JOURNAL OF RESEARCH of the National Bureau of Standards—D. Radio Propagation
Vol. 66D, No. 3, May–June 1962

Ionospheric Irregularities and Long-Distance Radio Propagation [1]

H. A. Whale [2]

Contribution From Seagrove Radio Research Station, Auckland, New Zealand

(Received October 25, 1961; revised January 2, 1962)

A study and interpretation of many effects observed in the reception of short-wave radio signals over long distance propagation paths. Particular attention is paid to the day-to-day wanderings of the apparent direction of arrival about its mean position. The importance of these wanderings with respect to the design of receiving antennas is discussed, as it has been found that once the regular diurnal variations have been established for medium distance circuits, considerable advantage can result from a reduction of the beam widths in the horizontal plane of antennas commonly in use.

At a receiving station situated a great distance from the transmitter there are three main classes of variation in the direction of the incoming signal.

A. The more or less regular diurnal changes in direction arising from the regular changes in ionospheric density and shape. These variations are quite small at short distances but may reach 180° at distances approaching half the earth's circumference.

B. The irregular day-to-day fluctuations in the direction of the incoming wave. These fluctuations are generally comparable in size to the diurnal variations over any particular path and are conveniently referred to as the "wanderings" of the received signal.

C. The comparatively rapid fluctuations in instantaneous bearing arising from the interference of the various rays arriving simultaneously at the receiving aerial. This is the effect which is referred to as "scintillation" of the signal in radio astronomy and this term is conveniently retained here.

1. Introduction

It is well known that the ionosphere usually behaves not as a specular reflector but as though it contained irregularities having the effect of introducing some degree of incoherence into a wave which is reflected by or transmitted through it. A considerable number of studies of this roughness of the ionosphere have been made, particularly in the measurement of ionospheric winds [Mitra, 1949; Briggs and Phillips, 1950], in radio astronomy [Hewish, 1951], and in its effects on radio direction finding [Bramley, 1951; Whale and Delves, 1958].

In the study of the propagation of radio waves over long distances, the degree of roughness of the ionosphere is important in that it determines the spread of directions over which the signals from a given station can be received. This spreading may be regarded from two different points of view; either from a consideration of the possible deviations from the great circle on any particular path, or from a consideration of the modifications to the polar diagram of the transmitting aerial introduced by the ionospheric scattering. Both approaches are useful to the communications engineer. It will be shown that at distances up to about 15,000 km the main part of the received energy is clustered about the great circle direction. It is only for stations within about 5,000 km of the point antipodal to the transmitting station that large deviations from the great circle direction regularly occur [Whale, 1959]. Exceptions to this general rule can arise either when the transmitting aerial is so sharply beamed that the signal is not received from the general direction of the transmitter but may arrive as a signal which has been scattered through a large angle by the rough ionosphere or the rough ground, or else when ionospheric conditions are such that the great circle path is closed to the particular frequency used, when a similarly scattered signal may arrive from directions well away from the great circle direction. These cases of irregular propagation are especially interesting in that, as in the case of VHF scatter propagation, communication may be possible in the absence of the normal requirements for regular ionospheric propagation along the path.

2. Overall Changes in Direction of the Received Signals

The measured bearing of a distant short-wave transmitter varies in a way that depends on a number of different factors. The overall effect of all the contributing factors may be seen in table 1, which gives the observed spreads of the bearings in some typical cases. Since there is usually a regular diurnal variation included in the changes, the statistical distribution of the variations is often not normal. In a normally distributed variation, the total width of the histogram at a horizontal

[1] Presented at the Spring URSI Meeting, Washington, D.C., 1961.
[2] Temporarily at Goddard Space Flight Center, Greenbelt, Md.

TABLE 1. *Total variations in the bearing of the signal received at Auckland*

Station	Frequency	Location	Angular distance from Auckland	Great circle distance	Months of observation	Standard deviation in degrees
	kc/s			*km*		
ZQD	9315	Fiji	19.1°	2,120	Aug. 53	1.3
					Mar. 54	1.3
					Apr. 54	1.3
VLQ9	9660	Brisbane	20.9°	2,320	Nov. 53	1.3
					Mar. 54	1.3
					Aug. 54	1.3
WWVH10	10000	Hawaii	63.8°	7,083	Nov. 53	2.7
					Mar. 54	2.3
					Apr. 54	2.0
					Jul. 54	2.3
					Jun. 54	2.0
					May 54	1.3
WWVH15	15000	Hawaii	63.8°	7,083	Apr. 54	1.3
					Mar. 54	1.7
HCJB	11915	Equador	103.0°	11,435	Aug. 54	2.0
					Sept. 54	1.7
	9745				Sept./Oct. 54	1.7
AYR78	11925	Brazil	107.9°	11,979	Oct. 54	1.7
BRAZZAVILLE	11970	Africa	135.0°	14,988	Sept. 54	5
					Jun./Jul. 55	11
GVY	11955	England	163.8°	18,185	Sept. 54	30
VOA	11940	Tangier	178.8°	19,850	Sept./Oct. 54	15

