The
Marconi Review

No. 131   4th QUARTER 1958   Vol. XXI

CONTENTS:

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THE SIGNIFICANCE OF PROPAGATION RESEARCH

IT is sometimes considered that propagation research is a highly specialised and academic subject remote from the realities of radio and often used as an exercise in abstruse mathematics. Admittedly when a paper on propagation is read the audience will usually be small compared with that which would be attracted by one on colour television, high fidelity reproduction, ferrites or transistors, except when some topic such as forward scatter propagation catches the popular imagination.

It must be conceded that the mathematics of propagation can be extremely difficult when a rigorous treatment is attempted, though in many cases the essential results can be obtained quite simply by a more direct appeal to physical principles. In fairness, however, it must be said that many other branches of radio are now leading to mathematics of considerable complexity and that propagation is not alone in producing papers that can be appreciated by only a few specialists.

The present issue of the *Marconi Review* is a reminder that propagation is in fact a subject of wide interest and that, in many of its aspects, it is intensely practical.

Even the mathematical paper aims at adapting an idealised theory more closely to the practical realities of tropospheric propagation, by drawing attention to the factors of prime importance in the use of propagation curves for great heights and distances, namely the position of the horizon and the rate of attenuation of signal with distance in the diffraction region.

Apart from its use for communications, radio has proved to be a scientific tool of great power. Radio sounding of the troposphere and ionosphere is furthering our knowledge of the structure and constitution of the atmosphere, while the science

of radio-astronomy has led to immense advances in the study of outer space and the nature of the universe. In these applications the interpretation of the experimental observations depends primarily on an appreciation of the propagation characteristics. The transmission of radio signals from rockets and satellites is not merely for communication and telemetry but also for the study of the propagation medium itself. The possibility of observing round-the-world echoes on the signals from satellites is an interesting example of propagation research that throws fresh light on a well-known but not fully understood phenomenon in high-frequency communication.

Although the explanation of whistlers on very low frequencies is based on a knowledge of magneto-ionic theory, their study is, nevertheless, playing an important part in the observational programme of the International Geophysical Year.

Whatever one may feel about the imminence of space travel, the prophets are already looking ahead to the problems that will arise when hundreds of satellites are encircling the earth and the moon with radio signals passing to and fro, and when communication with and between space-ships will be a vital necessity. It is even now being urged at international conferences that many channels should be reserved in all parts of the radio spectrum for astronautical purposes, with a claim for priority of treatment where problems of mutual interference arise between them and existing services.

Thus, while propagation may have earned the reputation of being academic, it is in fact full of romance. Not only is it basic to the whole of radio, but it also deserves to share something of the glamour of the more spectacular aspects of the field of electronic engineering that has developed from the radio art.

G. Millington.

PROPAGATION AT GREAT HEIGHTS IN THE ATMOSPHERE

By G. Millington, M.A., B.Sc., M.I.E.E.

This article considers tropospheric propagation over the earth through an atmosphere which is standard at small heights but in which the refractive index approaches unity asymptotically at great heights. The departure from the linear decrease leads in the geometric-optical region to a reduced horizon distance and in the diffraction region to a reduction in height-gain. The latter may be interpreted as an equivalent change in distance which is found to be effectively independent of frequency and identical with the decrease in horizon distance. It follows that the shape of the propagation curve as a function of distance is maintained and that the important thing to establish is the position of the horizon for the assumed model of the atmosphere. The theory is illustrated by using a refractive index that decreases exponentially to unity.

Introduction

IT is now twenty years since the theory of ground-wave propagation over a smooth spherical earth was first given in its general form by Wwedensky [1], van der Pol and Bremmer [2], and Eckersley and Millington [3]. Their results have formed the basis of many sets of propagation curves covering practically the whole range of radio frequencies. In most cases for frequencies above 30 Mc/s account has been taken of height-gain effects by giving curves for various heights of the terminals, while allowance has been made for standard atmospheric refraction by using an increased radius of the earth.

The atlas of curves published by the C.C.I.R. [4] has been recommended for international use, and more recently their range has been extended to still higher frequencies and greater heights by the Japanese [5] in partial fulfilment of a further C.C.I.R. Resolution [6]. It has long been recognised that the idealisations upon which these curves are based become extreme at frequencies where the irregularities of the terrain can be large compared with the wavelength and variations in the troposphere can lead to profound modifications in the mechanism of propagation.

It is the purpose of the present article to deal with one specific point, namely that even under normal tropospheric conditions the so-called standard atmosphere does not obtain at the great heights now under active consideration in the preparation of further C.C.I.R. curves. The standard atmosphere is based on the concept of a linear decrease of refractive index with height, the gradient being such that the constant radius of curvature of the nearly horizontal ray paths in the geometric-optical region is four times the radius of the earth, leading to a transformation in which the ray paths become straight and the radius of the earth is increased by a factor of four-thirds.

As is well known, the refractive index at the surface of the earth is greater than unity by only about 3×10^{-4}, and the gradient in question would reduce it to unity within a height of 8 km. It would be much more realistic to take as a model a refractive index variation that simulates a standard atmosphere near the earth but decreases smoothly towards unity asymptotically as free space conditions are approached at great heights. The precise manner adopted can be decided from

experimental evidence, but the order of the modification to the propagation based on a linear variation can be determined by taking, for example, an exponential decrease from the value at the earth to unity at infinity.

Although the actual changes in the refractive index are so small, discontinuities in the gradient can be all important. It is known, for instance, that the model assumed by Carroll and Ring ([7]), of a linear gradient up to the height where the refractive index has reduced to unity and then remains so, produces a profound modification to the attenuation with distance over the surface of the earth. In physical terms, at the level where the change in gradient occurs there is a partial reflection which at the small angles of elevation involved is sufficient to reduce greatly the attenuation of the propagation modes, so that relatively high field-strengths extend out to considerable distances.
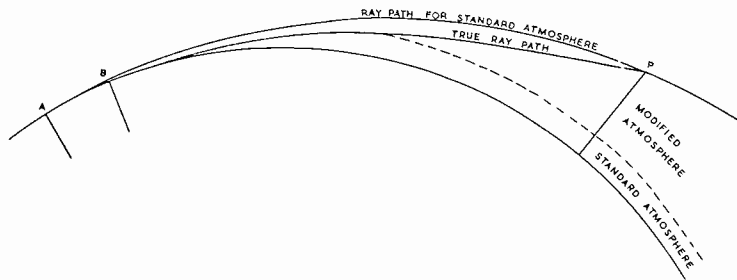

FIG. I

Reduction of horizon distance in the geometric-optical region.

These difficulties are overcome if a smooth and sufficiently gradual variation of refractive index is assumed. If it is effectively linear with height up to a certain level, the attenuation with distance round the earth is the same as if it continued so indefinitely. Below this level the field-strength is unmodified, but above it gradually falls below the value for a standard atmosphere.

The problem of propagation in such a modified atmosphere may thus be solved in terms of a height-gain correction to the solution for the standard atmosphere. This argument can be applied to each term of the diffraction formula expressed as the sum of an infinite number of exponentially attenuated modes, but it is sufficient to restrict it to distances beyond the horizon at which the first term is predominant even at the greatest height considered. In practice on the very high frequencies used in tropospheric propagation, the field-strength beyond the horizon drops away rapidly and becomes exponential with distance quite near in.

It was pointed out by Eckersley and Millington ([3]), ([8]), that at sufficiently great heights, an increase in height is equivalent to remaining at the same height and moving closer to the transmitter by a distance equal to the change in the horizon distance of the receiver, assuming that one is still below the horizon of the transmitter. The reduction in field-strength due to the departure from the standard atmosphere may similarly be regarded as equivalent to being at the same height in a standard atmosphere but at an increased distance from the transmitter. This in turn may be interpreted as remaining at the same distance but referring the curve of field-strength against distance to a reduced horizon distance.

Within the horizon, where the geometric-optical theory may be used, the modified atmosphere implies a decrease in the curvature of the ray path where the refractive index no longer decreases linearly with height. This results in a decreased horizon distance associated with a given height above the earth, as indicated in Fig. 1 where the horizon of the point P moves in from A to B.
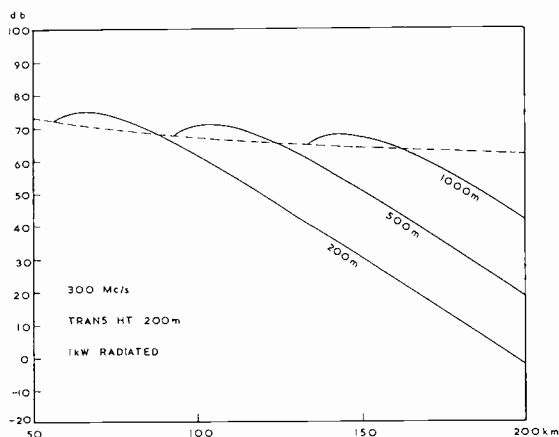

FIG. 2

Similarity of propagation curves for different heights.

It is one of the purposes of the present article to show that the equivalent reduction in horizon distance in the diffraction region is effectively independent of the frequency and is in fact essentially equivalent to the corresponding reduction in the geometric-optical region. It is clear from an inspection of propagation curves such as those contained in the C.C.I.R. atlas ([4]) that beyond the last maximum of the interference region within the horizon, the curves for different heights are similarly shaped, and that one can be very nearly superimposed on another by sliding it along the free-space inverse distance curve shown in Fig. 2.

It will thus appear that the practical effect of the modified atmosphere is simply to move the field-strength curve without change of shape back towards the transmitter along the free-space curve by a distance that is a function of the height but is independent of the frequency. The implications of this conclusion on the use of existing propagation curves will be discussed.

The Geometric-Optical Region

In the earlier article ([9]) published in the *Marconi Review*, a detailed analytical treatment was given of the geometry of ray paths in a standard atmosphere in terms of an equivalent radius of the earth defined by r_e where

$$\frac{1}{r_e} = \frac{1}{r_0} - \frac{1}{R_0} \tag{1}$$

in which r_0 is the actual radius of the earth and R_0 is the radius of curvature of a ray travelling horizontally near to the earth.

Here it is simpler to develop the analysis afresh with the simplifications which arise when considering only rays that leave the earth tangentially and when small path differences are not in question. If h is the height at a point P on a ray at a distance s from the point of tangency shown at A in Fig. 3, the angle of elevation ζ of the ray is very small. Thus for the element PQ of the ray path, the corresponding δh given by MQ can be taken as

$$\delta h = \zeta \delta s \tag{2}$$

Here δs is the projection of PQ and PM on the earth, but both PQ and PM may be taken as equal to δs since $h \ll r_0$ and $\cos \zeta$ can be taken as unity.

(145)

If PM subtends an angle $\delta\varphi$ at the centre of the earth and PQ an angle $\delta\psi$ at the centre of curvature of the ray path at P, then

$$\delta\zeta = \delta\varphi - \delta\psi \qquad (3)$$

where from the above argument

$$\delta\varphi = \frac{\delta s}{r_0} \text{ and } \delta\psi = \frac{\delta s}{R}$$

in which R is the radius of curvature of the ray path at P, so that from eqn. (3)

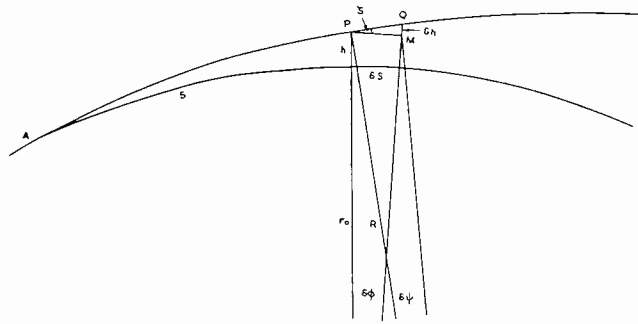$$\delta\zeta = \left[\frac{1}{r_0} - \frac{1}{R}\right]\delta s \qquad (4)$$

FIG. 3

Ray path geometry.

In the analysis, $\dfrac{h}{r_0}$ may be neglected in comparison with unity and the refractive index μ may be put equal to unity when changes in μ are not involved. For the tangent rays under consideration, it is thus possible to put

$$\frac{1}{R} = -\frac{d\mu}{dh} \qquad (5)$$

and for the standard atmosphere in which $\dfrac{d\mu}{dh}$ is constant, R can be put equal to R_0.

As $\zeta = 0$ when $s = 0$, eqn. (4) can be integrated directly with the aid of eqn. (1) to give

$$\zeta = \frac{s}{r_e}$$

Eqn. (2) then integrates to

$$h = \frac{s^2}{2r_e}$$

leading to the well-known horizon distance formula

$$s = (2r_e h)^{\frac{1}{2}} \qquad (6)$$

(146)

When $\frac{d\mu}{dh}$ is not constant, it is necessary to express s explicitly as an integral with respect to h. Substituting eqn. (5) into eqn. (4) and using eqn. (2),

$$\zeta\delta\zeta = \left[\frac{1}{r_0} + \frac{d\mu}{dh}\right]\delta h$$

so that

$$\frac{\zeta^2}{2} = \frac{h}{r_0} + \mu - \mu_0 \tag{7}$$

where μ_0 is the refractive index at the surface of the earth.

Eqn. (2) is then put in the form

$$s = \int_0^h \frac{dh}{\zeta} \tag{8}$$

where ζ as a function of h is derived from eqn. (7).

As μ decreases from μ_0 to unity with height, it is convenient to write

$$\mu = 1 + \eta g. \tag{9}$$

where g is a function of h that is unity at $h = 0$ and approaches zero as h is increased. Then

$$\mu_0 = 1 + \eta \tag{10}$$

where η is about 3×10^{-4}.

From eqns. (9) and (10)

$$\mu - \mu_0 = -\eta(1 - g) \tag{11}$$

so that eqn. (7) becomes

$$\frac{\zeta^2}{2} = \frac{h}{r_0} - \eta(1 - g) \tag{12}$$

For small values of h, g may be taken as

$$g \coloneqq 1 + g'(0) \cdot h + g''(0) \cdot \frac{h^2}{2} \tag{13}$$

so that, from eqn. (9)

$$\frac{d\mu}{dh} = \eta g'(0) + \eta g''(0) \cdot h \tag{14}$$

Thus, in order that the refractive index variation may correspond to a standard atmosphere near the earth, it follows from eqns. (5) and (14) that

$$g'(0) = \frac{1}{\eta R_0}$$

so that eqn. (14) becomes

$$g \coloneqq 1 - \frac{h}{\eta R_0} + g''(0) \cdot \frac{h^2}{2} \tag{15}$$

This gives

$$\eta(1 - g) \coloneqq \frac{h}{R_0} - \eta g''(0) \cdot \frac{h^2}{2}$$

(147)

which suggests writing

$$\eta \, (1 - g) = \frac{h}{R_0} \, (1 - \xi) \tag{16}$$

so that

$$\xi = 1 - \frac{\eta \, R_0}{h} \, (1 - g) \tag{17}$$

From eqn. (15), for small values of h

$$\xi \doteqdot \eta \, R_0 \, \frac{g''(0)}{2} \, h \tag{18}$$

Thus from eqns. (17) and (18), ξ is a function that progresses from 0 to 1 as h increases from 0 to ∞.

By using eqns. (1) and (16), eqn. (12) may be written

$$\frac{\zeta^2}{2} = \frac{h}{r_e} \left(1 + \frac{r_e}{R_0} \, \xi \right) \tag{19}$$

If now the equivalent radius r_e is written as

$$r_e = m r_0 \tag{20}$$

for the standard atmosphere $m = \frac{4}{3}$.   It follows from eqn. (1) that

$$R_0 = \frac{m}{m-1} \, r_0 \tag{21}$$

so that eqn. (19) becomes

$$\frac{\zeta^2}{2} = \frac{h}{r_e} \, (1 + [m - 1] \, \xi) \tag{22}$$

Eqn. (8) now gives

$$s = \int_0^h \left(\frac{r_e}{2h} \right)^{\frac{1}{2}} (1 + [m - 1] \, \xi)^{-\frac{1}{2}} \, dh \tag{23}$$

For the standard atmosphere, ξ is zero at all heights and eqn. (23) reduces to

$$s = \int_0^h \left(\frac{r_e}{2h} \right)^{\frac{1}{2}} dh \tag{24}$$

which leads to the value in eqn. (6).

The horizon distance in eqn. (23) is smaller than that in eqn. (24) by Δ, where

$$\frac{d\Delta}{dh} = \left(\frac{r_e}{2h} \right)^{\frac{1}{2}} \left[1 - (1 + [m - 1] \, \xi)^{-\frac{1}{2}} \right]$$

In order to remove the small difference aspect, it is useful to transform this expression to the form

$$\frac{d\Delta}{dh} = [m - 1] \, \xi \left(\frac{r_e}{2h} \right)^{\frac{1}{2}} \left[(1 + [m - 1] \, \xi)^{\frac{1}{2}} + 1 + [m - 1] \, \xi \right]^{-1} \tag{25}$$

For small values of h, ξ from eqn. (18) is proportional to h, so that $\dfrac{d\Delta}{dh} \propto h^{\frac{1}{2}}$ and $\dfrac{d\Delta}{dh} \to 0$ as $h \to 0$. Eqn. (25) leads to a simple numerical integration and $g(h)$ itself can be defined by numerical values subject to the condition in eqn. (15).
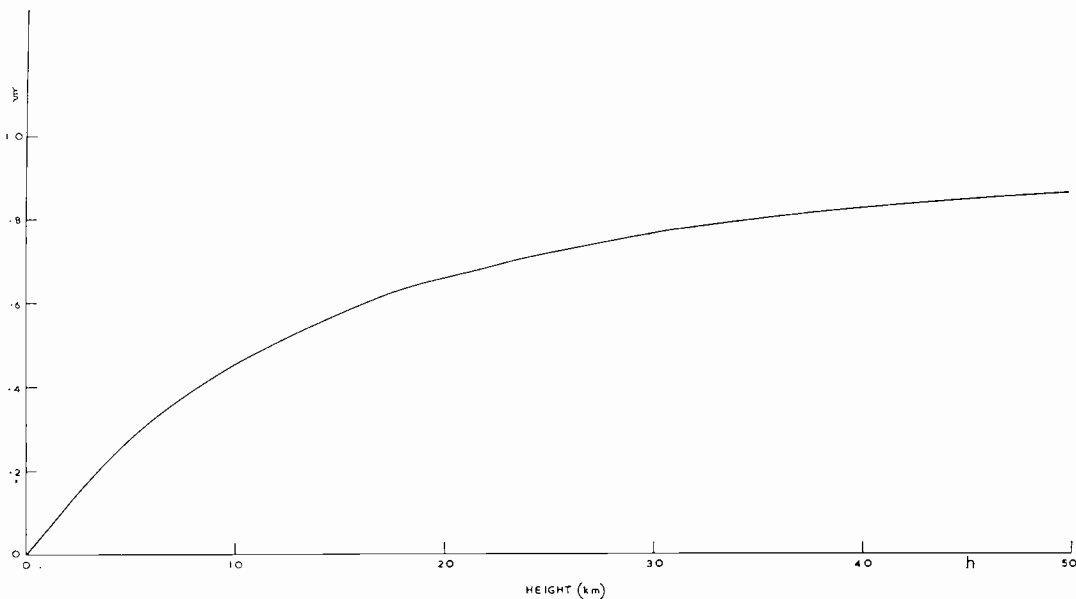

FIG. 4

Curve for ξ as a function of the height.

In order to examine the order of the effect under consideration, $g(h)$ can be taken as an exponential function satisfying eqn. (15), e.g.

$$g(h) = \exp\left[-\frac{h}{\eta R_0}\right] \tag{26}$$

It has in fact been found by Miss Stickland ([10]) that such a function gives a reasonable approximation to the normal type of variation found in the troposphere.

Using eqn. (26)

$$g''(0) = \frac{1}{\eta^2 R_0{}^2}$$

so that eqn. (18) gives

$$\xi \fallingdotseq \frac{h}{2\eta R_0} \tag{27}$$

for small values of h.

In the calculations η has been put equal to 3×10^{-4} and $m = \dfrac{4}{3}$, so that from

eqn. (21) $R_0 = 4r_0$. Taking $r_0 = 6370$ km., $\dfrac{1}{r_1 R_0} = 0\cdot131$ so that

$$g(h) = \exp\left[-0\cdot131h\right] \tag{28}$$

where h is in km.

From eqn. (17)

$$\xi = 1 - \frac{7\cdot64}{h}\left(1 - \exp\left[-0\cdot131h\right]\right) \tag{29}$$

with the initial form from eqn. (27) of
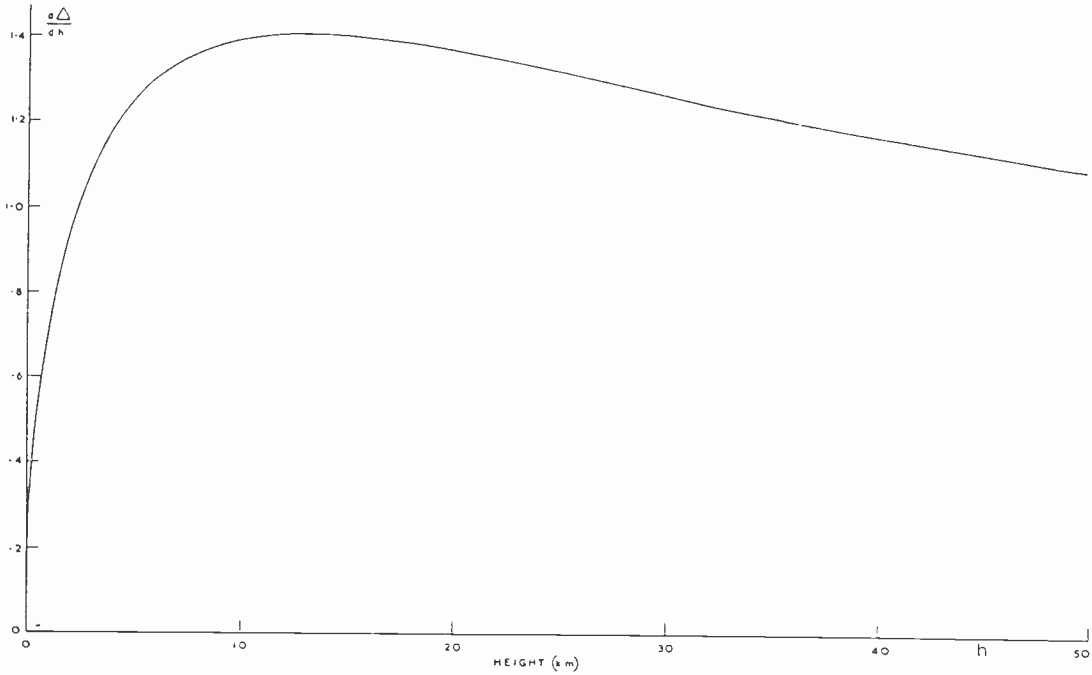
$$\xi \fallingdotseq 0\cdot065h.$$

FIG. 5

Curve for $\dfrac{d\Delta}{dh}$ as a function of the height.

Fig. 4 shows ξ as a function of h and Fig. 5 similarly gives $\dfrac{d\Delta}{dh}$ computed from eqn. (25) which takes the form

$$\frac{d\Delta}{dh} = 21\cdot72\,\frac{\xi}{h^{\frac{1}{2}}}\left[\left(1 + \frac{\xi}{3}\right)^{\frac{1}{2}} + 1 + \frac{\xi}{3}\right]^{-1} \tag{30}$$

with the initial value of

$$\frac{d\Delta}{dh} = 0\cdot710h^{\frac{1}{2}}$$

Fig. 5 can then be used to find Δ by numerical integration and the result is given

in Fig. 6. It will be seen that at a height of 10 km. the assumption of a standard atmosphere overestimates the horizon distance by over 11 km.

The Diffraction Region

In the diffraction region the field as a function of height above the earth and distance from the transmitter can be expressed in the spherical co-ordinates r and θ, where r is distance from the centre of the earth, so that if d is the distance measured over the surface of the earth

$$\theta = \frac{d}{r_0} \tag{31}$$
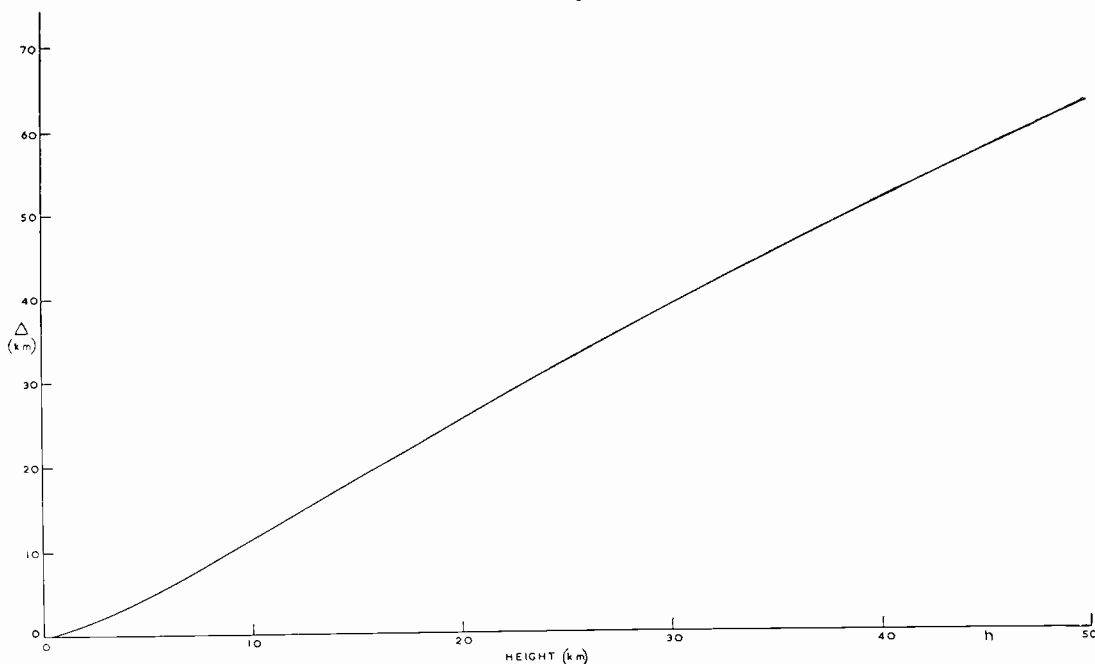
while

$$r = r_0 + h \tag{32}$$

FIG. 6

Curve for Δ as a function of the height.

