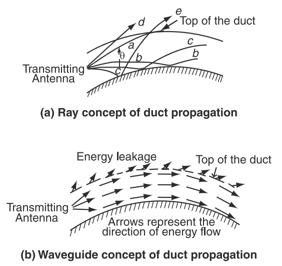
Chapter 3



Space Wave Propagation

Topics in this chapter include:

- Introduction
- Effect of imperfection of earth
- Effect of curvature of earth
- Effect of interference zone
- Shadowing effect of hills and buildings
- Absorption by atmospheric phenomena
- Variation of field strength with height
- Super refraction
- Meteorological conditions
- Scattering phenomena
- Tropospheric propagation
- Fading
- Path loss calculations

3–1 Introduction

Figure 3–1 shows the attenuation of ground waves for good and poor earth. It can be seen from these figures that with the increase of frequency, the rate of attenuation increases. The signal strength in case of poor earth reduces to the same level in 800 km for 1 MHz and a little over 200 km for 10 MHz. Similarly in good earth case, the signal strength reduces to −30 dB at about 1850 km for 1 MHz and nearly 750 km for 10 MHz. If the same rate of reduction is assumed, signal strength at 30 MHz in both the cases will reduce to almost negligible amplitudes after traveling only a very short distance. Except in case of sporadic E layer, the ionosphere too does not reflect energy towards earth at these frequencies. In such a situation, the space wave propagation is the only useful means for any effective and meaningful communication.

From Fig. 3–2, it can be seen that the energy contents of space-wave travel from transmitter to receiver partly through *direct wave* (*DW*) or *direct ray*(*DR*) and partly through the *reflected wave* (*RW*) or *reflected ray* (*RR*). In this figure, the earth curvature is neglected for simplifying the illustration and the analysis. The net field strength at the receiving antenna will be the vector sum of DW and RW fields. Up to a certain range of frequencies, the wave traveling through the space shall have negligible attenuation other than that caused by spreading phenomena. Also, DR and RR are almost 180° out of phase for both vertically and horizontally polarized waves. Beyond these frequencies, waves will be subjected to attenuation by rain, fog, snow, and clouds and due to absorption by gases present in the atmosphere. The field strength of a wave, in general, follows the inverse relation with the distance.

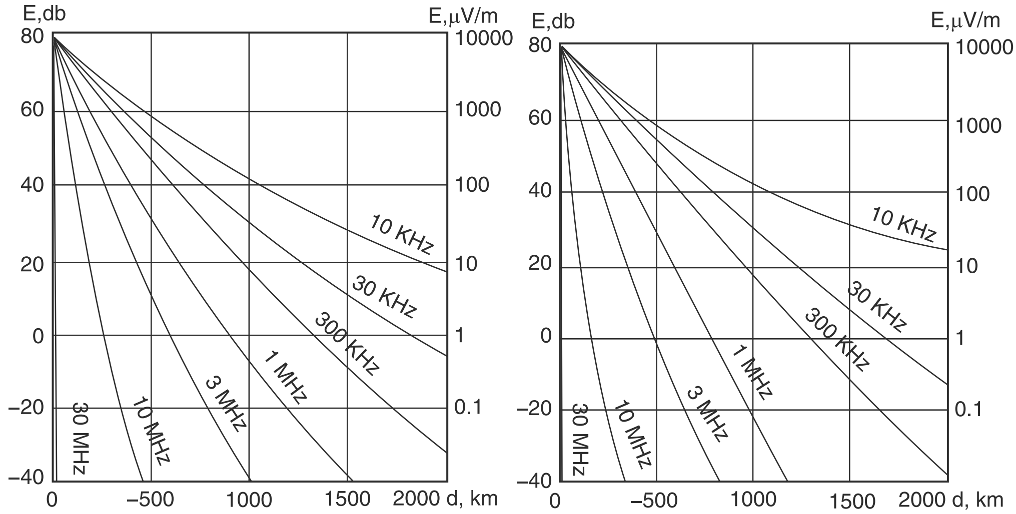


Figure 3–1 Variation of signal strength with distance at different frequencies.

3–2 Field Strength Relation

When the distance (d) between transmitting and receiving antennas is sufficiently large in comparison to antenna heights (h_t and h_r), the incidence angle ψ of the ray on earth is small. In view of Fig. 3–3, reflection from earth, irrespective of polarization, can be assumed to have no change in magnitude but with reversal of phase. Thus the two waves arriving at the receiver will have equal amplitudes but different phases. Assuming E_0 to be the amplitude of DW and RW at a unit distance at a distance d, the amplitudes of both (DW and RW) reduce to $E' = E_0/d$.

Figure 3–4(a), a modified version of Fig. 3–2, illustrates different parameters. These include the transmitting antenna T located at A, with height h_t, receiving antennas R located at B with height h_r, R_1 the distance traveled by DW, R_2 the distance traveled by RW both between T and R and the angle-ψ. The R_2 shown is the distance between T and R via 0, i.e., the point from where the wave reflects. Alternatively, it is the distance traveled by RR from T^* to R where T^* is the image of the transmitting antenna. Since the earth is assumed to be flat and perfectly conducting, the image will be a perfect replica of the source T and exactly $h_t$below the ground. The resultant field E can now be obtained from Fig. 3–4 (a and b) as below.

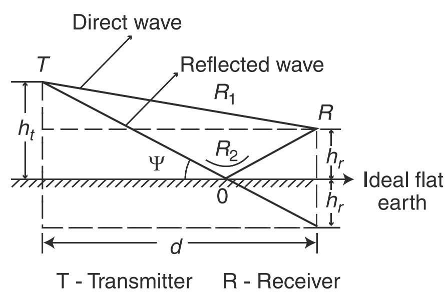


Figure 3–2 Direct and reflected waves.

$$R_1^2 = (h_t - h_r)^2 + d^2 \quad \text{or} \quad R_1 = d[1 + (h_t - h_r)^2/d^2]^{1/2} \tag{1}$$

$$\text{and} \quad R_2^2 = (h_t + h_r)^2 + d^2 \quad \text{or} \quad R_2 = d[1 + (h_t + h_r)^2/d^2]^{1/2} \tag{2}$$

If distance (d) is taken to be much greater than the heights of antennas (h_t and h_r), the wave fronts of the direct and ground-reflected waves can be assumed to coincide. Equations (1) and (2) can be re-written as

