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SOME MEASUREMENTS OF THE  
VARIATION OF POTENTIAL  
GRADIENT WITH HEIGHT  
NEAR THE GROUND AT  
KEW OBSERVATORY

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# SOME MEASUREMENTS OF THE VARIATION OF POTENTIAL GRADIENT WITH HEIGHT NEAR THE GROUND AT KEW OBSERVATORY

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## § 1—INTRODUCTION

In many of the problems of atmospheric electricity it is of some importance to know whether there is any appreciable volume charge of electricity in the air near the ground. Several methods of detecting the natural space charge in the air have been devised; one of these makes use of Poisson's equation

$$\frac{d}{dh} \left( \frac{dV}{dh} \right) = -4\pi\rho,$$

which states that the density of the space charge  $\rho$  is proportional to the rate of change with height of the potential gradient  $dV/dh$  (it is assumed that there is no variation of potential in the horizontal direction). The only measurement involved in this method therefore is the determination of the variation of potential gradient with height, but it is not at all easy to carry out such a measurement with sufficient accuracy to obtain a reliable estimate of  $\rho$ . The variation of potential gradient with height, near the ground has been investigated by A. Dauderer (1)\* and by H. Norinder (2)\*. Their results appear to depend on local conditions, so in order to obtain information about the space charge at Kew it was necessary to carry out experiments in the neighbourhood. A suitable site was available in the grounds of the Observatory.

## § 2—APPARATUS

The scheme adopted was to measure the potential difference between two points at a fixed vertical distance apart, the actual height of the points above the ground being varied. This was done by means of a pair of long stretched wires insulated at each end and carrying radio-active collectors at the mid-points; the system was supported at the ends by carriages which could be moved to heights varying from one to ten metres. A general view of the apparatus is shown in Fig. 1. Two wooden masts 11 m. high were erected in the Observatory paddock at a distance of 50 m. apart; each mast is fitted at the top with three steel guy-ropes which are anchored to the ground at points 6 m. from the bottom of the masts. The carriages for supporting the stretched wires are shown in Figs. 2a and 2b; they are arranged to slide on a hard-wood rail attached to each mast. In order to keep the sag of the two wires as nearly equal as possible the wires are maintained at the same tension by means of a single spiral spring and a pivoted beam on one of the carriages (Fig. 2b). The wires are of phosphor bronze 1.5 mm. diameter and the tension is about 30 lbs.; the sag of the wires is about 45 cm. When the apparatus is in use sulphur insulators are fitted at the ends of each wire. The wires are arranged to be one metre apart and to ensure that this spacing shall be accurate near the mid-point, light aluminium rods, each fitted with an ambroid insulator in the middle, are attached to the wires at one metre on each side of the mid-point. The radio-active

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\* The numbers in brackets refer to the bibliography on p. 12.

collectors, which are fitted at the mid-points, are in the form of tubes, 5 cm. long and 0.3 cm. diameter, split lengthwise into two halves so that they can be fitted round the wires, the halves being held together at the ends by small clips. The collectors are coated with polonium. Details of the construction of the spacing rods and the collectors are shown in Fig. 3.

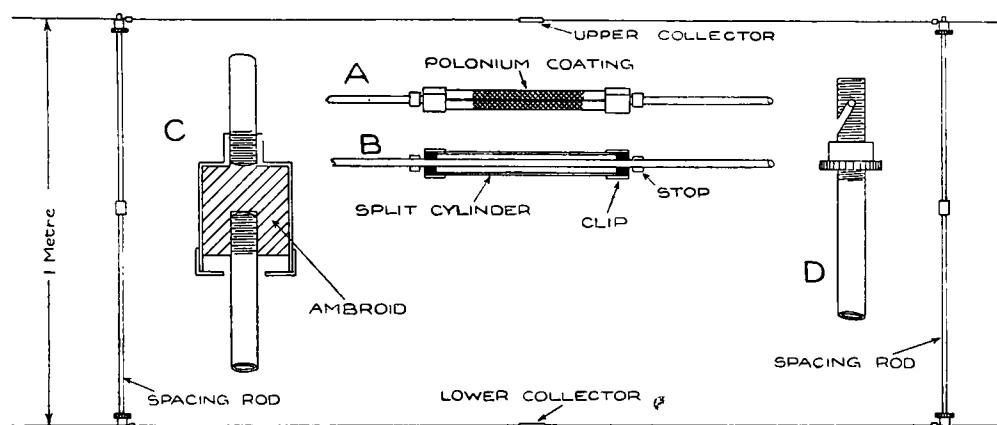


FIG. 3—THE DOUBLE COLLECTING SYSTEM.

THE INSET DIAGRAMS ON A LARGER SCALE ILLUSTRATE A, B, A COLLECTOR IN PLAN AND IN SECTION, C, A SPACING ROD INSULATOR, D, METHOD OF ATTACHING SPACING ROD TO WIRE.