As only relative values of field-strength are under discussion, it will suffice to work in terms of a height-gain function y defined so that the field is proportional to y/r. The inverse distance term is included to simplify the differential equation, derived from the wave equation by using a separation constant β, and which takes the form

$$\frac{d^2y}{dr^2} + \left(\frac{2\pi}{\lambda}\right)^2 \left[\mu^2 - \frac{\beta^2}{r^2}\right] y = 0 \tag{33}$$

where λ is the wavelength. The accompanying variation with θ in the diffraction region is of the form of $\theta^{-\frac{1}{2}} \exp\left[-j\frac{2\pi\beta\theta}{\lambda}\right]$ and the values of β corresponding to

(151)

the various propagation modes are found from the boundary conditions at the surface of the earth.

As the phase velocity at the surface of the earth contained in the exponential term $\exp\left[-j\frac{2\pi\beta\theta}{\lambda}\right]$, i.e. in $\exp\left[-j\frac{2\pi\beta}{\lambda}\cdot\frac{d}{r_0}\right]$ from eqn. (31), may be expected to approximate to that of a plane wave propagated through a medium of refractive index μ_0, it may be anticipated that $\frac{2\pi\beta}{\lambda}\cdot\frac{d}{r_0}$ is approximately equal to $\frac{2\pi}{\lambda}\mu_0 d$, so that β is nearly equal to $\mu_0 r_0$.

It will therefore be written

$$\beta = \mu_0 r_0 (1 - x) \tag{34}$$

where x is very small but has a positive imaginary part so that the real part of $-j\beta$ is negative and accounts for the attenuation of the wave over the earth.

By substituting eqn. (34) into eqn. (33) and changing the variable to h by means of eqn. (32)

$$\frac{d^2 y}{dh^2} + \left(\frac{2\pi}{\lambda}\right)^2\left[\mu^2 - \mu_0^2\left(\frac{1-x}{1+\frac{h}{r_0}}\right)^2\right]y = 0 \tag{35}$$

As even at the great heights in the troposphere under consideration $h \ll r_0$ it is legitimate to write

$$\left(\frac{1-x}{1+\frac{h}{r_0}}\right)^2 = 1 - 2\left(x + \frac{h}{r_0}\right) \tag{36}$$

so that eqn. (35) may be written

$$\frac{d^2 y}{dh^2} + \left(\frac{2\pi}{\lambda}\right)^2 F\cdot y = 0 \tag{37}$$

where

$$F = (\mu^2 - \mu_0^2) + 2\left(x + \frac{h}{r_0}\right) \tag{38}$$

in which μ_0^2 has been put equal to unity in the second term since F is seen to be the sum of two small terms.

As τ_i is very small, eqn. (9) gives

$$\mu^2 = 1 + 2\tau_i g$$

and

$$\mu_0^2 = 1 + 2\tau_i$$

so that

$$\mu^2 - \mu_0^2 = -2\tau_i (1 - g)$$

Thus from eqn. (16)

$$\mu^2 - \mu_0^2 = -\frac{2h}{R_0}(1 - \xi)$$

where ξ is defined by eqn. (17) as before.

Thus eqn. (38) becomes

$$F = 2\varkappa + 2h \left(\frac{1}{r_0} + \frac{1}{R_0} [1 + \xi] \right)$$

which with the aid of eqns. (1), (20) and (21) becomes

$$F = 2\varkappa + \frac{2h}{r_e} (1 - n_s + 1 + \xi) \tag{39}$$

It is interesting to note that the second term is the value of ζ^2 in eqn. (22) of the previous section.

Near the earth where the variation of refractive index is effectively linear and $\xi = 0$, eqn. (39) becomes

$$F = 2 \left(\varkappa + \frac{h}{r_e} \right) \tag{40}$$

and the equation for y, i.e., eqn. (37), takes the form

$$\frac{d^2 y}{dh^2} + \left(\frac{2\pi}{\lambda} \right)^2 . 2 \left(\varkappa + \frac{h}{r_e} \right) . y = 0 \tag{41}$$

By a linear transformation this equation may be converted to the standard form of Airy's equation. The solution required is that which corresponds to a single upward travelling wave. This problem has been studied in great detail in many papers, and here only the results required for the present argument will be given.

The solution takes the form of a single upgoing wave at heights somewhat greater than h_0 where

$$h_0 = \varkappa_R / r_e \tag{42}$$

where $\varkappa_R$ is the real part of $\varkappa$.

At this height the function F in eqn. (40) is near a zero, and below this height the Stokes phenomenon develops. Physically this means that the solution transforms into an upgoing and downcoming pair of waves which at the surface of the earth satisfy the reflection condition. At the frequencies considered here, it can be shown that the value of $\varkappa$ derived is very nearly independent of the earth constants and the polarization of the waves, and can therefore be found by assuming that the total field at the surface of the earth is zero.

From the known roots of the Airy functions this leads to the result that

$$\varkappa = \varsigma \left(\frac{2\pi}{\lambda} r_e \right)^{-\frac{2}{3}} \exp \left[j \frac{2\pi}{3} \right] \tag{43}$$

where ς is a constant given approximately by

$$\varsigma = \frac{1}{2} \left[3 \left(\frac{3\pi}{4} + n\pi \right) \right]^{\frac{2}{3}}$$

in which n is 0, 1, 2, . . . for the successive modes. For the first mode, this gives $\varsigma = 1.842$ while the accurate value is actually 1.856.

Using the latter value and converting from wavelength to frequency, eqn. (43) gives

$$\varkappa = 5.87 \times 10^{-4} f^{-\frac{2}{3}} \exp \left[j \frac{2\pi}{3} \right] \tag{44}$$

(153)

where f is the frequency in megacycles per sec.

It is to be noted that in eqn. (43) it is r_e and not r_0 that appears, and in deriving eqn. (44) m has been taken as $\frac{4}{3}$. Eqn. (42) now gives

$$h_0 = 2 \cdot 49 f^{-\frac{2}{3}} \tag{45}$$

where h_0 is measured in km.

Returning to the value of F in eqn. (39), the nature of the Stokes phenomenon close to the earth is not significantly altered provided that ξ is still very small at the height h_0. If this is so, the field conditions below this level are unmodified and the value of α is still given by eqn. (44). The attenuation round the earth is unaltered and the effect of the non-linear variation in refractive index is only to affect the height-gain at greater heights.

Attention can therefore be concentrated on the difference in height-gain, as the absolute value for a standard atmosphere continuing to indefinitely great heights has already been studied extensively.

Above the height h_0 where the solution has the form of a single upgoing wave, the form of the solution of eqn. (37) may be represented by the W.K.B. approximation

$$y \propto F^{-\frac{1}{4}} \exp \left[-\frac{j 2\pi}{\lambda} \int^h F^{\frac{1}{2}} \, dh \right] \tag{46}$$

The lower limit is left indefinite, since, in differencing the height-gain, the integral can be taken along the real axis from the point where the difference in the integrands becomes appreciable. If y_0 and F_0 are the values of y and F for the standard atmosphere, then

$$\frac{y_0}{y} = \left(\frac{F}{F_0} \right)^{\frac{1}{4}} \exp \left[-\frac{j 2\pi}{\lambda} \int^h (F_0^{\frac{1}{2}} - F^{\frac{1}{2}}) \, dh \right] \tag{47}$$

Only the modulus of $\frac{y_0}{y}$ is required, so that the imaginary parts of $F_0^{\frac{1}{2}}$ and $F^{\frac{1}{2}}$ have to be found, while the factor $(F/F_0)^{\frac{1}{4}}$ contributes only a fraction of a decibel change and can be omitted.

From eqns. (39) and (44)

$$F = a + j \, | \alpha | \, \sqrt{3} \tag{48}$$

where

$$a = - | \alpha | + \frac{2h}{r_e} \, (1 + [m - 1] \xi) \tag{49}$$

The required imaginary part of $F^{\frac{1}{2}}$ is given from eqn. (48) by

$$\text{I.P. of } F^{\frac{1}{2}} = | \alpha | \sqrt{\frac{3}{2}} \left[a + (a^2 + 3 | \alpha |^2)^{\frac{1}{2}} \right]^{\frac{1}{2}} \tag{50}$$

Similarly

$$\text{I.P. of } F_0^{\frac{1}{2}} = | \alpha | \sqrt{\frac{3}{2}} \left[a_0 + (a_0^2 + 3 | \alpha |^2)^{\frac{1}{2}} \right]^{\frac{1}{2}} \tag{51}$$

where

$$a_0 = - | \alpha | + \frac{2h}{r_e} \tag{52}$$

(154)

Writing

$$A = (a^2 + 3|\alpha|^2)^{\frac{1}{2}} \tag{53}$$

and

$$A_0 = (a_0^2 + 3|\alpha|^2)^{\frac{1}{2}} \tag{54}$$

the difficulty in computing the difference between the imaginary parts of $F_0^{\frac{1}{2}}$ and $F^{\frac{1}{2}}$ given by eqns. (51) and (50) may be removed by algebraical manipulation, giving

$$\text{I.P. of } [F_0^{\frac{1}{2}} - F^{\frac{1}{2}}] = |\alpha| \sqrt{\frac{3}{2}} \left[\frac{a - a_0}{B}\right] \left[1 + \frac{a + a_0}{A + A_0}\right] \tag{55}$$

where

$$B = (a_0 + A_0)^{\frac{1}{2}}(a + A)^{\frac{1}{2}}[(a_0 + A_0)^{\frac{1}{2}} + (a + A)^{\frac{1}{2}}] \tag{56}$$

The small difference is isolated in the term $a - a_0$ in eqn. (55) which, from eqns. (49) and (52), is given by

$$a - a_0 = \frac{2h}{r_e}[m - 1]\,\xi \tag{57}$$

It thus follows from eqns. (47), (55) and (57) that

$$\left|\frac{y_0}{y}\right| = \exp\left[\frac{2\pi}{\lambda}|\alpha|\sqrt{\frac{3}{2}}[m - 1]\int^h \frac{2h}{r_e}\frac{\xi}{B}\left[1 + \frac{a + a_0}{A + A_0}\right]dh\right] \tag{58}$$

Returning now to the attenuation round the earth given by $\exp\left[-\frac{j2\pi}{\lambda}\beta\frac{d}{r_0}\right]$ and giving β its value in eqn. (34) where μ_0 may here be taken as unity, the modulus determining the attenuation is given by $\exp\left[-\frac{2\pi}{\lambda}\alpha_I d\right]$. The value of α_I from eqn. (44) is $\frac{\sqrt{3}}{2}|\alpha|$, so that this attenuation, say L, is given by

$$L = \exp\left[-\frac{2\pi}{\lambda}\frac{\sqrt{3}}{2}|\alpha| d\right] \tag{59}$$

If now by the comparison of equations (58) and (59) a distance Δ is defined such that

$$\frac{2\pi}{\lambda}\frac{\sqrt{3}}{2}|\alpha|\Delta = \frac{2\pi}{\lambda}|\alpha|[m - 1]\sqrt{\frac{3}{2}}\int^h \frac{2h}{r_e}\frac{\xi}{B}\left[1 + \frac{a + a_0}{A + A_0}\right]dh$$

i.e., $\quad \Delta = \int^h \frac{2\sqrt{2}[m - 1]}{r_e B} h\,\xi\left(1 + \frac{a + a_0}{A + A_0}\right)dh \tag{60}$

then the decrease in height-gain is equivalent to retaining this standard atmosphere and moving away from the transmitter by the further distance Δ.

In this argument the $\theta^{-\frac{1}{2}}$ factor in the expression for the dependence of the field on θ has been omitted, since its effect is negligible in comparison with the exponential term in deciding the value of Δ.

When Δ has been found, the height-gain in decibels, say D, corresponding to eqn. (58) is most conveniently found by using equation (59) with $d = \Delta$ so that

$$D = 20\log_{10}L$$

i.e. $\quad D = 8\cdot686\frac{2\pi}{\lambda}\frac{\sqrt{3}}{2}|\alpha|\Delta \tag{61}$

As eqn. (58) is put in the form of $\frac{v_0}{v}$, this decibel value actually gives the number of decibels by which the field-strength is decreased at a given height by changing from the standard atmosphere to the one under consideration.

As h has been expressed in km., Δ in eqn. (61) is in km. Thus from eqns. (44) and (61) the decibel change is given on reduction by

$$D = 0 \cdot 0925 \, \Delta \, f^{\frac{1}{3}} \qquad (62)$$

At first sight the integrand in eqn. (60) looks cumbersome for computation, but actually it is found to be quite simple and straightforward in use. Moreover, although $\frac{h}{r_e}$ is very small, it rapidly becomes large compared with $|\alpha|$ as the height h_0 is left behind. Then A and A_0 in eqns. (53) and (54) approach a and a_0 respectively, so that eqn. (60) gives

$$\frac{d\Delta}{dh} = 4\sqrt{2} \, \frac{m - 1 \, h \xi}{r_e B}$$

where from eqn. (56)

$$B = (2a_0)^{\frac{1}{2}} (2a)^{\frac{1}{2}} [(2a_0)^{\frac{1}{2}} + (2a)^{\frac{1}{2}}]$$

so that

$$\frac{d\Delta}{dh} = \frac{2 \, m - 1 \, h \xi}{r_e \, a_0^{\frac{1}{2}} \, a^{\frac{1}{2}} \, a_0^{\frac{1}{2}} + a^{\frac{1}{2}}}$$

Now from eqns. (49) and (52)

$$a \simeq \frac{2h}{r_e} (1 - m - 1 \, \xi)$$

and

$$a_0 \simeq \frac{2h}{r_e}$$

so that finally on reduction

$$\frac{d\Delta}{dh} = |m - 1| \xi \left(\frac{r_e}{2h} \right)^{\frac{1}{2}} \left[(1 + m - 1 \, \xi)^{\frac{1}{2}} + 1 + m - 1 \, \xi \right]^{-1}$$

This is identical with the value obtained in eqn. (25) from the geometric-optical argument.

From eqn. (45) the following table may be constructed

f	λ	h_0
30 Mc s	10 m.	258 m.
300 Mc s	1 m.	55·6 m.
3,000 Mc s	10 cm.	12·0 m.
30,000 Mc s	1 cm.	2·58 m.

It is thus clear that on 30,000 Mc/s, the curve for $\dfrac{d\Delta}{dh}$ derived from eqn. (60), i.e. from

$$\frac{d\Delta}{dh} = \frac{2\sqrt{2}\,[m-1]\,h\xi}{r_e B}\left[1 + \frac{a + a_0}{A + A_0}\right]$$

differs imperceptibly from the curve in Fig. 5, and indeed this holds true when the scale is opened out as in Fig. 7. In the latter figure is also shown the curve for a frequency of 300 Mc/s. which approaches within 0·7% of the geometric-optical value at $h = 10$ km. It is terminated at $h = 0\cdot1$ km. which is less than twice the value of h_0. Below this height the curve formally crosses the other one and becomes of h^2 type.
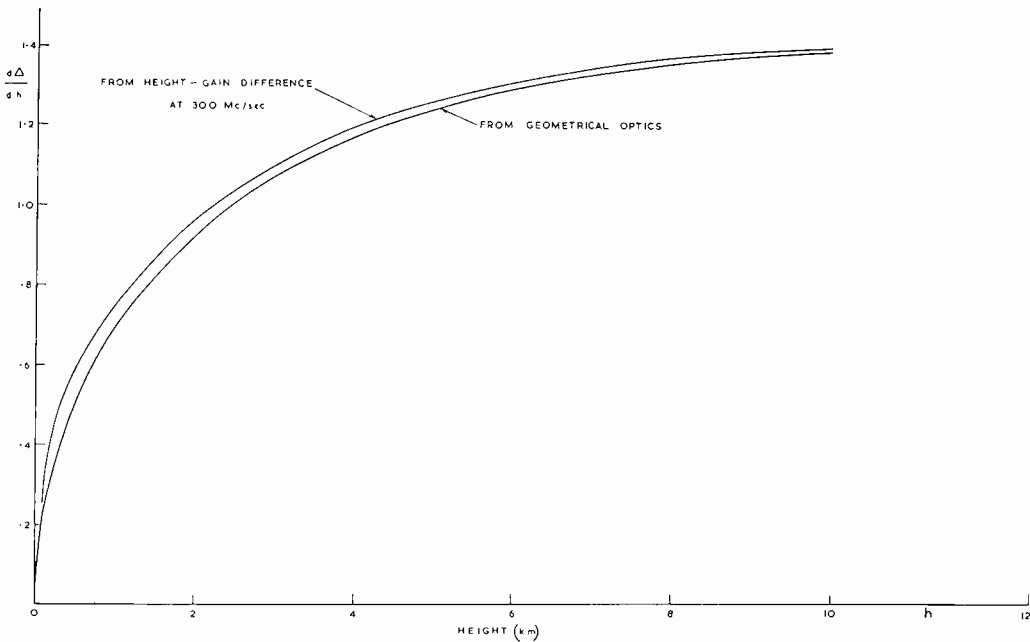

FIG. 7

Curves for $\dfrac{d\Delta}{dh}$ in the diffraction region.

It is in this region that the Stokes phenomenon occurs and the assumption of a single upgoing wave represented by the W.K.B. approximation no longer holds. This does not, however, affect the general argument concerning the height-gain difference D, given by eqn. (62), between the case of the standard atmosphere and of the actual refractive index variation, provided that the latter is effectively linear up to a height of say $2h_0$.

On 30 Mc/s where $h_0 = 258$ m. this condition is beginning to break down, but this means that the non-linearity of the layer is appreciable in the region where the Stokes phenomenon occurs and so affects the boundary condition determining the value of α. Also on vertical polarization over sea the earth constants begin to affect the value of ρ in eqn. (43), reducing its modulus and making it complex. At great

enough heights, however, $\dfrac{d\Delta}{dh}$ still becomes independent of α, so that the general relationship between the equivalent change in distance in the diffraction region and the reduction of horizon distance in the geometric-optical region is maintained.

With decreasing frequency the height-gain difference decreases as shown by eqn. (62), corresponding to the decreasing slope of the propagation curves in the diffraction region. In Fig. 8 are given curves for D for frequencies of 300, 3,000 and 30,000 Mc/s based on the integrated curve of Δ in Fig. 6. The small corrections shown in Fig. 7 at the lower heights are negligible when finding Δ and the corresponding D from eqn. (60). It will be seen that these differences in height-gain can be very considerable under some practical conditions.
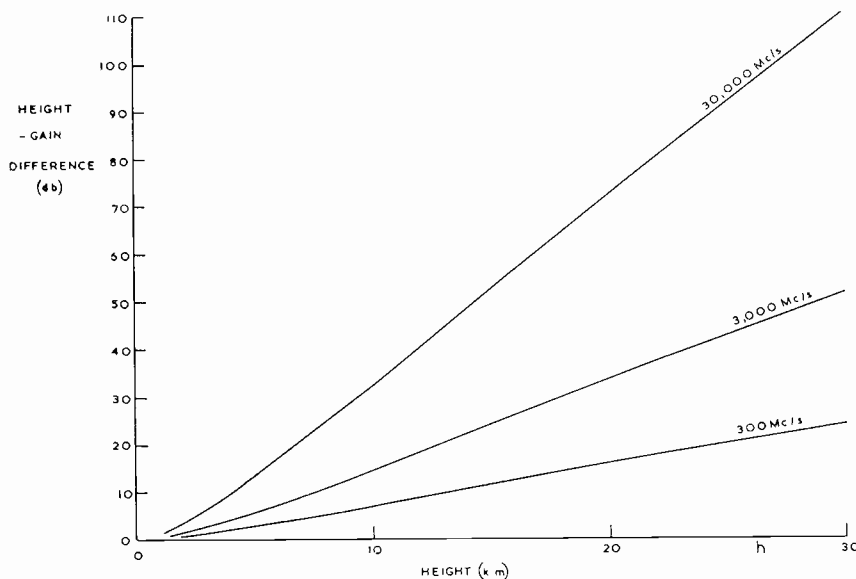

FIG. 8

Curves for the reduction in height-gain.

Conclusion

The analysis given in Sections 2 and 3 bears out the general picture anticipated in the Introduction where the similarity of the propagation curves for various heights, sufficiently large compared with a height now identified as h_0, was pointed out and illustrated in Fig. 2. The agreement between the Δ values in the geometric-optical and the diffraction regions, together with this similarity in the shape of the curves, leads to the conclusion that the effect of the non-standard atmosphere on the propagation curve of field-strength against distance at a given height is to shift the curve for the field at the same height in a standard atmosphere to the left, i.e. towards the transmitter, by the distance Δ.

This effect is shown in Fig. 9 for a height of 10 km. for the conditions of Fig. 2, i.e. a transmitter at a height of 200 m. radiating 1 kW on 300 Mc/s. The curve is shown for the modified atmosphere with a displacement of $\Delta = 11\cdot3$ km. derived from Fig. 6 and the accompanying decrease D is 7 db in agreement with Fig. 8. In Figs. 2 and 9 details of the earth constants and of the wave polarization are not given, as for

the conditions shown the curves are effectively independent of these factors. It should be pointed out that these figures are not constructed to high accuracy as they are only meant to illustrate the nature of the solution.

A great deal of time and effort has been spent in computing propagation curves to a high accuracy based on a precise mathematical formula for an idealized model of the earth and the surrounding atmosphere. Such curves are of great value as a background against which the propagation conditions for actual practical situations can be examined.
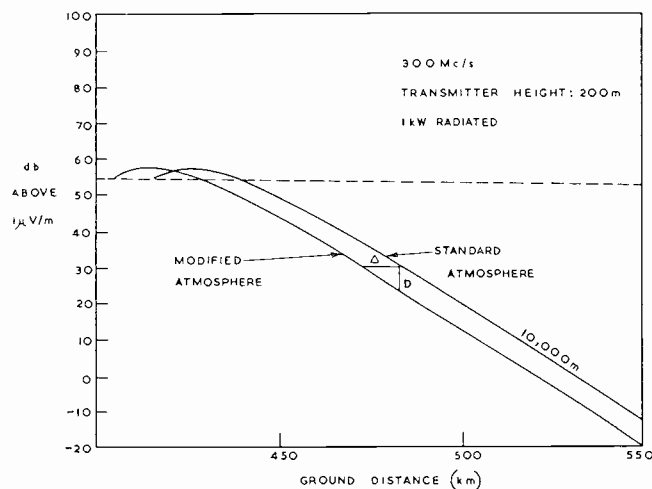

FIG. 9

Curves showing the shift due to the modification in refractive index at large heights.

There is a danger, however, that such curves may lead the radio engineer to think that field-strengths can be estimated to a far greater accuracy than is practicable.

It has been the purpose of the present paper to show that the field-strength at a given height and distance can be considerably modified by using a more realistic model of the atmosphere. The effect of a standard atmosphere is usually incorporated in the propagation curves by the use of an increased radius of the earth. It may well be argued that the curves should be computed for the type of atmosphere considered here which has a refractive index decreasing asymptotically to unity at great heights. Such an atmosphere based on an exponential law might be adopted as a new standard atmosphere which has the same properties and leads to the same propagation conditions at lower heights as the presently defined standard atmosphere.

However, the point which emerges strongly from the above analysis is that the really important factor is the position of the horizon distance to which the propagation curve has to be referred. A comparatively small change in this distance, causing a shift of the curve to the left or right, can make a considerable change in the field-strength in the diffraction region at a given height and actual distance from the transmitter, on account of the steepness of the curves. A strong case can in fact be made for providing the engineer with a technique for adjusting curves of a given shape with respect to the inverse distance curve for an estimated horizon distance. For this process the distance scale used in constructing the propagation curve must be linear in order to preserve its shape when shifted laterally.

Finally it may be stressed that this article has been restricted to the consideration of a specific point, namely to the use of a modified but still idealized atmosphere. In practice the atmosphere may be far from standard and a note of caution should be sounded that the use of propagation curves of the type under discussion may be quite unjustified at distances where the effects of partial reflections from inversion layers and of scattering from inhomogeneities can be dominant.

(159)

Acknowledgments

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BOOK REVIEW

Reflex Klystrons, by J. J. Hamilton. Chapman and Hall, London, 1958. 45 -.

The Reflex Klystron has established itself as one of the " tools of the trade " of the microwave engineer, but very often he has only the most rudimentary understanding of its principle of operation. In Mr. Hamilton's book, he has the opportunity to remedy this deficiency without a severe load on his time or energy.

In a book devoted almost entirely to one type of valve, it is, of course, possible to treat the subject matter in some detail, and the author has managed to present a good deal of both practical and theoretical information in a manner which makes it easily assimilated.

The first two chapters are devoted to a summary of the basic principles of the reflex klystron and of the characteristics of the microwave circuit, which is essential to its operation. They contain much useful information about cavity design and measurements, which will be of interest as much to the general microwave engineer as to the specialist embarking on valve development. In the next chapter the author describes the small signal theory of klystron operation and presents an outline of its extension to signals of large amplitude. This is followed by a description of the behaviour of the valve under practical operating conditions, which will be of considerable value to the everyday user of reflex klystrons.

The chapter on techniques of valve manufacture is necessarily somewhat restricted but presents a useful summary of the methods in current use. It is followed by a description of some representative types, and a list of valves which are commercially available. This is by no means comprehensive, but is sufficiently detailed to indicate the range of applications for which the reflex klystron is now in common use.

The final chapters on unconventional types and future trends seem to have been added as an afterthought, and do not contribute materially to the general theme of the book. They do, however, point out the limitations of the reflex klystron, and mention is made of the travelling wave tube and other devices in which some of the difficulties are overcome.

The book has been well prepared and is easily read. In this lies its greatest merit, since most of the information it contains is already available in a less convenient form elsewhere.

METEOR ACTIVITY AS A FACTOR IN IONOSPHERIC SCATTER PROPAGATION

By G. A. Isted*

Ionospheric scatter links for both experimental and communication purposes have been operating now for some years but, so far, no completely satisfactory theory has been advanced to explain all the observed propagation effects. Of the theories so far advanced, meteor activity and turbulence in the E-region are the most popular, and each is held by some to be self-sufficient to maintain the medium in the state necessary for the scattering of useful amounts of energy in the forward direction.

There can be no doubt that ionization by meteors does contribute to the general phenomenon of ionospheric forward scattering; indeed, much can be said for the theory that meteor activity may be responsible for a greater part of it. From time to time, however, certain characteristics have been observed which make the theory less plausible.

