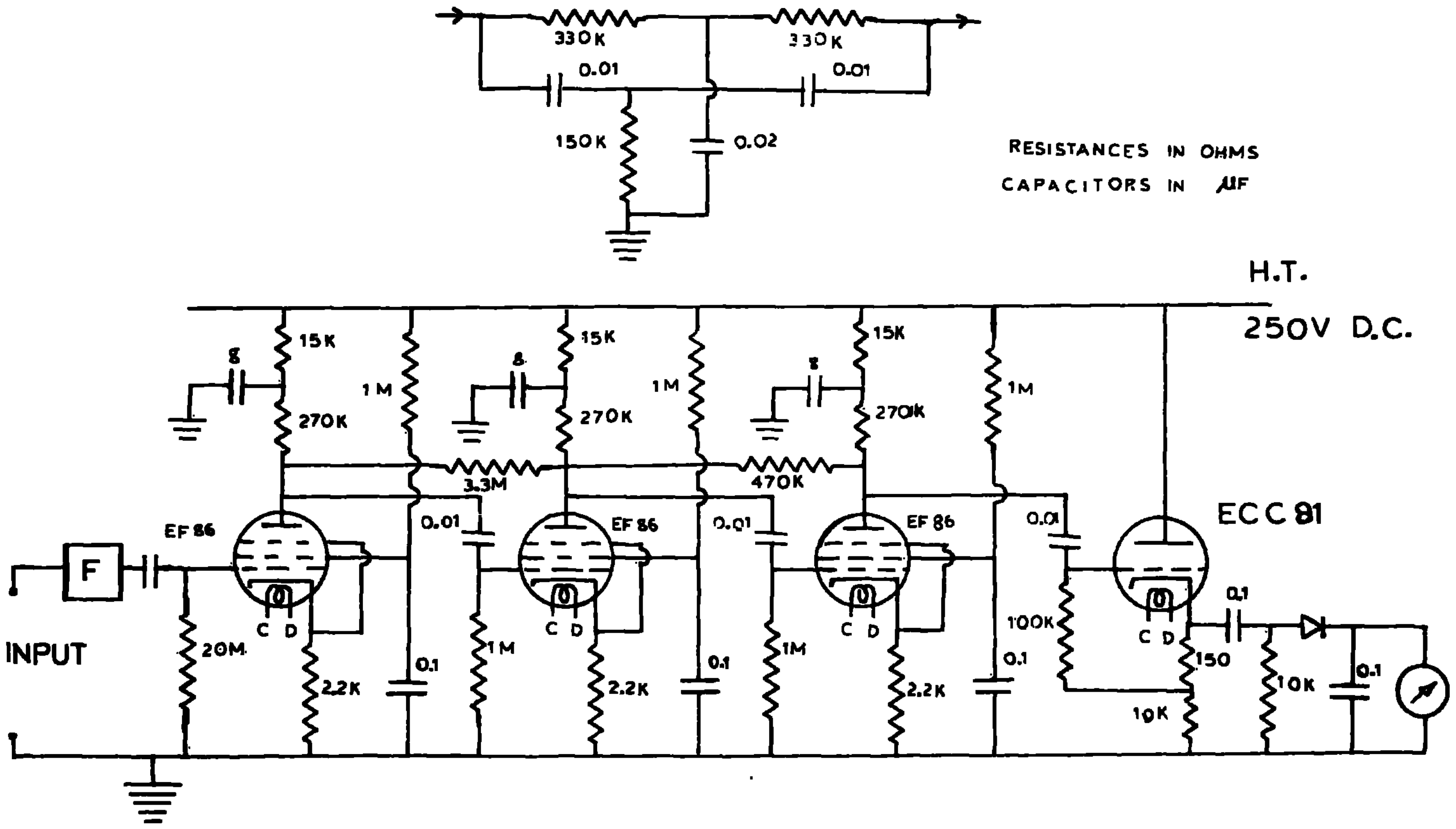
Fig. 4 The Field Mill Head Unit

THE HEAD UNIT

This contains the earthed rotor and insulated stator, the electric motor for driving the rotor, a cathode follower to enable a long cable to be used to carry the signal to the amplifier and a power supply for the cathode follower.

The design of the head unit had to be planned in such a way as to make the interior as accessible as possible to facilitate easy maintenance and checking in case of any break down. To achieve this the framework was constructed of angle iron welded together and completely covered with detachable aluminium sheets.

The stator and rotor in the shape of a cross (Fig. 4) were cut from brass and chromium plated to prevent corrosion and contact potentials. The stator was mounted on four polystyrene insulators, $\frac{3}{4}$" diameter and 1" long, with an earthed guard ring round it to minimise the chances of picking up any spurious signals. The rotor, firmly attached to the shaft of a mains operated, 3000 revolutions per minute synchronous motor was 5mm. above the stator and coaxial with it. A spring loaded carbon brush seated in a copper block bolted to the case of the mill, made contact with the motor shaft, thus forming the earthing device. The stator was connected to earth by screened cable, through the parallel combination of a 10^8 ohm resistor and a 100 pF capacitor.



MAINS FILTER CIRCUIT (F)

RESISTANCES IN OHMS
CAPACITORS IN µF

FIG. 6 THE MILL AMPLIFIER

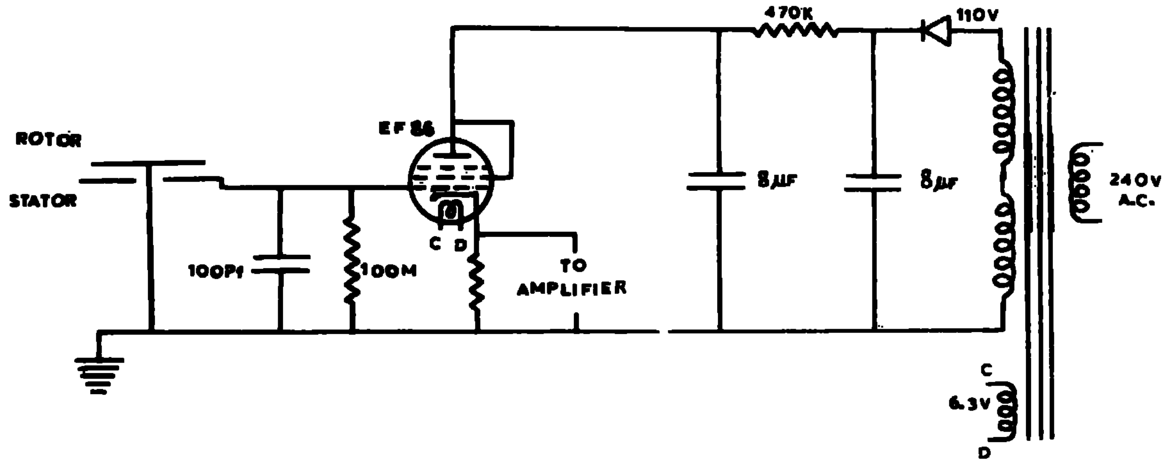


FIG. 5 THE CATHODE FOLLOWER

In order to match the high input impedance of the stator to the low output impedance provided by the cable carrying the signal to the amplifier indoors the alternating voltage across the resistor was fed directly to the grid of a cathode follower (Fig. 5) using screened cable. The Mullard EF86 valve was used for this purpose due to its good antimicrophonic properties, while vibration was avoided by mounting the valve on rubber foam. The heater voltage and H.T. for the cathode follower were provided by a transformer and metal rectifier. A "humdinger" was connected across the heater supply. This consisted of a 100 ohm potentiometer, the slider of which was earthed. When adjusted, the hum induced from the valve heater supply was reduced to a negligible proportion. Mains pick up was eliminated by screening the cathode follower from its power pack and the motor from both. The cables used were a screened three core mains cable and a 60 yards length of coaxial cable to carry the signal from the head unit to the amplifier.

THE FIELD MILL AMPLIFIER

This was required to amplify the signal from the field mill so that it can be recorded on a 1 mA. pen recorder. Owing to the low fields to be encountered during fine weather a three stage R-C coupled amplifier was used (Fig. 6). The valves used in all three stages were low noise pentode valves EF86, while the output stage was a cathode follower valve ECC81. Negative feedback was applied through the cathode resistors of all the

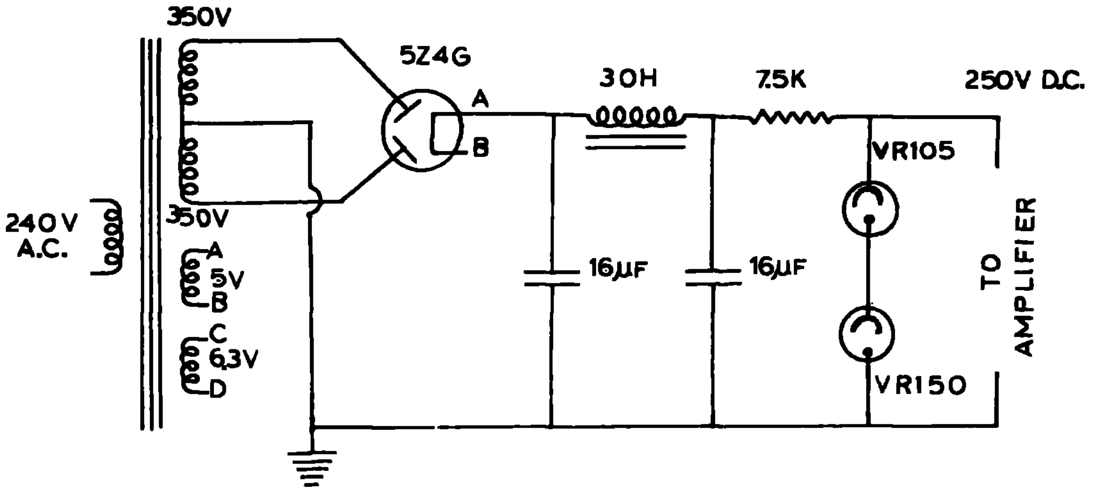


FIG. 7 THE POWER SUPPLY

valves and across the resistors joining the anodes of the first three valves. Mains pick up was almost completely got rid of by the use of a special mains filter circuit (Fig. 6) at the input of the amplifier. All the precautions mentioned resulted in a pick up level of 0.5 mV as measured on the cathode ray oscillograph. The overall voltage amplification was 1000. A crystal diode OC71 was used to rectify the current.

THE POWER SUPPLY

A conventional circuit (Fig. 7) was used as a power supply for the amplifier. Neon valves VR105 and VR150 were used for stabilisation purposes. The output of 250 volts at 25 mA. thus remained constant as the mains voltage was varied between 200 and 280 volts.

SIGN DISCRIMINATION

As already mentioned the field mill output can not indicate the sign of the potential gradient measured. For the purpose of the present investigation it was decided to determine the sign of the field by a zero displacement method as this could easily be backed off in the continuous balance circuit used for giving the correct potential of the surroundings. This was done by applying a known potential on a plate, held one inch above the rotor. The potential on the plate of 30 volts was big enough to make the effect of any contact potentials negligible and could enable negative fields of -200 $v.m.^{-1}$ to be detected. It is to be mentioned here that since measurements were taken in fine weather, negative fields were not expected to be encountered, except perhaps in the relatively few occasions when such negative fields do prevail in perfect cloudless days due to such things as pylons as found by Chalmers (1952), etc. Besides it would be very unreliable to look at the sky and decide whether the potential gradient was positive or negative. Hence the zero was not displaced very much as it is usual by this method to displace the zero by the amount corresponding to the largest negative potential gradient value to be measured.

