On the Diurnal Variation of Ultra-Short Wave Wireless Transmission.* By Mr E. V. Appleton, St John's College.

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During the last few years the intensive study of the transmission of very short waves has revealed to us some remarkable facts relating to their use in long-distance communication. The experimental data have been obtained mainly by wireless amateurs and the Marconi Company in England, and by Major Mauborgne and Dr A. H. Taylor† in America. The low attenuation of such ultra-short waves in long-distance transmission is, of course, well known and need not be emphasized here. But these waves have been found to possess other remarkable properties which make them extremely interesting from a scientific point of view. For example, with wave-lengths of the broadcasting band (300–500 metres) we are familiar with the general, though variable, increase of signal strength at night. But with much shorter waves (e.g. 30 metres) cases often occur in which signals, though heard loudly during the day-time, become inaudible at night. Also, during the day-time it is not usual for a long-wave station to be inaudible at moderate distances from the transmitter and yet easily audible at much greater distances. Yet this phenomenon is quite common when very short wave-lengths are used. In this communication an attempt is made to explain some of the more salient features of such phenomena in terms of the ionized layer theory.

In the first place it must be emphasized that the propagation of very short waves over long distances must be almost wholly due to atmospheric influences, since, for such high frequencies, the diffractive bending round the earth is small and the ground absorption considerable. For example, with a wave-length of 30 metres the effect of the ground ray is very small indeed except near the transmitter and, with increasing distance up to 500 miles, the signal intensity becomes quite negligible. At a distance of about 500 miles ‡, however, the signals become suddenly stronger and are detectable up to 1500 miles, beyond which reception becomes uncertain. There is thus a zone of silence round the transmitter with an outer radius of approximately 500 miles. If, in accordance with the theory of

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* The term "ultra-short" is here applied to wave-lengths less than the critical band indicated by the magneto-ionic theory (i.e. about 200 metres). It seems desirable, for historical reasons, to retain the term "short waves" for the broadcasting wave-lengths 200–600 metres.

† Taylor, *Proc. Inst. Rad. Eng.* vol. 13 (Dec. 1925).

‡ Day-time transmission is here considered.

atmospheric influence which has been shown to explain the phenomena on broadcasting wave-lengths, we interpret the sudden increase of signal intensity at 500 miles as being due to the effect of a ray deviated back to the ground by the upper atmosphere, it has been shown by Mr Barnett and the writer* that an estimate of the minimum number of electrons or ions in the ionized layer can be made. In this connection let us consider the case of refraction by a medium of gradually varying refractive index, the variation being so gradual that the medium may be considered as homogeneous within a few wave-lengths. Let *ABCDEF* be a ray which enters the ionized layer at *B* and emerges from it at *E* (see Fig. 1).

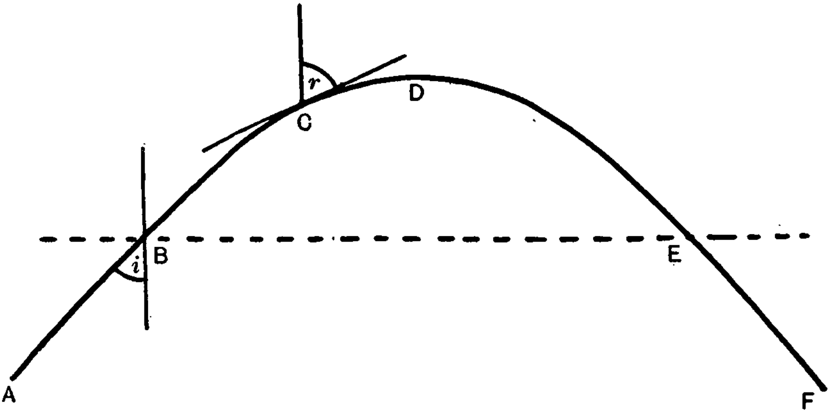

Fig. 1

Let i be the angle of incidence at the lower boundary of the ionized layer and μ_0 the refractive index of unionized air. Then it is easily shown from the general principles of optics that the refractive index μ at any point C is given by the relation

