REFLECTIONS

NIGHTTIME MEDIUM WAVE PROPAGATION BY IONOSPHERIC REFRACTION

by Randy Seaver

1. INTRODUCTION

The propagation of medium frequency radio waves by ionospheric refraction commonly called "skywave" propagation, is a very complex subject that has baffled, confused and intrigued propagation experts and medium wave listeners/DXers alike since the 1920's. Even today, there is a considerable range of opinion concerning the question:

> "Which ionospheric layers or regions refract medium frequency radio waves?"

The DX club technical literature presents a diverse array of opinion, including:

In G. Nelson's comprehensive article on "Medium Wave Propagation" (Reference 1), Figures 3a-1 and 3a-2 imply nighttime refraction form the F layer at an altitude of 300 kilometers. In the text, Nelson states:

> "Most of this highly absorbing ionization (in the D and E layers) disappears as soon as the ionosphere is no longer in daylight...and this region rapidly becomes transparent to MW signals after local sunset."

G. Nelson's articles on "MW Signal Paths" (Reference 2) and "Geographical Patterns in BCB DX Reception during Periods of High Auroral Activity" (Reference 3) indicate partial reflection by the E layer and reflection by the F layer. G. Nelson's article on "Skyline Blockage" (Reference 4) discusses the "normal night E" and "sporadic E" regions and notes the that the critical frequency of the night E layer often falls within the medium wave band.

Fr. Jack Pejza's excellent article, "A Beginner's Guide to the Ionosphere" (Reference 5), describes the composition of the ionosphere, discusses the refraction and absorption of radio waves by the ionosphere, and notes:

> "Nighttime skywaves frequently penetrate the E layer and are reflected from the F layer, particularly at the high frequency end of the MW band, and at nearly vertical angles of incidence."

F. Dinning's article, "Factors Affecting Propagation of the Medium Frequency Broadcast Band" (Reference 6), states that the night E layer contributes to MW signal attenuation, while the F layer is responsible for nighttime MW propagation.

Finally R. Schatz's recent article on "Medium Wave Ionospheric Propagation" (Reference 7) claims that E layer reflection is responsible for most medium wave long distance propagation.

The serious reader is urged to read the referenced articles to ascertain the context of the above quotes, statements and inferences.

The many technical books available on the subject of ionospheric propagation generally derive the magnetoionic equations, describe the effects of solar radiation on the Earth's atmosphere (including the ionosphere), describe the influence of the ionosphere and the Earth's magnetic field on radio wave propagation, and develop methods of estimating radio wave signal strengths at a receiver remote from a transmitter. Two of the best books are K. Davies' "Ionospheric Radio Propagation" (Reference 8) and Y. Al'pert's "Radio Wave Propagation and the Ionosphere" (Reference 9). However, there is a notable lack of meaningful discussion in these sources that adequately describe medium wave propagation.

The technical journal and technical report literature contains more specialized and detailed information on a wide range of subjects, but there are relatively few articles and reports that treat medium wave propagation. Two particular reports, one by Barghausen, Finney and Fisher entitled "Radio Broadcasting on Medium Frequencies" (Reference 10) and the other by Grudinskaya entitled "Propagation of Radio Waves" (Reference 11), state positively that the E region is responsible for long distance medium wave propagation.

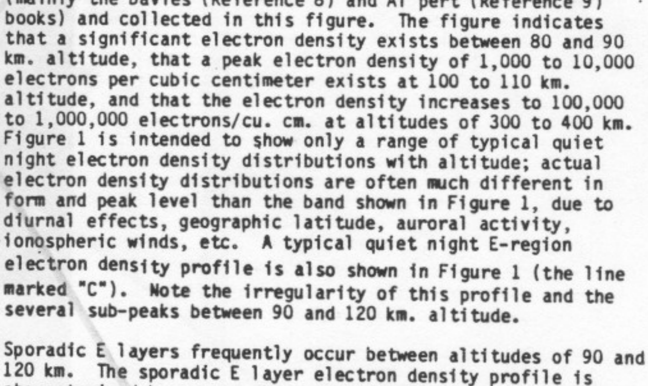
The author has been researching the general field of radio wave ionospheric propagation for several years, with a special interest in the medium frequencies. The subject matter is very broad, quite complex, and difficult to simplify so that the average person can understand it. This article examines the available data and information in order to answer the relatively simple question posed in the first paragraph above. The discussion is as non-technical as possible; however, the use of several algebraic equations is necessary to illustrate several important points. The following sections describe the characteristics of the nighttime ionosphere that affect radio wave propagation, provide a general discussion of the refraction of radio waves, and present the simplified theory for the determination of the altitudes at which the refraction of medium frequency radio waves occur.

