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Abstract

An experiment is described which uses a satellite-borne, two-frequency HF beacon to perform a synoptic investigation of ionospheric ducting. The expected ducting modes are described qualitatively and quantitatively using the AFCRL ray tracing computers. System calculations, based upon estimated ionospheric parameters, are contained in the Appendix.

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Investigating Ionospheric Ducting with the Orbis Beacon

1. DESIGN AND PURPOSE

Early in 1964, the ORBIS experiment will be launched. ORBIS, the mnemonic for Orbiting Radio Beacon Ionospheric Satellite, is the first attempt to perform a synoptic study of near critical frequencies transmitted from within the ionosphere. Since ORBIS will be riding 'piggyback' on an established and scheduled experimental vehicle, over which AFCRL has little control, orbital elements cannot be predicted with certainty. However, based upon past experience, it can be estimated that the inclination of the orbital plane with respect to the equator will be about 75°, the apogee about 230 NM and the perigee about 110 NM; and the range into which these may be expected to fall are 65° to 90°, 380 to 150 NM, and 80 to 180 NM respectively.

The ORBIS payload consists of a two-frequency beacon transmitting continuously on frequencies of 5.002 and 10.004 Mc, each of one watt nominal output (Figure 1). In addition, a few milliwatts will be 'leaked' on 15.006 Mc for tracking purposes. Because of the low orbital height, the lifetime of the vehicle will not exceed four to six weeks. Because of the necessity of optimizing life and output versus weight, it has been found necessary to limit the battery life to 20 days. In order to facilitate recognition in a crowded signal environment, the signal will be narrow band frequency modulated. Figure 2 shows the audio modulation as a function of temperature.

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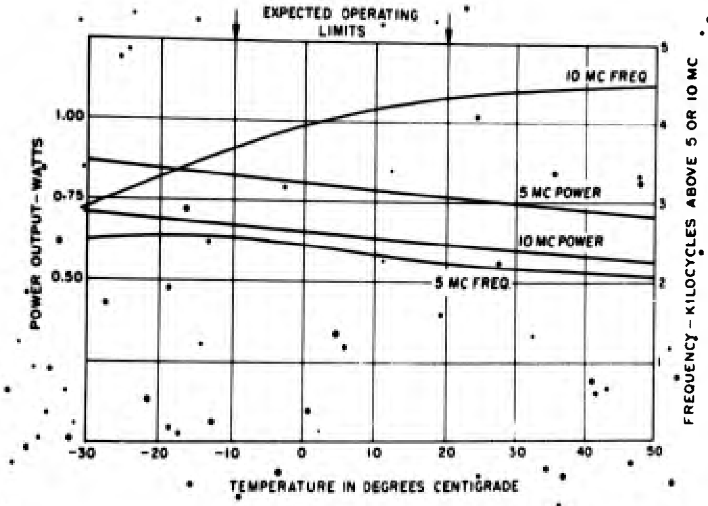

Figure 1. Power Output and Frequency as a Function of Temperature

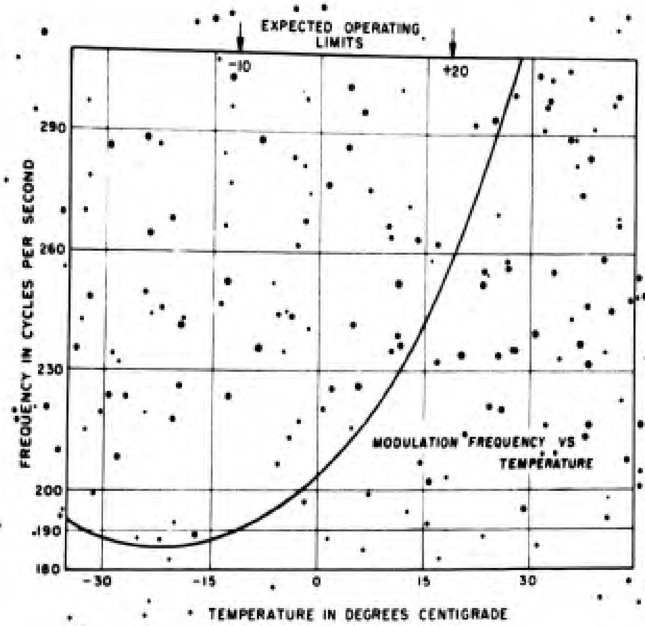

Figure 2. Audio Modulation as a Function of Temperature

The narrow band modulation will efficiently enable signal enhancement by audio filtering.