THE POTENTIAL BALANCING SERVO MECHANISM

The instrument used for this purpose is the continuous balance unit of a Honeywell Brown Electronics chart recorder. In its original form the balancing system continuously compares an input emf generated by a thermocouple, or other D.C. source, to an emf of known value supplied by the instrument. This is accomplished by a potentiometer method whereby the thermocouple voltage is measured against the slide wire voltage, which is maintained constant by a zener diode regulator unit. Any difference between the thermocouple voltage and the potentiometer slide is converted into A.C. by a vibrating reed and then amplified, first in voltage and then in power. This amplified output actuates a servo motor which drives the slide to the correct potential.

The conversion of any unbalanced D.C. voltage to an alternating

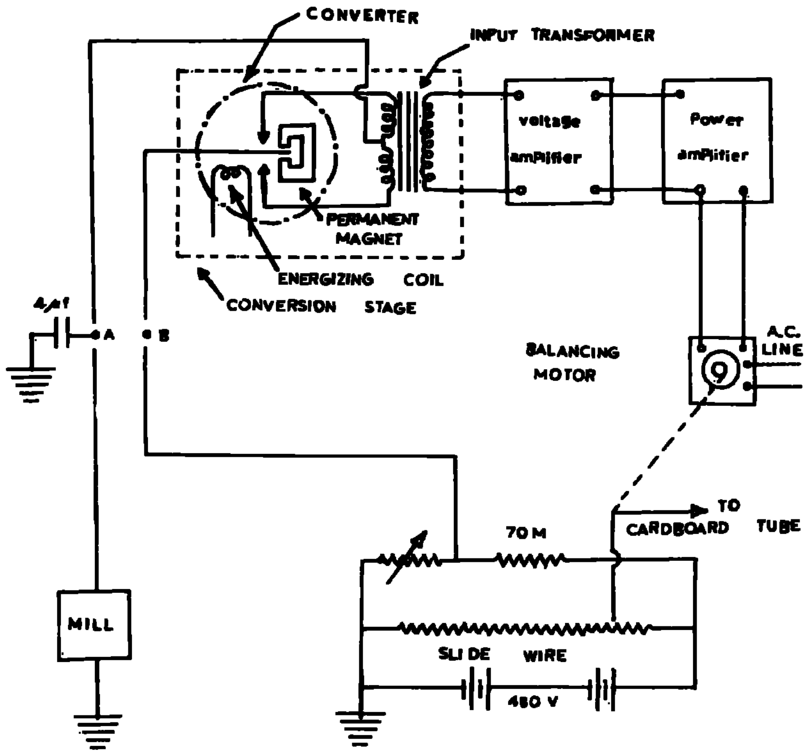


FIG. 8 THE CONTINUOUS BALANCE SYSTEM

voltage of proportional magnitude is accomplished by a converter and a specially designed input transformer. The converter is essentially a flat metal reed which is made to oscillate between two contacts connected to the opposite ends of the primary winding on the input transformer, by the action of the combined fields of a permanent magnet and a coil energized by line voltage (Fig. 8). When the coil is energized, the tip of the reed is polarised alternately N and S at line fequency. The reed is attracted to the magnet pole of opposite polarity. Consequently, the reed oscillates in synchronism with this line frequency. The unbalanced D.C. is impressed across the converter and the centre tap of the primary winding on the input transformer. Thus, as the vibrating reed moves from one contact to the other, any unbalanced D.C. voltage will cause direct current to flow first in one direction through one half of the primary winding, then in the opposite direction through the other half of the primary winding. This action generates an alternating flux in the input transformer core which in turn induces an alternating voltage on the transformer secondary. The alternating voltage thus created is timed with the A.C. supply voltage in such a way that a change in the thermocouple D.C. voltage operates the balancing motor in the proper direction to balance the circuit.

The balancing motor is a reversible, two phase induction motor, one phase of which is continuously energized by line voltage and the other by the amplified voltage; the direction of rotation of the motor thus depends on the phase relationship or timing of the two motor supply voltages.

The sensitivity of the amplifier can be varied, the motor responding to a minimum change in input of 0.03 mV at maximum sensitivity. The slide travels from one end of the wire to the other in 12 seconds.

For the balancing system to be of any use in maintaining the potential of the surroundings in the atmosphere during fine weather, the voltage across the slide wire must be of the order of a few hundred times that originally applied by the makers. This would mean that the original slide wire would not be able to carry the high current drawn from the high tension supply and so it must be replaced by one of high enough resistance. Unfortunately no wire of such a high resistance and of the desired length could be obtained. The problem was first tackled by Smiddy and Chalmers (1958) who wanted the instrument to balance continuously the outputs from a double field mill and thus bring and keep the mill at the potential of the surroundings. To do this the original slide wire supplied with the instrument had to be replaced by a composite resistance constructed on a tufnol strip fitting in the recorder in place of the wire. This consisted of 101, 10 B.A. bolts separated from one another by a gap of 1/64" so that the slide can move smoothly over the bolt heads. This made it impossible to hold the bolts in position by means of nuts and so the holes for the bolts in the tufnol strip were accurately drilled and tapped. To the reverse side of the bolt heads 100, 10,000 ohms resistors were carefully soldered in series. In operation, 3 of the contacts at one end and 4 at the other had to be shorted out to bring the pen zero and full scale in coincidence with zero and maximum voltage. Thus the wire had an effective resistance of 930,000 ohms.

For Smiddy's purpose it was then just a matter of feeding the two outputs of his double field mill into the input terminals A and B (Fig. 8) of the continuous balance unit. For the purpose of the present investigation the output of a field mill at ground level is required to be fed into the continuous balance unit such that the potential of the surroundings can be maintained continuously at the correct value, at any of two heights above the ground - namely 20 cm. and 100 cm. The use of a field mill at ground level for this purpose is justified by the many measurements made by previous workers showing that the field [redacted] remains practically constant in the lowest few metres above the ground. This was achieved by feeding the field mill output at terminal A and comparing it with a very small fraction of the slider voltage fed at B as shown in Fig. (8). The 70M ohms resistor had to be included so that the linearity of the composite resistance is not affected. The small tapping resistance itself is a variable one to facilitate the accurate adjustment of the slider voltage to that appropriate for the height required. The 4mfd capacitor across the input at A was found necessary to filter out any stray A.C. from the field mill amplifier to which the continuous balance circuit is very sensitive. The method of sign discrimination used in the field mill, already described on page 25, displaces the zero by a certain amount. This was backed off at A by a suitable external potentiometer circuit.

THE GAS METERS

For the measurement of the rate of flow of air through the conductivity chambers, two gas meters (one for each chamber) were purchased from the Northern Gas Board. The capacity of each meter is 400 cubic feet per hour and the accuracy claimed by the Board is 0.5 %. As these were connected to the conductivity chambers in the field some 60 yards away from the recording room it was found convenient to monitor their reading in such a way that a check of the flow rate could be made indoors. This was achieved by making the rotating arm of the gas meter close a microswitch especially fitted in the gas meter. The microswitch itself was part of a series circuit consisting of a 12V supply and a lamp indoors. This resulted in 5 flashes of the lamp for every two cubic feet of air sucked through, which could be accurately timed with a stop watch.

THE SUCTION FAN

The suction fan was a "Hoover Constellation" mains operated motor and fan assembled by Hoover Ltd. This was then encased in a brass cylinder with a 1" intake and a 1" exhaust. A "Y" shaped adaptor connected by 1" rubber tubing to both chambers enabled the fan to suck air through both.

The capacity of the fan (53 cubic feet per minute) was too great for the rate of flow required and so it was run at the reduced voltage of 50V while finer adjustment was made by manipulating jubilee clips placed round the rubber tubes joining the fan to the gas meters.

RECORDING

The early part of the work, mainly during the time of testing the apparatus, was recorded photographically. This was done by reflecting the light from critically damped galvanometers on to the slit of a slow rotating drum camera carrying 120 mm. sensitised paper. A "fogging lamp" was placed in front of the camera and was switched off for 3 seconds every half minute by a suitable cam rotated by a synchronous clock motor. This has the effect of giving a grey background on which white lines are produced by marks scratched on the camera lens. These white lines enable deflections caused by movement of the light to be measured accurately. The marks on the lens are usually arranged to give lines 1mm. apart when the "fogging lamp" is 50 cm. from the paper in the camera. As a result of the "fogging lamp" also, white lines are produced on the film at half minute intervals and these act as a time scale.

Fortunately, by the time the apparatus was ready for taking measurements on the site a pen recorder used by a fellow research student became available and was taken over by the author. This was a four channel

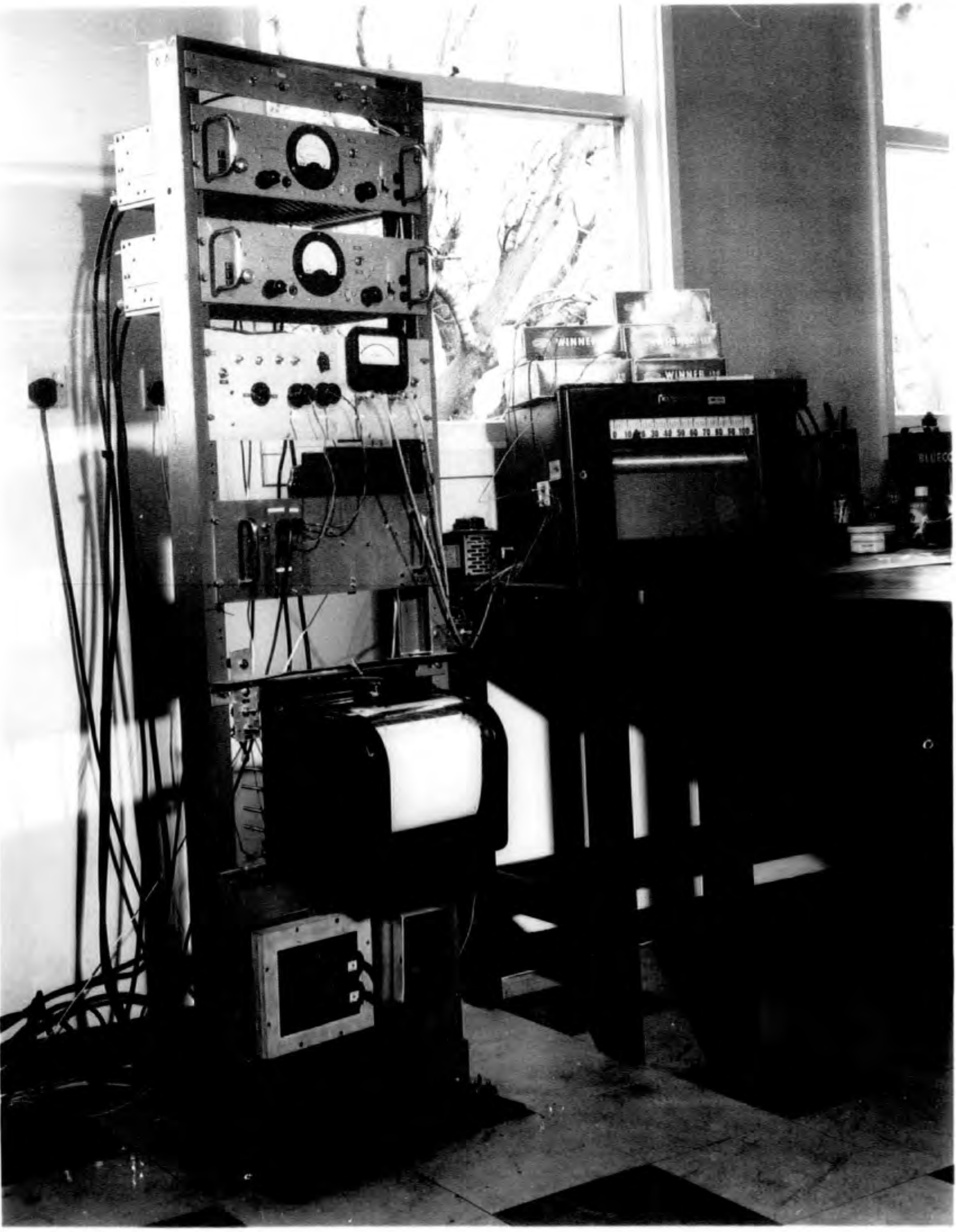


Fig. 9 The Instrument Panel

pen recorder manufactured by Everett Edgcumbe and Co. Ltd. It consisted of four entirely independent pen units writing on a chart driven by a mains operated synchronous motor. Each unit was essentially a moving coil, D.C. milliammeter, of high sensitivity, having a full scale deflection of 1 mA. The galvanometer response time is 0.5 seconds.