2. THE NIGHTTIME IONOSPHERE

Initially, we shall briefly discuss the ionospheric electron density distribution that occurs at night at the middle or low altitudes under quiet geomagnetic field conditions. This condition is of supreme interest to medium wave listeners/DXers. The electron density distribution in the ionosphere is of great importance because refraction and absorption of radio waves cannot occur without free electrons in the ionosphere.

Solar radiation produces ionization of molecules in the ionosphere such that there are some ions, some electrons, and many neutral molecules at altitudes above about 60 km. during the daylight hours. During the day, there are peak concentrations of electrons at altitudes of 60 to 80 km. (the D region), 90 to 120 km. (the E region), and 150 to 400 km. (the F region). At low altitudes, the ions and electrons recombine fairly rapidly after sunset, while at high altitudes (the F region) substantial numbers of electrons exist during the night. However, there are always <u>some</u> ions and electrons between 80 and 150 km. altitude even under equilibrium quiet night conditions. Figure 1 shows the variation in electron density distribution in the ionosphere for quiet night conditions; this data was obtained from a number of sources (mainly the Davies (Reference 8) and Al'pert (Reference 9) books) and collected in this figure. The figure indicates that a significant electron density exists between 80 and 90 km. altitude, that a peak electron density of 1,000 to 10,000 electrons per cubic centimeter exists at 100 to 110 km. altitude, and that the electron density increases to 100,000 to 1,000,000 electrons/cu. cm. at altitudes of 300 to 400 km. Figure 1 is intended to show only a range of typical quiet night electron density distributions with altitude; actual electron density distributions are often much different in form and peak level than the band shown in Figure 1, due to diurnal effects, geographic latitude, auroral activity, ionospheric winds, etc. A typical quiet night E-region electron density profile is also shown in Figure 1 (the line marked "C"). Note the irregularity of this profile and the several sub-peaks between 90 and 120 km. altitude.

Sporadic E layers frequently occur between altitudes of 90 and 120 km. The sporadic E layer electron density profile is characterized by a very sharp increase in the electron density with a peak electron density that can be many times that of the normal quiet night E-region electron density peak value. A typical sporadic E electron density profile is shown in Figure 1 (the line marked "D"). At night, sporadic E with a peak electron density of 300,000 (or more) electrons/cu. cm. occurs in the equatorial zone approximately 10-30% of the time during the months of October through April, in the middle latitudes it occurs approximately 10-30% of the time during the months of May through September, and in the polar zone it occurs 30-70% of the time throughout the entire year.



VERIFYING YOUR RECEPTION REPORT OF

WHAM radio 1180

RUST COMMUNICATIONS GROUP, INC. • 350 EAST AVE.
ROCHESTER, NEW YORK 14604 • U.S.A.

Date------ JAN 9,197[illegible]
Time----- 1038P EST
Location- PORTSMOUTH, NEW HAMSHIRE.

CLASS 1A CLEAR CHANNEL · 50,000 WATTS · SINCE 1922
william rust stations

Thank you,
Albert Davis
Chief Engineer

September 23, 1978.

Sources: Davies (Ref. 8) and Al'pert (Ref. 9)

Notes: Lines A and B are approximate extent of quiet night low and middle latitude electron density profiles
Line C is a typical E-region electron density profile
Line D is a typical sporadic E electron density profile.