The method of ORBIS is to provide two beacon frequencies, one of which is generally above the daytime plasma frequency and the other beneath it. Since the plasma frequency is a function of time of year, time of day, magnetic activity and geomagnetic latitude, some interesting effects can be predicted. For instance, the signal may be trapped at the point of transmission, ducted many thousands of miles and refracted down to a receiving station at one position, and ducted past another at a similar geomagnetic position. Since the signal will be monitored at many locations, these interesting 'skips' and 'hits' may be analyzed in synoptic fashion and a composite picture of the macroscopic structure thus postulated.

An earlier satellite-borne beacon experiment, Nora Alice, was performed by the University of Illinois (Swenson, 1962) in the latter part of 1961 and early part of 1962. In this experiment, a 20 Mc beacon was placed in a polar orbit by Discoverers 32 and 36. These orbits were as follows:

	Launch Date	Period Minutes	Apogee Miles	Perigee Miles	Inclination Degrees	Time in Orbit Days
Discoverer 32	Oct 13, 1961	90.8	246	147	81.7	31
Discoverer 36	Dec 12, 1961	91.5	280	148	81.2	86

The intent of the Nora Alice experiment was quite different than that of ORBIS, in that it was largely concerned with the geographical distribution of scintillation-producing ionospheric irregularities. Even though the scientific objectives of Nora Alice and ORBIS are quite dissimilar, the practical considerations such as beacon design, orbital parameters, and data collection techniques will be generally related. For example, the same basic beacon design will be used. The ORBIS beacon was built for the Radio Astronomy Branch by Professor G. W. Swenson Jr. who also designed and built the University of Illinois package. All data will be collected by ground receiving stations, and dispersed throughout the United States and Europe. Indeed, anyone who owns a receiver is a potential collaborator in the experiment. The rewards of the experiment can be great since a wealth of data covering ionospheric ducting may be obtained. This data could have a marked effect upon appreciation and use of the ionosphere as a communication medium.

2. IONOSPHERIC DUCTING

Since the altitude of the beacon may be anywhere from 80 to 380 nautical miles, the transmissions will occur most of the time within the ionosphere. Inasmuch as the height and density of the various inospheric regions vary as a function of

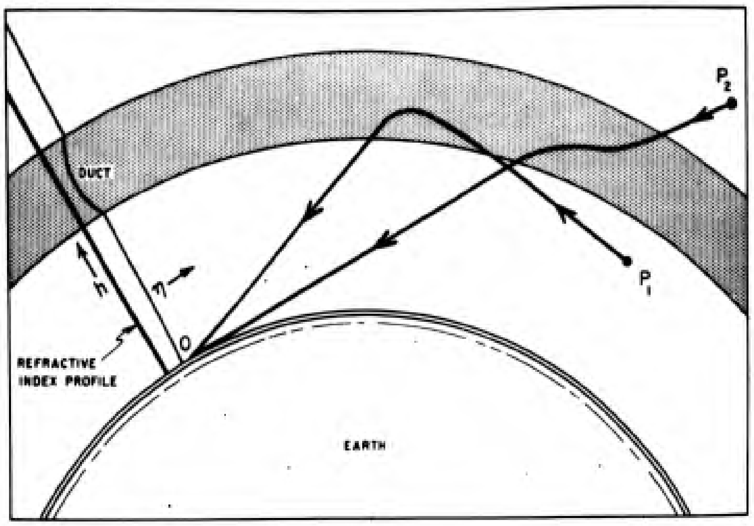

Figure 3. Ducting in a 'Trough' in the Refractive Index Profile (maximum in electron density profile)