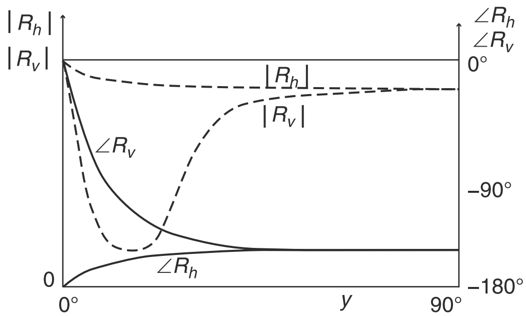


Figure 3–3 Variation of amplitude and phase of reflection coefficients for VPW and HPW.

$$R_1 = d[1 + (h_t - h_r)^2/2d^2] \quad \text{or} \quad [d + (h_t - h_r)^2/2d] \tag{3}$$

and $$R_2 = d[1 + (h_t + h_r)^2/2d^2] \quad \text{or} \quad [d + (h_t - h_r)^2/2d] \tag{4}$$

The difference in path lengths $R_2 - R_1$ is obtained to be

$$R_2 - R_1 = [(h_t + h_r)^2 - (h_t - h_r)^2]/2d^2 = 2\,h_t\,h_r/d \tag{5}$$

The phase difference corresponding to this path difference is

$$(2\pi/\lambda)(2h_t\,h_r)/d = (4\pi\,h_t\,h_r)\lambda d \text{ radians.} \tag{6}$$

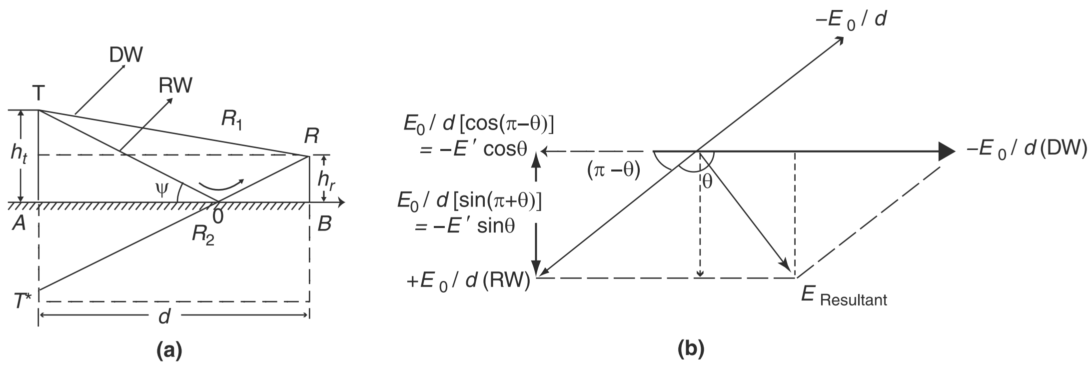


Figure 3–4 (a) Illustration of parameters (b) Illustration of field component of DW and RW.

It is because of this angle that the direct and indirect (reflected) waves fail to cancel and the resultant of two waves is 2 sin $[(2\pi\ h_t\ h_r)/\ \lambda d]$ times the amplitude of one of the waves (i.e., E_0/d). Thus the field strength E at receiver is

$$E = (2E_0/d)\sin[(2\pi\ h_t\ h_r)/\lambda d] \tag{7}$$

When $(2\pi h_t h_r)/\lambda d$ is less than 0.5 (true for large d), the sine of the angle can be replaced by the angle itself and thus 7 reduces to,

$$E = (2E_0/d)[(2\pi\ h_t\ h_r)/\lambda d] = [(4\pi\ h_t\ h_r)/\lambda d^2]E_0 \tag{8}$$

In the above equations, E_0 is the field intensity produced at a unit distance by direct ray emanating from transmitting antenna in the desired direction. E_0 will depend upon the directivity/gain (G_t) of the antenna and the transmitted power P_t. For the half-wave elevated transmitting antennas, E_0 = 137.6 $\sqrt{P_{kw}}$ mv/m at one mile distance.

It needs to be mentioned that in all above relations, the radiating and receiving elements are assumed to be omnidirectional. Rigorous analysis can, however, be done for vertically/horizontally polarized waves emanating from dipoles.

3–3 Effects of Imperfect Earth

To understand the effect of imperfection of the earth, the following aspects are to be noted.

- E_0/d is the field strength which actually corresponds to DW. It will also correspond to RW for perfectly conducting earth.
- $|R_h|$ and $|R_V|$ both are less than 1 for $\sigma \neq \infty$, the condition which normally prevails. Thus, the field strength at a distance d is always be less than E_0/d.
- Besides, $\phi \neq 180°$, i.e., there is no total phase reversal of RW. Thus RW < DW and the total field is less than that at $\sigma = \infty$.
- The effect is less on HPW than in case of VPW. For VPW, $|R_V| << |R_h|$at small angles.
- When $\sigma = \infty$, horizontal components of incident electric field E_i and reflected electric field E_r get cancelled at reflected surface and vertical components add together.
- For $\sigma < \infty$, $|R_V| < 1$, neither there is complete cancellation nor complete addition.

The variation of field strength with distance, obtained from (7) of Sec. 3–2 is illustrated in Fig. 3–5.

In Fig. 3–5 (*a*), d' is the distance at which free space field and oscillating field for a perfectly conducting earth become equal. It is less than the value that makes the angle $[(2\pi\ h_t\ h_r)/\ \lambda d]$ greater than λ / 6. It can be observed that the field strength oscillates about the value E_0/d, which corresponds to the strength of the direct ray (often called the free space (FS) wave). For a perfectly conducting earth, the maximum amplitude of these oscillations is twice of the free-space value. These maxima occur at such distances (related to the antenna heights), where DW and RW add in phase. The minima or nulls have zero amplitude in the case of a perfectly conducting earth, and occur at distances such that the DW and RW cancel each other. For $d > d'$,

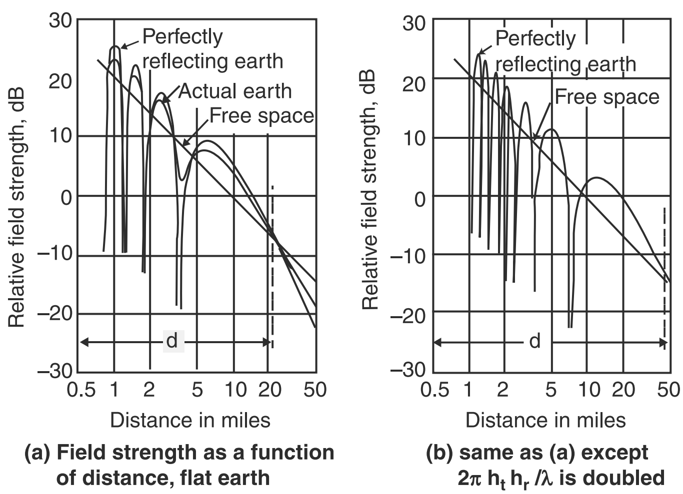


Figure 3–5 Variation of field strength with distance.

path lengths of DW and RW always differ by less tan λ / 6, in such cases E falls rapidly in accordance with the proportionality with distance square. For $d > d'$, the angle of incidence is so small that reflection takes place with the reversal of phase and no change in amplitude for both polarizations. The resulting field will be less than the free space value.