level which separates the upper and lower parts of the histogram into two equal areas is almost three times the standard deviation. We have therefore adopted one-third of the width at this level of the observed histogram as a simple measure of the spread whether the distribution is normal or not. With signals from nearly antipodal stations, both long and short paths are commonly observed; in such cases reciprocal bearings have been used in the histogram so that the bearings all lie in one half-plane. This means that the maximum measure that could be obtained for the tabulated standard deviation, even if the observed bearings were distributed uniformly over 360°, would be 60°. However, at these large distances the bearings tend to cluster into separate groups so that a more detailed investigation of the mechanisms involved is required.

3. Bending of the Ray by Effective Tilts of the Ionosphere

It has been shown by Bramley [1951] and others that some of the changes in the direction of the waves reflected from the ionosphere may arise from more or less regular changes in the shape of the ionosphere. Some of these, such as the ripples which have been extensively investigated by Munro [1950] give rise to relatively short period changes which can be eliminated by a time averaging of the results. Others, however, which are normally referred to as those arising from effective tilts of the ionosphere may persist for many hours. Some of these have been described previously. [Whale, 1956]. It has been shown that many of these large effective tilts arise by a process of refraction (prism effect) in a layer beneath the reflecting layer [Titheridge, 1958]. As these effects depend on the density and shape of the regular ionospheric layers, they may be removed from the results by a comparison of the measurements made on many successive days.

The general form of the daytime part of the regular diurnal variations may be pictured by considering the ionosphere as consisting of two hemispherical shells, the daytime hemisphere situated eccentrically about the earth so that the lower portion of the ionosphere is always toward the sun. An equatorial section viewed from the North Pole would then be as shown in figure 1a. As the earth turns, the effective tilt of the ionosphere over any point on its surface changes and the bearing of a reflected wave thus changes. However, since the

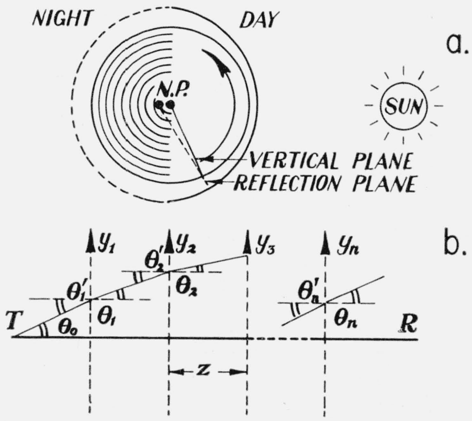

FIGURE 1. a. *Ionosphere pictured as two hemispherical shells, the center of the one nearer the sun being displaced away from the sun.*
b. *Bending of a ray at successive encounters with a scattering medium.*

shape of this equivalent ionosphere depends on the frequency and angle of incidence of the wave, this model is of limited value in calculating the actual variations. It is of interest that, with this configuration of earth and ionosphere, the ionosphere displacement changes the geometrical antipodal point into an antipodal area in the shape of a caustic surface. The orientation and size of this area will change with the time of day and with the latitude of the transmitter.

4. Wandering of the Received Signal

There is some spreading of the wave at each reflection at a rough surface (which may be the ground or the ionosphere) thus making possible a small change in the direction of a particular ray at each reflection. If each of these small changes is of the same size and in the same direction, the trace of the ray-path on the surface of a plane earth will be such that the reflection points all lie on a circle. We may regard this as being an extreme ray, all other rays lying within the limits of the zone bounded by the two extreme rays with the maximum allowable positive and negative curvatures; the energy initially transmitted in a particular direction becomes spread over some distance each side of the mean ray in this direction. For this plane case, if the extent of the spread is measured perpendicular to the line joining the transmitter to the receiver as in figure 2a, and all distances are measured as equivalent angular distances to facilitate later comparison with the spherical earth case, then the limiting distance Δy is given by

$$\Delta y = \pm K\Lambda^2 \tag{1}$$

where

$2K$ = curvature of the ray path,

Λ = equivalent angular distance $= \dfrac{d}{R}$,

d = distance from the transmitter to the receiver,

R = radius of the earth.

