On the Rotation of the Plane of Polarization of Long Radio Waves.

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1. *Introduction.*

The propagation of long* waves at great distances has been studied in great detail by Austin,† by Round, Eckersley, Tremellen, and Lunnon,‡ by Espenschied, Anderson, and Bailey,§ and by Yokoyama and Nakai.|| Thus the propagational characteristics of long waves, considered merely as channels of communication, are well known. There have remained, however, a number of unexplained directional effects of which one might quote as an example the difficulty, noticed by Round, Eckersley, Tremellen, and Lunnon, of receiving signals whose great circle path traversed the earth's magnetic poles.

Pronounced directional effects at short distances have been reported by Naismith.¶ He found that the intensity of the space wave from GKB, Northolt, was approximately twice as great at Manchester as at Exeter although both receiving points are at the same distance from the transmitter. At Manchester the receiver was north of the sender, while at Exeter the direction was west.

Unfortunately the majority of these long-wave observations have been purely measurements of electric intensity in the vertical plane containing sender and receiver. The experimental results, by which one might hope to check any proposed theoretical explanation of the effects observed, are therefore ambiguous in the sense that too many variable quantities are involved. It is otherwise, however, with Hollingworth's** exact measurements of polarization. By using an aerial system of two crossed loops and by measuring the e.m.f.'s in each of them as well as the phase angle between the two signals,

* *I.e.*, of the order 10,000 metres wave-length.

† Austin's publications are too numerous to mention in detail. Beginning with 'Bull. Bur. Stand.,' vol. 11, p. 69 (1914), there have been many papers in recent years in 'Proc. Inst. Rad. Eng.'

‡ 'J. Inst. Elec. Eng.,' vol. 63, p. 933 (1925).

§ 'Bell Syst. Tech. J.,' vol. 4, p. 459 (1925).

|| 'Proc. Inst. Rad. Eng.,' vol. 17, p. 1240 (1929).

¶ 'J. Inst. Elec. Eng.,' vol. 69, p. 875 (1931).

** 'Proc. Roy. Soc.,' A, vol. 119, p. 444 (1928). Observations were made at Slough, distant 396 kilometres from the transmitter at Ste. Assise, wave-length 14,350 metres.

he has been able to separate the effects of ground and space waves. His discovery of a rotation of the plane of polarization in the downcoming wave occurring as a characteristic feature of the sunrise and sunset periods is summarized in figs. 1 and 2.

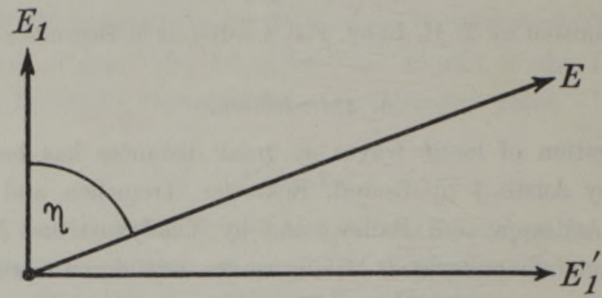

Fig. 1.—Electric forces in the downcoming wave, which is assumed to be travelling away from the observer and at right-angles to the plane of the diagram. For long waves, the normal and abnormal components E_1 and E'_1 are nearly in phase, so that their resultant E is a quasi-stationary vector whose plane of polarization is rotated through an angle η from the normal position of E_1.