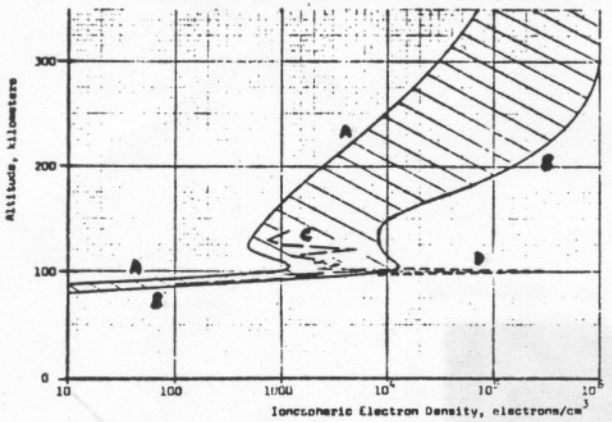


FIGURE 1. Typical Nighttime Ionospheric Electron Density Profiles

The electron density profile in the ionosphere can be measured in several ways. Rocket probes can measure the electron density as a function of altitude. Or, an ionosonde transmits a pulsed radio signal vertically over a wide range of frequencies and measures the time it takes to return each frequency back to Earth. The ionograms thus produced show the reflection heights of the signals versus frequency. The frequency below which the signals are returned from a given ionospheric region is called the critical frequency of that region. The higher the peak electron density in an ionospheric region, the higher the critical frequency of that region will be. For the normal quiet night E region, the critical frequency is usually in the range of 500 to 1,000 kHz, although occasionally the critical frequency can be as low as 250 kHz. Sporadic E critical frequencies are often 5,000 kHz and above. The critical frequency of the F region on a quiet night can be in the range 3,000 kHz to 10,000 kHz. The following sections will provide the equations that relate the critical frequency of an ionospheric region to the peak electron density of that region.

To summarize the most important points of information presented above:

a) A significant electron density exists at night at E region altitudes (90 to 120 km.), with a peak electron density of 1,000 to 10,000 electrons per cubic cm. (E region critical frequency of 250 kHz to 1,000 kHz, approximately), or more.

b) Above an altitude of about 150 km., the electron density continuously increases with altitude to a peak value of 100,000 to 1,000,000 electrons per cu. cm. at altitudes of 300 to 400 km. (F region), at night.

c) Sporadic E conditions frequently exist at night and may have peak electron densities of 100,000 electrons per cu. cm., or more.

d) The ionosphere should not be considered to be distinct layers with thin bands of electrons in each layer and with no electrons between layers, but rather as regions with a nearly continuous vertical electron density distribution from one region to the next.

e) Experimental data, in the form of ionograms, indicate that the critical frequency for the normal quiet night E region is usually in the range of 500 to 1,000 kHz, in the lower part of the medium wave band; critical frequencies of the night F region can be in the range 3,000 to 10,000 kHz. It is very important to note that ionograms are generated using vertical transmissions.

For a more detailed discussion of the geochemical processes that occur in the ionosphere, and the daily, monthly and yearly variations of electron density that occur in the various ionospheric regions, the reader should consult the Nelson (Ref. 2), Pejza (Ref. 5), Davies (Ref. 8) or Al'pert (Ref. 9) works.

3. REFRACTION OF RADIO WAVES

Refraction is defined as the change in direction of a wave (light, radio, sound, water, etc.) passing from one medium to another, caused by the change in velocity of the wave going from one medium to another. For example, a straight stick appears bent when partly immersed in water and viewed at an angle to the water surface; a ray of light of a given wavelength, in passing from air to glass, is bent due to the different velocities of the wave in air and glass. The refractive index is a measure of the bending of a ray when it passes from one medium to another. Consequently, the refractive index of the ionosphere (a magneto-ionic medium) controls the path of a radio wave as it travels from one point to another; the presence of free electrons in the ionosphere changes the refractive index from the refractive index for the neutral atmosphere.

The classical equation that defines the refractive index of the ionosphere in the presence of a magnetic field is called the Appleton formula; the books by Davies (Ref. 8), Al'pert (Ref. 9), and Budden (Ref. 12) provide excellent derivations of the Appleton formula and describe the various simplifications that can be made to the formula. The full solution of the Appleton requires a digital computer program, because the effects of the Earth's magnetic field and electron collisions in the ionosphere greatly complicate the Appleton formula.

In order to present a greatly simplified description of ionospheric propagation, we shall assume that the effects of the Earth's magnetic field and the electron collision rate in the ionosphere (and therefore ionospheric absorption) are negligible, thereby reducing the full form of the Appleton formula to the equation:

$$\mu^2 = 1 - \frac{80.5\,N}{(f_{kHz})^2} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where μ is the refractive index.
N is the electron density in the ionosphere (electrons/cm^3).
f_{kHz} is the radio wave frequency (kHz).