An important observable quantity is the angular deviation of the incoming ray from the great circle direction of the transmitter from the receiver. A simple geometric construction as in figure 2a shows that the limiting value of this angular deviation is

$$\Delta\theta = \pm K\Lambda. \tag{2}$$

These two relations have been plotted in figure 2b. In these curves the curvature of the limiting rays

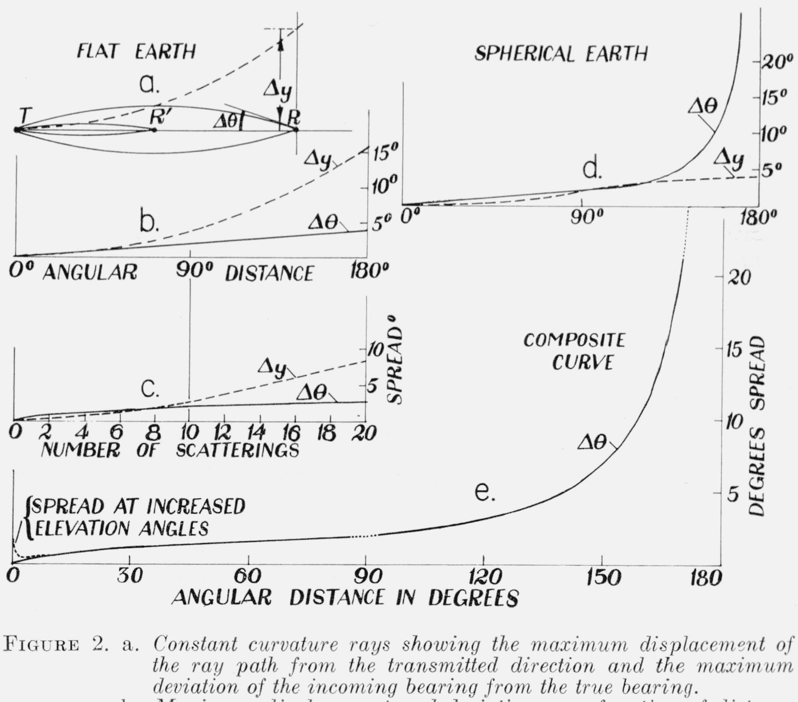

FIGURE 2. a. *Constant curvature rays showing the maximum displacement of the ray path from the transmitted direction and the maximum deviation of the incoming bearing from the true bearing.*

b. *Maximum displacement and deviation as a function of distance measured as an equivalent angular distance on a spherical earth.*

c. *Standard deviation of displacement and deviation from true bearing as a function of number of encounters with the scattering medium.*

d. *Maximum displacement and bearing deviation on the theory of small circle propagation.*

e. *Composite curve using scattering theory up to an angular distance of 90° and small circle theory at greater angular distances. Curves matched at 90°.*

has been chosen (in accord with the measured value) so that the deviation of the extreme ray from the great circle is 2° at an angular distance of 90°.

It has been shown by Whale [1959] that the path on a spherical surface of a ray with constant curvature is a small circle and that

$$\sin \Delta\theta = \pm K' \tan \frac{\Lambda}{2}, \tag{3}$$

where

Λ = the angular distance from the transmitter to the receiver,

K' = curvature measured as change in direction per unit angular distance traveled.

The energy is now spread over a distance perpendicular to the great circle given by

$$\Delta y = \pm K'(1 - \cos \Lambda), \tag{4}$$

where Δy is now a real angular distance.

Relations 3 and 4 are plotted in figure 2d, again with the curvature of the ray chosen so that $\Delta\theta = 2°$ at an angular distance of 90°.

These relations are of different form from those obtained in the simple analysis expressed by eqs (2) and (3), and it is suggested that since a statistical treatment of the curved earth case leads to even more complicated expressions, a compromise be adopted whereby the statistical expressions are used for angular distances up to 90°, and the spherical earth expression eq (3) thereafter. This treatment leads to results which are in substantial agreement with the experimental observations.

A typical composite curve in which eq 10 is used at angular distances up to 90° and eq (3) at greater distances is drawn in figure 2e, the two curves being matched at the changeover point so that $\Delta\theta = 2°$. At very short distances the elevation angle of the incoming ray will be large so that a small change in the direction of the ray at the ionosphere will lead to a large observed change in bearing. This effect is indicated by the dotted curve at small angular distances.