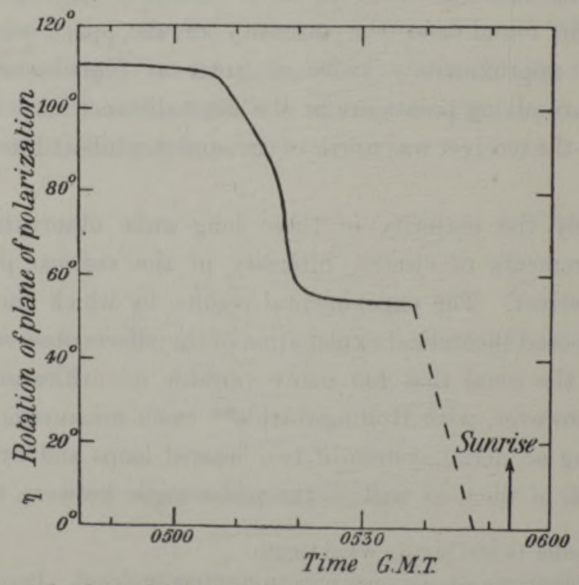

Fig. 2.—Experimental values of the rotation of the plane of polarization of the downcoming wave, as observed by Hollingworth for the morning of October 1, 1927. After 0540 G.M.T. the amplitude of the space wave appears to have been too small for satisfactory measurements of η.

In fig. 1 the direction of propagation of the downcoming wave is assumed to be perpendicular to the plane of the diagram and away from the reader. The normal component of electric force, *i.e.*, that contained in the vertical plane

which includes the sender and receiver, is $E_1 . \sin (pt + \phi)$, p being the angular frequency of transmission and ϕ the phase angle with respect to the ground wave. The abnormal component, which is parallel to the ground, is

$$E'_1 . \sin (pt + \phi + \xi),$$

where ξ is the phase difference between the electric components. Hollingworth's experimental results all agreed with his supposition that ξ was so small that the normal and abnormal components could be combined into a single equivalent force E, rotated through an angle η from the normal position of E_1. The orientation of this quasi-stationary vector was found to undergo definite cycles, a typical example* of which is shown in fig. 2 for the sunrise period for October 1, 1927.

The main features of the observed rotation of the plane of polarization of the electric force E were :—

(*a*) During the night the orientation of the plane of polarization was quite steady, the angle η being about 110°.

(*b*) Beginning at 45 minutes before sunrise and lasting for about 10 minutes, there was an abrupt reduction in η, until a second steady state was reached at an angle of about 50° to 60°.

(*c*) The second steady state lasted throughout the rest of the sunrise period during which measurements were possible. After 0540 G.M.T. on this morning the intensity of the space wave was small and the remainder of the curve, shown dotted, was filled in on the assumption that past experience had shown that the rotation was small during the day in summer. It would seem, however, that the dotted part of the curve should be disregarded since it was the intensity of the downcoming wave and not necessarily its rotation which was small during the day.

Characteristic sunset and sunrise cycles of field-intensity in the normally polarized component of electric force at the receiver, which are closely correlated with the rotation of the plane of polarization, have also been observed by Naismith and by Namba.† Nevertheless, the causes of these regularly occurring cycles of variation in the plane of polarization of the space wave have not yet, so far as we are aware, been elucidated. The present paper,

* Copied from fig. 6 of Hollingworth's paper (*loc. cit.*).

† 'Proc. Inst. Rad. Eng.,' vol. 19, p. 1988 (1931). The receiving system used by Namba appears to be open to objections which would make it difficult to accept his observations of both right- and left-handed senses of rotation of the plane of polarization.

therefore, attempts to show that the technique of the magneto-ionic ray theory,* which has been developed chiefly for short and medium wave propagation, is also adequate for the explanation of many of the apparent anomalies of long wave.

2. *Application of the Magneto-Ionic Theory to Long-Wave Propagation.*

(i) *Procedure.*—In what follows we shall use the methods advocated by Baker and Green.† These authors, it is true, were mainly concerned with the application of the magneto-ionic theory to medium-wave‡ propagation, but they give expressions for the limiting polarizations of the ordinary and extraordinary components§ of the downcoming wave which can readily be interpreted for use with long waves.

The procedure adopted here will be to calculate the limiting polarizations of both ordinary and extraordinary downcoming waves and then to combine them with suitable relative phases and amplitudes into a single space wave having, as in fig. 1, normal and abnormal components of electric force, E_1 and E'_1. If, as the long-wave experimental results show, these components can be further combined into a single force E which is not rotating periodically, then the conditions which must hold will give a relation between (a) the experimental values of η, the angular rotation of the plane of polarization of E from its "normal" position,|| and (b) the relative phases and amplitudes of the two downcoming waves.

