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THE PROPAGATION OF RADIO WAVES OVER THE EARTH

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ABSTRACT

Theory of radio wave propagation over the earth.—Larmor's theory of refraction due to the electrons of the Kennelly-Heaviside layer does not explain the "skip distances" for short radio waves (regions of silence around the transmitter which Taylor's measurements showed to be 175, 400, 700 and 1300 miles in radius in the daytime for waves of 40, 32, 21 and 16 meters, respectively, and which are surrounded by zones of strong signals). The range as a function of wave-length shows a minimum for about 200 meters which suggests the introduction of a critical frequency term. If the effect of the magnetic field of the earth on the motion of the electrons is taken into account, as suggested by Appleton and by Nichols and Schelleng, the modification of the Larmor theory necessary to fit it to the experimental facts is secured. A quantitative theory is here developed. The upper atmosphere is assumed to contain N free electrons per cc., and neglecting absorption the dispersion equations are worked out for various modes of polarization of the radio waves. Then the skip distances are computed, making various assumptions as to the electron density distribution. (a) Reflection theory. As a first approximation the layer is taken to be sharply separated from the un-ionized lower atmosphere. At this layer total reflection occurs in accordance with Snell's law. (b) Refraction theory. The following distributions are considered: (1) Density increasing linearly with the height h, beginning at a certain height h_0; (2) Density proportional to h^2; (3) Density proportional to e^h; (4) Density proportional to $h^{\frac{1}{2}}$. Comparison with the experimental skip distances shows good agreement, and indicates that the radio waves which just reach the edge of the zone beyond are refracted around a curved path, reaching in the daytime a maximum height of from 97 miles (case 1, $h_0=21$ miles, and case 2) to 149 miles (case 3). At this height the electron density comes out close to 10^5 electrons per cc. At night the electron density gradient is less and the height is greater. These conclusions agree with physical conceptions from other evidence. From the dispersion equations it follows that for waves of 60 to 200 meters, total reflection may occur from the electron layers at all angles of incidence. From this result, combined with interference between various modes of polarization of the radio rays, a detailed qualitative explanation of many fading phenomena is presented. Further conclusions are: That the ions in the atmosphere have little effect in comparison with the electrons; that for longer waves, the Larmor theory is correct; that short waves are propagated long distances by refraction in the upper atmosphere and reflection at the surface of the earth, not by earth-bound waves; that waves below 14 meters cannot be efficiently used for long distance transmission.

INTRODUCTION

THE conception that upper regions of the atmosphere of the earth relatively richer in ions and electrons than the lower levels may play an important role in the propagation of radio waves over the earth has become more firmly established with the years. It is the purpose of this paper to develop the conception in greater detail than perhaps has been done up to this time and to discuss the conclusions quantitatively in the light of new experimental observations on the transmission of short radio waves over long distances. The first suggestion[1] of ionized atmospheric layers in connection with radio waves was, as far as we know, published by Kennelly.[2] Heaviside[3] set forth similar ideas independently a few months later. We have therefore thought it correct to speak of the ionized layer as the "Kennelly-Heaviside layer," although the designation "Heaviside layer" has been widely used in the literature of radio.

Although no complete summary of the researches on electric wave propagation will be attempted here, a few of the more important steps may be outlined briefly. Our experimental knowledge of the variation of the strength of the received signal as the distance from the transmitting station is increased is due largely to the work on waves longer than 500 meters carried out in 1910 and 1913 by the United States Navy under the direction of Austin.[4] The results are usually expressed by the well-known Austin-Cohen formula, which showed, in particular, that the intensity of the received wave fell off faster than the distance from the source than would be required by a simple inverse square law. The mathematical researches of Nicholson,[5] Love,[6] and Van der Pol,[7] Macdonald,[8] Watson,[9] and others have led to the conclusion that a simple theory of diffraction of the waves around an earth of finite, or infinite, conductivity immersed in a limitless dielectric yielded an intensity decrement factor very much greater than the experimental factor of the Austin-Cohen formula. In order to obtain agreement with observations the presence of converging waves was necessary, which meant that a portion, at least, of the waves must be reflected or refracted downward from the ionized upper reaches of the atmosphere. This was in strong support of the Kennelly-Heaviside conception which just at that time had been given a more definite formulation by

[1] See L. Bouthillon, L'Onde Électrique **2,** 345 (1923).

[2] Kennelly, Electrical World and Engineer, p. 473 (March 15, 1902).

[3] Heaviside, Encyclopædia Britannica, Tenth Edition, Ninth Volume (No. XXXIII), p. 215 (December 19, 1902).

[4] Austin, Bull. Bur. Stand., **7,** 317 (1911).

[5] Nicholson, Phil. Mag. **22,** 157 (1910); **21,** 62 (1911).

[6] Love, Phil. Trans. Roy Soc. A, **215,** 105.

[7] Van der Pol, Phil. Mag. **38,** 365 (1919).

[8] Macdonald, Proc. Roy. Soc. **71A,** 251 (1903).

[9] Watson, Proc. Roy. Soc. **95A,** 546 (1919).

Eccles.[10] Eccles assumed an upper layer so intensely ionized as to reflect the rays without penetration, combined with an ionization of the middle atmosphere which bent them, and in his treatment dealt only with the motions of the heavy ions. It has remained for Larmor[11] in an interesting paper of accustomed clarity, to sketch a theory of refraction due largely to the free electrons. These were shown to be of such long free path as to exert a negligible absorption on the waves passing through them. Being lighter than the ions of Eccles only comparatively few electrons were necessary to produce sufficient bending of the rays.

At the end of the year 1924 it appeared that a reasonable and adequate theory of radio wave propagation had been rounded out, as yet qualitative to be sure, but requiring only obvious measurements to be placed on a quantitative basis. At this satisfactory stage, as has often happened before, new phenomena made their appearance which the theory was unable to cope with. Larmor's equations gave a refraction which decreased with the wave-length becoming small for waves below 60 meters, whereas the work of Reinartz[12] and Taylor[13] on the "skip distance" for waves below 60 meters immediately indicated a stronger refraction than for the long waves. Fortunately, at this time Appleton[14] pointed out that the free electrons would move in spiral paths at a specified frequency because of the magnetic field of the earth, and that perhaps peculiar effects would occur for waves near this frequency. This meant of course the introduction of a critical frequency term into the refraction equation, which produced exactly the modification required, i. e., it left Larmor's equations (which had neglected the magnetic field of the earth) approximately unchanged in the region of longer waves and brought the theory into agreement with the short wave data. It may be mentioned that we had already independently introduced a critical frequency term into the classical dispersion formula used by Larmor, basing the idea on the curve of Fig. 2, without however troubling as to the physical cause of the term. From Appleton's suggestion it was immediately possible to apply the classical formulas of magneto-optics to the Kennelly-Heaviside layer. While this was in progress the paper of Nichols and Schelleng[15] appeared in which similar ideas, again of independent origin, were taken up. However, this paper and theirs do not cover the same ground, for

[10] Eccles, Proc. Roy. Soc. **87A,** 79 (1912).

[11] Larmor, Phil. Mag. **48,** 1025 (December, 1924).

[12] Reinartz, "QST" **9,** 9 (April, 1925).

[13] Taylor, Proc. Inst. Radio Eng. **13,** 677 (December, 1925).

[14] Appleton, Proc. Phys. Soc. London **37,** Part 2, p. 22D (February, 1925).

