Antipodal Propagation

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~~Confidential~~

A discussion of the special considerations involved in the reception of a radio signal at a point antipodal to the transmitter.

INTRODUCTION

Probably everyone is acquainted with "whispering galleries." These are rooms which after construction (sometimes deliberately, sometimes accidentally) focus sound waves originating at some particular source to a second point. Many of these are well known. There is one, for instance, in the old State Capitol of Maryland in Annapolis; another in the U. S. Capitol, in Washington; and another in the Louvre in Paris. Probably the one best known in this country is that found in Statuary Hall in the old House of Representatives in Washington. The elliptical room, whose walls are fairly good reflectors for sound energy, has two foci, and a whisper at one is clearly audible at the other. However, should the speaker move even a foot from the focus and then shout, his voice will fail to carry and will not be heard at the other focus.

Something similar, of course, can be constructed for any type of wave motion. Signals radiating from one focus would converge at the second with but small attenuation.

In this connection it should be noted that natural whispering galleries are already in existence. One such gallery exists in principle for radio waves propagating between the ionosphere and the earth. The two foci are (a) the transmitter location itself, and (b) its antipode.

Although the actual case for the earth and its ionosphere is somewhat complicated, the conditions may be idealized as shown in Fig. 1. This diagram illustrates two concentric spheres, the inner one corresponding to the earth and the outer one to the ionic layer which reflects the radio wave in question. The outer surface of the inner sphere and the inner surface of the outer sphere will be taken as perfect specular reflectors. To simplify the treatment, the wavelength, λ, of the electromagnetic wave will be considered as much smaller than the separation of the spheres, z; i. e., $\lambda \ll z$.

The latter condition holds for both the HF and VHF bands. For example, the ionic layer allowing reflection may be the E, $F1$ or $F2$, which have altitudes of approximately 100 km, 200 km, and 300 km, respectively. When the wavelength is less than 1000 meters, the condition $\lambda \ll z$ holds, and ray tracing is valid.

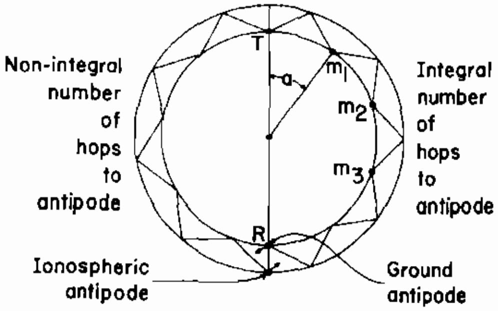

Fig. 1.

Figure 1 represents a meridional cross-section through the spheres, containing the center of the spheres, the radiator T, and the antipodal point R. Two rays are illustrated, both of which are re-focussed at the source T after one transit around the inner sphere. The ray which completes this transit in an odd number of hops is reflected from the outer sphere at the antipodal distance, while the ray making an even number of hops, intersects the true antipode of the source.

Radio waves of the latter type are of great potential interest. They must satisfy the relationship

$$m\alpha = \pi \tag{1}$$

where m is the number of hops to the antipode, and α is the central angle (at the center of the spheres) subtended by one hop. Obviously m must be a whole number.

It should be realized that Fig. 1 illustrates a cross-section through the spheres in *one* plane only. The same conditions occur in all planes passing through T and R. Thus the signal strength at the receiver is the intensity of all rays integrated through an azimuth of 360°, arriving at R. In the ideal case, this intensity is appreciable, and allows a clear, unambiguous interpretation of the signals radiated at the source.

Some comments may be made about those hops where

$$m\alpha = 2\pi, \tag{2}$$

m being integral. (This condition includes not only those cases where rays are focussed at the ground antipode, but also those where they are focussed at the ionospheric antipode. In either event the rays again pass through the source of radiation, T, after one transit around the earth.) When Equation (2) is satisfied, the reflections m_1, m_2, etc., at the inner sphere are termed *multiple image points.*

At the multiple image locations, rays arrive only along the great circle path containing both the receiver and the source, some being propagated along the short segment and others along the long segment of this path.

In the ideal case considered above, the time difference, Δt, between the arrival time of (a) the short-segment and (b) the long-segment rays is constant along the small circles containing the loci of all points m_1, m_2, etc., respectively (see Fig. 2). Each of the small circles is centered on the axis T–R. For one global transit, the time separation, Δt, attains its maximum at T and its minimum at R. At T, $\Delta t = t_l - t_s = t_l$, for the short-segment wave arrives at time $t_s = 0$ seconds, and the long-segment ray arrives at $t = t_l$, the time required for one transit around the sphere. At the antipode R, the geometrical short- and long-segment paths become equal, whence the time difference $t = t_l - t_s = 0$.