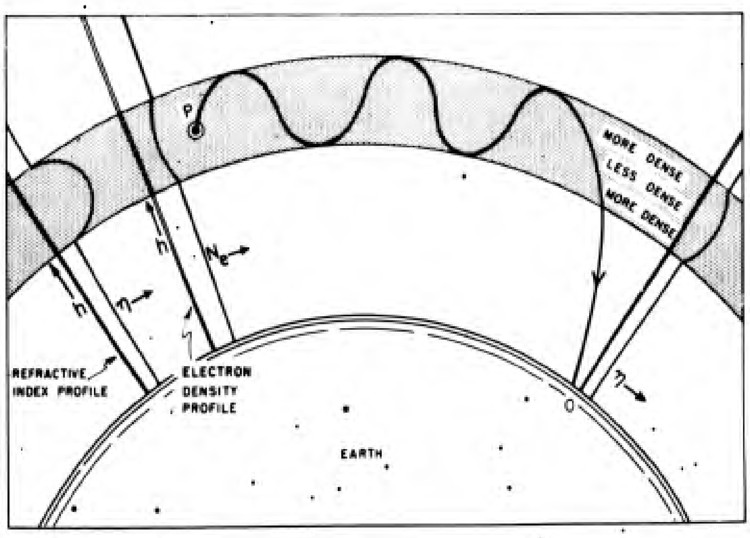

Figure 4. Ducting in a 'Trough' of the Electron Density Profile

latitude, time of day, time of year, solar and lunar tidal conditions, as well as geomagnetic activity, preliminary analysis of ionospheric positions or conditions must necessarily be qualitative rather than quantitative. With this in mind, the general ducting mechanisms may be examined.

A variety of ducting mechanisms could lead to anomalous propagation of radiowaves between a satellite and the surface of the earth. Propagation ducts occur at minima and maxima of the index of refraction profile in the ionosphere and troposphere, at the curved boundary between the ionosphere and troposphere, and along field-aligned irregularities in the magnetosphere.

The ducting due to an index of refraction minimum (Rawer) is represented in Figure 3. As the ray enters a region of decreasing index of refraction, it is bent away from the normal according to Snell's law. When it moves into a region of increasing index of refraction, it is bent toward the normal. Thus a ray originating below the duct (which could be a shell of maximum ionization), with appropriate launch angle, could reach an observer at 0. In a similar fashion, a ray originating above the duct at P_2 could be laterally deviated by the duct to the point 0 beyond the optical horizon.

The ducting due to an index of refraction maximum (which could be a shell of minimum ionization in the ionosphere) is represented in Figure 4. A ray launched at P might be trapped in the duct. If a non-uniformity in the index of refraction profile existed along the duct, a 'window' could be opened which would allow the ray to reach an observer at 0. For example, if the index of refraction maximum were to diminish beyond a certain value as one moved along a ray path, the ray would escape from the duct and emerge up or down depending on the gradient and the initial launch angle of the ray. In the downward case, this escape from the duct would permit reception of the ray at 0.

The case of ducting at the bottom of an ionospheric layer is represented in Figure 5. A ray launched at P at an appropriate angle would penetrate the ionosphere at (a) and be reflected out at (b) and proceed undeviated to (c). If the layer were uniform, the ray would continue indefinitely in this manner. A change in the electron density of the ionosphere beyond (c) could cause a ray to emerge at (d) and continue to an observer at 0.

In the magnetosphere in the frequency range up to 10 Mc, a ray launched along a magnetic field line would have a curvature due to refraction index changes brought about by changing electron density and changing magnetic field intensity (Booker, 1962). The curvature of the ray is not sufficient to follow the field line unless there exists field-aligned irregularities in electron density. In the presence of such irregularities, a ray could be ducted along the field line.