[15] Nichols and Schelleng, Bell System Techn. J. **4,** 215 (April, 1925).

in their paper no quantitative applications of the formulas to observations were made. The publication of this paper* has been delayed until the results of the observations on the secondary skip distances were available.

Data from Taylor's Range Chart

The observational data of interest in the present development are to be found in Taylor's Range Chart,[13] which presents in graphical form a summary of a large number of experimental observations on the transmission of radio waves of wave-lengths from 16 to 3000 meters over distances up to 10,000 miles. The experiments have been carried out during recent years by the Radio Division of this laboratory with the assistance of the American Radio Relay League and their co-workers in the foreign countries. On the chart, which is not reproduced here, are plotted the relative ranges of transmission of the various wave-lengths, as far as they have been investigated, reduced to a uniform condition, namely, 5 kilowatts in a normal transmitting antenna. The average ranges for day and night and for summer and winter are included.

From the chart certain new facts regarding the behavior of the short waves stand out. It has been found that for wave-lengths shorter than 50 meters the intensity of the received signal decreased as the distance from the transmitter was increased, reaching a value too small to be observed at a distance of a hundred miles or so. With further increase of distance the received signal remained undetectable until a region was reached where the received signal became strong again, rising rapidly to a maximum and thereafter decreasing rather slowly. The distance from the transmitter to the far edge of the region of silence, which we may call the "skip distance," was found to increase rapidly as the wave-length decreased; for a specified wave-length it was longer at night than in the day and longer in winter than in summer. The skip zone was not very sharply defined of course, but passed into the region of steady signals through a transition zone, sometimes called the "flicker" zone, where the signals were erratic and subject to violent fading. It may be emphasized that the skip zone was not merely a zone of uncertain signal reception, but a region where the signals were entirely absent for the most part; a conservative estimate would be that the intensity of the signal at a point three fourths of the distance out into the skip zone was at least 10^{-4} of the intensity of the signal

* A preliminary abstract of the present paper appeared in Science, p. 183 (August 12, 1925).

zone beyond. The skip distances, denoted by $2s$, averaged throughout a year, for full daylight conditions, for wave-lengths 16, 21, 32 and 40 meters were 1300, 700, 400 and 175 miles, respectively. These are plotted as rectangles in Fig. 1. The values naturally can not claim great accuracy and may perhaps be in error by as much as a hundred miles. The skip distances at night are not yet known with precision. This is due perhaps to an insufficiency of data, but more probably to the fact that conditions at night are so erratic that even more extended observations would fix the distances only within wide limits. Present information indicates, however, that the night skip distances are on a rough average three or four times the corresponding day values.

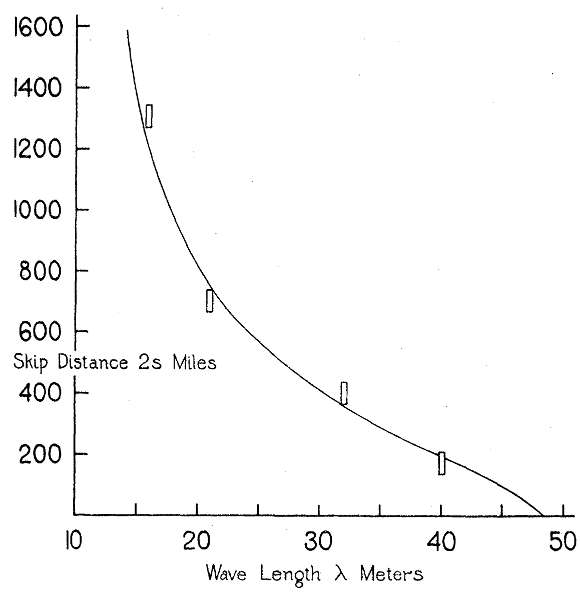

Fig. 1. The skip distances averaged throughout a year, for full daylight conditions, as a function of wave-length.

We regard these skip distance phenomena as demonstrating forcibly that two portions of the transmitted wave may be differentiated, one which clings to the earth and decreases rapidly in intensity until it is lost, and the other which moves in an upward direction and returns to the earth after refraction, with little attenuation in the Kennelly-Heaviside layer.

In Fig. 2 are plotted the ranges, under full daylight conditions, averaged throughout a year for uniform transmitting conditions, i. e. 5 kilowatts in a normal transmitting antenna, against the corresponding wave-lengths. Although the physical basis of the curve is essentially composite, for each wave-length may be propagated in a characteristic manner, the pronounced minimum in the curve at about 200 meters is taken to suggest a critical region of dispersion or of absorption. The agreement of the position of the minimum with the calculated critical wave-length 214 meters (§6) gives reality to this suggestion.

Dispersion Equations of a Magnetized Electron Gas

3. It is assumed that the regions of the Kennelly-Heaviside layer owe in the main their optical properties to the presence of the free electrons, and in the equations the influence of the magnetic field of

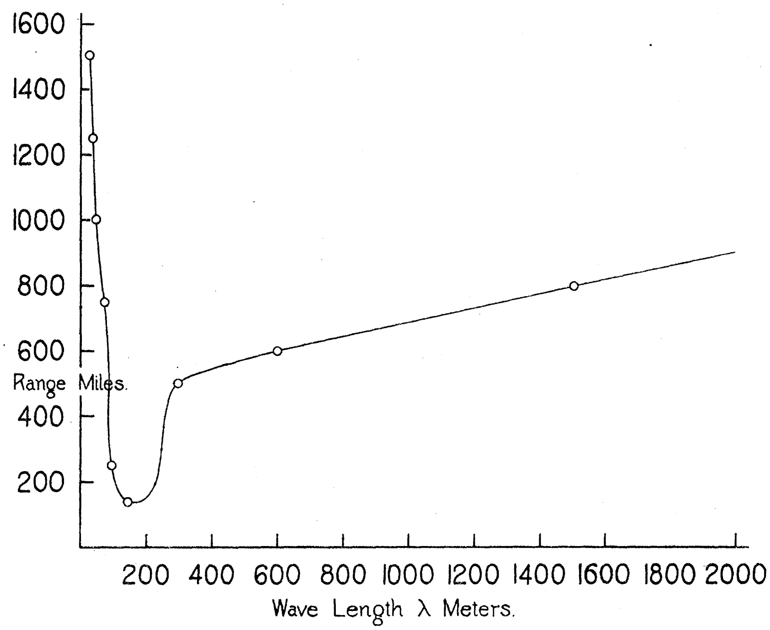

Fig. 2. The ranges, under full daylight conditions, averaged throughout a year, for uniform transmitting conditions, as a function of wave-length.

the earth is taken into account. We follow the classical electron theory of Lorentz,[16] and in application to the present problem we assume no restoring force on the electrons due to the medium, no absorption, and no effect of the electrons on each other; this amounts to placing a, f and g equal to zero in equations (198) (see Lorentz, loc. cit.,[16] p. 139). Let ξ and E_x be the X components of the displacement of the electron from its equilibrium position and the electric force, respectively, and η, ζ, E_y and E_z the Y and Z components of the quantities. The charge on the electron is denoted by e, its mass by m; N is the number of

[16] H. A. Lorentz, "The Theory of Electrons," Chapter IV (1916).

electrons per unit volume. The magnetic permeability of the medium is taken to be unity. All quantities are expressed in c.g.s., e.m. units.