In recent years the author has suggested that weather-cloud discharges may be capable of producing bursts of ionization similar to those produced by meteors. Evidence has been found, for example, of groups of bursts having regular spacing between bursts; furthermore some of these groups are associated with thunder-cloud discharges in a manner which cannot be ignored. Interesting evidence has come to light which shows that the seasonal variation of relatively local lightning activity has clearly defined minima at each of the equinoxes; similar well-defined seasonal minima have been observed in the United Kingdom during independent investigations of ionospheric forward-scatter propagation—this, despite the fact that the meteor theory would predict maximum ionization at the autumnal equinox.

One of the natural phenomena associated with ionospheric forward scatter transmission is the large number of audible Doppler beats which are present at most times. It has generally been accepted that they are produced, in association with a radio frequency wave, by meteors entering the earth's denser atmosphere. The careful analysis of these Doppler disturbances discloses the fact that there are as many which ascend in frequency as those which descend. The probability that the ascending type of beat could be caused by meteors has been investigated and the conclusion is reached that out of six Doppler disturbances only one should ascend.

Doppler disturbances have a similar diurnal distribution to that of transient echoes observed at vertical incidence on a frequency of 10 Mc/s, and it is suggested that they are each caused by a common mechanism not of meteoric origin.

Meteor activity may be found to play a relatively small part in ionospheric forward scatter propagation and it is possible that the weather-cloud discharge, or some other mechanism as yet unidentified, may instead prove to be the dominant factor.

Introduction

COMMUNICATION by means of scattering processes in the E-region of the ionosphere is now well established, and invaluable communication circuits, operating in the lower V.H.F. band, now exist between the United States of America and the United Kingdom, via intermediate relay stations situated in Greenland and Iceland; their performance outmodes all previous means of radio telegraph communication over routes which pass near or through the auroral zone.

This is particularly apparent when magnetic disturbances render useless the orthodox modes of H.F. communication utilizing the F_2 reflecting processes while, at the same time, the ionospheric scattering processes are observed to relatively immune to such disturbances.

Although satisfactory means have been found to make the best use of ionospheric scattering processes it cannot be said that agreement is unanimous upon the precise propagation mechanisms involved; of the theories so far advanced meteor activity and turbulence in the E-region are the most popular, and each is held by some to be self-sufficient to maintain the medium in the state necessary for the scattering of useful amounts of energy in the forward direction. Many of the less dogmatic of the theorists are in favour of a combination of both mechanisms in varying proportions.

There can be no doubt that transient echoes, caused by meteor ionization, contribute to the general phenomenon of ionospheric forward scattering; indeed, much can be said for the theory that meteor activity may be responsible for a major proportion of it. The principle characteristics in favour of the theory are the frequent burst-like character of the signal, the pronounced evening minimum and the systematic deviation of the angle of arrival with respect to the great-circle bearing—the latter two characteristics being dependent upon local time. From time to time, however, certain observations have been made which make the meteor theory less plausible and the object of this paper is to examine some of the unique characteristics of transient echoes in relation to the observed characteristics of ionospheric scatter propagation. Certain experiments will be described which have been carried out in an attempt to obtain a better understanding of the mechanisms involved in ionospheric scatter propagation.

Characteristics of Scattered Signals

A brief description of the salient characteristics of the scattered signal will enable the discussion which follows to be better understood. The outstanding feature of the signal in general is undoubtedly its extremely variable amplitude; it would appear to consist of several components, not all of which are present together.

(a) *The Background Signal.* This component varies rapidly in amplitude by some tens of decibels, with fading rates of the order of a few cycles per second. It is always present, but it nevertheless exhibits marked diurnal and seasonal variations.

(b) *Transient Echoes or Bursts.* Frequent sudden enhancements, with durations of the order of a few seconds, are super-imposed upon the background signal. Some of these bursts are accompanied by Doppler frequency shifts which, together with a direct C.W. signal, give rise to a musical note ascending or descending in frequency.

(c) *Long Bursts.* Occasional enhancements of signal by some 30-40 dB which last several minutes are observed on frequent occasions. It is believed that this type of burst is the result of drifting clouds of ionization, but just how these are produced is not clearly understood.

(d) *Sporadic-E Activity.* On occasions, the median signal level increases by some 60-80 dB for periods lasting from several minutes to several hours; this is more likely to occur in the summer months during the hours of daylight, although it has also been observed at other seasons and during darkness. As its name implies it is sporadic both in time of occurrence and geographical situation.

(e) *Seasonal and Diurnal Variations.* The signal resulting from a combination of the components (a), (b) and (c) above shows a marked minimum of amplitude each day at about 1800 hours local time. The maximum occurs sometime before noon, but its exact location seems to depend upon the horizontal beamwidth of the combined transmitting and receiving aerials. Well defined seasonal minima have been observed [1] [2] at both equinoxes from transmissions along great-circle routes running approximately North and South.

(f) *Doppler Frequency-shift Effects.* As stated in (b) above short enhancements of signals are often accompanied by a Doppler frequency shift which produces a musical note, either ascending or descending in frequency, when a C.W. signal is being observed. It has generally been supposed that this frequency shift is the result of a reflection from the moving head of a column of ionization, possibly produced by a meteor in its rapid flight through the atmosphere. It has been observed [3] that Doppler beat notes of this type have a well defined diurnal variation reaching a maximum of 0200 hours and a minimum at 1800 hours local time.

Examination of Unique Characteristics of Transient Echoes and Ionospheric Scatter

Height of Scattering Region

By general agreement it is considered that the mean height of the effective scattering region is somewhat below the normal E-layer, its mean height being about 86 Km. above ground. The height of this scattering region has been investigated by Bailey *et al* [4] and Pineo [5] who, with a one-way pulse transmission, used the observed height of the tropospheric scattering region as their reference; later a go-and-return pulse technique was used.

The results of these oblique incidence experiments indicate that a continuous narrow stratum of ionization is present most of the time, and it is probably this stratum which sustains the continuous background signal. The theory that the background signal is the result of overlapping of many reflections from ionized meteor trails at diverse heights above the ground would therefore seem to have been proved untenable.

However, on the other hand, Eastwood and Mercer [6] as early as 1946 carried out a series of experiments using wartime radar installations operating on frequencies between 22 and 44 Mc/s; in these experiments interest was concentrated on " transient echoes " and from their description it is clear that they were similar to those echoes which investigators to-day would consider to be reflections from meteors. Eastwood and Mercer established beyond reasonable doubt that the transient echoes which they observed were concentrated in a well-defined stratum at a height of 85-86 Km. above the ground. Thus it is probable that the transient echoes observed by them constitute the continuous stratum observed obliquely by Bailey *et al*. Eastwood came to the conclusion that in many respects the characteristics of transient echoes were similar to those which would be expected from meteor activity; it is difficult, however, to understand why this activity should be concentrated in a narrow stratum at a height which would seem much too low for exclusive meteor effects.

From the foregoing it would seem there is strong evidence in support of the theory that the scatter background signal results from numerous transient echoes of the type observed by Eastwood; while there is some evidence associating transient echoes with meteor ionization, other evidence is not altogether convincing.

Assocation of Electrical Discharges with Transient Echoes

Wilson ([7]) in 1925 suggested that, as the height is increased above the ground, the electric force required to reach the critical break-down value decreases much more rapidly than the electric field due to a charged weather-cloud and, because of this, he predicted that weather-clouds would be sufficient to produce ionization at a height of about 80 Km.; furthermore, in extreme cases, a sudden discharge of the upper pole of a charged cloud to the upper atmosphere might occur, but this discharge need not be in the form of lightning.

Wilson ([8]) had previously suggested that the earth's vertical electric field was maintained by upwardly directed thunder-cloud discharges, and he considered that the E-region was the means by which the energy so discharged was transferred to areas of clear sky; the energy there leaks down to the ground by conduction through the atmosphere, and gives rise to the observed vertical electric field.

Pawsey ([9]), Bauer and Flood ([10]) and Graf ([11]) have all observed transient radio echoes from thunder-cloud discharges; Rumi ([12]), who conducted a radar investigation into meteor reflections, stresses the fact that many of the returns which he analysed cannot in fact be explained in terms of known meteor reflection characteristics. He states that they can be attributed to upwardly directed discharges from weather-clouds to the ionosphere.
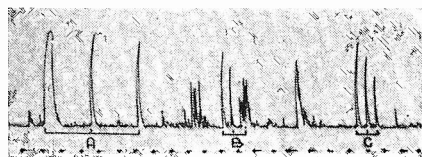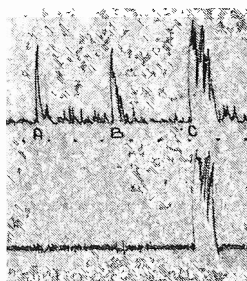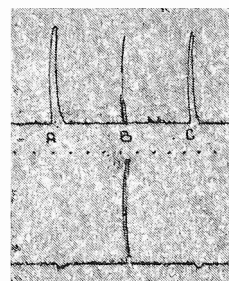

Fig. 1

Examples of regularly spaced bursts of ionization observed at a frequency of 53 Mc/s, 500 Km. from the transmitter.

(a)   (b)

Fig. 2

Examples of the association of lightning with regularly spaced bursts of ionization.

The author ([13]) ([14]) has investigated the signals received from a high-power continuous-wave transmitter radiating at a frequency of 53 Mc/s. The transmitter was situated nearly 500 Km from the receiver; at this distance the transient echoes, reputed to be caused by meteor activity, could be observed to the exclusion of the continuous tropospheric signal. When the signal was made to operate a high-speed recorder, it was observed that groups of signal bursts frequently occurred in which the individual bursts were equally spaced in time from one another.

Fig. 1 shows such a record where groups of three equally spaced bursts can be seen clearly at A, B and C. In this record time advances from left to right and is marked off at second intervals along the foot of the record; increases of amplitude appear as upward deflections. A unique characteristic to be noted in all three groups illustrated is the progressive decrease in amplitude of the individual bursts in a group.

During relatively local thunderstorm activity the recurrent bursts of the type described appear to be associated with lightning. High-speed records of this effect were made with the aid of a twin channel recorder operated by two separate but

similar receivers; one of them was tuned to the signal frequency of 53 Mc/s and recorded on the top trace; the other receiver was slightly detuned to an adjacent free channel and recorded on the bottom trace. Disturbances due to relatively local lightning flashes would record on both traces simultaneously, while the wanted radio signal would appear only on the top trace. Thus, from Fig. 2 (*a*) it can be seen that radio signal bursts A and B precede a lightning flash C, the time spacings between AB and BC being equal. In Fig. 2 (*b*) radio signal bursts A and C are equally disposed in time on either side of the lightning flash B.

It has been shown by Briggs [15] that among a random distribution of signal bursts grouping and regularity in spacing—within given limits—would be expected on a statistical basis, nevertheless the unique characteristics described above, and the growing number of reports which associate transient echoes with weather-cloud discharges, suggest that all meteor-like bursts of ionization may not in fact be due to meteors.

Association of Electrical Discharges with Seasonal Variations of E-region Scatter

In the preceding section the possible instantaneous effects of weather-clouds discharging to the E-region were considered; the long term trends in this respect are also worthy of note. In this connection it is interesting to compare the long-term measurement of atmospherics made by Reiter [16] in Munich, with the long-term measurement of signal level carried out by Bray *et al* [1] and by Isted [2], during separate investigations of ionospheric scatter propagation.

Reiter counted the number of impulses due to lightning occurring within a radius of 2,000 Km., which he observed in the frequency range 4-12 Kc/s. His results showed that over a period of five years two well-defined minima and two maxima occur per year; the first maximum occurs in the summer months and can be explained by the frequency of thunderstorms in Central Europe. The second maximum occurs in the winter and is not so easily explained, but in his analysis of the main weather processes, Reiter found that during the winter months violent invasions of polar air-masses into the Mediterranean area take place and form moist unstable gradients over the relatively warm sea which give rise to thunderstorms.
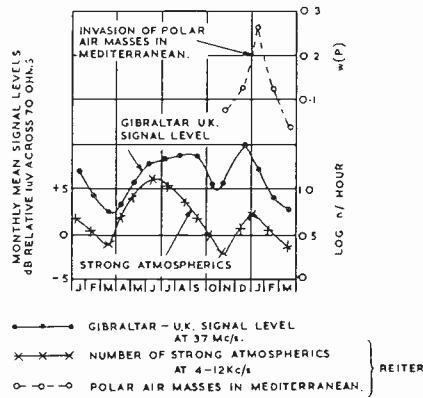

FIG. 3

Seasonal variation of strong atmospherics and polar air masses in the Mediterranean (Reiter) compared with mean signal levels observed from scatter transmissions.

Reiter's results are reproduced in Fig. 3. The curve labelled "Strong Atmospherics" represents the seasonal variation averaged over a period of five years; the summer and winter maxima are clearly seen. In the top right-hand part of the figure the number of observed invasions of polar air into the western Mediterranean during the winter months is shown; it would seem that the explanation given by Reiter for the winter maximum of atmospherics is well founded. The centre curve represents the seasonal variation of the mean signal level observed during an investigation carried out into the propagation characteristics of ionospheric forward scatter between Gibraltar and the United Kingdom, at a frequency of 37 Mc/s [17] [2]. The similarity between Reiter's "Atmospheric" curve and the mean signal level of the ionospheric

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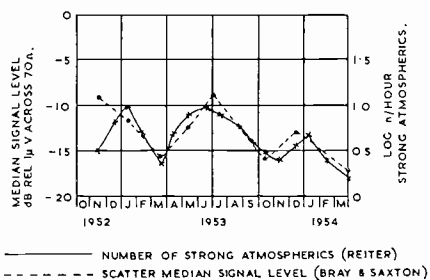SCATTER MEDIAN SIGNAL LEVEL (BRAY & SAXTON)

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Two suitable test paths were available near Chelmsford, England; one long ionospheric scatter path to Gibraltar in the south, and a short path to the B.B.C. Television Transmitter at Kirk-o-Shotts, Scotland, in the north. Bursts of signal from the Kirk-o-Shotts transmitter, reputed to be caused by meteor ionization, could be observed to the exclusion of the continuous background; of these signal bursts, those which exceeded a given amplitude were counted by means of an electro-mechanical device. The Gibraltar ionospheric scatter signal was integrated over a period of 20 seconds and recorded; the mean level was then estimated by eye.

Fig. 5 shows the number of signal bursts received per hour from the Kirk-o-Shotts transmitter, plotted against the mean signal level received from Gibraltar for the appropriate time and day.

A cursory glance is sufficient to show that the straightforward correlation sought for was not found. This lack of correlation could imply that the Kirk-o-Shotts signal bursts and the Gibraltar scatter signal are each influenced by a different mechanism or, alternatively, that each may be influenced by a common mechanism which is relatively local in effect—such as weather-cloud discharges. In any event, from this test, it would seem that the contribution of sporadic type meteors to long distance scatter propagation is very small indeed.

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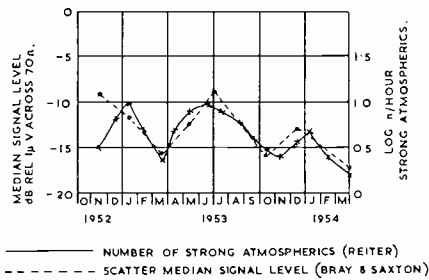
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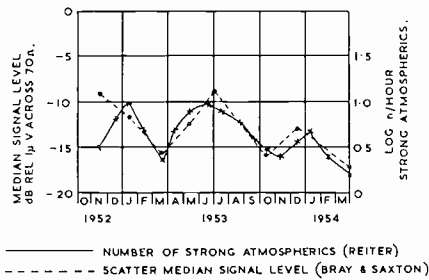

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Assocation of Electrical Discharges with Transient Echoes

Wilson ([7]) in 1925 suggested that, as the height is increased above the ground, the electric force required to reach the critical break-down value decreases much more rapidly than the electric field due to a charged weather-cloud and, because of this, he predicted that weather-clouds would be sufficient to produce ionization at a height of about 80 Km.; furthermore, in extreme cases, a sudden discharge of the upper pole of a charged cloud to the upper atmosphere might occur, but this discharge need not be in the form of lightning.

Wilson ([8]) had previously suggested that the earth's vertical electric field was maintained by upwardly directed thunder-cloud discharges, and he considered that the E-region was the means by which the energy so discharged was transferred to areas of clear sky; the energy there leaks down to the ground by conduction through the atmosphere, and gives rise to the observed vertical electric field.

Pawsey ([9]), Bauer and Flood ([10]) and Graf ([11]) have all observed transient radio echoes from thunder-cloud discharges; Rumi ([12]), who conducted a radar investigation into meteor reflections, stresses the fact that many of the returns which he analysed cannot in fact be explained in terms of known meteor reflection characteristics. He states that they can be attributed to upwardly directed discharges from weather-clouds to the ionosphere.
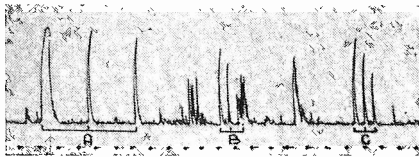

FIG. 1

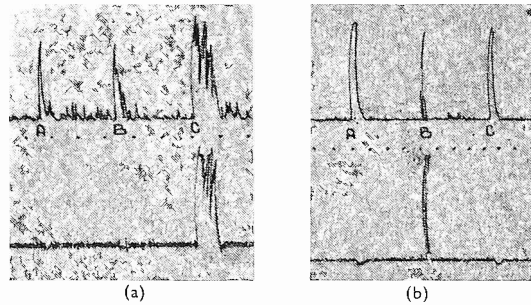*Examples of regularly spaced bursts of ionization observed at a frequency of 53 Mc/s, 500 Km. from the transmitter.*

FIG. 2

Examples of the association of lightning with regularly spaced bursts of ionization.

The author ([13]) ([14]) has investigated the signals received from a high-power continuous-wave transmitter radiating at a frequency of 53 Mc/s. The transmitter was situated nearly 500 Km from the receiver; at this distance the transient echoes, reputed to be caused by meteor activity, could be observed to the exclusion of the continuous tropospheric signal. When the signal was made to operate a high-speed recorder, it was observed that groups of signal bursts frequently occurred in which the individual bursts were equally spaced in time from one another.

Fig. 1 shows such a record where groups of three equally spaced bursts can be seen clearly at A, B and C. In this record time advances from left to right and is marked off at second intervals along the foot of the record; increases of amplitude appear as upward deflections. A unique characteristic to be noted in all three groups illustrated is the progressive decrease in amplitude of the individual bursts in a group.

During relatively local thunderstorm activity the recurrent bursts of the type described appear to be associated with lightning. High-speed records of this effect were made with the aid of a twin channel recorder operated by two separate but

similar receivers; one of them was tuned to the signal frequency of 53 Mc s and recorded on the top trace; the other receiver was slightly detuned to an adjacent free channel and recorded on the bottom trace. Disturbances due to relatively local lightning flashes would record on both traces simultaneously, while the wanted radio signal would appear only on the top trace. Thus, from Fig. 2 (a) it can be seen that radio signal bursts A and B precede a lightning flash C, the time spacings between AB and BC being equal. In Fig. 2 (b) radio signal bursts A and C are equally disposed in time on either side of the lightning flash B.

It has been shown by Briggs [15] that among a random distribution of signal bursts grouping and regularity in spacing—within given limits—would be expected on a statistical basis, nevertheless the unique characteristics described above, and the growing number of reports which associate transient echoes with weather-cloud discharges, suggest that all meteor-like bursts of ionization may not in fact be due to meteors.

Association of Electrical Discharges with Seasonal Variations of E-region Scatter

In the preceding section the possible instantaneous effects of weather clouds discharging to the E-region were considered, the long term trends in this respect are also worthy of note. In this connection it is interesting to compare the long-term measurement of atmospherics made by Reiter [16] in Munich, with the long term measurement of signal level carried out by Brav et al [1] and by Isted [2], during separate investigations of ionospheric scatter propagation.

Reiter counted the number of impulses due to lightning occurring within a radius of 2,000 Km., which he observed in the frequency range 4-12 Kc s. His results showed that over a period of five years two well defined minima and two maxima occur per year, the first maximum occurs in the summer months and can be explained by the frequency of thunderstorms in Central Europe. The second maximum occurs in the winter and is not so easily explained, but in his analysis of the main weather processes Reiter found that during the winter months violent invasions of polar air masses into the Mediterranean area take place and form moist unstable gradients over the relatively warm sea which give rise to thunderstorms.

Reiter's results are reproduced in Fig. 3. The curve labelled "Strong Atmospherics" represents the seasonal variation averaged over a period of five years, the summer and winter maxima are clearly seen. In the top right-hand part of the figure the number of observed invasions of polar air into the western Mediterranean during the winter months is shown; it would seem that the explanation given by Reiter for the winter maximum of atmospherics is well founded. The centre curve represents the seasonal variation of the mean signal level observed during an investigation carried out into the propagation characteristics of ionospheric forward scatter between Gibraltar and the United Kingdom, at a frequency of 37 Mc s [1] [2]. The similarity between Reiter's "Atmospheric" curve and the mean signal level of the ionospheric
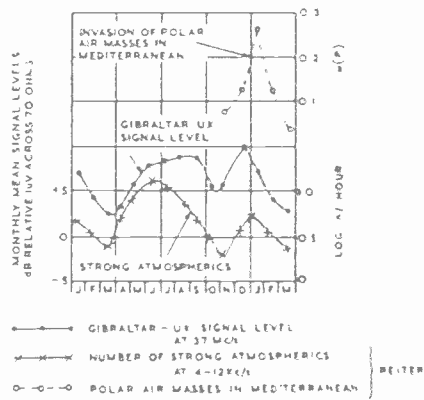

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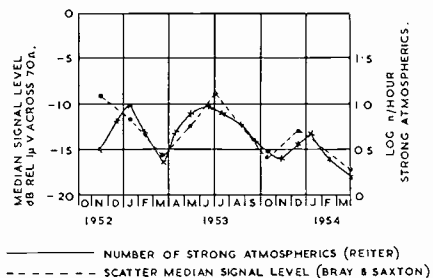

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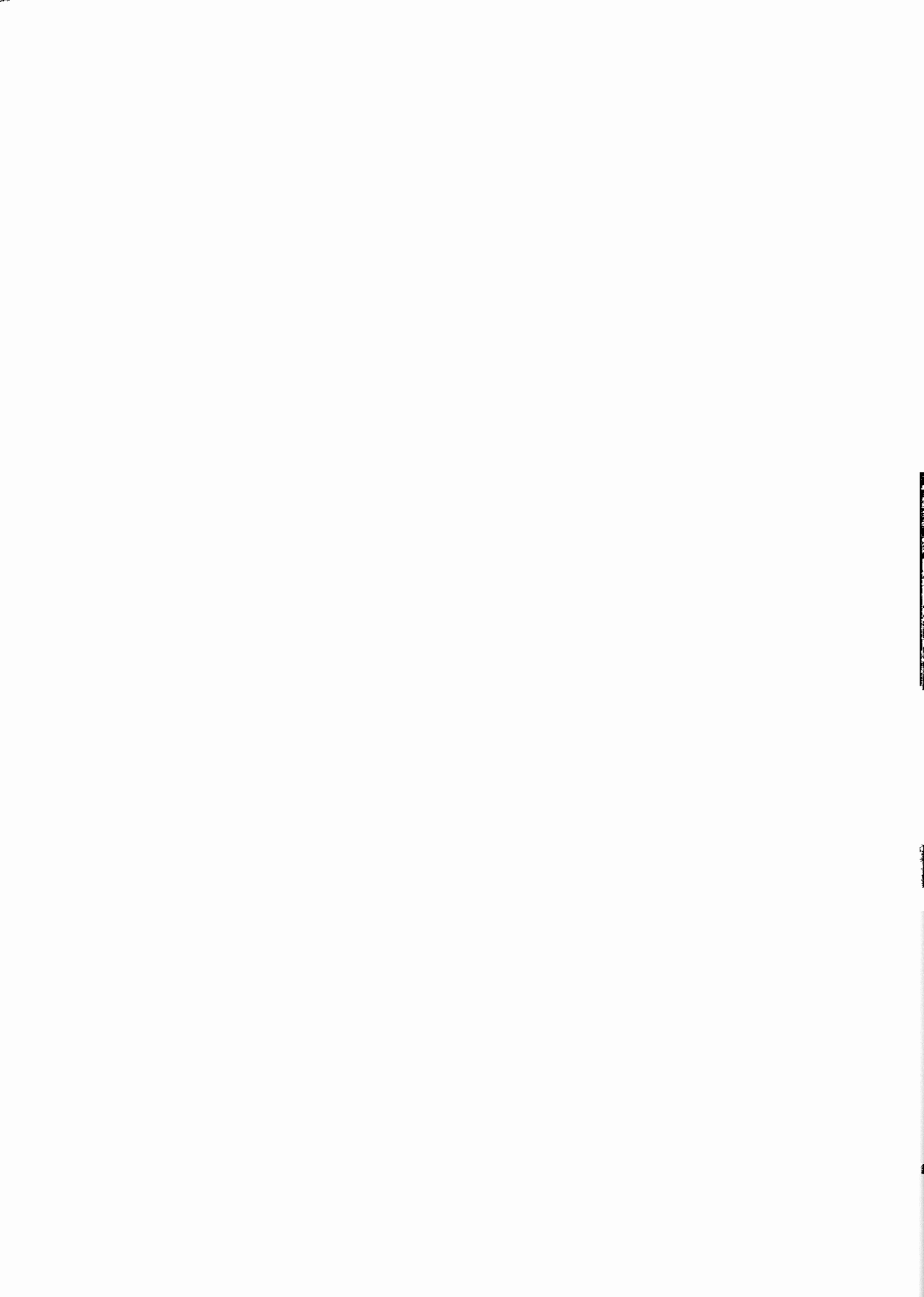
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Fig. 5 shows the number of signal bursts received per hour from the Kirk-o-Shotts transmitter, plotted against the mean signal level received from Gibraltar for the appropriate time and day.