$$\mu_0 \sin i = \mu \sin r \qquad \text{......(1),}$$

where r is the angle between the ray direction at C and the vertical. Now at the highest point D of the trajectory we have $r = \pi/2$ and, since μ_0 may be considered unity,

$$\mu_D = \sin i \qquad \text{......(2).}$$

Now according to the magneto-ionic theory, for wave-lengths which are small compared with the critical band, we may write approximately

$$\mu^2 = 1 - \frac{4\pi N e^2}{m p^2} \qquad \text{......(3),}$$

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* Appleton and Barnett, *Proc. Roy. Soc.* A, vol. 109 (1925).

where N is the number of electrons (of charge e and mass m) per c.c., and p is the angular frequency of the radiation. From (2) and (3) we deduce that

$$\cos i = 2\sqrt{\frac{\pi N}{m}}\,\frac{e}{p} \qquad \ldots\ldots(4),$$

so that if i and p are known, N may be estimated. In this way* it has been shown that the value of N is approximately 10^5 per c.c. We may further note that reflection at vertical incidence ($i = 0$) is possible when

$$p = 2e\sqrt{\frac{\pi N}{m}} \qquad \ldots\ldots(5).$$

If the electron concentration is not any greater than 10^5 per c.c. at any height, this would indicate that wave-lengths less than 100 metres would not be reflected at vertical incidence, but would penetrate the layer and leave the earth. If the maximum concentration were 10 times greater, the critical wave-length would be reduced $\sqrt{10}$ times.

Let us now consider the phenomena of ultra-short wave propagation over various distances. Consider a transmitter at T (see Fig. 2) and a receiver R moving successively to R_1, R_2, R_3 and R_4. Experiments show that a receiver near the transmitter, say at R_1, receives audible signals, but, with increasing distance, this signal disappears so that the transmitter is not heard at R_2 and R_3. At R_4, however, the atmospheric ray assumes prominence resulting in signals of appreciable intensity.

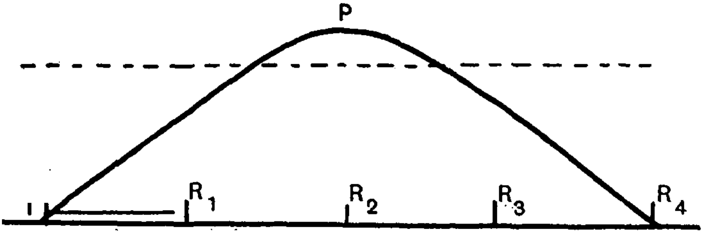

Fig. 2

To explain why the signals at R_4 are stronger than at R_3 we have to consider two possibilities. In the first place it can be shown that the "reflection coefficient" of the ionized layer for such cases as we are considering is greater the greater the angle of incidence, so that it might be argued that the increase of signal strength in

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* If the effective carriers were molecular ions, which is, however, unlikely, this number would be increased to 4×10^8 in the case of hydrogen and 3×10^9 in the case of nitrogen.

proceeding from R_3 to R_4 is due to the reduced absorption, due to the more nearly grazing incidence. According to this explanation the negligible signals at R_2 and R_3 are due to absorption-limitation. But there is a second possibility. We note from (4) that, as the angle of incidence is increased, fewer electrons are required to bring the ray horizontal and thus back to earth. We therefore can explain the phenomenon if we assume that the ray TPR_4 is a critical one, in that there are just sufficient electrons in the ionized layer to bend it back, while for smaller angles of incidence (and shorter distances) the rays suffer from electron-limitation and escape from the atmosphere altogether. The theory put forward here is that the second explanation is the correct one; that is to say that, in the wireless spectrum we employ wave-lengths which, in certain cases, the atmosphere, due to its finite electronic content, is unable to retain. The reason for the acceptance of the second alternative will now be discussed.