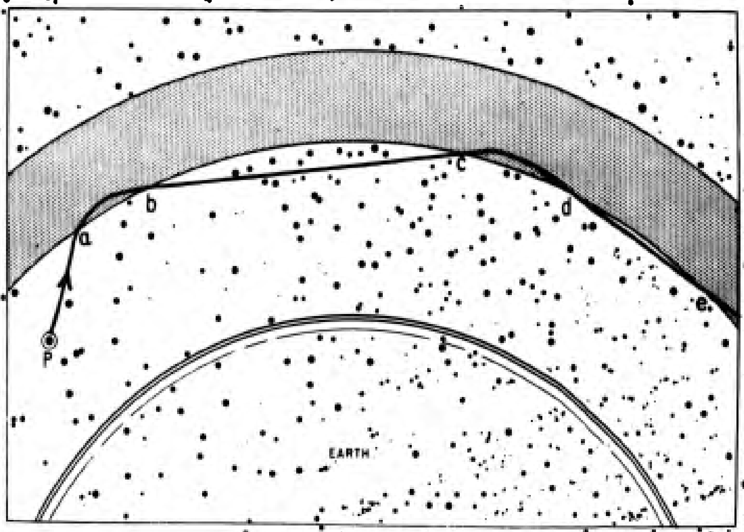

Figure 5. Ducting at the Lower Boundary of an Ionospheric Layer

3. DUCTING CALCULATIONS

In order to illustrate the ray tracing methods to be used in analyzing the data from the ORBIS experiment, consider Figures 5 and 6. Figure 5 is a qualitative picture of ray ducting in an ionosphere with electron density variation in the vertical profile only. It is inconvenient and inexact to present this situation in spherical coordinates because of the difference in scales required. Instead, a coordinate system has been chosen which essentially 'unbends' the curved representation and represents the curved surface of the earth as a straight line segment on the abscissa (Wong, 1960). Figure 6 is a ray tracing computed for the case of Figure 4 in such a coordinate system. For ease of visualization of the ray pattern, this axis is greatly contracted, since the ray paths of interest lie within a range of several hundred kilometers in the vertical direction and several thousand in the horizontal. As a consequence of the circle-to-line coordinate transformation, undeviated rays (straight lines) emerge as parabolas. Each curve in Figure 5 represents a ray path. The ionospheric model used is based on rocket soundings with an electron density peak at 300 kilometers and a critical frequency approximately one fourth the ray frequency. The electron density varies vertically but not laterally. For this model it is seen that rays launched with angles between -0.03 and +0.03 radians will be trapped in the ionospheric duct and propagated long distances. Lateral electron density variations could divert some of these rays to earth.

Now consider Figure 7. The electron density profile used here has the same

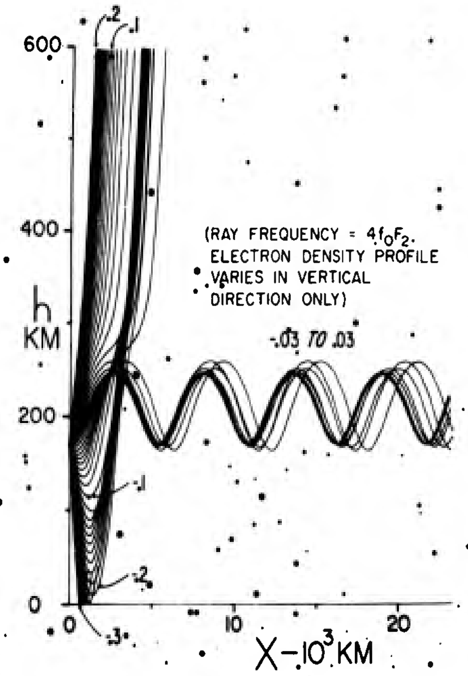

Figure 6. Ray Tracing

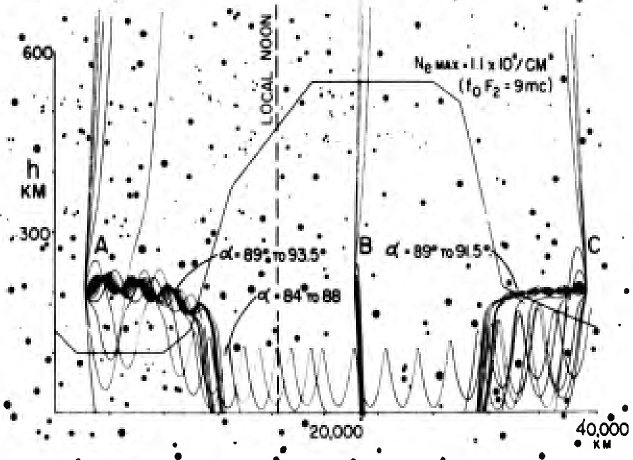

Figure 7. Ground Reception of Ducted 10 Mc Radio Signals from Satellite due to Day-Night Variation of Ionospheric Electron Density