THE INSTRUMENT PANEL

The vibrating reed electrometer indicator units, field mill amplifier and power pack, gas meter monitor light bulbs, pen recorder and a plug board were all mounted on a 16" steel rack as shown (Fig. 9). To the right of the rack can be seen the Honeywell Brown recorder, the continuous balance unit of which was used to maintain the potential of the surroundings as already described.

CHAPTER IV

INSTALLATION, PERFORMANCE AND CALIBRATION

THE SITE

The site chosen for the investigation was a field near Durham University Observatory. The Observatory building stands on a hill 120 metres above sea level and about one kilometer to the west of Durham City. It is surrounded, for the most part, by agricultural land and is well away from large sources of atmospheric pollution. About 30 yards due west of the building is a large field where instruments for the investigation of atmospheric electric parameters are usually erected.

THE CONDUCTIVITY CHAMBERS PIT

At a distance of 30 yards from the edge of the field nearest to the Observatory building a pit 7' x 5' x 4' was dug to house the two conductivity chambers, gas meters and suction fan. The four walls of the pit were brick lined and plastered with cement. Underneath the floor to a depth of two feet a sand bed was made before it was finally concreted. This was done to stop any moisture reaching the floor. At the appropriate height above the floor a concrete shelf 15" x 15" was made on which the suction fan was placed. Immediately behind the shelf a lead pipe 1" in diameter carried the exhaust through the pit wall 20 yards behind. A short length of rubber tubing at the end of the exhaust pipe enabled the exhaust to be always downwind, thus ensuring that the air expelled would

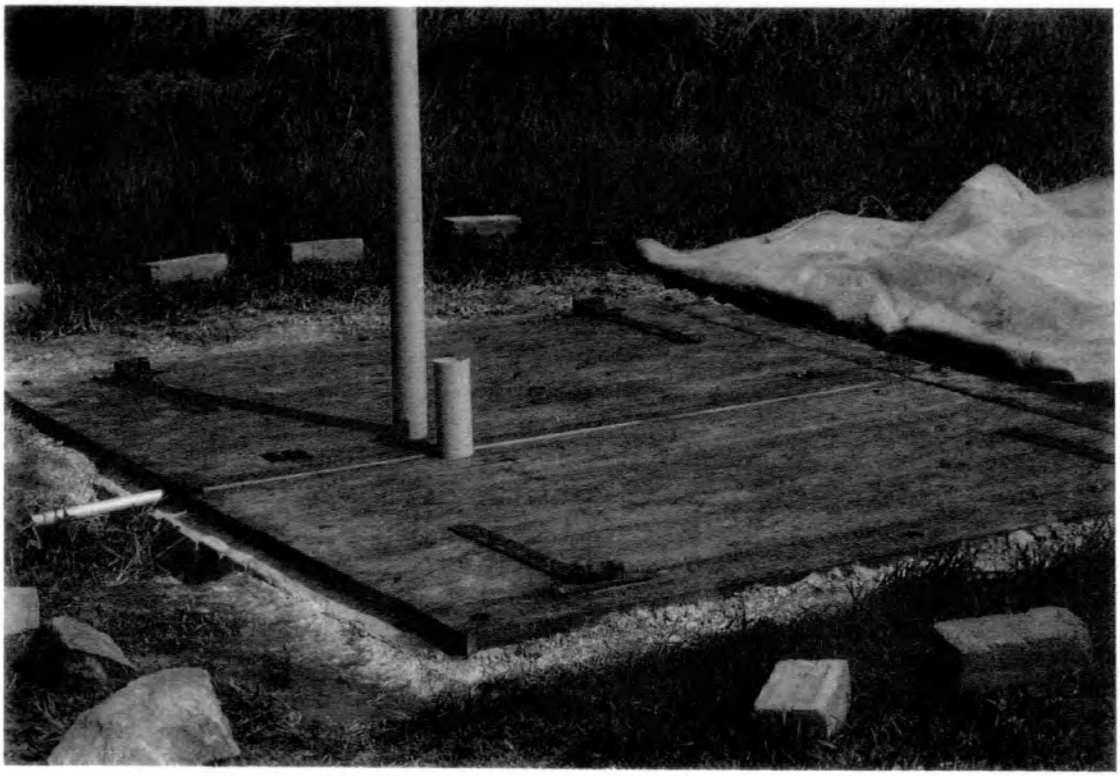
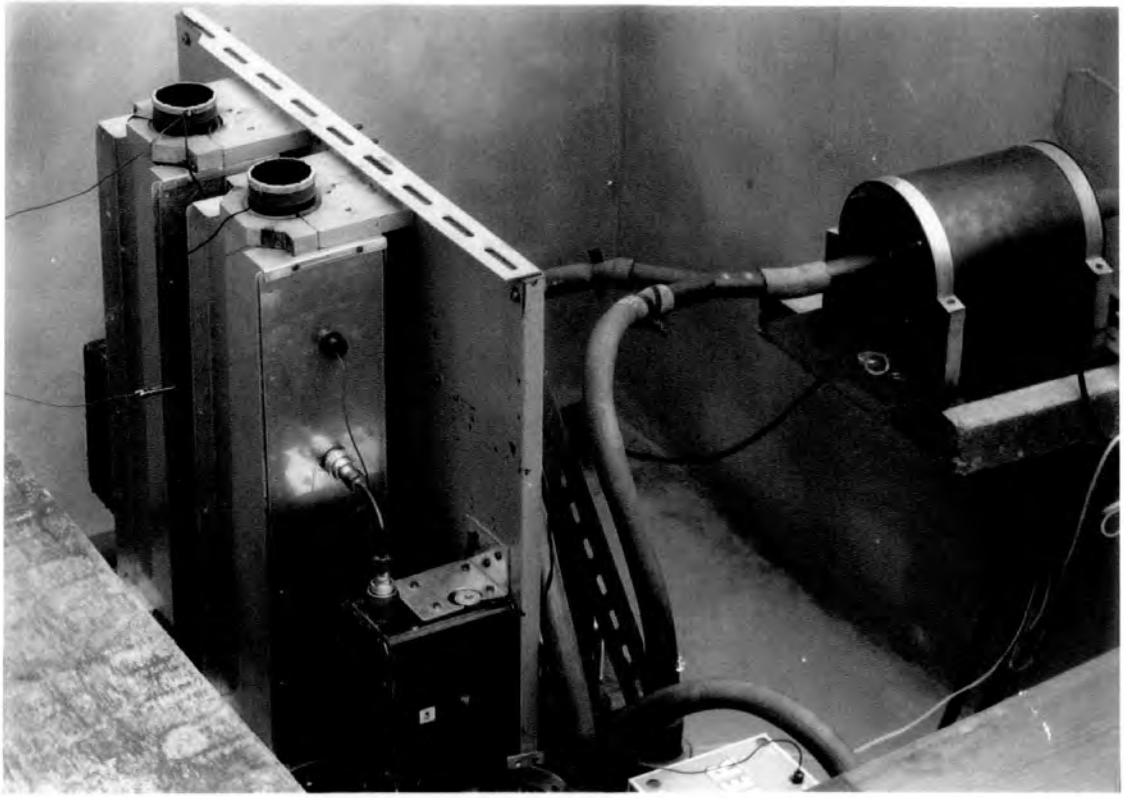


Fig. 10 The Conductivity Chambers Pit



not re-enter the conductivity chambers. On either side of the pit a 4 ft. 320 watts tubular heater was mounted on the floor. This was found necessary to keep away any moisture which otherwise might cause an insulation breakdown in the high insulation circuitory of the vibrating reed electrometer head units or the conductivity chambers. Cables were run from the Observatory to the edge of the field through a concrete duct and from there to the pit they lay on "T" shaped "handy angle" carriers. These would stop them being overgrown or accidentally cut when the field was mown. The "handy angle" carriers rose about 10" above ground, the nearest one to the pit being 10 ft. away, and so did not cause any serious distortion of the lines of force. The cables were led into the pit through a 4" 'L' shaped glazed pipe, the latter being tightly closed with a wooden lid to stop any precipitation from entering the pit.

The two conductivity chambers and their electrometer head units were fixed side by side on to a wooden board, with their intakes 8" apart. The whole board was then firmly fixed to a vertical "handy angle" frame concreted to the centre of the floor such that the two intakes were vertical and flush with the ground. Connection to the gas meters and the suction fan behind was then made with 1" rubber tubing. Fig. (10) is a photograph showing the inside of the open pit and the carboard tubes when the pit is closed. The pit was covered with two wooden hinged cellar type doors.

At the appropriate places two circular holes $2\frac{1}{2}$" diameter were cut into the doors to enable the introduction of cardboard tubes over the conductivity chambers intakes so that the required sign of conductivity could be measured at the required height. When not in use, the conductivity intake tubes were covered with aluminium tins and the wooden doors were closed. As a further precaution against any precipitation entering the pit through the doors, a large waterproof tarpaulin cover 12' x 8' hinged at the corners covered the whole pit as well as the 4" glazed pipe admitting the cables into the pit. The arrangement proved to be extremely effective.

THE FIELD MILL PIT

As the potential gradient was required to be measured at ground level, a concrete pit 18" x 18" x 16" was made 4 yards from the nearest conductivity chamber and due south of it. A small "handy angle" frame concreted to the floor of the pit enabled the field mill to be firmly fixed in position on a shelf with the rotor almost flush with the ground. A mains cable was led into the pit from the conductivity chambers pit nearby. This was required for running the motor and supplying power and heater voltage to the cathode follower within the mill. A 75 watts 240V A.C. light bulb enclosed in a small earthed aluminium box with a number of 4 B.A. clearance holes all round it, was fixed to the central "handy angle" frame. This provided enough heat to keep the surfaces of the polystyrene insulators supporting the stator, free from moisture and therefore maintain