For measuring the potential-difference between the two wires a Wulf bi-filar electrometer was used. At first it was thought that the measurement could be made by connecting one stretched wire to the fibres and the other wire to the insulated inner case of the electrometer, the outer case being earthed. It was found, however, that the inner case was not sufficiently well insulated and also that it was so close to the microscope objective that spark discharge occurred when high potentials were reached. The arrangement finally adopted was to connect the inner case to the outer case and to mount the electrometer on a sulphur insulator; then one stretched wire was connected to the fibres and the other to the case of the electrometer. With this arrangement it was necessary to guard against the electrometer being accidentally earthed by the observer when taking a reading; a glass screen placed in front of the microscope eyepiece was found to minimise the risk of this occurring during an observation.

The wires connecting the collecting system with the electrometer were of fine copper of sufficient length to be nearly taut when the carriages were at the top-most position; at the lower heights the connecting wires were coiled in the form of a spiral. The position of the electrometer with respect to the masts can be seen in Fig. 1.

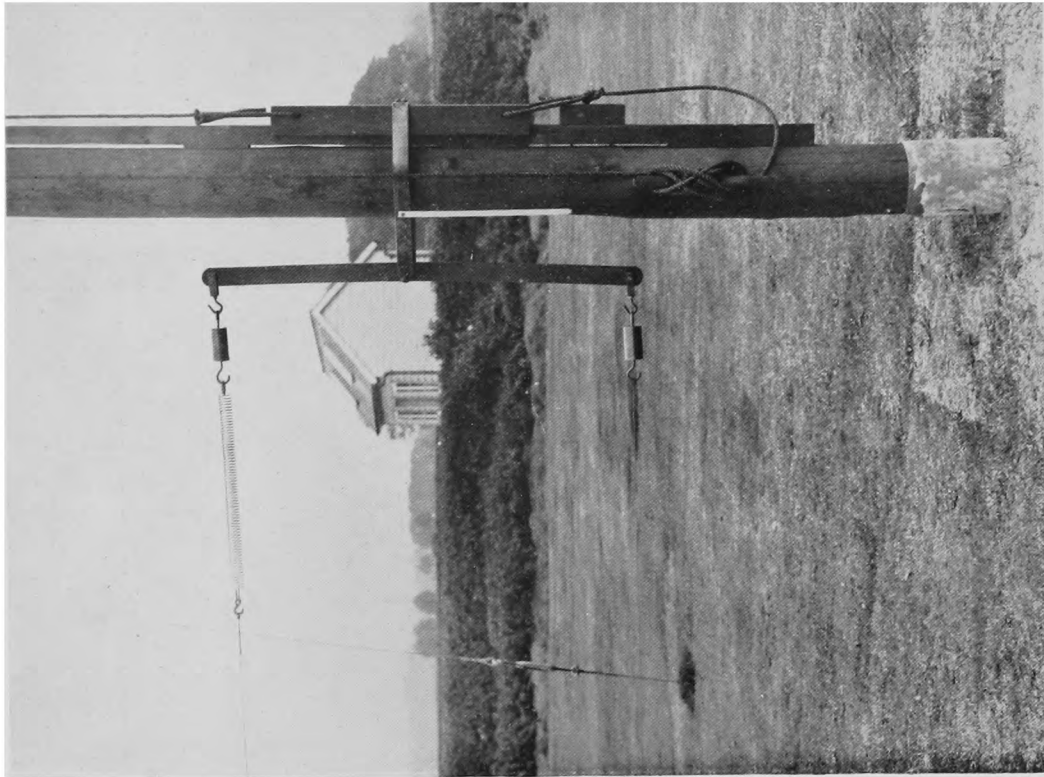
The suitability of the Observatory paddock as a site for absolute observations of potential gradient has been discussed recently by the author (3). The ground is flat and it is covered with grass which is kept very short by frequent mowing; at the site selected for the masts the distortion of the electric field due to permanent obstructions in the neighbourhood is not likely to be more than 2 per cent. An estimate of the effect of the presence of the masts on the field at the collecting points can be obtained by using the results of a theoretical investigation by Benndorf (4), who calculated the distribution of potential in the neighbourhood of a vertical pole regarded as an elongated ellipsoid. His results indicate that the field at the ground halfway between the masts is reduced by less than one per cent. by the presence of the masts; moreover, the change in this error up to the height of the masts is inappreciable. It appears then that any errors due to the distortion of the field at the positions of the collectors are small enough to be neglected, especially when variation with height is being considered.