It will further be necessary to form estimates of the differential absorption experienced by the two space waves, owing to loss of energy in the ionosphere by electronic collisions, in order to see whether the amplitudes assumed for them are consistent with their probable attenuation factors.

* *Cf.* Appleton, 'J. Inst. Elec. Eng.,' vol. 71, p. 642 (1932).

† "Rad. Res. Board Rep. No. 3, Australian Commonwealth Council Sci. Ind. Res.," Bull. 60, Melbourne (1932); and 'Proc. Inst. Rad. Eng.,' vol. 21, p. 1103 (1933).

‡ *I.e.*, transmission frequencies of about one-half of the gyroscopic frequency of electrons moving under the influence of the earth's magnetic field. At Slough the critical wave-length is 227 metres.

§ The ionosphere, as an aeolotropic medium, splits an incident wave into ordinary and extraordinary components, the former being that which is, for transmission frequencies not very far removed from the critical frequency, relatively little influenced by the presence of the earth's magnetic field.

|| The "normal" orientation of E should perhaps be defined as its steady day value, but this is different for each position of the receiving station. It is better, therefore, to follow Hollingworth and place the zero position of the plane of polarization of the downcoming wave in coincidence with that of the ground wave, *i.e.*, the vertical plane containing sender and receiver.

(ii) *Relation between the Rotation of the Plane of Polarization and the Characteristics of the two Downcoming Waves.*—The ratios of axes of the ellipses of polarization in the ordinary and extraordinary downcoming waves, if we neglect the effect of collisions between electrons and other particles in the ionosphere, are given by

$$R_a^2 + \frac{l^2}{n} \cdot q \cdot R_a - 1 = 0, \tag{1}$$

where

$$l = \sin\theta, \qquad n = \cos\theta, \qquad q = p_H/p. \tag{2}$$

The roots R_a and R'_a are the ratios of axes of the two ellipses, θ is the angle between the direction of propagation of the downcoming wave and the direction of the earth's magnetic field, and p_H is the electronic spiral angular frequency, having a value of about 8×10^6 radians per second for English conditions.

In the ordinary downcoming wave the orientation of the ellipse is such that the major axis is in the plane containing the directions of the earth's field and of propagation. The principal components of electric force, namely, those along the major and minor axes of the ellipse, are in space and time quadrature. Hence, in the transfer of the ellipse to that which is measured at the ground, it is necessary to introduce the quantities $R_e = E'_1/E_1$, ξ the angular phase difference between E'_1 and E_1, and S the angle through which the ellipse has to be turned. There are corresponding quantities for the extraordinary wave, R'_e and ξ', and the relations which we shall need are,

$$\cot\xi = \frac{(1 - R_a^2)}{2R_a} \cdot \sin 2S \tag{3}$$

$$R_e^2 = \frac{1-\rho}{1+\rho}, \tag{4}$$

where

$$\rho = \frac{(1 - R_a^2)}{(1 + R_a^2)} \cdot \cos 2S \tag{5}$$

$$\cos S = \frac{\cos i \cdot \cos\theta - \sin\delta}{\sin i \cdot \sin\theta} \tag{6}$$

$$\cos\theta = \cos i \cdot \sin\delta - \sin i \cdot \cos\delta \cdot \cos\gamma, \tag{7}$$

also

$$R_e \cdot R'_e = 1, \tag{8}$$

and

$$\xi' = \xi + \pi, \tag{9}$$

where δ is the dip angle of the earth's magnetic field, γ the magnetic bearing of the sender from the receiver, and i the angle of incidence at the ground of the downcoming wave.

From these expressions it is possible to calculate R_c, R'_c, ξ, and ξ'. Let us now use E_1 and E'_1 as the normal and abnormal components of electric force, as measured at the ground, of the *combined* waves. We then have

$$\left.\begin{aligned} E_1 &= A_1 \,.\, \sin(pt+\phi_1) + \frac{A_2}{R'_c} \,.\, \sin(pt+\phi_2-\xi') \\ E'_1 &= A_1 \,.\, R_c \,.\, \sin(pt+\phi_1+\xi) + A_2 \,.\, \sin(pt+\phi_2) \end{aligned}\right\}, \tag{10}$$

where ϕ_1 and ϕ_2 are the phases of the ordinary and extraordinary waves with respect to the ground wave, and where $A = A_1/A_2$ may be defined as the ratio of electric intensities in the two downcoming waves.