In practice, the rays will not be spread uniformly over a range of angles but the variation with angle will follow some statistical law. If it is assumed that the spread of the rays at each reflection obeys a normal distribution law, the distribution of angles and of the energy may be calculated for the plane earth case as in the next section.

5. Scattering at Successive Reflections

In figure 1b consider a transmitter at T with a power polar diagram given by $P(\theta_0) = \exp - B\theta_0^2$, θ_0 being measured from the line connecting the transmitter to the receiver. B is a factor specifying the sharpness of the aerial pattern, a large B indicating a narrow beam. If the distance perpendicular to the line $\theta_0 = 0$ is measured in units of the distance between successive reflection points (z in the diagram), then $\theta_0 = y_1$ for small angles. Similarly, $\theta_1 = y_2 - y_1$, etc.

At each reflection, the power incident in the direction θ is spread over a range of angles according to the law $\exp - A(\emptyset - \theta)^2$, where $\emptyset$ is the direction of the reflected wave and A is a scattering coefficient.

Then, if the symbols with primes refer to the wave incident on each reflection line and the unprimed symbols refer to that emergent from the reflection region, the distributions of power at the lines $n=1$, 2, 3 . . . are as follows:

$$P(\theta_1') \propto \exp - By_1^2$$

$$P(\theta_1) \propto \exp - (\overline{A+B}\, y_1^2 - 2Ay_1\theta_1 + A\theta_1^2)$$

$$P(\theta_2') \propto \exp - (\overline{A+B}\, y_2^2 - 2\,\overline{2A+B}\, y_2\theta_2' + \overline{4A+B}\, \theta_2'^2)$$

*　　　*　　　*　　　*　　　*

$$P(\theta_n') = P(\theta_{n-1}) \text{ with } \theta_{n-1} = \theta_n' \text{ and } y_{n-1} = y_n - \theta_n' \tag{5}$$

$$P(\theta_n) = \int P(\theta_n') \cdot \exp - A(\theta_n - \theta_n')^2 \cdot d\theta_n'$$
$$\propto \exp - \frac{A}{aA+bB}(A+nB)y_n^2 - 2(nA+cB)y_n\theta_n + (n^2A+eB)\theta_n^2 \tag{6}$$

where

$a = n(n+1)(2n+1)/6$

$b = n^2(n^2-1)/12$

$c = n(n-1)/2$

$e = n(n-1)(2n-1)/6 = a$ with n decreased to $n-1$.

These power distributions are a function of the distance, y, measured from the $\theta_0 = 0$ line and the direction of power flow, θ, measured as the acute angle between the direction of the incident or scattered energy and a line parallel to $\theta_0 = 0$.

The distribution of total power from all directions along the line y_n may be obtained by integrating $P(\theta_n)$ with respect to θ_n to give

$$P(y_n) \propto \exp - \frac{AB}{n^2A+eB} y_n^2, \tag{7}$$

which is, of course, a uniform distribution if $B=0$ (omnidirectional transmitting aerial) or $A=0$ (scattering is complete).

If the receiver is at the position $y_{n+1} = 0$, the distribution of power in the incoming fan of rays is given by putting $y_{n+1} = 0$ in $P(\theta'_{n+1})$ to give

$$P(\theta) \propto \exp - \frac{A(\overline{n+1}^2A + aB)}{aA+bB}\theta^2 = \exp - \frac{\theta^2}{2\sigma^2}. \tag{8}$$

In these equations, n is the reference number to the line at which a particular reflection occurs. For the usual case where the transmitter is on the earth's surface, the odd numbers refer to reflections at the ionosphere and the even numbers to reflections at the surface of the earth. Although the scattering coefficients will usually be different at the earth and the ionosphere and at different reflection points in either of these, it has been assumed for the purpose of this analysis, that an overall average value of A can be employed. If the receiver is also at the surface of the earth, the number of full hops between the transmitter and the receiver is $n/2$.

The equations may be interpreted in two different ways, either as specifying the statistical distribution of the energy at a particular time or else, as is discussed below, as specifying the distribution of energy which would be observed if the measurements were carried out over a low enough period.