### § 3—OBSERVATIONAL ROUTINE

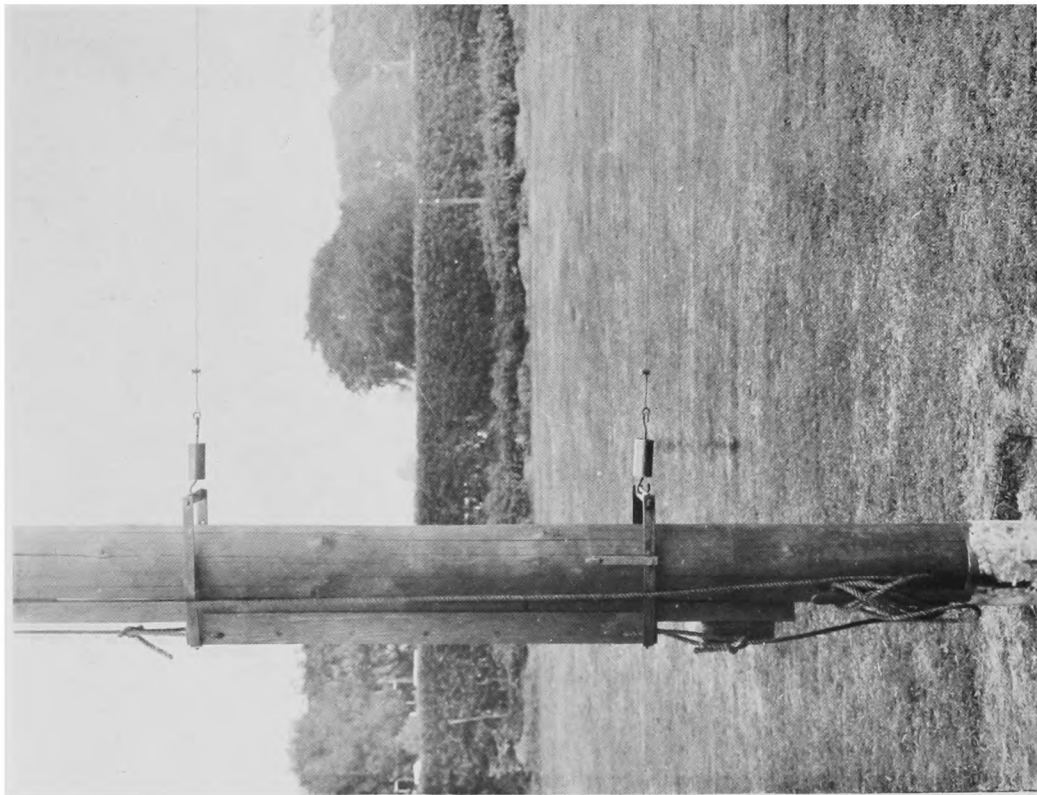
It was intended that each series of observations should consist of a set of



FIG. 1.—GENERAL VIEW OF THE MOVABLE STRETCHED-WIRE APPARATUS.



2b.



2a.

FIG. 2.—THE MOVABLE CARRIAGES FOR SUPPORTING THE WIRES.

measurements at five different heights, viz., 1, 3, 5, 7 and 10 m., but it was not always possible to carry out a whole series successfully. The height refers to the vertical distance between the ground and the point half-way between the collectors; to facilitate the rapid adjustment of the movable wire system to the desired height, marks were painted on the masts to indicate the positions of the carriages at the various heights (allowance being made for the sag of the wires). It was necessary to take account of changes in the absolute potential gradient occurring during a series of measurements at the different heights and for this purpose simultaneous control observations of the potential gradient at ground level were made by the Wilson test-plate method at the underground laboratory, which is in another part of the paddock, 80 m. from the movable collector system. From the beginning of 1932, the test-plate at the underground laboratory has been used as the standard exposure for absolute measurements of the gradient at ground level; a detailed account of the exposure and the use of this apparatus has been given by the author (3).

The Wulf electrometer was calibrated by means of a battery of dry cells, the 100 volt units of which were checked against Weston standard cells; the range of the electrometer is roughly 1,000 volts and the sensitivity about 6 volts per division.

#### § 4—ERRORS DUE TO INSULATION LEAK

The efficiency of the polonium collectors and the capacity of the wire system were such that the time required to reach half the true potential was about 35 sec. Since the voltage,  $v$ , acquired by a collector in a time  $t$  is given by

$$v = V (1 - e^{-t/RC})$$

where  $V$  is the true potential of the air round the collector,  $R$  the apparent resistance of the collector and  $C$  the capacity of the system, the time required for  $v$  to approach to within one per cent. of  $V$  is 200 sec. In the actual experiments the collectors were allowed to pick up for at least 4 minutes before the first reading was taken so that any errors due to the delay of the collector were negligible (provided there were no large or rapid fluctuations of  $V$ ).

The greatest source of trouble was the failure of the insulation when high potentials were reached. Moreover, since a differential method of measurement was employed, slight errors due to an inappreciable leak at the lower heights became more serious as the height (and therefore the voltage) increased. The effect of insulation leak on the voltage of a single wire collecting system may be taken into account by writing

$$v = \frac{LV}{R+L} [1 - e^{-(1/RC + 1/LC)t}]$$

where  $L$  is the insulation resistance of the system. Thus the final voltage which is attained is  $LV/(R+L)$  and the proportional error is  $(V-v)/V$  i.e.  $L/(R+L)$ . The proportional error in this case is independent of the actual voltage and it is negligible so long as the resistance of the collector is inappreciable compared with the insulation resistance. With a double wire system used differentially the proportional error increases with the mean voltage of the two wires. Thus if the potentials acquired by the two wires are

$$v_1 = \frac{L_1 V_1}{R_1 + L_1} = k_1 V_1 \quad \text{and} \quad v_2 = \frac{L_2 V_2}{R_2 + L_2} = k_2 V_2,$$

then the difference as measured is

$$v_2 - v_1 = \frac{1}{2}(k_2 + k_1)(V_2 - V_1) + \frac{1}{2}(k_2 - k_1)(V_2 + V_1).$$