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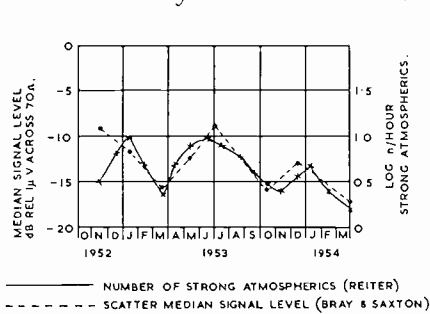

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(166)

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... were made by the Marconi Company in ... 1944 ... pulse sounder. The transmitter operating ... 30 Mc/s ... modulated by pulses of 100μ sec duration, ... The peak pulse power radiated from a half-... wave ... and was 25 Kw. A rhombic aerial ... ... characterized a suitable receiver, the output ... A ... cathode ray oscilloscope, the transmitted ... ... time base and a continuously moving ... ... received by the system. A five minute ... over a period of nearly two years. The

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MEAN SOLAR TIME ... HOURS TO A

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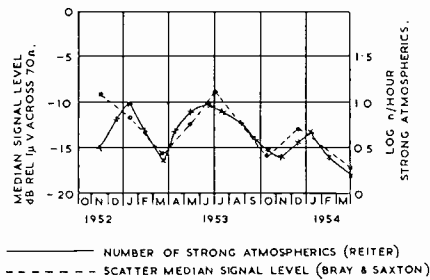
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equivalent frequency at vertical incidence. Most of the data concerning ionospheric scatter refer to the lower end of the V.H.F. band; therefore the equivalent frequency at vertical incidence is in the region of 10 Mc/s.

Observations of transient echo activity were made by the Marconi Company in the years 1944-45 by means of an ionospheric sounder. The transmitter, operating at a fixed frequency of 10·6 Mc/s, was modulated by pulses of 100μ sec. duration, at a repetition rate of 25 per second. The peak-pulse power radiated from a half-wave horizontal dipole situated λ/4 above ground, was 25 Kw. A rhombic aerial, the main lobe of which was directed vertically, energized a suitable receiver the output of which was connected to an " A scan " cathode ray oscilloscope; the transmitted pulse was arranged to trigger the oscilloscope time-base, and a continuously moving film through a camera recorded the information given by the system. A five-minute sample was recorded at hourly intervals over a period of nearly two years. The
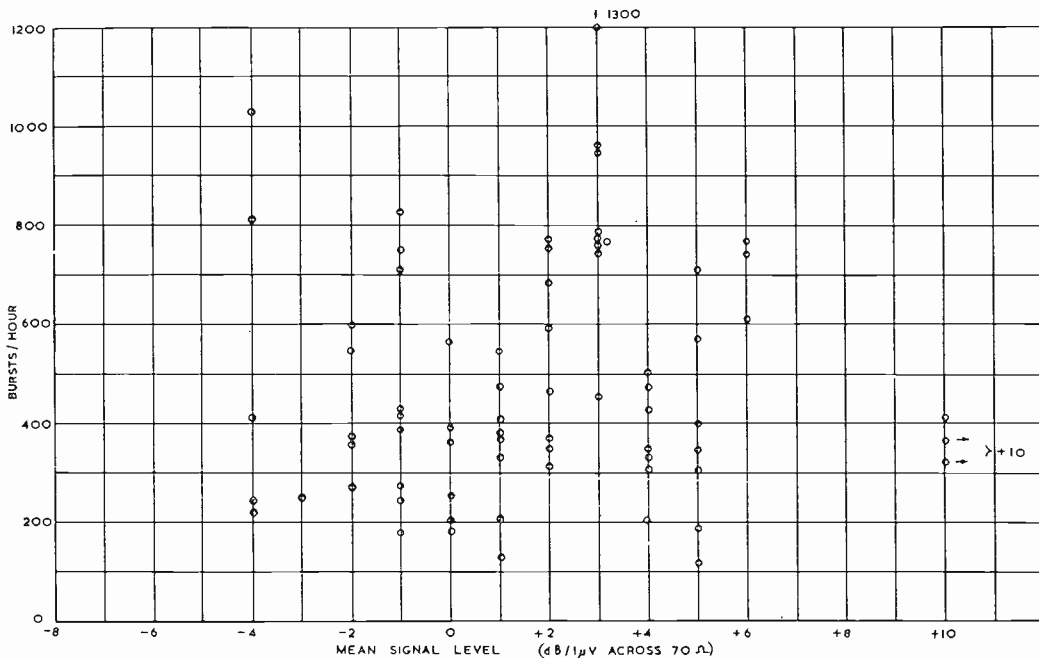

FIG. 5

Relation between the Gibraltar-United Kingdom scatter signal levels and transient echoes received from Kirk-o-Shotts.

complete analysis of the diurnal distribution of the transient echo activity observed under these conditions is presented in a simplified form in Fig. 6 (*a*) where the diurnal distributions are embodied in three curves—winter, summer and yearly mean.

Two outstanding points of importance are illustrated by the curves; firstly, the time of maximum activity throughout the seasons is constant at 0400 hours G.M.T. and secondly, the minimum of activity is correlated with sunset time; the latter effect is shown in greater detail in Fig. 6 (*b*), where the calculated sunset times for each month are compared with the observed times of minimum transient echo activity. These observations do not altogether agree with similar observations made by Eastwood and Mercer[6] at frequencies between 22 and 44 Mc/s and by Lovell[18] at a frequency of 70 Mc/s.

(167)

Lovell has reported that the analysis of his observations has shown a distinct seasonal variation; this, he claims, is due to the significant effect of day-time meteor streams. He shows that the diurnal distribution for January, observed on an aerial array rotating twice per minute, has a maximum activity at about 0400 hours G.M.T., while in June the maximum activity was observed at about 1000 hours G.M.T.; moreover, twice the number of echoes were observed during daylight in June than in January during night-time.

The results obtained by Eastwood and Mercer agree very well with those of Lovell except that they observed the same degree of activity throughout the year. The diurnal distributions for the months of January and June observed by Lovell are reproduced in Fig. 7 (*a*) and, for comparison, those observed by Eastwood and Mercer in Fig. 7 (*b*).
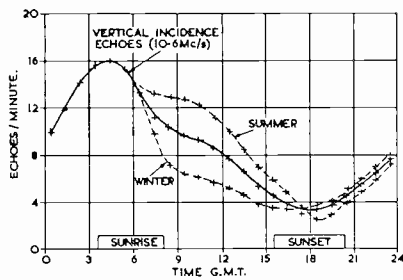

Fig. 6 (*a*)

Diurnal variation of ionospheric transient echoes at vertical incidence on a frequency of 10·6 Mc/s.
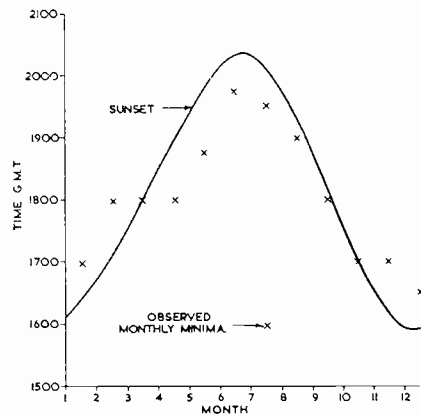

Fig. 6 (*b*)

Observed items of minimum transient echo activity compared to sunset times.

Lovell took over a quarter of a million echoes into account in his analysis and the reality of his results must be accepted; however, more than half a million echoes were included in the analysis of the Marconi investigation at 10 Mc/s, and the results obtained must be accepted as equally real. Considering that one set of observations was made at a frequency of 70 Mc/s and the other at 10 Mc/s, it seems likely that two entirely different phenomena, giving similar manifestations, are observed at the two frequencies in varying proportions.

Meteor Activity and Doppler Frequency-shift Effects

One of the interesting phenomena of ionospheric scatter transmission over long distances is the large number of audible Doppler beats which can be heard in the form of musical tones descending or ascending in frequency. These can be heard in varying numbers throughout the day and night.

In the past it has been believed that the Doppler beats observed are the result of meteors which are entering the earth's atmosphere from outer space. The audible beat is believed to be caused by a direct radio wave mixing with a wave which is reflected from the moving head of a column of ionization; the ionization is thought to be produced upon combustion of the meteor in its rapid flight into the earth's denser atmosphere.

An analysis has been made of the Doppler beat activity observed during the investigation into ionospheric scatter propagation between Gibraltar and the United Kingdom ([2]) ([3]) ([17]), at a frequency of 37 Mc/s. Samples of the Gibraltar signal were taken by arranging a magnetic tape to record the audio output from the receiver for a period of one minute at half-hourly intervals; the receiver, having a band-width of 1000 c/s, was used without the B.F.O. The samples were later analysed by playing back the record and counting the number of beats which could be heard above a certain threshold value. The analysis disclosed that there were two main types of beats—those which ascended in frequency and those which descended—and furthermore, that the two types were present in approximately equal numbers.

Beats descending in frequency usually became audible between 1000-500 c/s and fell in frequency until they became inaudible below 50 c/s. Ascending beats on the other hand, became audible at a frequency of about 50 c/s and rose to about 500 c/s. The low frequency limit of audibility of 50 c/s was imposed by the combined frequency response of the el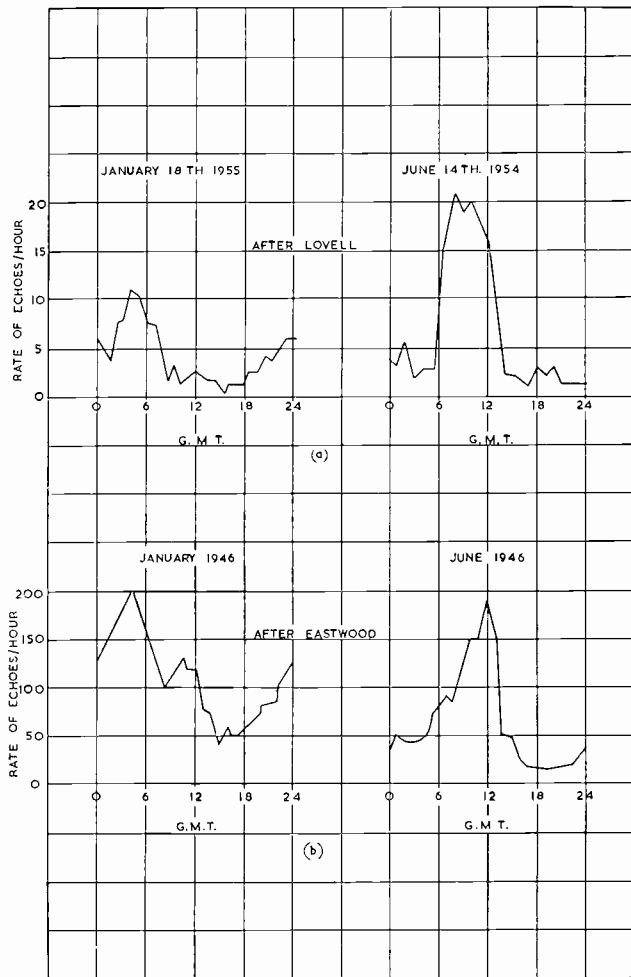ectronic equipment and the human ear. To observe frequencies below 50 c/s, however, a high-speed stylo-pen recorder was used; typical records are shown in Fig. 8 where time advances from right to left, and vertical deflections correspond to increases of amplitude. Second time-marks are recorded at the bottom of each record. In Fig. 8 (*a*) an unusually long descending beat is indicated by the arrow; the beat ends within a cycle or two of zero beat, and is followed by a period of greatly enhanced signal. This is typical of the behaviour of a meteor. A more common type of descending beat is shown in Fig. 8 (*b*) while an equally common type, but ascending in frequency, is shown in (*c*). A unique charac-

FIG. 7
Seasonal variations of meteor echoes as measured (a) by Lovell and (b) by Eastwood.

(169)

teristic of the ascending beat is the sudden commencement at, or very near to, zero beat.

The diurnal distribution of both types together shows that the maximum number occur between the hours of 0200-0400 G.M.T., and the minimum number at around 1800 G.M.T. A typical diurnal distribution—that for August—is shown in Fig. 9 (*a*), where it is seen that there is a maximum rate of occurrence of about 35 per minute, and a minimum rate of 3 or 4 per minute.

The ascending and descending types of Doppler beat were counted separately and the ratio of one to the other is shown in Fig. 9 (*b*).

Assuming that beats are caused by sporadic meteors the probability of an ascending beat being produced was investigated, and the number of meteors producing this effect deduced as a fraction F of the total number observed; the assumptions made as regards the average velocity of the meteors, the height at which reflections occur and the lower limit of audibility (50 c/s), were chosen with a view to making the fraction F nearest to unity. Under these conditions the predicted value of F is 0·17, i.e. one ascending beat for every six which descend. Furthermore, the fraction F can be shown to be inversely proportional to the relative velocity of meteors with respect to the scattering region; the velocity of sporadic meteors relative to the earth is determined largely by the earth's orbital velocity, components of this velocity being added to, or subtracted fr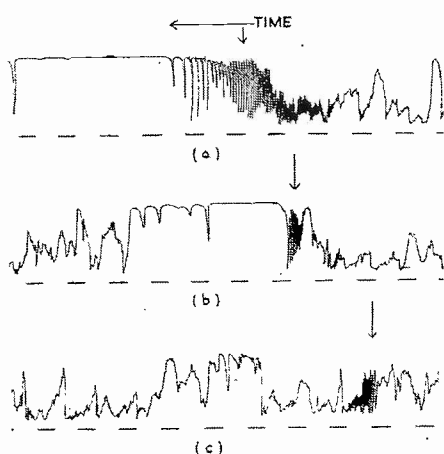om, the meteor velocity depending upon the earth's rotational position with respect to its orbit. The average relative velocity of sporadic type meteors should therefore reach a maximum at 0600 hours local time i.e., when the observing point is on the crown of the leading hemisphere considered in relation to the earth's orbit. Minimum relative velocity should occur at 1800 hours local time. A diurnal distribution of the fraction F would therefore be expected. In terms of the ratio of ascending to descending Doppler beats, therefore, the diurnal variation should show a maximum at 0600 hours, and a minimum at 1800 hours local time.

Reference to Fig. 9 (*b*) will show that this situation is far from being fulfilled, in fact, if any real deviation exists in that direction, it is at 1800 hours and not at 0600 hours as predicted; it is believed, however, that the actual deviations observed were caused by errors in counting because, at that time, the signal/noise ratio was low and the number of observable beats was small.

FIG. 8

Examples of Doppler Beats.
(*a*) *Long descending beat.*
(*b*) *Short descending beat.*
(*c*) *Short ascending beat.*

The fact that the analysis showed the ratio of descending to ascending beats to be only slightly greater than unity, and the fact that no systematic diurnal variation in this ratio was present, is probably significant evidence that a mechanism other than meteors alone must be producing the beats. Having made this point it is interesting to compare the diurnal distribution of Doppler beats shown in Fig. 9 (*a*) with the diurnal distribution of transient echoes observed at vertical incidence shown in Fig. 6 (*a*). The similarity of the diurnal distributions shown in the two curves very strongly suggests that they each represent a manifestation of a common mechanism; the evidence does not, however, suggest that the mechanism is of meteoric origin.

Conclusion

From the foregoing examination of the unique characteristics of transient echoes and ionospheric scatter it is clear that further investigation will be needed before it can be said that propagation by the ionospheric forward scatter mode is completely understood.

There would seem to be strong evidence in support of the view held by many investigators that an ionospheric scatter signal is produced, to a large extent, by the overlapping of many transient bursts of ionization 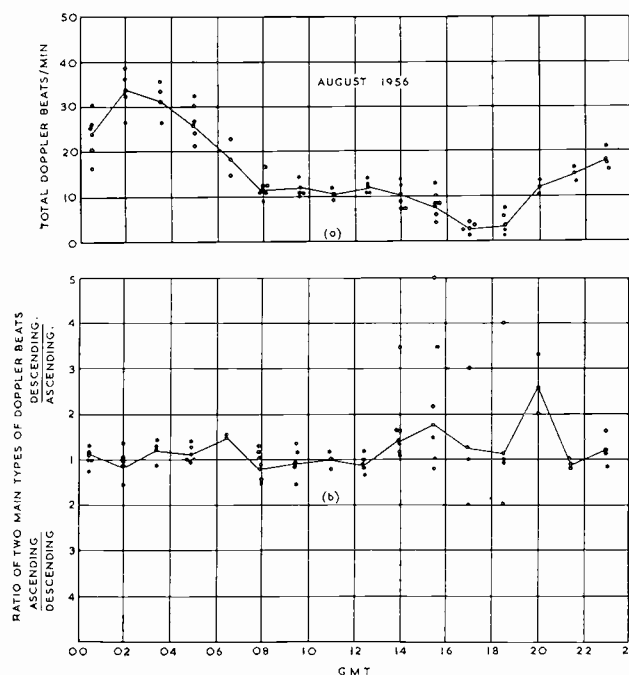which occur at a height of about 86 Km. above the earth. The origin of these transient bursts of ionization is, however, by no means certain; while there is no doubt that ionization is produced by meteors, some very pertinent questions must be answered by those who hold the view that the origin is wholly meteoric.

Why, for example, is the effective scattering region concentrated in a narrow stratum situated at an average height of 86 Km?

Is there, in fact, a strong connection between weather-cloud discharges and transient echoes, or are we to believe that, given suitable conditions, a meteor will itself initiate an electrical discharge? The electrification of clouds is one of the greatest of terrestial natural phenomena. Is it so inconceivable that it could

Fig. 9

(*a*) *Diurnal variation of Doppler beats.*
(*b*) *Ratio of descending to ascending beats for August,* 1956.
Frequency 37 *Mc/s.*

profoundly affect the state of ionization in the E-region through which the resulting discharged energy is known to be dissipated?

It is possible that the ascending Doppler beats which are observed on ionospheric scatter signals provide an important link with upwardly directed weather-cloud discharges. If these discharges do take place could they not cause a very intense pocket of ionization which would rapidly expand in the manner of a shell-burst, and give rise to the observed ascending Doppler beat frequency? It is certainly difficult to explain the ascending Doppler beats in terms of meteoric activity, particularly when the beat commences at zero frequency.

In the examination of some of the unique characteristics of transient echoes and ionospheric scatter propagation, considerable evidence is found which is inconsistent with the theory that meteor activity is an important factor in ionospheric scatter propagation. The author has come to the conclusion that meteor activity may, in fact, be found to be relatively unimportant, but it is possible that the weather-cloud discharge, or some other mechanism as yet unidentified, may instead prove to be the dominant factor.

Acknowledgments

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BOOK REVIEW

Calculus for Electronics, by A. E. Richmond. McGraw-Hill Book Co., Ltd., London, 1958. Price 46/6.

This is an introductory textbook of mathematics suitable for radio and electronics engineers who are already acquainted with fundamentals of algebra and trigonometry, including operations with complex numbers. The author provides at each stage of his argument well chosen examples (both worked out in the text and offered as exercises) and selects his material with great care. Such topics as Taylor's and Fourier Series are carefully and clearly introduced, while the last chapter deals with simple differential equations.

By limiting his subject matter to the needs of electrical engineers, Mr. Richmond is able to expand his treatment of functions of several variables and partial derivatives, which is not often found in books of this kind. Hence, such topics as differentiating and integrating circuits, valve characteristics, harmonic generation and analysis can be treated with the clarity and vigour they deserve.

The book is carefully edited and amply illustrated.

ROUND-THE-WORLD ECHOES

By G. A. Isted

Much is already known about the phenomenon of round-the-world echoes but, so far, no completely satisfactory explanation has been given for its unique behaviour. It is known for example that even after four or five circuits round the world the signal suffers very little distortion and that the attenuation between successive echoes is only of the order of a few dB. The observed facts indicate that the mode of propagation is unlikely to depend upon the conventional multi-hop reflection between the earth and the ionosphere.

Observations, made during an investigation into ionospheric scatter propagation at a frequency of 37 Mc/s, have shown that round-the-world echoes were present along a south-north route even when both the transmitting and receiving terminals were well inside the daylight hemisphere. Under the conditions of the experiment the signal seemed to have been propagated through areas where, in the normally accepted sense, the F_2 region could not have been the supporting mechanism.

Round-the-world echoes have also been observed from the signals radiated at 20 Mc/s by Satellite 1957 Alpha. At the time of the observation square-wave signals of 100 milliseconds duration were being radiated with an interval between them of approximately 240 milliseconds. Analysis of the records revealed the existence of two distinctly different beat notes, one from the square-wave signals themselves the other occurring during the intervals between them. The maximum time-delay between the two components was of the order of 140 milliseconds, which fairly identifies the component observed in the intervals between the radiated signals as a round-the-world echo. The difference in the beat note of the two components can be explained in terms of Doppler frequency shifts and divergent propagation paths.

The suggestion is put forward that transmission round the world is made possible by launching a radio wave against the ionosphere at an extremely small angle of incidence to produce a succession of reflections which are confined to the ionosphere itself. Such a shallow launching angle would be easily achieved by transmissions from satellites flying just below the ionosphere, but a tilted layer would be necessary initially to achieve the required launching angle from the ground.

Introduction

SOON after the systematic exploitation of short radio-waves for world-wide communication, it was observed that, from time to time, undesirable echoes followed the main signal received from a distant transmitting station; the time-delays of these echoes are quoted by Eckersley[1] to have been of the order of $\frac{1}{20}$-$\frac{1}{50}$ second and $\frac{1}{7}$ second. In the light of our present knowledge it seems likely that the shorter time-delays could have been caused by F_2 back-scatter in the manner described by Crow *et al* [2]; on the other hand similar short time-delays would be observed if signals transmitted from the antipodes could be propagated simultaneously round each hemisphere. The use of directive aerials would, under such conditions, eliminate the deleterious effects of the signal propagated along the unwanted route, and it is interesting to note that under similar conditions the Beam Service from the United Kingdom to Australia was maintained for several years on a single frequency by the simple expedient of switching the beam arrays through an angle of 180°; the need for separate day and night operating frequencies was thus avoided.

(173)

Eckersley ([1]) in 1927 pointed out that the echoes having time-delays of $\frac{1}{7}$ second on the main signal had undoubtedly been propagated once round the world; this type of echo, he stated, had been observed by J. G. Robb in the United Kingdom during the interception of transmissions from Poldhu, England, in 1925.

Transmission completely round the world, by the multi-hop mode of propagation, would seem to be perfectly feasible under suitable conditions of the ionosphere; there appears to be, however, another mode of transmission capable of propagating a radio signal round the world. The object of this paper is to review what is already known about round-the-world echoes or circulating signals as they will now be called, to resuscitate interest in the phenomenon and to draw certain conclusions from observations made of circulating signals received from the U.S.S.R. Satellite (1957 Alpha) and from V.H.F. Ionospheric Scatter transmissions.

Review of Past Investigations

Much is already known about the phenomenon of circulating signals but, so far, no completely satisfactory theory has been put forward which would account for many of the observed facts. The bibliography on the subject is very short and some of the references to the phenomenon are of a cursory nature and add little to our knowledge. Probably the most intensive investigation was carried out during World War II by von Schmidt and Hess, based on the very early work of Quaeck and Moegel in 1926; this investigation, carried out in Germany and Denmark, was described in detail by Hess ([3]) in 1948. A later investigation on a more modest scale was carried out in Holland by de Voogt ([4]) and described by him in 1950.

The propagation of short radio waves to great distances is sufficiently understood to state that true circulating signals possess certain unique characteristics; these appear to be very different to those which would be expected by the orthodox mode of multi-hop propagation.

Among the many known unusual characteristics of circulating signals, their ability to pass several times round the world without suffering serious distortion, and without being subjected to serious attenuation, are probably the most outstanding; nevertheless other characteristics are of great interest and it is worthwhile reviewing the situation in more detail.

Distortion

Hess ([3]) and von Schmidt ([5]) have both pointed out that the circulating signals are much less mutilated than a direct signal which has travelled a much shorter distance by a series of reflections or hops between the ionosphere and the ground; circulating signals which have passed three and four times round the world have failed to show appreciable distortion as shown by Hess ([3]), Humby *et al* ([6]) and Isted ([7]); this is in sharp contrast to the destructive phase interference and dispersive effects suffered by signals propagated by the multi-hop mechanism. Hess, in his paper, shows convincing records which demonstrate the difference which exists between the two modes of propagation.

Attenuation

Hess first drew attention to the low attenuation suffered by successive circulating signals round the world. This low attenuation has been confirmed more recently by Humby *et al* and Isted who have made measurements of circulating signal amplitudes; it would appear from their results that, although the first circulating

signal is heavily attenuated, each successive circulating signal thereafter is attenuated only by some 5-10 dB.

Circulating Time

Hess investigated at great length the time taken for signals to circulate round the world and he claims to have measured it to very great accuracies; he found that the average time taken in one complete circuit was 0·137788 second. De Voogt states that his measurements indicate time delays between 137 and 139 milliseconds. Quaeck and Moegel, von Schmidt and Isted all mention a figure of 138 milliseconds but Luscombe ([8]) finds a value of 140 milliseconds. It is clear that most investigations have shown that the circulating time is very close to 138 milliseconds. The influence of the radio frequency employed, time of day, season, ionospheric conditions and geographical position upon the circulating time is, by general agreement, small or negligible.

Activity

Quaeck and Moegel state that the propagation path followed by circulating signals is confined exclusively to the twilight belt round the world, but Marconi ([9]) and other investigators have found that this statement is not strictly true because circulating signals have been observed at places well displaced from twilight. The general opinion has been formed, however, that the greatest activity is likely to occur when the great circle path joining the transmitter and receiver lies within or near the twilight zone. These observations have led to the belief that the F_2 region of the ionosphere is implicated in the propagation mechanism because the highest mean density of ionization would be expected around the twilight belt. The opinion has also been expressed that circulating signal activity will be most likely to be observed for longer periods in the higher latitudes because of the longer twilight period there.

Direction of Arrival

Both Hess and de Voogt have carried out tests with directional aerials and they have both found that, generally speaking, circulating signals can be observed from both great-circle directions but on frequent occasions the signals arrive from only one direction of the great-circle route. Luscombe also carried out measurements on the direction of arrival of circulating signals along a route where the great-circle joining the transmitter and receiver was displaced 12° from true north; he found that the direction of arrival was close to the great-circle path. As regards the vertical angle of arrival von Schmidt states that his measurements indicate angles of the order of 20°; this is confirmed by Katowski, Shuettloeffel and Vogt ([10]) who have measured angles between 15° and 25°.

Theories of Circulating Signals

So far as the author knows only two theories have been put forward to account for the circulating signal. The first is probably the most obvious—that of multi-hop reflections between the ionosphere and the ground; this, as de Voogt rightly points out, involves on the average some 16 hops at a frequency of 20 Mc s; he shows at the same time that the period taken by a signal to encircle the world by this mode of propagation would vary throughout the seasons from 138·5 to 145·5 milliseconds.