4. *Propagation parallel to the magnetic field.* This case will apply approximately to North and South propagation. We denote the magnetic field by H and suppose it to have the direction of the axis of Z, which is also the direction of the propagation of the radiation. We take the radiation to be initially plane polarized. In Newtonian notation the equations of motion of the electrons are

$$\left.\begin{aligned} m\ddot{\xi} &= eE_x + He\dot{\eta}\,, \\ m\ddot{\eta} &= eE_y - He\dot{\xi}\,, \\ m\ddot{\zeta} &= eE_z\,. \end{aligned}\right\} \quad (1)$$

Let ϵ be the base of natural logarithms, and let all dependent variables of (1) contain the time only in the factor $\epsilon^{i2\pi tc/\lambda}$ where c/λ is the frequency, c is the velocity of light in vacuum, and i is $\sqrt{-1}$. The solution of (1) yields two vibrations circularly polarized in opposite directions, whose refractive indices μ are given by the relations

$$\mu^2 = 1 - \frac{C\lambda^2}{1 - \lambda/\lambda_0}\,, \quad (2)$$

$$\mu^2 = 1 - \frac{C\lambda^2}{1 + \lambda/\lambda_0}\,, \quad (3)$$

where

$$C = Ne^2/\pi m \text{ and } \lambda_0 = 2\pi cm/He\,. \quad (4)$$

The details of this solution are here omitted for they are essentially the same as those given by Lorentz. If the refraction is not great or the distance of propagation is small the wave remains coherent and the two circularly polarized components add to give in general an elliptically polarized wave. For equal intensities of the two components the resultant wave is plane polarized with the plane of polarization rotated from its original direction. If the two components are separated, by greater refraction or distance, each will proceed as a circularly polarized wave.

5. *Propagation perpendicular to the magnetic field.* In this case, which will refer approximately to East and West propagation, the initially plane-polarized wave is resolved in general into two component vibrations with electric vectors parallel and perpendicular to H, respectively. The solutions of the appropriate equations of motion of the electron

yield refractive indices μ for the parallel and perpendicular cases, respectively,

$$\mu^2=1-C\lambda^2\,, \tag{5}$$

$$\mu^2=1-\frac{C\lambda^2}{1-\lambda^2/\lambda_0^2(1-C\lambda^2)}. \tag{6}$$

If the wave remains coherent the two plane vibrations unite to produce in general an elliptically polarized wave, but if the two components are separated, each will proceed as a plane polarized wave. Eq. (5) of course represents the propagation in the absence of a magnetic field as discussed by Larmor. It may be mentioned in passing, although no use is made of the fact here, that for the plane polarized wave component of formula (6) the electrons describe ellipses whose planes are parallel to the direction of propagation of the wave and perpendicular to H. From one point of view these vibrations can not be said to be transversal. This peculiar instance was recognized long ago by Voigt. The case may be compared with the motion of the particles on the surface of deep sea waves on water.

6. In the general case of propagation at an angle with the magnetic field all four of the modes of vibration just discussed may occur in greater or less proportion, with the result that the wave, if coherent, will become elliptically polarized, the orientation of the axes and the eccentricity of the ellipse changing as the wave proceeds. If the refraction or distance of propagation is sufficiently great the various components may be separated from each other.

Taking the value of H for the earth's magnetic field to be 0.5 gauss, λ_0 from (4) comes out to be 214 meters. This is the value calculated by Nichols and Schelleng (loc. cit.) and is the value used for λ_0 throughout this paper. The minimum at about 200 meters of the curve of Fig. 2 agrees closely with $\lambda_0=214$ meters. This is regarded as an experimental confirmation, indirect of course, of the theoretical calculation.

To bring out the characters of the various dispersion formulas the curves 2, 3, 5 and 6 have been plotted in Fig. 3 from Eqs. (2), (3), (5) and (6) respectively, choosing $N=3.95\times10^5$ electrons per cc. In the region of wave-lengths less than 50 meters the curves do not differ greatly. With increase in λ all the curves of Fig. 3 descend to zero and μ becomes imaginary, remaining so for the longer waves in the case of curves 3 and 5. For curves 2 and 6 μ remains imaginary until wave-lengths λ_0 and $\lambda_0\sqrt{1-C\lambda^2}$ are reached, respectively. At these wave-lengths, called the "critical" wave-lengths, μ is $\sqrt{\pm\infty}$ and as λ is increased beyond them μ descends from high positive values finally to low values again. As a matter of fact the critical wave-length $\lambda_0\sqrt{1-C\lambda^2}$ appears to be of no physical importance, for, due to the presence of C in this expression, no wave can reach the region of electron density where this critical condition for the wave prevails.

7. *Absorption in the Kennelly-Heaviside layer.* Among various possible causes of absorption of energy from the electromagnetic wave by the upper reaches of the atmosphere the most important would seem to arise from collisions between electrons and molecules. This would

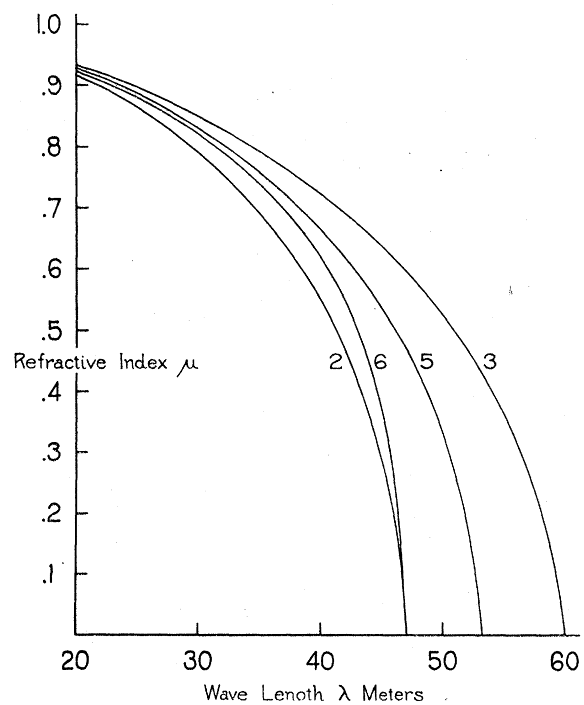

Fig. 3. Refractive indices of the Kennelly-Heaviside layer as a function of wave-length for rays in and perpendicular to the direction of the earth's magnetic field (Eqs. (2), (3), (5), (6)).

convert a portion of the energy of the wave into heat. Simple calculations, such as given by Larmor and by Nichols and Schelleng, indicate that the probability of collision is small, so that absorption due to this cause is negligible, except in the region near the critical wave-length λ_0 and for very long waves outside of the usual radio range, which have a very slow oscillation. In lower regions of the atmosphere, where the density of molecules is greater, absorption due to collision might exist even for shorter waves. If we assume that this type of absorption can be expressed as a frictional term in the equations of motion of the electron, which is no doubt permissible within limits, the dispersion formulas are all available in treatises on magneto-optics. For small absorption these differ from Eqs. (2), (3), (5) and (6) by wholly inappreciable amounts for wave-lengths removed by, say, 30 meters from $\lambda_0 = 214$ meters. Near to this critical region the absorption term produces complex modifications, which have been discussed by Nichols and Schelleng. It is, however, justifiable to neglect absorption as long as the critical region is avoided; and we have been content to avoid this region because of its complexity and because the observations on these wave-lengths are mainly qualitative.