The proportional error is

$$\frac{(V_2 - V_1) - (v_2 - v_1)}{V_2 - V_1} = 1 - \frac{1}{2}(k_2 + k_1) - \frac{1}{2}(k_2 - k_1) \frac{(V_2 + V_1)}{(V_2 - V_1)},$$

or since we may take the potential as being roughly a linear function of the height  $h$  the proportional error is

$$1 - \frac{1}{2}(k_2 + k_1) - \frac{1}{2}(k_2 - k_1) \frac{(h_2 + h_1)}{(h_2 - h_1)}.$$

To take a numerical example suppose the error of the upper wire is 1 per cent., i.e.  $k_2 = 0.99$ , and the error of the lower wire is 0.5 per cent., i.e.  $k_1 = 0.995$ , then when the wires are used differentially at 1 m. apart the proportional errors of the readings increase as follows:

|                         |                                    |            |       |       |       |       |
|-------------------------|------------------------------------|------------|-------|-------|-------|-------|
| Mean height<br>(metres) | $\left(\frac{h_2 + h_1}{2}\right)$ | .....1     | , 3,  | 5,    | 7,    | 10    |
| Percentage error        |                                    | .....0.75, | 1.75, | 2.75, | 3.75, | 5.75. |

Thus an error which is inappreciable at the lowest height may become serious at the greater heights; the increase in the proportional error may be as much as tenfold. If then we wish to keep the error at 10 m. to within say 1 per cent. we must not allow an error of more than about 0.1 per cent. at the lowest height. Some tests made on the collectors and insulating systems of each wire showed that in normal conditions the factors  $k_1$  and  $k_2$  varied between 0.9995 and 0.9988, i.e. the error of each system varied between 0.05 and 0.12 per cent. The insulation error of the differential system at the greatest height would therefore be not much more than 1 per cent., provided the leaks remained constant. Moreover, the leakage would be nearly as likely to increase as to decrease the observed potential gradient according to whether  $k_1$  or  $k_2$  happened to be the greater. Leakage tests carried out in the laboratory showed that there was practically no change in the insulation resistance of the insulators when the potential was increased from about 100 to 5,000 volts. Above this latter voltage the insulators behaved erratically; on some occasions the insulation held good up to considerably higher voltages, but on others deterioration occurred fairly rapidly. For these reasons it was extremely difficult to obtain reliable measurements of the potential gradient when the actual voltage of the wires exceeded about 5,000 volts and many of the observations made in winter, in which season the potential gradient at Kew often exceeds 500 volts per metre (v./m.), had to be rejected. It was fairly easy to detect unreliable observations by comparing the individual readings with the control observations; in a good series of observations the individual ratios differed from the mean by less than 3 per cent., but when leaks developed the departures of the individual ratios became considerably larger than this. Very little insulation trouble was experienced in the summer and equinoctial months (the potential gradient during those parts of the year being usually less than 400 v./m.), but attempts to make measurements in winter fogs, which were nearly always associated with high potential gradients and which might be expected to show marked variations of gradient with height, were nearly always marred by insulation failures.

## § 5—THE OBSERVATIONS

The number of occasions on which successful observations were obtained was 19, but for about half this number the series are incomplete owing to insulation failures. The measurements which are considered to be reliable are summarised in Table I in which the results are tabulated according to the magnitude of the potential gradient at ground level, the mean value during each series being given. For comparisons between the various heights the ratio of the gradient as measured by the wire system to that observed simultaneously at ground level is used. Almost every ratio represents the mean of 10 readings, but in a few cases a smaller number had to be used.



TABLE I—OBSERVATIONS OF THE VARIATION OF POTENTIAL GRADIENT WITH HEIGHT AT KEW,

(a) in turbulent air,  
(b) in comparatively still air.