shape as that in Figure 6, but f_oF_2 (that is, Ne max) varies along the ray path. This variation is shown on the graph and is representative of that found on a great circle path around the earth from night to day to night areas. Points A, B, and C are to be considered as satellite positions from which rays are launched. The critical frequency f_oF_2 varies from a minimum of about 4 Mc near point A, to a maximum of about 9 Mc near point B. The plotted rays are those of a 10 Mc signal. It is seen that ducting occurs from the launch point A to the region where the Ne max curve begins to rise. (This is similar to the situation shown in Figure 6). When the Ne max and the slope of the electron density profile begin to increase, the rays are refracted to lower altitudes. As these increases become sharper the rays are precipitated to the ground. A similar situation occurs for rays emanating from launch point C. One should then expect observation on the ground of satellite launched signals ducted over long distances. Thus observations along the horizon could be expected around sunrise or sunset, when the satellite is over the night side. A somewhat similar ducting situation could occur due to the latitudinal variation of f_oF_2 for propagation along a meridian line.

4. OTHER DUCTING MECHANISMS

Anomalous propagation due to tropospheric ducting is expected to be much less important than that due to ionospheric ducts since in the frequency range of interest, ionospheric variations in index of refraction are much higher than tropospheric variations. The possibility of such ducting should be kept in mind for low elevation angles. (Rawer, 1962). Ducting due to field-aligned irregularities would be difficult to observe since observations of such ducting require that the satellite be along the same field line as the receiver and that an irregularity in ionization density be along the field line. Such conditions could only be fulfilled for a very short time due to the rapid motion of the satellite. Since the satellite is not expected to come below the ionosphere, any ducting due to the boundary between the ionosphere and troposphere would be a complex phenomena that might involve reflections from the surface of the earth and then ducting by the layer. If a 'valley' in the ionization profile exists between the E and F layers, anomalous satellite-to-earth propagation might be observed as mentioned previously (Figure 4).

5. SUMMARY

An experiment is planned in which a satellite-borne beacon is to be orbited in the ionosphere between 80 and 360 miles in height. Every effort will be made to favor the low end of this region; however, since ORBIS will be merely a 'hitch-hiker', it must go where the vehicle takes it. It is anticipated that 5 and 10 Mc (nominal) signals will be propagated by ducting mechanism as well as by sky wave and scatter modes. It will be subject in a statistical fashion to refraction, diffraction, multipath effects, absorption, and free space attenuations. Its entrance into and emergence from the duct or ducts will also be a statistical function, since they will be dependent upon ionization and other processes which are only somewhat predictable. However, ray tracings indicate the approximate parameters under which the phenomonon can be expected. The possibilities of exploring the temporal effects of the upper atmosphere processes remain stimulating and encouraging.

Appendix

1. INTRODUCTION

The signal is attenuated because of distance, refractive effects, and absorption. Ducted signals, such as those shown in Figure 5, usually have a lower intensity on reaching the ground than would signals travelling the same free-space distance from a signal source. (It is assumed absorption effects have already been subtracted out). The reason for this is that the refractive properties of the ionosphere 'fan out' the ray pattern. The attenuating effects of distance and refraction can be combined by using an 'effective distance'. This parameter signifies for a given ray path the free-space distance which would give the same signal attenuation. An effective distance can be estimated for Case A in Figure 7. The ducted rays travel a distance of S = 9500 from the satellite to ground. On the ground they are spaced, in the plane of the figure, over S_1 = 1300 Km. Perpendicular to the page, the spread will be considered to be due to just free space attenuation. Rays subtending an angle $\alpha = 4.50^{\circ}$ perpendicular to the page will spread over an arc length of S_2 where:

$$S_2 = 9500 \text{ Km } (4.5^{\circ} \; \frac{\pi}{180^{\circ}}) = 750 \text{ Km} . \qquad (1)$$

Assuming the area A on the ground covered by these rays to be roughly an ellipse, the effective distance, D, is defined by:

$$D^2 = \frac{A}{\Omega} = \frac{\pi\left(\frac{S_1}{2}\right)\left(\frac{S_2}{2}\right)}{\pi\left(\frac{\alpha}{2}\right)^2} = \frac{S_1 S_2}{\alpha^2} \quad (2)$$

where Ω equals the solid angle subtended by ray bundle at source and the other symbols have already been defined. Substituting S_1 = 1300 Km, S_2 = 750 Km, and α = 4.50° into Eq. (2), the effective distance, D, approximately equals 13,600 Km. The effective distance, D, is related to the free-space distance S for this case by:

$$\frac{D}{S} = \frac{13{,}600 \text{ Km}}{9{,}500 \text{ Km}} \approx 1.4$$

or

$$D \approx 1.4S \quad (3)$$

The relation shown in Eq. (3) will be assumed true for any distance S considered in the following analysis of case A.