In the second theory von Schmidt has suggested that propagation of certain radio waves in the ionosphere is analogous to the propagation of seismic waves in the

ground. It is known from experiments in explosion seismology that, under certain conditions, shock-waves are propagated along a boundary separating two different media beneath the surface of the ground; it has been shown for example that if the velocity of wave propagation in the medium above the boundary is slower than that in the medium below it, rays with angles of incidence greater than the cut-off angle will be propagated along the boundary and will be continuously radiated into the upper-medium. Von Schmidt then views the mechanism upside down and, making the assumption that the velocity of radio-wave propagation is greater in a higher altitude medium than in one below it, shows that rays with an angle of incidence smaller than the cut-off angle enter the upper medium and are lost, those rays with angles of incidence greater than the cut-off angle will, however, be propagated along the boundary and will be radiated continuously downwards towards the ground. Von Schmidt, considering the theory in relation to circulating signals, claims that it provides an accurate assessment of the F_2 skip distance and the period of circulation of a radio wave round the world.

Hess concludes that, in order to account for the highly constant time interval which he has measured between successive circulating signals, the mean height of the boundary required in von Schmidt's theory is between 203-204 Km. above the surface of the earth.

Circulating Signals at a Frequency of 37 Mc/s

For the purpose of investigating the propagation characteristics of ionospheric scatter signals a test circuit was set up between Gibraltar and the United Kingdom [11]. The conditions of the test were as follows:—

Transmitter located at Gibraltar: 36°8'N, 5°19'W. Receiver located at East Hanningfield, Essex: 51°41'N, 0°34'E. Distance of Gibraltar to East Hanningfield: 1,110 miles. Transmitter power (cw): 30-40 kW.

Transmitting aerial: 4×4 curtain array with parasitic reflectors; plane-wave gain of 16 dB relative to a half-wave dipole. Horizontal polarization.

Receiving aerial: 1×8 stack of half-wave dipoles with parasitic reflectors; plain-wave gain of 12 dB relative to a half-wave dipole.

Orientation of transmitting array: 12° E of N.

Operating frequencies: 37·3 Mc/s, 48 Mc/s and 70 Mc/s.

During the tests at the frequency of 37·3 Mc/s, conducted mainly during 1956, a troublesome source of self-interference was found to be due to the effects of F_2 back-scattered signals having time-delays between 30 and 80 milliseconds on the main signal [2]; at times however an additional serious form of self-interference was observed to be present. When the transmitted pulse width was reduced to 10 milliseconds and the repetition rate decreased to four per second this latter form of interference was found to be due to signals which, having passed over the receiving point, continued onwards round the world and arrived again at the receiver after an interval of 138 milliseconds. At about the time of the autumnal equinox, 1956, these circulating signals were observed for about 50% of the days between 0900 and 1100 hours G.M.T. On many occasions the propagation conditions were such that the circulating signal was observed to have been repeated four or five times, each successive delay being 138 milliseconds.

Fig. 1 is a reproduction of a high-speed record, made on November 19th, 1956, between 0915 and 1207 hours G.M.T., on which the effects of both F_2 back-scatter and circulating signals are clearly shown. Increases in amplitude are denoted on the record by vertical deflections of the pen from the base-line. A range of about

30 dB in amplitude can be accommodated between the base-line and the saturation point of the apparatus. Time advances from right to left. Strip (a) in the Figure is typical of the signal pulses received by the ionospheric forward-scatter mode of propagation in the absence of other spurious components. The sequence of events under conditions of F_2 back-scatter and circulating signals, resulting from the transmission of a single pulse, " P," will be described with the aid of Strip (b).

The pulse propagated by the forward scatter mechanism is marked by an arrow at " P "; a further clean pulse displaced by 138 milliseconds from " P " is marked by an arrow at " 1," this pulse represents the first circuit round the world resulting from the original transmitted pulse " P "; successive circulating signals are indicated by arrows marked 2, 3 and 4, all of which are separated successively by a time interval of 138 milliseconds. There are indications that a fifth circulating signal was sometimes present; this can be seen as a small amplitude pulse falling in position on the left-hand side of the circulating signal marked " 3 " in the figure. The signal resulting from F_2 back-scatter is indicated by the arrow marked " S "; this follows the initial transmitted pulse after a time interval of 10-15 milliseconds. Strip (c) of the Figure was recorded about two hours after Strip (b) and shows clearly that the circulating signals have disappeared leaving only the relatively short time-delayed signals due to F_2 back-scatter.

It should be pointed out that the complicated pattern of the signal as shown in the Figure is due mainly to the fact that the transmitted pulse was repeated at 250 millisecond intervals and that the circulating signal was repeated at intervals of 138 milliseconds. The second circulating signal would therefore be received 276 milliseconds after the initial transmitted pulse, i.e. about 26 milliseconds after the succeeding transmitted pulse.
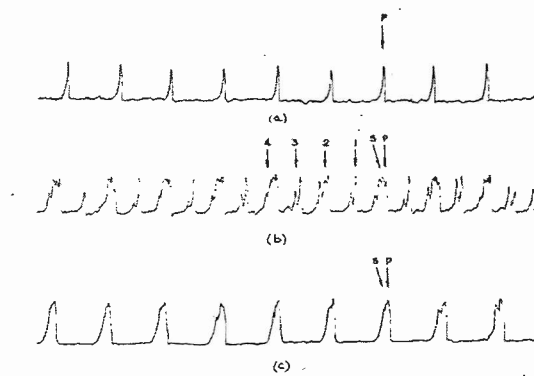

FIG. 1

High-speed amplitude recording of circulating signals.
(a) Forward scatter signal alone.
(b) Forward scatter signal together with circulating and F_2 back-scatter signals.
(c) Forward scatter signal together with F_2 back-scatter signal.
    Pulse duration : 10 milliseconds.
    Repetition rate : 4 per second.
    Frequency : 37 Mc/s.
    Path: Gibraltar—East Hanningfield, Essex.

In a previous paper ([7]) a more detailed reproduction of the record was given which demonstrated that the onset of the circulating signal was coincident with the commencement of F_2 back-scatter. This present record serves to illustrate that F_2 back-scatter can be present after the circulating signal activity has ceased; furthermore it can be seen from this record that the small amount of distortion and

the low attentuation suffered by succeeding circulating signals, described by other investigators, is readily observable.

Circulating Signals from Satellite 1957 Alpha

What are considered to be circulating signals resulting from transmissions, radiated at a radio-frequency of 20 Mc/s from the U.S.S.R. Satellite 1957 Alpha were recorded at the Marconi Research Laboratories, Great Baddow, England (51°45′N, 0°30′E) at approximately 0030-0033 hours G.M.T. on October 8th, 1957.

A standard communication receiver connected to a half-wave dipole aerial installed $\frac{3}{4}\lambda$ above the ground formed the basis of the receiving apparatus. The incorporated beat frequency oscillator of the receiver was adjusted to give a convenient but arbitrary audible note at the output of the receiver; a permanent record of the signal was made by means of a magnetic tape recorder connected to the output of the receiver. During the period to which these observations refer, the satellite was radiating square-wave signals of 100 milliseconds duration at a repetition rate of approximately three per second.
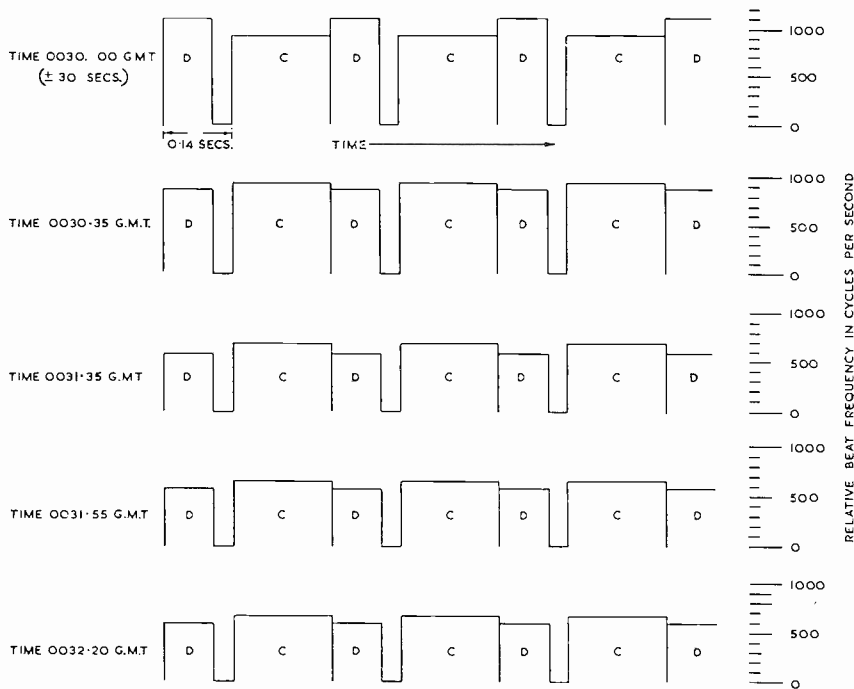

Fig. 2

Illustration of relative beat frequencies of direct and circulating signals received from U.S.S.R. Satellite. October 8th 0030-0033 G.M.T.

The orbit of the satellite on this particular occasion tracked up from South America in the dark hemisphere, and passed between Iceland and Scotland at approximately 0030 hours G.M.T., continued over Norway and entered the twilight zone at approximately 0043 hours G.M.T. over Russia. The experimental timing arrangements at this very early stage of the satellite investigation were rather

elementary, consequently times cannot be quoted to greater accuracies than $\pm$ 30 seconds.

Subsequent analysis of the record obtained on this particular occasion disclosed the fact that two distinct signals, each with a different beat frequency, were present; one beat frequency corresponded to the direct signal radiated from the satellite, the other occurred in the intervals between the radiated signals. Fig. 2 is an illustration of the signal made by playing back the original magnetic tape recording into a chart-recorder which gave an amplitude deflection proportional to frequency. In the portion of the record for 0030.00 hours G.M.T. the direct signals are shown at " D " and it will be seen that their beat frequency was 1100 c/s; the signals received in the intervals between the direct signals and marked " C " in the Figure gave a beat frequency of 920 c/s. The interesting point to note is that the time-interval between the commencements of the " D " and " C " signals was approximately 140 milli-seconds; this time-interval strongly suggests that the " C " signal was the original transmitted signal which had circulated once round the world. The reason why the circulating signal was about twice the length of the original direct signal is not immediately apparent but the original record suggests that a second circulating signal followed the first one. The illustration shows that by 0030.35 hours G.M.T. the beat frequency of the direct signal had decreased to 870 c/s but the beat frequency of the circulating signal had remained practically unchanged. By 0031.35 hours G.M.T. the beat frequency of the direct and circulating signals had decreased to 580 c/s and 640 c/s respectively. At 0031.55 and 0032.20 hours G.M.T. the respective beat frequencies remained unchanged.

The decrease in the beat frequency of the direct signal was due to the Doppler frequency shift associated with the satellite's nearest approach to the observer; this effect is well known and need not be enlarged upon here. The different rate of change in the beat frequencies of the direct and circulating signals suggests that different transmission paths were followed by each of the signals. There is good reason to believe that the transmission path of circulating signals is often associated with the twilight zone and it might therefore be expected that, if the satellite crossed this fixed transmission path, a Doppler frequency shift similar to that observed would be superimposed upon the circulating signal. Reference to Fig. 3 will show that the satellite was in fact near to the twilight zone at the time of the observation and that it crossed it obliquely. However, if the transmission path was in fact the twilight zone, it might have been expected that there would have been two components of circulating signals arriving from opposite directions. The evidence suggests that in this particular case the transmission path was unidirectional and, because of the fact that the Doppler beat frequency of the circulating signal decreased, the direction of transmission must have been approximately as indicated by the arrow in Fig. 3.

Discussion of Recent Observations

An examination of the new data concerning circulating signals brings to light one or two important points which, up to the present, have not been commented upon in the relevant literature.

The first points now to be commented upon concern the pulse transmissions from Gibraltar.

The receiving site, being less than 2000 Km from the transmitter was within the " skip-distance " by normal F_2 propagation; therefore there was no possibility of receiving the short-path direct signal propagated by the F_2 mechanism although, as previously described, the effects of F_2 back-scatter were readily observable.

(179)

It has long been suspected that the circulating signal mode of propagation is intimately associated with the F_2 region of ionization and the fact that they have been observed at frequencies as high as 37 Mc/s during a period of record high sunspot activity may therefore cause no undue surprise.

In describing the conditions under which the tests were carried out it was stated that signals, in the form of pulses, were radiated from Gibraltar by a directional aerial system oriented 12° East of North; Luscombe, who contemporaneously observed circulating signals resulting from the Gibraltar transmissions, confirmed that their azimuthal angle of arrival did not deviate from the great-circle path. It would therefore appear that the circulating signals had passed approximately through latitudes 80° North and South of the equator. An inspection of the published
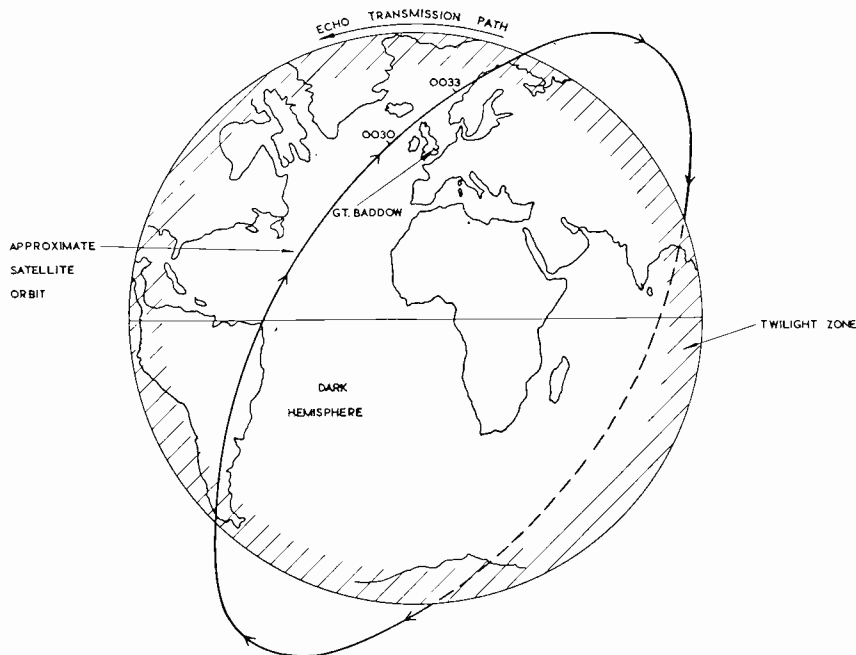

FIG. 3

Diagram illustrating relation between orbit of Satellite and twilight zone. October 8th, 1957, 0030-0033 G.M.T.

Maximum Usable Frequency (M.U.F.) prediction charts for the appropriate time and period shows that the F_2 normal mode of propagation could not have been supported at latitudes higher than 50° North and South of the equator. The M.U.F. in the region of Latitude 80° North was no greater than 22-24 Mc/s, while at Latitude 80° South it was no greater than 16-20 Mc/s. Thus the fact emerges that, in spite of the restricted M.U.F. for normal F_2 propagation, circulating signals were nevertheless propagated at 37 Mc/s through regions near to the Poles. It might of course be argued that, in the case of a multi-hop mode of propagation, it is unnecessary to rely upon a high M.U.F. over the Poles provided that a ground reflection occurs within the Polar Regions. If this condition was indeed being fulfilled evidence of a signal propagated by the multi-hop mechanism should have been observed; applying the

criterion that a signal so propagated would exhibit considerable distortion due to destructive phase interference and dispersive effects one must conclude that, because this distortion was not observed, reflections between ground and ionosphere were not involved.

The record shown in Fig. 1 indicates that the average attenuation between successive circulating signals is approximately 5 dB; this low attenuation is in sharp contrast to the great attenuation involved between the initial radiated signal and the first circulating signal. The inference to be drawn from the observed attenuation characteristics is that a transmission mechanism encircles the world in which the attenuation is very low but a wave which succeeds in energising it is first subjected to a very high attenuation.

From the evidence provided by the Gibraltar-U.K. experiments the influence of F_2 ionization upon circulating signals cannot be determined with any degree of certainty. The most that can be said is that whenever circulating signals were recorded the ionization density of the F_2 region was sufficient to support the normal mode of F_2 propagation at 37 Mc/s in the region of the transmitter; this is demonstrated by the simultaneous presence of F_2 back-scattered components of the transmitted signal. The converse, however, does not hold because the F_2 back-scattered component could be recorded for many hours of the day while the circulating signal would be completely absent.

The final point of comment here concerns the twilight zone. Much of the published literature associates circulating signals with the twilight zone but, during the Gibraltar-United Kingdom experiments, it was observed that circulating signals were received four to five hours after local sunrise; this represents a considerable displacement of the twilight belt from the great-circle path followed by the circulating signal. It can therefore be concluded that the great-circle path followed by the 37 Mc/s circulating signal included large extremes of solar illumination and it is therefore demonstrated that the association of circulating signals with the twilight belt is not very rigid.

In considering the observations on the signal radiated from the satellite, an examination of the F_2 M.U.F. prediction charts shows that at the time of the observations the Satellite was flying through an area in which the M.U.F. was only of the order of 10-14 Mc/s and therefore the signal radiated at 20 Mc/s was unlikely to have been propagated to great distances by the normal F_2 multi-hop mode of transmission, nevertheless the signals observed in the intervals between the direct signals radiated from the satellite had undoubtedly been transmitted round the world. In most other areas of the world however the M.U.F. values at that time would have supported propagation at frequencies greater than 20 Mc/s.

The most interesting aspect of the round-the-world transmission of signals radiated from the satellite lies in the fact that, in spite of the very low power radiated, the conditions necessary for circulating signal propagation were achieved; bearing in mind that a very high attenuation has normally been observed between a signal radiated from the ground and its first circulating component, it would seem that in this particular case the circulating signal observed from the satellite could not have been subjected to that initial attenuation; it is concluded therefore that the satellite was at that time actually flying within or near the medium responsible for the circulating signal mode of propagation. From the published data ([12]) it would appear that the height of the satellite at the time of the observation was 240 ± 13 Km. above the earth; it was therefore within the lower part of the F_2 ionized region.

From the foregoing it seems probable that the F_2 region is in some way the

supporting mechanism for circulating signals; on the other hand there is no evidence which suggests that the normally accepted mode of multi-hop transmission between the ionosphere and the ground is in any way involved; indeed, the observed low attenuation suggests that the signals are not propagated to any great extent through the absorbing D region.

Many of the unique characteristics of circulating signals can be explained if it is assumed that a radio wave can be launched against the ionosphere at an extremely shallow angle of incidence, such as might have happened in the case of the satellite when it was at a height of 240 Km., a succession of glancing reflections confined to the ionosphere might then follow even when the density of ionization was very low.
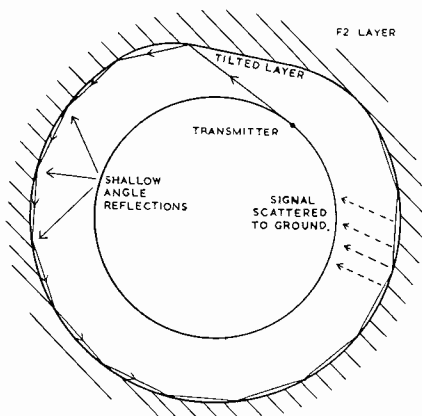
To achieve the same necessary glancing angle at the ionosphere by a radio transmission from the ground a tilted ionized layer would have to be invoked (see Fig. 4). A tilted layer is a well-known feature of the F_2 region and its occurrence at twilight might be expected; a tilted layer, furthermore, would provide a ready explanation for the unidirectional characteristics so often observed in circulating signal propagation. The signal which is observed on the ground would be due to a small amount of energy scattered downwards each time the circulating signal passed overhead.

It is possible therefore that a series of reflections confined to the ionosphere itself could explain all the known characteristics of circulating signals with the possible exception of the highly constant time interval of circulation measured by Hess; this, it would seem, should be dependent upon frequency, time of day and season.

FIG. 4

Suggested mechanism of circulating signals by a tilted layer and shallow ionospheric reflections.

Conclusion

It has been shown that circulating signals are not restricted to frequencies below the normal F_2 M.U.F. as at present generally understood but that they are capable of being propagated through areas of low ionization densities.

It is possible that the observation of signals from the satellite may provide an important clue to the understanding of the mechanism responsible for circulating signals and the suggestion that this mechanism is associated with reflections at glancing angles of incidence which are confined solely to the ionosphere may be worthy of further consideration.

It is possible that some of the other unusual propagation phenomena observed on the signals radiated by satellites [12] [13] may be explained in terms of circulating signals.

Although, up to the present, circulating signals have not caused serious disruption to orthodox modes of communication the phenomenon assumes considerable importance in connection with the operation of ionospheric scatter communication links.

Acknowledgments

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BOOK REVIEW

Long-Wave and Medium-Wave Propagation, by H. E. Farrow.   Iliffe & Sons, Ltd.   4s. 6d.

This booklet makes available to a wider public the substance of some lectures given at the B.B.C. Engineering Training Department. As such it will be useful to those concerned with the design and operation of transmitting stations in relation to the problems of reception on the long-wave and medium-wave bands. It contains much information expressed in a simple way that it would be difficult for the intended reader to obtain from the literature, including some propagation curves based on the C.C.I.R. ones, together with a ground conductivity map of the British Isles and a description of the method of calculating field-strengths over mixed paths.

It is a pity that in his attempt to keep the treatment simple the author has allowed his descriptions to be somewhat loose in avoiding, for instance, any reference to the radiation resistance of the aerial in discussing the effect of earth losses on the field at 1 km. Nor is it clear what is meant by a field-strength of 9-10 mV/m. being necessary at night using a single transmitter with a poor aerial unless it is related to some radiated power, since the deciding factor is the distance at which the ground-wave ceases to predominate over the sky wave. In dealing with the ionosphere it is difficult to avoid over-simplification with regard to the frequency dependence of the absorption, and although the text could have been made more precise in places, the treatment is adequate within the limits the author has set and contains some useful curves.

The retention on most of the figures of an irrelevant drawing number is an unfortunate oversight in preparing them for publication, though the format is on the whole satisfactory. The utility of the booklet would have been increased by the addition of some further references to some of the well-known handbooks dealing in more detail with the topics discussed, but even so it fulfils a useful purpose in providing a basis of information for the engineer who wishes to know how the technique of broadcasting on the longer waves is related to the propagation characteristics.

PROPAGATION MEASUREMENTS AT 858 MC/S OVER PATHS UP TO 585 KM.

By G. C. Rider, B.Sc.

The tests described in the paper have been made over five paths in Great Britain during the last two and a half years. The objective was to obtain the " know-how " in the application of the tropospheric scatter mode of propagation. The paths investigated have been progressively increased in length up to a total distance of 585 Km.

The transmitting site has remained fixed throughout the tests. Facilities for scanning were provided on the transmitting aerial, so that the beam could be directed towards the various receiving sites. The first test was over a distance of 158 Km., and this was followed by twelve months of recording over a 322 Km. path. During this period height-gain and space-diversity tests were carried out. Finally the range was extended to 575 and 585 Km.; for these latter paths concurrent signal and fading recordings were made at a site in the mid-path region.

The mean diurnal variations of signal are presented for three paths, and their significance is discussed in relation to meteorological conditions. The effect of mean refractive index gradient upon median signal levels is examined. A good correlation is found between the presence of low signal and a polar air mass over the propagation path.

The fading ranges and rates measured over the 322 Km. path are presented in some detail, and the correlations—positive between fading rate and wind velocity, and negative between signal level and wind velocity—are discussed. Correlation coefficients between the fading on spaced aerials are shown for aerial spacings varied both horizontally and vertically, and a height gain curve has been derived from the vertical measurements. The height gain effect is of limited practical significance, but the persistence of the vestigial lobe pattern with increasing height appears to favour the reflecting layer mechanism of propagation. The negative correlation between signal strength and wind velocity also seems to point in this direction. Wind velocity has been found to be associated with the time-lag for maximum cross-correlation between the fading on horizontally spaced aerials.

An experimental approach to the problem of assessing the bandwidth potentialities of a tropospheric scatter system has been made by recording the phase variations of a 1 Mc/s modulation, the record being interpreted as a plot of changes in the mean path length with time.

Finally the obtrusive signal flutter attributed to aircraft is discussed and assessed.

Introduction

THE purpose of this paper is to present the results of some propagation measurements at a frequency of 858 Mc/s made in the United Kingdom over the last two and a half years. The motive has been to obtain practical knowledge and experience in the tropospheric scatter propagation field. The routine measurement of signal strength and fading parameters has been accompanied by tests of polarization, height-gain and diversity, and an investigation of multipath time-delays. Fig. 1 shows the position of the receiving sites, and the path lengths. The first test site, which was at Grantham, was used for three months and that at Catterick for over a year. The remaining sites were used for periods of two or more weeks.

