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MEASUREMENT OF GROUND CONSTANTS

BY

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HORIZONTAL POLARIZATION

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ABSTRACT

This report covers the research undertaken in measuring conductivity and dielectric constant of the ground at radio frequencies by using a horizontally polarized wave (set up by a local elevated transmitter) and a loop direction finder arranged to indicate vertical angles. There are described and shown two sets of transmitting and receiving apparatus which were used, and the sites for which the ground constants were measured. Included as an appendix is a brief digest of methods and results obtained by others, during the last decade, for the measurement of ground constants.

Most of the work involved development of method rather than taking and reporting of a large number of ground conductivity measurements.

However, two sets of measurements made at 7 megacycles showed:

(a) For a site consisting of 8 feet of damp silty clay below a thin surface gravel and above a pea-size wet gravel, using a calibrated Model OF field strength meter as detector-amplifier:

$$\begin{aligned}\text{Conductivity } \sigma &= 1.5 \pm 0.07 \times 10^8 \text{ esu} \\ \text{Dielectric Constant } K &= 10 \pm 1\end{aligned}$$

(b) For a site consisting of a lenticular layer of damp silty clay about 1 foot thick above a pea-size wet gravel of unknown thickness the ground constants measured using an NC-100 receiver as the detector amplifier:

$$\begin{aligned}\sigma &= 1.7 \pm 0.17 \times 10^8 \text{ esu} \\ K &= 5 \pm 1\end{aligned}$$

These tests indicate that ground constants can be measured accurately on sites physically suitable for direction finding (i.e., level ground, free of trees, and a space of suitable size) provided that:

(a) The measurements are made above 5 megacycles and below about 30 megacycles. For sites to be used at lower frequencies than suggested, the strata at the site not effectively penetrated by the higher frequencies (but effectively penetrated by the lower ones) can be examined for their properties, perhaps, where they outcrop under conditions suitable for measurement.

(b) The near-surface strata should be nearly parallel with the surface and be free of faults, dikes or other igneous intrusions, and other discontinuities in general such as depositional material filling depressions eroded in the bed strata. Such conditions would be indicated by the site having different values of ground constants for different traverses over the surface being investigated.

The measurement of ground constants at about 7 megacycles can be made successfully with either of the two sets of apparatus herein described; however, further experimental work to determine the limits of applicability in frequency range, and developmental work in design and construction of light, easily-portable equipment for field use seems desirable.

AUTHORIZATION

1. The authorization for this research problem is:
 - (a) Bureau of Ships letter, reference (a), authorizing the formation of a Direction Finding Site Factors Board.
 - (b) Upon termination of the duties of this board by direction of the Bureau of Ships in September 1943, the project was continued under Bureau of Ships letter, reference (b).

STATEMENT OF PROBLEM

2. The problem assigned was:
 - (a) To perfect a method for measuring the conductivity σ and the dielectric constant K of the ground by means of horizontally polarized electromagnetic waves; these waves being produced by an elevated, local transmitter and received by a loop antenna and associated indicated apparatus.
 - (b) To design equipment that can be used to measure the ground constants and thereby give a quantitative estimate of the suitability of a site for a direction finder station.
 - (c) That the equipment should be simple enough to permit operation by inexperienced personnel.

KNOWN FACTS BEARING ON THE PROBLEM

3. Many methods, to determine one or both of the electrical

ground constants, σ and K , have been used, to various degrees of accuracy, which may be classified as follows: Direct current, commutated direct current, audio frequency currents, radio wave attenuation, wave tilt (vertical polarization), buried Lecher wires, wave reflection and interference, and sampling using a soil condenser. (For more extended discussion of these methods, see Appendix).

4. SMITH-ROSE

Extensive examination of the effects of moisture content, frequency, and temperature on the electrical properties of soil samples have been carried out by Smith-Rose (References (c) and (d)) for controlled conditions using a soil condenser. A summary of the results of these examinations are as follows:

(a) Moisture Content

The conductivity and dielectric constant varied widely with moisture content (Figures 2 and 4), as for example, at 1.2 megacycles σ ranged from 10^5 to about 2×10^8 esu and K from 3 or 4 to 30 or 50 for dry to normally moist samples. However, for normally moist earth samples (16-30% moisture) the variation was much less extreme, as for example at Site I, σ varied from 0.8 to 1.4×10^8 and apparent K from 27 to 36.

(b) Frequency

The conductivity increased with frequency, although the change was less for moist than with dry samples (Figure 1). At one time (1933) it was thought the conductivity might increase greatly in the very high frequency range (VHF), as indicated in Figure 5, but in later tests by Smith-Rose (references (e) and (f)) and McPetrie and Saxton (reference (g)) it was shown that the rise was at most not more than 5 or 10 times the d-c value, in this range. For moist soil the dielectric constant decreased, with an increase in frequency, toward a limiting value (Figures 3 and 5), but for dry soil the change with frequency was very small for the medium frequency and high frequency range.

(c) Temperature

At 20°C the temperature coefficient for conductivity was about 2.3% per degree Centigrade (Figure 7 and Table 1 on same page) and the effect of temperature (above 0°C) on the dielectric constant was negligible (Figure 6). It is to be noted that for both conductivity and dielectric constant,

there was a sharp break in continuity at the freezing point of water. (See Appendix, paragraph 30(a)5, footnote)

(d) Integral Effects of these Variations

For the integral effect of these variations it was found that:

(1) At the depth of a foot the normal moisture condition was found to prevail throughout the year under the severest conditions of drought, and even the surface soil quickly drained to a normal moisture content after a rain for land in an open field near the National Physical Laboratory.

(2) For England, at least, there is an average 20°C diurnal temperature change producing a 1.4°C change at a depth of one foot, and the 30°C seasonal change gives a 20°C change at 3 feet and an 0.3°C change at 30 feet.

(3) Assuming average earth values of $\sigma = 10^8$ esu and $K = 20$, the depth of "effective" penetration (depth at which the induced r-f current had reduced to 10% of its surface value) was calculated to be:

<u>Kc</u>	<u>Depth (meters)</u>
200	25
1000	12
10,000	5

From the sampling data (Table II) the effective depths (for 10 megacycles) were calculated as 1.5 meters at Rugby and 4 at Baldock.

5. BARFIELD

Barfield (reference (h) and Appendix 34) made wave tilt measurements of the ground constants extending over a long period of time to determine integrated seasonal effect, and concluded that there was no pronounced change for these ground values, at least for the low lying cultivated ground of England, for radio frequencies below 40 megacycles. However, Barfield used graphical methods of evaluating the ground constants, and his measurements seemed to lack the accuracy and precision of the soil condenser method. Also, he failed to find any variation of the ground constants with frequency, such as Smith-Rose did, probably for the same reason.

6. DIAMOND, LIFSCHUTZ AND POAST

Page 127 of reference (i) recommends that cables entering a direction finding station be buried to certain depths,

according to the conductivity of the soil, so as to have a negligible effect on bearings, as shown in the table below: (Negligible effect is taken to be that for which the field strength of the reradiation is equal to 10% of the incident wave.)

Ground Conductivity (esu)		Recommended Depth (feet)
4.5×10^7	Average Land	20
9.0×10^7		10
1.8×10^8	Good Conducting Land	5
4.5×10^8		2
4.5×10^{10}	Sea Water	1/2

Note: σ in electrostatic units (esu) = 9×10^{20} σ in electromagnetic units (emu)

For poorly conducting soil, it would be necessary to bury cables to a considerably greater depth to reduce re-radiation to a negligible value. For example, for sandy land, with a σ of 9.0×10^6 esu, the cables would have to be buried to 100 foot depth.

7. GROSZKOPF AND VOGT

Groszkopf and Vogt (reference (s); Appendix 42) observed that for a highly conductive substratum not too deeply buried beneath a poorly conducting surface stratum, the effective conductivity of the site increased sharply as the radio frequency was reduced to a low enough value that a substantial part of the ground current induced by the passing wave could be borne by the more conductive substratum.

8. The method here outlined for the measurement of ground constants is based upon the deformation of the free-space electromagnetic wave in passing over the surface of a medium of finite conductivity and with dielectric constant greater than for free space. The theory of such propagation has been vigorously pursued for half a century, and is not satisfactorily completed yet. In consideration of other methods of determining ground constants (as described in Appendix), which use wave propagation theory, the wave propagation analysis used in each case should be associated with the results thereby obtained; a check in values got by methods not subject to wave propagation analysis (as notably the soil condenser method) is most gratifying. A brief historical survey (reference (j)) of wave propagation analysis follows:

(a) ZENNECK (Ann. Physik 23 (1907) p 846) showed that an electromagnetic wave with a forward tilt, following a plane

earth of finite conductivity, and attenuated in a vertical as well as in a horizontal direction is compatible with Maxwell's equations, and showed that such a wave would explain many observed phenomena in radio transmission (although there was no proof at that time that radio antennae set up such a wave).

(b) SOMMERFELD (Ann. Physik 28 (1909) p 665) undertook to complete Ze-neck's work, and identified the surface wave component of the total field.

(c) WEHL (Ann. Physik 60 (1919) p 481), questioning the work of Ze-neck and Sommerfeld, made a new derivation consisting of a superposition of a surface wave on a space wave.

(d) BURROWS (Nature, 15 August 1936; IRE 25 (1937) p 219) showed that the two solutions differed in just the surface wave expression, and careful measurements by him supported Wehl's solution.

(e) Although the matter is far from closed, the analysis of Sommerfeld and charts of Rolf (based on Sommerfeld's analysis) do not hold for ultra-high frequencies where the displacement current is appreciable, whereas the formulae of van der Pol, Niessen, Burrows, Strutt and Norton, as extensions of Wehl's analysis, are in agreement with experimental observations.

THEORETICAL CONSIDERATIONS

9. Briefly, the graph and equations used in the evaluation of ground constants, conductivity σ and dielectric constant K , are obtained as follows:

(a) NORTON (reference (k)) obtained for the field of a vertical magnetic dipole above a finitely conducting plane earth (at a distance greater than a wavelength from the transmitter) the equation:

$$H_{//} = H_{om} \left\{ \cos \psi_1 \frac{e^{-ikr_1}}{r_1} \left[\psi_1 \right] + \cos \psi_2 R_1 \frac{e^{-ikr_2}}{r_2} \psi_2 \right. \\ \left. + \cos \psi_2 (1 - R_1) f(P_m, B_m) \left[\cos \psi_2 \frac{k}{\sqrt{n^2 - \cos^2 \psi_2}} \frac{d}{2} \right] \frac{e^{-i(\phi + kr_2)}}{r_2} \right\} \quad (1)$$

where H_{om} is the value of the magnetic radiation field at a unit distance from a vertical magnetic dipole in free space

ψ_1 is the angle between the horizontal and the direct ray to the given point in the field

ψ_2 is the angle between horizontal and the reflected ray

i is $\sqrt{-1}$

e is 2.718...

k is $\frac{2\pi}{\lambda}$

$\underline{\psi}_1 = \cos \psi_1 \underline{k} + \sin \psi_1 \underline{d}$ a unit vector, the $\underline{d} - \underline{k}$ plane being taken as the plane of incidence with $\underline{k}$ vertical and $\underline{d}$ horizontal

$\underline{\psi}_2 = \cos \psi_2 \underline{k} - \sin \psi_2 \underline{d}$

r_1 is the distance from dipole to chosen field point

r_2 is total distance from dipole to chosen field point via reflection point from the ground

R_1 is the reflection coefficient.

