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GEOPHYSICAL MEMOIRS No. 45

(Fifth Number of Volume V)

Measurements

of the

Effective Electrical Conductivity of the Air

and the

Earth's Electric Field

at and near Ground Level by means of the

Wilson Universal Electrometer

By R. E. WATSON, Ph.D.

Published by Authority of the Meteorological Committee.



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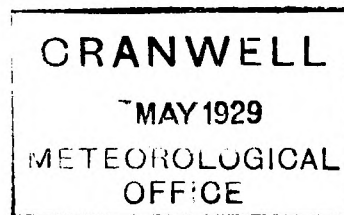


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MEASUREMENTS OF THE EFFECTIVE ELECTRICAL CONDUCTIVITY OF THE AIR AND THE EARTH'S ELECTRIC FIELD AT AND NEAR GROUND LEVEL BY MEANS OF THE WILSON UNIVERSAL ELECTROMETER

§ 1—INTRODUCTION

At Kew Observatory on all fine days the effective electrical conductivity of the air is measured by means of a Wilson universal electrometer, over a fixed site on the lawn covered by short grass. As shown in Fig. 1, the instrument rests on a tripod standing 1 metre above the lawn, the test plate and guard ring being 30 cm. above the tripod head.

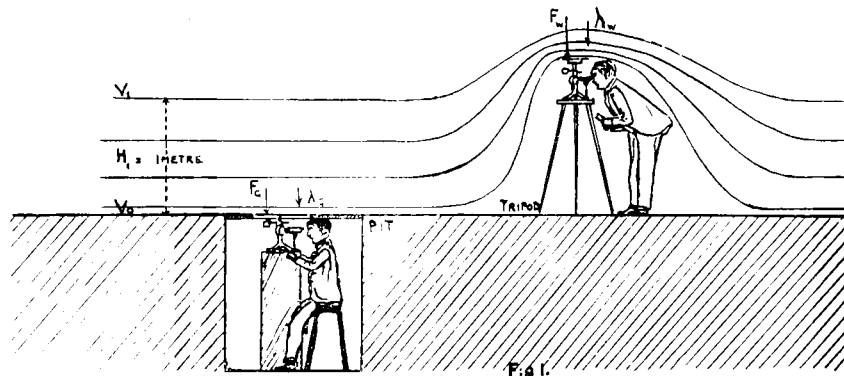


FIG. 1.—CONFORMATION OF EQUI-POTENTIAL SURFACES OF EARTH'S ELECTRIC FIELD OVER WILSON ELECTROMETER, IN PIT AND OVER TRIPOD ON LAWN.

Referring to Fig. 1, the vertical electric field 130 cm. above ground level is considerably increased by the presence of the instrument and observer, the increase being such that there is a possibility of saturation potentials being reached and the conductivity of the air, λ_w , being affected. It has long been suspected that λ_w obtained by this method required the application of a factor, probably greater than unity, to reduce it to the corresponding value λ_g at ground level in the open, where the earth's electric field F_g , and presumably the conductivity λ_g are constant over a large area. In 1914, G. M. B. Dobson¹ made some experiments to determine such a factor, but his results were not considered final and no factor has been applied. The data regarding atmospheric electricity for Kew Observatory published in the *Observatories' Year Book* include the air-earth current and the potential gradient. The conductivity λ_w itself is not published, but the air-earth current i , obtained from the product of λ_w and the simultaneous potential gradient as given by the

¹ Gordon Dobson—"Atmospheric electricity observations at Kew Observatory."—*Proceedings of the Physical Society of London*—Vol. XXVI, Part V., Aug. 15, 1914.

Kelvin water dropper electrograph. The latter is standardised by absolute observations of potential (V) at 1 metre and 2 metres (H) on the lawn near the site of the conductivity observations. The Wilson instrument measures what will hereafter be called the effective conductivity $\lambda_w = \frac{i_w}{F_w}$, and the published value of the air-earth current is deduced from the values of $\frac{V_1 - V_0}{H_1} \times \frac{i_w}{F_w}$ where $\frac{V_1 - V_0}{H_1}$ is the average potential gradient between the ground and a height of 1 metre above the ground (cf., Fig. 1.). Assuming the conductivity λ_g and the earth's electric field F_g at ground level to be the true values, the two questions which arise are :

- (i) Is F_g equal to $\frac{V_1 - V_0}{H_1}$?
 and (ii) Is $\frac{i_w}{F_w}$ equal to $\frac{i_g}{F_g}$?

§ 2—MEASUREMENT OF EFFECTIVE CONDUCTIVITY AT GROUND LEVEL

The following account describes a method used at Kew Observatory in the summers of 1926 and 1927 to measure (i) the effective conductivity λ_g , and (ii) the earth's electric field F_g at ground level in the open free from all obstructions.

Surrounding the Observatory lawn is a paddock in the middle of the eastern portion of which (a rectangle 140 yds. long and 70 yds. wide), a pit was dug 6 ft. long, 4 ft. wide and $5\frac{1}{2}$ ft. deep. A stone pillar was set up at one end of the pit, the height being adjusted so as to support a Wilson electrometer with its test plate flush with the surrounding turf. (See photograph facing p. 8, Fig. 3a.) The pit was entirely covered by a flat roof of sheet zinc supported on wire netting, a circular hole being suitably cut to allow of the exposure of the test plate and guard ring. A smaller hole with a movable cover enabled the covering cap to be placed over the test plate when readings were taken. The observer was seated inside the pit and nothing projected to disturb the electric field or the exposure of the test plate—see Fig. 1.

Using two instruments Nos. 4011 and 7960 simultaneous observations of the conductivity of the air were made in the pit and on the usual site over the tripod on the lawn. In order to eliminate any instrumental differences the instruments were interchanged twice during each experiment to give the same mean time at the two stations. The same method was employed at both stations simultaneously.

The two instruments No. 4011 and No. 7960 were identical in construction, except that No. 4011 had originally a guard ring of only 17 cm. diameter, while that of No. 7960 was 24 cm. diameter. They were compared simultaneously on similar tripods on the lawn in order to determine any instrumental differences, the positions of the instruments being interchanged. Later on in 1927 the guard ring of No. 4011 was made equal to that of No. 7960, and the instruments were again compared. Both before and after the change, the conductivities obtained with the two instruments agreed to within 1% in the mean of the series, the individual comparisons varying from +6% to -4% of the mean value.

A considerable number of preliminary experiments were carried out with the above two instruments in the summer of 1926. Owing however to the intensified electric field over the tripod, the conduction current measured there was much bigger than at ground level, with the result that the differences in reading of the gold leaf of the tripod instrument were correspondingly bigger than those of the

pit instrument. The readings in the pit were often so small that the error in the result often amounted to 100 % and it was decided to modify the apparatus before the summer of 1927.

The modified form of apparatus used in the pit in 1927 was designed to give increased sensitiveness by catching a bigger conduction current. A test plate was made with a diameter of 23.5 cm. as compared with 7 cm. in the normal instrument, thus increasing the area from 49 sq. cm. to 550 sq. cm. It was so made that it was easily interchangeable with the normal test plate when an interchange of instruments took place during a comparison. Also in the pit 4 cm. below the level of the modified test plate and parallel to it, an earthed metal plate E, Fig. 2 (b) was fitted on a wooden frame, thus forming a fixed air condenser with the test plate, and shielding the latter from any electrical influences inside the pit. It is very important that the distance of the earth plate below the test plate should remain constant as in the normal instrument.

The following sketch, Fig. 2, shows the comparative sizes of the normal Wilson instrument (a) and the modified test plate (b) :—

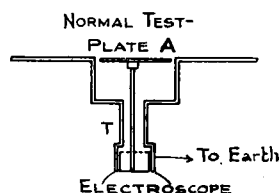


FIG. 2 (a)—SKETCH OF WILSON ELECTROMETER, NORMAL TEST PLATE AS USED ON TRIPOD.

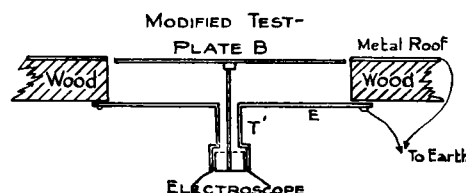


FIG. 2 (b)—SKETCH OF WILSON ELECTROMETER, MODIFIED TEST PLATE AS USED IN PIT.

The modified test plate B was the same size as the guard ring and test plate of the normal instrument A. In the normal instrument the guard ring is attached to the electrometer by means of a tube T, which is part of the guard ring fitting; in the modified form the tube T was replaced by another tube T', an exact duplicate of T which just reached inside the earth plate E.

A cylindrical cover was made for the modified test plate in form similar to an inverted frying pan (see photograph, Fig. 3a), the handle being 50 cm. long. The end of the handle was pivoted at the side of the pit, and could be raised and rotated through 180° away from the test plate by means of another handle operated by the observer inside the pit. In this position 1 metre away from the exposed plate, it slipped into a hollow so that the top of the cover was flush with the ground and no distortion of the earth's electric field resulted.

§ 3—MEASUREMENT OF THE EARTH'S ELECTRIC FIELD. ARTIFICIAL FIELD APPARATUS.

During the summer of 1927 a method was devised for utilising readings of the Wilson electrometer for measuring the earth's vertical electric field. The method differs from that described by Wilson² for standardising the instrument, in that the "compensator" is not used but remains in its zero position throughout, where, as experiment showed, varying charges on the compensator have no effect on the scale

² C. T. R. Wilson.—"On the measurement of the Earth-Air Current and on the Origin of Atmospheric Electricity." *Cambridge Proc. Phil. Soc.*, Vol. XIII, Pt. VI., 1906.

value or zero position of the gold leaf. Thus the method is applicable to any ordinary gold leaf electroscope having a suitable test plate, and for this reason details of its reliability are added.

The test plate of the electrometer was suitably exposed in a known artificial field and the charge induced on the plate was measured as a deflection of the gold leaf in terms of scale divisions of the eye piece. The operations were the same as those for measuring the earth's field in the first part of the conductivity experiments, viz., momentarily earth the test-plate system while exposed to the artificial field; shield the test plate from the field by covering with an earthed disc, and take a reading of the gold leaf g_1 ; then earth the leaf and take another reading g_0 . The difference $g_1 - g_0$ in scale divisions is a measure of the known electric field applied to the test plate, and so a scale value is obtained for converting deflections of the gold leaf into potential gradient values.