|     | Date                  | Hour<br>G.M.T. | Mean<br>potential<br>gradient<br>v./m. | Ratio :—<br>Potential gradient at variable height<br>Potential gradient at ground level |                  |                  |                  |                  |
|-----|-----------------------|----------------|--|---|------------------|------------------|------------------|------------------|
|     |                       |                |  | 1 m.  | 3 m.             | 5 m.             | 7 m.             | 10 m.            |
| (a) |                       |                |  |   |                  |                  |                  |                  |
| 1   | 1933 May 15 ..        | 14             | 185                                    | .98   | ..               | ..               | .98              | 1.00             |
| 2   | 1933 April 8 ..       | 12             | 211                                    | 1.00  | 1.00             | .99              | 1.00             | .99              |
| 3   | 1932 Oct. 6 ..        | 15             | 249                                    | 1.02  | ..               | ..               | ..               | (.92)            |
| 4   | 1933 May 12 ..        | 11             | 260                                    | .99   | 1.00             | .98              | .99              | (.90)            |
| 5   | 1933 April 11 ..      | 11             | 266                                    | 1.01  | .97              | .99              | 1.00             | 1.01             |
| 6   | 1932 Nov. 23 ..       | 11             | 310                                    | 1.00  | .99              | .96              | .98              | .99              |
| 7   | 1933 April 6 ..       | 12             | 312                                    | .98   | .99              | .98              | .98              | .93              |
| 8   | 1932 Nov. 3 ..        | 15             | 355                                    | ..  | 1.01             | 1.00             | (.84)            | ..               |
| 9   | 1933 April 13 ..      | 11             | 368                                    | .98   | .97              | .99              | 1.01             | .97              |
|     |                       | Mean           | 280                                    | .99 <sub>4</sub>  | .99 <sub>0</sub> | .98 <sub>4</sub> | .98 <sub>1</sub> | .96 <sub>4</sub> |
| (b) |                       |                |  |   |                  |                  |                  |                  |
| 10  | 1932 Nov. 7 ..        | 12             | 443                                    | .98   | 1.00             | 1.01             | .97              | ..               |
| 11  | 1934 Feb. 7 ..        | 11             | 485                                    | .98   | .98              | .99              | ..               | .98              |
| 12  | 1932 Nov. 11 ..       | 12             | 536                                    | .99   | (.97)            | ..               | ..               | ..               |
| 13  | 1932 Dec. 14 ..       | 12             | 542                                    | ..  | .95              | .98              | (1.01)           | ..               |
| 14  | 1933 Nov. 16 ..       | 11             | 575                                    | 1.00  | ..               | ..               | ..               | (1.03)           |
| 15  | 1934 Feb. 8 ..        | 11             | 650                                    | 1.00  | 1.02             | .98              | .95              | .97              |
| 16  | 1933 Dec. 19 ..       | 11             | 664                                    | ..  | 1.00             | ..               | ..               | ..               |
| 17  | 1932 Dec. 6 ..        | 15             | 717                                    | .97   | .98              | ..               | ..               | ..               |
| 18  | 1933 Dec. 12 ..       | 11             | 762                                    | .98   | ..               | ..               | ..               | .94              |
| 19  | 1933 Nov. 8 ..        | 11             | 805                                    | (.97)   | ..               | ..               | ..               | (.88)            |
|     |                       | Mean           | 618                                    | .98 <sub>5</sub>  | .98 <sub>7</sub> | .99 <sub>0</sub> | .97 <sub>0</sub> | .96 <sub>1</sub> |
|     | Mean of all series .. |                | 457                                    | .99 <sub>0</sub>  | .98 <sub>9</sub> | .98 <sub>6</sub> | .97 <sub>9</sub> | .96 <sub>3</sub> |

NOTE: Figures in brackets are obtained from less than 10 readings and they are given half-weight in deriving the means.

The meteorological conditions in which the observations were made can be divided roughly into two classes. The conditions associated with potential gradients exceeding 400 v./m. were those in which convection was extremely small, visibility was poor or bad and the air was comparatively still; such conditions should be favourable for the accumulation of volume charge in the air. In the other class there were stronger winds, good visibility and more turbulence and convection; in these conditions the mixing of the air would tend to prevent the accumulation of space charge. It is surprising that the ratios corresponding to the one class of conditions show no striking differences from the ratios associated with the other class. The change of potential gradient with height is comparatively small in nearly every series.

The results obtained in some of the individual experiments are shown in Fig. 4 in which potential gradient is plotted against height. To eliminate the variation of the gradient with time each value observed with the wires has been multiplied by a factor  $P/p$ , where  $p$  is the corresponding value of the control measurement and  $P$  is the average value of the control measurement during each series. At the lower gradients the changes between each pair of heights do not amount to more than about 10 or 15 v./m., and even with a gradient of 650 v. m. the greatest

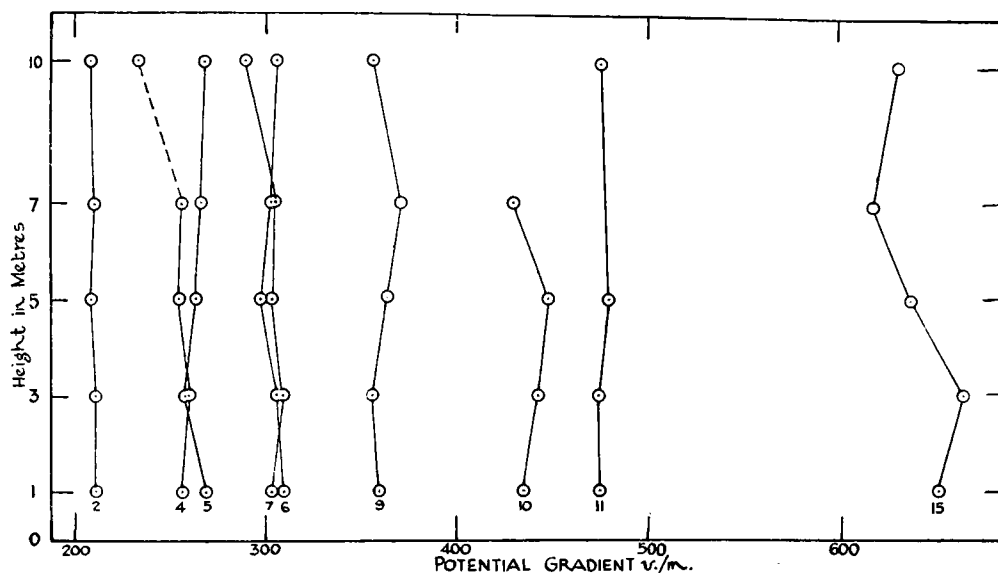


FIG. 4.—SOME INDIVIDUAL OBSERVATIONS OF THE VARIATIONS OF POTENTIAL GRADIENT WITH HEIGHT; THE FIGURE BELOW EACH CURVE IS THE SERIAL NUMBER OF THE EXPERIMENT.

change from one height to the next is only 30 v./m. With such small variations as these it is not surprising that the curves show few points of resemblance.