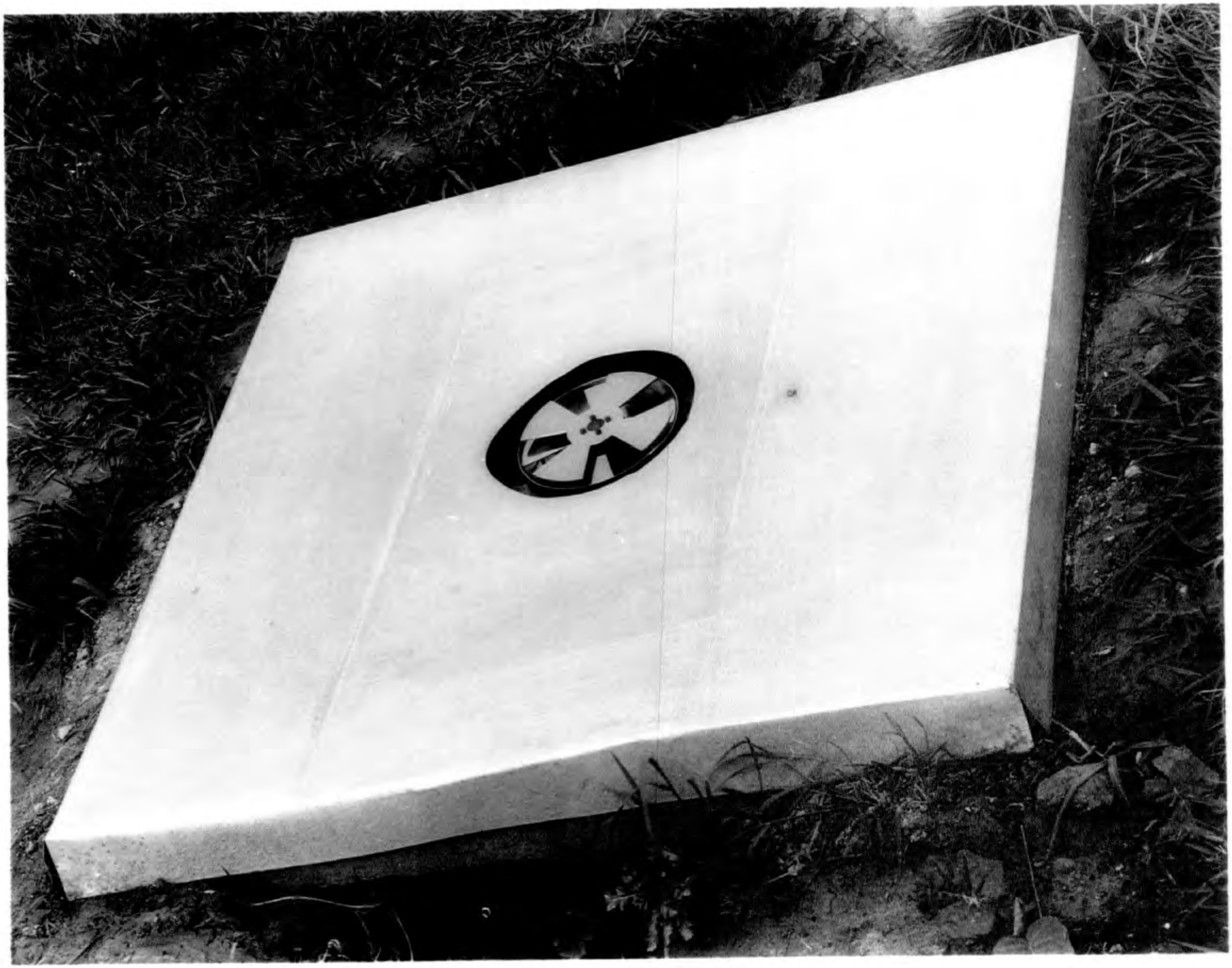


Fig. 11

its high insulation properties. An earthed aluminium sheet level with the ground covered the pit and a central hole in it exposed the rotor to the ambient potential gradient (Fig. 11). When not in use a large aluminium sheet covered the whole pit and thus kept all precipitation from entering it. A coaxial cable from the mill carried the signal to the amplifier indoors.

THE CONDUCTIVITY CHAMBERS

Since the two chambers were to be used in comparing conductivities of opposite signs at the same level or those of the same sign at different levels, it was necessary to make sure that under identical conditions both gave the same reading for the same sign of conductivity measured. Tests in the laboratory, first near a window and later near a door, have shown differencies as high as 6%. This was very surprising because the measured capacities agreed to within 1%. It was therefore decided that this might have been due to turbulence in the air inside the laboratory and so the experiment was repeated with both chambers - intakes 8" apart - on a field nearby. Agreement to 1% was then found as well as an extremely high correlation.

The necessity of the chambers to be in a pit underground made it obvious that the smaller the pit the less expensive it would cost to make, and the more efficient it would be to keep it dry and clean. With this in mind it was at first envisaged that the chambers could be mounted horizontally with right angled elbows at the intakes. It was feared that the arrangement might result in the loss of ions of both signs due to turbulence in the bend. To test this, one chamber was fitted with a right angled elbow and the other was left without an elbow, but adjusted so that its intake was at the same level and 8" away from the elbow intake. With conditions otherwise identical, the reading from the chamber with the elbow was as much as 25% lower than that without. The experiment was repeated many times using different rates of flow but in no case was the difference between the two less than 15%. It has been suggested that the loss of ions could be very much reduced if the vertical end of the elbow had a funnel shaped intake. This when tried showed a slight improvement and it was then thought that perhaps the diameter of the funnel as well as its height were critical. So the decision was made to mount the chambers vertically in a big pit rather than indulge in trial and error experiments in aerodynamics.

A further possible error found necessary to investigate was the absorbtion or combination of ions in their passage along the cardboard tube. This was done by slipping a cardboard tube one metre long over one chamber and raising the other one so that its intake was level with the top of the intake tube. The potential at both intakes was maintained at the correct value of the surroundings. Then the conductivity of one sign was measured. The experiment was repeated many times and again carried out a number of

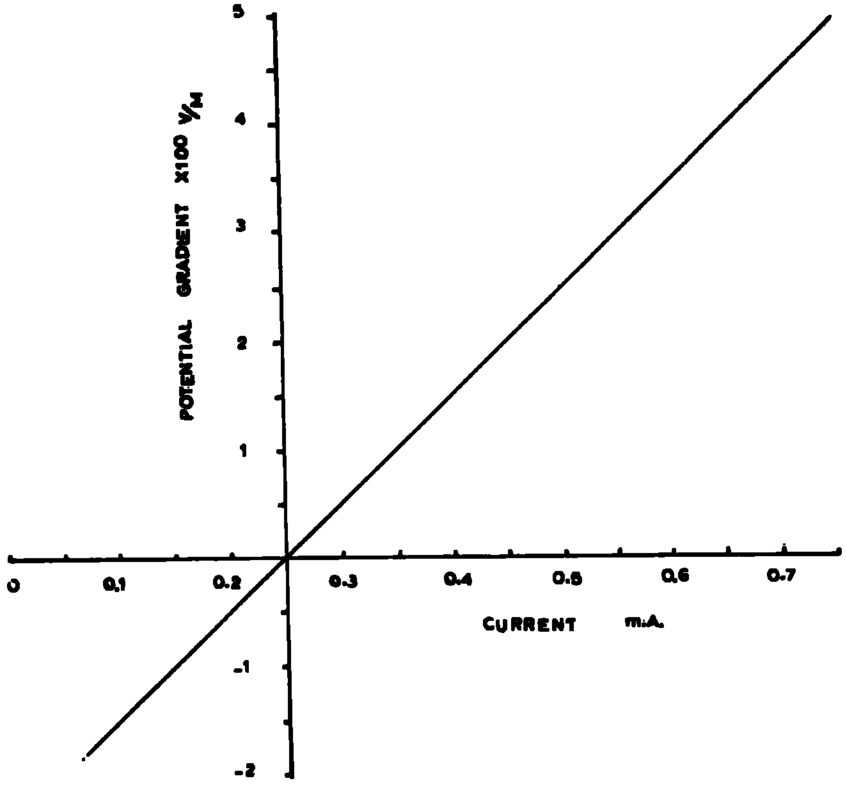


FIG. 12 FIELD MILL CALIBRATION

times for the conductivity of the other sign. Results showed that for both positive and negative ions differencies in the readings of both chambers never exceeded 1%. It was therefore decided that no correction was necessary on account of the cardboard tube.

THE FIELD MILL

No snags were encountered with the field mill and its performance was very satisfactory. Calibration was made in situ by applying known potentials to an insulated calibration plate held 50 cm. above the rotor. The calibration plate area of one square metre was big enough for any edge effects to matter. Fig. (12) shows the calibration curve. The field mill head unit is sensitive to all electrostatic fields including those set up within itself by contact potentials and accumulations of surface charge. Since these parameters can be quite variable and since the gain of the electronic amplifier can possibly vary, frequent checks of zero level and sensitivity are essential. These were generally made at the start of each recording and consisted of covering the mill with the insulated calibration plate which was first earthed and then raised to a known potential (usually the potential which gives rise to a half scale deflection on the field mill channel on the recorder). Any necessary adjustment was then made by the potentiometer by way of which the voltage is applied to displace the zero as the means of sign discrimination already described.

THE VIBRATING REED ELECTROMETERS

Apart from infrequent insulation breakdowns due to dampness these instruments behaved satisfactorily. However, in the early part of the work considerable trouble was encountered which was later traced to be due to piezoelectricity produced in the cable joining the collecting rod in the chamber to the input terminal of the head unit. This was overcome by soldering the ends of the two 'Plessey' plugs concerned to the two ends of a bent copper pipe 1/2" in diameter, and passing an antimicrophon cable through it. This provided a direct rigid connection and completely eliminated the trouble.

In order to maintain a good zero stability the manufacturers recommend that the instrument should be switched on for at least 24 hours before being used. As measurements to be made could not possibly be ascertained 24 hours in advance, the instruments were left switched on throughout the period of the investigation. The day to day zero stability of better than $\pm\frac{1}{2}$ mV claimed by the manufacturers was in fact maintained and zero checks were only made at intervals of roughly once a week.

CHAPTER V

THE STATISTICAL PRINCIPLES INVOLVED

The nature of the parameters involved in this investigation is such that a statistical analysis is about the only logical way of dealing with them. Like all atmospheric electric parameters conditions can not be controlled at will nor can they be reproduced accurately - or even approximately - for purposes of comparison. Furthermore the two parameters being measured - potential gradient and conductivity - vary from day to day and indeed from minute to minute. Hence the following brief survey of the general principles involved will now be given.

SAMPLE STATISTICS

Sampling is the selection of a proportion of the population to obtain information concerning the nature of that population. The primary task in embarking on a sampling inquiry is to derive statistics which yield the information required about the population. Consequently the main line of endeavour in such cases lies in estimating with the greatest accuracy (which is largely a matter of choosing the right statistics and minimising sampling variability), or in ensuring that sufficient material is available to enable the requisite comparisons to be made with significance (which is largely a matter of sample size and selecting the most suitable tests of significance). Nothing can alter an existing population and theory will, as a rule, only react on the sampling process by indicating, for example, that the sampling must be random.

ESTIMATION AND CONFIDENCE LIMITS

Statistics aim at estimating the value of a parameter in the parent from the information given by the sample, provided that the sample is drawn in an unbiased manner. Let us consider what we mean by "estimation". We know, or assume as a working hypothesis, that the parent population is distributed in a form which would be completely determinate if we knew the value of some parameter θ. Given a sample of values x_1, x_2, x_3, ... x_m we require to determine, with the aid of the x's, a number which can be taken to be the value of θ, or a range of numbers which can be taken to include that value.

A single sample, considered by itself, may be rather improbable, and any estimate based on it may therefore differ considerably from the true value of θ. It appears, therefore, that we cannot expect to find any method of estimation which can be guaranteed to give us a close estimation of θ on every occasion and for every sample. We must be content with formulating a rule which will be the best possible in the sense that it will have a high probability of being correct in the long run. Thus we have to regard our method of estimation as generating a population of estimates and to assess its merits according to the properties of this population. The formula used to make an estimate is called the Estimator and the value reached by using the formula is called the estimate. In general the accuracy of an Estimator increases with the number of items in the sample data. A good Estimator will be unbiased and will converge more and more closely (in the long run) on the true value as the sample size increases.

Let us now consider the specification of the intergal within which the true value being estimated may be said to lie with a specified probability. This is done by referring the distribution to the Normal Scale, where the probability of a deviation of up to one standard deviation on either side of the mean is 68%. This means that the population mean can be taken to lie in the range of one standard deviation either way, the confidence in this claim being expressed by saying that in a long series of estimates of this kind, if we were to use exactly the same sort of argument, we should expect to be correct 68% of the time. If we allow two standard deviations on either side of the mean then referring to the Normal Scale we find that in this range the probability increases to 95% i.e. we could now hope to be correct in 95 out of every 100 such predictions. Similarly with three standard deviations on either side the probability becomes 99.7%. The statistician can never be certain of the correctness of his estimate of a parameter or any other conclusion based on sample data. Any inference or conclusion based on sample data is made at a specified level of confidence, usually at the 95% level.