In practice, the power is not received over the whole of this calculated range of angles all the time. The energy appears to come from different directions at different times; the probability that any particular direction will occur being related to the calculated power distribution. The experimental distributions are obtained by counting the number of occasions a bearing occurs within a small range of angles (for example, a range of one degree). Since each bearing measurement is regarded as independent, we may take the probability of obtaining a bearing within a particular range as equivalent to the power distribution given above, so that the standard deviation σ of the observed bearing distribution may be obtained from eq (8) as

$$\sigma=\left\{\frac{aA+bB}{2A(\overline{n+1}^2A+aB)}\right\}^{1/2} \tag{9}$$

$$=\left\{\frac{n(2n+1)}{12(n+1)A}\right\}^{1/2} \quad \text{for a wide beam transmitting aerial, i.e., } B=0, \tag{10}$$

and this

$$=\left\{\frac{n}{6A}\right\}^{1/2} \quad \text{for large } n. \tag{11}$$

The wandering of the bearing is difficult to measure in the presence of the scintillations normally introduced by the interference of the various rays since these scintillations are, at angular distances up to about 135°, generally comparable to or greater than the wanderings. While a considerable amount of work in the field of radio astronomy and in the study of ionospheric winds has been directed toward a measurement of the factors with which we are concerned here, these results generally refer to a particular place at a particular time and are of limited use in an attempt to gain knowledge of the average behavior that is important in radio communications. Some methods of investigation which are of value depend on:

A. The measurement of the effective polar diagram of a transmitting antenna at a considerable distance from the transmitter or, as an equivalent experiment, the measurement of the polar diagram of a receiving antenna when receiving a signal from a distant transmitter.

B. The measurement of the incoming bearing of a signal over a period of some hours on a large number of successive days.

C. The measurement of the relationship between the bearing and the elevation angle of an incoming wave.

6. Day-to-Day Variation of the Bearing of a Distant Transmitter

Over the past few years extensive measurements of the bearing of distant radio transmitters have been made at Seagrove, Auckland. Those made on the rotating interferometer [Whale, 1954] are of particular value in this investigation since it is very easy to obtain the hourly or half-hourly averages from the records obtained with this type of equipment. By this averaging, the scintillation effects and short period variations are removed from the results.

The measurements for a particular time of day have been averaged over each month and then the spread of the bearings about the average calculated. This figure (the standard deviation of the spread) is then a measure of the amount by which the ray can wander from the mean path dictated by the average ionospheric conditions. A number of the results obtained by this method have been plotted in figure 3b. The months and frequencies chosen were determined only by the requirement that enough measurements be available to enable the spread to be calculated. The full line curve is a repeat of the composite curve drawn in figure 2e.

It is to be noted that the observations plotted at an angular distance of about 160 to 170° from the receiving station at Auckland refer mostly to stations in Europe. Most of the paths from Europe to Auckland pass through or near the auroral absorbing regions which may limit to some degree the amount by which the paths can vary. Such an effect would lead to the relatively low observed spreads at these angular distances.

On the other hand, since the elevation angle of the incoming signal for short distance transmissions is commonly observed to be greater than for the longer distances, a large number of hops and thus a greater spread may be expected at the shorter distances.

7. Relation Between the Bearing and the Elevation Angle

We may take expression (3) as indicating the allowable wanderings of the received ray at some fixed distance as a function of the hop length since K' depends on the hop length and is thus directly related to the elevation angle of the received ray, the larger deviations being associated with the higher elevation angles (shorter hops). This effect has been observed in a number of experiments although it may often be obscured by other effects.

Some typical results are given in figure 3a. One example of this effect (fig. 3a, BPO) has been discussed previously [Whale, 1956b] and it was shown there that the results indicated that eq (3) could be written $\sin\theta=\pm.028\tan\frac{\Lambda}{2}$, a result in good agreement with eq (14) which is derived below.

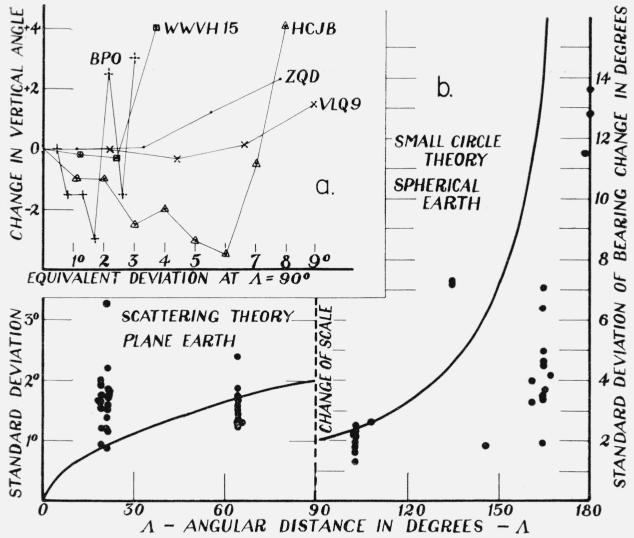

FIGURE 3. a. *Change in received vertical angle as a function of the deviation from the true direction of a signal. The deviation is normalized to an equivalent deviation at an angular distance of 90° by use of the theoretical curves in b.*