For a wave traveling near the earth the matter of absorption is quite different. This has been discussed by Zenneck,[17] Sommerfeld and others who showed that the earth absorption may become very high for the shorter waves. The successful radio transmission to distances as great as half-way around the earth with waves below 90 meters proves that the attenuation is small, no matter to what cause it is attributed, and this combined with the pronounced earth absorption for the shorter waves leads forcibly to the conclusion that the waves must travel in the upper atmosphere and that the absorption in these regions is slight.

Reflection Theory

8. It is assumed that the lower levels of the atmosphere of the earth are relatively free from electrons and that the lower surface of the Kennelley-Heaviside layer, the region of relatively great electron density, is sharply marked. A radio ray transmitted in an upward direction would travel in a straight line and after reflection from the layer would return in a straight line to the earth. Actually, of course, the optical constants of the lower atmosphere merge without discontinuity into those of the electronic regions, so that a ray instead of being sharply reflected is refracted along a curved path. As often happens in theoretical physics, we consider first the simple case of sharp reflection and then pass to a refraction theory which is probably more in accord with the real state of things. Moreover, many of the conclusions of the reflection theory are found to be unchanged for the refraction theory.

We take the lower boundary of the layer, represented by AE in Fig. 4, to be a spherical surface parallel to the surface of the earth and at a height h above the earth. The radius of the earth is R. Let CAF

[17] Zenneck, "Wireless Telegraphy," 3rd Ed., p. 248 (1915).

be the path of a radio ray transmitted from C which is reflected from A at an angle ϕ and let the length of the arc CF be $2s$; s subtends the angle θ at the center of the earth. *It is now assumed that when $2s$ is the observed skip distance for a specified wave-length ϕ is the critical, or Snell, angle of total reflection of the wave from the layer.* Since the refractive index of the atmosphere below the layer is unity this assumption of course involves the condition that the refractive index of the layer is less than unity for those wave-lengths for which a skip distance exists. Otherwise a critical angle of total internal reflection would be impossible and no skip zone would exist. If μ is the refractive index of the Kennelly-Heaviside layer, then from Snell's Law,

$$\mu = \sin\phi \ . \tag{7}$$

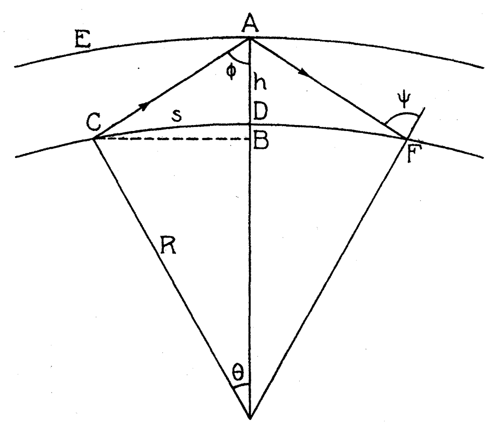

Fig. 4. Reflection from the Kennelly-Heaviside layer.

From the geometry of Fig. 4,

$$\sin\phi = CB/AC = R\sin\theta / \{R^2\sin^2\theta + (R+h-R\cos\theta)^2\}^{1/2} \tag{8}$$

and

$$s = R\theta \ .$$

The discussion is limited for the moment to the special case of dispersion represented by Eq. (2). When this equation was combined with (7) and (8) to eliminate ϕ and θ there resulted a relation between the unknown quantities h and C, the known constants R and λ_0, and the observed quantities λ and s. The substitution of the observed skip distances $2s$ for wave-lengths 16 and 40 meters into this relation yielded two equations in h and C. Eliminating C from these led to a quartic equation in h, which determined h and thence C. with these values of h and C, with $R = 3970$ miles and with $\lambda_0 = 214$ meters the $2s,\lambda$ curve was plotted and readjusted to approximate a least square solution.

The final $2s,\lambda$ curve is shown in Fig. 1, and the values of h and C corresponding to this curve were 152 miles and 3.54×10^{-8}, respectively. With this value of C in (4) together with the usual values of the electronic mass and charge, N came out to be 3.95×10^{5}. The agreement between the theoretical curve and the observed values in Fig. 1 is regarded as a confirmation of the correctness of the theory. Further, the values of h and N which have emerged appear reasonable. h is well within the aurora domain which, according to Stormer[18] is between 50 and 300 miles above the earth. In this region where the pressure may be of the order of 10^{-5} atmospheres a simple calculation indicated that an electronic density of the order of 10^{5} per cc. is easily possible, the electrons supposedly being caused mainly by the ultraviolet light of the sun. The values for N and h appeared to be quite definitely established as far as the present theory and calculations were concerned, for a variation in them of as little as 20 percent gave rise to discrepancies between the calculated and observed skip distances. Further, N and h did not depend at all critically on the value chosen for λ_0, changing, for example, by only a few percent when λ_0 was varied from 120 to 300 meters. The reason for this lay in the nature of the dispersion equation (2), and the fact that the wave-lengths below 60 meters were remote from the critical wave-length λ_0. It would therefore appear that N and h and the refraction of the rays are little influenced by time or space variations in the earth's magnetic field.

9. The dispersion curve, μ against λ, plotted from Eq. (2) with $\lambda_0=$ 214 meters and $N=3.95\times10^{4}$, is shown by curve 2, Fig. 3. The Snell angles ϕ calculated by means of (7) for wave-lengths 16, 21, 26, 32 and 40 meters were 71.8, 65.2, 58.4, 49.2 and 33.4 degrees, respectively. The angles which the direction of the down-coming wave at the edge of the skip zone makes with the vertical are for the respective wave-lengths 79.5, 70.6, 62.1, 51.8 and 34.8 degrees. These were calculated from the relation $\psi=\phi+\theta$ (see Fig. 4). An experimental determination of these angles would offer direct evidence concerning the present theory. In such experiments complicating effects of the ground at the receiving station should be avoided or recognized.

Since h is roughly proportional to s, the fact that the night skip distances are about three times the day values indicates that h at night is three times the day value. The angles ψ will be greater at night than in the day by amounts corresponding to the change in θ.

10. Because of the bulge of the earth and the curvature of the layer, the curve of Fig. 1 ceased to exist at wave-length 14 meters. The

[18] Stormer, Proc. Phys. Soc. London, **37**, part 2, 50 D (1925).

Snell angles for wave-lengths shorter than this being so nearly 90° that even rays transmitted horizontally from the surface of the earth could not be totally reflected from the layer. Since it appears that the overhead reflected (or refracted) wave and not the ground wave is all-important in long-distance short wave radio transmission, *the present theory indicates that communication over long distances by means of wave-lengths less than 14 meters will be relatively difficult.* This is due to the mechanism of the propagation entirely apart from the inherent technical difficulties in the apparatus for producing these very short waves with appreciable intensity. The few experiments which have been made in this region support this conclusion; for example, no long distances have been reached in the case of tests with 5 meter waves. It is hardly necessary to remark that due to unusual ultra-atmospheric conditions, etc., long distance communication with very short waves may be successful at times. Such cases should prove to be the exception rather than the rule.