Figure 2 shows a radio wave leaving the Earth's surface at an elevation angle, Δ, entering the ionosphere at an altitude h_o (point "o"), being gradually refracted by the ionosphere, until the ray is parallel to the Earth's surface at point "r"; the ray is then gradually refracted back to Earth. From equation (1) above, we can see that at altitudes below the base of the ionosphere (i.e., no free electrons), the refractive index, μ, is 1.0; as the electron density increases, the refractive index decreases. At point "r", the electron density has increased to the level necessary to refract the wave back to Earth. The electron density required to refract the wave back to Earth can be estimated by applying Snell's Law to a spherical ionosphere. Simply stated, Snell's Law says that when a wave enters a region with a lower refractive index it is bent from the normal. The equation that relates the refractive index at point "r" on Figure 2 to the initial elevation angle, Δ, (see Davies (Ref. 8) or Al'pert (Ref. 9) for the derivation is:

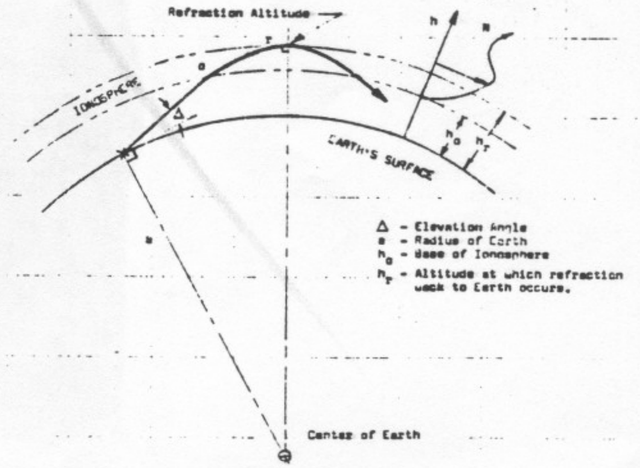


FIGURE 2. Ray Geometry with Oblique Incidence

$$\mu_r = \frac{a \cos \Delta}{a + h_r} \quad \ldots\ldots\ldots \quad (2)$$

where μ_r is the refractive index when the ray is parallel to the Earth's surface (or 90 degrees to the normal to the Earth's surface).

h_r is the altitude at which the ray is parallel to the Earth's surface. h_r is called the refraction altitude.

s is the radius of the Earth (approximately 6370 km.).

Setting $\mu = \mu_r$ and substituting Equation (2) into the simplified Appleton formula (Equation (1)), we can obtain an equation relating the frequency at which refraction back to Earth occurs to the ionospheric electron density, for a given refraction altitude and ray elevation angle:

$$(f_{kHz})_c = \sqrt{\frac{80.5 \; N_r}{1 - \left(\frac{a \cos \Delta}{a + h_r}\right)^2}} \quad \ldots\ldots \quad (3)$$

where $(f_{kHz})_c$ is the oblique critical frequency for refraction back to Earth at the altitude h_r.

N_r is the electron density (electrons/cm^3) in the ionosphere at the altitude h_r.

Δ is the elevation angle of the ray at the Earth's surface.

If the peak electron density of an ionospheric layer is N_{peak}, occuring at an altitude h_{peak}, then the oblique critical frequency of that ionospheric layer can be found by sustituting $N_r = N_{peak}$ and $h_r = h_{peak}$ into Equation (3) above. It is evident that the oblique critical frequency of an ionospheric layer is dependent upon the value of the elevation angle of the ray relative to the surface of the Earth. Radio waves at frequencies below the oblique critical frequency of an ionospheric region will therefore be refracted back to Earth by that region, while radio waves at frequencies above the oblique critical frequency of the ionospheric region will continue higher into the ionosphere until the waves encounter an electron density sufficient to refract the wave back to Earth.

4. MEDIUM WAVE REFRACTION ALTITUDES

In this section, we shall use the equations for the critical frequency of an ionospheric region developed in Section 3 above to determine the altitude at which refraction back to Earth occurs, assuming different values for the peak electron density in the ionospheric regions.

Initially, we shall consider the special case of radio waves propagated vertically (Δ=90 degrees). While this case is of little practical use, it is of importance because it is the propagation mode by which ionograms are generated, and, therefore, the vertical critical frequencies of the various ionospheric regions are measured. The variation of vertical critical frequency with ionospheric electron density is shown in Figure 3 (this curve was calculated using Equation (3) and an elevation angle (Δ) of 90 degrees). The peak electron density in an ionospheric region can be easily deduced from an ionogram using Figure 3; for instance, if an ionogram indicated that the critical frequency of the nighttime E region was 500 kHz (a typical value), then Figure 3 indicates that the E region peak electron density would be about 3,100 electrons per cubic centimeter.