Alternatively we may write

$$\left.\begin{aligned} E_1 &= \sqrt{A_1^2 + A_2^2 \,.\, R_c^2 - 2A_1A_2R_c \,.\, \cos(\phi_2-\phi_1-\xi)} \,.\, \sin(pt+Z_n) \\ E'_1 &= \sqrt{A_1^2 \,.\, R_c^2 + A_2^2 + 2A_1A_2R_c \,.\, \cos(\phi_2-\phi_1-\xi)} \,.\, \sin(pt+Z_a) \end{aligned}\right\}, \tag{11}$$

where

$$\left.\begin{aligned} \tan Z_n &= \frac{A_1 \,.\, \sin\phi_1 - A_2 \,.\, R_c \,.\, \sin(\phi_2-\xi)}{A_1 \,.\, \cos\phi_1 - A_2 \,.\, R_c \,.\, \cos(\phi_2-\xi)} \\ \tan Z_a &= \frac{A_1 \,.\, R_c \,.\, \sin(\phi_1+\xi) + A_2 \,.\, \sin\phi_2}{A_1 \,.\, R_c \,.\, \cos(\phi_1+\xi) + A_2 \,.\, \cos\phi_2} \end{aligned}\right\}. \tag{12}$$

On combining E_1 and E'_1 into the equivalent vector E, rotated through an angle η from E_1, we have

$$\left.\begin{aligned} E &= E_1 \,.\, \cos\eta + E'_1 \,.\, \sin\eta \\ 0 &= E_1 \,.\, \sin\eta - E'_1 \,.\, \cos\eta \end{aligned}\right\}, \tag{13}$$

whence

$$\tan\eta = E'_1/E_1, \tag{14}$$

and the condition that E should not rotate periodically is $Z_n = Z_a$. Now from (12) it follows that

$$\tan(Z_a - Z_n) = \frac{R_c \,.\, \sin\xi \,.\, \{A_1^2 - A_2^2 - 2A_1A_2R_c \,.\, \cos(\phi_2-\phi_1-\xi)\} + A_1A_2(1+R_c^2) \,.\, \sin(\phi_2-\phi_1)}{R_c \,.\, \cos\xi \,.\, \{A_1^2 - A_2^2 - 2A_1A_2R_c \,.\, \cos(\phi_2-\phi_1-\xi)\} + A_1A_2(1+R_c^2) \,.\, \cos(\phi_2-\phi_1)}. \tag{15}$$

Hence,

(*a*) if either A_1 or A_2 is zero, then $Z_a - Z_n = \xi$, which is the condition applicable* in general to medium-wave propagation ;

* *Cf.* Appleton and Ratcliffe, 'Proc. Roy. Soc.,' A, vol. 117, p. 576 (1928) ; Green, "Rad. Res. Board Rep. No. 2, Australian Commonwealth Council Sci. Ind. Res.," Bull. No. 59, p. 15, Melbourne (1932).

(*b*) if R_c is zero, then $Z_a - Z_n = \phi_2 - \phi_1$, this being the condition applicable to propagation transverse to the earth's magnetic field, for all wave-lengths ;

(*c*) if $\xi = 90°$, $R_c = 1$, and in addition $A_1 = A_2$, then $Z_a = Z_n$. Hollingworth* finds that this condition has a general application to short-wave propagation ;

(*d*) if $\xi = 0$, and in addition $A_1A_2(1 + R_c^2) . \sin(\phi_2 - \phi_1) = 0$, then $Z_a = Z_n$.

Expression (15) has general application ; in the particular case of long-wave propagation we can safely assume that ξ is small for almost all conditions† that are likely to be met in practice, so that (*d*) above is relevant. It follows that the combined space wave is plane polarized when—

(*a*) either the ordinary or the extraordinary wave has zero intensity ; or

(*b*) the two downcoming waves are in phase.