2. ANALYSIS OF CASE A (Figure 7)

It is desirable to observe the satellite signal above background noise for considerable distances beyond the optical horizon. For the case under discussion, it will be shown that the signal should be observable above noise at a range of 4000 Km.

a. The optical horizon for a satellite at an altitude, h = 300 Km (the height F_2 of the maximum electron density of Figure 7) is about two thousand kilometers. Using a path length range of 4000 Km, the effective distance from Eq. (3) is then:

$$D \approx 1.4S = 1.4\ (4000) = 5600 \text{ Km} \quad (4)$$

b. The sky temperature T at 10 Mc is taken to be 10^6 degrees absolute. The equivalent brightness B is then:

$$B = \frac{2\,KT}{\lambda^2} = \frac{2 \times 1.38 \times 10^{-23} \times 10^6 \text{ janskys}}{900 \text{ meters}^2 \text{ radian}^2}$$

or

$$B \approx 3 \times 10^{-20} \frac{\text{janskys}}{\text{radian}^2} \qquad (5)$$

Taking one square radian as an angular aperture of a typical receiving antenna the noise power received at this antenna would be 3×10^{-20} janskys. It is required that the satellite signal be considerably above this level.

c. The intensity of the satellite signal having a power output of 0.7 watts (Figure 1) at an effective distance of 5600 Km (ignoring absorption) is:

$$\frac{0.7 \text{ watts}}{4\pi\,(5600 \text{ Km})^2} = \frac{0.7 \text{ watts} \times 10^{-12}}{4\pi\,(5.6)^2\,(\text{meters})^2} = 1.8 \times 10^{-15} \frac{\text{watts}}{\text{meters}^2} \qquad (6)$$

For a receiver bandwidth of 1 KC this corresponds to:

$$\frac{1.8 \times 10^{-15}}{10^3} = 1.8 \times 10^{-18} \text{ janskys} \qquad (7)$$

d. The absorption can be calculated from:

$$\text{db (loss)} = 20 \log \epsilon^{\int k dx} \qquad (8)$$

where: 1) the integration is taken over the ray path
2) k the absorption coefficient is approximately

$$k = \frac{2\pi e^2}{mc} \cdot \frac{n \nu_c}{\omega^2} \qquad (9)$$

with e being the electron charge, m its mass, c the velocity of light, n the electron density ν_c the collision frequency, and ω the angular frequency of the radio wave. Both n and ν_c are functions of position. For the case under discussion, ducting occurs at around 200 Km and (A, Figure 7) on a night side path. Taking reasonable average values of $n = 2 \times 10^5$ electrons/cm^3 and $\nu_c = 2 \times 10^3$/sec with a path length of 4000 Km, the absorption in the duct can be estimated from Eqs (8) and (9) as about 7 db, or a factor of five. Adjusting the signal for this loss yields:

$$\text{Signal} = \frac{1.8 \times 10^{-18} \text{janskys}}{5} = 3.6 \times 10^{-19} \text{ janskys}$$

e. Upon emerging from the duct at a shallow angle, the rays will, in the D and E regions, suffer considerable further attenuation. For early morning, a 10 db loss should be sufficient to account for this. Now with the post-detection filtering techniques to be used on the signal, a 10 db signal enhancement is expected. Assuming this enhancement equals the E and D absorption, the signal to noise ratio from the above calculations is:

$$\frac{\text{Signal}}{\text{Noise}} = \frac{3.6 \times 10^{-19} \text{ janskys}}{3 \times 10^{-20} \text{ janskys}} \approx 10$$

The signal should thus be observable above noise at a range of 4000 Km.

3. 5 MC NOISE

In preparation for this experiment, a special 5 Mc receiver system has been set up to measure the radio noise background. During the day the received signal level is low, being primarily local man-made interference. The cosmic background and equatorial thunderstorm noise is greatly attenuated by D region absorption. As the solar illumination of the ionosphere decreases, the cosmic component increases but is exceeded after sunset by E and F propagated equatorial noise. Directional antenna patterns are being constructed to study the possibility of cancellation of the equatorial noise.

Acknowledgments

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