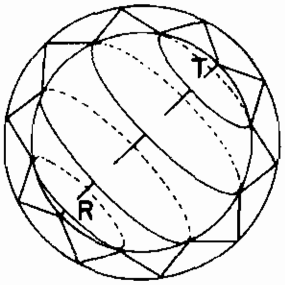

Fig. 2.

The time required for HF radio waves to make one transit around the globe has been measured on a great number of occasions and found to be fairly constant at $t = 0.13788$ seconds. The transit is made via a multihop propagation between the ionosphere and earth, as in the ideal case portrayed in Fig. 1.

The magnitude of the time separation between the long- and short-segment paths provides some indication of the fading expected at different locations. Severe fading would result when the two waves arrive sufficiently out of phase to produce destructive interference, with markedly distorted signals. Thus the least interference between the two signals may be found at the sites T and R. (The fading which occurs because of interference between the ordinary and extraordinary rays, lateral reflections to the receiver, and polarization, will not be considered here.)

Maximum fading between the signals of the long- and short-segment paths probably may be expected at first-hop distances from the antipode, where the time separation, Δt, is small, and the signal intensities are approximately equal. Appreciable fading would not be expected at the antipode, since all geometric paths from T are equal. In practice, however, the electrical paths to the antipode are of different lengths for different rays, because of differences in the dielectric constant, the presence of ionospheric discontinuities, differences between day and night paths, and so on.

Several interesting aspects of the ideal model may be noted. With two perfect, concentric, spherical reflectors, energy radiated from a source T is reflected indefinitely without loss. Thus, the entire volume between the two spheres may become uniformly filled with the radiated energy, which is confined without loss between the two spheres.

It should be noted that in Fig. 1, only one ray path was shown in the T-m_1-m_2-R plane. However, a number of rays may propagate from T to R provided an integral number of reflections takes place with each. For example, assume that Equation (1) is satisfied. If the central angle is now halved, the number of hops is doubled and, in general, $ma = 2m(a/2) = \ldots = (m\,n)\,(a/n) = \pi$. When no energy is lost or dissipated by the spherical reflectors, emissions at any frequency in the electromagnetic spectrum, radiated at angles satisfying Equation (3), arrive at the source T after one spherical transit. Any ray not arriving at T at the first transit will arrive there (approximately, if not exactly) at some later time.

As perfect specular reflectors are non-existent, the energy loss arising from multiple reflections within the two concentric reflectors should be examined. If the reflectance at each reflection point is r, the final intensity is given by

$$I = I_0\,(r)^m \tag{4}$$

where I is the final intensity; I_0, the initial intensity, and m the number of reflections since emission. An indication of the decrease in intensity for various values of reflectance and after a given number of reflections is given in Table 1.

THE IONOSPHERE AND THE EARTH

The actual ionosphere and earth depart from the simplified model described above. Although any particular ionic layer is not spherical, its average departure from sphericity (about 50 km in a radius of 6550 km) is about 0.7 per cent for the E, $F1$ and $F2$ regions. The ionic surface contains height, density and slope discontinuities, especially across the sunrise-sunset line, in the vicinity of the geomagnetic equator and in polar regions. A slope discontinuity, by changing the angle of incidence and reflection, will direct a ray away from an expected multiple image point, m_1.

TABLE I

Effective Reflectivity After Multiple Reflections*

n	*Reflectivity*			
	$r = 0.8$	$r = 0.9$	$r = 0.95$	$r = 0.99$
1	0.800	0.900	0.950	0.990
5	0.328	0.590	0.774	0.951
10	0.107	0.349	0.599	0.905
15	0.0352	0.206	0.465	0.860
20	0.0115	0.122	0.359	0.817
25	0.0038	0.072	0.277	0.778
30	0.0012	0.042	0.215	0.740
35	0.0004	0.025	0.166	0.704
40	0.0001	0.015	0.132	0.669

* $R_{eff} = r^n$, where: R_{eff} = effective reflectivity
r = reflectivity
n = number of reflections

Another discrepancy which may be important for antipodal radio wave propagation on the earth is the very low electron concentration existing in the winter polar ionosphere. Near the winter pole direct sunlight is absent for some months even at ionospheric altitudes. Under these conditions the electron density falls to low values, and the critical frequencies of the E- and F-layers become rather small. The outer sphere of the ideal model (Fig. 1) then contains a "circular hole" through which HF radiation may escape into space. The radius of the missing spherical zone on the earth is about 15° and represents about 2 per cent of the area of the ionosphere.