We may reject (*a*) as a special case of (*b*) and notice that the latter condition is consistent with Hollingworth's observation that night-to-day variations in the phase angle between the surface and space waves are small. It is to be inferred, therefore, that differential changes in phase between the components of the downcoming wave are of second order of smallness. Using (*b*) in (14), we have

$$\tan \eta = \frac{1 + A . R_c}{A - R_c} \qquad (16)$$

which is the required relation between the amount of rotation of the plane of polarization and the relative intensities of the ordinary and extraordinary rays.

(iii) *Differential Absorptions of the two Downcoming Waves.*—In the notation used by Baker and Green, the formula‡ for the complex refractive

* 'J. Inst. Elec. Eng.,' vol. 72, p. 229 (1933).

† The exception is for transmission along the earth's field, when the polarizations of both downcoming rays are circular. For a wave-length of 10,000 metres, however, marked departures from linear polarization are only encountered when the angle between the direction of propagation and the earth's field is less than 30°. For these conditions the calculations of the next section show that A_1 and A_2 are nearly equal whence, from (*c*) above, the polarization of the combined wave is still plane.

‡ Hartree, 'Proc. Camb. Phil. Soc.,' vol. 27, p. 143 (1931), has suggested modifications to this formula which are designed to allow for local " polarization " effects in the medium. However, Baker and Green have demonstrated that such modifications cannot alter the limiting polarizations of either of the two downcoming rays. We have also been able to show that, for the conditions of long-wave propagation considered here, differential absorption of the two downcoming rays is similarly unaffected. Thus it is immaterial to the conclusions of the present paper whether the Hartree terms are included in the formula ; for brevity, they have been omitted.

index of the ionosphere is, after allowance has been made for electronic collisions,

$$(\mu - j\zeta)^2 = 1 - \frac{(1-\varepsilon_1)\{\varepsilon_2 - \frac{1}{2}l^2q'^2 \pm \sqrt{\frac{1}{4}l^4q'^4 + n^2 \, . \, \varepsilon_2^2 q'^2}\}}{\varepsilon_1 + n^2q'^2(1-\varepsilon_1)}, \tag{17}$$

where

$$\left.\begin{aligned} \varepsilon_1 &= 1 + g' \\ \varepsilon_2 &= 1 + g' - g'q'^2 \\ g' &= \frac{kq'}{p_{\mathrm{H}}(q'^2-1)} \\ q' &= \frac{p_{\mathrm{H}}}{p - j\nu} \\ k &= \frac{4\pi \, . \, \mathrm{N}e^2}{mp} \end{aligned}\right\} \tag{18}$$

Also μ is the refractive index, $\zeta \, . \, p/c$ the logarithmic attenuation factor per unit distance, N the number of electrons per cubic centimetre, of charge $-e$, mass m and frequency of collision ν, and j has its usual operational significance.

Ordinarily the evaluation of ζ is a difficult matter unless certain drastic assumptions are made. For long-wave propagation, p^2 may be neglected in comparison with p_{H}^2. In addition we choose the condition* that $k \ll p$. Expression (17) then reduces to

$$(\mu - j\zeta)^2 = 1 + g'\{1 - \tfrac{1}{2}l^2q'^2(1 \pm 1)\} \tag{19}$$

if we make the further temporary assumption that $n^2q'^2 \ll \frac{1}{4}l^4q'^4$, which excludes propagation exactly along the earth's field. It can then be shown that,

$$\frac{\zeta_{\mathrm{ord.}}}{\zeta_{\mathrm{ext.}}} = 1 + \frac{l^2p_{\mathrm{H}}^2}{p^2+\nu^2} \tag{20}$$

and, for the special case of propagation along the earth's field,

$$\frac{\zeta_{\mathrm{ord.}}}{\zeta_{\mathrm{ext.}}} = 1 - \frac{4pp_{\mathrm{H}}}{p_{\mathrm{H}}^2+\nu^2} \doteqdot 1,$$

agreeing with (20). Hence it follows that—

(*a*) when $p^2 + \nu^2 \gg l^2p_{\mathrm{H}}^2$, the two waves are equally attenuated ; and

(*b*) when $p^2 + \nu^2 \ll l^2p_{\mathrm{H}}^2$, the extraordinary ray has the greater intensity.