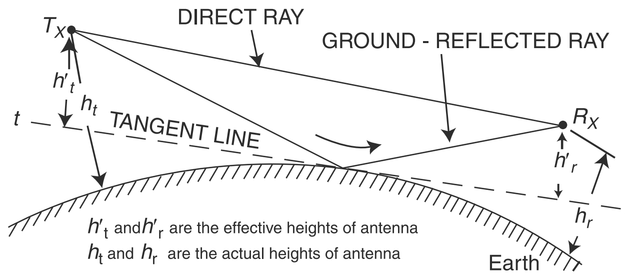


Figure 3–6 DR and RR over curved earth.

If the argument of sine in (7) is changed (say doubled), by changing h_t, h_r or the frequency the resulting field will be as shown in Fig. 3–5 (*b*). In this case the field fluctuates more rapidly and the average field strength at any distance is more than in case shown by Fig. 3–5 (*a*). Also, $d'' > d'$ where d'' is the distance at which free space and oscillating fields are equal for perfectly conducting earth.

3–4 Effects of Curvature of Earth

Due to Curvature of Earth:

- The effective and actual antenna heights shown in Fig. 3–6 differ. The quantum of difference will depend on the separation between T_x and R_x.
- There is a change in the number and location of maximas and minimas as illustrated in Fig. 3–5.
- There is reduction in d', beyond which the two waves tend to be out of phase.
- The wave reflected by the ground diverges. Thus, RW at R_x antenna is weak. This effect is less when the incident angle is moderate or large and more when this angle is small. Near grazing angle, the field strength of RW reduces significantly at the receiver by the divergence effect.
- At large distances, for small incidence angles and DW and RW in phase opposition, the resultant E at R_x is appreciably greater than that if earth were flat.
- The last two effects of curvature try to neutralize each other. Thus, (8) of Sec. 3–2 is reasonably accurate.

3–5 Effect of Interference Zone

This effect is shown in Fig. 3–7 wherein if the receiving antenna falls in the shadow zone, logically there should not be any reception. However, in view of diffraction phenomena some signal arrives at the receiver.

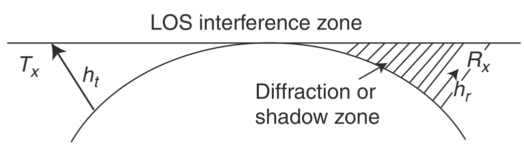


Figure 3–7 Result of diffraction phenomena.

3–6 Shadowing Effect of Hills and Buildings

At VHF and above, serious disturbances in space wave propagation are caused by trees, buildings, hills and mountains. These obstacles cause reflection, diffraction and absorption. Losses caused by absorption and scattering increase with the increase of frequency until f exceeds 3 GHz. Beyond this frequency, building walls and wood become opaque to the waves. At higher frequencies, the received signal strength is considerably reduced at position on the shadow side of any hill. Figure 3–8 illustrates the shadowing effect of hills and building. In view of Fig. 3–8 (*a*), the reduction in R_2 can be seen and thus equations (7) and (8) of Sec. 3–2 will yield an altogether different result. It is not only the reduction in R_2, the obstructive object also scatters the energy. Therefore, to estimate the real impact the analysis in normally carried out by replacing the actual obstruction by an equivalent knife edge shown in Fig. 3–8 (*b*).

3–7 Absorption by Atmospheric Phenomena

In very high frequency ranges, the rain attenuates the wave partly due to absorption and partly by scattering. This attenuation is a function of wavelength, permittivity, drop diameter and drop concentration, and the losses due to scattering. Serious attenuation is observed at $\lambda = 3$ cm for heavy rains (not cloud burst) and at $\lambda = 1$ cm for moderate rains. Since attenuation is proportional to the mass of water/unit volume and drop size for cloud and fog are smaller than rain drops, serious attenuation occurs below $\lambda = 1$ cm due to clouds and fog. Losses in ice are considerably less than in liquid water. The attenuation by dry hail storm is less than that due to rain except in mm region where it is comparable. As water content in even a heavy snow storm is quite small, the attenuation caused by snow is always small. Due to molecular interaction, absorption of energy takes place at certain wavelengths due to water vapors and gases with peaks noted at $\lambda = 1.33$ cm, 1.7 mm and 1 mm. Peaks due to absorption by O_2 molecules occur at $\lambda = 5$ mm and 2.5 cm.

3–8 Variation of Field Strength with Height

The impact of height on the distribution of field is shown in Fig. 3–9. Figure 3–9(*a*) illustrates the impact when the earth is assumed to be flat and Fig. 3–9(*b*) for a curved earth. The locations of minimas and maximas depend on h_t, h_r, frequency and the distance between the transmitter and receiver. The field strength contours are produced by a transmitter located on ground radiating a vertically polarized wave.

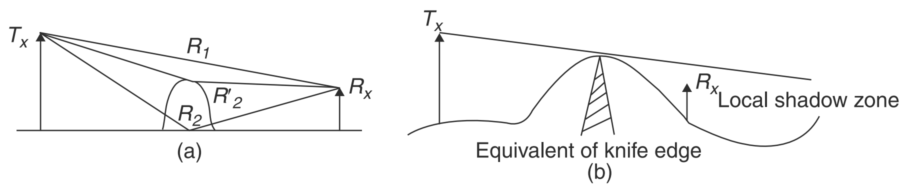


Figure 3–8 Shadowing effect and its equivalent.