The effect of the ionospheric hole may be visualized from Fig. 3. With the outer sphere essentially missing within the winter polar circle, radio waves transmitted at the winter pole would escape directly into space. No ionospheric reflections would be possible, and the waves could be received only within the ground-wave, radio line-of-sight, and diffraction regions. Tangent HF rays from the transmitter would not encounter a reflective ionic layer. For a transmitter at the winter pole, transmitted HF energy can escape into space.

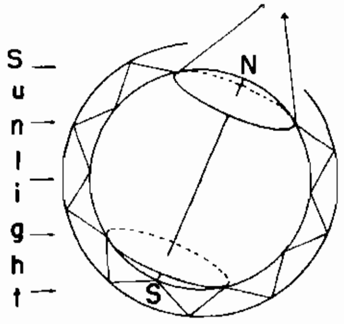

Fig. 3.

It should be noted that by the reverse of this mechanism, extraterrestrial emissions either from natural or satellite transmitters may be channelled to the antipodal receiver.

If the transmitter were at the summer pole and the receiver at the winter pole, somewhat similar conditions would exist. In this case, all energy transmitted at an appropriate frequency could be successively reflected by multihop as the wave was propagated towards the winter pole. Near this pole, however, the lack of a reflecting region for HF radio waves would permit the energy to escape into space instead of being returned to the earth at the pole itself (see Fig. 3). It should be noted that the further the location of the transmitter and receiver from the winter pole, the smaller the fraction of energy escaping by this mechanism.

The preceding example represents an extreme. Most transmitters on earth are at considerable distances from the geographic poles. Thus, while the peculiarities of the polar ionosphere present some problems, they may not pose a major obstacle in antipodal propagation. While the winter polar ionosphere represents a hole in the HF reflector, the high latitude ionosphere during the equinoxes presents absorption problems. If equinoctial absorption occurs simultaneously in both polar regions, spring and fall may offer the greatest difficulty to antipodal propagation. In general, however, if a sufficient number of rays are directed to the antipode, adequate reception will be possible.

It should be recognized that with the ideal model, radiation at all wavelengths may be reflected. In practice, however, the normal diurnal variation of the ionosphere will limit the efficiency of propagation of different frequencies. These limitations arise from the daily variations in the electron concentration and in the altitude of the maximum electron density. In operating practice these variations may be roughly interpreted in terms of changes in the maximum and lowest usable frequencies, respectively. If at any particular ionospheric refraction point the operating frequency exceeds the local penetration frequency, a portion of the wave energy escapes. Similarly with absorption: if the operating frequency is locally absorbed, a portion of the wave energy is lost. If for the entire path sufficient energy penetrates the layers, the MUF is exceeded and the possibility of reception of the radiated energy is greatly reduced. Likewise, if for the entire path absorption is appreciable, the LUF has not been exceeded and reception of the radiated energy again becomes difficult.

In general, the ionosphere is inhomogeneous and anisotropic, both with respect to space and time. Its electron density at some locations or on some occasions may be low enough to allow energy from the incident ray to escape, either partially or completely, or to be absorbed. Whether this condition will negate successful antipodal propagation depends upon the fraction of energy lost or absorbed. Ultimately, of course, the occurrence of favorable periods is a function of season, time of day and portion of the solar cycle.

The initial model considered two concentric specular reflectors. For very low frequencies, where reflection may be considered to occur at the lower boundary of the *E* layer, this model probably describes actual propagation conditions. The outer reflector appears sufficiently smooth and regular everywhere except in the winter polar region. Thus, with VLF and LF, antipodal propagation possibilities are probably good throughout the 24-hour period, and during both winter and summer.

Consider a second model where the reflectivity of one hemisphere of the outer sphere differs from that of the other. The latter case better approximates the true characteristics of the earth and the ionosphere, where the day and night ionospheres have somewhat different properties.

This case applies more aptly to HF propagation where hemispheres having distinct reflectivities must be carefully considered. The ionospheric layers in the illuminated and the dark hemisphere differ not only in electron density but in altitude. In general, a variety of abnormalities in reflectivity occur, caused by: different ionic densities; abnormalities such as sporadic E, trans-equatorial F, and auroral ionization; different layer altitudes; different refractivity gradients; layer tilts; and so on.

Thus, for HF, the height of the reflector (external sphere) is different over the day and night hemispheres, while the twilight ionosphere may be considered as a transition zone between the two, with the result that the antipode for HF may not be a true optical focus, but rather an aberration.