In the averages for the two groups and for the complete set of observations in Table I the ratios are given to the third decimal place, but it is doubtful whether very much significance can be attached to the third figure; for this reason the third figures are printed in small type. The fact that most of the average values run in a reasonably smooth sequence does perhaps offer some justification for giving the third figures in the means.

The average ratio for the height of 1 m. is 0.990. This is consistent with the results of independent comparisons made between the gradient immediately above the test-plate and the potential measured by a single stretched wire 1 m. above the ground in the paddock; these comparisons showed that the two methods are in agreement, on the average, to within less than 1 per cent., the mean ratio being 1.007. The fact that the ratio given by the double wire system is slightly less than this is probably accounted for by the presence of the tall masts. The individual values of the ratios at 1 m. vary by about  $\pm 2$  per cent., and a variation of about

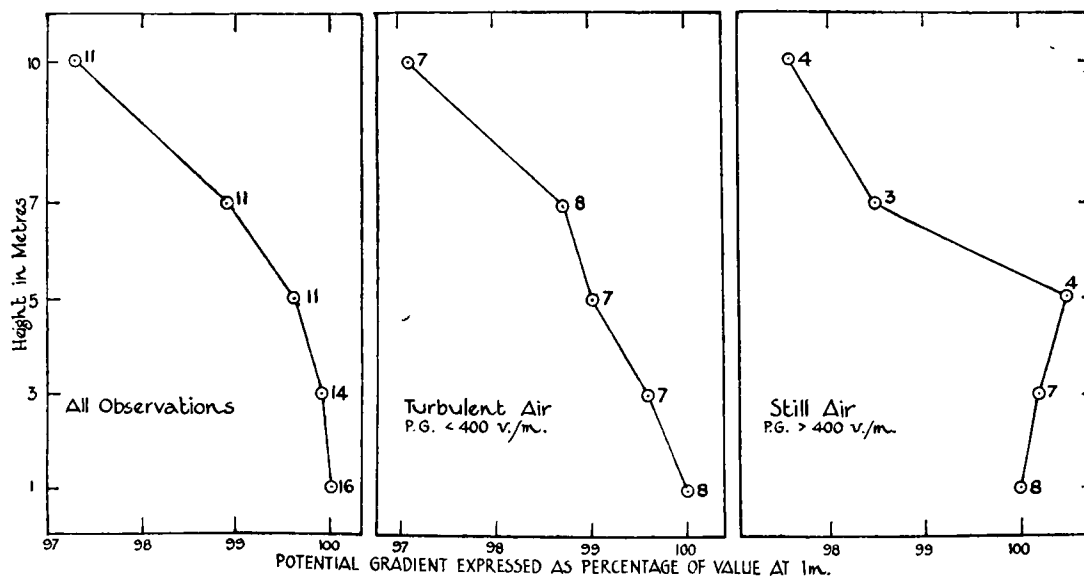


FIG. 5 —AVERAGE VARIATIONS OF POTENTIAL GRADIENT WITH HEIGHT; THE FIGURE AGAINST EACH POINT IS THE NUMBER OF OBSERVATIONS.

the same extent was found in the comparisons with the single wire at 1 m., but the variations showed no connexion with potential gradient, conductivity, wind force or direction. If they are genuine natural variations due to space charge then it appears that the latter is not closely connected with these factors.

The average variation of potential gradient with height, derived from all the observations, is shown in Fig. 5; the diagram also includes graphs based on the averages for the two groups of conditions. In obtaining the mean ratios the figures which are not quite reliable (indicated by brackets in Table I) have been given half weight. It will be seen that the change of gradient between 1 m. and 10 m. is on average less than 3 per cent. In turbulent conditions the decrease is fairly steady all the way up, but in quiet conditions there is a very slight increase up to 5 m. followed by a more rapid decrease up to 10 m. Norinder's observations (2, p. 94) in winter months showed a variation of the latter type with a maximum gradient at about 4 m. above the ground, but the variations were very much larger than those found at Kew. Thus the increase in the gradient up to 4 m. was about 50 per cent. and the decrease between 4 m. and 10 m. was about 40 per cent. In summer months Norinder observed that on the average the gradient increased with height from 1 m. up to 10 m. by about 40 per cent. These changes are very large compared with those observed at Kew where, on the average, the gradient up to 10 m. does not vary from the value at ground level by more than 3 per cent.