b. *Experimental values of the day to day bearing changes.*

8. Antenna Directivity

In the design of an antenna for the reception of long-distance short-wave signals the three different types of variation which have been mentioned previously have to be considered.

A. The diurnal changes in average direction are relatively small at distances less than about 5,000 km but may be so large at distances over 15,000 km that different antennas for use at different times of the day and at different seasons may be required.

B. The day-to-day wanderings of the signal seem to arise from a scattering process and are thus largely unpredictable. In the absence of a direction finder associated with the receiving antenna the design must be such as to ensure reception in spite of these wanderings. Again, these variations are small at short distances but may become very large at distances greater than about 15,000 km. Some improvement in the prediction of the wandering of the wave may be possible with those waves which have passed near to the auroral regions, since it has been found [Whale, 1959] that the directions are influenced by the position and size of the auroral absorbing zones.

C. There are rapid fluctuations in the apparent direction of the wave, arising from the interference between the various components arriving simultaneously at the receiver. This spread seems to be of the same order of magnitude at all distances [Whale and Delves, 1958] so that it may be insignificant compared to the other variations at the greater distances. However, it has also been shown that the fading of the received signal arises mainly from these interference effects, so that they are of prime importance in the design of diversity receiving systems.

The overall behavior may be thought of as being made up of an average diurnal variation on which is superimposed both the irregular variation arising from scattering processes and the rapid scintillations arising from interference effects. Pictorially, as seen from the receiver, this corresponds to a rather blurred patch in the sky (the aggregate of interfering rays) moving haphazardly about a mean position determined by the characteristics of the regular ionospheric layers at that time. This situation is illustrated in figure 4 for a particular month of observations.

The mean direction determines the point at which the main beam of the receiving antenna should be pointed. The beam must then be wide enough to accept the signal as it wanders around this direction. As an example, the average loss due to the changes of the mean direction of the signal as the beam is narrowed can be calculated from eq (8).

For a given transmitted power, the power P_0 received on a non-directional antenna at $y_n=0$ is given by

$$P_0=P_T\left\{\frac{6AB}{\pi n(6nA+\overline{n-1}\,\overline{2n-1}B)}\right\}^{1/2}$$

With a receiving antenna of power polar diagram $\frac{C}{\pi}\cdot\exp -C\theta^2$ (where the factor $\frac{C}{\pi}$ represents the gain of the aerial and is inserted so that the total area under the integrated power polar diagram is equal to a constant, in this case unity), the power received is

$$P_C=P_T\left\{\frac{6ABC}{\pi^2 n(6nA+\overline{n-1}\,\overline{2n-1}B)(1+\gamma C)}\right\}^{\frac{1}{2}}$$

where

$$\gamma=\frac{(n-1)(2\,\overline{2n-1}A+\overline{n-1}\,\overline{n-2}B)}{2A(6nA+\overline{n-1}\,\overline{2n-1}B)}=2\sigma^2$$

thus

$$\frac{P_C}{P_0}=\left\{\frac{C}{\pi(1+\gamma C)}\right\}^{\frac{1}{2}}.$$

If there were no scattering at each reflection γ would be zero, since $A\rightarrow\infty$, so that the loss due to the scattering is given by the relation

$$\frac{(P_C/P_0)\text{ with scattering}}{(P_C/P_0)\text{ with no scattering}}=\left\{\frac{1}{1+\gamma C}\right\}^{\frac{1}{2}}=L. \tag{12}$$

This relative loss of signal as the receiving antenna beam is made very narrow corresponds to the "aperture to medium coupling loss" considered by Booker and deBettencourt [1955] and Gerks [1955].