The artificial electric field apparatus consisted of a double gallows framework (see photograph, Fig. 4)³ about six feet high, from the mid-point of which a flat insulated metal plate 1 metre square was suspended, forming a horizontal plane over a similar metal plate. The lower plate was supported on four adjusting screws capable of giving slight adjustments in level, while the upper plate could be raised or lowered to any convenient height by means of a rope and pulley. A hole slightly larger than the guard ring of the Wilson electrometer was cut in the lower plate which was fitted on the framework at such a position that when the whole arrangement was fastened on the bench supporting the electrometer in position, the guard ring and test plate were coplanar with the lower plate. This plate, the case of the electrometer and the negative pole of a H.T. battery were connected to earth, while the positive pole of the battery was connected through a high resistance to the upper metal plate, thus giving a vertical electric field between the plates. Varying voltages were applied to the upper plate, and calibrations were carried out at 10 cm., 15 cm. and 20 cm. between the plates. (It can be shown theoretically that if the distance between the plates does not exceed half the distance of the edge of the Wilson electrometer test plate from the extreme outside edge of the plates of the artificial field, then the electric field is practically constant in magnitude and parallel in direction over the whole test plate.) The observer sat quite underneath the lower earthed plate and no distortion of the field could be caused by his presence.

At the conclusion of the series of experiments in 1927 it was discovered that in one particular the wooden frame supporting the roof of the pit was not an exact duplicate of the wooden frame supporting the lower earth plate of the artificial field. The sections of the two frames in plan were identical, but the thickness of the wood used for the pit framework was $1\frac{3}{8}$ inches, while that used for the artificial field was 1 inch. Thus, the earth plate (E, Fig. 2 (b)) fitted below the test plate was $\frac{3}{8}$ inch further from the test plate when in the pit than when it was in the artificial field for standardisation. By interchanging the frames it was shown that a fixed condenser effect was produced making all readings of the electric field over the pit too big by $1.4/1$, almost the ratio of the thicknesses of the wooden frames in the pit and in the artificial field. The factors obtained each day for converting readings of the Wilson instrument into electric field readings by the artificial field standardisation were corrected for this fixed condenser effect.

The results of a calibration of both instruments, No. 4011 and No. 7960, with the modified test plate are given in Table I and shown graphically in Fig. 5 (a) and (b).

³ The artificial field was used indoors shielded from the earth's field, but owing to the smallness of the room it was impossible to take the photograph indoors and the apparatus had to be brought outside to be photographed.

TABLE I—CALIBRATION OF WILSON ELECTROMETERS IN ARTIFICIAL FIELD
(MODIFIED TEST PLATE).

May 19th, 1927.

Scale Values in Volts per Metre per Division.

Volts Applied	No. 7960. Distance between plates			No. 4011. Distance between plates		
	10 cm.	15 cm.	20 cm.	10 cm.	15 cm.	20 cm.
	v/m/div.	v/m/div.	v/m/div.	v/m/div.	v/m/div.	v/m/div.
63.1	45.7	46.6	46.8	42.1	43.8	44.2
53.8	45.2	45.0	45.5	42.3	43.1	44.0
47.7	45.4	45.4	45.9	41.5	43.6	45.0
31.4	45.4	46.5	44.8	42.8	43.5	44.8
22.2	45.4	46.3	44.5	41.2	43.1	44.4
16.2	45.5	46.2	43.1	42.7	43.3	43.4
Means	45.4	46.0	45.1	42.1	43.4	44.3
Final Means	45.5 v/m per div.			43.3 v/m per div.		

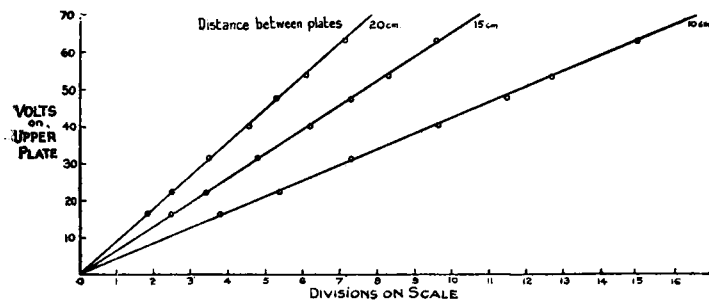


FIG. 5(a).

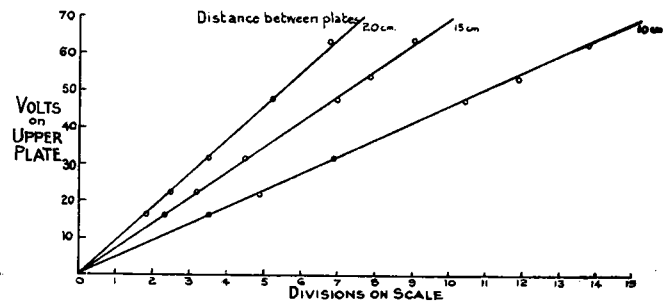


FIG. 5(b).

FIGS. 5 (a) AND 5 (b)—CALIBRATION CURVES OF WILSON ELECTROMETER, (MODIFIED TEST PLATE) IN ARTIFICIAL FIELD.
5 (a) No. 7960; 5 (b) No. 4011.

The strength of the electric field though not stated in the table can be seen at a glance from the voltages applied and the distance apart of the plates. The maximum field applied was 630 volts per metre, and the minimum 80 volts per metre, which values cover all the natural electric fields encountered at ground level in the conductivity comparisons. The results show that the scale value is linear between the above limits, and indicate the remarkable consistency to be attained by this method. The instrumental error in the calibration (probably due to the error in adjusting the distance apart of the plates of the artificial field) is of the order of 1 or 2 per cent. The scale value changes very slightly from day to day^{*} owing to leakage of charge from the gold leaf chamber, thus if the instrument is used for absolute measurements of electric field strength at ground level it must be calibrated each day. As, however, the artificial field is permanently set up the calibration takes only a few minutes. The earth's electric field over the tripod was about six times that at ground level, thus the instrument with the small test plate as used on the tripod was calibrated up to the maximum field strength measured, viz., 4000 volts per metre. The following Table II gives the results obtained which are shown graphically in Fig 6.

* If the instrument were supplied with a condenser attached to a standard battery to give a constant voltage to the gold leaf chamber as in the Lütz form of the apparatus, the scale value should remain constant from day to day.

TABLE II—CALIBRATION OF WILSON ELECTROMETER No. 7960.
(SMALL TEST PLATE.) 10 CM. BETWEEN PLATES.

Volts Applied	42.0	63.1	84.2	105.0	126.0	146.9	167.9	188.7	209.7	230.6
Potential Gradient—v/m	420	630	840	1050	1260	1470	1680	1890	2100	2310
Deflection—Scale Divs.	1.2	1.8	2.4	2.9	3.6	4.1	4.8	5.4	6.0	6.6
Scale Value—v/m per div.	350	350	351	361	350	358	350	350	350	350

Volts Applied	251.5	272.5	293.6	314.6	335.2	355.5	376.5	397.5	418.2
Potential Gradient—v/m	2510	2720	2940	3150	3350	3560	3760	3980	4180
Deflection—Scale Divs.	7.2	7.9	8.6	9.1	9.9	10.4	11.0	11.9	12.5
Scale Value—v/m per div.	349	345	342	347	339	342	342	334	334

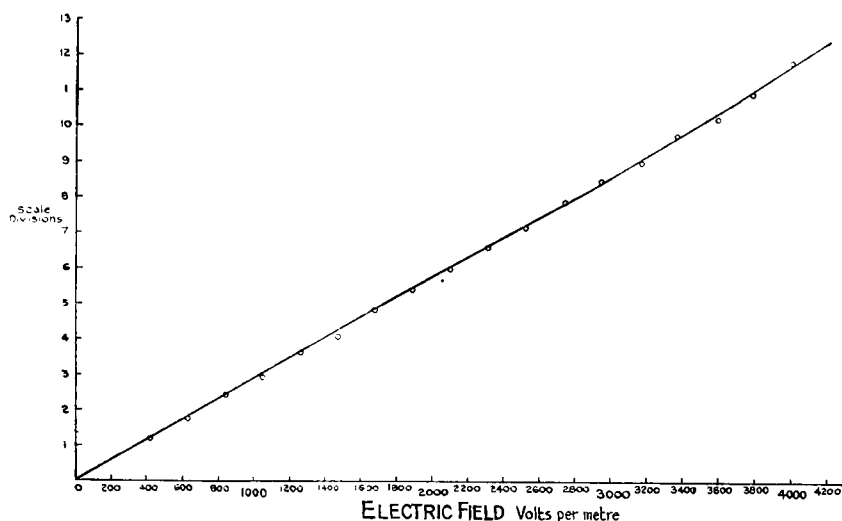


FIG. 6—CALIBRATION CURVE OF WILSON ELECTROMETER (NORMAL TEST PLATE) IN ARTIFICIAL FIELD.

The gold leaf can only be read to the nearest one tenth of a division, thus the consistency attained in the artificial field is remarkable. The scale value is linear up to 2500 volts per metre (which covers all potential gradients met with except those on June 14th), after which point it is slightly reduced.

The linearity of the scale of the electrometer was also tested by applying small voltages to the test plate and noting the deflections. A battery of six Weston standard cells was connected across a megohm divided into tenths. The negative pole of the battery and the case of the instrument were earthed, and a wire in an insulated handle was used to connect momentarily the successive terminals of the divided megohm with the test plate. The following Table III and the curve, Fig. 7, show that the electrometer has a linear scale for deflections up to 10 divisions, which more than covers the range of readings met with in normal observations of electrical conductivity of the air.

To face p. 8.



FIG. 3(a).—PIT APPARATUS, SHOWING MODIFIED TEST-PLATE EXPOSED.

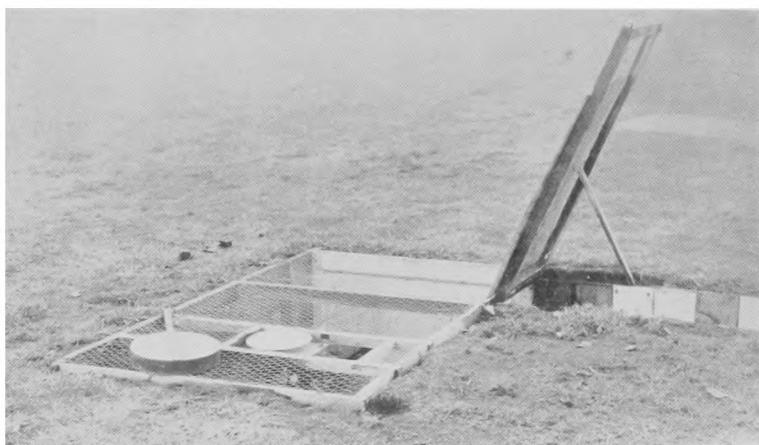


FIG. 3(b).—PIT APPARATUS, SHOWING ZINC ROOF REMOVED.