The theoretical decrease of potential gradient due to electrode effect has been discussed by F. J. W. Whipple (5), who derived the following formula connecting  $F$ , the potential gradient at a height  $h$ , with  $F_0$  the gradient at ground level:

$$F = F_0 \left( \frac{1 + e^{-h/a}}{2} \right)$$

where  $a$  is given by

$$a^2 = \frac{\kappa}{4\pi(\lambda_1 + \lambda_2)},$$

$\lambda_1$  and  $\lambda_2$  being the positive and negative conductivities and  $\kappa$  the coefficient of eddy diffusion. Using the value of  $10^4 \text{ cm.}^2/\text{sec.}$  for  $\kappa$  and  $10^{-4} \text{ E.S.U.}$  for  $(\lambda_1 + \lambda_2)$ , these being rough average values, Whipple calculated the magnitude of  $a$  to be about 30 m. For heights which are fairly small compared with  $a$  the expression for  $F$  may be written

$$F = F_0 \left( 1 - \frac{h}{2a} + \frac{h^2}{4a^2} \right)$$

Very close to the ground the decrease of  $F$  with height should follow a linear law. Taking  $a$  as 30 m. the ratios of  $F/F_0$  should decrease with height as follows:

|                 |       |       |       |       |       |       |
|-----------------|-------|-------|-------|-------|-------|-------|
| Height (metres) | 0     | 1     | 3     | 7     | 7     | 10    |
| $F/F_0$ ..      | 1.000 | 0.983 | 0.953 | 0.924 | 0.897 | 0.862 |

In the observations made in turbulent conditions the decrease does show some tendency to obey the linear law, but the amount of decrease is only about one quarter of that indicated by the above theoretical values. It appears that the electrode effect is not so marked as these theoretical figures would indicate. For the observations made in quiet conditions, the coefficient of eddy diffusion was probably comparatively small and the corresponding value of  $a$  probably lower than 30 m., in which case the theoretical decrease in the gradient would be even greater than that indicated by the above figures; the experimental results however show no such large decrease. It should be noted that Whipple's formula is not intended to be more than a first approximation and that it throws no light on the occurrence of an increase of potential gradient with height: the formula depends on the assumptions that  $\kappa$  is constant as well as  $\lambda_1$  and  $\lambda_2$ .

## § 6—ESTIMATES OF THE VOLUME CHARGE

Poisson's formula enables us to obtain the average density,  $\rho$ , of the volume charge between any two heights  $h_1$  and  $h_2$  thus:

$$\rho = -\frac{F_1 - F_2}{4\pi(h_1 - h_2)},$$

where  $F_1$  and  $F_2$  are the potential gradients, expressed in electrostatic units, at the two heights. Since we are observing ratios of the gradient referred to  $F_0$  at ground level we may write

$$\rho = -\frac{(F_1/F_0 - F_2/F_0)F_0}{4\pi(h_1 - h_2)} \text{ E.S.U. per unit volume.}$$

If the gradients are measured in volts per metre and the heights in metres, the formula reduces to

$$\rho = -\frac{(F_1/F_0 - F_2/F_0)F_0}{37.7(h_1 - h_2)} \text{ E.S.U./m}^3$$

This formula has been applied to the three sets of average values of the ratios given in Table I and the estimates of the volume charge so derived are given in Table II. It should be emphasized that these estimates have a very low order of accuracy since they are based on the differences between measurements which, in most cases, change by less than one per cent. In fact, it is doubtful whether very much significance can be attached to the figures appearing in the second decimal places in Table II; for this reason these figures are printed in small type.

TABLE II

|                        | Mean<br>potential<br>gradient<br>v./m. | Volume charge at Kew: E.S.U./m <sup>3</sup> |                   |                   |                   |                   |
|------------------------|--|---|-------------------|-------------------|-------------------|-------------------|
|                        |  | Height intervals (metres from ground)       |                   |                   |                   | Mean              |
|                        |  | 1-3   | 3-5               | 5-7               | 7-10              |                   |
| Turbulent air .. ..    | 280                                    | +0.0 <sub>2</sub>                           | +0.0 <sub>2</sub> | +0.0 <sub>1</sub> | +0.0 <sub>4</sub> | +0.0 <sub>2</sub> |
| Still air .. ..        | 618                                    | -0.0 <sub>2</sub>                           | -0.0 <sub>2</sub> | +0.1 <sub>6</sub> | +0.0 <sub>5</sub> | +0.0 <sub>4</sub> |
| All observations .. .. | 457                                    | +0.0 <sub>1</sub>                           | +0.0 <sub>2</sub> | +0.0 <sub>4</sub> | +0.0 <sub>7</sub> | +0.0 <sub>3</sub> |

The results may be summed up by saying that on the average the volume charge at Kew is very nearly zero, but that in quiet conditions a charge of the order of +0.1 E.S.U./m<sup>3</sup> occurs between the heights of 5 and 10 m. above the ground. The values of the volume charge obtained by Norinder (2) from observations of the change of potential with height at Uppsala are, on the whole, very much larger. Norinder did not use the differential method but obtained simultaneous records, over short periods, of the potentials of three wires, two of which were at a fixed distance apart on a movable framework whilst the third was kept at a fixed height. A summary of his estimates of volume charge is given in Table III.