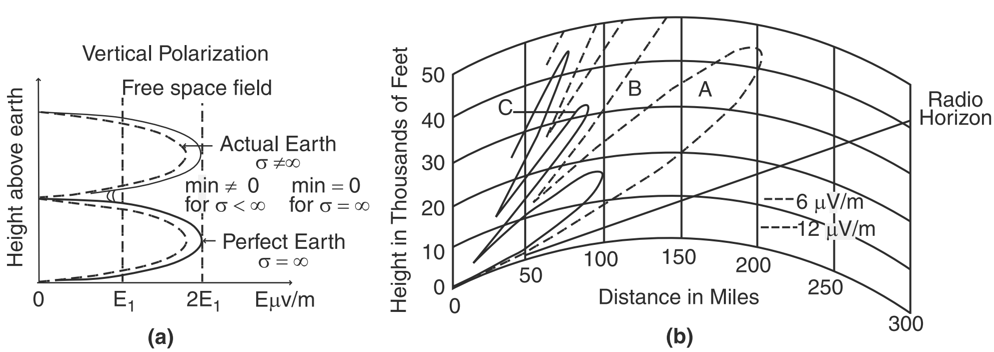


Figure 3–9 Variation of field strength with height.

3–9 Super Refraction

The *refractive index* 'n' (= $\sqrt{\varepsilon}$) for free space is given by the relation:

$$n = 1 + \frac{80}{T}10^{-6}\left(P + \frac{4800w}{T}\right) \tag{1}$$

where, T is the absolute temperature of air, P is the air pressure in millibars and w is the partial pressure of water (humidity) in millibars.

In connection with n, the following points need to be noted:

- The gradient of the refractive index n is not always uniform.
- It is often divergent from the mean value, particularly in the lower 5 km of the troposphere.
- The variation becomes important if $\lambda < h$; (where h is the height above the ground), since ray paths are dependent on variation of n with height.
- The variation of n leads to the phenomena such as reflection. refraction, scattering, fading and ducting.
- The duct can be assumed to be a waveguide with leakage.

The actual 'n' is often replaced by a *modified index* 'N' bearing the relation:

$$N = n + h/a \tag{2}$$

Relation (2) involves radius of earth 'a' (a = 6.37 $\times 10^6$ m) and thus 'N' accounts for the earth's curvature. N is always approximately equal to unity since $h << a$. In view of the importance of its actual value, it is further convenient to introduce a new parameter called the *refractive modulus* 'M'.

$$M = (N - 1) \times 10^6 \tag{3}$$

The gradient of N can be written as

$$\frac{dN}{dh} \times 10^6 = \frac{80}{T}\frac{dP}{dh} - \frac{80}{T^2}\left(P + \frac{9600w}{T}\right)\frac{dT}{dh} + \frac{80 \times 4800}{T^2}\frac{dw}{dh} + \frac{10^6}{a} \tag{4}$$

In this equation, the first term on the right-hand side is always negative and the last term is always positive. Signs of the other two terms depend on atmospheric conditions. In standard atmosphere, temperature decreases with height @ 6.5°/km and w decreases linearly. Thus, the second and third terms are both negative and their values in standard atmosphere are such that dN/dh is positive with a value usually taken as 0.118×10^{-6} /m. This value is expressed in terms of dM/dh is given as 0.118M units/m and corresponds to -0.039×10^{-9}.

Under certain atmospheric conditions, dT/dh and dw/dh may greatly differ from standard values, particularly when warm dry air passes over a cool sea surface. The air close to water will be cooled and an increase in temperature with the height will result. Also, water vapour contents will decrease with height much more rapidly than usual. Both of these factors reduce dM/dh which may become negative over a region close to sea surface and result in what is called a *surface duct*. Under certain other conditions, dM/dh may assume negative value a little higher in the atmosphere making an *elevated duct*.All conditions which make dN/dh less than the standard values are called *super-standard* and improve radio wave propagation. Also, the conditions which make dM/dh greater than the standard values are called *sub-standard making the signals below normal*. Figure 3–10 shows different type of refractive index profiles observed.

When dM/dh is negative, the curvature of rays passing through the atmosphere is greater than that of the earth. As a result energy, originated from the antenna and initially directed approximately parallel to the earth surface, tends to be trapped and propagates around the curvature of the earth in a series of hop. dM/dh = 0.036 units/ft for standard atmosphere. Normally, at quite high altitudes n is not a function of

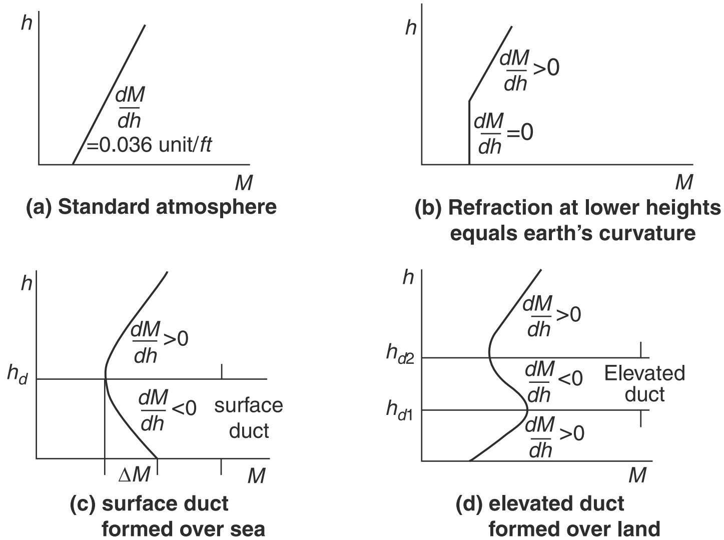


Figure 3–10 Different type of refraction index profiles.

height, $dM/dh = 0.048$ units/ft. the effect of different rates of variation of n on wave propagation is shown in Fig. 3–11.

Thus, the radius of the earth is to be simultaneously adjusted so as to preserve the correct relationship between the ray path and the curvature of the earth. This adjustment has to be such that the ray path and the curvature are to be seen as parallel and the ray path as a straight line. The amount of change in the earth's radius required to achieve the above is to multiply the radius by a factor k, where k is given by

$$k = \frac{Equivalent\ earth\ radius}{Actual\ earth\ radius} = \frac{0.048}{dM/dh} \tag{5}$$

In (5), dM/dh represents the change in M with height. For $dM/dh = 0$, k is infinite and for standard atmospheric conditions:

$$dM/dh = 0.036, \quad \text{thus } k = \frac{0.048}{0.036} = \frac{4}{3} = 1.33 \tag{6}$$

The maximum possible distance at which direct wave transmission is possible between a transmitting and receiving antennas with heights h_t and h_r is often referred as the line of sight (LOS) distance and is equal to the sum of horizontal distances calculated separately for individual antenna heights. When distance involved is less than LOS value, the path is often referred to as being *optical*. This is in the sense that the ray can pass directly between transmitting and receiving antennas. When duct propagation exists, LOS and diffraction zone concept no longer apply and energy travels long distances with low attenuation.