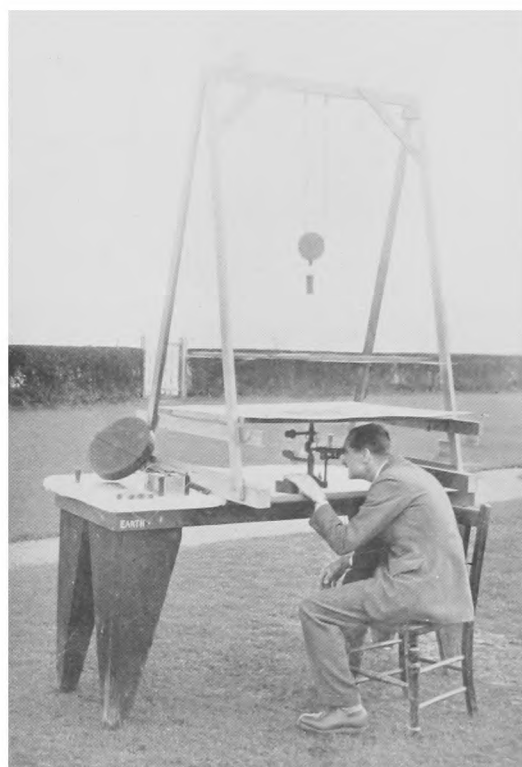


FIG. 4.—ARTIFICIAL ELECTRIC FIELD APPARATUS.

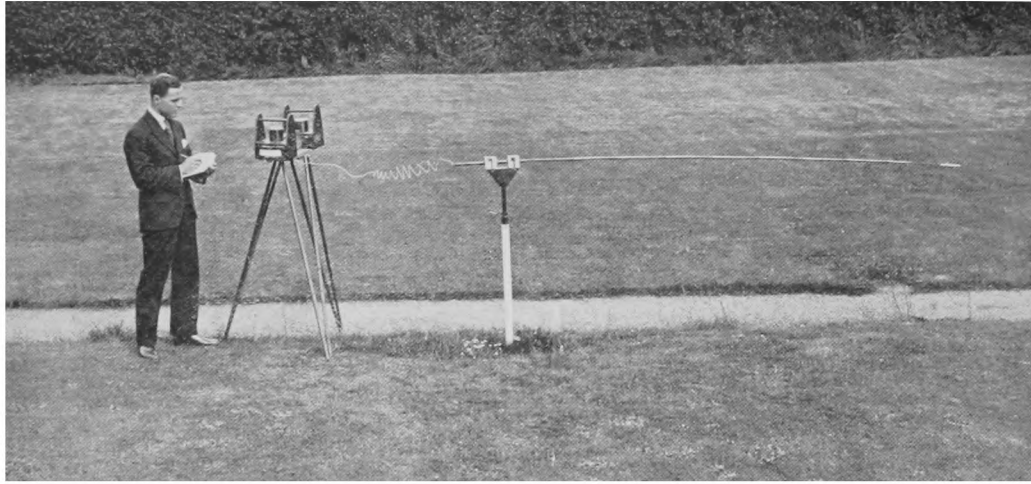


FIG. 8.—BAMBOO ROD APPARATUS FOR ABSOLUTE OBSERVATIONS OF ATMOSPHERIC ELECTRICAL POTENTIAL GRADIENT ON LAWN.



FIG. 10.—STRETCHED WIRE APPARATUS.

TABLE III—TEST OF LINEARITY OF SCALE OF WILSON ELECTROMETER NO. 4011
(SMALL TEST PLATE)

June 2nd, 1927

Volts Applied	Reading (Divs.)	Deflection (Divs.)
0	22.8	—
.61	21.6	1.2
1.22	20.4	2.4
1.83	19.3	3.5
2.44	18.2	4.6
3.06	17.1	5.7
3.67	16.0	6.8
4.28	14.9	7.9
4.89	13.8	9.0
5.50	12.7	10.1

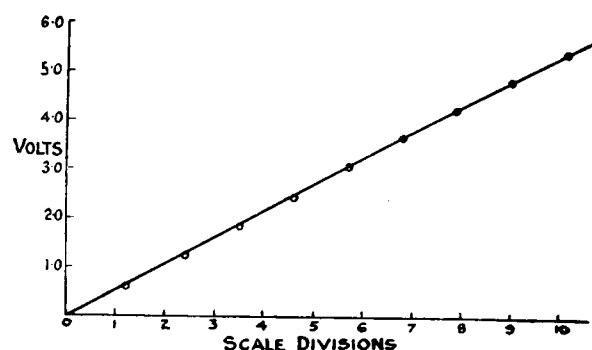


FIG. 7—CURVE SHOWING LINEARITY OF WILSON ELECTROMETER SCALE

§ 4—ABSOLUTE MEASUREMENTS OF THE EARTH'S ELECTRIC FIELD.

In order to investigate question (i) of the original problem, viz., whether $F_G = \frac{V_1 - V_0}{H_1}$, since F_G was measured by the Wilson electrometer in the pit and $\frac{V_1 - V_0}{H_1}$ by a special apparatus on the lawn of the Observatory, it was necessary to carry out certain preliminary potential gradient measurements. These are comparatively unimportant in themselves, but they all bear on the main question, and form connecting links between the Kelvin water-dropper electrograph (from which the potential gradient is obtained for the published value of the air earth current), and the field at ground level F_G . The experiments are described in detail below:—

(i) *Comparison of stretched wire and bamboo rod apparatus for absolute observations of atmospheric electrical potential gradient.*—The electrograms are standardised from absolute observations taken over an open site on the Observatory lawn, with what is known as the "bamboo rod" apparatus.⁵ The site of the pit in the paddock is more open than the lawn, consequently the "exposure factor," that is the factor to convert volts registered by the water dropper to volts per metre over the pit, would be greater than that for the lawn site. As the bamboo rod has fixed fittings on the lawn, some other apparatus had to be used for absolute observations over the pit, and the Simpson stretched wire apparatus was used. To ensure that there was no instrumental difference between the two methods of obtaining absolute potential gradient the two apparatus were compared over the same spot on the Observatory lawn. The bamboo rod apparatus consists essentially of a long insulated bamboo rod about 2.5 metres long, supported in a horizontal position at right angles to a vertical rod which can slide up and down in a vertical tube (see photograph, Fig. 8). This tube is driven into an exposed level portion of the lawn so as to protrude about 1 metre above it, and the bamboo rod can be adjusted to a height of 1 or 2 metres above the lawn (see photograph). The end of the bamboo rod furthest from the support is fitted with a metal tube which carries a lighted fuse⁶, the tube being connected by a thin copper wire along the rod to an Ayrton Mather electrostatic voltmeter, set up on a tripod 2 metres from the upright support in prolongation of the bamboo rod. Thus, the voltmeter, and observer reading it, are about 4.5 metres

⁵ C. Chree : *Phil. Trans. R. Soc.*, 215, A, 1915, p. 135.

⁶ The fuse referred to consists of blotting paper impregnated with lead nitrate paste and rolled up tightly to form a pencil 5 inches long. This burning fuse is a very efficient collector, and "picks up" the potential of its immediate surroundings in about a quarter of a minute.

from the burning fuse. To carry out the comparison of the two apparatus the wire of diameter 1.2 mm. (S.W., Fig. 9) was stretched horizontally by means of an ordinary tennis net stretcher between two sulphur insulators attached to vertical rods which could slide in vertical tubes driven into the ground (see photograph, Fig. 10). The rods could be raised or lowered to any height between 1 and 2 metres above the ground, and by means of sliding rings on the fixed tube, the wire could be adjusted to any height above the ground below 1 metre. A tiny metal turntable carrying a tube for accommodating a lighted fuse could be clamped at any position on the wire. From a terminal fixed at one end of the wire a fine copper wire was carried to an electrostatic voltmeter. The stretched

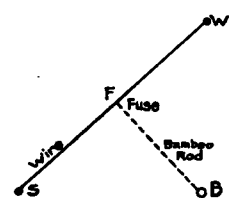


FIG. 9—COMPARISON OF BAMBOO ROD AND STRETCHED WIRE. SKETCH OF RELATIVE POSITIONS.

wire was arranged so that the mid-point F came exactly over the end of the fuse attached to the bamboo rod B. Observations were then taken every half minute for periods of about ten minutes with each apparatus alternately, one being completely removed while the other was in use. The absolute observations were meaned and compared with simultaneous readings of the Kelvin water-dropper electrograph, the resulting "exposure factor" forming the basis of comparison. Two day's results are given in Table IV, one for a summer day and the other for a winter day.

TABLE IV—COMPARISON OF STRETCHED WIRE AND BAMBOO ROD APPARATUS.

Date	Time	Potential			"Exposure Factor"	
		Wire	Rod	Water-Dropper	Wire	Rod
1927	h. m. h. m.	v/m.	v/m.	volts		
May 20th	13 55—14 03	—	114	54	—	2.11
"	14 16—14 24	116	—	55	2.11	—
"	14 30—14 42	—	108	52	—	2.08
"	14 59—15 07	—	123	61	—	2.05
Dec. 17th	11 55—11 58	743	—	363	2.06	—
"	12 03—12 08	—	858	405	—	2.12
"	12 13—12 18	860	—	409	2.10	—
"	12 20—12 25	—	829	393	—	2.11
"	12 29—12 34	667	—	327	2.04	—
				Means	2.08	2.09

The means, and even individual observations, are in such close agreement that the two pieces of apparatus may be regarded as interchangeable.

(ii) *Comparisons of potential gradient over the lawn and in the paddock.*—The Kelvin water-dropper electrograms were utilised for this comparison. Simultaneous observations of potential gradient were made for prolonged periods over the pit in the paddock, by means of the stretched wire and fuse, and on the lawn by the bamboo rod apparatus. "Exposure factors" for the two sites were obtained with respect to the Kelvin electrograph and the factors used as a basis of comparison. The paddock site is more open than the lawn, which is somewhat affected by thermometer screens and a privet hedge. The results are shown in Tables V (a) and V (b).