From the measurements in figure 3b, it has been found that the spread of the deviations is about

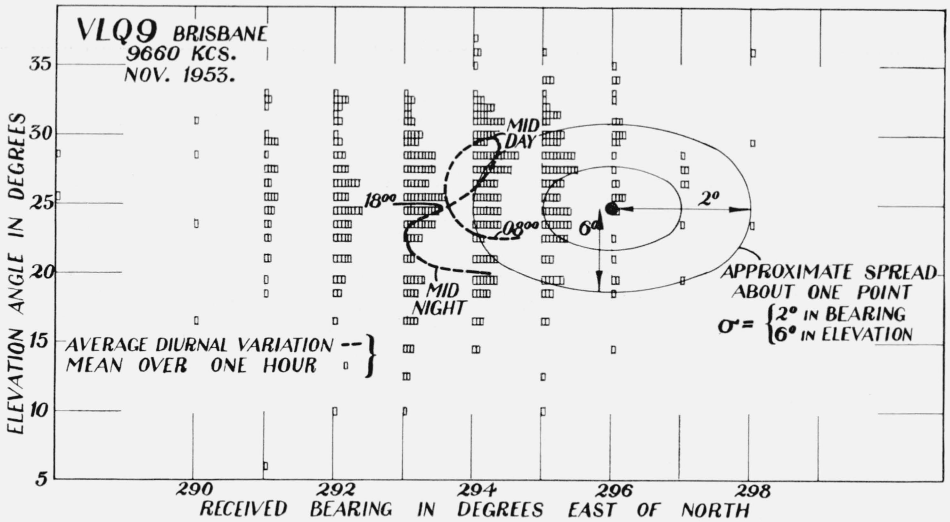

FIGURE 4. *Rapid, diurnal, and day-to-day variations in the direction of arrival of a short-wave signal.*

The diurnal variation averaged over the whole month is shown as a dashed line; the individual measurements averaged over 1 hr are shown as small rectangles; the average spread of the cone of rays associated with any one of these measurements is indicated by the ellipse with standard deviation 2° in bearing and 6° in elevation angle.

$\pm 2°$ at a distance of about 10,000 km. If the beam-width of the transmitting antenna is relatively wide, as was the case in these measurements, the factor A can be calculated from eq (10). Assuming a five-hop path so that $n+1=10$ we find that:

$$A=1{,}160.$$

Then, from eq (12), if the transmitting antenna beam is broad compared to that of the receiving antenna,

$$L=(1+C/408)^{-\frac{1}{2}}\approx 1-C/816. \tag{13}$$

It is to be noticed that the loss from this cause does not become appreciable until C approaches a value of approximately 100. This corresponds to an antenna beam-width of about $\pm 5°$, a value that may be approached with large antennas in the range of wavelengths used for short-wave transmissions over a fixed path (point-to-point transmissions).

At the longer distances the random deviation of the rays from the mean direction increases rapidly in the way indicated by eq (3). If we again take the standard deviation at a distance of 10,000 km as 2°, we may obtain from eq (3) that

$$\sigma=\sin^{-1}\left(.035\tan\frac{\Lambda}{2}\right) \text{ where } \Lambda \text{ is the angular distance.} \tag{14}$$

Then,

$$L=(1-2C\sigma^2)^{\frac{1}{2}}\approx 1-\left(C\tan^2\frac{\Lambda}{2}\right)/816 \text{ up to } \Lambda=170°. \tag{15}$$

Comparing this expression with eq (13), it is seen that the coupling loss increases at the greater distances since the effective value of C increases as $\tan^2\frac{\Lambda}{2}$.

The beam width of the receiving antenna may also have an effect on the degree of fading of the signal fed into the receiver. This arises since the fading is due mainly to the interference of the various rays in the cone of rays arriving at the receiver. The spread of these rays has been measured by several techniques using various time constants, the average value being about 2.5° [Whale and Delves, 1958] for those waves leading to fading rates of periods longer than one or two seconds and about 4.5° [Waite, 1958] including those leading to fading rates of periods less than a second. The spread does not vary much with frequency or distance. Narrowing the beam of the receiving antenna restricts the spread of the cone of rays effective at the receiver and thus reduces the rate of fading. This may be visualized in two different ways: the reduction of the number of interfering rays each of which is varying in phase at a fixed rate, will lead to a slowing down of the interference effects, or the reduction in the spread of the effective cone of rays will lead to an increase in the size of the instantaneous interference pattern on the ground. This pattern is moving about on the ground at a rate determined mainly by the rate at which the phases of the component interfering waves are changing, so that an increase in its size leads to a slowing of the fading rate at a receiver fixed in position on the ground.