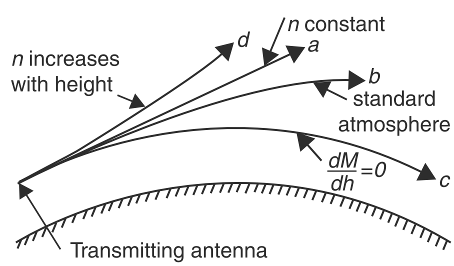
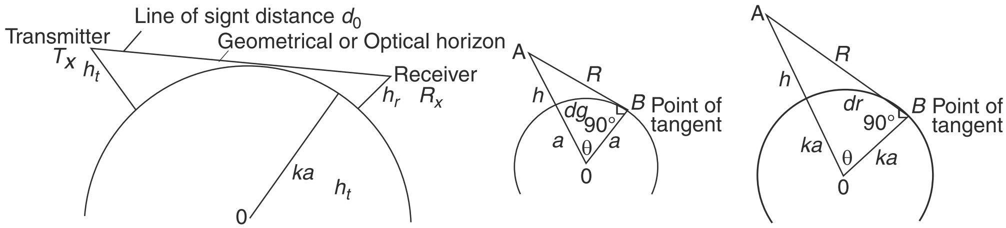


Figure 3–11 Effect of variation of n on wave propagation.



(a) (b) (c)

Figure 3–12

Optical and Radio Horizon terms are also frequently used in connection with the point-to-point communication and radars. In order to understand these terms, let us consider different segments of Fig. 3–12. In view of Fig. 3–12*a*, the line of sight is the straight line distance between T_x and R_x that is tangent to the surface of the earth. This distance d_0 along LOS is

$$d_0 = \sqrt{2Kah_t} + \sqrt{2Kah_r} \tag{7}$$

where h_t and h_r are height transmitting and receiving antennas, a is the earth's radius and K is the factor accounting for refraction due to a uniform gradient of refractivity. The point of tangency of the LOS with the earth is termed as geometrical or *optical horizon*. A good optical path requires that the ground, including any obstructions thereat, be outside the first Fresnel zone surrounding the direct path. The Fresnel zone may be defined as a cylindrical surface of revolution having the direct path as its axis, and possessing a contour such that the distance from the transmitting antenna to point on the surface plus the distance from this point to the receiving antenna is one half wavelength greater than the direct path between T_x and R_x.

To further elaborate the effect of refraction, consider a transmitting antenna at a height h_t above the earth's surface. The geometrical horizon distance dg can be obtained from Fig. 3–12*b*. From the geometry, with $h_t << a$ such that θ is small for the tangent falling at B,

$$R^2 = (a + h_t)^2 + a^2 \tag{8}$$

$$dg = a\theta \approx a \sin\theta = a\frac{\sqrt{(h_t + a)^2 - a^2}}{h_t + a} = a = \frac{\sqrt{h_t + 2aht}}{h_t + a} \tag{9}$$

Since $h_t << a$

$$dg \approx \sqrt{2ah_t} \tag{10}$$

The radio horizon distance dr can be obtained from Fig. 3–12*c* following the same procedure.

$$dr = ka\theta \approx ka \sin\theta = Ka = \frac{\sqrt{(ht + ka)^2 - (Ka)^2}}{ht + ka}$$

$$= Ka\frac{\sqrt{h_t^2 + 2Kah_{\ t}}}{h_t + Ka} \approx \sqrt{2Kah_t} \tag{11}$$

Since $K > 1$, *dr* has to be greater than *dg*. Since for standard atmospheric conditions, $K = 4/3$ the radio horizon distance *dr* is

$$dr = \sqrt{\frac{4}{3}}\sqrt{2ah_t} \approx 1.155dg \tag{12}$$

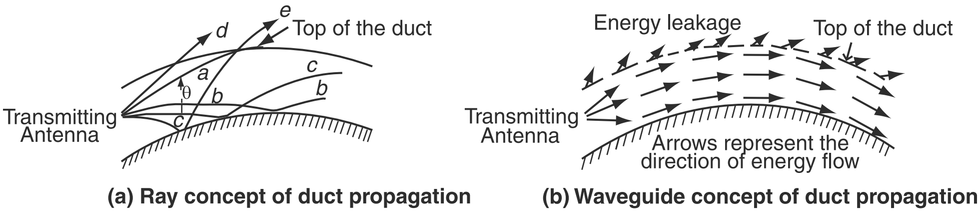


Figure 3–13 Ray and waveguide concepts of duct propagation.

If ΔM is the total decrease in M (generally not greater than 50 units) from bottom to the top of the duct the wavelength $\lambda = \lambda_{Max}$ at which the duct propagation ceases is given by

$$\lambda_{Max} = 2.5 h_d \sqrt{[\Delta M \times 10^{-6}]} \quad (13a)$$

where, h_d is the height of the duct as shown in Fig. 3–13 and may be of the order of 10's of feet to 100's of feet. There is always some leakage of energy from the duct which increases as the ratio of λ/h_d increases.

Duct propagation is limited to UHF and microwave frequencies. For duct formation, it is necessary that antenna height remains less than or equal to h_d. Ground-based ducts over sea or water stretches occur less frequently and generally temporarily. Elevated ducts are always present over oceans or in trade wind belts. For surface duct of height h_d, λ_{Max} for which trapping occurs is more accurately given by

$$\lambda_{\max} = \frac{8\sqrt{2}}{3} \int_0^{h_d} \{N(h) - N(h_d)\}^{1/2} dh \quad (13b)$$

The duct formation and its waveguide equivalent are shown in Fig. 3–14.

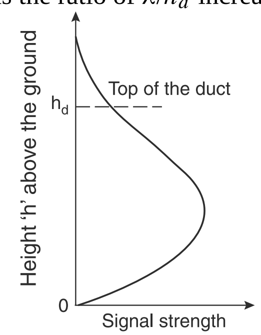


Figure 3–14 Variation of signal strength with height.

EXAMPLE 3–9.1 The transmitting and receiving antennas with respective heights of 49 m and 25 m are installed to establish communication at 100 MHz with a transmitted power of 100 watts. Determine the LOS distance and the received signal strength thereat.