By Fresnel's equation $E_{1r} = R_1 E_{1d}$ where E_{1r} is the electric field strength vector of the reflected ray normal to the plane of incidence, and E_{1d} is the electric field strength vector of the direct ray in the plane perpendicular to the plane of incidence.

$$R_1 = \frac{\sin \psi - \sqrt{n^2 - \cos^2 \psi}}{\sin \psi + \sqrt{n^2 - \cos^2 \psi}}$$

where $n^2 = K + iX$ is the complex index of refraction, composed of dielectric constant K and $X = 1.797 \times 10^{15} \sigma_{\text{emu}}/\text{Mc}$

$$f(P_m, B_m) e^{i\phi} = 1 + i e^{-P_1} \sqrt{\pi P_1} \operatorname{erfc}(-i\sqrt{P_1})$$

the surface wave attenuation function, where

$$P_1 = P_m e^{iB_m} = \frac{ikr_2}{2 \cos^2 \psi_2} \left[\sin \psi_2 + \sqrt{n^2 - \cos^2 \psi_2} \right]^2$$

the wave surface attenuation function can be solved graphically from Plates 9 and 10 of reference (1) from P (P_m) and B (B_m). $90^\circ \leq B_m \leq 180^\circ$

$$\text{For } d > \lambda \text{ and } |n^2| > 10 \quad f(P_m, B_m) e^{i\phi} = \frac{e^{iB_m}}{2 P_m}$$

(b) For the field intensity at the surface of the ground, $r_2 = r_1$ and $\psi_1 = \psi_2 = \psi$

$$H_{//} = H_{om} \cos \psi \left[(1 - R_1) f(P_m, B_m) e^{i\phi} + (1 + R_1) \left[\cos \psi \underline{k} + \sqrt{n^2 - \cos^2 \psi} \underline{d} \right] \frac{e^{ikr_1}}{r_1} \right] \quad (2)$$

which can be written as:

$$H_{//} = H_{//d} \left[\frac{d + \frac{\cos \psi}{\sqrt{n^2 - \cos^2 \psi}} k}{\sqrt{n^2 - \cos^2 \psi}} \right] e^{i\omega t} \quad (3)$$

Substituting in

$$ae^{-ib} = \frac{\cos \psi}{n^2 - \cos^2 \psi} = \frac{1}{K' - 1 + jX'} \quad (4)$$

where

$$\begin{aligned} K' &= K/\cos^2 \psi \\ X' &= X/\cos^2 \psi \end{aligned}$$

then

$$H_{//} = H_{//d} \left[d \cos \omega t + \frac{k}{a} \cos (\omega t + b) \right] \quad (5)$$

Hence this vector magnetic field from a vertical magnetic dipole rotates in an ellipse in the plane of incidence. By the properties of the ellipse, the magnetic vector reaches its maximum value for $\omega t = -S$ and its minimum extension for $\omega t = \pi/2 - S$

where

$$S = \frac{1}{2T} \left[\sqrt{1 + 4T^2} - 1 \right] \quad (6)$$

$$T = \frac{a^2 \sin 2b}{2 [1 + a^2 \cos 2b]} \quad (7)$$

$$\begin{aligned} \text{and } \tan \theta &= a [\cos b + \sin b \tan S] \\ r &= \tan S \cos \theta \end{aligned} \quad \begin{aligned} (8) \\ (9) \end{aligned}$$

the measurable properties of the magnetic field ellipse of polarization being θ , the angle between the major axis and the earth plane, and r , the ratio of minor axis to major axis (see paragraph 14c). To make quick evaluations of K' and X' , Norton drew up Figure 8, (reference (k), (l), and (i)) expressing θ and r in parameters of $K' = 5, 10, 20$ and 80 . The key to reading Figure 8 is that for both θ and r curves, a common value of K' and of X' must be picked - i.e., having a value of θ , four values (possibly) will be found on the $\theta - K'$ curves; now try each intercept in turn to see which lies closest to a vertical line through the r intercept with the $r - K'$ curves. Then second approximations must be made until r and θ define unique values of K' and X' . The mathematical analysis was based on the assumption that the field

was being measured at the earth's surface; hence ψ' is re-defined as in Figure 8 for the last equations, and the height of the receiver is restricted to be less than $1/20$ of a wavelength above the earth's surface. Then

$$K = K' \cos 2\psi' \quad (10)$$

$$\sigma = X' \cos 2\psi' f_{Mc} 5.5638 \times 10^{-16} \text{ emu or} \quad (11a)$$

$$\sigma = X' \cos 2\psi' f_{Mc} 5.007 \times 10^5 \text{ esu} \quad (11b)$$

(c) For high frequencies, $X' \ll (K' - 1)$, and the equations reduce to:

$$K' = \frac{1}{\sin^2 \theta} \quad (12)$$

$$X' = \frac{2r}{\sin^2 \theta \tan \theta} \quad (13)$$

(d) For low frequencies, $X' \gg (K' - 1)$, and

$$X' \approx \frac{1}{2 \tan^2 \theta} = \frac{1}{2r^2} \quad (14)$$

$$K \text{ is indeterminate} \quad (15)$$

(e) For calculation of data it is desirable to have an analytical rather than a graphical solution, and for this purpose Norton's equations have been reduced to explicit functions of r , θ and ψ' :

$$A \equiv \frac{(1 - 2r^2) \tan \theta - r^2 \tan^3 \theta}{r} \equiv \frac{(1 - 2r^2) \tan \theta}{r} \quad (16)$$

$$B \equiv 1 + (2 - r^2) \tan^2 \theta \equiv 1 + 2 \tan^2 \theta \quad (17)$$

$$C \equiv 1 + r^2 \tan^2 \theta \equiv 1 \quad (18)$$

$$\sin 2b \equiv \frac{AC + B\sqrt{A^2 + B^2 - C^2}}{A^2 + B^2} \equiv \frac{A + B\sqrt{A^2 + B^2 - 1}}{A^2 + B^2} \quad (19)$$

$$a^2 \equiv \frac{2r \tan \theta}{(1 - r^2 \tan^2 \theta) \sin 2b - 2r \tan \theta \cos 2b} \equiv \frac{2r \tan \theta}{\sin 2b} \quad (20)$$

$$\cos 2b = \sqrt{1 - \sin^2 2b} \quad (21)$$

$$K' = 1 + \frac{\cos 2b}{a^2} \quad (22)$$

$$X' = \frac{\sin 2b}{a^2} \quad (23)$$

$$K = K' \cos^2 \psi \quad (24)$$

$$\sigma = X' \cos^2 \psi_{Mc} \cdot 5.007 \times 10^5 \text{ esu} \quad (25)$$

10. Method of Measurement

A shielded loop, reading vertical angles and located less than $1/20$ of a wavelength above a plane ground, can be used in conjunction with an elevated transmitting loop, a wavelength or more from the point of transmission, to evaluate the electrical earth constants, K and σ . The procedure is to elevate the transmitting loop to sufficient height to give a measurable field intensity at the receiver, and to orient it so that its axis lies in the plane of incidence passing through the center of the receiver loop. The receiving loop, built to rotate about the horizontal axis (Figure 8) and to measure vertical angles, is located on the earth plane and oriented so that its axis lies also in the plane of incidence --i.e., so that the horizontal axes of rotation of the transmitting and receiving loops are parallel and both normal to the plane of incidence and with centers in the plane of incidence. Then, with transmitter in operation, the receiving loop is rotated about its horizontal axis of rotation until the minimum response is observed (which is then recorded), and the angle θ (Figure 8) is measured. The output of the receiver is proportional to the field strength (or is calibrated so) and this reading of output is proportional to the minimum magnetic field ellipse vector. The angle is the tilt of the major axis of the ellipse to the plane of the earth. The loop is then rotated through 90° about its horizontal axis of rotation (which lines up the plane of the loop with the minimum field ellipse axis), and hence the reading of the receiver is now proportional to the strength of the major magnetic field ellipse vector, and the maximum response is recorded. The quantity r , the ratio of minimum to maximum field strengths, is then calculated, and r with θ , the angle of field ellipse tilt, can then be used to obtain K' and X' by means of the last group of equations (Numbers 16 through 23) or Figure 8. In order to obtain K and σ from K' and X' , it is necessary to calculate ψ , the angle of incidence, obtained as indicated in Figure 8. Then the values of K and σ are given by equations 24 and 25.

11. Actually, the transmitting antenna used was an electric dipole instead of a loop. This is permissible where the receiver loop lies in the equatorial plane of the transmitting electric dipole. (Footnote 20, page 60 of reference (e)). The general advantage of using a horizontally polarized field

in measuring ground constants is that a shielded loop can be used to make the observations instead of an electric dipole, which is subject to greater disturbances of the field, such as caused by the presence of the receiver and operator. On the other hand, using a loop necessitates care in electrical design, such as is well known in direction finding work, to offset antenna effect.

12. EXPERIMENTAL WORK

The following outlines the experimental work undertaken by this Laboratory in the study of the measurement of electrical ground constants for 2 to 10 megacycle range by Wave Tilt techniques:

(a) A Model DAF loop, type "S", was mounted in a suitable wooden tilting frame and connected with a Model OF meter as receiver. The transmitter was a small battery-operated unit mounted on a tall stool with a 40 foot horizontal dipole antenna stretched out on wooden stakes. This apparatus, used at 1 to 3 megacycles, was unsuccessful as the minimum response disappeared into the noise level, due to combined effects of necessary long distance between transmitter and receiver for these frequencies, low output of transmitter and closeness of transmitter to ground.

(b) A successful measurement of ground constants was made using a special loop and a Model OF meter as receiver, with a small battery transmitter mounted in an elevated position, measurements being made at 7 megacycles. Further tests with this set-up were not possible, the Model OF meter being required for a problem of higher priority.

(c) A National NC-100 receiver was next used with the special loop with a Model TCS-5 transmitter mounted in an elevated position. Only one preliminary test (at 10 megacycles) with fair results could be made at this site, the transmitter position being required for a higher priority problem.

(d) With a new transmitting antenna (having a lower tuning frequency) and transmitter located in a new elevated position, measurements were made at 7 megacycles, using a Model LCa signal generator as a received signal reference standard. Further investigations at the time had to be abandoned due to the setting in of winter.

(e) As a matter of interest, arrangement had been made for the modulation of the transmitter, and a corresponding band pass filter was made for the receiver, but these were never used in the field because of suspension of operations.

13. DETAILS OF EQUIPMENT DESIGN

Special Loop

The special tilt loop was constructed as follows:

- (a) It was essential that the direction finding loop be electrically symmetrical with respect to ground, which condition was achieved with proper shielding. The loop, 17" square, consisted of 5 turns spaced 1/2" apart, 1/2" from the shield on the edge of the windings and 1" from the shield on the side along the windings, with means also of tapping the center turn. (Figures 10, 11; Plate 1).
- (b) The shield was made of 1/64" galvanized iron, and an 8" cubical metal box was mounted at the bottom of the loop. (Plate 1). A small spirit level was mounted on the shield. The shield was supported on carefully constructed bearings, the pivot points being located so that the loop would nearly balance in any position, to facilitate accurate dip readings. Wing bolts were used to hold the loop in place. All metal parts of the shielding were electrically bonded.
- (c) The wooden frame consisted of two parts as shown in Figure 1. Three pieces of bakelite rod 2" in diameter and 1" in length were mounted on the base as mounting feet. When the NC-100 was used with the loop (Figure 3), a large wooden T was mounted to the loop shield base, with the bakelite feet moved to the extremities of the T.

14. Model OF meter - Special Loop Receiver - Battery Transmitter set. (As in 12 (b), and Plates 1 and 2)

For the Model OF meter set:

- (a) The field strength meter used as an indicating device was the "Interference Locator", Navy Model OF, with frequency ranges of 150-350 and 550-20,000 kc manufactured by the Ferris Instrument Corporation. (Figure 10)
- (b) The transmitter used was a small battery-operated unit in the Laboratory which had a frequency range of 600 to 9800 kc. It had a tuned dipole antenna 10 feet long that was placed in a horizontal position. (Plate 2)
- (c) The site used was the flat ground in front of DF-4 house (Figure 9) with the transmitter located on the roof, north-west corner of the building, and the receiver in the road (Plate 1). The ground here was 8 feet of damp silty clay, beneath a thin gravel road bed, and above a wet small-size

gravel. The geometry of the site (Figure 8) was $a = 23' 7"$, $d = 92-1/2'$ and $z = 20"$. As an example of readings, the first readings (Table 3) for the minimum and maximum response on the OF meter scale, when calibrated with a 605-B signal generator, were 300 and 3220 microvolts, giving a ratio r of 0.0931 (see sentence after equation 5). With the wave tilt 6.4° as read off the protractor attached to the tilt loop (Plate 1; defined in Figure 8), the ground constants were evaluated as $K = 8$ and $\epsilon = 1.5_1 \times 10^8$ esu.

15. Models NC-100 Receiver - TCS-5 Transmitter for 10 Megacycles (as in 12 (c)).

The transmitter was located in the middle of the roof of DF-6 house (similar to DF-4, Plate 2), the antenna wire being stretched to the railing around the roof. The Model TCS-5 transmitter, giving 40 watts cw output, was modified for dipole operation and an antenna tuner built for a 30 foot stretched-wire dipole, tuning from 2 to 10 megacycles. The output of the receiver was measured on a calibrated G. R. Milliwatt Output Meter, Type 583-A, which was plugged in at the phone outlet. The receiver (Figure 11, Plate 3) was located 1540 feet away (Figure 9). Power was supplied by a D. W. Onan and Sons, Model 580E-3, gasoline power plant.