Equipment

The transmitter had a mean output power of 200 w. when amplitude modulated with a 1 kc/s sine wave, and it was installed in a trailer (Fig. 2) with the aerial feed horn mounted upon the roof on a steel-lattice boom. The trailer was movable over
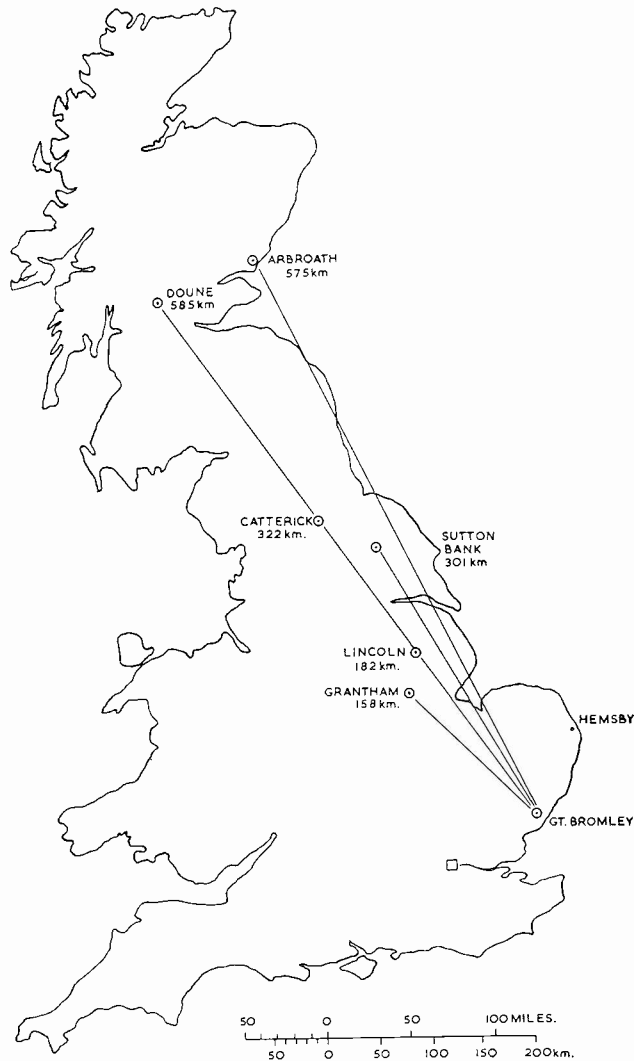

FIG. I

Map showing propagation paths and distances.

an arc of railway-line, and the movement served to steer the aerial beam in azimuth. Vertical movement of the beam was achieved by elevating or depressing the boom and feed horn. A 9·1 m. (30 feet) diameter spherical reflector having an aperture ratio 1·5 was used as the transmitting aerial in conjunction with the movable feed

horn, the long focus permitting the beam to be scanned through $\pm 12°$ in azimuth, and from 0° to 12° in elevation, without appreciable degradation of gain or lobe pattern.

In each of the two receivers a crystal-controlled oscillator was used for frequency changing, and a low-noise balanced crystal mixer was followed by a 13·5 Mc/s I.F. amplifier, and a 1 kc/s audio amplifier of bandwidth 50 c/s. This arrangement limited the effective receiver bandwidth, and allowed very low signals to be measured without demanding an unreasonable degree of frequency stability either from the transmitter drive or from the receiver frequency-change oscillators.

Two pen-recorders were employed, the fading data being taken from the records of a fast response recorder capable of faithfully reproducing frequencies up to 10 c/s, whilst the hourly median levels were taken from a recorder driven by a circuit
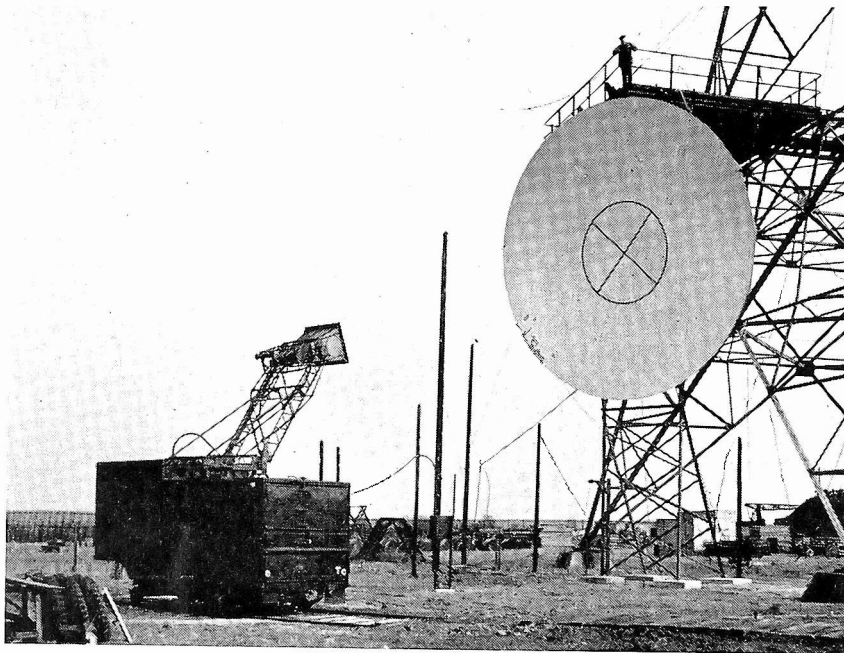

FIG. 2

858 Mc/s Transmitter cabin and aerial—Great Bromley.

averaging the receiver output over a period of 20 sec. The receiver had an accurately linear characteristic.

The main receiving aerial was a 3 m. (10 feet) diameter paraboloid, mounted on a trailer at a height of 3 m.; for the twin-receiver tests, a 1·23 m. (4 feet) diameter paraboloid was used together with a horn of similar gain.

Hourly Median Path Attenuation

The hourly median path attenuation varies with the time of day, the period of the year and the path length, and will be considered first; consideration of the fading parameters will then follow.

(186)

Fig. 3 presents the mean of the hourly median path attenuation for each hour of the day, measured over the paths to Grantham, Catterick and Arbroath at distances of 158, 322 and 575 Km. respectively. The shape of these curves should be accepted with some reserve however, since although they present a true summary of measurements made, they are not 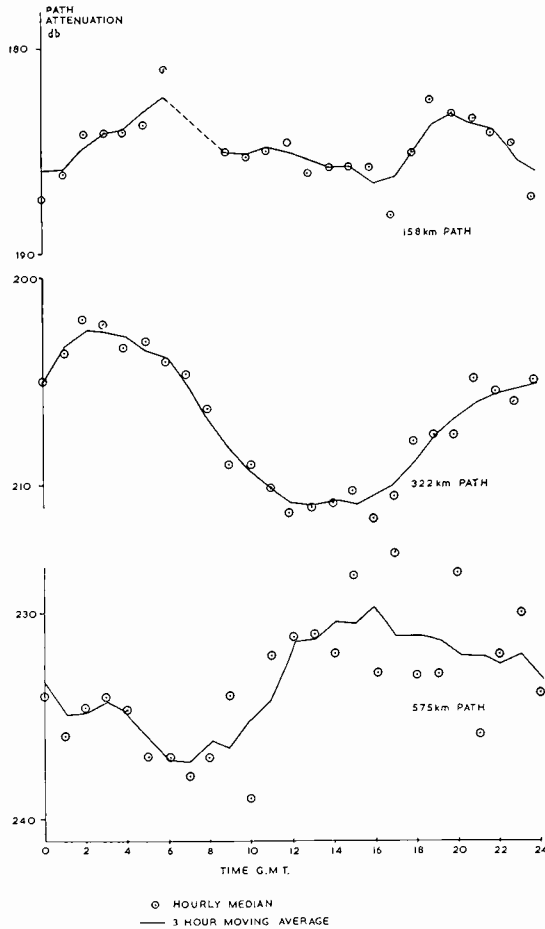necessarily typical of days in general. The curve for the 575 Km. path, for instance, is based upon far fewer measurements than the curves for the shorter paths; it should be noted, furthermore, that calm radiation nights—which largely contribute to night-time high signal-levels—were rarely encountered during the period of observation over this path. It should be pointed out, however, that observations of path attenuations carried out during the day-time are unlikely to give an over-optimistic estimate of the performance of the path for other times. The monthly mean path attenuations shown in Fig. 4 for the 322 Km. path are therefore taken for the midday hours alone in order to present, as far as possible, only the seasonal changes attributable to variations in the scattering mechanism.

FIG. 3

Diurnal variation of hourly median path attenuations.

Meteorology and Hourly Median Path Attenuations

Two attempts will now be described to relate these time-variations in the hourly median path attenuation to meteorological conditions. The first approach is summarized in Fig. 5. Here the mean refractive index gradient, expressed as effective earth's-radius, is plotted against the hourly median attenuation for the appropriate hour. The meteorological data used were those published for the upper-air station at Hemsby ([1]) (see Fig. 1). The dashed line on the graph is calculated on the hypothesis that the signal variation is caused by a change in the scattering angle consequent upon a change in the ray curvature due to refraction. A $\left(\sin^{-4}\dfrac{\theta}{2}\right)$ scattering law was used.

(187)

The trend of the observed points shows sufficient agreement with the predicted slope to suggest that the postulated mechanism is operating modified, however, by the dependence of the scattering coefficient upon height, which has not been considered here.

In the second approach the path attenuations are grouped, for the synoptic hours, in accordance with the air-mass present in the common scattering volume.
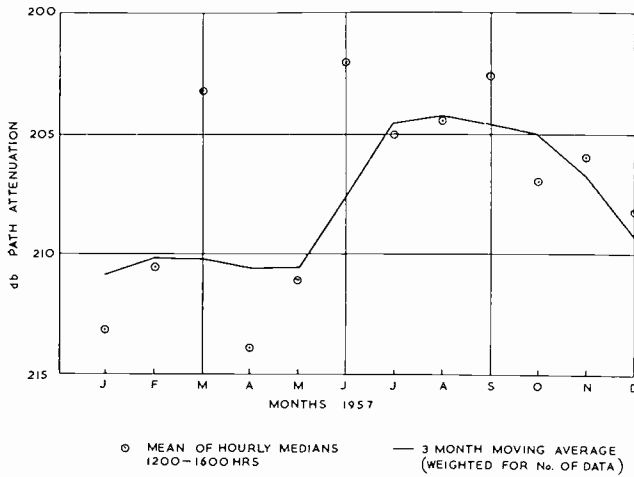

FIG. 4

Seasonal changes in hourly median path attenuation, 322 Km. path.

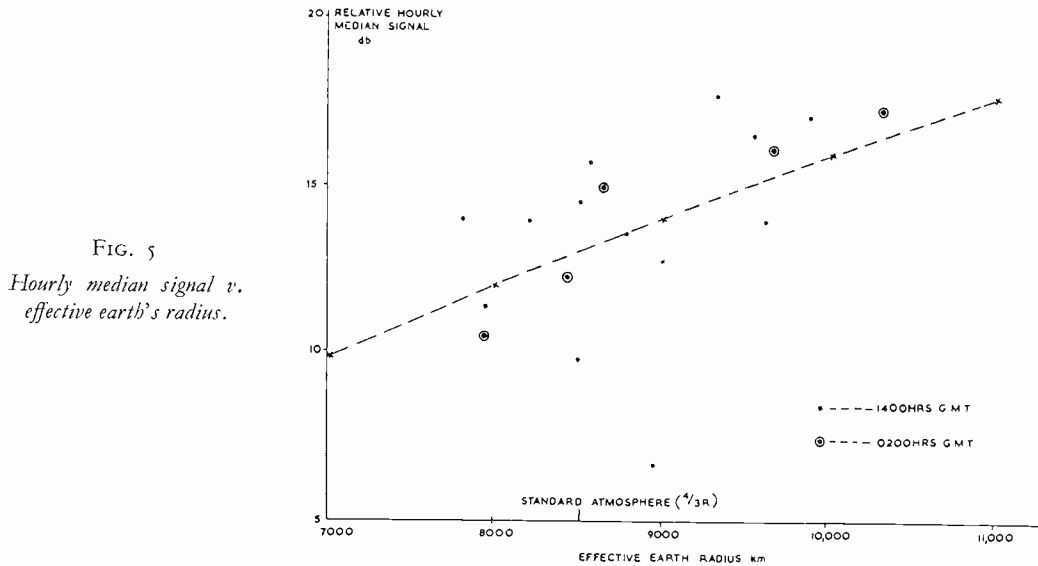⊙ MEAN OF HOURLY MEDIANS 1200—1600 HRS. — 3 MONTH MOVING AVERAGE (WEIGHTED FOR No. OF DATA)

FIG. 5

Hourly median signal v. effective earth's radius.

Fig. 6 shows the signal distribution obtained with two such groups and, as more data become available, it is hoped to make a more detailed identification of the air-mass present. This approach appears to offer a useful empirical method for comparing the median path attenuations on similar paths in differing climates.

It would appear that there is more reason to attribute the changes in signal from hour to hour, and indeed from season to season, to the successive advent of anti-cyclones and depressions than to the diurnal changes in the meteorological elements, which are relatively of less importance in the middle and upper troposphere.

Path Attenuation v. Distance

The hourly median path attenuations are finally displayed, in Fig. 7, according to their dependence upon path length. The average of all the hourly figures for each site has been used for this purpose. Following Norton *et al.* ([2]), angular distance is used as abscissa. The rate of attenuation is seen to be larger than that derived from Norton's ([2]) empirical curve, and larger also than that predicted by Richards ([3]) for an inverse square decay of $\overline{\Delta n^2}$ with height.

Fast Fading

Two parameters of the fading signal have been measured from the fast response recordings. The fading rate " F " is defined as the number of positive crossings per
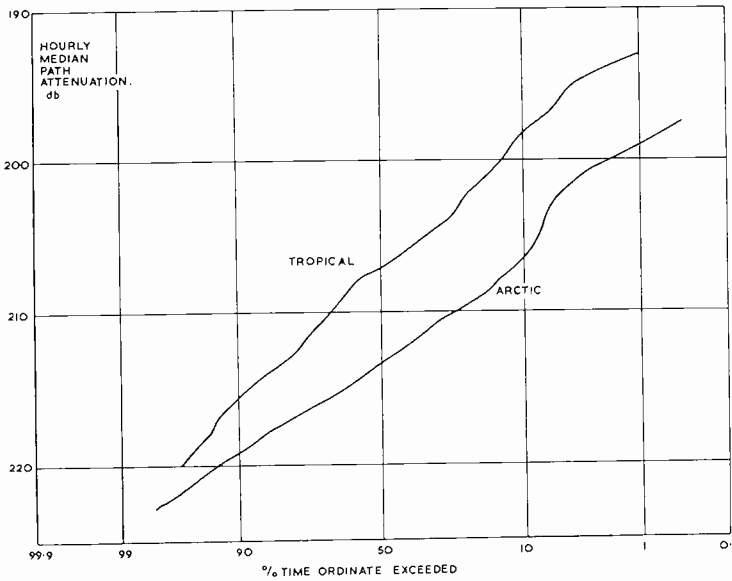

FIG. 6

Distribution of hourly median path attenuation for arctic and tropical air in the common scattering region.

minute of the median level of the sample, and the fading range " R " as the difference in the levels exceeded by the sample for 10% and 90% of the time. One-minute samples were analysed for each parameter and a cumulative distribution of the values obtained over the 322 Km. path, to which the bulk of the data accumulated refers, is given in Fig. 8. The fading rates measured at 575 Km. are also shown. The dependence on distance mentioned by Norton *et al.* ([4]) was not observed.

As will be seen later, the signal is quite frequently affected by reflection effects from aircraft. The samples analysed for Fig. 8 were taken at regular time intervals, and are therefore representative of the conditions actually prevailing. These recordings were re-examined for a sample period, and those showing any sign of the aircraft effect were discarded. The remaining data, which are representative simply of propagation conditions, are presented in Fig. 9, and show well the association between the lowest fading rates and the greatest fading ranges. These occur at times of highest signal, usually at night, and contribute largely to the form of the diurnal curve already shown.

Fading and Wind

The fading parameters have been considered in relation to the wind velocity in an attempt to produce some evidence distinguishing between the turbulent scatter model and that which invokes portions of reflecting layers. The wind is thought of as promoting propagation in the former case by increasing the turbulence, and as inhibiting the propagation in the latter case by breaking up and dissolving any stratification which existed. The normal presence of some measure of stratification is shown both by published data of refractometer soundings and by observation of the clouds.

The wind velocity data used—the best available—are taken from the regular meteorological soundings at a height of 4,200 m. over Hemsby. Hemsby is about
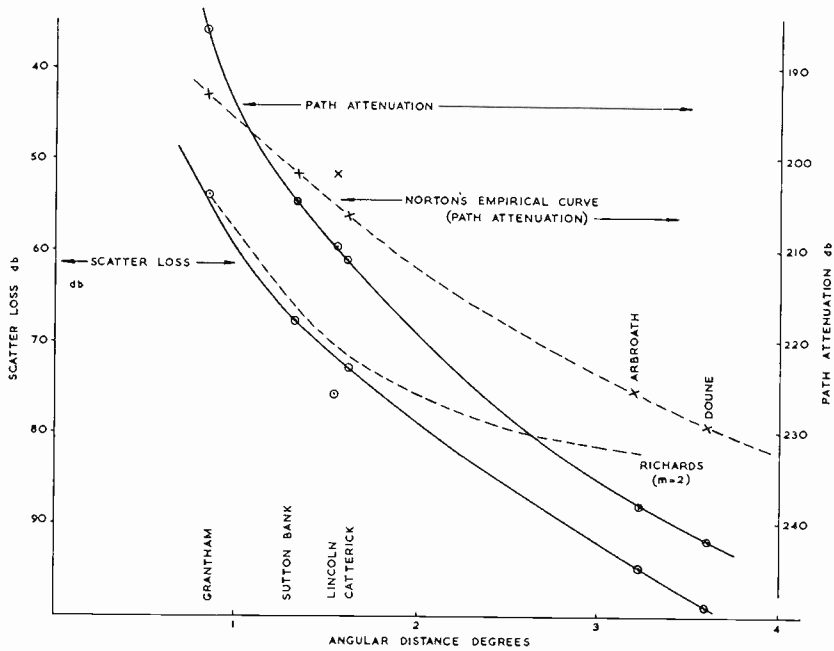

Fig. 7

Path attenuation and scatter loss v. angular distance.

○ *Measurements.*

× *Calculated using Norton's* ([2]) *empirical curve.*

160 Km. from the scattering region, and this fact doubtless increases the element of randomness in the correlations computed.

The correlation between wind and fading is summarized in Table 1 and is discussed later in conjunction with further evidence arising from the diversity tests.

The magnitude of the correlation between signal level and wind speed is insufficient to give much support to the reflection hypothesis although the sign of the correlation suggests it.

It may be of interest to note that synchronous fading records over 182 and 322 Km. paths show, as expected, no sign of correlation. The same is true of the hourly median values, where for the period of the tests—about fifty hours—a coefficient of $+0.04$ has been evaluated.

TABLE 1. CORRELATION COEFFICIENTS

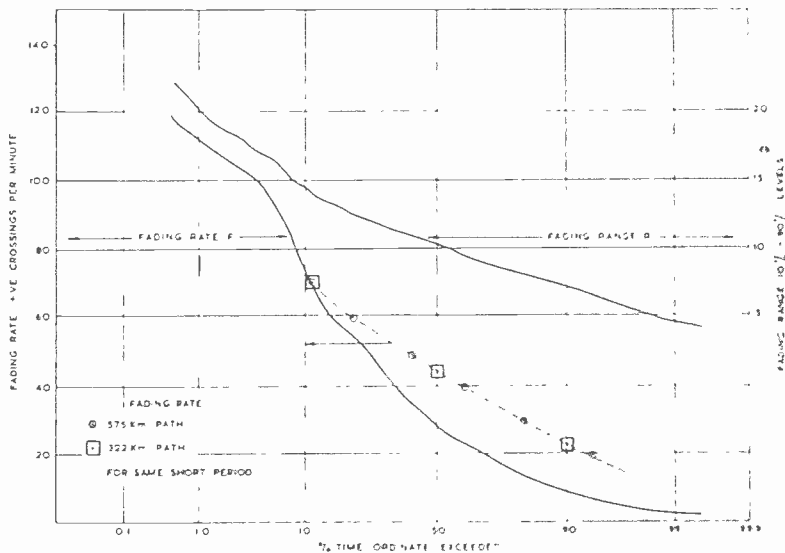|	Component of Wind		
	Across Path	Along Path	Wind Speed
Fading Rate ...	-0.5	0.4	—
Fading Range ...	Not Significant	0.3	—
Hourly Medn. P.A.	—	—	-0.2

FIG. 8

Distribution of fading rate and fading range.

Spaced Diversity and Height Gain

Spaced diversity and height gain tests were carried out at Catterick, over the 322 Km. path. The aerial spacings were varied, up to 30 m. horizontally, and up to 25 m. vertically. Here a 30 m. (100 feet) mast was used, having mounted upon it a vertical railway carrying the aerial and head amplifier. A reference aerial, the standard receiving aerial at this site, was located at a height of 3 m. above ground;

(191)

it was an electromagnetic horn, very similar in gain and beamwidth to the 1·2 m. (4 feet) diameter movable paraboloid.

In each test, simultaneous one-minute samples were taken of levels from the respective spaced aerials, using the twin-channel fast recorder. Levels for the computation of correlations were read at 1·25 sec. intervals. About twenty runs were made under various conditions, and Fig. 10 shows the results. Figs. 10 (a) and (b) are aligned to share a common scale of aerial spacings. Fig. 10 (c) is a " Height-Gain " curve derived from the observational data of Fig. 10 (b). The ordinate in this case is aerial height above ground, and the ordinate scale is aligned with that of Fig. 10 (b) so that, for example, an aerial height of 20 feet represents a vertical spacing of 10 feet. The abscissa here is the mean difference in level between the signals on the two aerials. This has been referred to the value at a height of 20 feet, since its actual value is irrelevant, depending on the slight difference in aerial gain. 20 feet was found by averaging to be the optimum height, with the ground conditions obtaining, and quite a well-marked lobe structure, albeit of small
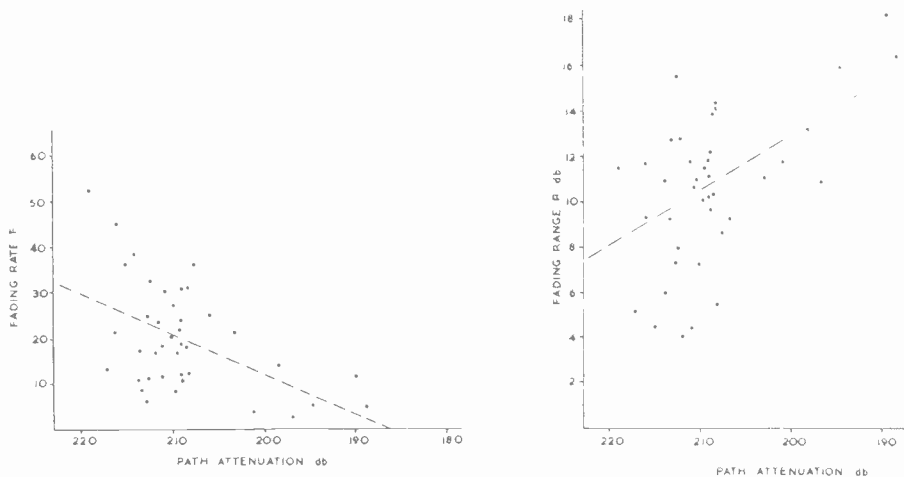

FIG. 9

Fading rate and fading range v. path attenuation for 322 Km. path. Aircraft effects excluded.

amplitude, may be seen in the curve Fig. 10 (c). The pattern repeats itself well as between successive tests up to a height of about 30%, above which level the coherence between different tests rapidly vanishes.

It is of interest to compare this curve with that of correlation coefficients for varying aerial spacings. The fluctuations in the relative signal level over about the first 30% are seen to be closely mirrored by the variations in the mean correlation coefficient, which are superimposed upon the steady decay of correlation with increased aerial spacing.

This effect, and the decay of the height-gain pattern, may most easily be understood in terms of the polar diagram produced by the moving aerial and its image in the ground. As the aerial height increases, the lobes become sharper and sweep downward, a maximum signal position occurring as the lobe sweeps over the scattering region. For small aerial heights the width of the lobe is sufficient to embrace the whole scattering region, i.e. there is as yet no diversity effect due to the

relative phases from individual scatterers differing for the two aerials (here aerial and image). However, when the lobes become too narrow to embrace the scattering volume, there will no longer be a coherent variation of signal with aerial height.

Attention will now be directed to the correlation plot. When both aerials are at positions of maximum signal—in our case the reference aerial coincides with the first maximum—each has a lobe embracing the scattering region, and positively correlated signals will appear on each. If now one aerial moves to a minimum, so that the trough between its lobes is directed to the centre of the scattering region, its signal will be contributed predominantly by the peripheral scatterers, and will be less correlated with that on the other aerial.
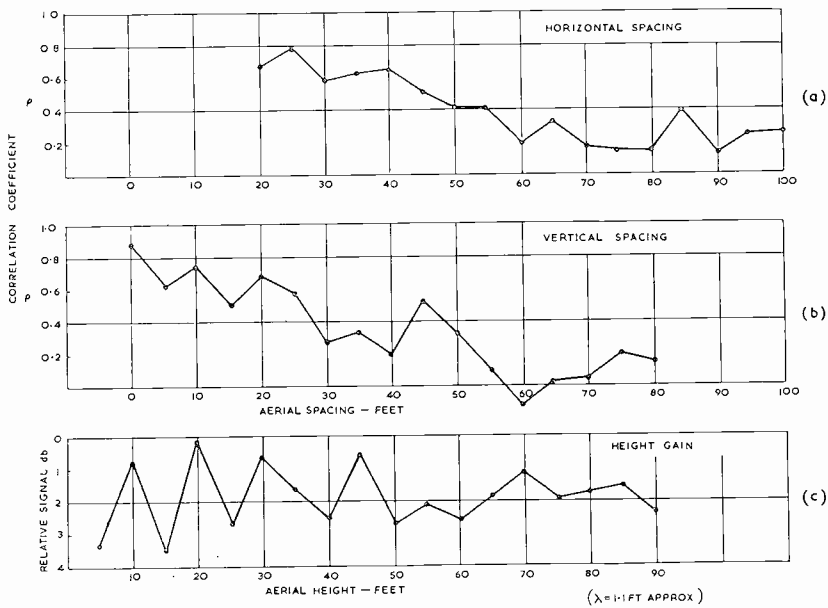

FIG. 10

Diversity fading correlations and height-gain curve for 322 Km. path.

(a) *Horizontal aerial spacing v. fading correlation.*
(b) *Vertical aerial spacing v. fading correlation.*
(c) *Height-gain curve.*

An estimate of the vertical angle subtended by the scattering region can be deduced from this argument.

Since the height above ground of the scattering region is great compared with that of the receiving aerials the ground reflection will take place near to the aerial, and simple plane-earth geometry will suffice.

We consider the lobe pattern of the receiving aerial together with its image in the ground. Since the aperture of the reflector is small (about 4λ) the lobe pattern in the direction of the scattering region will be unaffected by the directional pattern of the aerial itself.