TIME SERIES

A time series is a series of values assumed by a variable at different points of time. Let us consider only cases where the variable is univariate and denote its value at time t by u_t. The study of such series forms an important branch of statistics because the majority of types of time variation encountered in practice are not of the regular functional type in which u_t can be represented exactly by a mathematical function of t. They present in some degree those irregularities of a random character which can only be discussed in terms of probability. In general it is possible to observe a time variable at any instant, and thus the temporal intervals between successive members of the series need not be the same. Practice and theory alike, however, usually require the observations to occur at regular intervals. It must not be overlooked that the method of determining the values of the series at fixed equal intervals of time may suppress evidence of oscillatory movements which have a period equal to those intervals or to some submultiple of them. Sometimes, in fact, it is known that oscillation exists in a series, and the interval is so chosen to exclude them from consideration.

A general survey of time series suggests that the typical time series may be regarded as composed of three parts:

(a) a trend, or long term movement

(b) an oscillation about the trend of greater or less regularity

(c) a random, irregular or unsystematic component.

It is customary to regard the series as composed of these three elements superposed on one another. In other words, the movement of the series is considered as the sum of three different components which may be generated by different casual systems. Particular series, of course, need not exhibit them all and can be entirely one or the other. The primary problem of time series analysis from the statistical point of view is to isolate the three parts for individual study.

AUTOCORRELATION

Having isolated the "trend" and "oscillation" factors, the series will then be one which presents - in general - fluctuations of a more or less regular kind. The question now arises as to whether the selection of one value from the population would bias the chances of any other for inclusion. It will now be required to determine the period over which observations must be combined to get a set of them which is independent. This is done by looking at the correlation coefficient of the record against itself with various time lags. Such a procedure is called autocorrelation. The time lag interval necessary to give a correlation coefficient which is insignificant at the 95% level is known as the correlation length. Those values of the series which are separated by a time interval in excess of the correlation length may be regarded as independent of one another.

CHAPTER VI

ANALYSIS AND DESCRIPTION OF RESULTS

The following investigations were carried out in fair weather conditions:

(a) simultaneous measurement of the positive conductivity and the negative conductivity at ground level .

(b) simultaneous measurement of the positive conductivity at ground level and the positive conductivity at (i) 20 cm., (ii) 100 cm., above the ground.

(c) simultaneous measurement of the negative conductivity at ground level and the negative conductivity at (i) 20 cm., (ii) 100 cm., above the ground.

It is to be noted that for the purpose of undergoing investigations (b) and (c) air from the appropriate level was sucked into one of the conductivity chambers through a vertical cardboard tube of that height tightly fitting the outer cylinder of the chamber. The introduction of the tube in this manner would no doubt distort the lines of force. To correct for this the intake of the cardboard tube was surrounded by a narrow aluminium band continuously maintained at the right potential of the surroundings by utilising the output of a field mill at ground level and the continuous balance arrangement, already described (page 26).

Since recording was always made in fair weather conditions the period of continuous recording varied from one hour to four hours depending on the state of the weather. Records of duration less than an hour or so were rejected from the analysis in order to satisfy certain statistical requirements. The records of conductivity and potential gradient were read at minute intervals from the recording chart prior to analysing them in the way to be described.

THE COMPUTER PROGRAMME

The nature of the data to be analysed is such that the 'trend' and 'oscillation' factors, already mentioned as typical of many time series, can be ruled out. This being the case autocorrelation could be done. Owing to the tedious mathematical work involved it was decided to make use of the University Elliott 803 computer. The programme required would be one which would enable the correlation length to be determined. The value of the correlation length so determined will have to be used to group the individual observations in the record into groups with an interval equal to the correlation length. The mean value of each group would then have to be determined, giving in effect one independent value in that record of observations. Finally, the mean of all the independent values is worked out. As two sets of data are usually investigated (i.e. either the polar conductivities of the same sign at different heights, or the polar conductivities of opposite sign at the same level), the whole

TABLE 1

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        139
LAG      R           Z          95% LEVEL
  1    0•553       0•623       0•167
  2    0•370       0•388       0•167
  3    0•276       0•283       0•168
  4    0•299       0•308       0•169
  5    0•217       0•220       0•169
  6    0•003       0•003       0•170
  7   -0•174      -0•176       0•171
  8   -0•127      -0•128       0•171
  9    0•009       0•009       0•172
 10   -0•011      -0•011       0•173
 11   -0•094      -0•094       0•173
 12   -0•137      -0•138       0•174
 13   -0•136      -0•137       0•175
 14   -0•097      -0•097       0•175
 15   -0•141      -0•142       0•176
 16   -0•176      -0•178       0•177
 17   -0•150      -0•151       0•177
 18   -0•078      -0•078       0•178
 19   -0•109      -0•110       0•179
 20   -0•110      -0•110       0•180


  1    0•683       0•836       0•167
  2    0•500       0•549       0•167
  3    0•435       0•466       0•168
  4    0•350       0•365       0•169
  5    0•259       0•265       0•169
  6    0•089       0•089       0•170
  7   -0•018      -0•018       0•171
  8   -0•065      -0•065       0•171
  9   -0•010      -0•010       0•172
 10   -0•130      -0•131       0•173
 11   -0•279      -0•287       0•173
 12   -0•297      -0•306       0•174
 13   -0•271      -0•278       0•175
 14   -0•299      -0•308       0•175
 15   -0•301      -0•311       0•176
 16   -0•278      -0•286       0•177
 17   -0•284      -0•293       0•177
 18   -0•152      -0•154       0•178
 19   -0•034      -0•034       0•179
 20   -0•055      -0•055       0•180



ENO=   23
 66•500 51•167
 57•500 39•000
 52•000 29•500
 46•500 28•833
 52•333 34•333
 50•333 35•500
 53•500 37•667
 54•000 35•333
 47•000 31•167
 55•167 34•500
 59•000 36•833
 48•833 30•333
 51•833 30•333
 54•333 34•667
 52•333 34•500
 45•167 28•333
 49•333 32•167
 53•833 36•000
 54•000 34•667
 54•667 36•167
 52•000 34•000
 56•167 36•167
 53•333 35•500