* Meaning that we confine our calculations of absorption to those regions where N is of the order unity. However, considerable portions of the atmospheric paths of long waves will be in such regions.

We immediately derive three working rules for long-wave propagation, namely :

(*a*) for propagation approximately longitudinal to the earth's magnetic field, the ordinary and extraordinary downcoming rays are receivable with comparable intensities ;

(*b*) for propagation approximating to the transverse type, the extraordinary ray reaches the ground with much the greater intensity ;

(*c*) however, if the collision frequency is very great, for example, if the absorption occurs comparatively near to the earth's surface and not entirely where the wave is bent over in the Kennelly-Heaviside layer, then, whatever the direction of transmission, both waves are equally attenuated.

3. *Interpretation of Hollingworth's Experimental Results.*

Observations were made at Slough of the transmissions from Ste. Assise, near Paris. Approximate values of the experimental constants are given below.

Assuming the height of the Kennelly-Heaviside layer to be 80 kilometres, the ground wave path being 396 kilometres, then $i = 68°$; also $\delta = 67°$ and $\gamma = 160°$, whence from (7) we have that θ, the angle between the directions of propagation and the earth's field is 47°, and the propagation of the downcoming wave tends to the transverse type.

The wave-length of the Ste. Assise transmissions being 14,350 metres, $q = 63$, and hence the solution of (1) is :—

$R_a = 1/49$ for the ordinary ray, and

$R'_a = -49$ for the extraordinary ray.

From (6), $S = 169°$, hence we have from (3), (4), and (5) that

$R_c = 0 \cdot 19$, $\xi = 6°$, ordinary, and

$R'_c = 5 \cdot 2$, $\xi' = 186°$, extraordinary.

Thus E_1 and E'_1 are very nearly in phase for the ordinary ray and in anti-phase for the extraordinary ; also the major contribution to the normal electric component E_1 in the combined wave is from the ordinary ray.

We next seek information from the previous section on the differential absorption of the two rays. Since transmission approximates to the transverse type, the extraordinary ray has much the greater intensity during the night. During the day, however, when absorption can occur in the lower

atmosphere, both waves may be equally attenuated. Hence, during the sunrise period we should be prepared to use values of A between 0 and 1, the former corresponding to night conditions.

Substituting these values of A, and the known magnitude of R_c in (16), we obtain the following values for the amount of rotation of the plane of polarization :—

$\eta = 101°$ for night conditions, and

$\eta = 56°$ for the steady post-sunrise value.

Hollingworth's experimental results for a typical day (fig. 2 of this paper) give about 110° for the steady night value of η and 50° and 60° for the post-sunrise period. There can be very little doubt, therefore, that the analysis developed here is adequate* to explain this rotation of the plane of polarization.

It is interesting, moreover, to see what additional information may be available. Expression (20) tells us that, during the night when the ordinary ray suffers the greater attentuation, $p^2 + \nu^2 \ll l^2 p_H^2$, so that the collision frequency must be much less than 7×10^6. Reference to Pedersen† suggests that this collision frequency might hold at a height of about 70 kilometres, so that at night-time the absorption would chiefly occur at heights greater than 70 kilometres. Now Hollingworth states that the probable height which long waves attain in the Kennelly-Heaviside layer is 75–85 kilometres. We infer that differential absorption takes place, during the night, in the region where the wave is bent over.

During the day, equality in amplitude of the two downcoming rays probably means that differential absorption occurs in a region where the collision frequency is much greater than 7×10^6, *i.e.*, at heights much less than 70 kilometres. Now Hollingworth has observed that the commencement of the rapid change-over from night to day conditions is at 45 minutes before sunrise in October and 55 minutes in June, both times corresponding to a position of the sun 7° below the horizon for the mid-point of the path between sender and receiver. That is to say, the daytime type of differential absorption begins at the moment when it is sunrise at a height of 47 kilometres above the earth's surface. At this height the collision frequency should be, according to Pedersen, a little greater than 10^8 and hence much greater than our critical value of

* We are aware of two other possible explanations of Hollingworth's results. These are discussed and rejected in the next section.