Nonetheless, and in spite of these many potential difficulties, a number of isolated examples indicate that an antipode focus exists much more frequently than commonly thought. The potential of antipodal propagation for communication purposes is such as to warrant further investigation.

ROUND-THE-WORLD SIGNALS

A fair number of studies have been made on "round-the-world" propagation. These investigations were made on a comparison of the long- and short-segment great circle path signals emanating from a given transmitter.

Initial investigation by Quaek (1926), Quaek and Morgel (1926, 1927, 1929), Eckersley (1927) and Taylor and Young (1928) were devoted mainly to determining the time interval, t, elapsing between the reception of the short- and long-segment radiations. The results indicated discrepancies in Δt exceeding 5 per cent. However, careful examinations with more refined equipment later indicated that Δt had a constancy within 0.004 seconds (Hess, 1948, 1949).

The early experiments prompted von Schmidt to undertake (1934–1936) a theoretical analysis of propagation in the spherical shell existing between two concentric spheres. He formulated the sliding-wave hypothesis of ionospheric propagation to clarify the observations. In von Schmidt's (1936) sliding-wave theory, the transmitted wave propagates along the lower boundary of an ionospheric limiting surface. Just as a ground wave travels with constant velocity along the ground, the sliding wave was assumed to travel as a surface wave along the lower surface of the ionosphere. This wave radiated continuously, and at a definite angle, from the ionosphere to the earth.

Von Schmidt's theory was in contrast to the multiple-reflection theory which ultimately superseded it (Hamburger and Rawer, 1947; Lassen, 1948). The latter merely represented a multihop path between the ionosphere and earth as shown in Fig. 1. While both theories were current, a series of practice observations was initiated in Germany to determine which hypothesis could best clarify the observations. The investigations provided very accurate values of Δt. From these measurements, it was found that the distance between the transmitter and receiver could be obtained with accuracies of ±25 km, provided that the separation between transmitter and receiver was at least 1000 km. The recordings also confirmed earlier results which indicated that HF signals could be detected at very distant receivers.

In the course of the observation, it was discovered that in addition to the short-segment and long-segment transmissions, signals which had made more than one transit around the earth were detectable. Several instances were found where signals were received after a third or fourth transit around the globe.

An indication of the size of the antipodal observation area has been given by various researchers. Whales (1956) predicted that the antipodal area could have a radius of about 500 km centered on the antipodal point. His conclusions were based on angle-of-arrival measurements. It was assumed that the ionosphere acts as a diffuse reflector, and that impinging rays may be deviated by angles of up to 0.5°, per reflection. Round (1925) considered that antipodal signals should be received within a radius of about 1000 km from the antipode; however, the results do not confirm the existence of such a large area. Guierre (1920) found that for very low frequencies signal strengths decrease at about 1000 km from the antipode.

Guierre studied field intensities of radio waves, radiated from Lyon, at the antipodal point near Chatham Island. Day and night intensities were practically identical. One test indicated that when the Lyon transmitter was received strongly at the antipode, a diminution in signal strength was observed up to about 800 km from the antipodal point. On another occasion a second intensity maximum was observed about 600 km from the antipode, while at the same time lower signal intensities were observed between the two sites. The effect may perhaps be explained as a multiple image formed one ground reflection away from the antipode.

Round and others (1920) noted that even within an area of about 1000 km from the antipode, fading could become sufficiently strong to make the signals unintelligible. However, when a directional antenna was employed, it was possible to reject the interfering signal (which arrived at an azimuth of close to 180° from the stronger signal) and thus noticeably improve the readability.

There are several possible mechanisms for causing the observed interference and fading. For a non-antipodal receiver, the superposition of radio rays arriving from both the short- and long-segment great-circle paths can add characters and, on occasion, make the signal completely unintelligible, particularly with high-speed messages.

Antipodal reception has been observed sporadically. Observation from Pyongtaek and Chunchow, Korea, in 1957 indicated that voice and CW were received from Brazil and from naval traffic in Brazilian waters. Reception generally was possible between 03–08 and 17–24 LST. In late 1956 and early 1957, tests at Seoul, Korea showed that reception of 100- to 200-meter radiations originating in South America was possible "every day or so." Generally, however, the tests were conducted for rather limited time periods.