TABLE Va—COMPARISON OF POTENTIAL GRADIENT OVER Paddock AND LAWN

Date	Duration	Lawn Site B			Paddock Site P			Ratio Paddock Lawn
		Absolute Potential Gradient	Mean Electro-graph	"Exposure Factor"	Absolute Potential Gradient	Mean Electro-graph	"Exposure Factor"	
1926	Mins.	v/m.	Volts		v/m.	Volts		
Oct. 8th	53	189	92	2.03	209	92	2.27	1.12
" 18th	17	369	177	2.08	398	168	2.37	1.14
" 19th	44	499	239	2.09	538	237	2.28	1.14
Mean				2.07			2.31	1.13s

On days when no simultaneous observations were made on the lawn, the monthly "exposure factor" determined in the routine observations was used, and the following results deduced:—

TABLE Vb—COMPARISON OF POTENTIAL GRADIENT OVER Paddock AND LAWN

Date	Duration	Monthly "Exposure Factor"	Paddock Site P			Ratio Paddock Lawn
			Potential Gradient	Electro- graph	"Exposure Factor"	
1927	Mins.		v/m.	Volts		
April 13th	45	2.06	260	110	2.36	1.15
" 19th	41	2.05	235	104	2.26	1.10
May 4th	21	2.02	174	76	2.29	1.13
" 18th	38	2.02	185	79	2.34	1.16
" 20th	16	2.02	145	64	2.27	1.12
Mean		2.03			2.30	1.13 ₂

The final mean ratio, paddock : lawn 1.13, shows that if the Kew electrograms were standardised by the more open paddock site instead of the lawn site, the potential gradient readings, and the derived air-earth current values, would all be increased by 13 per cent.

§ 5—COMPARISONS OF POTENTIAL GRADIENT BY WILSON ELECTROMETER AT GROUND LEVEL AND BY STRETCHED WIRE

In order to compare potential gradients as measured by a stretched wire and fuse with those measured by a standardised Wilson electrometer at ground level, a stretched wire apparatus 9 metres long was set up over the pit used for the conductivity experiments, and a series of experiments was carried out. The stretched wire ran from S.W. to N.E., the fuse being at its mid-point, making it about 1 metre in a horizontal direction from the Wilson test plate as shown in Fig. 11. Further along the wire 1 metre from the fuse, a fine vertical "lead in" wire was occasionally connected between a Wulf electrometer inside the pit and the stretched wire, for taking absolute readings of the potential gradient. At

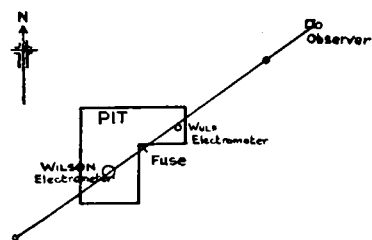


FIG. 11.—SKETCH PLAN OF PIT AND STRETCHED WIRE.

other times these readings were taken by an observer with the electrometer 2 metres in prolongation of the stretched wire.

Series I—To find the effect of an earthed wire on the potential gradient at ground level.—In this case no lighted fuse was attached to the stretched wire, but the wire was earthed and readings of the potential gradient were taken at ground level by the Wilson electrometer every quarter of a minute for five minutes, with the wire 1 metre above the test plate. The wire was then entirely removed to a safe distance, and readings of the Wilson instrument taken for ten minutes when the wire was replaced and readings resumed for another five minutes. A "quick run" record was started on the Kelvin water-dropper electrograph and "exposure factors" corresponding to the times of the experiment were compared, so that intermediate changes in potential gradient were eliminated. The following mean results were obtained:—

	Duration	Potential Gradient (Ground)	Kelvin Water-dropper Electrograph	"Exposure Factor"	Ratio Wire present Wire absent
	Mins.	v/m.	Volts		
Earthed wire present ..	21	269	127	2.12	0.76
Earthed wire absent ..	21	351	126	2.79	

Thus the effect of the earthed wire at 1 metre is to reduce the potential gradient below it to three quarters of the normal value⁷.

Series II—Fuse burning on stretched wire.—The above experiment was then repeated, but having a fuse alight when the stretched wire was present, and the following mean values were found :

		Duration	Potential Gradient (Ground)	Kelvin Water-dropper Electrograph	" Exposure Factor "	Ratio Wire absent Wire present
		Mins.	v/m.	Volts		
Wire present	36	329	113	2.91	1.00
Wire absent	28	327	113	2.90	

Thus when the fuse is alight the stretched wire takes up the potential of the air in which it finds itself and there is no diminution of the electric field below it.

Series III—Effect of presence of observer and instruments—Fuse burning (a) "lead in" wire.—In this series an observer with tripod and electrostatic voltmeter was stationed two metres in prolongation of the end of the stretched wire, that is 7 metres from the burning fuse and 8 metres from the Wilson electrometer test plate. Readings of potential gradient at ground level were then taken with (i) the observer and instruments in position, and (ii) removed to a safe distance. A "lead in" wire was attached from the stretched wire to the Wulf electrometer in the pit, and the following observations resulted :

		Duration	Potential Gradient (Ground)	Kelvin Water-dropper Electrograph	" Exposure Factor "	Ratio Observer absent Observer present
		Mins.	v/m.	Volts		
Observer present	12	244	78	3.13	1.00
Observer absent	16	253	81	3.12	

⁷The reduction of the earth's field at ground level over the Wilson test plate, as found in Series I, by introducing an earthed wire one metre above it, is amply confirmed by a theoretical treatment of the problem, as shown below :

Let W (Fig. 11(a)), represent the cross-section of a fine wire, radius a , stretched horizontally above the ground, and at a height h above it.

Let the wire be earthed, i.e., at zero potential, in the earth's vertical electric field, the normal strength of which is F . It is required to find the potential of any point P , distant r from the axis of the wire and at a height z above the ground.

Let W^1 be the image of W , at a depth h below the ground, and let the distance of P from the axis of W^1 be r^1 .

If " a " is very small compared with h and r , the general expression for the potential V of P is :

$$V = \left[z + \left(\frac{h \cdot \log_e \frac{r}{a} - h \cdot \log_e \frac{r^1}{a}}{\log_e \frac{2h}{a}} \right) \right] F \quad (1)$$

If P is now moved to G , that is at ground level immediately below the wire so as to satisfy the condition of the experiment in Series I above then

$$z = 0, \text{ and } r = r^1 = h$$

Thus differentiating (1) above to get the field strength at G , we have

$$\left(\frac{\partial V}{\partial z} \right)_{z=0}^{r=r^1=h} = \left[1 - \frac{2}{\log \frac{2h}{a}} \right] F$$

Substituting the actual experimental conditions, $h = 1$ metre and $a = .6$ mm. we get

$$\left(\frac{\partial V}{\partial z} \right)_{z=0}^{r=r^1=h} = \left[1 - \frac{2}{8.11} \right] F = \left[1 - .25 \right] F = .75 F$$

FIG. 11 (a)—SECTIONAL DIAGRAM OF AN EARTHED WIRE OVER A PLANE SURFACE IN THE EARTH'S ELECTRIC FIELD.

That is the electric field is reduced to three quarters of its normal value, which is what was found by experiment.

Thus the presence of the instrument and observer, about 1 metre high and 8 metres away has no effect on the potential gradient.

Series III—(b) "Lead in" wire removed.—The "lead in" wire from the stretched wire to the Wulf electrometer in the pit was then taken away and the above experiment repeated, with the following results :

	Duration	Potential Gradient (Ground)	Kelvin Water-dropper Electrograph	"Exposure Factor"	Ratio Observer absent Observer present
Observer present ..	Mins. 12	v/m. 301	Volts. 88	3.43	1.01
Observer absent ..	12	309	89	3.47	

The final ratio again shows that the instruments and observer have no effect on potential gradient readings at ground level at 8 metres distance. The mean "exposure factor" has risen, however, from 3.12 with the "lead in" wire present, to 3.45 with the "lead in" wire removed, an increase of about 10 %.

Series IV—Comparison of Potential Gradient at 1 metre and at Ground Level.—In this series simultaneous observations were made of the potential gradient as measured by the Wilson electrometer at ground level, and as measured by a stretched wire and lighted fuse at 1 metre above ground level, the wire being about 15 metres from the pit. The experiment was carried out many times, but only one series of results is shown below in Table VI :—

TABLE VI—POTENTIAL GRADIENT AT GROUND LEVEL AND 1 METRE ABOVE GROUND

Feb. 26th. Time	Potential Gradient		Electrograph	"Exposure Factor"		Ratio Wire Wilson
	Wire	Wilson		Wire	Wilson	
h m m	v/m.	v/m.	Volts.			
15 32-42	197	191	79	2.49	2.42	1.03
15 45-55	274	271	113	2.42	2.40	1.01
h m m						
15 57-16 07	282	278	116	2.43	2.40	1.01
Means 30 min. ..	251	247	103	2.45	2.41	1.02

The final mean ratio from all observations was 1.01. It indicates that for all practical purposes the Wilson instrument at ground level, measuring the charge due to the earth's electric field, gives the same potential gradient as measured by the potential at a point one metre above the ground, although there is a tendency for the latter to be slightly the larger.

Series V—Potential gradient at ground, 1 metre, 1½ metres and 2 metres.—With the wire in the same position as above, simultaneous observations were taken of the potential gradient at ground level in the pit, and by the fuse and stretched wire raised successively to 1, 1½, 2, 2, 1½ and 1 metre above the ground. This order of proceeding was adopted to get the same mean times for the same height, and so eliminate as far as possible any differences due to changes of potential gradient

during the comparisons. The observations were made on four days in April and May, 1927, and the means for all observations are shown below in Table VII :—

TABLE VII—POTENTIAL GRADIENT AT GROUND LEVEL AND IN THE SPACE INTERVAL UP TO 1, $1\frac{1}{2}$ AND 2 METRES ABOVE GROUND

Height above Ground	Duration (Mins.)	Potential Gradient		Ratio Wire Wilson
		Wilson	Wire	
1 metre ..	51	184	183	1.00
$1\frac{1}{2}$ metres ..	56	189	185	0.98
2 metres ..	58	191	184	0.96

Although the observational error is of the order of 2 %, there is the same tendency on all days for the potential gradient to decrease with height from 1 metre to 2 metres. This is not in accord with Norinder's⁸ observations during the summer months.

From the foregoing it is safe to say that for all practical purposes the value of the average potential gradient $\frac{V_1 - V_0}{H_1}$, as measured at Kew by the bamboo rod apparatus is equal to that at ground level F_G , or answering question (1), $F_G = \frac{V_1 - V_0}{H_1}$.

§ 6—METHOD OF USING WILSON ELECTROMETER AT KEW FOR CONDUCTIVITY OBSERVATIONS

Before proceeding to a discussion of the results of the comparisons of the conductivity measured over the tripod and at ground level it should be mentioned that the method of experiment adopted at Kew differs slightly from that described by Wilson⁹, and is chosen to ensure that the working condition of the instrument is always the same whenever a reading of the gold leaf is taken. Briefly it is as follows :—

A—With the compensator fully withdrawn, i.e., in its zero position, and the test plate exposed to the earth's field the test plate system is momentarily earthed. The shielding cover is then replaced, leaving the gold leaf deflected. A reading g_1 is now made, the plate system earthed and the "earth" reading g_0 taken. The difference $g_1 - g_0$ is a measure of the charge Q_1 on the test plate due to the field above it since the field, $F_w = \frac{4\pi Q_1}{A}$ where A is the area of the plate.