Let θ be the vertical angle between maxima for low angle lobes, and h the aerial height above the ground reflecting plane. We may simply obtain
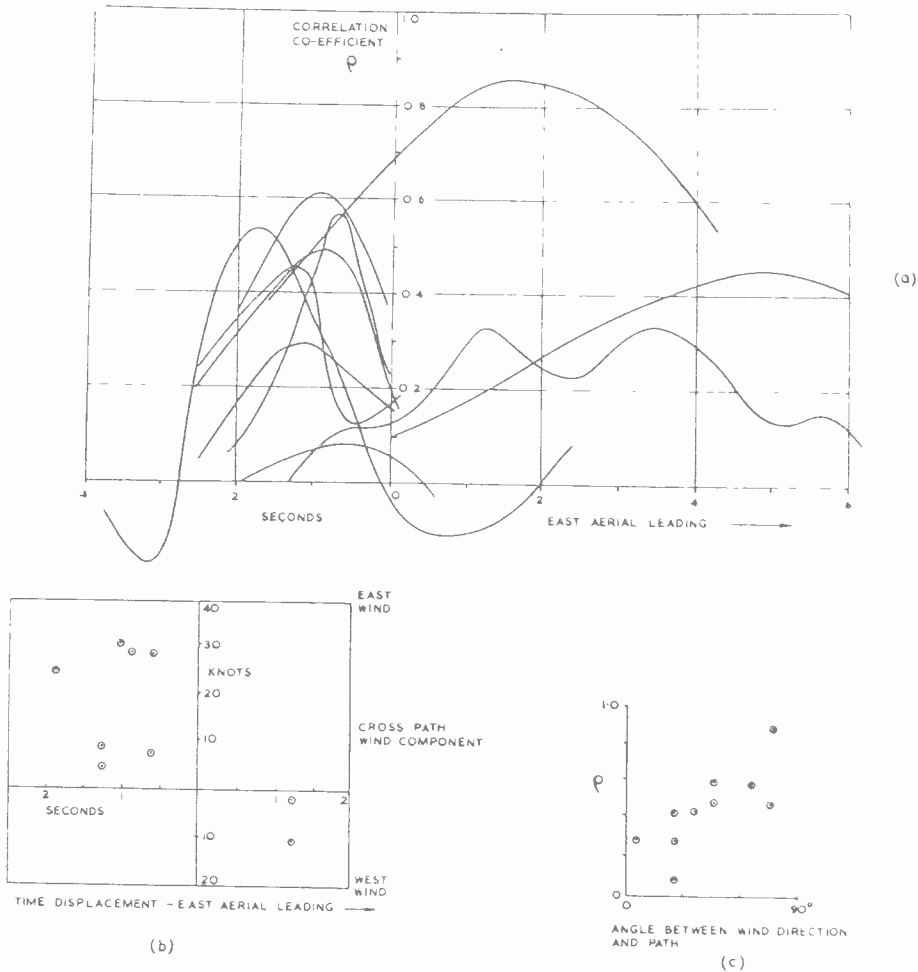
$$\theta = \frac{\lambda}{2h}$$

FIG. 11

The effect of cross path wind velocity upon diversity fading correlations— 322 Km. path.

(a) *Fading correlation v. time displacement.*

(b) *Time displacement for maximum correlation v. cross path component of wind speed.*

(c) *Maximum correlation v. inclination of wind direction to propagation path.*

From Fig. 10 (b) we may see that the fluctuations in the correlation coefficient super-imposed upon its general decay have ceased by the time the value $h = 19$ m. (60 feet). If this value of h is taken as giving a lobe spacing such that two lobes are directed toward the scattering region, we have, from the above expression, a vertical angle of 32′ subtended by the scattering region.

Time Lag in Horizontal Diversity Fading

A point of interest, which is quite evident on inspection of the horizontal diversity fading records, is the time lag between the pattern of fading upon widely spaced aerials. For a number of tests on aerials at 30 m. (100 feet) spacing, correlation coefficients have been evaluated for various time lags.

Referring now to Fig. 11, we see in graph " a " some of these lag correlograms. Graph " b " shows the time lag for maximum correlation plotted against the best available figure for the cross-wind component in the common scattering region—that for Hemsby at a height of 3,000 m. There appears to be little doubt that the time lags are in fact caused by the drift of the scattering sources through the common scattering volume when under the influence of the prevailing wind. Graph " c " also substantiates this, showing the maximum lag correlation to be higher when the wind is blowing more exactly across the path.
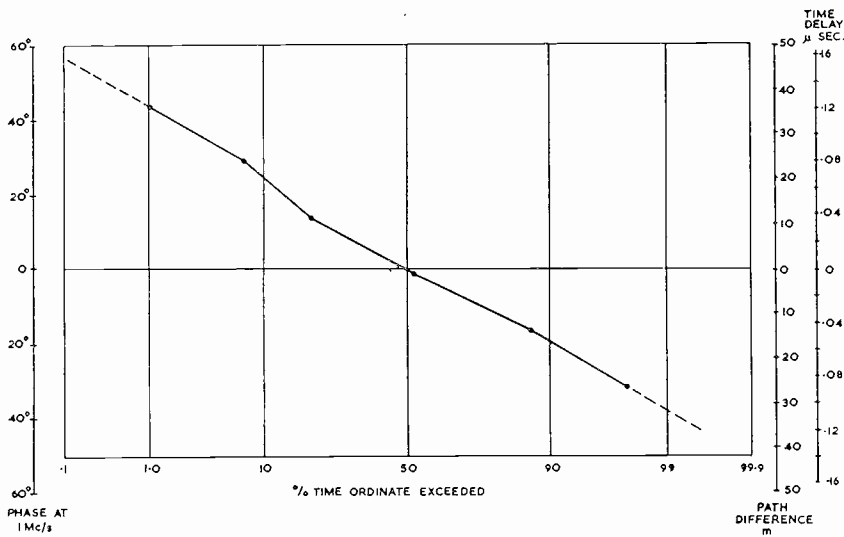

Fig. 12

Cumulative distribution of time delay over 322 Km. path. (The ordinate origins are placed on the median values.)

If the correlation between fading rate and wind velocity shown in Table 1 is also considered, it seems evident that the movement of scattering sources with wind is an important cause of fading; this influence would not vary with path length except insofar as the wind itself is dependent on height. Fading rates measured over the 575 Km. path were seen (Fig. 8) to accord well with those measured at 322 Km.

Modulation Phase Measurements

A pulse system was first tried to assess the time delays involved in the propagation and hence the bandwidth potentialities of the medium. However, the signal/noise ratio was found to be inadequate for too large a part of the time, and the system now described was devised to enable useful time delay measurements to be made whilst retaining the narrow bandwidth used for field strength measurements.

High stability crystal oscillators were used at both terminals; at the transmitter, 1 Mc/s sine-wave amplitude modulation was derived from the oscillator. At the

receiver, crystal-controlled frequencies of 999 kc/s and 1 kc/s were derived, the former being mixed with the incoming signal modulation to give a 1 kc/s tone having phase variations identical with those of the received modulation. This was then passed through the receiver audio-filter, giving an output of adequate S/N ratio to work a phase comparator. The crystal-controlled 1 kc/s source was used as the reference. The phase record is interpreted as a measure of the changes in path length, or time delay, suffered by the scatter signal, and Fig. 12 shows the distribution obtained from the data available. The instantaneous path is seen to differ from its median value by more than 38 m. in length or $0.15\ \mu$ sec. in delay for 1% of the time. It may be calculated that a ray-path, to give this additional path length, would require to be scattered from a point offset by $1.5°$ from the direction of the centre of scattering. A value for the angle subtended at the receiver by the effective scattering region is thus provided, and may be compared with the figure of $0.5°$ (32 min.) found in a section above. This latter figure applies only to the vertical angle subtended at the receiver by the scattering region, and, in view of the somewhat arbitrary assumptions made, the two measurements seem not entirely incompatible.
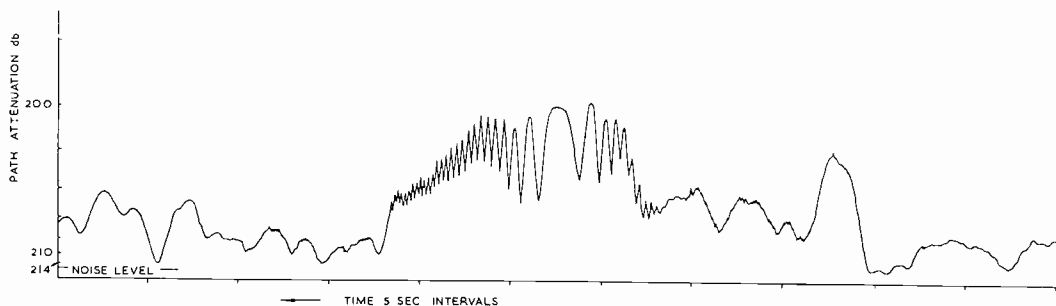

FIG. 13

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Significance of the Aircraft Reflections

Significant amplitude changes (i.e. > 3 db) have not been observed at beat frequencies greater than about 4 c/s so that an. A.G.C. system would not be defeated.

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The general picture presented by the measurements described accords well with comparable published results.

However, the attenuation rate of 0·103 db/Km. may be noted, as also the diversity distances which are larger than was expected. Finally, the failure to detect a dependence of fading rate upon distance is worthy of note.

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Introduction

SINCE about 1930 it has been realized that wave propagation in the metric, decimetric and centimetric bands can be profoundly influenced by the troposphere, by virtue of changes in its refractive index amounting to only a few parts in a million. In the present discussion attention will be directed to diurnal variations in signal strength which, in favourable circumstances, can be a prominent feature of very short-wave propagation. These variations have an important influence on the engineering and operation of V.H.F., U.H.F. and S.H.F. radio links.

The salient characteristics of this phenomenon were first observed and satisfactorily explained by Englund, Crawford and Mumford [1] in 1940. In prolonged propagation tests of an optical overland path near New York they observed, on wavelengths of 4 m. and 2 m., a marked tendency, particularly in summer, for the signal strength to remain nearly constant during the morning and afternoon, while becoming extremely variable between the hours of 1800 and 0900. These nocturnal fluctuations, which intermittently gave rise to signal strengths much above the steady day-time level, were attributed to disturbing reflections from elevated inversion layers, in conjunction with variable ray bending near the ground which modified the diffracting effect of the earth's surface.

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Diurnal variations are usually more pronounced in summer than in winter because higher temperatures increase the humidity lapse rate, thereby increasing the refractive index gradient. For this reason diurnal effects tend to be more marked in tropical regions than in temperate zones. To give an example of the magnitudes likely to be experienced, conventional radio paths selected for V.H.F. radio links in Nigeria, Ghana and Kuwait have been found to give nocturnal signal strengths often 20-25 db above the steady daytime level on a frequency of 180 Mc/s. These occasions are however often interrupted by deep fades.

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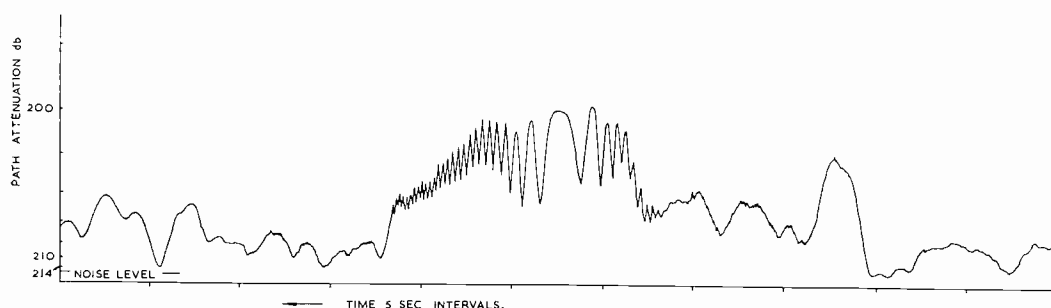

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Acknowledgments

The author is grateful to the Engineer-in-Chief, Marconi's Wireless Telegraph Co., Ltd., for permission to publish the paper. The assistance given by the author's colleagues in the provision of the equipment and the conducting of the tests, and particularly the help of Mr. F. S. Immirzi in the reduction of data, is gratefully acknowledged.

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operating a recorder whose deflection was nearly proportional to the received signal level expressed in decibels above 1μV. The recorder sampled the signal strength once a minute, some of the intervening time being occupied in automatic calibration of the receiver. Except for a few breakdowns, signal strength was continuously recorded from August 27th, 1955, to March 1st, 1956, so that nearly 4,000 hours of effective recording were secured.
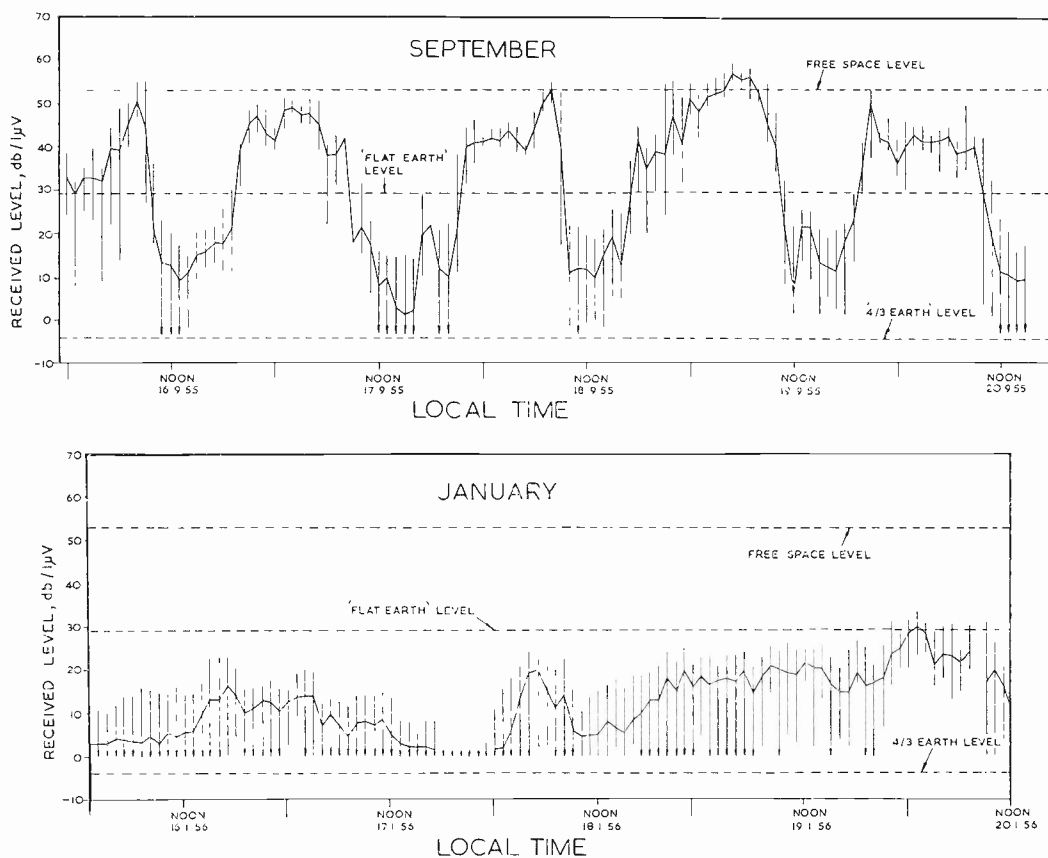

FIG. 1
Hourly signal ranges, 80 Mc/s, Bahrain-Doha.

Features of Signal Behaviour

Fig. 1 shows, by means of vertical bars, the maximum and minimum signal strength observed in any hour, indicated in local time, while the inter-connecting lines show the hourly median signal strength. The upper chart shows typical diurnal variations observed during September while the lower chart, which is characteristic of January, shows a random pattern with no discernible diurnal variations. September showed the greatest diurnal variations of the six-month test period. The difference between mean day-time and night-time levels often amounted to 40 db in that month, and diurnal variations were repeated with remarkable regularity. Well-defined variations persisted throughout October, interspersed with occasional erratic periods. During November and December the irregularities increased, but even in the latter

month distinct diurnal cycles were apparent for a few successive days. During January diurnal patterns were only occasionally perceptible. February and early March, while very erratic, occasionally showed some very well-defined diurnal changes.

Fig. 2 shows samples of signal strength records. The upper trace, obtained in September, shows a typical nocturnal disturbance with fading from a high level, resulting probably from interference between strong multiple reflections at grazing incidence from an elevated inversion layer. The decline after 0900 hours local time from the free space level to that consistent with a standard atmosphere reflects the decay of the inversion due to increasing convection. The lower trace, obtained in October, shows an early morning period with a very high level devoid of fading, followed at about 0930 hours by a very abrupt drop in signal strength symptomatic
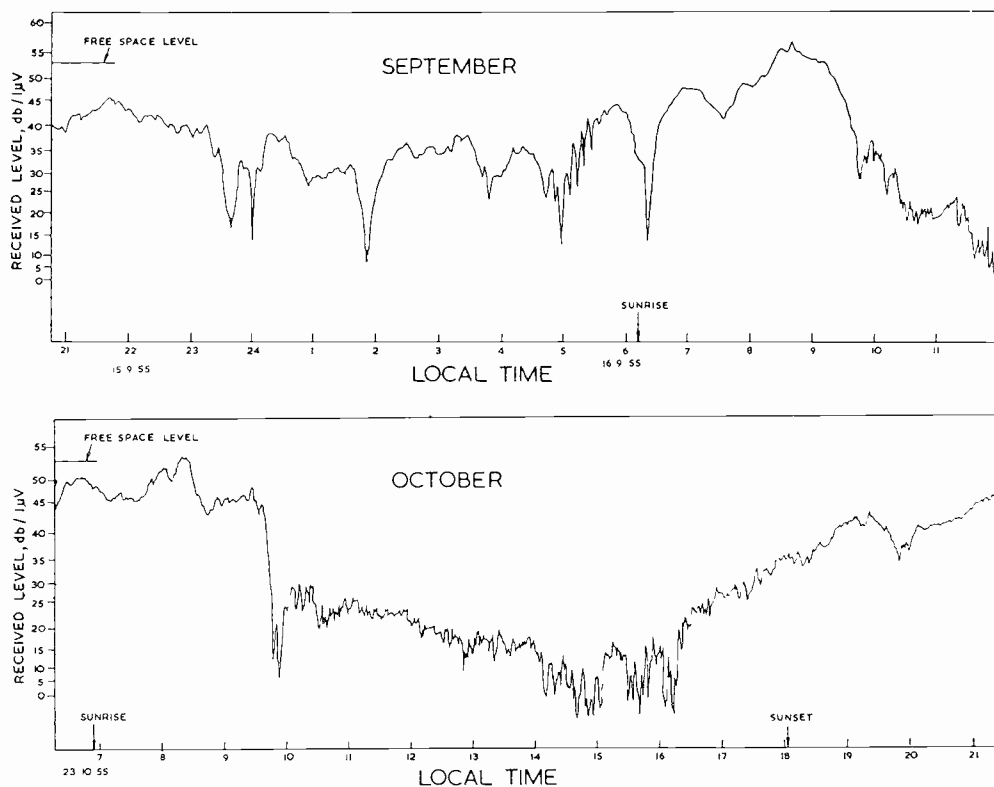

FIG. 2

Illustrative signal records, 80 Mc/s, Bahrain-Doha.

of a rapidly dispersing nocturnal inversion. The fluctuations immediately following the fall indicate interference between a partial reflection at the dissolving inversion layer and a diffracted wave propagated near the earth's surface. Thereafter until about 1400 hours, the signal pattern implies a substantially unstratified atmosphere exhibiting steadily declining refraction. After 1400 hours there is significant interference from a weak reflection at a developing inversion layer which, after 1630 hours, is providing the dominant signal.

(201)

The upper trace on Fig. 3 shows a typical January record. Although refraction near the surface appears to be slightly greater than standard in the daylight hours, the resulting diffracted signal is weak enough to be very vulnerable to partial reflections from weak inversion layers. There is a small increase in atmospheric stratification and surface refraction during the evening. Finally, the lower trace shows a diurnal cycle obtained in February. It comprises firstly, a steady early morning period when the received signal is derived mainly from a near-specular reflection at an elevated inversion. Secondly, there is a mid-day period consistent with a well-mixed standard atmosphere and thirdly, there is a steady growth in signal strength after 1700 hours indicative of the returning nocturnal inversion, which culminates in a period of near-specular reflection after 2000 hours.
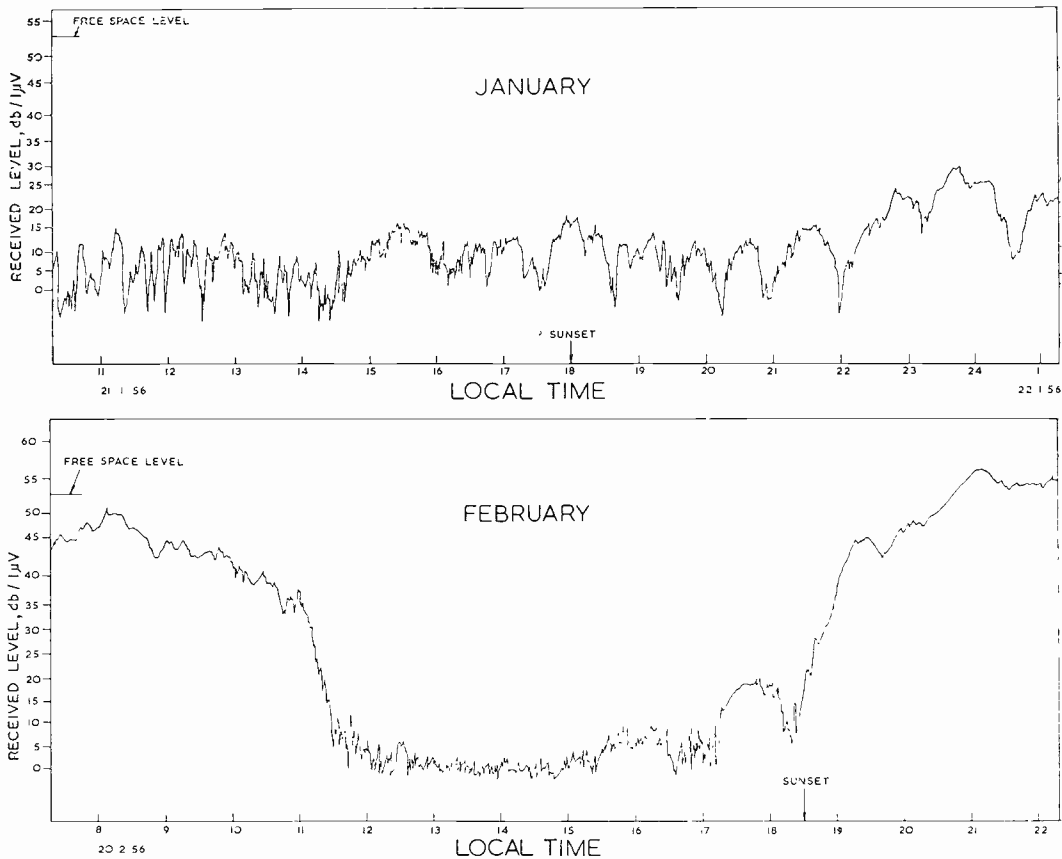

FIG. 3

Illustrative signal records, 80 Mc/s, Bahrain-Doha.

Statistical Features

Fig. 4 illustrates the statistical character of the diurnal variations over the six months' test period. It has been constructed by analysing the variations in the hourly median level for a selected hour of the day during the one-hundred-and-sixty days for which complete records were obtained. Each curve shows for the specified times of day the hourly median level exceeded for the indicated percentage of the

(202)

total number of days tested. It is seen that the weaker hourly median levels, namely those exceeded during a high percentage of days, show progressively reduced diurnal variation until by the time the 99 level is reached the diurnal effect is barely perceptible. It is reasonable to conclude that higher percentage levels, which have important engineering significance, will show even less variation, and from this it is inferred that the troughs of fades attain a fairly constant low level which is independent of the time of day.

Attention will now be briefly directed to the behaviour during the period 1400-1600 hours when the hourly median signal strength is least, and the contrasting period 0200-0400 hours when the signal strength is near its maximum. Fig. 5 shows
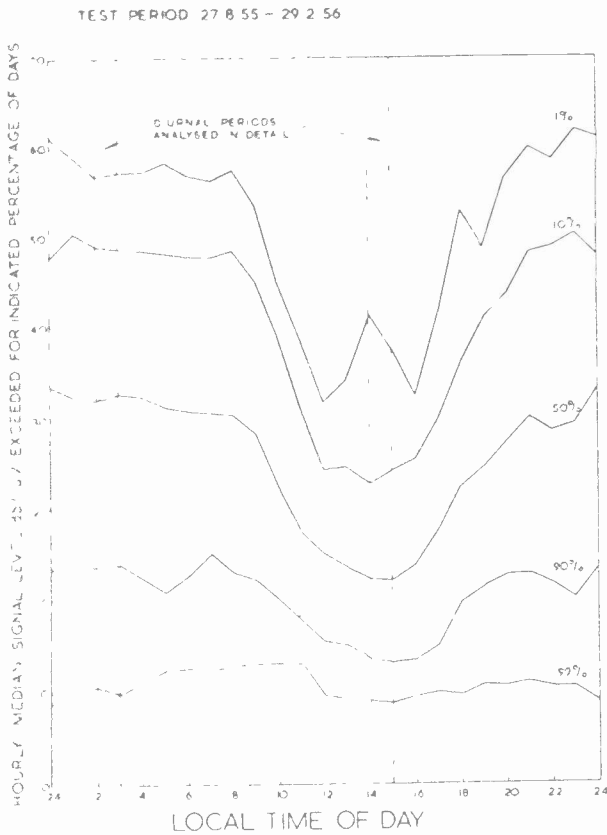
TEST PERIOD 27 8 55 – 29 2 56

FIG. 4
Statistics of diurnal variations, 80 Mc s, Bahrain-Doha.

the seasonal trends for these extreme periods of the diurnal cycle. To smooth the effects of short term weather changes the hourly median levels for the respective day and night periods have been averaged over a week, and plotted against the appropriate week of the test. A seasonal trend with a minimum in January is clearly evident, but while the weekly mean night-time levels experience a seasonal variation of perhaps 35 db, the day-time levels experience a variation of only about 20 db. It will be noticed furthermore that by mid-January the difference between day time and night time levels has narrowed to insignificance, but that it widens

rapidly again thereafter. Extrapolating the trends on the chart to the unrecorded seasons, it seems likely that both day-time and night-time weekly mean levels would show broad maxima in early July.