11. The foregoing calculations have been based on dispersion equation (2) which refers to one of the circularly polarized waves arising from propagation along the magnetic field. They are, furthermore, valid and accurate, within limits, for the general case of propagation of a wave with electric vector at a random and changing angle to the magnetic field, because the general case differs but slightly from the special case in the region of wave-lengths below 40 meters. This is evident when the μ,λ curves for the various dispersion equations, Eqs. (2), (3), (5) and (6), are compared. These are plotted in Fig. 3, curves 2, 3, 5, and 6 respectively, using the constants $\lambda_0=214$ meters and $N=3.95\times10^5$ or $C=3.54\times10^{-8}$. For wave-lengths below 40 meters the refractive indices for the various curves are closely the same, and hence the Snell angles and the skip distances are approximately the same. In this connection curve 3 may be disregarded for it refers to one of the component waves of propagation parallel to the magnetic field and wherever this exists the other component represented by curve 2 also must exist. The skip distances from curve 2 are all less than those from curve 3 and are therefore the ones which would be observed. The cases of propagation which differ most widely are, then, those represented by curves 2 and 5. These yield skip distances which differ by about 60 miles, those from curve 5 being the greater. If Eq. (5) instead of (2) had been used h and N would have come out roughly 10 percent different from the values for (2). Therefore the values of h and N, which have been determined from curve 2, may be considered to be sufficiently accurate for the general case, which lies

somewhere between the conditions of the curves 2 and 5; especially so, since the values can only be looked upon as rough averages of quantities which probably vary each moment of the day throughout the year. It follows at once from the approximate sameness of curves 5 and 6 which refer roughly to East and West propagation, and of curve 2, which refers to North and South propagation, that the skip distances do not vary appreciably with the compass direction of propagation. This is in accord with the experimental observations.

In the band of wave-lengths between 50 and 60 meters the curves of Fig. 3 suggest an appreciable variation in skip distance with the mode of propagation. For example, if the conditions of curve 3 obtained, we might expect a skip distance of 120 miles for a 50 meter wave, whereas under the conditions of curve 2 no skip distance would exist. There is some evidence that this effect exists although the observations are none too certain because of the ground wave which may fill in the skip region. However, there is noticed at times an unusual flickering in the intensity of signals in this region which farther away are stronger and steadier.

12. Up to this point we have mentioned only the contribution of the electrons to the dispersion in the upper atmosphere, and we may now show that the more massive ions have little influence. In the dispersion formulas (2), (3), (5) and (6) the effect of the ions on μ may be calculated to a first approximation by adding another term (or terms, there being a term for each type of ion) similar to the last term of each equation, using the mass of the ion instead of the electron, which for, say, a nitrogen ion is 10^4 greater. The quantity $C = Ne^2/\pi m$ in the numerator of the ionic term is then 10^{-4} of the corresponding quantity for the electronic term for the same density of ions and electrons, the denominators being approximately the same for short waves. Therefore the ionic term will be negligibly small compared to the electronic term, except for very long waves outside of the usual radio range unless there are at least 10^3 as many ions as electrons. Such a preponderance of ions is hardly to be expected in general. In view of this and of the good agreement of the theory with the observations, as indicated in Fig. 1, the conclusion may be emphasized that *the reflection (or refraction) of radio waves in the layer is caused in general by the electrons and not by the more massive ions*. This may be regarded as a definite proof of the presence of considerable numbers of electrons in the upper atmosphere of the earth.

Refraction Theory

13. The physical conditions in the upper atmosphere are scarcely such as to render tenable a theory of reflection, for the transition from

the low electron density of the lower atmosphere to the higher concentration of electrons in the Kennelly-Heaviside layer must be gradual and not abrupt. We therefore pass to a theory of refraction as offering a more exact picture of actual conditions, with the preliminary remark that the results of the refraction theory are for the most part identical with those of the reflection theory. This is to be expected since reflection is only a special case of refraction. We must now call attention to a circumstance which throws further doubt on a reflection theory and which supports a refraction theory. If we suppose, as has been done, that the edge of the skip zone marks the Snell angle of total reflection then, as we pass into the skip zone to points where reflection occurs at angles less than the critical angle, the reflected intensity will become less, but will not drop to zero, and in the case of rather oblique incidence, as with the 16 meter wave, the reflected intensity may be decreased by only a few percent. It would therefore follow that the intensity of the signals would drop off very slowly as the skip zone was entered never reaching low values except at nearly normal incidence, and even there not zero. It is well known, on the contrary, that the signal intensity at, say, a distance of one fourth of the way in from the outer edge of the skip zone, is less than 10^{-4} of the intensity in the region beyond the skip zone. This discrepancy in the case of the reflection theory does not occur for the refraction theory.

The calculations become much simpler if we consider the case of a flat earth instead of the curved earth discussed heretofore. For a flat earth Eq. (8) of the reflection theory becomes

$$s = h \tan \phi \tag{9}$$

which is of course a close approximation to (8) for short distances, up to 1000 miles. It will be shown later, however, that entirely apart from this approximation, the flat earth calculation can be referred to a curved earth with exactness.

The elaboration of a refraction theory requires the determination of the ray-paths of the wave, and these may not be determined explicitly without a knowledge of the variation of the optical constants of the atmosphere with the distance above the earth. The method of procedure has thereupon consisted in assuming a number of types of this variation and in investigating the results of these assumptions.

14. It is assumed that the surface of the earth is flat and that the refractive index μ of the region lying above the earth is a function of y and not of x, where Y and X are the coordinate axes in the vertical and horizontal directions, respectively. μ is assumed finite, single-valued and continuous for a specified wave throughout the region. Let ABC,

Fig. 5, be the ray which is projected from a point A on the surface of the earth at an angle ϕ with the vertical let μ_0 be the refractive index of the atmosphere at A. Let adjacent elements on either side of a point B on the curve make angles i and $i+di$ with the vertical, and let the refractive indices at these elements be μ and $\mu+d\mu$, respectively. Then, from Snell's Law

$$(\mu+d\mu)/\mu=(\sin i)/\sin(i+di).$$

Whence

$$\mu=\alpha/\sin i,$$

where α is a constant of integration. From the initial conditions $\mu=\mu_0$, $i=\phi$, we obtain

$$\alpha=\mu_0 \sin\phi \tag{10}$$

and

$$\mu=(\mu_0 \sin\phi)/\sin i \tag{11}$$

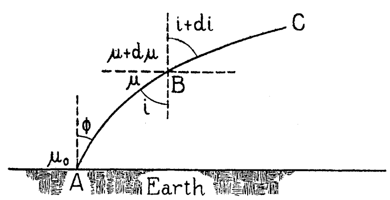

Fig. 5. Refraction of a radio ray in an electron atmosphere of variable density.

This is Snell's Law generalized for the present problem. Since (11) must be satisfied at every point of the ray-path, the differential equation of the path is

$$dy/dx=-\cot i=-\sqrt{(\mu^2-\alpha^2)/\alpha^2} \tag{12}$$

where $\mu=f(y)$ and α is independent of x and y. This may not be integrated explicitly and therefore the equation of the ray-path can not be determined, unless $\mu=f(y)$ is known. In order to proceed farther various assumptions as to $f(y)$ are made and investigated in the following paragraphs.