† "Propagation of Radio Waves," Copenhagen (1927), p. 43, fig. IV, 6.

7×10^6. It is to be inferred that differential absorption takes place in the post-sunrise period in a region between 47 and 70 kilometres above the earth's surface.

4. *Discussion.*

The results of the previous section suggest that the magneto-ionic theory is capable of providing an explanation of the phenomenon of the rotation of the plane of polarization of long waves, in quantitative agreement with Hollingworth's experimental observations. However, we are aware of two other interpretations of the magneto-ionic theory which could, under certain conditions, allow of a rotation of the plane of polarization. These alternatives arise when expression (1) for the limiting polarizations of the downcoming rays is modified to include collisions between electrons and other particles in the ionosphere, this involving the substitution of q' for q.

Recently, Ratcliffe* has suggested that the effect of such a modification is that all waves, of whatever frequency, are circularly polarized at ground level, the only exception being for propagation exactly transverse to the earth's magnetic field. This interpretation of the magneto-ionic theory is in conflict with the conclusion reached by Baker and Green that electronic collisions have no very great effect on the limiting shapes of the polarization ellipses. For the purposes of the present paper, however, we would point out that Hollingworth's experiments cannot satisfactorily be aligned with Ratcliffe's interpretation of the magneto-ionic theory, reserving the discussion of the more fundamental question for another place.

An attempt to construct, on these lines, an explanation of the rotation of the plane of polarization of the combined downcoming wave, would appear to involve the assumptions that—

(*a*) the amplitudes of the circularly polarized ordinary and extraordinary downcoming rays are equal, both night and day ;

(*b*) the lengths of their atmospheric paths are equal during the day ;

(*c*) the ordinary component lags behind the extraordinary at night.

Now we have already noted that a differential change in path-length between the two component rays is probably of second order of smallness. It is also possible to show that, for long-wave propagation, such a path difference is more likely to involve a retardation of the extraordinary ray behind the ordinary than *vice versa* as required by (*c*) above. Hence this alternative

* "Wir. Eng. and Exp. Wir.,' vol. 10, p. 354 (1933).

explanation of Hollingworth's results seems less probable than the one we have suggested in previous sections.

The other possibility arises out of the suggestion made by Baker and Green that electronic collisions have the effect of rotating the axes of the polarization ellipse.* Remembering that both the ordinary and the extraordinary components in the downcoming wave are nearly plane polarized, and considering each separately, it can be shown that $\eta_{\text{ord.}}$ is 11° and $\eta_{\text{ext.}}$ is 101° for the Ste. Assise-Slough conditions. Now the effect of collisions is to rotate the axes of each ellipse in the sense that $\eta_{\text{ord.}}$ tends to decrease in magnitude, and $\eta_{\text{ext.}}$ to increase, so that in neither case can we attain the full range of variation in the rotation of the plane of polarization from 50° to 110° such as was measured by Hollingworth.

At this point it will be useful to examine, from the standpoint adopted in this paper, those other long-wave anomalies which are associated with asymmetrical propagation. However, it is to be emphasized that the explanations which will be put forward must inevitably be qualitative, the lack of precision being due to the fact that the experimental observations were confined to the normal component of electric force at the receiver.

At short distances there are Naismith's observations of the Northolt transmissions in which he found that, during the daytime, the intensity of the space wave at Manchester was approximately twice as great as at Exeter. Both receiving points were distant about 240 kilometres from the transmitter, the magnetic bearings of Northolt from each of them being 164° and 81° respectively. Calculations then give 35° and 63° for the angles between the directions of propagation of the downcoming waves and the lines of force of the earth's field, so that Manchester would correspond roughly to longitudinal transmission and Exeter to transverse. It is important to remember, however, that the measurements were made in the middle of the day when there should be no differential absorption in either type of propagation. In this case we have from (11) that

$$\frac{(\mathrm{E}_1)_{\mathrm{M}}}{(\mathrm{E}_1)_{\mathrm{E}}} = \frac{1-(\mathrm{R}_e)_{\mathrm{M}}}{1-(\mathrm{R}_e)_{\mathrm{E}}} = \frac{1-0\cdot20}{1-0\cdot53} = 1\cdot7,$$

showing a marked superiority at Manchester in the strength of the normal component of electric force, which was that observed.