B—The earth connection is broken, and the cover removed at a recorded time. By moving the compensator inwards the test plate system is kept at earth potential (indicated by reading g_0) for a period of 5 minutes, during which the ionic air earth current reduces the charge on the test plate. After this interval the cover is replaced, the compensator is returned to its zero position, and a third reading g_2 taken. Then earthing the test plate system gives another zero potential reading g'_0 . The difference $g'_0 - g_2$ is a measure of the change in charge, say, dQ , which has been effected in 5 minutes by the air-earth current i_w , represented by $\left(\frac{dQ}{dt} \times \frac{1}{A}\right)$.

⁸ H. Norinder—"Researches on the height variation of the atmospheric Potential Gradient in the Lowest Layers of the Air"—*Geog. Ann., Stockholm*, 3, 1921, pp. 1-96 and 4, 1922, pp. 116-21.

⁹ Loc. cit., pp. 369-74.

C—Operation A is now repeated, the difference in readings being a measure of the charge Q_2 induced by the earth's electric field $F_w = \frac{4\pi}{A} Q_2$ at the time.

Taking $\frac{1}{2} (F_{w_1} + F_{w_2})$ as the mean electric field strength during the 5 minutes exposure and defining the effective conductivity $\lambda_w = \frac{i_w}{\bar{F}_w}$ in general terms, we get,

$$\lambda_w = \left(\frac{dQ}{dt} \times \frac{1}{A} \right) \div \frac{1}{2} \left(\frac{4\pi Q_1}{A} + \frac{4\pi Q_2}{A} \right) \text{ e.s.u.}$$

$$\text{or } \lambda_w = \frac{1}{2\pi} \times \frac{1}{Q_1 + Q_2} \times \frac{dQ}{dt} \text{ e.s.u., where } dt = 5 \text{ minutes.}$$

Thus λ_w becomes a constant multiple of the ratio of two readings of the gold leaf divided by the time of exposure. The advantage of the method lies in the fact that the compensator is not involved when any readings are taken, thus obviating calibration of the compensator, whose charge is more liable to change during a long comparison, than that of the enclosure around the gold leaf. While the method assumes that the mean of F_{w_1} and F_{w_2} represents the mean potential gradient during the exposure of the test plate it may not do so with a rapidly changing field, but in a comparison with two instruments both would presumably be equally affected. The presence of the observer, however, near the tripod when measuring F_{w_1} and F_{w_2} will reduce these values as compared with the mean value of the electric field during the exposure when he has moved to a safe distance, thus tending to increase the value of λ_w . The question as to what is actually measured by the Wilson electrometer is discussed later—(see page 20).

§ 7—DISCUSSION OF RESULTS

The total duration of the comparisons on different days varied from 20 minutes, the period of a routine observation, to several hours on days suited for long comparisons without deterioration in the insulation of the apparatus. Also in order to decrease the percentage error of measurement of the charge lost by the plate during exposure to the air-earth current, the time of exposure was increased to 10, 20 and on one day to 30 minutes. Half way through the series, to test the effect of site on the conductivity above the tripod, the tripod was moved into the open paddock 15 metres to the south-west of the pit.

Before the pit apparatus was modified, there was only one comparison of the effective conductivities over the tripod and at ground level, in which the observational error was of the same order as those carried out in 1927 with the large pit test plate. On this occasion only one instrument was used, No. 7960. It was exposed first for 20 minutes on the tripod on the lawn (for four 5-minute intervals), then for 40 minutes in the pit (for eight 5-minute intervals) and again for 20 minutes on the tripod in order to get mean values of the conductivity corresponding to the same mean time. The following mean results were obtained :—

$$\begin{array}{l} \text{Effective conductivity at ground level } \lambda_g = 0.46 \text{ ohms}^{-1} \times 10^{-16} \\ \text{,, ,, over the tripod } \lambda_w = 0.40 \text{ ,, } \times \text{ ,,} \\ \text{Ratio } \frac{\lambda_g}{\lambda_w} = 1.15. \end{array}$$

The comparisons with the modified pit apparatus lasted from April 8th to June 14th, 1927. Except on June 2nd, when the wind changed rather suddenly in the afternoon

from west to east, changing atmospheric conditions from clear to hazy, the ratio between the effective conductivities at ground level and over the tripod did not vary decisively during any one day. From day to day, however, as local conditions of haze and mist varied, so the ratio varied, and on June 2nd when local conditions were varying rapidly, so the ratio of effective conductivities changed correspondingly rapidly.

(a) *Two representative days, (i) Steady conditions, (ii) Varying local conditions.*—In order to illustrate the effect of (i) steady clear atmospheric conditions, and (ii) varying local atmospheric conditions, the results of two representative days are given below in detail in Tables VIII and IX, and shown graphically in Figs. 12 and 13. They indicate the consistency to be expected in long observations of this nature with instruments 15 metres apart. The mean values given are for observations lasting twenty minutes. The instruments were interchanged during the experiments, mean values by No. 4011 being shown by circles and those by No. 7960 by crosses in Figs. 12 and 13. Owing to the big difference in magnitude electric fields measured over the tripod are shown on a closer scale than those at ground level.

(i) June 13th represents conditions (i) above. The day was cloudless with a light north-west wind and brilliant sunshine. There was very little atmospheric pollution and electrical conditions were very steady throughout the six hours' observations.

TABLE VIII—CONDUCTIVITY, ELECTRIC FIELD AND AIR-EARTH CURRENT

June 13th, 1927.—Steady clear conditions.

Mean Time	Effective Conductivity			Electric Field			Air-Earth Current Ground	Instrument
	Ground	Tripod	$\frac{\text{Ground}}{\text{Tripod}}$	Ground	Tripod	$\frac{\text{Tripod}}{\text{Ground}}$		
h m	ohms ⁻¹ × 10 ⁻¹⁶	ohms ⁻¹ × 10 ⁻¹⁶		v/m.	v/m.		amps × 10 ⁻¹⁶	
10 13	·25	·21	1·19	480	2795	5·8	1·20	} 7960 (Ground). 4011 (Tripod).
10 34	·25	·20	1·25	510	2940	5·8	1·27	
11 03	·26	·23	1·13	430	2485	5·8	1·12	} 4011 (Ground). 7960 (Tripod).
11 25	·28	·27	1·04	395	2065	5·2	1·11	
11 47	·33	·33	1·00	355	1755	5·0	1·17	} 7960 (Ground). 4011 (Tripod).
12 08	·46	·44	1·05	265	1315	5·0	1·22	
12 41	·60	·55	1·09	175	920	5·3	1·05	} 7960 (Ground). 4011 (Tripod).
13 02	·60	·55	1·09	165	945	5·7	1·00	
13 36	·60	·55	1·09	170	850	5·0	1·02	} 4011 (Ground). 7960 (Tripod).
13 58	·54	·51	1·06	190	960	5·0	1·03	
14 21	·52	·47	1·11	205	1070	5·2	1·07	} 7960 (Ground). 4011 (Tripod).
14 43	·65	·54	1·20	170	995	5·9	1·11	
15 13	·50	·46	1·09	165	895	5·4	0·83	} 7960 (Ground). 4011 (Tripod).
15 34	·45	·43	1·05	185	1040	5·6	0·83	
Means ..	·45	·41	1·10	275	1500	5·3	1·07	

The normal daily decrease in the earth's electric field from 480 v/m. at 10h. to 165 v/m. at 13h. was accompanied by a corresponding increase in conductivity from 0·25 to 0·60 ohms⁻¹ × 10⁻¹⁶, while the air-earth current decreased slightly with the reduction in the field. There was a slight instrumental difference between the instruments, comparison with the Kelvin electrograph showing No. 7960 to be reading lower than No. 4011, but this affects only the electric field strength conversions and not the conductivity, which being derived from a ratio of two readings of the same instrument is independent of the absolute scale value of the instrument. Also, since the electrometers were interchanged to give the same mean time for the final means,

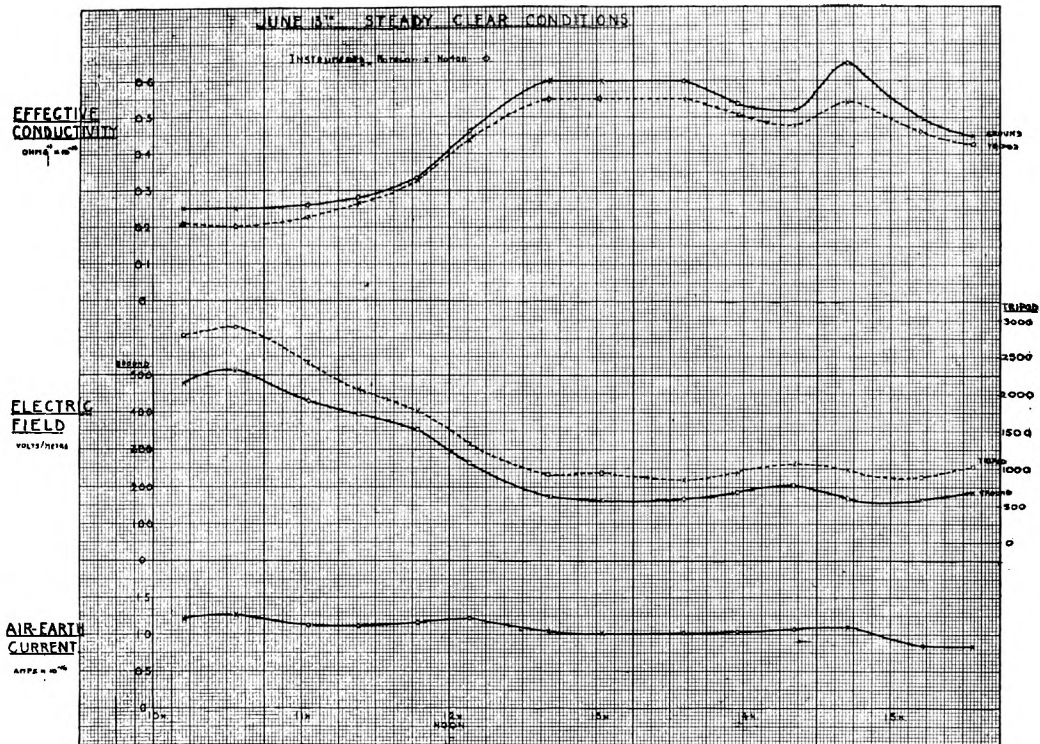


FIG. 12.—EFFECTIVE CONDUCTIVITY ; ELECTRIC FIELD AND AIR-EARTH CURRENT, OVER GROUND AND TRIPOD FOR STEADY CLEAR CONDITIONS.