Table 1 provides five examples of the variation of the vertical critical frequency with the peak electron density in an ionospheric region, using the ionospheric density curves shown in Figure 1 and based on Equation (3).

TABLE 1-VERTICAL RAY PROPAGATION (Δ=90 Degrees)

Electron Density Profile file (from Figure 1)	Peak value of N (e/cu.cm.)	Critical Freq. (kHz)
Quiet night E-region (100 km)	1,000	286
Quiet night E-region (100 km)	10,000	897
Sporadic E layer (100 km)	350,000	5,308
Typical night F-region (300 km)	100,000	2,838
Typical night F-region (300 km)	1,000,000	8,973

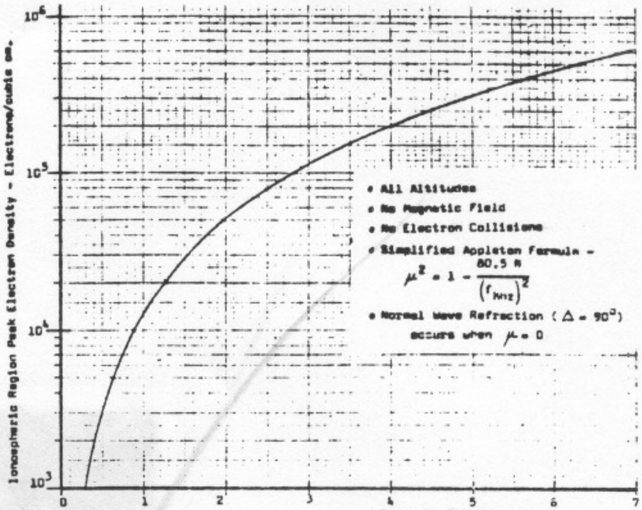


FIGURE 3. Normal Ray Critical Frequency

The data shown in Table 1 indicates that if the E-region peak electron density is 10,000 electrons per cu. cm. at an altitude of 100 km., then waves propagated vertically at frequencies below 897 kHz will be refracted back to Earth while waves with frequencies above 897 kHz will not be refracted back to Earth at an altitude of 100 km., but will continue upward until the electron density is great enough to refract the wave back to Earth. It is very important to note that radio waves may be refracted back to Earth from altitudes less than the altitude at which a peak electron density occurs. For instance, consider a radio wave with a frequency of 1,200 kHz; Figure 3 indicates that an electron density of about 18,000 electrons per cu. cm. is required to refract this vertical wave back to Earth; Figure 1 indicates that refraction back to Earth from a sporadic E layer or from the F-region (at altitudes ranging from 165 to 275 km. depending upon the electron density profile) is possible.

We shall now consider the general case of oblique ray propagation (i.e., an elevation angle less than 90 degrees), wherein the effects of elevation angle and altitude play a critical role in determination of the oblique critical frequency of an ionospheric region. Figure 4 shows the variation of the oblique ray critical frequency as a fuction of the elevation angle of the ray relative to the surface of the Earth for several values of ionospheric electron density, for an altitude of 100 km. This figure was generated using Equation (3); similar plots may be calculated for other altitudes.

Table 2 below considers the same five cases shown in Table 1 above, wherein the maximum electron density in an ionospheric region is known and the oblique critical frequency of that region is to be found; an elevation angle of 5 degrees to the Earth's surface was assumed for this case. Note also that the E-region values can be found from Figure 4, while the sporadic E layer and F-region values must be calculated from Equation (3).