16. Models NC-100 Receiver - TCS-5 Transmitter for 7 megacycles (as in 12 (d)).

After being required to move from DF-6, the only available place suitable for locating the transmitter was on the DF-5 house which required an auxilliary antenna structure (Plates 4 and 5). When built, it was found that the highest frequency at which the antenna tuned was under 8 megacycles because of the tubular sections. These tubular sections were guyed with heavy waxed cord trussed on 5 foot wooden dowels. The transmitting set-up is shown on Plate 6 and the receiving set-up on Plate 3. The suspension of operations at this time did not permit the use of the 1000 cycle oscillator in Plate 6 and 1000 cycle band-pass filter in Plate 3. The TCS-5 transmitter was not equipped for mcw emission. This necessitated the use of cw emissions, requiring great care in tuning to maintain the stability of the beat note frequency. This suggested the use of external modulation on the transmitter as well as a filter on the receiver to reduce the noise level. The NC-100 used in these experiments had been previously modified, adapted for battery operation, and shielded. An output meter was connected to the speaker transformer (speaker disconnected), which gave quite sufficient output, and a Model LCa Standard Signal Generator was used for checking receiver input ratios.

DATA OBTAINED

17. The data taken, and ground constants calculated thereby,

using the special loop-OF meter-battery transmitter set, for 7 megacycles, are given in Table 3. The data and calculated values of ground constants are given for the observation made using the special loop with the NC-100 receiver and the TCS-5 transmitter at 7 megacycles in Table 4.

DISCUSSION OF PROBABLE ERRORS

18. Instrument Errors

Instrument errors are as follows:

(a) For the Model OF meter:

(1) The errors are mostly of a type such as cancel out for the ratio of field strengths involved, so that the effective accuracy of the meter was considerably improved, especially with the readings checked against a 605-B standard signal generator. The accuracy of r , the ratio measured by this instrument, was therefore taken to be 5% or better.

(2) The angle of tilt, θ , was carefully read to 0.1° , great care having been taken in the construction of loop, shield, bearings, and frame. For angles of 5° to 6° , the variation in the tangent function of 0.1° is about 2 per cent.

(3) Using the OF meter set (12 (b); Table 3), the overall accuracy was taken to be about 5 per cent in measuring r and θ , and this accuracy is preserved in making calculations of ϕ (see equations in Theoretical Considerations). The evaluation of K , involving a difference, cannot be measured better than to one significant figure.

(b) For the NC-100 Receiver set:

(1) The NC-100 Receiver lacked the stability of the OF meter and the accuracy of the measurements of field strength ratio is therefore less than that of the signal generator, and thought to be about 10%.

(2) The θ measurements were made with the same loop as used in the OF meter set, but with a large T-base added. The variation of θ was 0.6° over the group of observations (Table 4).

(3) Using the NC-100 Receiver set the overall accuracy on ϕ was taken to be 10% and 20% on K .

19. Site Errors

Norton's equations were based on the assumption of a plane homogeneous earth:

(a) For the OF meter measurement the level site was 8 feet of silty clay (with isolated small patches of fine sand, characteristic of flood plain sediment), above a horizontal layer of fine wet gravel, above, in turn, probably the bed-rock strata (effect considered negligible for this frequency and depth, regardless of inclination and character). Hence, an effective value was obtained for this frequency.

(b) For the NC-100 site:

(1) The NC-100 site was considerably different (Plate 7), a small stream having eroded out the clay to form a small depression between the plain on which the transmitter was located and the gravel terrace (with perhaps a foot of clay along its 6° decline toward the transmitter) on which the receiver was located. In evaluating ψ (Figure 8), the 6° slope was measured with a spirit level mounted on the tilt loop, and the 1° elevation of the transmitter above the horizontal at the receiver, were used to determine the 150 foot height of the transmitter above the plane determined by the terrace. The terrace extended about 100 feet toward the transmitter from the receiver before dipping sharply to the gentle decline stretching to the creek bank, and the geometrical point of reflection for the reflected wave was about 60 feet from the receiver on the terrace.

(2) As the gravel terrace also dipped about 6° from the horizontal normal to the transmitter-receiver traverse, another error was introduced that was equivalent to having the transmitting antenna not exactly horizontal. Norton (reference (1)) states that not having an electric dipole exactly parallel with the reflecting plane introduces stray electric fields, but that these are not as troublesome for measuring ground constants as for testing direction finders.

(3) Due to the lenticular nature of the surface clay (and probably the gravel, also) an error was introduced because the horizontal axis of rotation of the loop did not intersect the loop axis. For homogeneous ground, changing the point of reflection for the two positions of the loop involved in making the maximum and minimum intensity readings would cause no error of consequence (the slight variation in ψ).

20. The bakelite feet placed on the loop shield base helped to determine accurately the reflecting plane, an inherent difficulty in such a field problem and accentuated by the 0.1° tilt angle accuracy attempted. A T-shaped base was added to stabilize the loop and more accurately determine the representative plane of the ground for the second set. The ground on which to mount the receiver had to be picked for smoothness.

21. The most apparent difficulty introduced by the site was the Doppler effect caused by the reflected wave from near-by airplanes in flight. An airplane within a mile made the taking of readings out of the question, which suspended operations for quarter hour intervals quite frequently (three large flying fields were within three miles). Erratic fluctuation of the output meter needle for the second set (Model NC-100) was the most apparent source of instrument error (believed to account for the greater part of variation in readings) and the resultant effect of many airplanes in the vicinity was thought to be responsible for part of this fluctuation.

22. The other errors of the site can only be surmised, especially with the limited experimental work done on this project. One questionable factor would be the effect of reflected waves from the hill along the east side (northeast to south-southwest) of the site (Plate 7). There was a 50 foot grounded steel mast at DF-4 house (Figure 9) resonant at 5.5 megacycles with loops on top, and at DF-6 house a 20 foot horizontal conductor, pivoted to swing about a vertical axis, and tuned loops. The DF-5 house, over which the transmitting dipole was symmetrically located, was a shielded room (Plate 4). From the nature of the gently rolling ground, there was the possibility of more than one reflected wave for the NC-100 receiver set measurement.

RESULTS OF TESTS AND DISCUSSION

23. Test results and discussion are as follows:

(a) Using the special tilt loop-OF meter-battery transmitter and the site in front of DF-4 house (8 feet of silty clay, with small patches of fine sand above a small wet gravel), the site measured at 7 megacycles (Table 3):

$$\begin{aligned}\sigma &= 1.5 \pm 0.07 \times 10^8 \text{ esu} \\ K &= 10 \pm 1\end{aligned}$$

(b) Using the special tilt loop with the NC-100 receiver, and

with the TCS-5 transmitter mounted on DF-5 house and the much larger site (foot of silty clay above a pea-size wet gravel) the ground constants measured at 7 megacycles:

$$\sigma = 1.7 \pm 0.17 \times 10^8 \text{ esu}$$

$$K = 5 \pm 1$$

(c) For comparison, others have obtained, for somewhat similar ground, the values:

SMITH-ROSE (reference (d)) -- Soil Condenser Method - 10 megacycles (Table 2)

<u>Soil</u>	σ (esu)	<u>Apparent K</u>	<u>% Moisture</u>
Brown sandy clay	3.8×10^8	19	19
Dark grit and clay	1.2	19	18
" " " "	3.3	22	18
" " " "	3.2	24	15
Fine gravel	0.85	10	6.5
Coarse gravel	0.30	6.5	2.9

RADIO RESEARCH BOARD (reference (m)) - Electric Wave Tilt - Broadcast Band

Moist clay $\sigma = 1.5 \times 10^8 \text{ esu}$

FELDMAN (reference (n)) -- Soil Condenser Method - 18.75 megacycles

Dry sub-soil clay $\sigma = 0.88 \times 10^8 \text{ esu}$ $K = 14.5$

For a more extended table of ground constants for various soils, as measured by Smith-Rose using a soil condenser, see Table 2 (reference (d)), which seems to be the most accurate table of ground constants for radio frequencies, published to date. A very extensive table, with more exact geologic identification of soils and minerals is given by Heiland (reference (o)), pages 657-667. These were measured by many different people, using a variety of methods. Feldman (reference (n)) has a short table of his own measurements with some geological description of soil measured.

24. It would appear that this method of measuring ground constants for the DF station site by employing a horizontally polarized field set up by an elevated local transmitter and using a tilt loop to measure the constants of the resultant field would afford one of the most pertinent methods yet found for such measurements, at the higher frequencies: This is because such ground constants are of interest only as they appear to a given wave at a given angle of incidence in a

given azimuth--and this method most closely measures the constants in this manner. While there are too many variables to permit describing good direction finder sites in terms of one ground quality, the most generally acceptable parameter for all around use would be one of high conductivity. The suitable range of frequencies for proper application is rather arbitrarily set, the limiting condition for the shorter waves being that the loop, with its distributed capacity, must be capable of being tuned, with the loop of sufficient size to give enough signal for accurate measurement of the minima. The limiting condition for longer waves is that the transmitter must be elevated to sufficient height to have a measurable field strength at the receiver and still have the transmitter and receiver at least a wavelength apart. Also, to measure a site for long wavelengths, a large site of a suitable character must be used. At low broadcast frequencies the polarization ellipse flattens out and the K ceases to be determinate, but then for these frequencies the electrical property of the ground is not as much affected by the dielectric constant since the ground current is chiefly conductive. For very high frequencies the field ellipse flattens out again making radii ratio, and hence σ , difficult to determine (equations 12, 13, 14 and 15); but at these frequencies, the conductivity does not become very large (references (e), (f), (g) and (q)), and the ground current is chiefly a displacement current. Flattening of ellipse affirms the upper limit for measuring σ ; if r can be measured to only 0.01, then by Figure 8, the limit is 30 megacycles.

25. It would seem that maximum and minimum signals could be best standardized geometrically as suggested by Groszkopf and Vogt (reference (p), Appendix 43), which would considerably simplify the electrical requirements put upon the receiver and would dispense with the use of a standard signal generator. With the simplification of the electrical requirements, it would be possible to use a midget receiver mounted in the loop shield, dispensing with a shielded cable; hence the equipment could be considerably condensed and lightened, as would be most desirable for field use. The minimum responses observed must be so far above noise level as to make the noise output negligible, and the minimum response is, in turn, not less than about 1% of the maximum response. The receiver must be capable of handling the maximum response, although no difficulty is encountered if the receiver is not linear. Groszkopf and Vogt (reference (u)) used an output voltmeter giving full scale deflection for 25 microamperes, and found it quite suitable, as described in the Appendix (45).

26. For actual site investigation it seems advisable not to attempt measurements below 5 megacycles because of the site

and transmitter-elevation dimensions required, but rather rely upon geological identification of conditions that the longer waves would meet by deeper penetration at a given site, and perhaps, if possible and convenient, test near-surface strata of the site where they can be found to outcrop in a measurable way. According to Grammar and Goodman (ARRL Antenna Book, 1942, p 19) the radiation from a horizontal dipole is impractical at about 3° or less to the horizontal. Taking, therefore, 3° as our minimum tolerable radiation angle, then for 5 megacycles, the radiating dipole would have to be elevated to 10 feet. For a 5-30 megacycle range (and distance of one wavelength between transmitter and receiver) it would seem possible to use a small test oscillator, which would be battery-operated by self-contained cells and vibrator pack; hence it would be easily portable and could be elevated on a very tall step ladder at the site.

27. It is preferable that personnel engaged in making ground measurements by any method be familiar with the science of field geology, as often the geologic condition at a site is buried under plant growth, snow and ice or sediment, and measured values are apt to be misleading. Also, a person experienced in geology, after making some electrical measurements, might be in a position to evaluate many sites by eye, through proper identification of the geologic conditions of the site involved. It might even be expected that sites could be picked, according to their electrical constants, by the use of a geologic and topographic map by such a person after some experience.

CONCLUSIONS

28. It is concluded that the measurement of ground conductivity of radio direction finder sites by this Wave Tilt method, using horizontally polarized waves, is not only feasible in practice but probably represents the most pertinent method. It yields results commensurate with the effects of the ground of such sites on actual radio waves of frequencies and angles of arrival and polarization normal to station usage, rather than the arbitrary results obtained by other methods.

RECOMMENDATIONS

29. It is recommended that:

(a) This method of measuring ground constants -- using a horizontally polarized wave created by an elevated transmitter and evaluated with a loop collector system -- be used in making desired ground measurements for 5-30 megacycles at proposed radio station sites.

(b) Personnel engaged in making ground measurements be familiar with at least elementary field geology, when possible, so that gross errors due to the lack of understanding of the nature of an observed site may be avoided.

(c) The site be electrically surveyed by this method with several traverses and frequencies, the regions of reflection being as far apart as convenient and along different azimuths as a check on homogeneity of the site and observer's technique.

(d) Further experimental work be undertaken at the Laboratory, under a specially assigned problem from the Bureau of Ships, on the measurement of ground constants by this method, such research to investigate the change in the nature of the ground constants with frequency; the most desirable frequencies at which to measure prospective radio sites; development of equipment along lines suggested by Groszkopf and Vogt (paragraph 43) with special attention to the possibility of producing light, compact, standard ground-testing units for field use.

APPENDIX

For the purpose of giving a well-founded report on the subject of ground conductivity measurement, a brief digest is here given of some of the leading papers on this subject. A summary of all numerical values given in this appendix are listed, for purpose of comparison, in Table 5.