Solution

λ at 100 MHz = 3 m. In view of (7) for 4/3 model and a = 6370

$$d_0 = \sqrt{2kah_\mathrm{t}} + \sqrt{2kah_\mathrm{r}} = \sqrt{2ka/1000}\left(\sqrt{h_\mathrm{t}} + \sqrt{H_\mathrm{r}}\right)$$

$$= \sqrt{2\frac{4}{3}\frac{6370}{1000}}\left(\sqrt{h_\mathrm{t}} + \sqrt{h_\mathrm{r}}\right) = 4.12\left(\sqrt{h_\mathrm{t}} + \sqrt{H_\mathrm{r}}\right)$$

Thus, LOS distance = 4.12 ($\sqrt{49}$ + $\sqrt{25}$) = 12 × 4.12 = 49.44 km

$$E_r = [88\sqrt{P}/\{\lambda d^2\}]\, h_t\, h_r\, V/m = [88\sqrt{100}/\{3 \times (49.44 \times 10^3)^2]\, 49 \times 25$$

$$= [880/\{3 \times (2444 \times 10^6)] \times 1225 = 12 \times 10^{-4} \times 1225 = 1.47\mathrm{W}$$

EXAMPLE 3–9.2 Calculate the maximum distance at which signal from transmitting antenna with 144 m height would be received by the receiving antenna of 25 m height. Also, calculate the radio horizon distance for k =4/3 model earth of 6370 km radius.

Solution

LOS distance = 4.12 ($\sqrt{h_t} + \sqrt{h_r}$) = 4.12 ($\sqrt{144}$ + $\sqrt{25}$) = 4.12 × 17 = 70.04 km

The surface range to the radio horizon from radar $=\sqrt{2Kah_t}=\sqrt{2\frac{4}{3}\times 6370\times \frac{144}{1000}}=4.12\sqrt{144}=$ 49.44 km

EXAMPLE 3–9.3 A transmitting antenna of 100 m height radiates 40 kW at 100 MHz uniformly in azimuth plane. Calculate the maximum LOS range and strength of the received signal at 16 m high receiving antenna at a distance of 10 km. At what distance would the signal strength reduce to 1mV/m ?

Solution

LOS distance = 4.12 ($\sqrt{h_t} + \sqrt{h_r}$) = 4.12 ($\sqrt{100}$ + $\sqrt{16}$) = 4.12 × 14 = 57.68 km $\lambda = 3\,\text{m}$

$$\text{Field strength at 10 km} = E_s = \frac{88\sqrt{P}}{\lambda d^2} h_t h_r = \frac{88\sqrt{40\times 10^3}}{3\times 10^4 \times 10^4} \times 100 \times 16$$
$$= 98.36 \text{ mV / m}$$

Distance at which the field strength will reduce to 1mV/m

$$d = \left[\frac{88\sqrt{P}}{\lambda E} h_t h_r\right]^{1/2} = 9.688 \times 10^4 \text{ m} = 96.88 \text{ km}$$

EXAMPLE 3–9.4 A directional antenna with 10 dB gain radiates 500 watts. The receiving antenna at 15 km distance receives 2 micro-watts. Find the effective area of the receiving antenna. Assume negligible ground and ionospheric reflections.

Solution

Given d = 15 km, G_t = 10, W_t = 500 W, $W_r = 2\times10^{-6}$W, to find A_e

$$\text{Since} \quad W_r = \frac{W_t G_t}{4\pi d^2} A_e$$
$$A_e = \frac{W_r 4\pi d^2}{W_t G_t} = \frac{2\times 10^{-6} \times 4\pi \times (15\times 10^3)^2}{500 \times 10} = 1.13\,\text{m}^2$$

EXAMPLE 3–9.5 Calculate the maximum frequency which can be transmitted by a duct of height 1000 m if the total change in M is of the order of 0.036.

Solution

In view of (13a)

$$\lambda_{Max} = 2.5 h_d \sqrt{[\Delta M \times 10^{-6}]} = 2.5 \times 1000 \times (0.036 \times 10^{-6})^{1/2}$$
$$= 0.19 \times 2500 \times 10^{-3} = 0.475$$
$$\text{Thus,} \; f_{max} = c/\lambda_{Max} = 3 \times 10^8 / 0.475 = 631.6\,\text{MHz}$$

3–10 Meteorological Conditions Predicting Super Refraction

Both the conditions associated with fine, calm and anti cyclonic weather, i.e., increase in temperature (called *temperature inversion*) and rapid decrease of w (humidity) with height result in decrease of refractive index n with height. In cold, rough weather the lower temperature is usually well mixed and n is more or less standard. When the day is warm, land and air both become warm. After sunset, if the sky is clear, land radiates its heat and its temperature falls rapidly. As a result, earth and lower layer of atmosphere cool down but the upper layer remains unchanged. It results in temperature inversion. If this inversion is sufficiently intense, it results in super reflection. Though this effect is common over deserts, it can also occur anywhere if the sky is clear and the land is dry. It maximizes in early morning and disappears after sun rise. Such conditions frequently exist over the sea, particularly near coasts where air close to sea tends to be damp and cool while the upper layer is dry and warm.

3–11 Scattering Phenomena

Reception far beyond the optical horizon in VHF and UHF range is possible due to scatter propagation. Both troposphere and ionosphere are in continual state of turbulence. This gives rise to local variation in $'n'$ of the atmosphere. Waves passing through such turbulent regions get scattered. When λ is large compared to the size of the turbulent eddies, waves scatter in all the directions. When λ is small compared to these irregularities then most of the scattering takes place within a narrow cone surrounding the forward direction of propagation of the incident radiation. To receive scattered signal at a point well beyond the horizon, the transmitting and receiving antennas must be of high gain and must be so oriented that their beams overlap in a region where forward scattering is taking place. The scattering angle should also be as small as possible. This process is shown in Fig. 3–15. Since the scattering process is of random nature, the scattered signals continuously fluctuate in amplitude and phase over a wide range. The scattering is of significant practical utility in the following regions:

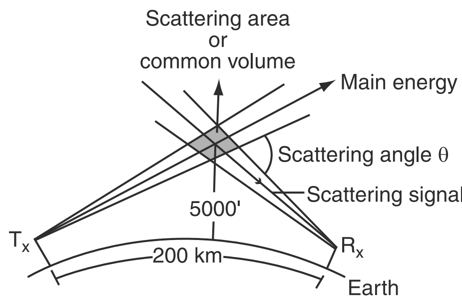


Figure 3–15 Illustraction of the scattering process.

- **500 MHz onwards with troposphere as the scattering medium**. It is called *tropospheric scattering*. Depending upon the bandwidth of transmitter, its maximum range lies between 300 to 600 km.
- **30 to 50 MHz with ionosphere as medium**. It is called *ionospheric scattering* and mainly occurs in the E region with maximum range of about 2000 km. The level of scattered signals in this case is much small, some 10 to 20 dB below the free space signal for the same distance.