TABLE III—VOLUME CHARGE AT UPPSALA; E.S.U./m<sup>3</sup>

| Height intervals<br>(metres) | 1.25-<br>2.25 | 3.25-<br>4.25 | 5.25-<br>6.25 | 8.25-<br>9.25 |
|------------------------------|---------------|---------------|---------------|---------------|
| Summer .. ..                 | -0.15         | -0.07         | 0             | -0.05         |
| Winter .. ..                 | -0.08         | -0.17         | -0.05         | +0.29         |
| Spring and Autumn ..         | -0.04         | -0.08         | +0.11         | +0.19         |
| Year .. ..                   | -0.09         | -0.18         | +0.02         | +0.07         |

The mean potential gradient at Uppsala is less than 100 v./m. and the volume charge is mostly negative. Norinder also obtained a year's continuous records of the potentials at three heights and from these he found that the volume charge between 1 and 3 m. was nearly always negative, the mean value being  $-0.2$  E.S.U./m<sup>3</sup>. Daunderer (1), using a similar method at Bad Aibling, obtained mean values of  $+0.6$  and  $-0.5$  E.S.U./m<sup>3</sup> in summer and winter respectively.

Of estimates of the volume charge obtained by other methods, those of Kähler (6), who used the Kelvin wire cage method, may be mentioned. Kähler found that the volume charge at Potsdam is nearly always positive, the monthly mean values varying from about  $+0.27$  E.S.U./m<sup>3</sup> in the winter to about  $+0.11$  in the summer. Obolensky (7), who used the aspiration method at Pavlovsk, obtained values of roughly the same magnitude as those found at Kew, the monthly means for the winter and equinoctial months varying between  $+0.01$  and  $+0.08$  E.S.U./m<sup>3</sup> and those for the summer months between  $+0.01$  and  $-0.23$  E.S.U./m<sup>3</sup>. Brown (8), who also used the aspiration method, obtained an annual mean of  $+0.085$  E.S.U./m<sup>3</sup> at San Francisco.

It may be noted that the mean value of  $+0.0_3$  E.S.U./m<sup>3</sup> obtained at Kew is equivalent to an excess of 60 positive ions per c.c. whilst the higher value of  $+0.1_6$  E.S.U./m<sup>3</sup>, associated with quiet conditions, indicates an excess of about 300 positive ions per c.c. Some measurements, by L. H. Starr, of atmospheric ionisation at Kew shew that at 15h. G.M.T. the average concentrations of positive and negative small ions are about 205 and 155 per c.c. respectively. The excess of positive small ions is therefore almost sufficient to account for the average volume charge. In quiet conditions however the small ion content is low and the net excess of the positive ions is diminished; in such conditions it is probable that the large ions produce most of the volume charge. The small magnitude of the volume charge at Kew indicates that the numbers of positive and negative large ions must be very nearly equal, for even if we attribute the whole of the charge to the large ions a preponderance of 300 per c.c. in a total number of 30,000 per c.c. (which is about the average large ion content at Kew in quiet conditions) gives a ratio of the numbers of positive and negative large ions of only about 1.02. The average large ion content in all conditions is about 15,000 per c.c. and an excess of 60 ions per c.c. would correspond with a ratio of less than 1.01. In the theory of the equilibrium of atmospheric ionisation it is often convenient to assume that the positive and negative large ions are equal in numbers (9); it is useful therefore to note that this assumption is, for all practical purposes, supported by our observations.

## § 7—CONCLUSIONS

It is considered that as a means of measuring volume charge the method adopted in this investigation is not satisfactory when potentials exceeding 5,000 volts are involved, owing to insulation difficulties. In summer and equinoctial months such high voltages are not very frequent at Kew, but they are likely to occur a few metres above the ground in winter fogs.

The variation of potential gradient between the ground and 10 m. at Kew is very small; on the average there is a decrease of about three per cent. in 10 m. The change of gradient is more uniform in turbulent air than it is in comparatively still air. Over the range of height considered the average density of the volume charge is practically zero; it is small enough to be accounted for by the excess of positive small ions at Kew (on the average about 50 per c.c.). In comparatively still air an average charge of the order of  $+0.1$  E.S.U./m<sup>3</sup> occurs between 5 and 10 m. above the ground; this is more than can be accounted for by the small ions and it is probably the large ions which are effective in such conditions, but the necessary excess of positive large ions required is so small compared with their total number that for most purposes we may regard positive and negative to be equally numerous.

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## BIBLIOGRAPHY

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1. A. DAUNDERER : Über die in den unteren Schichten der Atmosphäre vorhandene freie elektrische Raumladung ; Dissertation, K.Tech. Hochschule, Munich, 1908.
  2. H. NORINDER : *Stockholm, Geogr. Ann.*, **1**, 1921, p. 1.
  3. F. J. SCRASE : *London, Geophys. Mem.* No. 60, 1934.
  4. H. BENNDORF : *Wien, S.B. Akad. Wiss.*, IIa, **115**, 1906, p. 445.
  5. F. J. W. WHIPPLE : *Terr. Magn. atmos. Elect., Baltimore*, **37**, 1932, p. 355.
  6. K. KÄHLER : *Met. Z., Braunschweig*, **44**, 1927, p. 1.
  7. W. N. OBOLENSKY : *Ann. Phys., Leipzig*, **77**, 1925, p. 644.
  8. J. G. BROWN : *Terr. Magn. atmos. Elect., Baltimore*, **35**, 1930, p. 1.
  9. F. J. SCRASE : *London, Geophys. Mem.* No. 64, 1934.