30. Smith-Rose (Reference (d)) gives the following summary of the development of ground constants measurement methods up until about 1934.

(a) Low Frequency Methods

The low frequency methods are as follows:

(1) No ordinary d-c measurement was cited.

(2) Gish and Rooney used a direct current source but reversed the current 60 times a second. At Watheroo, Australia a site was measured as having $\sigma = 10^6$ esu for surface sand, $\sigma = 13 \times 10^8$ down to a depth of several hundred meters and 1.4×10^8 further down to 600 meters; later these variations in conductivity were confirmed by another method used on the same site. (Cairns wave tilt method). Gish and Rooney used 4 electrodes equally spaced in a line on flat ground, the two outer stakes bearing the current and the potential being measured across the two inner stakes. Changes of conductivity with depth were indicated by the successive resistance values measured as the stakes were separated. This is one of the few electrical methods of geophysical exploration suitable for oil exploration.

(3) Tagg and Megger, using a 50 cycle current, measured a site in Southern England using a similar method and obtained $\sigma = 0.5 \times 10^8$ esu. (An instrument known as a "Megger", working on the 4-stake, low frequency method, but reading the conductivity directly, has been on the market for a number of years for ground conductivity measurements needed for laying pipelines, earthing plates for power lines, etc)

(4) Collard used two earthed circuits and measured the mutual impedance at 3000 cps to get $\sigma = 36 \times 10^8$ esu at one site and 1.5×10^8 at two other sites in Southern England.

(5) Higgs at the National Physical Laboratory used 50 cycle current and obtained 0.75×10^8 esu for normally

moist soil at normal temperature. He measured the thermal coefficient of conductivity to be 3% rise per degree Centigrade for a limited range above zero, which is consistent with the concept that the conduction current at this frequency is chiefly electrolytic*.

(b) Condenser-Reactance Methods

Condenser-reactance methods are as follows:

(1) Ratcliff and White (1930) used a soil condenser for samples over a range from 0.2 to 5 Mc, the dielectric constant correspondingly changing from 40 to 12 and conductivity varying erratically but lying between 0.2 and 0.5×10^8 esu for these frequencies for two sites. For the samples dried out, $K = 5$ and $\sigma = 0.5 \times 10^6$ were obtained.

(2) Strutt (presumably at Eindhoven, Holland) got $\sigma = 0.33 \times 10^8$ to 0.44×10^8 for surface soil as frequency was varied from 200 to 500 kc.

(3) Feldman made measurements at Holmdel, N.J. for 9.4-37.5 Mc measuring black top-soil loam to have $\sigma = 0.8 - 1.5 \times 10^8$ esu and $K = 12-23$. Higher values were obtained with wet soil. Clay sub-soil at 3 feet had the value of $\sigma = 1.9 \times 10^8$ $K = 28$; at Netcomb, N.J. he measured clay (with stone chips) to have $\sigma = 0.1-0.3 \times 10^8$ and $K = 7-10$ at each site. He found a 10% increase in σ in going from 9.4 to 37.5 Mc for both sites; K decreased somewhat more rapidly with increasing frequency. No temperature or moisture content values were recorded.

(c) Wave Tilt Methods

Wave tilt methods are as follows:

(1) Barfield and Smith-Rose (1924) used an electric dipole at broadcast frequencies and found the conductivity

 * Of the types of conduction-electronic, electrolytic and dielectric - the latter occurs appreciably for a particular ion only in a small range corresponding to the relaxation time of the polar molecule. For water, for example, this relaxation time is 25×10^{-12} seconds⁽¹⁾, corresponding to the period of a centimeter radio wave. With many kinds of ions present in the electrolyte in the near surface of the earth, dielectric conduction due to anomalous dispersion should occur at high frequencies (HF) and beyond, because of the short relaxation times of most inorganic polar molecules. Electronic conduction would not occur appreciably except for soil very rich in oxides or ore bodies or graphite deposits.

(1) Debye Polar Molecules Chemical Catalogue Co., New York, 1929, P. 85

at a site in Southern England to be $\sigma = 0.6 - 4.7 \times 10^8$ esu but found no correlation between frequency or nature and condition of soil at the receiver and the value measured. Later researches gave a value of $\sigma = 0.9 \times 10^8$ esu for 620 - 860 kc.

(2) Barfield and Munro used an electric dipole at 19 Mc and obtained $\sigma = 0.5 - 2.5 \times 10^8$ esu for the value at Slough.

(3) Cairns at the same site at Watheroo, Australia as Gish and Rooney used, concluded that the deep, highly conductive subsoil affected wave propagation despite the highly resistive top soil.

(4) Bailey, Dean and Wintringham used a wave antenna and obtained $\sigma = 1.0 - 2.5 \times 10^8$ esu in Great Britain and 0.14×10^8 at Houlton, Maine at 60 kc.

(d) Field Attenuation Method

The disadvantages of this method of measuring are that an assumed theory of process of attenuation must be used, and only average values for the whole path of travel is obtained. The results obtained were as follows:

(1) Ratcliff and Barnett used Sommerfeld analysis to get $\sigma = 1.6$ and 0.5×10^8 at 190 and 830 kc respectively.

(2) Barfield (1926) measured field strength of a 825 kc carrier wave from London out for distances up to 150 km and obtained $\sigma = 0.2 - 1.0 \times 10^8$ esu. From subsidiary experiments he concluded that this difference in value was because of the difference in tree density in different directions.

(3) Munro at Slough measured σ to be $0.8 - 3 \times 10^8$ esu.

(4) Rolf and Lenoire used the Rolf modified Sommerfeld equations in Sweden at the Motala and Karlsborg Stations for 230 kc and obtained $0.05 - 0.09 \times 10^8$ for σ and $K = 15$. For the 1 Mc station at Malmö, $\sigma = 1.3 \times 10^8$ and $K = 10$ were obtained.

(5) Kirby and Norton also used the Rolf-Sommerfeld equations from 0.6 to 1.0 Mc and obtained $\sigma = 0.3 - 1.0 \times 10^8$ and an average K of 13 for various transmitting stations in the U.S.

(6) Cherry at Melbourne, Australia using 810 kc obtained $\sigma = 3.6 \times 10^8$ in a direction of bare ground, 3.0×10^8 for land in another direction covered with low scrub and light timber, and in a third direction where the ground was thickly timbered he obtained $\sigma = 0.9 \times 10^8$ *. This reduction in σ with heavy timbering is what Barfield had also observed. Cherry used another site at 580 kc, and obtained 0.45×10^8 .

(e) Ground Constants for UHF

The apparent dielectric constant is chiefly a function of K at very high frequencies, and the ground current is chiefly that of displacement, unless σ increases greatly with frequency. Ground constants for UHF are as follows:

(1) Strutt in Holland buried 100 meter parallel wires 2 Cm apart and 30 cm deep and for 0.5 - 20 Mc obtained $\sigma = 0.45 \times 10^8$, K = 10 as calculated from the exponential drop of the current amplitude along the wires.

(2) Strutt also used transmitting and receiving antenna to measure ground constants at 210 Mc to calculate, by interference effects, the ground to have a value of σ greater than 10^9 esu for soil that had a value of 10^8 at 1 Mc frequency.

(3) McPetrie and Smith-Rose made a field attenuation measurement at Teddington, and obtained $5 - 30 \times 10^8$ esu for 30-60 Mc and about 95×10^8 for the same site at 190 Mc, and hence concluded that σ might greatly increase with frequency in the ultra high frequency region as sketched in with a dotted line in Figure 5**

31. The Radio Research Board***(Reference (m)) reported in 1929 the following measurement of ground constants made in 1924 using an electric dipole at various broadcast frequencies for selected receiver sites. The equation used to evaluate was (as modified from Zenneck's equations):

* No mention was made of the geologic conditions for the three directions, in the brief summary given.

**It is to be noted that later tests did not confirm these high values of σ for these frequencies.

***Probably the same experiment as cited in Paragraph 30.(c). (1)

$$\sigma = \frac{4 \tan^2 \theta}{f} \text{ esu}$$

for the conditions that $\sigma \gg f$ (frequency in cycles) and θ (angle of minimum response) is small. In the first experiment a 30' copper wire was stretched on a wooden tripod 20' high. This required very careful shielding of leads and receiver, the residual pickup finally being disposed of by reversing input leads. For broadcast transmitters 9-30 miles away and frequencies of 43 to 670 kc the tilt angles were 0.7 to 2.7° and $\sigma = 0.7 - 0.8 \times 10^8$ esu at Slough. The second set had a 15' dipole on a correspondingly smaller tripod which was used at various sites in Southern England giving $\sigma = 0.14$ to 4.7×10^8 esu for transmitters 1-60 miles away. One site was purposely picked with a 16° incline, but with angles measured with reference to this surface rather than to lines of gravitational equipotential; the value measured compared favorably with that obtained nearby on level ground.

32. Feldman (Reference (n)) applied reflection equations similar to Fresnel's equations but with complex indices of refraction, and used an elevated transmitter and receiver (electric and magnetic dipole combination) to determine reflection coefficients. The relation of the theory of physical optics to Sommerfeld's analysis of the ground wave was discussed. He showed that the modified Fresnel equations applied to short wave communication via the Kennelly-Heaviside layer. His equations failed for near-grazing incidence, and then merged into the Sommerfeld surface wave equations. He showed that the ground effect is to always discriminate against waves at low angles. He used Sommerfeld's analysis to measure ground constants by wave tilt using an electric dipole, and checked these values with a soil condenser (Paragraph 30b, 3), with fair agreement, after allowance had been made for stratified ground. A quite complete bibliography was given. Frequencies of 9-30 Mc were used.
33. Smith-Rose (Reference (c)) described measurements of ground conductivity using a soil condenser, and derived a relation for apparent dielectric constant. He described tests done at the National Physical Laboratory to determine the relationship of moisture content of ground and frequency for dielectric constant and conductivity (Figures 1, 2, 3, 4, 5), as discussed in this paper under "Known Facts Bearing on the Problem". Also in the paper by Smith-Rose there is a discussion of current flowing at a given depth as a function of ground conductivity.

34. Barfield (Reference (h)) used an electric dipole for radio frequencies up to 60 Mc to determine σ and K for various sites. He also determined the seasonal variation of σ and K. He found for σ there was no appreciable seasonal change, but there was quite a change from wet to dry weather. He concluded that K varied from 10 to 30 for wavelengths above 7 meters, and σ varied from 0.5 to 4×10^8 for wavelengths between 15 and 50 meters for typical sites in Southern England. The theory used was that of Zenneck and Sommerfeld, the constants being obtained by plotting the angle of tilt against frequency and finding curves parametric in σ and K which fitted the observed data*.

35. Smith-Rose (Reference (d)) in this paper gave a historical outline of the measurement of ground constants as repeated here in this Appendix, Paragraph 30. He then gave a review of the frequency-moisture content dielectric constant-conductivity relationships as given in his 1933 paper (Appendix Paragraph 33) plus variation of dielectric constant and conductivity with temperature (Figures 6 and 7 and Table 1). In this paper, the variation of apparent dielectric constant and conductivity with frequency were cut short at 10^7 Mc. A more extended table of ground constants as measured with a soil condenser is given (Table 2) and there is given again a discussion of penetration of waves into the ground.

36. McPetrie (Reference (q)), working on 1.5 and 0.46 meter waves used electric transmitting and receiving dipoles, horizontal in a vertical plane with centers on a vertical line, held at a constant distance apart and raised to different heights above the ground and measured the variation in response at the receiving antenna. He concluded that σ was below 10^9 and $K = 7-16$, although in a previous experiment he had got $\sigma = 95 \times 10^8$, using the same site at the same wavelength of 1.6 meters. For 0.46 meters, he got $K = 7-20$ and up to 40×10^8 esu for σ .

37. Smith-Rose and McPetrie (Reference (e)) used long Lecher wires 2 cms apart to measure ground constants at 1.5 meters by comparing the wavelength on the wires in air and in a wooden container $6 \times 13 \times 16$ cms, which was packed with earth and could be slid along the wires. The values obtained were: $K = 10-12$ and $\sigma = 10-28 \times 10^8$ esu.

* This did not seem to give very exact values.

38. Smith-Rose (Reference (f)) extended the investigation of ground constants using a small soil condenser for 1 to 100 Mc range in this paper. He concluded that for normally moist earth the conductivity rose from about 10^8 to about twice this value at 100 Mc (in contradiction to his graph in Figure 5), and the apparent dielectric constant reduced from 10^5 at 50 cps to 15 at 100 Mc (as in Figure 5). Also, in this paper, he compared his values of conductivity with those obtained by Broughton Edge for a resistivity map of Great Britain (British Electric and Allied Industries Research Association), for which frequencies up to 3000 cps were used and measurements were made for a depth of 500 feet. In 12 out of 16 cases, his surface values checked very well with values obtained by Edge. Smith-Rose did not find any great change in conductivity for the 50-1000 cycle range except for highly resistive stone and slab.