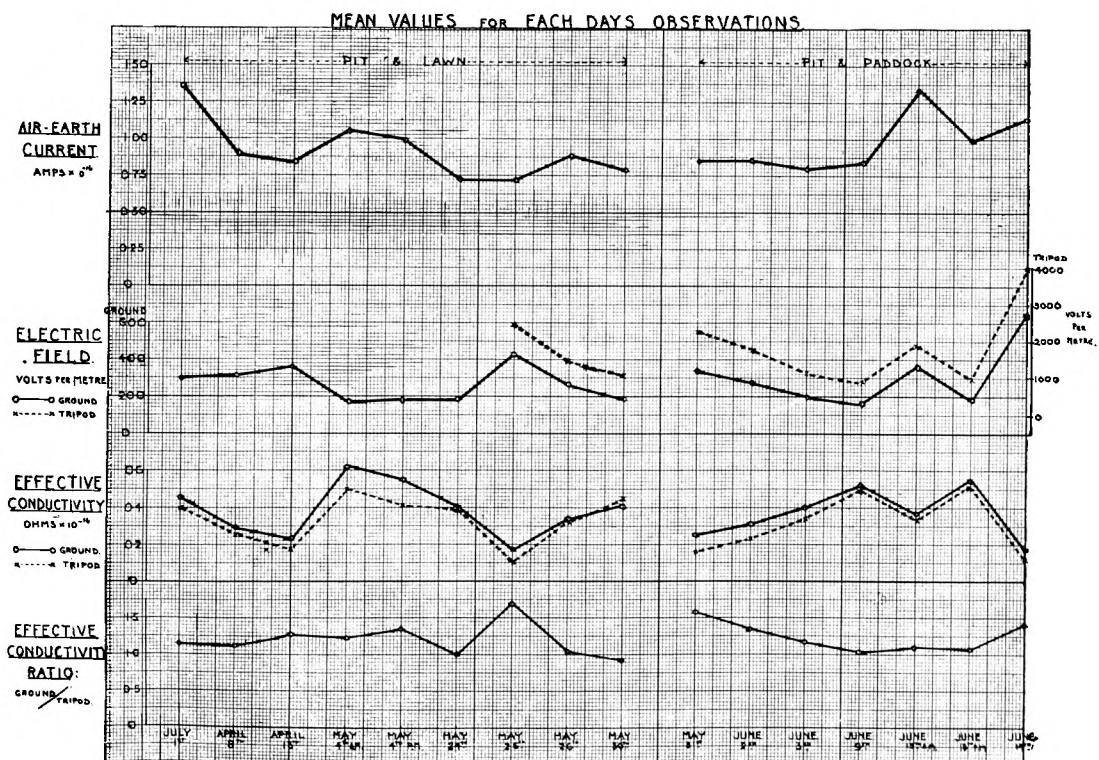


FIG. 14.— AIR EARTH CURRENT ; ELECTRIC FIELD AND EFFECTIVE CONDUCTIVITY RESULTS FROM ALL OBSERVATIONS.

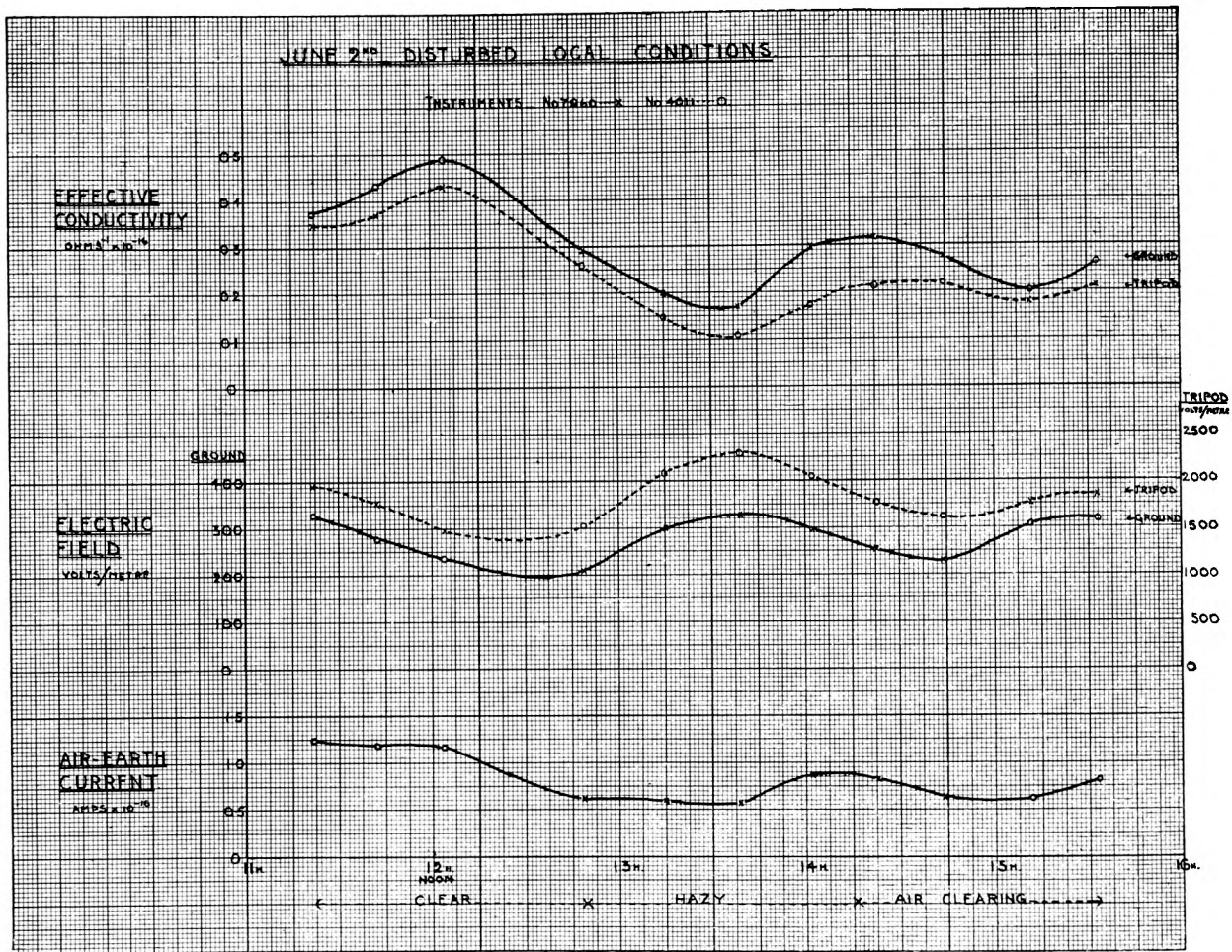


FIG. 13.—EFFECTIVE CONDUCTIVITY; ELECTRIC FIELD AND AIR EARTH CURRENT, OVER GROUND AND TRIPOD FOR DISTURBED LOCAL CONDITIONS.

the mean ratios of the conductivities, 1.10, and the electric fields, 5.3, should not be affected. For fine weather conditions these values indicate the differences introduced by using the Wilson electrometer on a tripod instead of at ground level in the open. In the case of the effective conductivity the error is one of -10 per cent. The mean of the air-earth current during this particular set of observations, $1.07 \text{ amps} \times 10^{-16} \text{ per cm}^2$, is 14 per cent greater than that for the whole series of observations.

(ii) June 2nd is representative of conditions (ii) above. When the experiments were started at 10h. the day was fine, with bright sunshine and a light west wind. About 13h. the wind changed to east and remained light. As generally happens at Kew with such a wind, a smoke cloud was carried over the Observatory from London, and the weather became dull and hazy until about 15h. when the air cleared perceptibly. With the change in wind about 13h. the earth's electric field, which had been decreasing in the normal daily manner, was increased from 210 v/m. to 325 v/m., while the conductivity over the tripod was reduced from .26 to .11 $\text{ohms}^{-1} \times 10^{-16}$, although the conductivity at ground level was reduced by only one third.

TABLE IX—CONDUCTIVITY, ELECTRIC FIELD AND AIR-EARTH CURRENT

June 2nd, 1927.—Disturbed Local Conditions.

Mean Time	Effective Conductivity			Electric Field			Air-Earth Current (Ground)	Instrument
	Ground	Tripod	$\frac{\text{Ground}}{\text{Tripod}}$	Ground	Tripod	$\frac{\text{Tripod}}{\text{Ground}}$		
h m	$\text{ohms}^{-1} \times 10^{-16}$	$\text{ohms}^{-1} \times 10^{-16}$		v/m.	v/m.		$\text{amps} \times 10^{-16}$	
11 22	.37	.35	1.06	330	1955	5.9	1.22	4011 (Ground). 7960 (Tripod).
11 43	.43	.37	1.16	275	1760	6.4	1.18	
12 04	.49	.43	1.14	235	1485	6.3	1.15	
12 49	.29	.26	1.11	210	1510	7.2	0.61	7960 (Ground). 4011 (Tripod).
13 15	.20	.15	1.33	300	2080	6.9	0.60	
13 41	.17	.11	1.54	325	2280	7.0	0.55	
14 02	.30	.17	1.77	295	2040	6.9	0.89	4011 (Ground). 7960 (Tripod).
14 23	.32	.21	1.52	255	1775	7.0	0.82	
14 44	.28	.22	1.27	225	1625	7.2	0.63	
15 12	.20	.18	1.11	305	1755	5.8	0.61	4011 (Ground). 7960 (Tripod).
15 33	.26	.21	1.24	315	1850	5.9	0.82	
Means ..	.30	.24	1.29	280	1830	6.5	0.83	

The conductivity ratio, ground : tripod showed an increase with increase in pollution, such as is shown by the results in general from clear days to polluted days. The ratio of the electric field over the tripod to that at ground level also showed an increase with increase in pollution, but the increase in the field over the tripod was not sufficient to compensate for the deficiency of the effective conductivity, and the air-earth current was not maintained at its former value when the air was clear. The air-earth current at ground level, which was fairly steady at about $1.2 \text{ amps} \times 10^{-16} \text{ per cm}^2$ before the change in wind direction, was reduced to about half its former value by the smoke-laden air, and varied considerably with the clearing of the air later. The mean value, .83 $\text{amps} \times 10^{-16} \text{ per cm}^2$ for $4\frac{1}{2}$ hours of this variable day is 10 per cent less than the mean value obtained from the whole series of observations.