TABLE 2-OBLIQUE RAY PROPAGATION (Δ=5 Degrees)

Electron Density Profile (from Figure 1)	Peak value of N (e/cu. cm.	Critical Freq. (kHz)
Quiet night E-region (100 km)	1,000	1,455
Quiet night E-region (100 km)	10,000	4,601
Sporadic E layer (100 km)	350,000	27,317
Typical night F-region (300 km)	100,000	14,549
Typical night F-region (300 km)	1,000,000	46,010

Comparison of the oblique ray critical frequencies of the E and F-regions of the ionosphere shown in Table 2 with the vertical ray critical frequencies of Table 1 demonstrates the dependence of the oblique critical frequency of an ionospheric region on the elevation angle of the ray relative to the Earth's surface and on the peak electron density of the ionospheric region. For example, if the peak electron density of the E-region is 10,000 electrons per cu. cm. at an altitude of 100 km., then the critical frequency of the E-region for vertically transmitted waves will be 897 kHz, while for waves with a 5 degree elevation angle the oblique critical frequency of the E-region will be 4,601 kHz. Therefore, waves transmitted at frequencies below 4,601 kHz at an elevation

T45-4-4

angle of 5 degrees will be refracted back to Earth by an E-region with a peak electron density of 10,000 electrons per cu. cm., while waves at frequencies higher than 4,601 kHz will continue upward into the ionosphere until the electron density is great enough to refract the wave back to Earth.

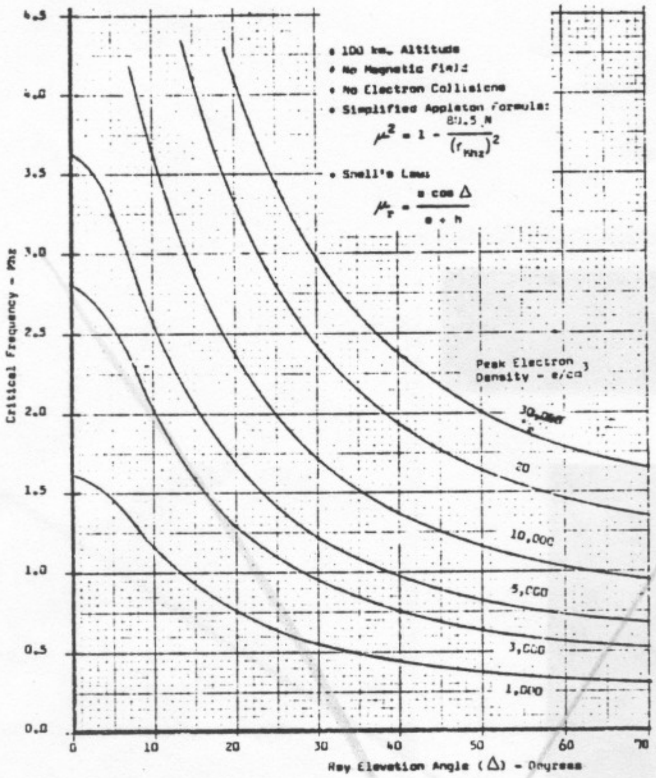


FIGURE 4. Oblique Ray Critical Frequency

Figure 4 can be used in several other ways, such as:

1) Assume a wave frequency of 1,000 kHz and a minimum quiet night peak electron density of 1,000 electrons/cu. cm. at an altitude of 100 km. (E-region). Figure 4 shows that waves propagated at elevation angles below 13 degrees will be refracted back to Earth by this ionospheric region, while waves at elevation angles greater than 13 degrees will not be refracted back to Earth at this altitude, but will continue upward into the ionosphere until the electron density is great enough to cause refraction back to Earth. Similarly, consider an E-region peak electron density of 10,000 electrons/cu. cm. at an altitude of 100 km.; Figure 4 indicates that a wave of frequency of 1,000 kHz will be refracted back to Earth for elevation angles of 64 degrees or less, but for elevation angles greater than 64 degrees, the wave will continue upward into the ionosphere until the electron density is great enough to refract the wave back to Earth.

2) Assume a wave frequency of 1,000 kHz, and an elevation angle of 30 degrees at the Earth's surface. Figure 4 indicates that an electron density of 3,500 electrons/cu. cm. is required to refract this signal back to Earth. Figure 1 shows typical quiet night E and F-region electron density profiles. For the minimum electron density profile (Line A on Figure 1, with a peak E-region density of about 1,200 electrons/cu. cm.), the altitude at which 3,500 electrons/cu. cm. occurs is about 200 km. For the maximum electron density profile (line B on Figure 1 with a peak E-region electron density of 13,000 electrons/cu. cm.), the altitude at which refraction back to Earth occurs is about 95 km.