39. Norton (Reference (k)) derived equations for the electromagnetic field, set up in air above a plane-surfaced medium having conductivity σ and dielectric constant K , as created by vertical and horizontal electric and magnetic dipoles. He then showed how these equations applied to the measurement of ground constants as measured by an electric dipole, deriving a graph (Figure 8) from which the values could be obtained once θ , the angle of tilt, and r the axis ratio of the polarization ellipse of electrical field were known. Reduced cases for high and low frequency were also given as an indication of the variation of the ellipse of polarization with frequency: very thin and tilted over for very high frequencies (VHF), straightening up and widening with high frequencies (HF) and becoming nearly vertical and thinning toward medium frequencies (MF).

40. Heiland (Reference (o)) in his chapter on electrical geophysical methods described the use and theory of the soil condenser, and measurement of ground constants using a vertically polarized wave according to Zenneck's analysis. Sketches are also given of the shape of the ellipse of polarization for waves above variously stratified ground according to Zenneck. A very complete table of ground constants is given for minerals and various geologic grounds, as measured by various people using different methods. Low audio frequency methods are also described in great detail.

41. Stratton (Reference (j)) goes into detail on the theory of wave propagation and includes the theoretical derivations on which ground constant measurements are based. The section in this book referred to is an historical sketch of the development of analysis of wave propagation over a medium with constants K and σ , as repeated in this report in paragraph 8.

42. Groszkopf and Vogt (Reference (s)) after considerable work in this field, reconsidered their simplified Zenneck equations for measuring K and σ of a homogeneous plane earth by the wave tilt method using an electric dipole. Then the equations of Hück (Ann. Physik 27 (1908)P 43)---based on the paper by Zenneck (Ann. Physik 23 (1907) p. 846) for a two-stratum ground---were simplified and computing graphs were given. Measurements and analysis were made on actual ground and it was of interest to see, in one case, the manner in which the effective ground conductivity sharply increased when the radio frequency of the passing wave was sufficiently reduced so that an appreciable part of the induced ground current could be carried by a highly conductive sub-stratum.

43. Groszkopf and Vogt (Reference (p)) described a new ground constants instrument in which calibration of the maximum-minimum field strength ratio, r , is effectively done geometrically. (It was necessary to assume non-linear response of the receiver, and to calibrate the two voltages (used in r) a signal generator, in their preceding experiments, was used for this purpose). They used an electric dipole (vertically polarized waves) which was operated as follows: The dipole was "homed" by being set in the wave front; then rotated through 90° about a vertical axis to place it in the plane of the ellipse of polarization. In the plane of the ellipse of polarization the dipole was rotated about a horizontal axis until the minimum response position was found, and the receiver gain was adjusted to give a convenient output meter reading. The dipole was then rotated through 90° about the horizontal axis, which lined the dipole up along the major ellipse radius and gave a maximum response. This was not recorded, but instead the dipole was then swung around an axis lying in the plane of the ellipse of polarization and parallel to the minimum ellipse radius until the selected minimum response reading on the output meter was repeated; the angle then formed between the dipole and plane of the ellipse, angle R , is recorded, and by trigonometry,

$$r = \frac{\text{minimum response}}{\text{maximum response}} = \cos R$$

Hence, the minimum requirements are placed upon the electric equipment, and a standard signal generator is dispensed with.

44. Groszkopf and Vogt (Reference (t)) applied Norton's equation of the field above a plane earth for a vertical electric dipole (Equations 55 and 70, Reference (k)) to the determination of the error they had assumed from using the less exact Zenneck equations in the measurements of ground constants by wave tilt. They assumed in Norton's equations

the value of F (Sommerfeld attenuation factor) as unity (not greater than a 2% error) and calculated the field at the earth's surface (justifiable insofar as Norton assumed a plane homogeneous earth) and concluded that for the receiver at four wavelengths from the transmitter the error was only 4% in the use of the less exact equations.

(These equations are, for explicit solutions of σ and K:

$$\sigma = \frac{f \sin 2\theta}{2\rho^2} \quad \text{esu} \qquad K = \frac{2\sigma \cot 2\theta}{f}$$

$$\text{where } \rho^2 = \frac{(r^2 - 1) \sin^2 \theta + 1}{(r^2 - 1) \cos^2 \theta + 1}$$

$$\theta = \cos^{-1} \frac{\tan 2\theta}{2} \left(\frac{1}{\rho} - \rho \right)$$

Where θ is the angle between minimum response and the earth plane, and r is the ratio of minimum to maximum response.)

45. Groszkopf and Vogt (Reference (u)) described a new conductivity meter which incorporated the geometrical determination of r (paragraph 43) and was thereby greatly simplified compared to previous equipment they had used. The instrument consisted of a $1\frac{1}{2}$ meter dipole with a midjet self-contained receiver mounted at the middle, and the whole supported on a tripod. The receiver was 6 x 13 x 33 cms and weighed 2.5 kg. It covered a range of 1.5 to 15 Mc, requiring a field strength of 1 $\mu\text{v}/\text{m}$ for the lower and 20 $\mu\text{v}/\text{m}$ at the upper end of the band. The output meter gave full scale deflection for 25 microamperes. Electrical circuit diagrams of the receiver were given. The equipment was easily portable, and carried conveniently in three canvas bags.

46. Norton (Reference (1)) and Diamond, Lifschutz and Poast (Reference (i))--the pertinent parts of these are given in "Theoretical Considerations", paragraph 9.

47. McPetrie and Saxton (Reference (g)) determined the ground constants at 60 Mc using a horizontal linear dipole 12 meters above the ground and a parallel linear receiving dipole (in the same vertical plane with center on same vertical line as center of transmitting dipole) which was moved to successive positions from 0.5 to 3 meters above the ground, the response going through successive maxima and minima. Using curves calculated

for a previous paper, "On the Reflection Coefficient of the Earth's Surface for Radio Waves", Jour. IEE 82 (1938) p 214, they calculated the values of σ and K and found them to lie between $K = 20 - 15$ and $\sigma = 1 - 3 \times 10^8$ esu for one site. They measured grounds varying from clay to gravel, and observed the K to change from 60 to 5 and σ to change from not more than 10^9 to less than 10^8 esu.

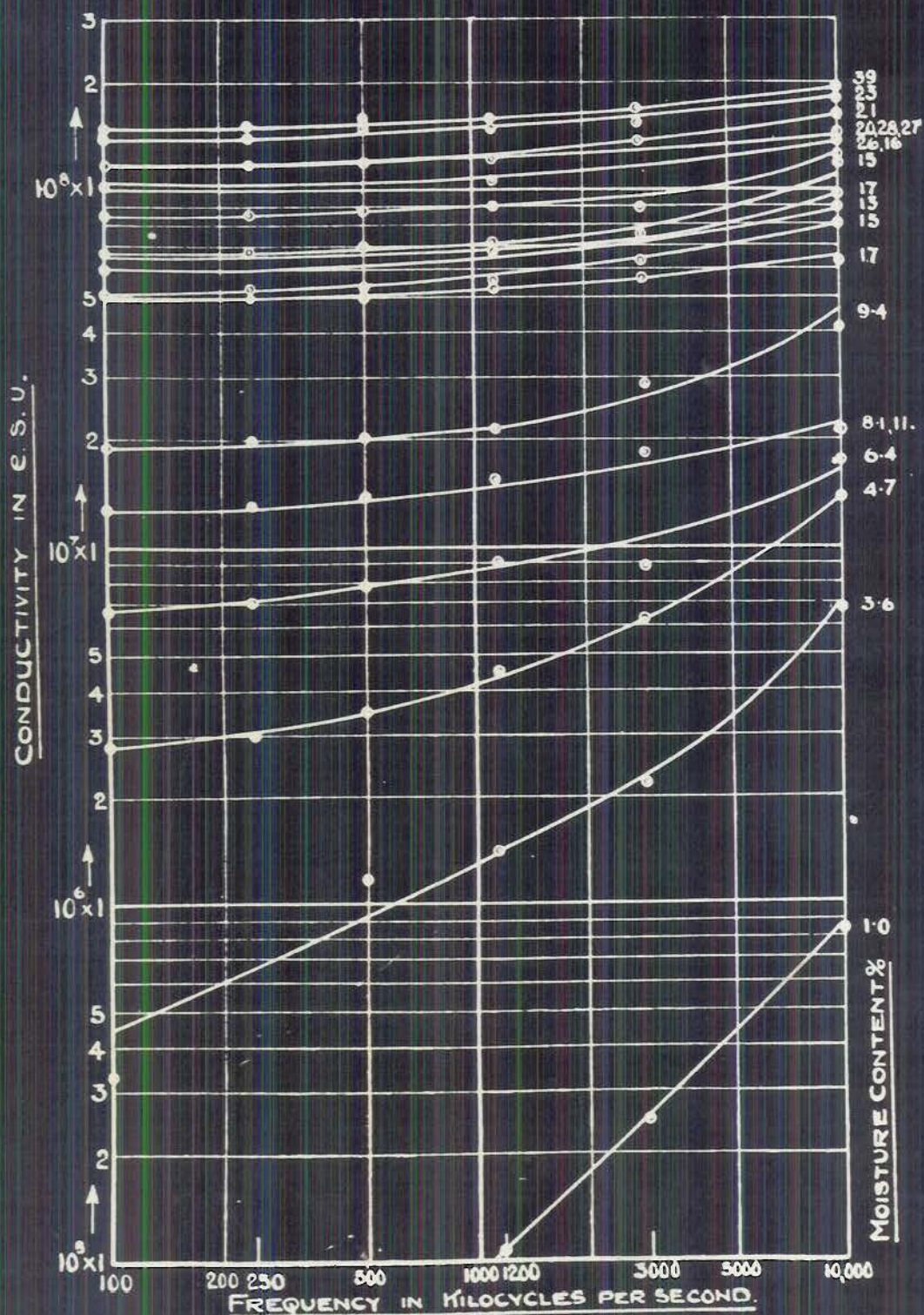


FIG. 1.—Relation of conductivity to frequency and moisture content for soil from Site I (N.P.L.).

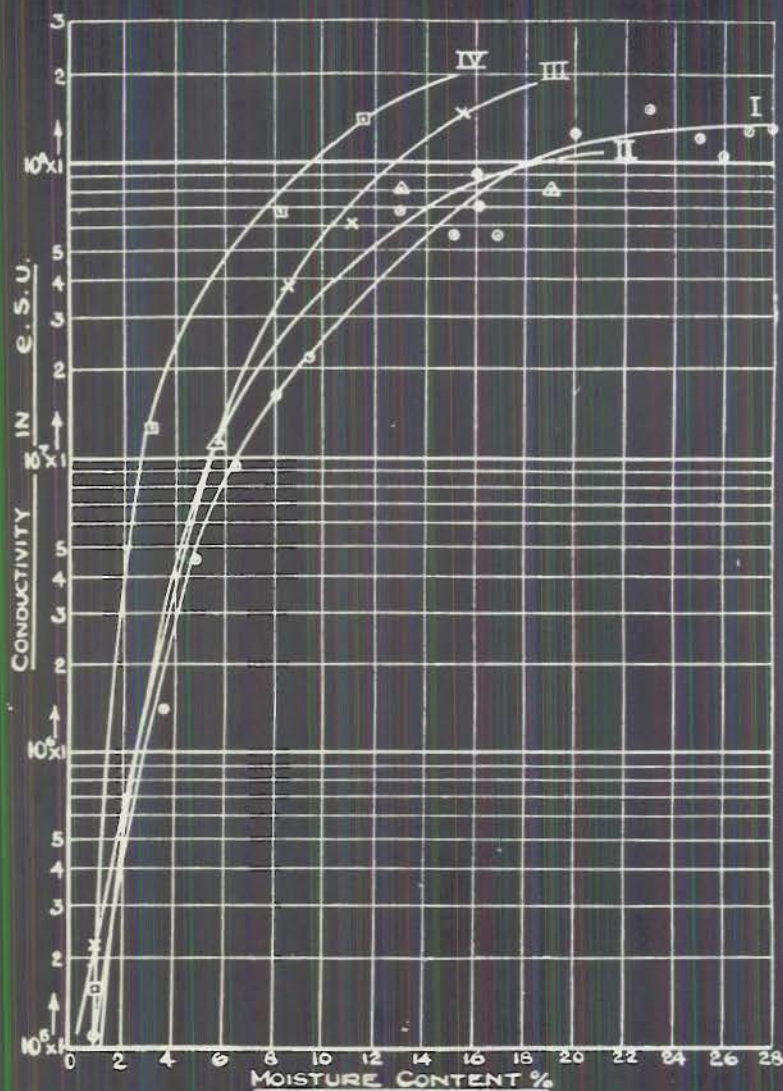


FIG. 2.—Relation between conductivity and moisture content for soils from Sites I-IV (N.P.L.) at a frequency of 1,200 kilocycles per second.