It has been shown that, in the case of the longer wave-lengths of the broadcasting band (300–500 metres), the rays returned from the upper atmosphere are, in general, of greater amplitude at night than during the day. The theory of diurnal variation which has been advanced to explain this is that the ionization, which produces the reduction in refractive index necessary to bring the ray horizontal, exists at lower levels during the day-time than during the night. In this case there is no electron-limitation of bending since the rays are bent down both by day and by night. But, due to the higher level at which bending occurs at night, the absorption resulting from collisional "friction" is smaller than that experienced during the day. Thus, if the first alternative considered in the case of ultra-short waves is correct, and the negligible signal intensity at R_3 is due to the excessive absorption of the ray reaching that point in the day-time, we should expect the absorption to be less at night and a signal strength increase to ensue. The signal strength at R_4 should also increase and the outer radius of the silent zone should be decreased. But in practice no such increases of signal intensity do occur; in fact the signals normally obtained at the edge R_4 of the silent zone disappear, the radius of the zone being increased. The theory of electron-limitation here presented adequately explains this, for if there are only just enough electrons to deviate the ray down in the day-time, there will not be enough at night when recombination of the ions has taken place in the lower layers of the atmosphere and it is necessary to deviate rays through larger angles to bring the waves down to the same receiver. Thus the outer radius of the silent zone should increase.

For longer distance transmission, where the bending is adequate and not electron-limited both by night and by day, we should expect an increase of signal intensity at night due to the reduced absorption, so that the maximum range of audible signals should increase. This, again, is in agreement with the experimental facts.

If we assume that the sun is the source of ionization during the day the ionized layer should be lower in summer day-time than in winter day-time. Thus, according to the explanation given above, the outer radius of the silent zone and the maximum range of audibility should be greater in the latter case than in the former. Since the ionizing agent is removed at sunset, recombination takes place, so that the height of the layer responsible for ray deviation is, in general, higher during the night than during the day. The silent zone will thus have its maximum radius and the maximum long-distance ranges will therefore be attained at night in winter, when the layer is at its highest level during the year.

Since only one ray reaches a point just outside the silent zone it is clear that signal variations due to interference phenomena, such as have been shown to exist with broadcasting wave-lengths, cannot occur. Now it is remarkable that fading is less pronounced just outside the silent zone than at greater distances. The fading that exists at the shorter distances is thus most probably due to changes in the polarization of the waves. It may be noted that, according to the magneto-ionic theory of atmospheric influence, the plane of polarization of ultra-short waves is rotated by transmission through ionized gas in the earth's magnetic field whether the propagation is east and west or north and south.

Let us now consider the relation between the outer radius D of the silent zone (the "skipped distance" as it is sometimes called) and the wave-length. Let AB in Fig. 3 (which is not to scale) represent part of the circumference of the earth, the centre of which is at O.

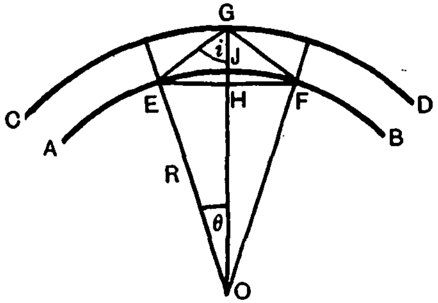

Fig. 3

Let CD similarly represent the ionized layer, so that JG the height of the layer is h. The wireless ray EG is incident at an angle i on the layer at G. EJF is the distance D of transmission and R

is the radius of the earth. If the angle EOH is θ it is easily shown that

$$D = 2R\theta \qquad \text{......(6)},$$

and

$$\cos^2 i = \frac{(h + R - R\cos\theta)^2}{(h + R - R\cos\theta)^2 + R^2\sin^2\theta} \qquad \text{......(7)}.$$

But, in the cases that we are considering, θ is small, so that from (4) and (7) we have

$$\cos^2 i = \frac{4\pi N e^2}{mp^2} = \frac{\left(h + \dfrac{R\theta^2}{2}\right)^2}{\left(h + \dfrac{R\theta^2}{2}\right)^2 + R^2\theta^2}.$$