The examples provided above illustrate the dependency of medium wave refraction altitudes on the elevation angle of the ray relative to the Earth and on the peak electron density in the E-region of the ionosphere. The reader can, if he wishes work out any number of cases using different electron densities, elevation angles or frequencies to determine refraction altitudes with the aid of Figures 1, 3 and 4.

It is important to note that this discussion and the data presented herein are based on the simplified Appleton equation (Equation(1)), which assumes that the effects of the Earth's magnetic field and ionospheric absorption are negligible. In reality, the Earth's magnetic field plays an important role in medium wave propagation and the assumption that its effects are negligible is not rigorous. Therefore, the data presented in this section should be considered approximate, but it does relatively easily illustrate the basic concepts that underlie medium frequency ionospheric propagation.

5. CONCLUSIONS

Certain general conclusions can be made at this time concerning nighttime medium wave ionospheric propagation based on the discussion and data presented above. These conclusions include:

1) The critical frequency of the night E-region (approximately 90 to 120 km. altitude), measured with a vertical transmission, is usually in the range of 500 to 1,000 kHz (corresponding to peak E-region electron densities of about 3,000 to 13,000 electrons per cu. cm., respectively), although it can be as low as 250 kHz (about 1,000 electrons per cu. cm.); nighttime sporadic E layers occur often, and can have critical frequencies of 5,000 kHz or more. The F-region (approximately 150 km. and above, with a peak value between 250 and 400 km.) usually has nighttime critical frequencies of 3,000 to 10,000 kHz (corresponding to peak F-region electron densities of 100,000 to 1,000,000 electrons per cubic cm., respectively), depending upon geographic latitude, season, and time of day.

2) Long distance, multi-hop medium wave propagation at night in the low and middle latitudes usually occurs over paths with low elevation angles and E-region refraction altitudes (i.e., 90 to 120 km.), because the oblique critical frequency of the E-region is usually greater than 1,600 kHz for paths with elevation angles less than 5 degrees. The exceptions to this rule might be high frequency (e.g., greater than 1,200 kHz), two or three hop paths with a low E-region peak electron density.

3) Short distance, single hop medium wave propagation at night may occur by either E-region or F-region refraction, depending upon the wave frequency, the elevation angle of the ray, and the E-region peak electron density. A wave at a high medium frequency and a high elevation angle will be more likely to penetrate the E-region and be refracted by the F-region than will a low frequency of low elevation angle wave.

4) When a medium frequency wave does penetrate the E-region and is refracted by the F-region of the ionosphere, the altitude at which refraction back to Earth occurs will be below the altitude at which the F-region peak electron density occurs, because the wave frequency is much less than the oblique critical frequency of the F-region.

6. REFERENCES

1) Nelson, G.P., "Medium Wave Propagation", How to Listen to the World, World Publications, 1970.

2) Nelson, G.P., "MW Signal Paths, Parts I-IV", DX News, National Radio Club, issues of 3/8/69, 2/28/70, 3/21/70, 4/25/70.

3) Nelson, G.P., "Geographical Patterns in BCB DX Reception during Periods of High Auroral Activity", DX News, National Radio Club, issue of 8/28/71.

4) Nelson, G.P., "Skyline Blockage of MW Signals", DX News, National Radio Club, issue of 2/28/73.

5) Pejza, Fr. J., "A Beginner's to the Ionosphere", DX Monitor, International Radio Club of America, issues of 3/25/72 and 4/8/72.

6) Dinning, F., "Factors Affecting Propagation of the Medium Frequency Broadcast Band", DX News, National Radio Club, issue of 3/21/77 (originally published in Medium Wave News, England).

7) Schatz, R.F., Medium Wave Ionospheric Propagation", DX News, National Radio Club, issue of 6/12/78.

8) Davies, K., Ionospheric Radio Propagation, National Bureau of Standards, NBS Monograph 80, 1965.

9) Al'pert, V.L., Radio Wave Propagation and the Ionosphere; Volume I, The Ionosphere, Consultant's Bureau, New York-London.

10) Barghausen, A.F., Finney, J.W., Fisher, R.M., "Radio Broadcasting on Medium Frequencies", National Bureau of Standards, NBS Report 9196, April, 1966

11) Grudinskaya, G.P., "Propagation of Radio Waves", Air Force Systems Command, Foreign Technology Division, Report No. FTD-MT-24-382-68, 1968

12) Budden, K.G., Radio Waves in the Ionosphere, Cambridge Univ. Press, 1961.