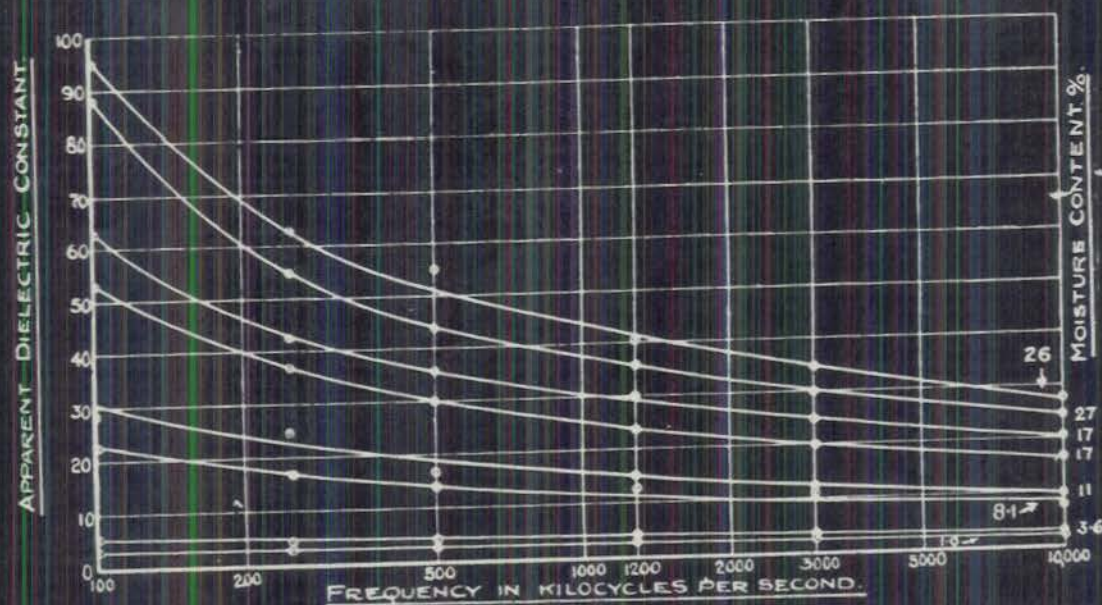


FIG. 3.—Relation of apparent dielectric constant to frequency and moisture content for soil from Site I (N.P.L.).

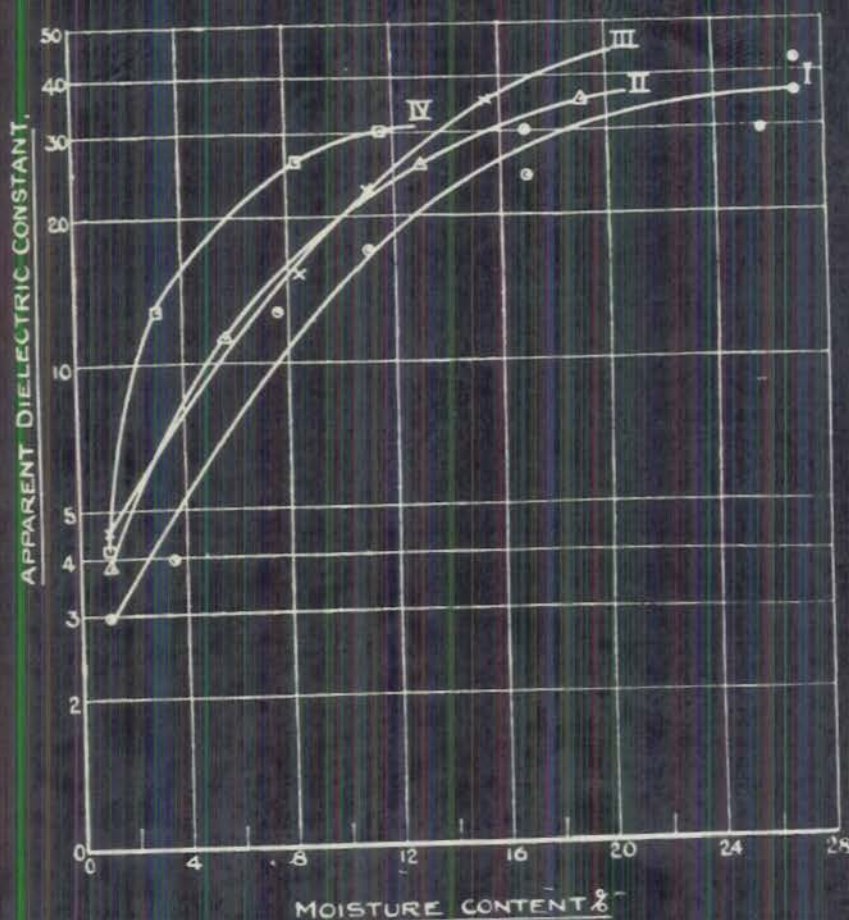


FIG. 4.—Relation between apparent dielectric constant and moisture content for soils from Sites I-IV (N.P.L.) at a frequency of 1,200 kilocycles per second.

TABLE 1.
*Temperature Coefficients of Conductivity of Various
Types of Soils.*

Site	Type of soil	Conductivity (in e.s.u.) at 20° C.	Tempera- ture coefficient of con- ductivity at 20° C.
			per cent per deg. C.
N.P.L. ..	Sandy loam	1.2	2.3
Daventry ..	Brown sand	0.11	2.2
Dousland ..	Dark brown loam	0.26	2.1
Washford Cross	Red-brown clay	3.1	2.3

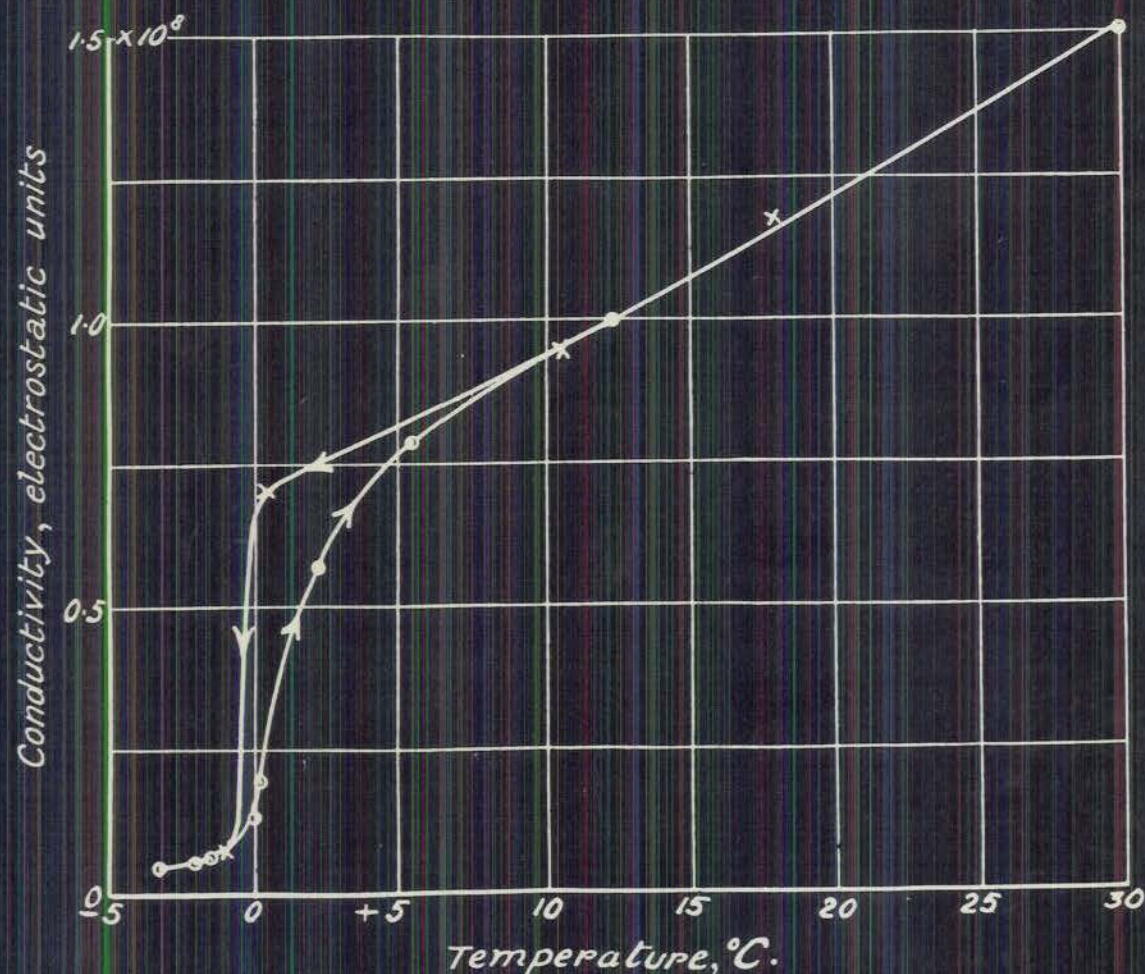


FIG. 7.—Variation of conductivity with temperature of normal sample of soil from Site No. I (N.P.L.).

Frequency = 1 200 kilocycles per sec.

FIGURE 7

From Reference (1)

THE POLARIZATION OF THE VECTOR MAGNETIC FIELD FROM A VERTICAL MAGNETIC DIPOLE

$$\Gamma = H_1/H_2; \quad d > \lambda; \quad z < \lambda/20; \quad \tan \psi = (a + z)/d;$$

$$K = K' \cos^2 \psi; \quad \sigma = x' \cos^2 \psi f_{Mc} 5.56387 \times 10^{-16} \text{ e.m.u}$$

LOOP AXIS
TRANSMITTING LOOP

ARRANGEMENT OF APPARATUS FOR MEASUREMENT OF GROUND CONSTANTS. RECEIVING LOOP SHOWN IN POSITION FOR MEASURING θ AND MAGNETIC FIELD H_1 CORRESPONDING TO MINOR AXIS OF THE ELLIPSE

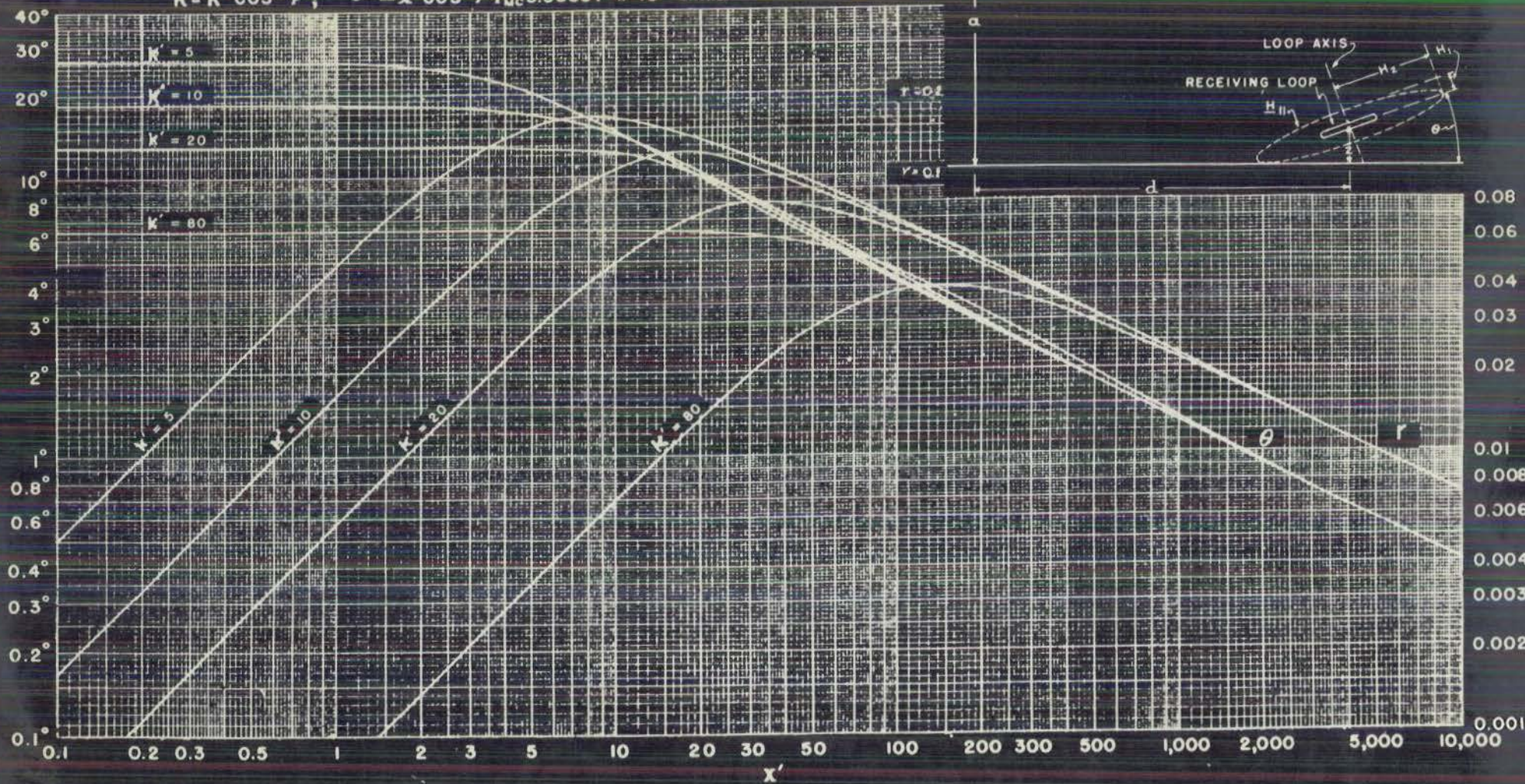
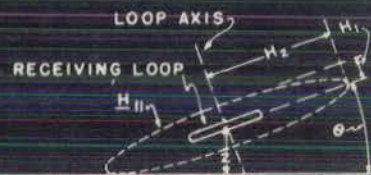