A rather notable feature of Fig. 13 is the lag of about 20 minutes in changes of the earth's electric field after the changes in effective conductivity, if we consider a maximum of the electric field to correspond with a minimum of conductivity. This lag is a question for further investigation.

The daily means from all the observations are summarised in Table X below, and represented graphically in Fig. 14. The mean weather conditions for the period of observation are also added.

TABLE X—MEAN DAILY VALUES FROM ALL OBSERVATIONS

Date	Duration of Observation	Effective Conductivity			Electric Field.			Air-Earth Current	Weather			
		Ground	Tripod	Ground Tripod	Ground	Tripod	Tripod Ground		Wind	Cloud	Sun	Atmosphere
1926	H. M.	Ohms ⁻¹ × 10 ⁻¹⁶	Ohms ⁻¹ × 10 ⁻¹⁶		v/m.	v/m.		Amps × 10 ⁻¹⁶				
Pit and Lawn.	Equal Test Plates.											
July 1st	1 20	·46	·40	1·15	295*			1·36	E. 3.	Fr. Cu. 3	Bright.	
Pit and Lawn.	Modified Test Plate in Pit.											
1927												
April 8th	— 20	·29	·26	1·12	310*			·90	S.W. 2.	A.Cu. } Cu. } 2	Weak.	
April 13th	— 20	·23	·18	1·28	360*			·83	W. 1-2	A.Cu. 7	None.	
May 4th	1 20	·62	·50	1·24	170*			1·05	SSE. 3.	Ci. 6 } Cu. 3 }	Intermittent.	
May 4th	— 20	·55	·41	1·35	180*			·99	SSE. 3.	Ci. 4 } CuNb4 }	Intermittent.	Slight haze.
May 24th	1 0	·40	·40	1·00	180*			·72	WNW. 3.	Ci. Cu 5 } A. Cu. 2 }	Bright.	
May 25th	1 20	·17	·10	1·70	425†	2450	5·8	·72	ENE. 1.	Overcast.	None.	Misty.
May 26th	7 30	·34	·33	1·03	260	1445	5·6	·88	NNE. 3.	Cu. 3.	Bright.	
May 30th	5 0	·41	·45	0·91	190	1060	5·6	·78	ESE. 3.	A. Cu. 1 } Fr. Cu. 4 }	Bright.	
	Means.			1·20			5·7	·86				
Pit and Paddock.	Modified Test Plate in Pit.											
May 31st	1 20	·25	·16	1·56	340	2290	6·7	·85	E. 2.	A. St. 10.	Dull.	Hazy.
June 2nd	4 10	·31	·23	1·34	275	1790	6·5	·85	W. 1.	Ci. St. 3.	Bright, then hazy.	
June 3rd	2 0	·40	·34	1·16	200	1125	5·6	·80	NNW. 2	Ci. Cu } 3 Ci. St. } 3	Sun through Ci. St.	
June 9th	4 0	·52	·50	1·04	160	885	5·5	·83	NW. 3.	Cu. } 6 St. Cu. } 6	Intermittent.	
June 13th	2 40	·37	·34	1·10	360	1900	5·3	1·33	NW. 1.	None.	Brilliant.	
June 13th	2 40	·55	·52	1·07	180	955	5·3	·99	NW. 1.	None.	Brilliant.	
June 14th	— 40	·17	·12	1·40	655	4000	6·1	1·13	NE. 3.	A. Cu. 8.	Sun through thick haze.	
	Means.			1·24			5·9	·97				
Final Means				1·21			5·8	·94				

* Values derived from Kelvin electrograms by application of appropriate "exposure factor."

† Values of electric field at ground level corrected for "condensor effect" in pit apparatus.

(b) *Effective electrical conductivity of the air.*—From the above table, if we regard the ratio of the conductivities of the air over the ground and over the tripod on any day as being representative of the electrical conditions on that day, and give equal weight to each day on that account, the trifling differences between the comparisons carried out on the lawn site and in the paddock show the two sites to be practically identical as far as the tripod instrument is concerned. On this assumption the final mean ratio, ground: tripod, from all days is 1·21. This indicates that during the summer season the method of measuring the electrical conductivity of the air by the Wilson electrometer, 130 cm. above ground level results in a reduced value, on the average ($\frac{21}{100}$) 17·5 per cent less than that at ground level in the open. The ratio from day to day varies considerably according to the state of the atmosphere. On days of bright sunshine with winds from a westerly direction it is considerably smaller than on days when there is haze or mist, carried towards the Observatory from London by easterly winds which pollute the atmosphere.

Even in the summer months under discussion the ratio rose to 1.4 on June 14th, 1.6 on May 31st and to 1.7 on May 25th, representing an increase of roughly one third above the final mean ratio. Thus, as Kew is unquestionably a place where atmospheric pollution affects electrical conditions to a big extent it is only natural to suppose that in the dirtier equinoctial and winter months the ratio of the effective conductivities at ground level and over the tripod would be considerably greater than the final mean of 1.21, as on the three days quoted. Hence, assuming the same potential gradient at 1 metre as at ground level, since air-earth current values are dependent on those of effective conductivity, the natural inference is that winter values of air-earth current published for Kew require a large plus correction. It is hoped to decide this point by introducing some warming and drying arrangement into the pit, so that comparisons may be carried out throughout the whole year without fear of deterioration of the insulation of the instruments.

(c) *Electric field measurements.*—The comparisons of the earth's electric field above the tripod and at ground level, as measured by the induced charge on the Wilson electrometer test plate, after standardization in the artificial field, show that

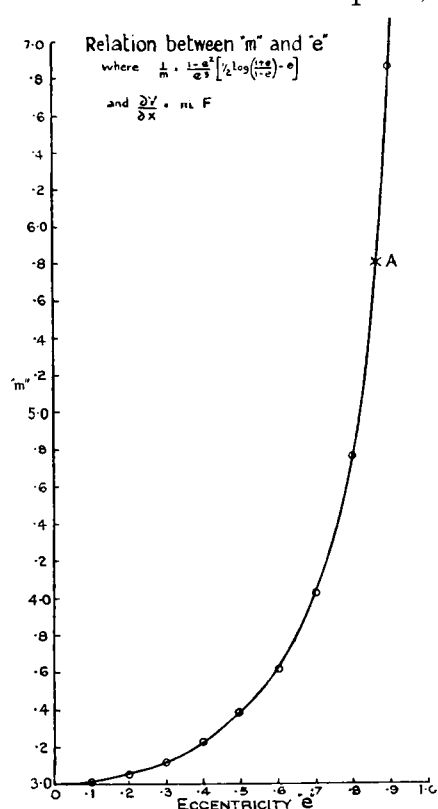


FIG. 15.—GRAPH SHOWING RELATION BETWEEN ECCENTRICITY e OF AN ELLIPSOID OF ROTATION AND THE VARIABLE m .

the normal undisturbed field is increased nearly six fold just above the tripod test plate by the presence of the instrument and observer.

It is interesting to note that the observed increase is almost identical with that obtained from a theoretical consideration of the problem. By the application of a well-known theorem,¹⁰ it can be shown that the potential gradient $\frac{\delta V}{\delta x}$, at

the vertex of an ellipsoid of rotation in a uniform electrostatic field of strength F is mF where $\frac{1}{m} = \frac{1 - e^2}{e^3} \left[\frac{1}{2} \log \frac{1 + e}{1 - e} - e \right]$, e being the eccentricity of the ellipsoid. Fig. 15 shows graphically the relation of m to e . The mean ratio of the earth's electric field over the tripod to that at ground level for all the observations was 5.8. Referring to the curve, Fig. 15, the eccentricity e of an ellipsoid of rotation corresponding with a 5.8-fold increase of the normal field would be .86 (as shown at A). For this value of e the semi-major axis is equal to the diameter, which is approximately the dimensional condition supplied by the Wilson electrometer on the tripod when the observer is present, as shown in Fig. 1.

The ratio of the field above the tripod to that at ground level is more consistent from day to day than the ratio of the conductivities at the two places. When the atmosphere is quite clear as on June 13th, the ratio is apparently independent of the strength of the field. There is, however, a general tendency for the ratio to increase with the increase in the earth's electric field, when the increase is associated with haze or mist. Under these conditions it has been noted that the conductivity is everywhere reduced, but more over the tripod than on the ground, thus the increase in potential over the tripod cannot be proportional to the decrease of the conductivity, and so keep the current constant in the two places. It is difficult to give any clear

¹⁰ J. H. Jeans—"Electricity and Magnetism," Cambridge, 1908—p. 249—Equation (216).

explanation of the complicated ionic changes that must be going on in highly polluted air which is in motion, but it is probable that in the strong electric fields met with over the tripod test plate, the saturation point in the air-earth current is often reached, which would account for the reduced value of i_w and thus for $\lambda_w = \frac{i_w}{F_w}$

From the theoretical standpoint it is difficult to see how the shape of the ellipsoid of rotation, enclosing instrument and observer, could change with a change in the normal field, but the problem is not purely electrostatic, and its solution might have to be sought by the introduction of a free volume charge with increase of the field due to increased pollution. On calm days with a polluted atmosphere, the formation of a free negative charge bound to large ions near the ground is quite possible, owing to the abstraction of the small positive ions into the ground by the earth's field. Moreover, the effect must be widespread and not confined to the small space just above the tripod, because the method of measuring the field by the Wilson electrometer entails violent disturbance of the air near the test plate, when the test plate is covered and uncovered.

(d) *Air-earth current*.—It has been shown that the effective conductivity over the tripod $\lambda_w = \frac{i_w}{F_w}$ is smaller than at ground level, $\lambda_g = \frac{i_g}{F_g}$ by amounts varying from 10 % on fine clear days, to 70 % on dull, hazy and misty days, the mean difference in summer being 17.5 %. Also that the earth's electric field F_g in the open paddock is greater than that on the lawn, $\frac{V_l - V_o}{H_l}$ by 13 %. Thus on the average published values of the air-earth current for Kew, obtained from the product of the effective conductivity over the tripod and the electric field over the lawn are too small by $\left[\left(117.5 \times \frac{113}{100} \right) - 100 \right] = 33 \%$. From the foregoing series of observations the final mean of the air-earth current at ground level, i_g , was $0.94 \text{ amps} \times 10^{-16} \text{ per cm}^2$. Had it been obtained by the normal routine method, i.e., i_w , it would have been $0.71 \times 10^{-16} \text{ amps. per cm}^2$, which is very similar to the mean values from the months of April, May and June (the period under review), for the last few years. These mean values in $\text{amps.} \times 10^{-16} \text{ per cm}^2$ are: 0.75 (1927), 0.74 (1926), 0.98 (1925), 0.88 (1924), 0.76 (1923), 0.82 (1922) and 0.79 (1921).