 53•029
 34•638       $MORE DATA PLEASE
```

operation has to be repeated for the other set of data.

At first it appeared as if two programmes would be required, one for working out the correlation length and the other for working out the effective observations. This would have meant putting in the same data twice. Then it was realised that a lot of computer time could be saved by combining the two programmes into one with a "data wait" instruction between them. (For actual programme see Appendix I). By having the output of the autocorrelation part of the programme on the teleprinter the correlation length can be decided at a glance. This is then punched out while the computer is "waiting" and fed in as the necessary interval required for the second part of the programme for going through the same data and grouping them as well as calculating their means.

A typical data sheet is shown in Table I which refers to a record of positive and negative conductivities measured at ground level. The number (139) at the top is the total number of observations (N) in the record taken at one minute intervals. R is the correlation coefficient and Z is a normalised value of R. The use of Z enables the correlation length to be decided immediately, without having to refer to Tables as is usually the case, because when the value of Z is less than the corresponding value shown under the 95% level column, then R ceases to be significant. Thus in the example shown the correlation length is 6. Feeding this figure

TABLE 6

POSITIVE CONDUCTIVITY & NEGATIVE CONDUCTIVITY AT GROUND LEVEL

N	ENO	$\frac{\lambda_+(\varphi)}{\lambda_-(\varphi)}$	wind speed $m.sec.^{-1}$	wind direction	Date
76	25	1.52	2	S.E.	7.8.64
113	10	1.33	6	N-N.W.	28.8.64
105	10	1.42	3	N.E.	31.8.64
130	14	1.45	4	S.E.	1.9.64
223	24	1.48	2	N.E.-N.W.	3.9.64
139	23	1.53	1	N.W.	17.9.64
147	29	1.43	4	N.W.	18.9.64
74	37	1.35	6	S.W.	26.9.64
99	14	1.36	5	S.W.	28.9.64
59	19	1.34	5	W-N.W.	29.9.64
122	30	1.33	7	S.W.	15.3.65
65	10	1.56	1	S-S.E.	3.4.65

OVERALL MEAN RATIO = 1.43

STANDARD DEVIATION = 0.08

TABLE 4

NEGATIVE CONDUCTIVITY AT GROUND LEVEL & NEGATIVE CONDUCTIVITY AT 1 METRE ABOVE GROUND

N	ENO	$\frac{\lambda-(g)}{\lambda-(1m)}$	wind speed m.sec.$^{-1}$	wind direction	Date
150	37	1.35	2	S.W.	7.10.64
168	33	1.27	6	S.W.	8.1.65
152	50	1.28	7	N.W.	15.2.65
62	31	1.21	8	S.W.	25.3.65
134	22	1.29	5	S.W.	29.3.65
117	39	1.25	7.5	N.W.	13.4.65
106	17	1.31	3	N.W.	13.4.65
126	24	1.25	8	N.W.	16.4.65

OVERALL MEAN RATIO = 1.28

STANDARD DEVIATION = 0.04

TABLE 4

NEGATIVE CONDUCTIVITY AT GROUND LEVEL &
NEGATIVE CONDUCTIVITY AT 20 cm. ABOVE GROUND

N	ENO	$\frac{\lambda_{-(g)}}{\lambda_{-(20)}}$	wind speed m. sec.$^{-1}$	wind direction	Date
84	16	1.20	2	S.W.	3.5.65
60	20	1.17	6	S.W.	4.5.65
95	47	1.07	11	N.W.	5.5.65
81	40	1.08	10	N.W.	6.5.65
119	29	1.19	3.5	S-S.W.	13.5.65
198	49	1.12	8	N.W.	19.5.65
158	14	1.15	5	S-S.E.	20.5.65
84	7	1.19	3	S-S.E.	21.5.65
83	7	1.18	5	S-S.W.	22.5.65
110	27	1.13	7.5	S.E.	24.5.65

OVERALL MEAN RATIO = 1.15

STANDARD DEVIATION = 0.02

TABLE 3

POSITIVE CONDUCTIVITY AT GROUND LEVEL &

POSITIVE CONDUCTIVITY AT 1 METRE ABOVE GROUND

N	ENO	$\frac{\lambda_{+(g)}}{\lambda_{+(1)}}$	wind speed m.sec.$^{-1}$	wind direction	Date
78	11	1.24	4	W-N.W.	21.9.64
90	10	1.35	1	S.W.	23.9.64
153	21	1.28	3	N.W.	29.964
95	23	1.28	4	S.E.	30.9.64
106	9	1.31	2	S.W.	6.10.64
97	48	1.13	12.5	W-S.W.	28.6.65
163	11	1.30	2	S.E.	29.6.65
170	18	1.27	3	S.E.	29.6.65
160	32	1.26	4	N.E.	1.7.65
94	10	1.25	5	N.W.	2.7.65

OVERALL MEAN RATIO1 (EXCLUDING RECORD ON 28.6.65) = 1.28

STANDARD DEVIATION = 0.03

TABLE 2

POSITIVE CONDUCTIVITY AT GROUND LEVEL &

POSITIVE CONDUCTIVITY AT 20 cm. ABOVE GROUND

N	ENO	$\frac{\lambda_{+(g)}}{\lambda_{+(20)}}$	wind speed m. sec.$^{-1}$	wind direction	Date
219	21	1.19	3	N.E.	3.6.65
216	24	1.21	4	S-S.W.	4.6.65
163	16	1.21	3	S.E.	5.6.65
114	12	1.24	3	S.E.	7.6.65
191	27	1.22	4	N.E.	9.6.65
137	22	1.21	4	N.E.	9.6.65
217	19	1.20	4	S-S.W.	14.6.65
96	48	1.18	9	S-S.W.	14.6.65
164	27	1.22	3	S.W.	16.6.65
138	34	1.18	10	S.W.	17.6.65
147	18	1.21	6	S.W.	18.6.65

OVERALL MEAN RATIO = 1.21

STANDARD DEVIATION = 0.01

enabled the computer to calculate the effective observations (ENO) in the record as well as their mean.

DESCRIPTION OF RESULTS

The results are presented in tabular form (Tables 2 - 6), from which the following points are derived:

(i) the positive conductivity measured at ground level is always greater than the negative conductivity at the same level, with a mean ratio of positive to negative of 1.43. Table 6

(ii) the positive conductivity decreases with height in the first metre above the ground, the decrease being relatively rapid in the first 20 cm. The mean ratios of the positive conductivity at ground to that at 20 cm. and 100 cm. are 1.21 and 1.28 respectively

(iii) the negative conductivity also decreases with height in the first metre above ground, the decrease being relatively slow in the first 20 cm. The mean ratios of the negative conductivity at ground to that at 20 cm. and 100 cm. are 1.15 and 1.28 respectively.

(iv) the total conductivity was never constant over the whole range of the investigation.

(v) the ratios of the conductivities investigated are affected by the wind speed.

(vi) on two occasions during the winter months the potential gradient was highly positive with values between 300 and 400 v.m.$^{-1}$ As a result

1. The Positive Conductivity at Ground Level
2. The Negative Conductivity at Ground Level
3. The Potential Gradient at Ground Level

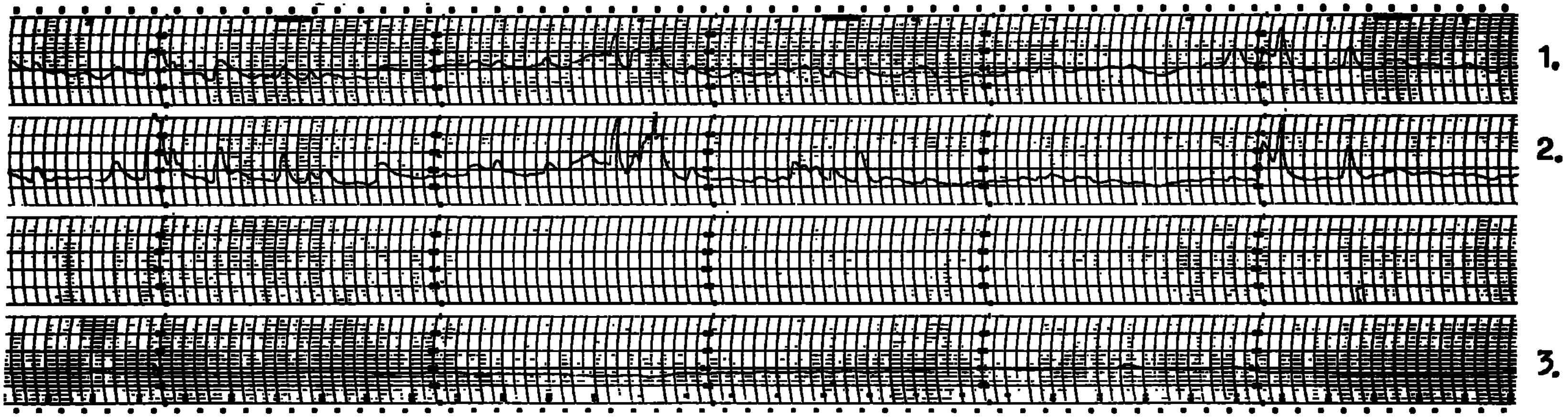

FIG. 14

1. The Positive Conductivity at Ground Level
2. The Negative Conductivity at Ground Level
3. The Potential Gradient at Ground Level

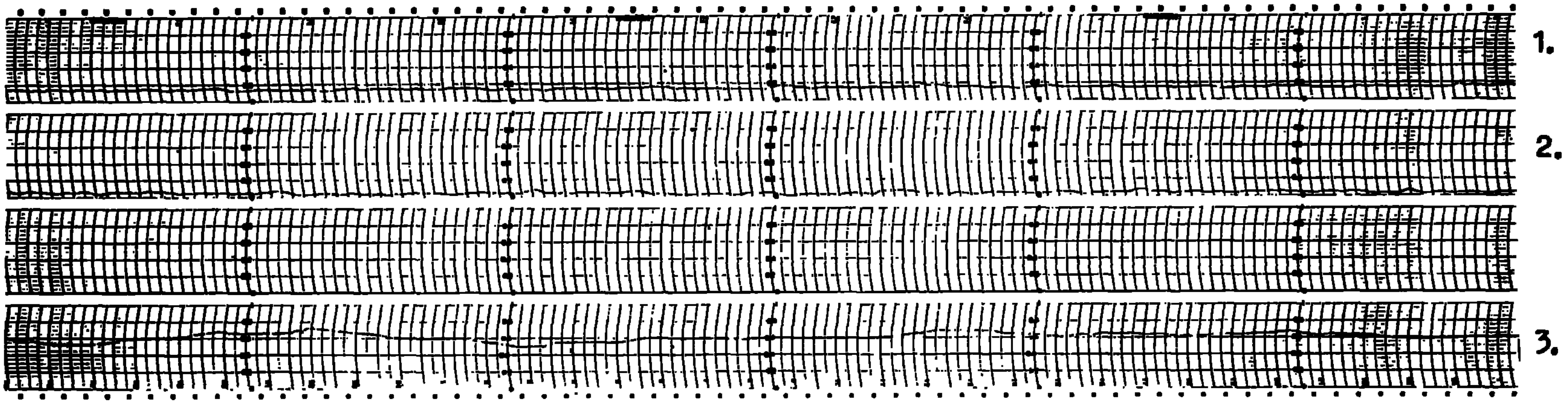

FIG. 13

both polar conductivities measured at ground level decreased, with the negative conductivity having values just greater than zero (Fig. 13).

(vii) On a number of occasions both polar conductivities were found to have extremely high values (going off scale at times) which fluctuated quite irregularly (Fig. 14). A closer look has revealed that in all such occasions the wind was blowing from the East. An easterly wind would blow from Durham City and so, if anything, the conductivity would be expected to decrease. No logical explanation could be given for this.

CHAPTER VII

DISCUSSION OF THE RESULTS

QUALITATIVE CONCLUSIONS

By the time the equipment was constructed, tested and installed on site it was late spring in 1964. Recording started from June, 1964 and continued until July, 1965. This made it possible to make measurements during the four seasons of a year. Records have brought out the following qualitative conclusions:

Seasonal Variation:

The conductivity was found to reach a maximum during the summer and fell off to a minimum during the winter months. This may be attributed to the variation of atmospheric pollution. This is maximum during the winter when fog and mist are frequently encountered as well as smoke from domestic fires. All these sources of pollution cause a large decrease in the number of small ions and hence a corresponding reduction in the conductivity.

Diurnal Variation:

The conductivity remained fairly constant during any one day dropping in the late afternoon or early evening. In fact an early morning maximum is generally reported. Here again air pollution is the main factor responsible for the observed variation.

RELATION TO WEATHER:

A considerable lowering of the conductivity was noted whenever the air was misty and damp; a large number of the small ions being then attached to large ions or Aitken nuclei. The conductivity in clean, dry air was comparatively very much greater.

RELATION TO POTENTIAL GRADIENT:

When conductivity changes occurred the potential gradient generally followed the well known inverse relationship with conductivity. However, there were times when short period variations in the conductivity did not affect the potential gradient at the surface. This is probably due to the sudden introduction of a small pocket of air whose conductivity differs from that of its environment; such a mass of air would not cause rapid changes in the potential gradient because of the relaxation effect.

DISCUSSION

The fact that the positive conductivity is always greater than the negative conductivity at ground level implies the existence of a positive space charge. This is to be expected since very close to the earth's surface there is the effect of the α rays from the outermost layers of the earth and the ionised air diffusing out of the ground. Chalmers (1957) points out that the latter contains an excess of positive ions because the relatively greater mobility and diffusion coefficient of the negative ions make them so readily drawn into the interstices of the ground.

Also the fine weather positive potential gradient tends to drive positive ions towards the ground and negative ions away from it. The positive space charge at the ground found in the present investigation is in good agreement with the findings of Law (1963). The agreement is not so good with the results of Hogg (1939b). According to Hogg the negative conductivity at the surface is always very nearly zero. This is what one would expect from an electrode effect where no ions are coming out of the ground and for perfectly still air in conditions of uniform ionisation. These ideal conditions are seldom found over land. It is to be noted, however, that Hogg undertook most of his investigations at Kew during the winter months of 1937 - 1938, which he himself described as "notoriously foggy". Kew is a very highly polluted area and so it is not surprising to note that Hogg quoted an average potential gradient value during the period of investigation of 500 $v.m.^{-1}$ On the very few occasions in the present investigation when the potential gradient exceeded 300 $v.m.^{-1}$ the negative conductivity decreased very nearly to zero (Fig. 13). It thus seems reasonable to suggest that the very low values of negative conductivity found by Hogg are a direct result of the high potential gradients encountered, presumably due to the high degree of pollution in Kew. Under such conditions the great abundance of large ions and nuclei suffices to remove the relatively less abundant small negative ions near the ground. This process no doubt also exists during the periods of the usually small positive potential gradients which dominate fair weather conditions. But in this case the number of large ions and nuclei is far too small to enhance the electrode effect.

The observed decrease of both conductivities with height in the lowest metre of the atmosphere can be explained in terms of ionisation near the ground due to the radioactivity of the soil and the radioactive gases derived therefrom. The α rays from the soil are likely to be mainly effective in the first few centimetres of the air above the surface, whereas the effect of the more penetrating β particles can extend further upwards to about 30 cm. or so. The rate at which the radioactive gases emerge from the ground depends on atmospheric pressure and the condition of the soil. Turbulent diffusion in the atmosphere disperses the gas whose greatest concentration can thus be expected near the ground. Pierce (1958) showed that the rate of production of ions due to radioactivity decreases from about 60q at 1 cm. above the surface, to about 8q at one metre above. Law (1963) found that the number of small ions, both positive and negative, decreased with height above the ground up to 150 cm. Hogg (1939b) on the other hand found the positive conductivity to decrease in the first metre upwards, but the negative conductivity to increase slightly. This is perhaps to be expected in the normal fine weather potential gradient of the atmosphere if no negative ions are coming out of the ground.

Although the wind speed was not simultanously recorded with the

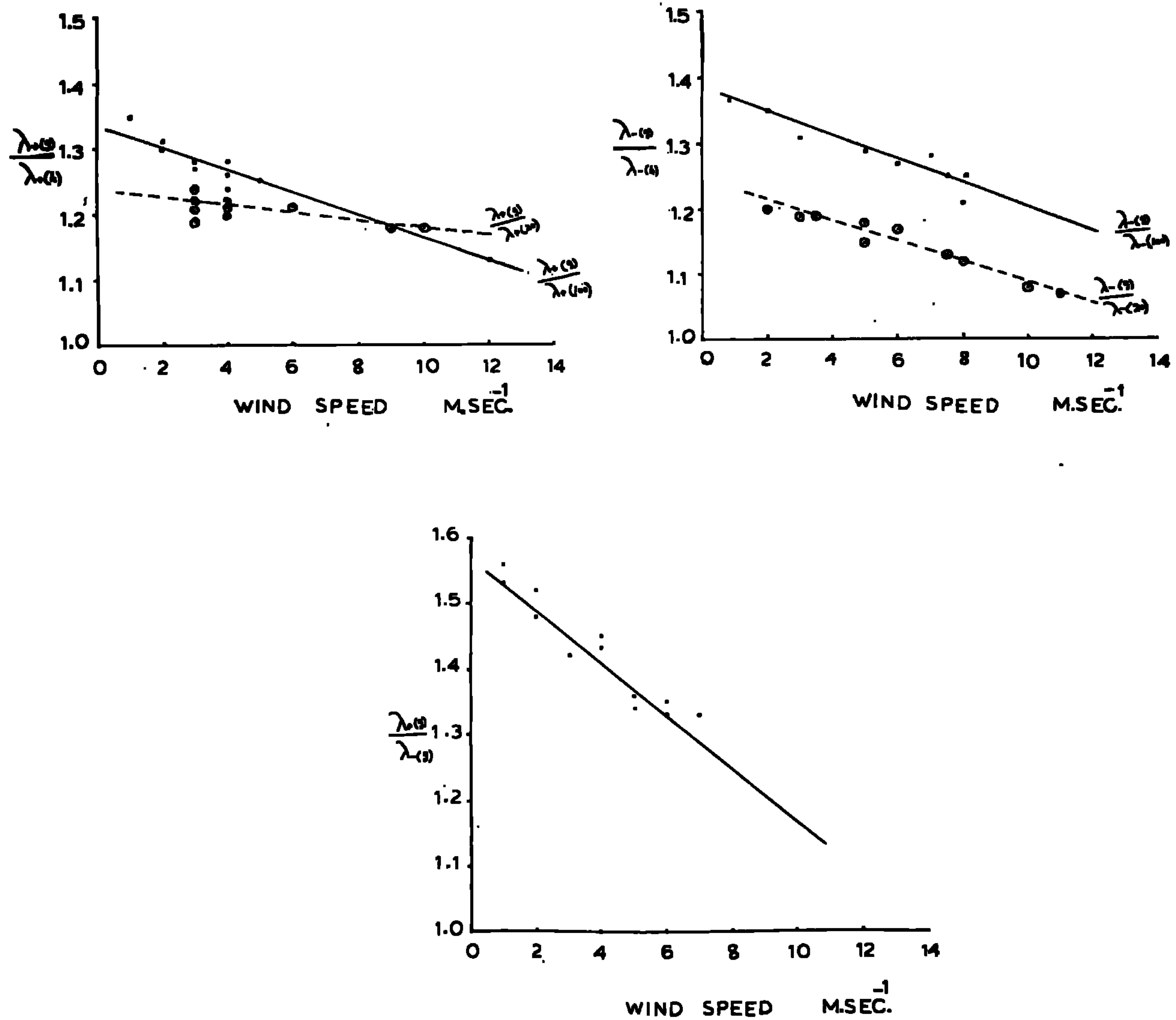$\frac{\lambda_{+(5)}}{\lambda_{+(1)}}$
1.5
1.4
1.3
1.2
1.1
1.0
0
2
4
6
8
10
12
14
$\frac{\lambda_{+(5)}}{\lambda_{+(20)}}$
$\frac{\lambda_{+(5)}}{\lambda_{+(100)}}$
WIND SPEED M.SEC.$^{-1}$
$\frac{\lambda_{-(5)}}{\lambda_{-(1)}}$
1.5
1.4
1.3
1.2
1.1
1.0
0
2
4
6
8
10
12
14
$\frac{\lambda_{-(5)}}{\lambda_{-(100)}}$
$\frac{\lambda_{-(5)}}{\lambda_{-(20)}}$
WIND SPEED M.SEC.$^{-1}$
$\frac{\lambda_{+(5)}}{\lambda_{-(5)}}$
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
2
4
6
8
10
12
14
WIND SPEED M.SEC.$^{-1}$

FIG.15

conductivity and potential gradient, a mean value during the period of recording could be taken from the observatory anemometer records. As it turned out the great majority of records were taken when the wind speed was less than about 6 m.sec.$^{-1}$ On very few occasions the wind speed was in the range 8 - 15 m.sec.$^{-1}$ Although an exact correlation with wind could not be made the results do show that the conductivity is very slightly affected by wind speed variations in the range of up to about 6 m.sec.$^{-1}$ In very calm conditions, however, the ratios of positive and negative conductivities to the corresponding values higher up increased appreciably. A similar increase was also noted in the case of the polar conductivities measured at ground level. Graphs of the different ratios of conductivities investigated against wind speed are plotted in Fig. 15. It must be remembered that the observatory anemometer is about 50 yards away from the recording site and stands at a height of 35 ft. above ground. Also, the wind direction must be taken into account as some parts of the site are more exposed than others. However, it is reasonable to conclude that wind plays an important role in mixing in the lower layers of the atmosphere. Also, the general tendency of the ratios to increase as the wind speed decreases, as brought out by the graphs, seems to suggest that calm conditions are essential for the enhancement of the electrode effect.

CONCLUSION. Ionisation in the lowest metre of the atmosphere at Durham is not uniform, but decreases with height, owing to the effect of the radioactivity of the soil. This results in the total conductivity being variable in a similar manner. The variation of the radioactive emanation in the air is directly affected by the role which the wind plays in the mixing of the air. In most conditions overland these effects combine against the enhancement of the electrode effect. It is for this reason that an enhanced electrode effect could only be found over lakes (Muhleisen, 1961) or in Greenland ice cap (Ruhnke, 1962). A strong manifestation of the effect was reported by Crozier (1963) in the New Mexico semidesert during night time periods of very low wind velocity.

APPENDIX I