FIGURE 8

FIGURE 5



FIG. 9

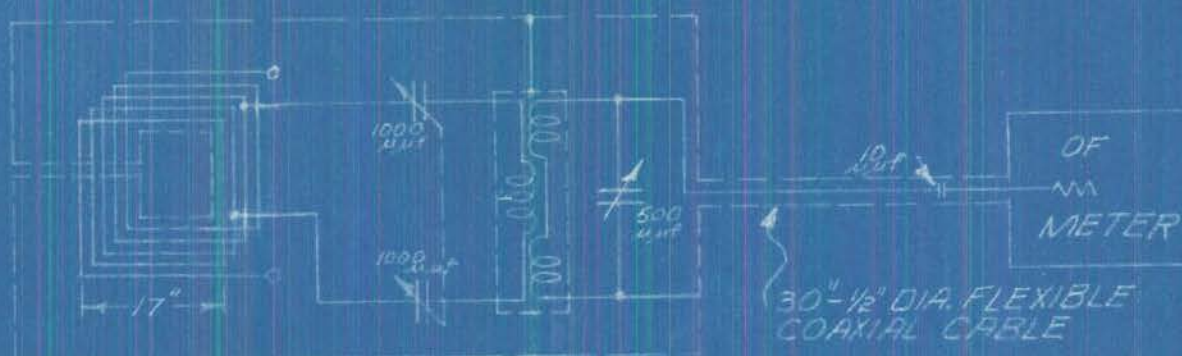


FIG. 10: MODEL OF METER INPUT CIRCUIT.

CIRCUIT CONSTANTS	
LOOP INDUCTANCE	
1-TURN	2.5 μh
5-TURNS	49 μh
LOOP DISTRIBUITED CAPACITY	
1-TURN	70 μuf
5-TURNS	410 μuf
TRANSFORMER	
PRIMARY INDUCTANCE	1.4 μh
SECONDARY INDUCTANCE	5.5 μh
MUTUAL INDUCTANCE	.079 μh

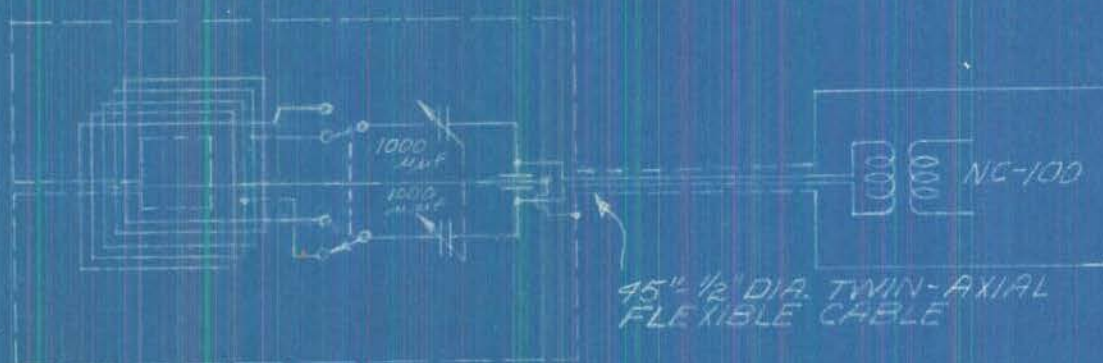


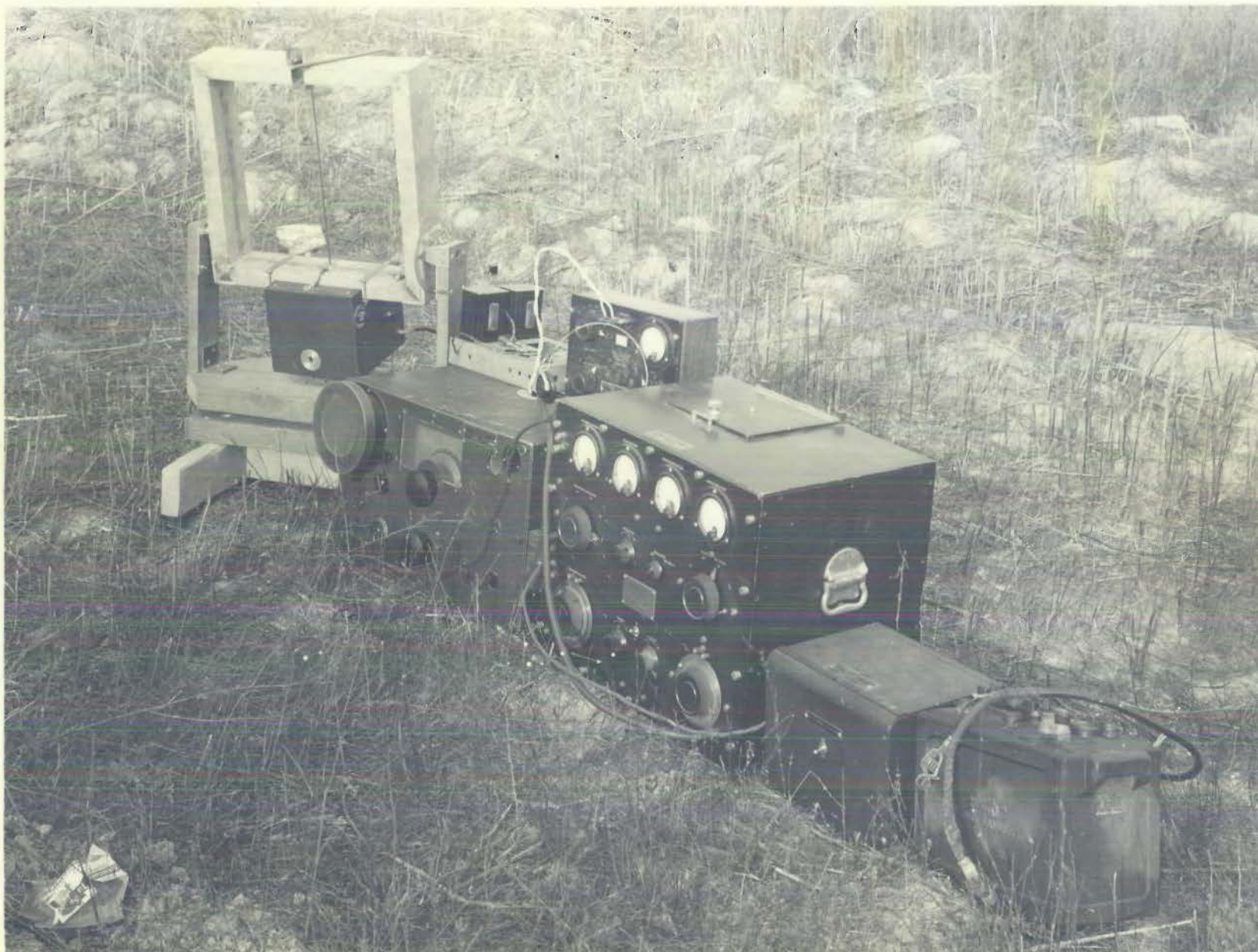
FIG. 11: NC-100 RECEIVER INPUT CIRCUIT.



SPECIAL LOOP -- MODEL OF RECEIVER



BATTERY-OPERATED TRANSMITTER
USED WITH MODEL OF METER SET ON DF-4 HOUSE



SPECIAL LOOP
NC-100 RECEIVER WITH SIGNAL GENERATOR.
(TRANSMITTER OFF TO THE RIGHT)



TCS-5 TRANSMITTER
(LOOKING TOWARD THE RECEIVER SITE)



TCS-5 TRANSMITTER
(SHOWING GASOLINE POWER GENERATOR)



TCS-5 TRANSMITTER
(SHOWING ELECTRIC POWER SUPPLY AND MODULATOR)



NC-100 RECEIVER SITE
(TAKEN FROM SAME POSITION AS PLATE 5)

TABLE 2.

Measurements of Samples of Soil taken from Different Depths at Various Sites.

From Reference (4)

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity (in e.s.u.) at 20° C. and at frequencies in kilocycles per sec. of:—				Apparent dielectric constant (in e.s.u.) at frequencies in kilocycles per sec. of:—	
						1	100	1 200	10 000	1 200	10 000
90	Rugby Radio Station (1)	Lower lias	ft. Surface	Dark fibrous loam	60	3.0×10^8	3.4×10^8	3.9×10^8	6.0×10^8	100	55
92			1	Loam and clay	33	6.5	7.0	7.0	9.0	95	43
93			2	Clay and sand	26	7.5	8.0	8.0	12.0	105	48
94			3	Blue clay	25	8.0	9.0	9.5	11.0	95	46
95			10	Blue clay	23	6.0	6.5	7.0	8.5	60	29
97	Rugby Radio Station (2)	Lower lias	Surface	Loam	22	0.55	0.65	0.70	1.1	35	25
104			1	Loam and clay	13	0.85	0.85	1.2	1.4	32	21
105			3	Blue clay	27	6.5	7.5	8.0	13.0	125	75
106			5	Clay and sand	21	5.5	5.5	6.5	9.0	75	42
107			10	Blue clay	25	7.0	8.0	8.5	12.0	70	40
98	Baldock, Herts (P.O. Receiving Station)	Chalk	Surface	Fibrous loam	21	0.85	0.90	0.95	1.4	39	23
99			1	Chalky loam	21	0.55	0.55	0.85	0.95	41	25
100			2	Chalk	24	0.28	0.26	0.38	0.61	28	21
101			3	Chalk	27	0.65	0.70	0.80	1.0	35	29
102			5	Chalk	26	0.91	1.4	1.6	2.0	45	38
103			10	Chalk	27	1.3	1.4	1.5	1.9	44	34
108	Tatsfield, Kent (B.B.C. Receiving Station)	Upper greensand	Surface	Fibrous loam	37	2.7	3.4	4.0	5.0	80	49
109			1	Brown, sandy clay	19	2.2	2.4	2.4	3.8	39	19
110			2	Brown sand	15	1.8	2.0	2.1	3.3	33	19
111			3	Light brown sand	13	1.4	1.5	1.6	2.1	33	25
112			5	Light brown sand	20	2.3	2.3	2.5	4.0	60	37
113			10	Yellow sand	15	1.5	1.7	2.0	2.9	60	28
114	Brookmans Park, Herts (London Regional Station)	London clay	Surface	Fibrous loam	19	0.90	0.95	1.1	1.7	48	25
115			1	Stony loam	18	0.85	0.90	0.95	1.4	40	24
116			2	Light sandy clay	22	0.50	0.65	0.70	1.6	45	24
117			3	Sandy clay	22	1.1	1.2	1.5	2.9	70	33
118			5	Sandy clay	21	1.5	1.7	1.9	2.6	75	36
119			8 to 10	Clay and shingle	10	1.5	1.6	1.6	2.7	42	23

TABLE 2

TABLE 2.—Continued.

Measurements of Samples of Soil taken from Different Depths at Various Sites.