3–12 Tropospheric Propagation

The scattering phenomena discussed above can be utilized for the communication purpose. A general mathematical relation governing the received power at a distance can be derived as below:

Consider an omnidirectional antenna which radiates uniformly in all directions. Let the transmitted power be denoted by P_t and the power density (i.e., the power per unit area) in free space at a distance R from the transmitter is denoted by P_{rf}. It will be equal to the transmitted power divided by the surface area $4\pi R^2$of an imaginary sphere of radius R. Thus

$$P_{rf} = \frac{P_t}{4\pi R^2} \text{ watts} \tag{1}$$

If the transmitting antenna is directional with gain G_t, the increased power reaching the point of observation as compared to the power that would have been reaching in case of an omni-directional antenna is given by

$$P_{rf} = \frac{P_t G_t}{4\pi R^2} \text{ watts} \tag{2}$$

At the point of observation, the receiving antenna will capture a portion of this radiated power. If the effective capture area of the receiving antenna is A_r, the received power will be

$$P_{rf} = \frac{P_t G_t A_r}{4\pi R^2} \text{ watts} \tag{3}$$

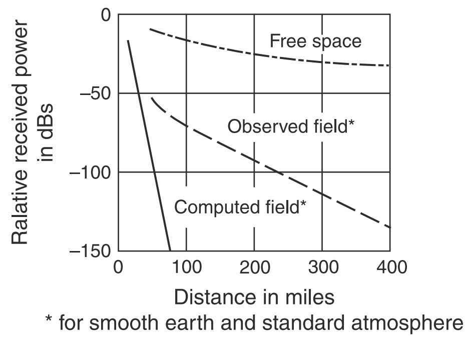


Figure 3–16 Relative received power for observed field and computed field.

The antenna gain G_r and the effective area A_r for receiving antenna bear the following relations:

$$G_r = \frac{4\pi A_r}{\lambda^2} \quad \text{or} \quad A_r = \frac{\lambda^2 G_r}{4\pi} \tag{4}$$

Substitution of A_r in the expression of P_{rf} results in

$$P_{rf} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \text{ watts} \tag{5}$$

In all above relations, λ is the wavelength.

In case of involvement of scattering process, P_{rf} will be obtained by multiplying RHS of (5) by an attenuation factor F given by

$$F = \frac{2}{R\sqrt{\pi}}\sqrt{\sigma(\theta)v} \tag{6}$$

where $\sigma(\theta)$ is the effective scattering cross-section, v is the scattering (common) volume and θ is the scattering angle, both shown in Fig. 3–15.

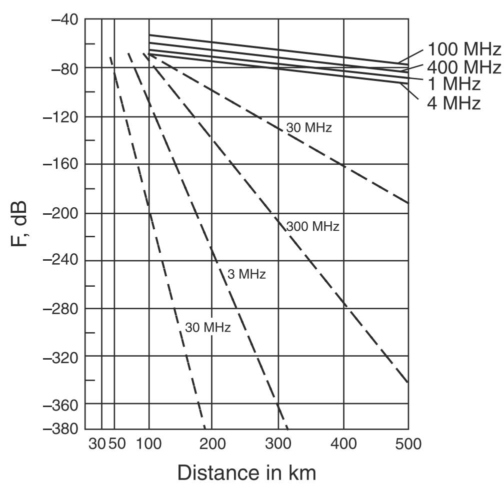


Figure 3–17 Variation of attenuation factor *F* index *n* with distance.

As reported in the literature, the received power at different distances was computed for smooth earth and standard atmospheric conditions in view of (9) of Sec. 3–9 alone and after incorporating attenuation factor spelled by (10). It is further mentioned that when the power at these distances was experimentally measured, the results were quite surprising. Figure 3–16 illustrates a plot of received power vs the distance containing these results. It can be noted that the theoretically computed values have much steeper slope than for those experimentally obtained in the shadow zone. To further elaborate, Fig. 3–17 illustrates variation of attenuation factor **F** with distance for a number of frequencies. There are mainly two interpretations for the availability of strong signals which are termed as *turbulent scattering theory* and *layer reflection theory.*

1. **Turbulent Scattering Theory** *P* According to this theory there is a turbulent variation of refractive index '*n*' with height. The twinkling of stars, wavering appearance of objects seen over the earth's surface, heated by the sun, and random erratic appearance of exhaust gases left by the aircraft engines are said to be the result of turbulent variation of *n*.
2. **Layer Reflection Theory** *P* In this theory, it is presumed that there are a large number of randomly distributed layers with different refractive indices. These layers result in scattering of part of the transmitted energy towards the earth.

Whether there is a turbulent change of *n* or there are large number of randomly dispersed layers in common volume, it is observed that attenuation does not exceed 100 dB even in the worst case at a distance of 500 km.

Figure 3–18 illustrates the refractive index profile plotted by a refractometer (with fading) at 3.67 GHz. it can be noted that despite fading of the signal, the profile is sufficiently stable.

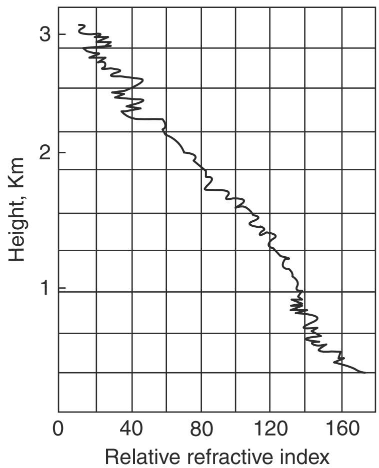


Figure 3–18 Variation of refraction with height.

EXAMPLE 3–12.1 A wave originates from the transmitting antenna with 10 dB gain and 100 watts radiating power at 10 MHz. It is received by an antenna with 15 dB gain located at a 20 km distance. Calculate the received power if the wave (a) travels in free space, (b) gets attenuated due to scattering from common volume of 1000 m^3 with an effective scattering cross-section of 0.1 m^2.