On substituting for D from (6) this becomes

$$\frac{4\pi N e^2}{mp^2} = \frac{\left(h + \dfrac{D^2}{8R}\right)^2}{\left(h + \dfrac{D^2}{8R}\right)^2 + \dfrac{D^2}{4}} \qquad \text{......(8)}.$$

There is therefore no very simple exact relation between p and D, but, since in most practical cases the first term of the denominator of the right-hand side of (8) is small compared with the second, we may write

$$\frac{4\pi N e^2}{mp^2} = \frac{\left(h + \dfrac{D^2}{8R}\right)^2}{\dfrac{D^2}{4}} \qquad \text{......(9)},$$

or

$$\frac{\lambda D}{h + \dfrac{D^2}{8R}} = \text{const.} \qquad \text{......(10)},$$

λ being the wave-length.

Thus the product of λD should increase slowly with increasing values of D. What experimental evidence there is supports this.

Due to the earth's curvature there is, however, a limit to the value of D, when the deviation of the ray is a minimum. This case is obviously that in which the ray leaves the transmitter along the tangent to the earth at that point. In this case it is easy to show that the maximum value of D ($D_{\text{max.}}$) is given by

$$D^2_{\text{max.}} = 8Rh \qquad \text{......(11)},$$

so that on substituting for R in (10) we find

$$\frac{\lambda D}{D^2_{\text{max.}} + D^2} = \text{const.}$$

It is also of interest to consider the effects of electron-limitation in the case of maximum D and calculate the minimum wave-length

($\lambda_{\text{min.}}$) for which the minimum deviation referred to above can be brought about. On substituting the maximum value for D in (9) we find that

$$\frac{Ne^2}{\pi mc^2}\lambda^2_{\text{min.}} = \frac{2h}{R} \qquad \text{......(12).}$$

Thus certain rays of the wave-lengths greater than the value given by (12) are imprisoned by the atmosphere and brought to the ground, but all rays of wave-length less than the critical value escape from the atmosphere altogether. If we again take N as 10^5 per c.c. and h as 60 km. we find that $\lambda_{\text{min.}}$ is about 10 metres. Too much importance should not be attached to the exact value of 10 metres in view of the uncertainty in the values of N and h, but it appears that wave-lengths less than a certain critical value in this range are of no use for long-distance communication in that the atmosphere does not bend them back to the ground. It is suggested that experiments to find the critical wave-length $\lambda_{\text{min.}}$ might be used to estimate N or h if one or the other is known.

In connection with the above discussion of imprisoned and escaping rays and wave-lengths it should be noted that, according to the magneto-ionic theory, there are cases in which, due to the influence of the earth's magnetic field, certain rays from long wave-length transmitters are split up into two elliptically polarized components for one of which the refractive index is greater than unity. This component is therefore not deviated back to the ground and so escapes via the atmosphere.

In the above calculations it has been assumed, for simplicity, that the deviation of the ray takes place at one point in the layer. This, of course, cannot be the case; the bending must be gradual. If a case of gradual bending of the rays be considered it is easy to show that the maximum value of N might be slightly larger than 10^5 electrons per c.c., but that it is unlikely that it is larger than 10^6 per c.c.

SUMMARY.

An interpretation of ultra-short wave wireless phenomena is given which indicates that the maximum number of electrons per c.c. in the atmospheric ionized layer is of the order 10^5 to 10^6.

In conclusion, I wish to express my indebtedness to Mr C. W. Goyder and Mr A. H. Cooper for experimental data on this subject.

Note added March 17th. After the proofs of this paper had been returned to the printer the February issue of the *Physical Review* reached London (March 15th), containing an article by A. Hoyt Taylor and E. O. Hulbert dealing with the same subject. Similar conclusions are arrived at regarding the maximum electronic content of the ionized layer.