```
AUTOCORRELATION   /  K.HIGAZI '

BEGIN
   REAL SUM1,SUM2,LSUM1,LSUM2,SUMA1,SUMA2,PROD,R,Z,LEVEL,
MEANX,MEANY,POS,NEG'
INTEGER J,K,D,L,N,INT,ENO,A,B'
   REAL ARRAY X(1:2,1:300)'
   SWITCH SS:=INPUT,CALCULATE'


   J:=1'

   INPUT:
     READ X(1,J),X(2,J)'
     IF X(1,J) LESS 0 THEN GOTO CALCULATE'
     J:=J+1'  GOTO INPUT'

   CALCULATE:
     N:=J-1'  PRINT N,£
LAG£S6?R£S8?Z£S5?95% LEVEL?'
  FOR D:=1,2 DO
BEGIN
          SUMA1:=SUMA2:=0'
  FOR J:=1 STEP 1 UNTIL N DO
        BEGIN
        SUMA1:=SUMA1+X(D,J)'
         SUMA2:=SUMA2+X(D,J)**2'
      END'
    FOR L:=1 STEP 1 UNTIL 20 DO
          BEGIN
           PROD:=0'
                   FOR J:=1 STEP 1 UNTIL (N-L) DO
              BEGIN
                 PROD:=PROD+X(D,J)*X(D,J+L)'
               END'
             SUM1:=LSUM1:=SUMA1'
            SUM2:=LSUM2:=SUMA2'
              IF L GR 0 THEN
              FOR K:=1 STEP 1 UNTIL L DO
              BEGIN
                   SUM1:=SUM1-X(D,(N-K+1))'
                   SUM2:=SUM2-X(D,(N-K+1))**2'
                   LSUM1:=LSUM1-X(D,K)'
                   LSUM2:=LSUM2-X(D,K)**2'
                                                        END'
                    R:=(PROD-(SUM1*LSUM1)/(N-L))/
   SQRT((SUM2-(SUM1**2)/(N-L))*(LSUM2-(LSUM1**2)/(N-L)))'
                   Z:=LN((1+R)/(1-R))/2'
                   LEVEL:=1.96/SQRT(N-L)'
 PRINT PUNCH(3),   DIGITS(2),L,PREFIX(££S3??),ALIGNED(1,3),
        R,ALIGNED(1,3),Z,ALIGNED(1,3),LEVEL'
            END'
     PRINT PUNCH(3), ££L3?? '
 END'
WAIT'



READ INT'      ENO:=ENTIER(N/INT)'

PRINT ££R100??,PUNCH(3),££L3??,DIGITS(3),SAMELINE,£ENO=?,ENO'

MEANX:=0'
MEANY:=0'

FOR A:=1 STEP 1 UNTIL ENO DO
BEGIN POS:=X(1,INT*(A-1)+1)'   NEG:=X(2,INT*(A-1)+1)'
      FOR B:=2 STEP 1 UNTIL INT DO
      BEGIN POS:=POS+X(1,INT*(A-1)+B)'
            NEG:=NEG+X(2,INT*(A-1)+B)'
      END'
      POS:=POS/INT'    NEG:=NEG/INT'
      PRINT ALIGNED(2,3),POS,SAMELINE,NEG'
MEANX:=MEANX +POS'
MEANY :=MEANY +NEG'
END'
MEANX:=MEANX/ENO'
MEANY:=MEANY/ENO'