15. *Case 1. Electron density proportional to height.* It is assumed that the electron density sets in at the surface of the earth and increases proportionally with the height above the earth. We write

$$N=\beta y \tag{13}$$

where N is the electron density at a point y cm above the surface of the earth. Then, from (3) for each of the dispersion formulas (2), (3), (5), and (6),

$$\mu^2=1-\gamma y \tag{14}$$

where γ is determined by identifying (14) with each dispersion formula in turn. At the surface of the earth $y=0$ and from (14) $\mu=1$. Therefore, from (10)

$$\alpha=\sin\phi. \tag{15}$$

Introducing (14) into (12) and integrating gives for the equation of the ray-path,

$$x^2=\{4\alpha^2(1-\alpha^2-\gamma y)\}/\gamma^2. \tag{16}$$

This is a parabola. The constant of integration has been eliminated by a shift of the curve along the X axis. The maximum height h above the earth reached by the ray is

$$h=(1-\alpha^2)/\gamma. \tag{17}$$

The ray comes down to the earth again at a distance $2x_0$ from its starting point, where

$$x_0=2\alpha\sqrt{1-\alpha^2}/\gamma\ . \tag{18}$$

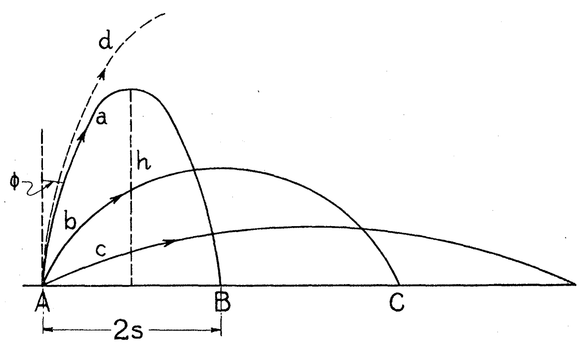

Fig. 6. Refraction of radio rays transmitted from A at varying angles through an electronic atmosphere whose density is proportional to the height.

Combining (18) with (15) and (17) leads to

$$x_0=2h\tan\phi\ . \tag{19}$$

The ray-paths plotted from (16) for a specified wave transmitted from A, Fig. 6, at increasing angles ϕ are illustrated by curves a, b, and c, Fig. 6. It is seen that as ϕ increases h decreases and $2x_0$ increases. *We may now identify AB, the distance between the feet of curve a, as the skip distance for the wave in question.* This means that any other ray such as d, whose angle of projection ϕ is less than that of ray a, will not return to the earth between points A and B; it may possibly return at some distant point or perhaps not at all. It follows, therefore, that the law of electron distribution given by (13) ceases to hold above the summit of curve a. Just what will be the law above h is of course unknown, but this much can be said, that the electron density must increase less rapidly above h than it did below h. *Therefore the "height of the Kennelly-Heaviside layer" means merely the distance above the earth to the region where the rate of increase in the electron density with the height becomes less. And because of its physical appeal, in spite of other mathematical possibilities, we take this region to be the region of maximum electron density.*

According to the supposition just made that AB of curve a, Fig. 6, be the skip distance for the wave, formula (19) becomes

$$s=2h\tan\phi\,. \tag{20}$$

We might now introduce the observed skip distances into (20) and from the relation $\mu=\sin\phi$ at the height h and one of the dispersion equations determine h and N, just as was done in the case of reflection. It is not necessary to do this, however, because of the similarity of (20) and (9). It is seen that these formulas, which refer to a flat earth, are the same except that h of (20) is one-half h of (9). We may therefore conclude that if the skip distance refraction formula for a curved earth corresponding to (20) had been developed, it would be nearly the same as (8) which is the reflection formula for a curved earth corresponding to (9). This is true because only matters of geometry enter into the transformation from a curved to a flat earth. We may finally conclude that *all the numerical facts of this refraction case are exactly the same as those which have been derived from the reflection theory, except that h is one-half the h of the reflection theory.* h is now 76 miles, but N, the calculated $2s,\lambda$ curve, the angles at which the rays at the edge of the skip zone descend to the earth, etc., are as before.

We may now emphasize the contention stated in §13, which pointed out that within the skip zone the intensity of the received signal is known to be 10^{-4} or less of the intensity in the surrounding signal zone. The refraction theory is in accord with this, for referring to Fig. 6, there is no ray-path possible which connects the transmitter A with a receiver inside the skip zone.

16. *Case 1a.* The assumption of (13) and the result that for $y=76$ miles $N=3.95\times10^5$ electrons per cc is scarcely possible, for this would mean that at a height one mile above the earth there are 5×10^3 electrons per cc which is probably too large a number in general. If we then suppose that there are no electrons in the lower atmosphere up to a height h_0 and that the linear density law (13) sets in thereafter, it is easily seen that the ray-paths are straight lines in the region h_0, changing to arcs of parabolas in the region above h_0 and finally be-

coming straight lines again when the ray returns to levels below h_0. The skip distance formula corresponding to (20) is in this case

$$s=(h_0+2h')\tan\phi \cdot \tag{21}$$

$h'+h_0$ is the height of the summit of the ray above the earth, which is the height of the Heaviside layer. As h_0 increases from 0 to 76 miles, $h'+h_0$ increases from 76 to 152 miles, and we pass from the electron distribution of (13) to the case of abrupt reflection. Because of the similarity of (21) and (20) all that has been said of the applicability of the reflection theory results to Case 1 applies equally well to the present case of refraction.

17. *Case 2. Electron density proportional to square of height.* In the notation of Case 1, it is assumed that

$$N=\beta y^2 . \tag{22}$$

Proceeding exactly as in Case 1, the equation of the ray path is

$$y=(\sqrt{1-\alpha^2}/\sqrt{\gamma})\sin(x\sqrt{\gamma}/\alpha) , \tag{23}$$

which is a sine curve. The skip distance formula is

$$s=(\pi h/2)\tan\phi , \tag{24}$$

and the height h comes out to be 97 miles.

18. *Case 3. Electron density proportional to exp. (height).* It is assumed that

$$N=\beta\epsilon^y \tag{25}$$

and proceeding as before the equation of the ray-path is

$$x=\frac{\alpha}{\sqrt{1-\alpha^2}}\log_\epsilon\left\{\frac{2(1-\alpha^2)-\gamma\epsilon^y+2\sqrt{(1-\alpha^2)(1-\gamma\epsilon^y-\alpha^2)}}{\gamma\epsilon^y}\right\} . \tag{26}$$

The skip distance formula is

$$s=(\tan\phi)\log_\epsilon\left\{2\epsilon^h-1+2\sqrt{(\epsilon^h-1)\epsilon^h}\right\} , \tag{27}$$

from which h is 149 miles. This is a special case of an exponential distribution, but possesses all the essential features of a more general type which would be described by $N=\beta e^{by}$, where b is a constant.

Since the skip distance formulas (24) and (27) are similar to (9), the reflection theory results also apply to these cases, the height of the Heaviside layer being different, of course. Furthermore, corollary cases similar to Case 1a when carried out for Cases 2 and 3 gave results exactly similar to those of Case 1a. This is so evident that the details are omitted.

19. *Case 4. Electron density proportional to square root of the height.* From the assumption that

$$N = \beta y^{1/2} \tag{28}$$

the equation of the ray-path is

$$x = (4\alpha/\gamma^2)\sqrt{1-\gamma y^{1/2}}\left\{1+2\alpha^2/3+(1-\gamma y^{1/2})/3\right\} . \tag{29}$$

The skip distance formula is

$$s = (8/3)h \tan\phi \cdot (3/\cos^2\phi - 1) . \tag{30}$$

It was found impossible to choose constants for the dispersion formulas such that (30) be in accord with the observed skip distances. Similar discrepancies with observation resulted from the assumption that $N = \beta y^{1/3}$ and $N = \beta y^{1/4}$.

20. *Case 4a.* In this instance we modify Case 4, just as was done in Case 1a, and assume that no electrons exist below a height h_0 and that the electron distribution of Case 4 begins there. The skip distance formula becomes

$$s = h_0 \tan\phi + (8/3)h' \tan\phi \cdot (3/\cos^2\phi - 1) . \tag{31}$$

It was found that this formula was at variance with the observed skip distances as long as the second term was important, which occurred when h_0 was small. As h_0 becomes larger the second term becomes of less effect, and we appoach the sharp reflection case and better agreement with observation.