As will be seen, however, from the following values, the normal published air-earth current at Kew is much smaller than that at other European stations typified by:

- (i) ¹¹Göttingen—(Gerdien, 1906)— $i = 2.7 \text{ amps.} \times 10^{-16} \text{ per cm}^2$.
- (ii) ¹²Potsdam—(Kähler, 1910—1911)— $i = 2.37$ „ „
- (iii) ¹³Davos—(Dorno, 1909—1910)— $i = 1.71$ „ „

and the difference in magnitude requires explanation.

From the theory of the method of using the Wilson electrometer at Kew, it is obvious that at ground level what is measured during the exposure of the test plate is the reduction of the induced negative charge on the plate by an influx of positive ions brought to the plate by the downward ionic current, that is the positive conduction current, usually denoted by $\lambda_+ F$. Also the electric field F is measured before and after the exposure *by the same instrument*, thus the quotient of the positive conduction current and the electric field $\frac{\lambda_+ F}{F}$ gives us λ_+ , and not $(\lambda_+ + \lambda_-)$

¹¹ Gerdien—*Göttingen Nachr. Ges. Wiss.*, 1907.

¹² K. Kähler—loc. cit., pp. xxv.

¹³ C. Dorno—*Studie über Licht und Luft des Hochgebirges*—Vieweg & Sohn (1911).

which is the usual expression for the conductivity. Now as the difference of the measurements of the effective conductivity of the air between the electrometer on the tripod and at ground level is so small when the air is homogeneous near the ground, it follows that the same phenomenon is recorded over the tripod test plate as over the ground test plate. Thus the conductivity measured at Kew, which has been named the effective conductivity, and defined as $\lambda_w = \frac{i_w}{F_w}$ is solely the positive conductivity, universally defined as λ_+ , and the derived air-earth current, $i = \lambda_w \times \frac{V_1 - V_0}{H}$ is the positive conduction current, universally given by $i_+ = \lambda_+ F$.

The continental stations quoted above measure λ_+ , λ_- and F separately, and the published results of air-earth current refer to the total current $i = (\lambda_+ + \lambda_-) F$. The ratios of $\lambda_+ : \lambda_-$ at Göttingen, Potsdam and Davos are 0.98, 1.16 and 1.13 respectively. Thus, applying these ratios to the total air-earth current values quoted, we get for the positive conduction current $i_+ = \lambda_+ F$ at the three stations 1.34, 1.27 and 0.91 amps. $\times 10^{-16}$ per cm². respectively. These figures approximate much more closely to the mean obtained in the foregoing experiments, viz., 0.94 amps. $\times 10^{-16}$ per cm².

This view of the electrometer is held by other observers, notably Lutz¹⁴ and Lautner, who use the Wilson instrument, or an adaption of it, for the measurement of the electrical conductivity of the air. Thus if the value of the ratio $\lambda_+ : \lambda_-$ for stations giving the total air-earth current is not known, since λ_+ is almost equal to λ_- , the values of the air-earth current from these other stations should be halved to make them comparable with Kew values.

The Göttingen figures quoted above are derived from the Gerdien aspiration apparatus, while those from Potsdam and Davos are from continuous or quasi-continuous records using the Schering method. In the Gerdien method, air is aspirated through a cylindrical tube, 16 cm. diameter and 56 cm. long, along the axis of which, fitted symmetrically in the outer tube is an insulated charged rod, 24 cm. long and 1.45 cm. diameter. The inner rod is charged to between 150 and 200 volts, and the loss of charge, due to the impinging of ions of sign opposite to that on the rod, is measured by a Wulf electrometer connected to the rod. The instrument is portable and can be used at any convenient height above ground level.

According to the theory¹⁵ of the instrument, so long as the velocity of the air stream does not fall below the minimum at which saturation currents are established, the number of ions reaching the charged rod is independent of the velocity of the air stream, and only those ions are caught which have sufficient velocity to carry them across the space to the rod before they are carried past it.

The aspiration experiment takes 10 minutes and an experiment is then done to determine the correction for leakage in the insulation of the instrument. The conductivity of the air is calculated from the capacity and dimensions of the apparatus, the fall in potential of the charged rod during the period of aspiration, and the time of aspiration.

By charging the inner rod alternately negatively and positively, the conductivities λ_+ and λ_- for positive and negative ions are obtained. Then simultaneous observations of the earth's electric field F enable the conduction current $(\lambda_+ + \lambda_-)F$ to be determined.

¹⁴ C. W. Lutz—"Luftelektrische Messungen am Erdmagnetischen Observatorium (Sternwarte)—München. Sitz Ber. Akad. Wiss., 1911, pp. 305-60.

¹⁵ Gerdien—*Terr. Mag. Washington D.C.*, 10, 1905, pp. 69-71.

In the Schering method two insulated wires 20 metres long are stretched horizontally one above the other, 1 metre apart, the lower one being $\frac{1}{2}$ metre above the ground. The wires are enveloped at a distance of $\frac{1}{2}$ metre by open-mesh, blackened wire netting which is earth connected. By connecting momentarily with the poles of a battery the wires are charged to +220 volts and -220 volts respectively. The loss in potential of the wires due to attracted ions from the air, of sign opposite to that of the charge on the wires, is then measured by means of a Benndorf electrograph. The experiment takes about 10 minutes, if desired it can be repeated, the wires being charged in the opposite way. From the capacity and dimensions of the apparatus, the loss of potential, and the time taken for this loss, simultaneous values of λ_+ and λ_- are calculated. The strength of the earth's electric field F is recorded on another Benndorf electrograph, and thus the ionic conduction current $(\lambda_+ + \lambda_-) F$ is obtained.

There seems to be no doubt that by both the above methods and by the Wilson instrument at ground level two definite physical quantities are measured, but these two quantities are not one and the same thing.

Considering the question in the light of the results obtained in the pit at ground level, let us take a vertical column of air AB (Fig. 16) of 1 sq. cm. cross section extending from the ground λ to 1 metre above it at B. Speaking in general terms, let us call the normal value of the earth's electric field F , the conductivities due to positive and negative ions λ_+ and λ_- respectively. In the foregoing experiments we have demonstrated two things:—

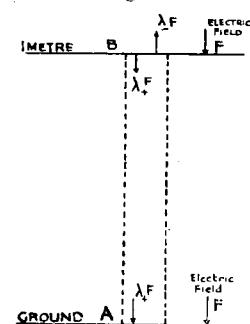


FIG. 16. - DIAGRAM ILLUSTRATING RELATION OF AIR-EARTH CURRENT AT GROUND LEVEL AND AT 1 METRE ABOVE IT.

- (i.) That the electric field F at ground level is the same as 1 metre above the ground. (Thus in the column A B there must be the same distribution of positive and negative ions per unit volume throughout.)
- (ii.) That at the ground surface only the positive conduction current $\lambda_+ F$ enters the ground.

The ionic conduction current across the top of the column at B will be $\lambda_+ F$ downwards and $\lambda_- F$ upwards. That is, each second, a positive charge $\lambda_+ F$ enters the column, and a negative charge $\lambda_- F$ leaves the column, which is equivalent to a total positive charge of $(\lambda_+ F + \lambda_- F)$ entering the top of the column.

At A on the ground the conduction current is $\lambda_+ F$ downwards, that is a positive charge $\lambda_+ F$ flows out of the column into the ground each second, but no negative charge into it. Hence from the actions at the top and base of the column the increase in positive charge per unit time in the column is $(\lambda_+ F + \lambda_- F - \lambda_+ F) = \lambda_- F$. Now if this increase in the positive charge in the column actually occurred, the value of the electric field below B would rapidly increase. But we have shown that the field below B remains uniform, therefore there must be some agency which counteracts the accumulation of positive charge in the column, equalising the distribution of positive and negative ions throughout.

The problem has not been solved in the present investigation, but it is believed that turbulence in the air would be sufficient to prevent an accumulation of positive charge in the column by carrying a positive conduction current of magnitude $\lambda_- F$ upwards against the electric field, and it is hoped to test this belief experimentally in the near future.

In any case the Wilson electrometer at ground level does measure something which is actually occurring in Nature immediately above its test plate, undisturbed by any effects produced by apparatus or observer above the ground, and for this reason its use in this way is to be widely encouraged.

§ 8—CONCLUSIONS

The general conclusions from the foregoing experiments referring to the Wilson electrometer used on a tripod 130 cm. above ground level, with the method adopted at Kew for measuring the electrical conductivity of the air are :—

- (i.) The results as a whole show that the method is reliable.
- (ii.) The effective conductivity of the air $\frac{i_w}{F_w}$ over the tripod compared with $\frac{i_g}{F_g}$ at ground level depends on the meteorological state of the atmosphere. On fine clear days it is too small by 10 per cent, and on dull, hazy or misty days it is too small by anything from 10 per cent to 70 per cent. A mean from all results shows that $\frac{i_w}{F_w}$ is 17.5 per cent less than $\frac{i_g}{F_g}$.
- (iii.) The average value of the earth's electric field up to 1 metre above the ground (F) in the open is greater than that on the lawn $\frac{V_1 - V_0}{H_1}$ by 13 per cent.
- (iv.) The earth's electric field just above the tripod test plate, 130 cm. above ground level, is increased to about six times the normal undisturbed field by the presence of the instrument and observer.
- (v.) During varying atmospheric conditions involving changes in the ionic content of the air, the electric field changes lag behind the conductivity changes, as would be expected if the current flows downward from above.
- (vi.) When obtained from the product of the effective conductivity and the electric field, the air-earth current as published at Kew is too small for the reasons stated in (ii.) and (iii.) above. On the average in summer the values are too small by 33 per cent.
- (vii.) In general, during the summer daytime the air-earth current is fairly steady varying about 15 per cent on either side of a mean of 0.94×10^{-16} amps. per cm^2 .
- (viii.) The view is expressed that the Wilson electrometer measures only the conductivity due to positive ions, λ_+ , and therefore published values of air-earth current (although small owing to the undoubted polluted atmosphere of the place), represent only the positive conduction current ($\lambda_+ F$). This fact should always be borne in mind when comparisons are made with other stations which give the air-earth current as $(\lambda_+ + \lambda_-) F$.

I am indebted to Dr. G. C. Simpson, C.B., F.R.S., Director, Meteorological Office, for his continued interest in the experiments, to Dr. F. J. W. Whipple, Superintendent, Kew Observatory, for his suggestions in the discussion of the results and to Mr. H. L. Wright, M.A., Kew Observatory, for his assistance with the simultaneous observational work.

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