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity (in e.s.u.) at 20° C. and at frequencies in kilocycles per sec. of:—				Apparent dielectric constant (in e.s.u.) at frequencies in kilocycles per sec. of:—	
						1	100	1 200	10 000	1 200	10 000
121	Daventry, Northants	Upper lias	ft. Surface	Fibrous loam	per cent 28	0.85×10^8	0.95×10^8	1.1×10^8	1.6×10^8	48	30
122			1	Sandy loam	16	0.34	0.34	0.40	0.61	20	17
123			2	Brown sand	14	0.29	0.29	0.33	0.46	20	14
124			3	Brown sand	5.0	0.10	0.11	0.12	0.19	11	8
126			5	Sand and sandstone	8.5	0.075	0.090	0.12	0.22	14	9
125			10	Sand and sandstone	24	0.26	0.33	0.44	0.80	47	31
127	Washford Cross, Somerset (West Regional Station)	Red marls	Surface	Reddish-brown loam	23	1.5	1.7	1.8	2.3	46	32
128			1	Reddish-brown clay	20	1.5	1.7	1.8	2.5	50	33
130			2	Reddish-brown clay	18	2.6	2.8	3.1	3.6	80	45
129			3	Reddish-brown clay	21	4.7	4.9	5.5	8.0	130	85
131			5	Reddish-brown clay	19	2.8	3.1	3.3	4.2	55	40
132			10	Reddish-brown clay	15	4.3	4.5	4.5	6.1	70	55
133	Brendon Hills, Somerset	Devonian	Surface	Black fibrous loam	210	1.3	1.5	1.8	2.5	90	65
134			1	Loam and slate	9.0	0.026	0.030	0.040	0.060	12	10
135			2	Loam and slate	9.0	0.016	0.016	0.026	0.035	9.0	8.0
136			3	Loam and slate	8.0	0.0055	0.0060	0.013	0.015	7.0	6.5
137			5	Loam and slate	5.5	0.0022	0.0039	0.0085	0.016	6.0	5.5
S. 7			10	Slate	—	0.00026	0.0025	0.0092	0.046	9.5	8.0
140	Merrivale, Dartmoor, Devon	Granite	1	Gritty loam	18	0.12	0.12	0.16	0.18	22	15
141			2	Gritty loam	13	0.14	0.14	0.18	0.20	14	13
S. 1			3 to 10	Granite	—	0.00090	0.0070	0.028	0.11	12	8.5
S. 2			3 to 10	Granite	—	0.00070	0.0050	0.019	0.095	10.0	7.5
S. 3			3 to 10	Granite	—	0.00039	0.0021	0.011	0.050	9.5	7.5
S. 5			3 to 10	Granite	—	0.000015	0.00090	0.0024	0.015	7.0	6.5
139	Dousland, Dartmoor, Devon	Devonian	Surface	Loam	47	0.55	0.60	0.70	0.85	50	30
142			1	Dark brown loam	41	0.24	0.24	0.31	0.47	32	27
S. 4			Below 1	Slate	—	0.00028	0.0017	0.011	0.050	9.5	8.0
S. 6			Below 1	Granite	—	0.000030	0.00026	0.0016	0.0070	6.0	6.0

143	Moorside Edge,	Millstone	Surface	Fibrous loam	130	1.2×10^8	1.6×10^8	1.8×10^8	3.9×10^8	95	40
144	Yorks (North	grit	1	Dark grey clay	60	1.2	1.4	1.6	3.1	75	36
145	Regional		2	Dark grey clay	35	0.70	0.95	1.0	2.4	85	33
146	Station)		3	Dark grey clay	39	1.1	1.5	1.6	3.1	75	36
147			5	Dark grey clay	19	0.85	1.0	1.2	2.9	70	31
148			10	Yellow and grey clay	15	0.31	0.33	0.37	0.75	28	16
149	Westerglen,	Boulder	Surface	Fibrous loam	38	0.55	0.65	0.75	1.1	50	20
150	Falkirk (Scot-	clay	1	Fibrous loam	30	1.0	1.0	1.1	1.5	60	20
151	tish Regional		2	Clay and loam	19	1.1	1.1	1.2	1.7	60	21
152	Station)		3	Dark grit and clay	18	0.60	0.70	0.80	1.2	50	19
153			5	Dark grit and clay	18	1.9	2.2	2.5	3.3	75	22
154			10	Dark grit and clay	15	2.1	2.3	2.6	3.2	80	24
160	Teddington,	London	Surface	Fibrous loam	26	1.0	1.1	1.2	1.7	40	14
161	Middlesex	clay	1	Sandy loam	20	0.65	0.70	0.90	1.1	22	14
162	(N.P.L.)		2	Sandy loam	13	0.60	0.65	0.65	1.0	20	12
163			3	Fine gravel	6.5	0.50	0.60	0.65	0.85	20	10
164			5	Coarse gravel	2.9	0.17	0.18	0.21	0.30	12	6.5
166			7	Fine sand	2.6	0.14	0.14	0.15	0.21	7.5	5.0
165			10	Sand and shingle	20	1.2	1.4	1.5	1.8	31	16
167	Wychbold,	Red marls	1	Red clay and loam	15	1.5	1.8	2.0	3.3	49	22
168	Droitwich		2	Red clay	13	3.1	2.9	3.0	4.7	42	23
169	(Midland		3	Red clay	14	2.1	2.2	2.4	4.0	60	29
170	Regional		5	Red clay and stones	15	3.9	4.6	4.8	8.5	55	31
171	Station)		10	Red clay and stones	21	3.7	4.0	4.2	7.0	60	30
172			20	Red clay suspension	31	6.0	7.0	7.5	11.0	65	16
173			30	Red clay suspension	41	6.0	7.0	7.0	12.0	65	38
174			40	Red clay suspension	25	5.5	6.5	6.5	10.0	60	13
175			50	Red clay	27	7.0	7.5	8.5	12.0	60	16
176			100	Grey clay and salt	28	16.0	21.0	22.0	25.0	—*	—
177			150	Red clay and salt	27	—	← about 100 →			—*	—
178			200	Red clay and salt	24	—	← about 100 →			—*	—
179			250	Red clay and salt	22	2.2	2.3	2.4	2.4	30	13
180			300	Red clay and salt	21	7.0	8.0	8.5	17.0	95	24

* The values of the dielectric constant for samples Nos. 176, 177, and 178, were difficult to measure accurately owing to the high conductivity of these samples. Sufficient measurements were made, however, to indicate that the dielectric constant was negligible compared with the conductivity; that is, $\kappa f/(2\sigma) \ll 1$.

TABLE 3

Numerical Evaluation of Ground Constants

Using the Model OF Meter Set at 7 Mc

Field Ellipse Tilt	Axes Ratio			Dielectric Constant	Ground Conductivity (esu)
θ°	r	K'	X'	K	$\sigma \times 10^{-8}$
6.4	.0931	8.6	46.4	8	1.5 ₁
6.8	.0886	13.3	43.8	12	1.4 ₅
6.5	.0921	10.3	45.8	10	1.4 ₉
6.4	.0907	10.6	47.2	10	1.5 ₄
			Mean	10	1.4 ₉
		Average Deviation		± 1	$\pm .03$
		Precision		10%	2%

$$\cos^2 \psi = 0.929$$

TABLE 4

Numerical Evaluation of Ground Constants

Using the NC-100 Receiver Set at 7 Mc

Field Ellipse Tilt	Axes Ratio			Dielectric Constant	Ground Conductivity (esu)
θ°	r	K'	X'	K	$\sigma \times 10^{-8}$
5.2	.1006	6.9	53.7	7	1.8 ₅
5.6	.1000	3.3	50.7	3	1.7 ₅
5.5	.0976	*	53.1	*	1.8 ₃
5.7	.1046	4.0	47.7	4	1.6 ₄
5.6	.1070	5.7	47.0	6	1.6 ₁
5.7	.1080	5.1	45.8	5	1.5 ₇
5.5	.1101	7.9	46.0	8	1.5 ₈
5.8	.1108	5.4	43.9	5	1.5 ₁
			Mean	5	1.6 ₇
		Average Deviation		± 1	± 0.11
		Precision		20%	6 $\frac{1}{2}$ %

$$\cos^2 \psi = 0.984$$

*For $X' \gg (K' - 1)$, K is indeterminate.

TABLE 5 SUMMARY OF NUMERICAL VALUES GIVEN IN APPENDIX

Date	Investigator	$\epsilon \times 10^{-8}$	K	Type of Soil or Site Conditions	Location	Method
1927	Gish & Rooney Paragraph 30 (a) 2	.01 13 1.4		Surface Sand 200 meters deep 600 meters deep	Watheroo, Aus.	DC with 60 cycle Reversal
1931	Tagg & Megger Paragraph 30 (a) 3	0.5			Southern England	DC with 50 cycle Reversal
1932	Collard Paragraph 30 (a) 4	.6 1.5		Site #1 Site #2	Southern England	Mutual Imp. of 2 Earthed Ckts at 3000 cycles
1930	Higgs Paragraph 30 (a) 5	.75		Sand, normal Moisture content and temperature	Slough, England	50 cycle
1930	Ratcliff and White Paragraph 30 (b) 1	0.2-0.5 (Irratic) .05	40-12 5	Samples from two sites; same samples dried out		Condenser-reactance 0.2-0.5 Mc.
1930	Strutt Paragraph 30 (b) 2	0.33-0.44			Eindhoven, Holland (?)	Condenser-reactance 5200-5500 Kc
1933	Feldman Paragraph 30 (b) 3; 32	0.8-1.5 1.9 0.1-0.3	12-23 28 7-10	Black top soil Clay subsoil	Holmdel, N.J. Netcomb, N.J.	Condenser-reactance 9.4-37.5 Mc
1924	Barfield & Smith-Rose Paragraph 30 (c) 1	0.6-4.7 0.9			Southern England Slough, England	Wave Tilt, Electric Dipole 620-860 Kc.
1932	Barfield & Munro Paragraph 30 (c) 2	0.5-2.5			Slough, England	Wave Tilt, Electric Dipole, 19 Mc
1928	Bailey, Dean & Wintringham (Par 30(c) 4)	1.0-2.5 0.14			Great Britain Houlton, Maine	Wave Antenna 60 Kc

TABLE 5 SUMMARY OF NUMERICAL VALUES GIVEN IN APPENDIX cont'd

Date	Investigation	$\sigma \times 10^{-8}$	K	Type of Soil or Site Conditions	Location	Method
1926	Ratcliff & Barnett Paragraph 30 (d) 1	1.6 (190 kc) 0.5 (830 kc)				Field Attenuation Sommerfeld Analysis
1926	Barfield Paragraph 30 (d) 2	0.2-1.0				Field Attenuation 825 kc
1932	Munro Paragraph 30 (d) 3	0.8-3			Slough, England	Field Attenuation
1930	Rolf & Lenoire Paragraph 30 (d) 4	.05-.09 (230 kc)	15		Motola & Karls- borg Stations, Sweden	Field Attenuation Rolf-Modified Sommerfeld Analysis
		1.3 (1 Mc)	10		Maluno, Sweden	"
1932	Kirby and Norton Paragraph 30 (d) 5	0.3-1.0	13 (Aver)		U.S., Various sites	Wave Attenuation 0.6-1.0 Mc
1930	Cherry Paragraph 30 (d) 6	3.6 (810 kc) 3.0 0.9 0.45 (580 kc)		Bare ground Low scrub & light timber Thickly wooded Site #2	Melbourne, Australia	Wave Attenuation
1930	Strutt Paragraph 30 (e) 1	0.45	10		Holland	Lecher Wires 0.5-20 Mc
1929	Strutt Paragraph 30 (e) 2	10 (210 Mc) 1 (1 Mc)		Same site	Holland	Antenna Interfer- ence Effect
1929	McPetrie & Smith- Rose Paragraph 30 (e) 3	5-30 (30-60 Mc) 95 (190 Mc)		Same site	Teddington, England	Field Attenuation
1924	Radio Research Board Paragraph 31	0.7-0.8 .14-4.7		Large Dipole Small Dipole	Slough, England Southern England	Wave Tilt, Electric Dipole

TABLE 5 (Cont'd)

TABLE 5 SUMMARY OF NUMERICAL VALUES GIVEN IN APPENDIX Cont'd

Date	Investigation	$\sigma \times 10^{-8}$	K	Type of Soil or Site Conditions	Location	Method
1934	Barfield Paragraph 34	0.5-4	30-10			Wave Tilt, Electric Dipole (50-15 meters)
1934	Smith-Rose Paragraph 35	(See Table 2)				
1934	McPetrie Paragraph 36	10(1.5M) 40(.46M)	7-16 7-20			Wave Interference
1932	Smith-Rose & McPetrie Paragraph 37	10-28	10-12			Lecher Wire (at 1.5M)
1935	Smith-Rose Paragraph 38	1 to 2	10^5 to 15^*	Normally moist		Condenser Reactance 50 cycles to 100 Mc
1943	McPetrie & Saxton Paragraph 47	1-3 10-1	20-15 60-5	Site 1 Ground changed from clay to gravel		Interference effect 60 Mc

TABLE 5 (Contd.)

* Apparent dielectric constant: $K' = K \left(1 - i \frac{2\sigma}{Kf} \right)$