21. In taking up the refraction cases 1, 2, and 3 in turn we have passed from an electron distribution linear with the height progressively to electron distributions for which the N, y curve becomes more and more convex to the Y axis, approaching the distribution for sharp reflection, and have arrived at heights of the Heaviside layer which became in turn nearer to 152 miles. All these have yielded the same $\lambda, 2s$ curve in agreement with observation, i. e., the curve of Fig. 1, and therefore all are equally possible as far as this agreement is concerned. On the other hand, it has been shown in Case 4 that an electron distribution for which the N,y curve is concave to the Y axis led to pronounced discrepancies with the observed skip distances. This is all in comforting agreement with reasonable expectation. On general physical grounds one would expect an electron distribution whose rate of increase became greater with the height, whereas it is difficult to imagine the stable existence of a distribution whose rate of increase became less with the height. The conclusion to be derived is *that the electron density N,*

during full daylight and averaged over all the days of the year, of the atmosphere of the earth increases with the height y in such a way that the N,y curve is for the most part convex to the Y axis, and that N reaches a maximum value of the order 10^5 *for a height which is between 70 and 150 miles.*

Again, the increase of the skip distance at night which indicates an increase in h is to be expected. For, with the removal of the sun's radiation, (electromagnetic, electronic, etc.), which is probably the most potent cause of ionization in the atmosphere, recombination of the ions and electrons will occur. The electron density therefore becomes less and the radio rays must search higher altitudes before being turned back to the earth.

22. Certain details of the dispersion equations (2), (3), (5) and (6) are of interest. From all the equations at any wave-length less than $\lambda_0 = 214$ meters, μ decreases to zero and becomes imaginary as N (or C) increases. This means that a ray of this wave-length directed normally upwards passes through regions of decreasing μ (and hence moves with increasing velocity) until it reaches that electron concentration for which $\mu = 0$ and there is totally reflected (or refracted) back to the earth. *Therefore wave-lengths from about 60 to 200 meters will be totally reflected from the layer at all angles of incidence.* The different component modes of polarization will penetrate to different heights. For waves shorter than 50 meters, N can not become large enough to make μ imaginary, since the calculations fix the maximum value of N as 10^5, and hence these rays are not totally reflected at normal incidence, but at a greater angle; this of course is the essence of the fore-going skip distance theory.

For waves longer than 214 meters, μ decreases to zero and thence to imaginary values with increase of N in the cases of equations (3), (5) and (6). From Eq. (2) however, μ is always positive for these waves and increases from 1 as N grows larger. *Therefore for waves longer than 214 meters the modes of polarization corresponding to equations* (3) (5) *and* (6) *will be totally reflected from the layer at all angles of incidence, the mode of equation* (2), *however, always being refracted upward and being probably lost.* (Eq. (5) has further mathematical complexities which appear to be of no physical significance). The prediction that these waves suffer total reflection even at normal incidence should perhaps admit of direct experimental proof. For long waves, greater than 500 meters, (3) reduces approximately to $\mu^2 = 1 - C\lambda\lambda_0$ and (5) and (6) to $\mu^2 = 1 - C\lambda^2$. These are about the same for small values of C, and the latter is the refraction formula for zero magnetic field. Hence the earth's magnetic field has little influence in the bending of the long waves, and therefore Larmor's development, which neglected the magnetic field of the earth and referred to long waves is valid throughout.

Distortion of the Received Wave

23. We must now call to mind certain well-known radio phenomena concerning the distortion of the received wave usually resulting in fading, i. e., fluctuations in intensity, of continuous wave signals and in poor modulation and fading of speech signals. Two general types of fading are differentiated, which we now recognize as attributable to quite different causes. One type, which is common to all wave-lengths is an intensity fluctuation of relatively long period, of the order of a second or more. This is usually more noticeable at nearer distances than at greater distances from transmitter, and in general the longer the wave the slower the fluctuation. The other type is a fading at high speed, the signal intensity often varying from full strength to practically zero at a low audio frequency of the order of, say, 100 oscillations per second. This appears as a change in the quality of the heterodyne note when continuous wave signals are being received and as bad distortion in the case of speech signals. The audio frequency fading characteristic applies only to certain bands of wave-lengths at certain distances from the transmitter; it is, generally speaking, less observable in the day time and at longer distances. More specifically, for waves longer than 800 meters, roughly, the high speed fading rarely occurs; in the broadcast band, 300 to 600 meters, it is noticeable only at intermediate distances, at night especially, from about 100 to 1000 miles from the transmitter. In the region of shorter wave-lengths from 60 to 120 meters the high speed fading is violent at night for distances from roughly 5 to 300 miles from the transmitter. For the wave-lengths 16 to 40 meters the audio frequency fading is found in the flicker zones at the edge of the skip regions. Every detail of these fading phenomena finds a ready explanation in terms of the refraction ideas of this paper, and although qualitative, furnishes strong confirmation of those ideas.

24. With regard to the fading at low frequency, of a few seconds in period, we adopt the view, already suggested by many others, that this is due to a distortion of the received wavefront by motions of large clouds of the refracting electron medium. On the assumption, which appears very reasonable, that the bodily motions of the electron clouds are of the same order of velocity and extent as the air movements and

currents in the lower atmosphere, one would expect low frequency fluctuations in a wave refracted through such a medium. The phenomenon is a repetition on a larger and slower scale of the twinkling of the stars or of the unsteadiness of a scene viewed over the surface of a hot road. For longer waves motions of larger electron clouds are necessary to modify the wave-front, and these on the average would be expected to be slower than in the case of smaller clouds, so that the fading would be slower. Futher, for long distances for all wave-lengths the integrated cloud movements and hence the refraction effects would be expected to average out. This is all in accord with observation.

25. The audio frequency fading is attributed to shifting interference patterns, and finds its optical analogue in the "light beats" of Airy and Righi.[19] Thus, considering the band of waves from 300 to 600 meters, which exhibit occasionally audio frequency fading at distances from 100 to 1000 miles from the transmitter, it is seen from §22 that the various polarization components of the wave, except that of Eq. (2) are totally reflected from the layer at all angles of incidence. Therefore, in this instance any receiver, no matter where situated, may expect to receive in general four possible rays, the ground wave and the three overhead waves of Eqs. (3), (5) and (6) which travel to the receiver by different paths. In the first 100 miles from the transmitter the ground wave is sufficiently intense to drown out any variations contributed by the overhead components. Beyond 100 miles the intensity of ground wave for these wave-lengths becomes comparable with or less than that of the overhead waves, with the result that a complicated interference pattern of various states of polarization and intensities is formed about the receiver. Movements of the electron layer will cause this pattern to shift to and fro, thereby causing the rapid fluctuation of signal intensity. In daylight the electrons gather into low lying clouds of relatively great density gradient, so that the paths of different overhead rays are relatively close together and the interference pattern becomes broad and hazy. Its movements therefore cause little change in the signals. At night, however, the electrons are more diffuse and their density gradient is much less, so that the ray paths are more wide'y separated. The interference bands are therefore narrower and sharper and the motion of the pattern will cause rapid and violent intensity variations. At distances greater than 1500 miles the ray paths are so long that the interference pattern becomes indistinct in both day and night and the average effects on it of electron cloud movements become less. It is interesting that these

[19] Airy and Righi, Journal de Physique, **2**, 437 (1883).

considerations call for the propagation of even these relatively long waves to great distances by an overhead route.