PRINT ££LLL??, ALIGNED(2,3), MEANX, MEANY, £    $?,PUNCH(3),
£MORE DATA PLEASE?'
```

AN EXPLANATION OF SOME OF THE SYMBOLS USED IN THE ALGOL PROGRAMME.

SUM1	the sum of the first (N-L) numbers
SUM2	the sum of the squares of the first (N-L) numbers
LSUM1	the sum of the last (N-L) numbers
LSUM2	the sum of the squares of the last (N-L) numbers
SUMA1	the total sum of N numbers
SUMA2	the total sum of the squares of N numbers
MEANX	the mean of the effective number of observations for the first set of data
MEANY	the mean of the effective number of observations for the second set of data
LEVEL	the level of significance
PROD	the sum of the products
INT	the interval corresponding to the correlation length
ENO	the effective number of observations
L	the lag
N	the total number of observations
R	the correlation coefficient
Z	the normalized value of the correlation coefficient.

ACKNOWLEDGEMENTS

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APPENDIX II

TESTS OF THE EFFECT OF THE BEND

To test the effect of the bend a dust free room with little disturbance from human sources was used. One chamber lay horizontal on the bench with the right angled elbow slipped on so that its intake was vertical. The other chamber did not have an elbow but was clamped to the same bench with its intake being vertical and level with the elbow intake. The two intakes were 8" apart.

As a preliminary test both intakes were set at a distance of 3' from a window in the room. The window was opened and the room was closed. Air was drawn through the two chambers at the same rate, as measured by gas meters - one connected to each chamber - The suction fan exhaust was placed outside the room so as not to cause any disturbance of the air in the room. This showed that the chamber with the elbow lost about 20% of the ions of either sign. It was felt that some of the ions could very well have been lost due to the different paths taken by the air to enter the chambers from the large area of the open window.

A more reliable method of testing was seen to be one in which the room was completely closed and the ions were produced artificially from a source which can be placed symmetrically to both chambers and whose distance from the chambers can be varied at will. So it was decided to use a poloniun ion generator. This consisted of a brass tube 5 cm. in diameter with a strip of polonium 210 foil placed 2 cm. below the top of the tube. An electric fan propelled air up the tube and into the room. Ions of the required sign were separated by connecting the same sign terminal of a high tension battery to the tube.

Since polonium 2IO is the last radioactive element in the radium decay series, only α-rays are emitted producing only small ions.

These tests were carried out repeatedly with ions of either sign and with different rates of flow between one and three litres per second. This was necessary to coincide with the range of flow rate anticipated in the actual experiment. The generator was always symmetrical with both intakes, and its distance away from the chambers was so adjusted that the electrometer reading was appropriate to the rate of flow, as calculated approximately for the ions in the atmosphere. It is these tests which finally revealed a loss of I5-25% of the ions, of either sign, depending on the rate of flow. The loss is thought to be the result of the ions diffusing to the walls of the elbow in turbulent conditions.

That turbulence does exist in such a right angled elbow, is supported by theoretical consideration. It is known that in a fluid motion where the velocity diminishes in the direction of motion the external flow may become separated from the wall and eddies of considerable size are formed owing to the backward flow of the inner parts of the boundary layer. In the case of a right angled elbow there is a transverse fall of pressure in the curved portion of the flow. By Bernoulli's equation, the velocity is therefore increased on the inner side of the curve and decreased on the outer; i.e. the conditions associated with the separation of flow are satisfied at the outer boundary, even though the flow becomes re-attached to the wall downstream.

Boundary layers may be influenced artificially so as to prevent separation of the flow taking place. One way of doing this is to raise the velocity of the incoming fluid very rapidly from a very small value to that required in the experiment. This is achieved by making the fluid traverse a pipe of very wide cross section passing into a narrow one

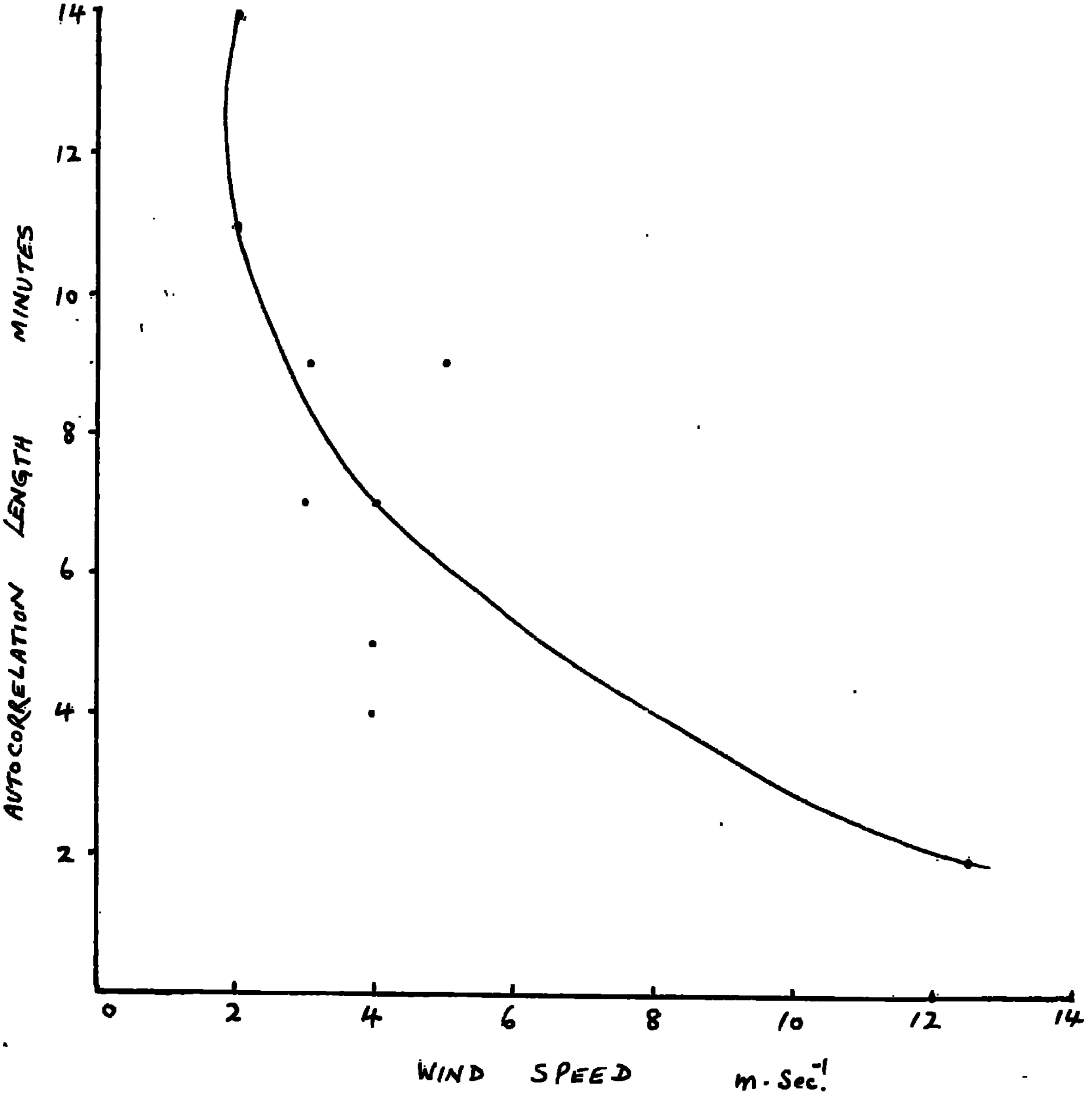
14
12
10
8
6
4
2
AUTOCORRELATION LENGTH MINUTES
0
2
4
6
8
10
12
14
WIND SPEED m·Sec.$^{-1}$

FIG. 16

(with the cross section to be used in the experiment). This was tried in the case of the elbow by using a cone 9" in diameter at the intake, 5" high, terminating into $2\frac{1}{4}$" diameter, which fits tightly over the elbow intake. The above tests for ions of both signs were made many times, with an improvement in the loss of 5%. It was therefore decided that the dimensions of the cone might be critical. This and the fact that large dimensions of the cone might raise difficult practical problems in windy conditions finally turned the balance in favour of mounting the two chambers vertically without the elbows.

AUTOCORRELATION LENGTHS AND THEIR RELATION TO CONDUCTIVITY AND WIND SPEED

The autocorrelation analysis of the results described in Chapter VI gives a correlation legth, L, which is the time interval by which observations have to be separated for any one of them not to depend on the previous ones. This autocorrelation length was found to be different for different records, presumably due to different conditions in which the records were taken. This would suggest that the phenomena have a "memory". One is readily reminded of the well known memory of the atmosphere, better known as the relaxation time, T. This not only gives the rate at which a conductor loses charge, but also the rate at which the electrical conditions in the conductor adjust themselves after a change. It was thought reasonable to look for a relation between L and T.

Considering the case of an exponentially decaying function, the autocorrelation coefficient r(k) for any lag of k is given by:

$$r(k) = e^{-k/T}$$

Thus from a correlogram (a curve of r(k) against k) an estimate of the value of T should be that value of k which makes $r(k) = 1/e$.

The autocorrelation coefficient for many of the records already analysed by the computer was used to plot correlograms, and a comparison was made between the estimated T from the correlograms and those calculated from the equation:

$$T = \frac{\varepsilon_0}{\lambda}.$$

This comparison showed no agreement at all. The lack of any comprehensible relation was further brought out by plotting L against T; the result was a mass of points scattered all over the graph. This would seem to imply that the observed T can not be due to "electrical decay", but must be related to some other effect such as mechanical turbulence.

The next thing to do was to look for a relation between the autocorrelation length and the wind speed, W, using the data in Tables 2-6. Such a plot was made for the data in each Table. A relation seems to exist between the two, which was best brought out by the data in Table 3, as shown in Fig.16 . However, this can not be ascertained with any great confidence, as in nearly all the cases, there was not enough dispersion of the wind speeds.

THE REGION OF COLLECTION OF THE AIR

As already mentioned, the rate of flow of air through the conductivity chambers was 2 litres per second. With such a flow rate it was realised that the air being sampled must have been coming from a slightly higher level. To find out just how much higher, a simple experiment was undertaken. A candle was lit up, and then extinguished so that smoke was coming out of it. On a calm day, the candle was placed directly above one of the chambers, through which air was drawn at the usual rate. The candle was moved up and down until the smoke was just seen to be going into the chamber. The height of the candle above the intake was then measured. The experiment was repeated many times and a mean value for the height of 2 cm. was found.

THE TWO RECORDS WITH THE HIGH POTENTIAL GRADIENT

The first record was taken on the afternoon (3p.m. - 5p.m.) of the 7th. of April, 1965. The wind direction was S.W., with a speed of 4 m.sec.$^{-I}$ It was misty.

The second record was taken on the morning (10.30a.m. - 12.40p.m.) of the 9th. of April, 1965. The wind direction was S - S.W., with a speed of 3 m.sec.$^{-I}$ It was cloudy.

Similar conditions did in fact occur many times during the period of the investigation, but the potential gradient showed its normal values. This would suggest that on the two particular occasions above, the high values of the potential gradient were due to some local effect, especially as they occurred within two days of each other.

THE IMPORTANCE OF THE RESULTS

The importance of the results of ~~then results of~~ the present investigation are three fold :

(i) The disagreement with the findings of Hogg. This can not be attributed to any radical change in the method of investigation; the present work is in fact a more refined repeat of Hogg's work. However, the fact that agreement with Hogg was achieved on the two occasions when the potential gradient was over 300 v/m , seems to suggest that the main difference is perhaps due to the pollution level in Durham and Kew. Increased pollution would decrease the conductivity and increase the potential gradient. Kew being a highly polluted area accounts for the high potential gradients (300 - 600 v/m) reported by Hogg. Durham, on the other hand, is comparatively very much less polluted, with the potential gradient ranging between 80 and 150 v/m. Support is lent to this suggestion by the day time results of Law in Cambridge which are in full agreement with the results of the present work, although Law used a completely different method of investigation. His potential gradient values were between 60 and 100 v/m. High potential gradients can probably explain the very high ratio of $\frac{\lambda_{+g}}{\lambda_{-g}}$; since there is always a positive space charge at the ground, a large condensation nucleus content would decrease λ_{-g} more than it would λ_{+g}. Also with the fine weather positive potential gradient negative ions move upwards and positive ions move downwards. Explanation would still have to found for Hogg's result that the total conductivity remains constant within the first metre above ground.

(ii) The autocorrelation length. This varied between 2 minutes and 14 minutes, and is perhaps typically 7 minutes. The very existence of this time lag necessary between observations before they can be taken to be independent of one another, suggests that non-continuous measurements of atmospheric electric phenomena are not after all undesirable. It does appear that the autocorrelation length is a direct consequence of the prevailing wind speed, and so if a direct relation can be established between them, the worker in atmospheric electricity can choose his own interval of observation. This is particularly helpful in cases where continuous recording presents a formidable practical problem.

(iii) The effect of the wind speed. This caused all the ratios measured to tend towards unity. An explanation for this can be found in terms of the turbulent mixing of the air near the surface, caused by the wind. With very strong winds the air would be so thoroughly mixed that the electric field would not be able to separate ions of both signs, and so the ratio would be unity. In these conditions of turbulent mixing, very close to the surface no negative ions would be expected to leave the ground and the current will be carried into the ground by the positive ions only, resulting in an electrode effect in the first few centimetres instead of the expected one in the first metre. The reconciliation of this would need to be looked into in greater detail.

FUTURE WORK

The present results show that pollution can be a very important factor in the conduction of electricity close to the surface of the earth. As such,measurements similar to those undertaken in this work will be desirable in localities with different levels of pollution.

Further work will required to determine any relation which might exist between autocorrelation length and wind speed. From the practical side simultaneous measurements of both polar conductivities at ground level as well as wind speed would be the best ones to make. Such measurements would have to be made over a wide range of wind speeds. They would also be useful in confirming or otherwise, the apparently non-existent relation between autocorrelation length and relaxation time.

USEFUL VALUES

The following values were calculated from the records :

(i) The overall mean value of the total conductivity at ground level = $I.09 \times IO^{-I4}$ $Ohm^{-I}.m.^{-I}$

(ii) The potential gradient varied between 80 and I50 v/m , with a mean value of IOO v/m.

(iii) The mean value of the conduction current, as calculated from the above values = $I.09 \times IO^{-I2} A/m^{2}$

(iv) The total conductivity at ground level, during the month of September,I964 had a mean value of $I.29 \times IO^{-I4}$ $Ohm^{-I}.m.^{-I}$ This is to be compared with a value of $7.6 \times IO^{-I5}$ $Ohm^{-I}.m.^{-I}$ on I5.3.I965, and a value of $8.I \times IO^{-I5}$ $Ohm.^{-I}m.^{-I}$ on 3.4.I965.