Other observations made by Naismith are, at first sight, more difficult to explain in terms of the magneto-ionic theory. He found that the characteristic

* The possibility of this effect occurring has also been noted recently by Mary Taylor, 'Proc. Phys. Soc.,' vol. 45, p. 245 (1933).

sunset cycles of intensity in E_1, which are closely correlated with Hollingworth's rotation of the plane of polarization, were absent both at Manchester and at Exeter, though clearly noticeable at Aberdeen, which is geographically very much in the same direction from Northolt as is Manchester. In this case we are dealing with night conditions for which, in general, there should be differential absorption.

At Exeter, with transverse propagation, the sunset period should have been accompanied by an increase in intensity of the extraordinary ray and a rotation of the plane of polarization. However, at all times the contribution to the normal component of electric force by the extraordinary ray was small, owing partly to the value of R'_c and partly to the excess of ground wave, so that its increased intensity at sunset would have relatively little effect.

At Manchester, although the intensities of both downcoming rays were sufficiently great to make a characteristic sunset cycle observable if it occurred, yet in this case the type of propagation was nearly longitudinal, for which there is little differential absorption and consequently no very obvious sunset cycle.

We are therefore left with the observation of the sunset cycle at Aberdeen, very nearly due north of Northolt. The ground wave-path was 632 kilometres, so that the angle between the earth's field and the direction of propagation of the downcoming wave was 53°. Hence, although transmission was in the magnetic meridian, it was approximately of the transverse type, so that differential absorption explains the observation of the sunset cycle at Aberdeen.

In long distance propagation too little is known of the geometry of the ray paths to permit of a unique explanation of various cases. However, we may take as an example the experience of Round, Eckersley, Tremellen, and Lunnon when they were taking observations between Wyndham and Colombo of the difficulty of receiving signals from Rugby, the great circle between sender and receiver passing over the polar regions. If this single observation is typical of normal ionization conditions,* an explanation may be suggested. It is to be supposed that propagation over such distances would be effected by a few reflections at nearly grazing incidence, for which conditions the rays would be travelling nearly normally to the earth's magnetic field for considerable distances in the polar regions. In this case $R_c = 0$ and $R'_c = \infty$, and the normal component of electric force would be due only to the ordinary ray, which is highly attenuated. On the other hand, after combining incident and reflected waves at the receiver, the abnormal component of electric force

* *Vide* Appleton, Naismith, and Builder, 'Nature,' vol. 132, p. 340 (1933).

is also small, owing partly to good reflection at the long wave-length but chiefly to the large angle of incidence of the downcoming rays.

The qualitative agreement found here between the experimental observations of asymmetrical long-wave propagation and the magneto-ionic theory lends support to the applicability of this hypothesis to Hollingworth's results. The agreement does not seem to be fortuitous and suggests that the procedure we have used is applicable to very long waves, although it is not obvious that methods based on a ray treatment should be adequate in such cases.

5. *Acknowledgments.*

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6. *Summary.*

Although the main features of long-wave propagation are well known, there have remained a number of apparent anomalies, chiefly in connection with short distance transmission, which have not yet been elucidated. Of these, the most prominent is the discovery by Hollingworth in 1927 of a regularly occurring cycle during the sunrise and sunset periods in which the plane of polarization of the downcoming wave changes rapidly from the steady night value of about 110° to the steady post-sunrise value of 50° to 60°.

The present paper shows that the technique of the magneto-ionic theory, hitherto used exclusively in connection with the propagation of short and medium waves, gives a feasible explanation of some long-wave anomalies, in remarkable quantitative agreement with Hollingworth's exact measurements. This agreement between theory and experiment does not seem to be fortuitous and suggests that the procedure recently advocated by Baker and Green for medium-wave propagation is also applicable to very long waves, although it is not at all obvious that methods based on a ray treatment should be adequate in such cases.