By similar reasoning fast fluctuations would not be expected to occur for long waves at any place, because in the near distances the ground wave is strong and in the far distances the interference pattern is diffuse. In the case of the 16 to 40 meter band it is easily seen that the possibilities for sharp interference exist only on the edge of the skip zones.

26. The discussion of the wave band from 60 to 120 meters is along similar lines. Here, however, the rapid fading occurs at distances as small as 5 miles from the transmitter. This means that for these waves at this distance the over-head components reach the receiver with an intensity comparable with that of the ground wave, even after traveling 100 miles or so up into the upper atmosphere and being reflected back at nearly normal incidence! There seems to be no escape from the conclusion that the ground wave in this case dies out rapidly and that the over-head components are very perfectly reflected. Thus what has long been an exceedingly puzzling phenomenon finds an equally startling explanation, startling at least until one accepts these ideas.

27. The various components of the wave, besides interfering, also may arrive at a receiver at different times, because of the different paths which they traverse. This will have no effect on the interference patterns just discussed, if the wave trains are long, as in continuous wave signals, but will become an additional cause of distortion in the case of short wave trains, such as the modulated waves of speech signals. In order to estimate the magnitude of this we assume that the electron distribution of Case 1a is the one which actually exists for daylight conditions and take $h_0=30$ miles; $N=0$ at this height. From the skip distance data and Eq. (21), $h'=61$ miles and $h_0+h'=91$ miles where $N=3.95\times10^5$. This gives the electron density gradient. From this and the dispersion equations (2), (3), (5) and (6) it is found that $\mu=0$ at heights 69, 86, 78 and 64 miles, respectively. These are the heights where total reflection occurs for the respective waves, as discussed in §22. Assuming normal incidence the differences of the paths of the rays from the transmitter to the region of total reflection and back to the receiver are roughly 20 miles, or 10^{-4} seconds. The rays, moreover, pursue their respective paths with different speeds, which are slower in the longer paths. Calculation shows that this will increase the time differences of the paths by two or three times, making them, say, 3×10^{-4} seconds. This would perhaps be barely perceptible in speech signals. At night, however, the ray-path differences would be

increased roughly three times, and the time differences would be of the order of 10^{-3} seconds or more, which would cause strong distortion of the speech signals. This estimate of the time differences of the rays has depended on the electron distribution assumed for the calculation. This suggests that an experimental analysis of the distortion in signals of wave-lengths 60 to 120 meters received at short distances from the transmitter would perhaps lead to more definite information about the electron distribution.

Long Distance Transmission

27. In the light of the foregoing conclusions it is of interest to consider the character of the reception at various distances from the transmitter. No attempt to cover all details will be entered upon, but a few cases deserve remark. It is convenient to make the diagrams from the reflection theory; the conclusions from these will be the same as from a refraction theory. In Fig. 7 the curved line AL is the surface

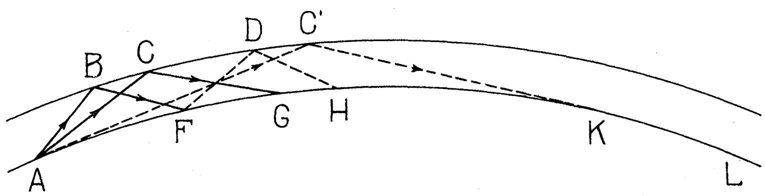

Fig. 7. Paths taken by radio rays in traveling around the earth.

of the earth and BC' the Kennelly-Heaviside layer at a height of 150 miles. Suppose that the radio rays from the transmitter A are confined to the space BAC. The upper limiting ray AB descends to F, where AF is the first skip region, is reflected back to D, down again to the earth at H, etc., continuing around by successive reflections. The lower limiting ray may be tangent to the earth as shown by AC' or may be inclined at an angle to the horizontal in the manner of AC. In the latter case if $AG<AH$, where $AH=2AF$, there exists a second smaller skip region GH. From a continuation of the drawing further skip zones are found at greater distances. These are possible, but perhaps not probable because they become successively smaller and more ill-defined.

If the bundle of transmitted rays is limited on its lower side by the tangent ray AC', which is reflected to the earth again at K, the region KL can be reached by a ray from A only after at least one ground reflection and two layer reflections (refractions). With a layer height of 150 miles AK is 2000 miles. The region FK, on the other hand, can be reached by a ray which has experienced only one layer reflection and no ground reflection. Therefore, because the ground reflecting power may vary with the locality, one might expect possibilities of poorer signals in the region *KL* than in the region *FK*, quite apart from the difference in remoteness; or, more graphically, the poor reception at a station 5,000 miles away may be due to a forest 2500 miles away. This distinction between the regions less and greater than 2,000 miles would seem to be generally valid at all wave-lengths for which the direct ground wave is inoperative and for all the electronic distributions permissible in §§15 to 20.

The observational data relevant to these questions are none too certain, but a recent program of tests with the 25.6 meter transmitter from this station (NKF) has permitted a few conclusions. A portion of the program involved the reception of the signals at every hour of a 24-hour day by some forty stations scattered to 7000 miles distance. In the first place, the first daylight skip zone for 25.6 meters was found to be between 500 and 600 miles, which is in excellent agreement with Fig. 1. Secondly, no secondary skip zone, as *GH*, Fig. 7, appeared; the region from 700 to 1200 miles in daylight being unmistakably one of good signals. This meant merely that the lower transmitted rays were probably near to tangency with the earth, as AC', Fig. 7. In this connection it might be possible to elevate the ray AC' until the second skip zone was produced, by properly loading and exciting the transmitting antenna.[20] Thirdly, the signals in the region from 2000 to 3000 miles appeared more uncertain than in the region within the 2000 mile mark. The observations referred mainly to over-land waves and it would be of interest to repeat them with over-sea waves.

In general, for the shorter waves observations by many receiving stations in the United States indicate better signal reception in the region extending from the first skip zone to 2000 miles than in the region between 2000 and 4000 miles where at least one earth reflection is involved. At greater distances, however, from 5000 to 10,000 miles the short wave signals are very reliable, much more so than in the 2000 to 4000 mile zone. This is to be expected because, with increase of distance, there are a greater number of possible ray-paths connecting the transmitter and receiver, so that a local disturbance, such as a poor earth reflection, etc., of any one ray will have small influence on the signal. One might expect the inverse distance law of signal intensity to hold approximately in this region for the short waves.

[20] Van der Pol, Proc. Phys. Soc. London **29,** 269 (1916-1917).

At the antipodes of the earth there is a concentration of ray paths and a corresponding increase in signal strength. This has been frequently observed.

For radio communication over longer distances, of the interplanetary order, waves shorter than 40 meters would appear to be best able to pierce our own electron atmosphere as well as that of another planet. The circularly polarized long wave of Eq. (2) is of speculative utility, depending as it does on the intensity of magnetization of the electron atmosphere. Venturing even further into the realm of conjecture, the course of a ray proceeding in interplanetary space would be influenced by the electrons distributed from the sun. If this distribution were impartial in all directions, the electron density increases toward the sun, and the radio ray would be diverted towards the sun. It might pass beyond the influence of the sun after a small deflection, or it might spiral towards the sun until it reached that electron density requisite for total reflection, whereupon it would pursue an enlarging spiral until free again.

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October 17, 1925.