Solution

In view of (25 and 26)

$$(a)\quad P_{rf} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} = \frac{100\times 10\times 15\times 300\times 300}{4\pi\times 4\pi\times(20\times 10^3)^2} = \frac{135\times 10^7}{640\times 10^8} = 21.1\text{mW}$$

$$(b)\quad F = \frac{2}{R\sqrt{\pi}}\sqrt{\sigma(\theta)v} = \frac{2}{20\times 10^3\sqrt{\pi}}\sqrt{0.1\times 1000} = \frac{10^{-3}}{1.77} = 0.565\times 10^{-3}$$

Net $P_{rf} = 21.1\times 0.565\times 10^{-6} = 11.9215\times 10^{-6}$watts

3–13 Fading

The tropospheric signals often suffer from fading which is a phenomenon of reduction of signals due to variation in refractive index. This variation is attributed to sudden changes in temperature, pressure and humidity. Figure 3–19 shows the variation of signal in view of the fading phenomena.

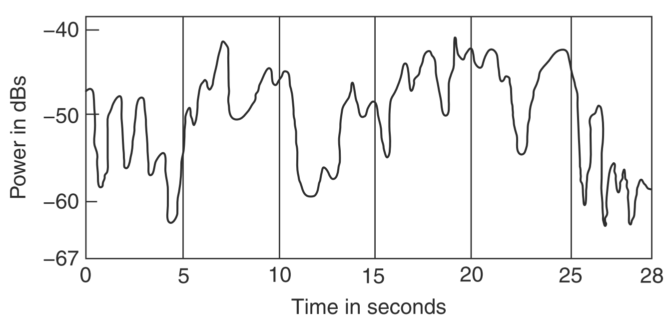


Figure 3–19 Fading phenomena.

Fading normally is of Rayleigh nature. It can be classified in many ways. It can be fast or slow, single path or multi-path and short term or long term. For fast or multi-path fading, the duration is of the order of 0.01 second. Also, for long-term fading, on an average, the variation of the signal is of the order of 10 dB. It has been observed that the summer signals are about 10 dB stronger than winter signals. Also, the morning and evening signals are nearly 5 dB more than afternoon signals.

The fading phenomena may occasionally result in sudden disruption of communication. To avoid the same, the techniques employed are called *diversity techniques*. These include (two or four fold) space diversity, frequency diversity, time diversity, modulation diversity and the polarization diversity.

Though the frequency range for tropospheric communication links varies between 300 to 10000 MHz, frequencies from 700 to 5000 MHz are more commonly used. Below 700 MHz, the antenna becomes too large and the scattering volume too inadequate. Also, above 5000 MHz, there are excessive attenuation due to oxygen, water vapors and rain. Besides, non availability of high power transmitters also makes the use of higher frequencies impractical.

3–14 Path Loss Calculations

The basic path loss for general communication is given by the relation

$$\text{path loss} = 32.45 + 20\log_{10} f_{MHz} + 20\log_{10} d_{km} \quad (1)$$

$$\text{The total path loss in dBs} = L_{\text{total}} = L_{fs} + L_s + L_{\text{ref}} + L_{\text{fad}} + L_{\text{cpl}} + G_t - G_r \quad (2)$$

where L_{fs} is the free space path loss and is given by

$$L_{fs} = 10\log_{10}(4\pi d/R)^2 \quad (3)$$

L_s is the medium scattering loss and is given by

$$L_s = 57 + 10(\theta - 1)10\log_{10}(f_{MHz}/400) \quad (\text{for } \theta_0 > 1°) \quad (4)$$

$$\theta = (\theta_0 - \theta_1 - \theta_2) = [(d - d_1 - d_2)/R]\,(180/\pi) \text{ degrees} \quad (5)$$

$$L_{\text{ref}} = -0.2(N_S - 310),\ N_s = (n_s - 1) \times 10^{-6} \quad (6)$$

n_s is the surface refractive index,
L_{fad} is the fading margin in dBs, and
L_{cpl} is the aperture to medium coupling loss and is given by

$$L_{\text{cpl}} = 0.07\exp[0.055\,(G_t + G_r)]\ \text{dB} \quad (7)$$

G_t and G_r are gains of transmitting and receiving antennas. The parameters $\theta_0, \theta_1, \theta_2$, d, d_1 and d_2 are shown in Fig. 3–20.

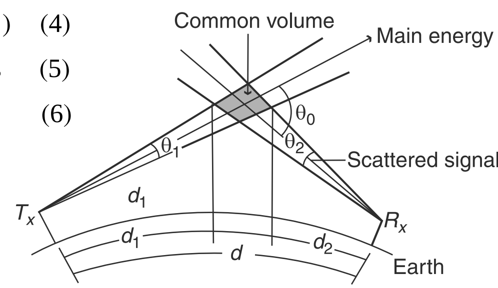


Figure 3–20 Parameter involved in loss calculation.

EXAMPLE 3–14.1 Find the basic path loss for communication between two points 3000 km apart at a frequency of 3 GHz.

■ Solution

In view of (1)

$$\begin{aligned}\text{Path loss} &= 32.45 + 20\log_{10} f_{\text{MHz}} + 20\log_{10} d_{\text{km}}\\ &= 32.45 + 20\log_{10}3000 + 20\log_{10}3000\\ &= 32.45 + 20\times 3.4771 + 20 \times 3.4771 = 171.534\ dB\end{aligned}$$

Problems

3–9–1 **LOS distance.** The transmitting and receiving antennas with respective heights of 64 m and 25 m are installed to establish communication at 10 MHz with transmitted power of 100 watts. Determine the LOS distance and the received signal strength thereat.

3–9–2 **Maximum distance and radio horizon distance.** Calculate the maximum distance at which signal from transmitting antenna with 121 m height would be received by the receiving antenna of 16 m height. Also, calculate the radio horizon distance for $k = 4/3$ model of earth with standard value of radius.

3–9–3 **Signal strength.** A transmitting antenna of 100 m height radiates 50 kW at 30 MHz uniformly in azimuth plane. Calculate the maximum LOS range and strength of the received signal at 9 m high receiving antenna at a distance of 20 km. At what distance would the signal strength reduce to half of that received at 20 km?

3–9–4 **Effective area.** A directional antenna with 20 dB gain radiates 300 watts. The receiving antenna at 25 km distance receives 10 μW. Find the effective area of the receiving antenna. Assume negligible ground and ionospheric reflections.

3–9–5 **Maximum frequency.** Calculate the maximum frequency which can be transmitted by a duct of 100 m height if the total change in M is of the order of 0.040.

3–12–1 **Power received.** Calculate the power received at 100 km distance if a wave originates from the transmitting antenna with 10 dB gain and 500 watts radiating power at 15 MHz. Assume the same gain for the receiving antenna.

3–14–1 **Basic path loss.** Find the basic path loss for communication between two points, 2000 km apart, at a frequency of 5 GHz.

Note: (References are given at the end of Chapter 25)