9. The Effective Polar Diagram of an Antenna

An interesting measurement of the effective polar diagram of a transmitting antenna at a distance of 3,650 kms has been made by Silberstein [1957]. In this experiment the transmitting antenna of known polar diagram was rotated in steps, the average field strength being measured in each case, and thus the effective polar diagram determined. From the published curve we may deduce that the main lobe of the transmitting antenna had a directivity which could be expressed approximately as

$$\text{Power in direction } \theta \propto \exp - 3.4\theta^2.$$

The actual spread of the incoming waves was not measured. The experiment involved the measurement of the field-strengths with a non-directional antenna at various distances off the axis of the main beam of the polar diagram of the transmitting antenna. In this case we can compare the results with the variation of power with y as given in eq (7), i.e.,

$$P(y) \propto \exp - (ABy^2)/(n^2A + n(n-1)(2n-1)B/6).$$

If the path were predominantly two-hop as seems likely, we may put $n=4$. If the spread at each scattering were as much as one-tenth of the beam width of the transmitting antenna (a value which would indicate considerably more scattering than average) the effective value of B would be reduced from about 3.4 to about 3.15. It is doubtful if this difference would be measurable. The results of this experiment may be interpreted, as was pointed out by the author, as confirming that the ionospheric scattering is unimportant in its influence on the shape of the main beam of the polar diagram of a transmitter over this distance. However, the experimental results confirm that the relatively small effect present is most effective in removing any sharp nulls from the transmitting directivity pattern.

10. Conclusion

An interpretation has been given of some of the effects observed in the reception of long-distance short-wave radio signals. Particular emphasis has been placed on the day to day wanderings of the bearing about its mean direction, as it is an aspect which has previously received little attention. The importance of these wanderings in the design of receiving antennas is discussed, and it is found that for medium distance circuits—provided the regular diurnal variations in the direction of the incoming wave are known—antenna beam-widths in the horizontal plane could advantageously be reduced considerably from those in common use at this time.

This work was carried out at the Seagrove Radio Research Station of the Physics Department, University of Auckland. This work was mainly supported by grants from the New Zealand Department of Scientific and Industrial Research, N.Z. Post Office and N.Z. Broadcasting Service.

11. References

Bramley, E. N., Diversity effects in radio propagation studies, Proc. IEE (London) **98,** No. 51, 19–25 (1951)

Briggs, B. H., and G. H. Phillips, A study of horizontal irregularities of ionosphere, Proc. Phys. Soc. (London) **B63,** 907–923 (1950).

Booker, H. G., and J. T. deBettencourt, Theory of radio transmission by tropospheric scattering using very narrow beams, Proc. IRE **43,** No. 3, 281–290 (1955).

Gerks, I. H., Factors affecting spacing of radio terminals in a UHF link, Proc. IRE **43,** No. 10, 1290–1297 (Oct. 1955).

Hewish, A., The diffraction of radio waves in passing through a phase-changing ionosphere, Proc. Roy. Soc. (London) **A209,** 81–96 (1951).

Mitra, S. N., A radio method of measuring winds in the ionosphere, Proc. IEE (London) **96,** No. 43, 441–446 (1949).

Munro, G. H., Travelling disturbances in the ionosphere, Proc. Roy. Soc. (London) **A202,** 208–223 (July 1950).

Silberstein, R., The long distance horizontal radiation pattern of a high frequency antenna, IRE Trans. Ant. Prop. **AP–5,** No. 4, p. 397 (Oct. 1957).

Titheridge, J. E., Variations in the direction of arrival of high frequency radio waves, J. Atmospheric and Terrest. Phys. **13,** 17–25 (1958).

Waite, C. W., Thesis for M. Sc., Auckland Univ. Library (1958).

Whale, H. A., A rotating interferometer for the measurement of the direction of arrival of short radio waves, Proc. Phys. Soc. (London) **B66,** 533–562 (1954).

Whale, H. A., Effective tilts of the ionosphere at places about 1000 kms apart, Proc. Phys. Soc. (London) **B69,** 301–310 (1956a).

Whale, H. A., An estimate of the size of the antipodal area in short wave radio propagation, J. Atmospheric and Terrest. Phys. **9,** 159–161 (1956b).

Whale, H. A., and L. M. Delves, Some relations between the bearing and amplitude of a fading radio wave, J. Atmospheric and Terrest. Phys. **13,** 72–85 (1958).

Whale, H. A., The effects of ionospheric irregularities and the auroral zone on the bearings of short-wave radio signals, J. Atmospheric and Terrest. Phys. **13,** 258–270 (1959).

(Paper 66D3–194)