Fig. 6 illustrates the wide divergence between cumulative distributions of hourly median levels applicable respectively to the specified day-time and night-time hours. For the nocturnal hours the free space level was exceeded for as much as 5% of the time. Similar curves for the period December-January, when signal strengths were weakest, show a much reduced divergence between day-time and nocturnal levels. Moreover, the free space level was never reached during that period.
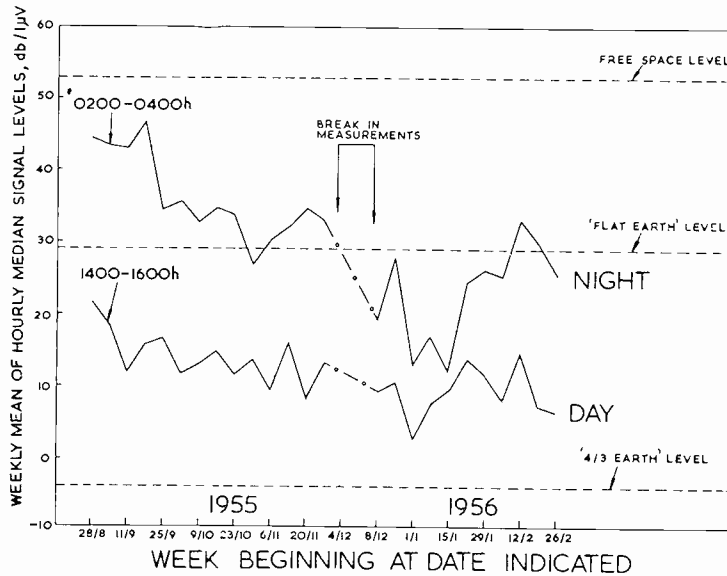

FIG. 5

Seasonal variations for day-time and night-time periods.

Association Between Radio and Meteorological Behaviour

Throughout the period of the radio tests, regular meteorological soundings were made by the Royal Air Force near the transmitting terminal at Bahrain. These soundings were made daily at 0600 and 1800 hours local time, and modified refractive index profiles derived from them have served to confirm the existence of intense atmospheric stratification inferred from many recordings of the 3·75 m. transmission. To limit the labour involved in extracting M profiles, attention has been confined to the synoptic hours associated with very high and very low hourly mean signal strengths.

Inspection of the chart of diurnal variations previously illustrated (Fig. 4), shows the synoptic hour 0600 to be associated with characteristically high signal levels well suited to this purpose. The synoptic hour 1800 generally shows intermediate levels rapidly increasing towards the typically high nocturnal values. Thus although of interest as representing a transitional state, this hour has little utility in the investigation of the extreme conditions to which this discussion is confined. Unfortunately no meteorological soundings exist for the period noon to 1600 hours associated with low signal strengths, and therefore to obtain examples of low levels

it is necessary to search for the few uncharacteristic occasions when weak signals occurred during the synoptic hours available.

Adopting the arbitrary criterion that a weak signal has an hourly mean level at least 40 db below the free space level, fourteen examples of such signals were found to occur in the morning synoptic hour 0600, and two examples in the evening synoptic hour 1800. Fig. 7 (*a*) shows representative *M* profiles associated with some of these occasions. As expected these exhibit fairly uniformly graded atmospheres with a tendency, however, for refraction to exceed the standard value.

Attention will now be directed to meteorological soundings associated with very high hourly mean levels, arbitrarily defined as lying within 14 db of the free space level. In this category thirty-one examples were found for the complete test period
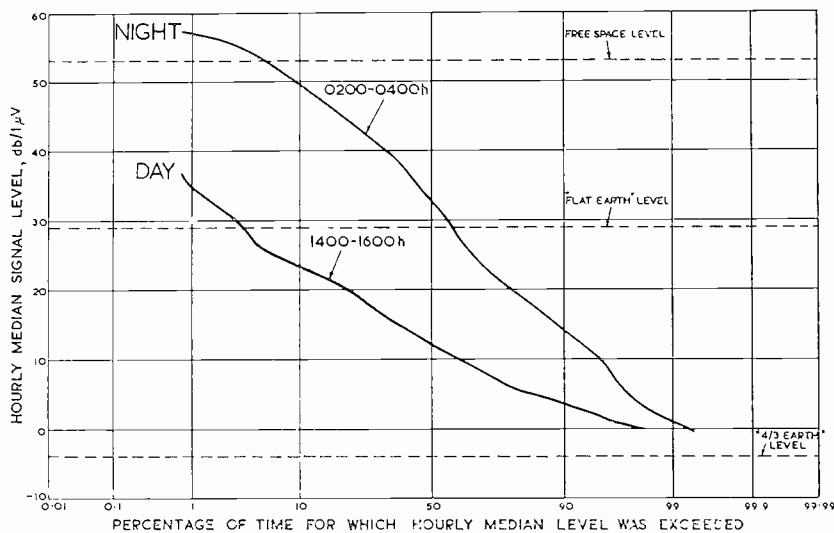

FIG. 6

Cumulative distributions for day-time and night-time periods.

of which five examples, illustrated in Fig. 7 (*b*), show zero or slightly positive *M* gradients over the first few hundred metres. The remaining twenty-six examples show pronounced ducts. Of these, seven show elevated *M* inversions as illustrated in Fig. 7 (*c*), while the remaining nineteen ducts show ground-based *M* inversions which will be separately considered later.

Apart from one anomaly, where a profile associated with a low signal strength exhibited a weak surface duct, the character of each profile investigated has been found compatible with the associated signal level. In view of this qualitative correspondence it was considered worth computing, for the test path and the test wavelength, the theoretical signal strengths based on the available *M* profiles, for comparison with the hourly mean signal strengths measured during the corresponding synoptic hours.

Comparison Between Measured and Theoretical Signal Strengths

Taking first the simplest category of profile, illustrated in Fig. 7 (*a*) and having a fairly uniform *M* gradient, theoretical signal levels have been based mainly on Eckersley's Propagation Curves for a smooth curved earth, whose radius has been suitably adjusted to allow for the required gradient of modified refractive index.

(205)

Fig. 7 (*d*) shows, for horizontal polarization, the theoretical relationship between the positive gradient of modified refractive index dM/dh, and the signal strength over the tested path. It should be noted that the path is non-optical and comprises gently undulating terrain with no significant hills and a short stretch of sea, and thus lends itself fairly well to idealization. The relationship of Fig. 7 (*d*) has been restricted to positive values of dM/dh for reasons which will become apparent. It is quite accidental that it is approximately linear over the range considered.

Fig. 7 (*e*) shows measured signal strengths plotted against their calculated values for various situations. The crosses refer to the weak signals associated with profiles
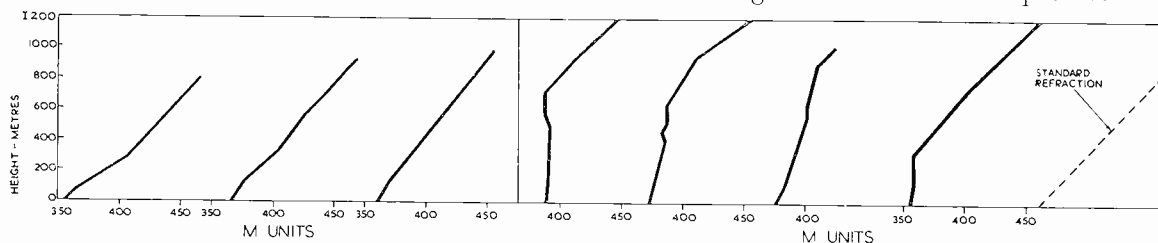

FIG. 7 (*a*)
Profiles associated with weak signals.

FIG. 7 (*b*)
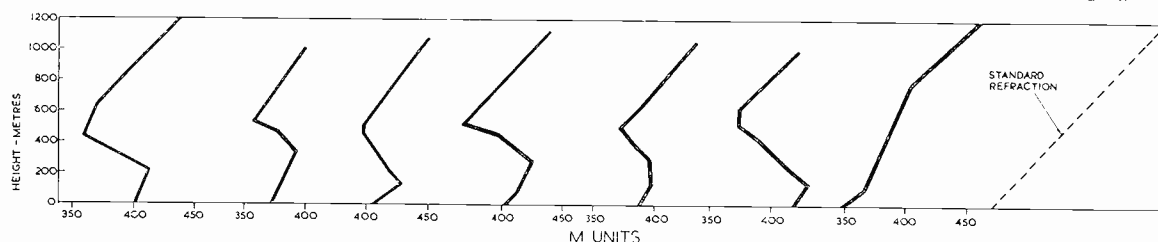*Profiles with zero or small positive gradients associated with strong signals.*

FIG. 7 (*c*)
Profiles showing ducts with elevated M inversions, associated with strong signals.

in category (*a*). In general the measured levels substantially exceed the theoretical figure due, it is believed, to partial reflections or scattering from atmospheric irregularities. These, while often too small to be revealed by the relatively large-scale meteorological soundings, can nevertheless dominate the weak diffracted signals associated with moderate surface super-refraction.

The circles refer to the high signal levels associated with profiles in category (*b*), which have zero or small positive values of dM/dh near the surface. Once again the measured levels much exceed the theoretical values. While strong reflections at very grazing incidence from small discontinuities may well account for this in some cases, there is another modifying factor to be considered. The condition under discussion is one of incipient duct formation, where the track-width of the first transmission mode, as defined by Booker ([12]), is very large. In this narrow region it is quite unrealistic to compute signal strength on the basis of a uniform M gradient to infinity, which is the idealization implicit in Fig. 7 (*d*). In practice, uniform M gradients are maintained only over a limited height interval and this shortcoming restricts the valid range of the theoretical relationship. As a rough guide to the magnitudes applicable to the present test, M profiles in category (*b*) show fair uniformity of positive M gradient up to heights of at least 300 m. if small-scale irregularities are ignored. Consideration of the track-width of the first transmission mode in relation to the above height leads to the conclusion that Fig. 7 (*d*) becomes

unusable only when dM/dh becomes less than about ·01. Although the invalid region is quite small, the situation is worsened in practice because the meteorological measurements are insufficiently accurate to make the small but critical distinction between zero and small positive values of dM/dh. Thus slightly inaccurate surface gradients measured from the M profiles which nominally fall in the valid region of the curve may actually lie in the unusable region in some cases.

The profiles illustrated in Fig. 7 (c) will now be considered. These indicate pronounced elevated M inversions from which radio waves can be reflected. The reflection coefficients of such layers have been calculated by Millington ([13]), after idealization in a mathematically convenient way. For layers having a negative
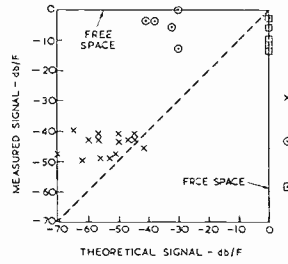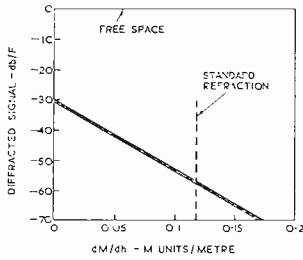

FIG. 7 (d)

Theoretical relation between diffracted signal strength and dM/dh for horizontal polarization. $\lambda = 3·75$ *m.*

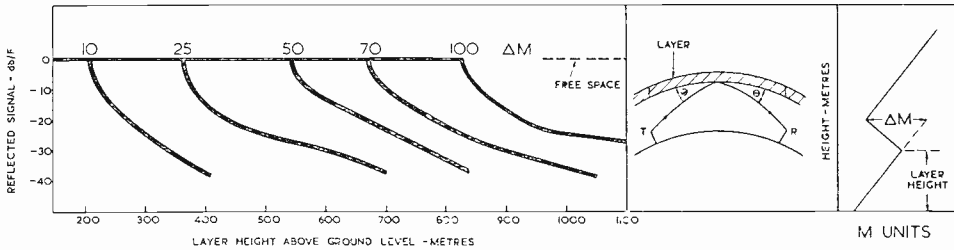FIG. 7 (e)

Theoretical versus measured signal strengths.

FIG. 7 (f)

Theoretical relations between reflected signal strength and layer height. $\lambda = 3·75$ *m. Layer thickness* 300 *m.*

refractive index gradient and finite thickness Millington has shown that for any thickness of layer, total internal reflection will occur if the grazing angle is less than a critical value depending only on the total change of refractive index across the layer. For grazing angles exceeding the critical value, the reflection coefficient declines in a rapid but complex way, governed by the layer thickness expressed in wavelengths. Millington's idealization implies zero refractive index gradient outside the layer, where in practice the gradient is usually negative. The major effect of this departure from the prescribed idealization is to reduce the grazing angle θ on account of downward ray-bending, as indicated diagrammatically on Fig. 7 (f). There is also a secondary influence connected with the fact that negative gradients outside the layer necessarily reduce the discontinuity in slope on entering and leaving the layer which is implicit in Millington's idealization. In the limit, when the slopes outside it and inside it become equal, the layer vanishes. A simple modification has been devised which, while conforming to Millington's results for layers suiting his idealization, at the same time gives no reflected signal when the layer vanishes on

(207)

account of the effect just mentioned. This empirical adjustment, which is not claimed to be rigorously accurate in intermediate cases, involves an M deficit ΔM which is defined on the idealized M curve in Fig. 7 (f). The effective total change in refractive index across the layer, which is a fundamental parameter in Millington's analysis, is then taken as $\Delta M \times 10^{-6}$.

Based on these principles, the chart of Fig. 7 (f) shows theoretical signal strengths over the test path due to reflection at representative elevated layers 300 m. thick at various heights above the surface. To conform broadly to M profiles typical of category (c) the chart is based on a uniformly graded atmosphere below the layer
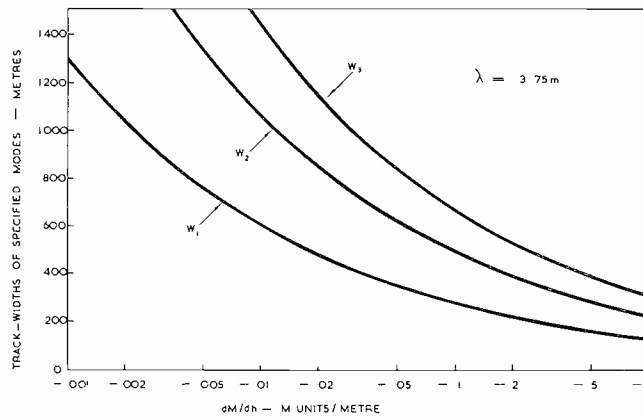

Fig. 8 (a)

Theoretical relations between dM/dh and respective track-widths W_1, W_2 and W_3 for the first three transmission modes on a wavelength of $3·75$ m.

corresponding to an effective earth radius factor of 2. The values of ΔM shown on the chart cover a range representative of the M profiles under consideration. Signal strengths are expressed relative to the free space level.

The chart clearly shows the layer heights above which total internal reflection, implying " free space " signal strength, gives way to a rapidly declining level. The seemingly unrelated shapes of the curves in this region result from interference effects characteristic of layers of finite thickness. Being based on various idealizations the curves should not be interpreted too literally, but they serve to illustrate the very high levels obtainable by reflection at even minor discontinuities if the ray incidence is sufficiently grazing. For example when ΔM is only 10, which is probably too small a figure for reliable evaluation from the meteorological soundings, this suffices at a height of 200 m. to give a reflected signal of " free space " level. Moreover, a much weaker discontinuity, or an equal discontinuity at a greater height, is still capable of swamping weak diffracted signals associated with moderate super-refraction near the surface. It is for this reason that the measured signals associated with the crosses on Fig. 7 (e) mostly exceed the theoretical figures based on diffraction in a uniformly graded atmosphere.

The reflection chart just considered may be used to estimate the reflected signal strengths from elevated layers in category (c) by applying the layer height and M deficit derived from the appropriate M profile. In this way it has been found that all layers placed in this category should give rise to total internal reflection, and hence a

" free space " reflected signal. The conforms satisfactorily to the measured signal strengths which, it will be recalled, were selected for their closeness to the " free space " figure. On Fig. 7 (*e*) this association is represented by the line of squares to the right of the chart. In this situation the diffracted signal propagated below the layer is, of course, negligible in comparison with the reflected signal. The substantial fades sometimes associated with this condition are thought to result from interference between multiple ray paths via the reflecting layer which, as is well known, are geometrically possible with spherical stratification and a concentric reflecting earth.

Propagation in Ducts

We shall now briefly consider some salient features of propagation in ducts having ground-based M inversions, as an aid to assessing particular examples associated with high signal levels over the path under discussion.
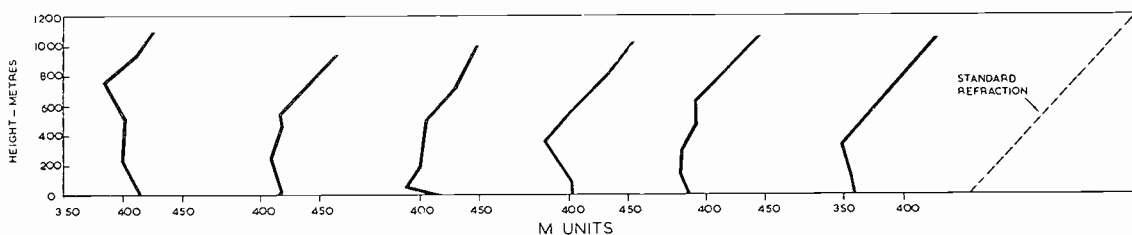

FIG. 8 (*b*)
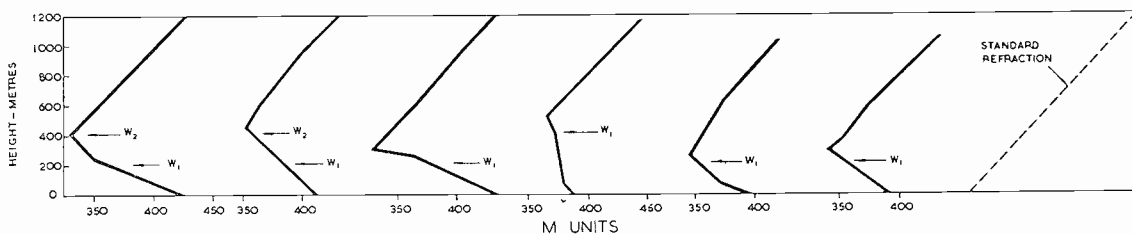*Profiles showing ground-based M inversions incapable of trapping on 3·75 m.*

FIG. 8 (*c*)
Profiles showing ground-based M inversions capable of trapping one or two modes on 3·75 m.

The basic features of propagation within a duct have been simply explained by Appleton [14] by considering interference between upgoing ground-reflected waves and downward-refracted waves within an M inversion. In this way Appleton shows that in a simple surface duct having an M deficit ΔM, a wavelength λ will be propagated freely only if the height of the M inversion is $\lambda/2\sqrt{2\Delta M}$, where ΔM is here expressed in M units $\times 10^{-6}$. For a smaller duct thickness upgoing and downcoming waves interfere destructively and therefore do not travel far. Although a wave treatment of the problem as given by Booker [12] is essential for estimating the signal strength in the duct, Appleton's simple treatment shows quite satisfactorily the vital role played by the wavelength in duct propagation. Moreover it is in fair numerical agreement with conclusions based on Booker's principle which states that, when the height of an M inversion equals the track-width of the first transmission mode—subsequently defined—the associated wave is propagated to great distances, because leakage from the top of the track is then suppressed.

When an M inversion is just thick enough to trap the first mode, energy in the higher order modes leaks freely from the top of the duct so that the contributions of these modes to the received signal can usually be neglected. Thus in this case the signal strength depends on the position of the terminals in relation to the track of the first mode, and on the fraction of the transmitted power supplied to that mode—factors which Booker presents in the form of propagation curves for the mode in question. If the M inversion is just thick enough to include the track-width of the second mode, the contributions of the first and second modes, derived from the appropriate propagation curves, must be combined to obtain the requisite signal strength. Once again higher order modes may be neglected in such a case. If many modes are trapped, as might occur for example on centimetric wavelengths in the region under review, the terminals are intervisible from the radio aspect, and the signal strength may be calculated on a ray basis to give a value in the neighbourhood of free space.

Without entering deeply into the numerical consequences of Booker's mode theory it may be stated that when the terminals lie within an M inversion extending over the track-widths of the first or higher-order modes, signal strengths within the duct may be expected to be very high at points well beyond the transmitter's geometrical horizon. The non-optical path under discussion has amply confirmed this expectation as will be shown.

The characteristic transmission modes, whose properties are governed by the necessity of satisfying the boundary conditions at the earth's surface, are associated with track-widths whose size increases with the order of the mode. When dM/dh is positive—a condition already considered—the track-width is represented mathematically as a complex quantity, connected with the fact that physically it is somewhat ill-defined due to leakage from the top of the track. We are at present concerned with negative values of dM/dh—the duct condition—where the track-width is precisely defined.

Following Booker, the track-widths of the first three modes under ducting conditions are respectively given in metres by:—

$$W_1 = 54 \cdot 1 \lambda^{\frac{2}{3}} [-dM/dh]^{-\frac{1}{3}}$$
$$W_2 = 95 \cdot 2 \lambda^{\frac{2}{3}} [-dM/dh]^{-\frac{1}{3}}$$
$$W_3 = 128 \cdot 6 \lambda^{\frac{2}{3}} [-dM/dh]^{-\frac{1}{3}}$$

where λ is the wavelength in metres and dM/dh—a negative quantity in this case—is the modified refractive index gradient expressed in M units/metre. Fig. 8 (a) shows the relation between these track-widths and dM/dh for the test wavelength of $3 \cdot 75$ m.

Analysis of Observed Ducts

M profiles showing ground-based M inversions have been found associated with high signal levels in nineteen cases. All but one of them came from the morning meteorological sounding. A selection of the profiles is given in Figs. 8 (b) and 8 (c). To determine how many transmission modes, if any, are trapped by a particular duct, the track-widths of the first three modes have been obtained from Fig. 8 (a), using initially the surface value of dM/dh derived from the M profile. In seven cases, of which six are illustrated in Fig. 8 (b), the track-width of the first mode significantly exceeds the height of the M inversion, indicating absence of trapping. In the remaining twelve cases the M inversion covers the track-width of the first mode, while in two of these cases the second mode is also just trapped.

Fig. 8 (*c*) shows examples of this last category. Where a mode is trapped the top of the associated track is indicated with an appropriately marked arrow, adjusted to be consistent with the average refractive index gradient over the whole track. The first two profiles illustrate two noteworthy occasions, both occurring in September, when the second mode was just trapped on the wavelength of 3·75 m. The first profile shows the remarkably large M deficit of 90 M units while the third, which fails by a small margin to trap the second mode, shows a deficit of 100 M units.

The author is not aware of M deficits of quite this magnitude having been observed elsewhere, nor can he discover other reliable evidence of trapping on such a long wavelength.

It is of interest that the nineteen surface ducts found to be associated with very high signal strengths yielded as many as seven examples incapable of trapping the test wavelength. It can only be presumed that in this latter category the progress towards trapping was sufficiently advanced to cause a substantial reduction in leakage of the first transmission mode and hence high signal levels. It may well be that a detailed numerical analysis of such cases on the lines described by Booker [12] would yield signal strengths conforming to the high values observed.

General Conclusions

It may be of value to review some important features of the investigation just described.

The radio measurements, reinforced by the meteorological soundings, have enabled a clear distinction to be made between three main types of propagation operating over the radio path at various times. Firstly, there is the association between weak signals and an approximately standard atmosphere which, however, exhibits signal strengths significantly greater than would be expected from the M gradients observed. This excess is attributable to the influences of scattering and partial reflection from small atmospheric discontinuities which, as is well known, become dominant well in the diffraction region. Secondly, there is the powerful influence of reflections from well-defined discontinuities which can easily give rise to " free space " signal levels. Thirdly, many examples have been given of the association between high signal levels and surface ducts, most of which have been found capable of trapping the first mode.

The investigation has shown, furthermore, that high signal levels are also associated with M profiles in the difficult category involving a zero or small positive M gradient maintained over a limited height interval near the ground. This situation, it will be recalled, cannot be assessed by conventional methods because these are invalidated by the great height of the track-width of the first mode in relation to the restricted height of the ground-based linear region of the profile.

In conclusion the remarkably intense nocturnal surface ducts encountered are worthy of comment. Observation of those ducts was virtually confined to the synoptic hour 0600. If meteorological soundings had been taken in the period midnight-0400 hours, when signal strengths were generally at a maximum, it is likely that ducts even more intense than those observed would have been discovered, for on several occasions in this period signal strengths exceeded the free space level by some 6 db. The presence of pronounced ducts certainly conforms broadly to the climatological description of the Persian Gulf given by Durst [2], but his detailed information is unfortunately relevant to the Gulf itself rather than the surrounding terrain, where the situation is profoundly altered, as already explained, by the heating and cooling of the land.

A search in the literature for direct evidence of trapping from one-way communication or radar systems yields many examples of very long ranges over sea on wavelengths as long as $1\frac{1}{2}$ m., but any evidence of exceptional ranges over land is very scanty. Durst ([2]) quotes the example, already mentioned, of large nocturnal increases in range experienced by $1\frac{1}{2}$ m. and 7 m. radars in Bengal when looking inland over the Ganges delta. There was, however, an accompanying " skip-distance " effect, indicating near-specular reflection at long ranges from an elevated inversion layer. Although providing an interesting parallel with some of the Persian Gulf observations, this effect is, of course, quite distinct from trapping and throws no further light on that subject. While it seems that documentary evidence of trapping is confined to wavelengths of $1\cdot5$ m. and below, it is submitted that the present observations, made in exceptional climatic conditions, provide evidence of recurrent nocturnal trapping on a wavelength of $3\cdot75$ m., which is perhaps longer than has hitherto been considered possible.

Acknowledgments

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A search in the literature for direct evidence of trapping from one-way communication or radar systems yields many examples of very long ranges over sea on wavelengths as long as $1\frac{1}{2}$ m., but any evidence of exceptional ranges over land is very scanty. Durst [2] quotes the example, already mentioned, of large nocturnal increases in range experienced by $1\frac{1}{2}$ m. and 7 m. radars in Bengal when looking inland over the Ganges delta. There was, however, an accompanying " skip-distance " effect, indicating near-specular reflection at long ranges from an elevated inversion layer. Although providing an interesting parallel with some of the Persian Gulf observations, this effect is, of course, quite distinct from trapping and throws no further light on that subject. While it seems that documentary evidence of trapping is confined to wavelengths of $1\cdot5$ m. and below, it is submitted that the present observations, made in exceptional climatic conditions, provide evidence of recurrent nocturnal trapping on a wavelength of $3\cdot75$ m., which is perhaps longer than has hitherto been considered possible.

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