ANTIPODAL PROPAGATION

Before discussing some general features to be expected in antipodal propagation, the identification of the antipode on earth might be mentioned. The location of antipodal pairs may quickly be discerned from the definitive relationships $\theta = \theta_a$, and $\theta' = 180° - \theta'_a$, where

θ = latitude (°N)
θ' = longitude (°W)
θ_a = antipodal latitude (°S)
θ'_a = antipodal longitude (°E)

In general, no large continents seem to be antipodal, a fact which may account for the lack of reports concerning this type of propagation.

The hours of reception of signals from the antipode require study. Many reports have been prepared regarding reception of radio waves over very long distances, but the stations studied were not strictly antipodal. The results clearly indicate that radio-wave radiations at distances of 10,000–15,000 km from the transmitter may be received without difficulty for about 4–6 hours daily. When the stations were more closely antipodal, reception was possible for 5–7 hours daily (Hess, 1938, 1939). Guierre (1920) reported 24-hour reception of the radiated transmissions from the antipodal point. Whether the reception occurred constantly or sporadically throughout the day is not known. It should also be noted that the antipodal image of Sputnik I was received on a number of transits; but the satellite constitutes a special case, (Wells, 1958; Manning, 1958), particularly for transmissions which occurred outside the ionosphere.

FADING

While fading, at times severe, has been known for some time in reception over very long distances, few reports indicate the presence of fading at the antipode. Fading over long paths may arise from interference between the short-segment and long-segment great circle waves at the receiver site.

At the antipode, where the geometrical paths are equal, fading may be produced by variations and fluctuations of the refractive indices along the path. This type of fading, however, would probably be extremely rapid, and minor in comparison with other propagation effects. Nevertheless, when extremely high-speed transmissions are involved, or if small phase shifts are to be measured, the small differences in electrical length of the various paths may be significant. Obviously, the employment of directive antennas oriented along the most favorable path will diminish or entirely remove any potential interference between the daylight and darkness rays.

Antipodal reception would not require the utilization of large, expensive antennas. Long wire, rhombic, and a variety of omnidirectional antennas have been utilized for very-long-distance propagation studies, and would be suitable for reception at the antipode. When fading caused by destructive interference between the day and night waves is severe, use of directional antennas will usually remove the fading and permit unambiguous reception of the desired signal.

While relatively few results are available on antipodal propagation, the few tests which have been undertaken indicate that omnidirectional antennas of relatively simple design are effective. In view of the paucity of data on this topic, however, a study of the comparative performance throughout the day of both omnidirectional and directional antennas is required.

Direction finding at very long distances has been attempted on many occasions. In general, the results seem to be characterized by a definite difficulty in choosing a bearing. At a frequency of 10 kc/s and at distances of about 19,000 km from the transmitter, tests have indicated (Namba, Iso and Ueno, 1931)[1] that the bearing angle is a function of the time of day. In this instance angles for the closely antipodal signal changed markedly with time. When the Monte Carlo transmitter was monitored at Tokyo (true bearing 90°) the DF reading showed an apparent arrival of the wave from the West (270°) during the morning. At about 1000 LST, no bearing could be measured. Later, the signal arrived from about 45°. The bearing then gradually veered eastward, passing through 90° and becoming 150° at local sunset. After sunset, measured DF values slowly returned to the true bearing of 90°.

The effect may be easily explained if it is accepted that the wave propagated principally in the dark hemisphere. Although Tokyo and Monte Carlo are not strictly antipodal, the change in bearing angle indicates that the direction of the strongest wave more or less followed the sun, and moved around the earth with the twilight, dark, and daylight zones.

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[1] S. Namba, E. Iso, and S. Ueno, "Polarization of High Frequency Waves and Their Direction Finding," *Proc. I.R.E.*, Vol. 19, p. 2000, (1931)—Editor.

SUMMARY

Antipodal reception is clearly possible, since it has been observed in the past, at least for limited hours of the day. Further, on theoretical grounds its use as a standard procedure seems promising, although several comprehensive studies are needed. Thus, the number of hours per day during which reception is possible is not fully known, and it is uncertain whether omnidirectional or directional antennas (possibly rotated during the course of the day) are preferable; and whether fading or auroral absorption is in reality a difficulty. The investigations could indicate the potential of the method and possibly determine what antenna improvements would optimize the results.

From the preceding discussions, it is clear that in principle the antipodal focus may be utilized to receive signals (in the range 15 kc/s to perhaps 60 mc/s) radiated within the spherical shell bounded by the earth's surface and the ionosphere. In practice, however, the actual state of the bounding surfaces will influence the intensity of the refracted signal and the possibility of reception. Even if calculations are made, the anticipated signal strengths may depart appreciably from those later experienced.