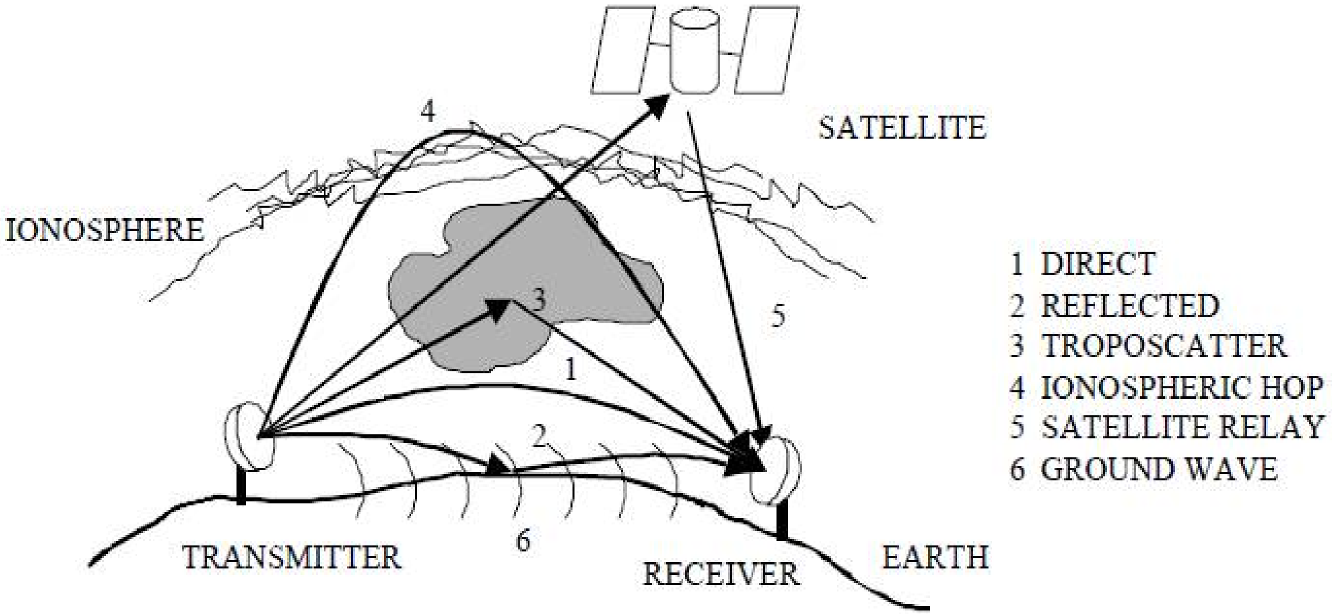
Propagation

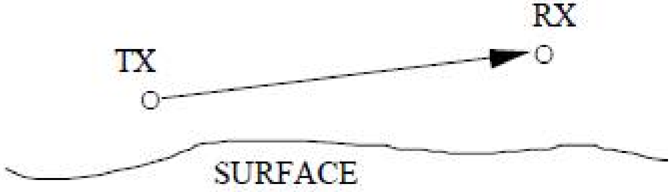
Radiating systems must operate in a complex changing environment that interacts with propagating electromagnetic waves. Commonly observed propagation effects are depicted below.



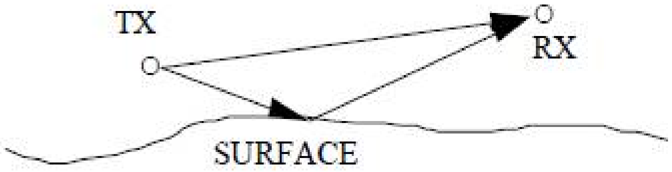
<u>Troposphere</u>: lower regions of the atmosphere (less than 10 km)
<u>Ionosphere</u>: upper regions of the atmosphere (50 km to 1000 km)

There are may propagation mechanisms by which signals can travel between the radar transmitter and receiver. Except for line-of-sight (LOS) paths, the mechanism's effectiveness is generally a strong function of the frequency and transmitter-receiver geometry.

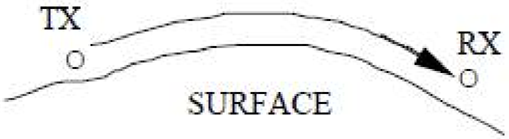
1. direct path or "line of sight" (most radars; SHF links from ground to satellites)



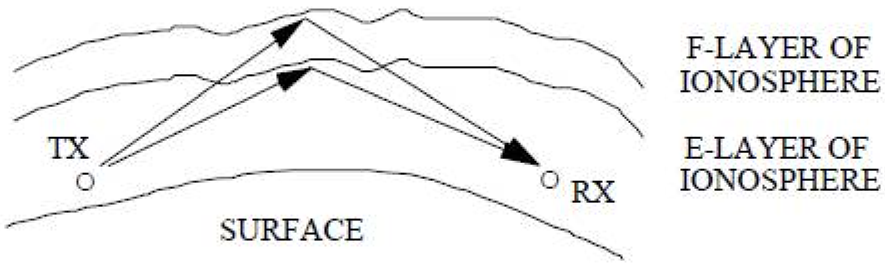
2. direct plus earth reflections or "multipath" (UHF broadcast; ground-to-air and air-to-air communications)



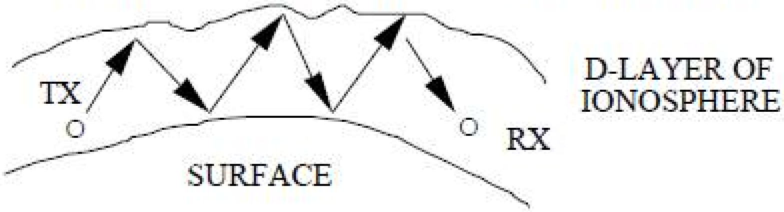
3. ground wave (AM broadcast; Loran C navigation at short ranges)



4. ionospheric hop (MF and HF broadcast and communications)

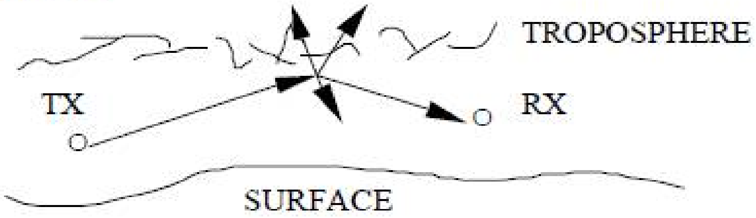


5. waveguide modes or "ionospheric ducting" (VLF and LF communications)

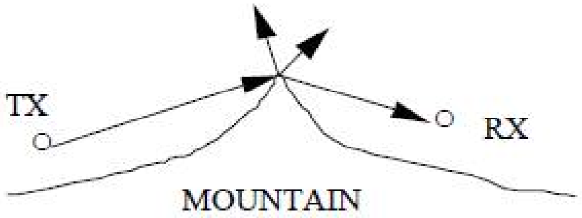


Note: The distinction between ionospheric hops and waveguide modes is based more on the mathematical models than on physical processes.

6. tropospheric paths or "troposcatter" (microwave links; over-the-horizon (OTH) radar and communications)



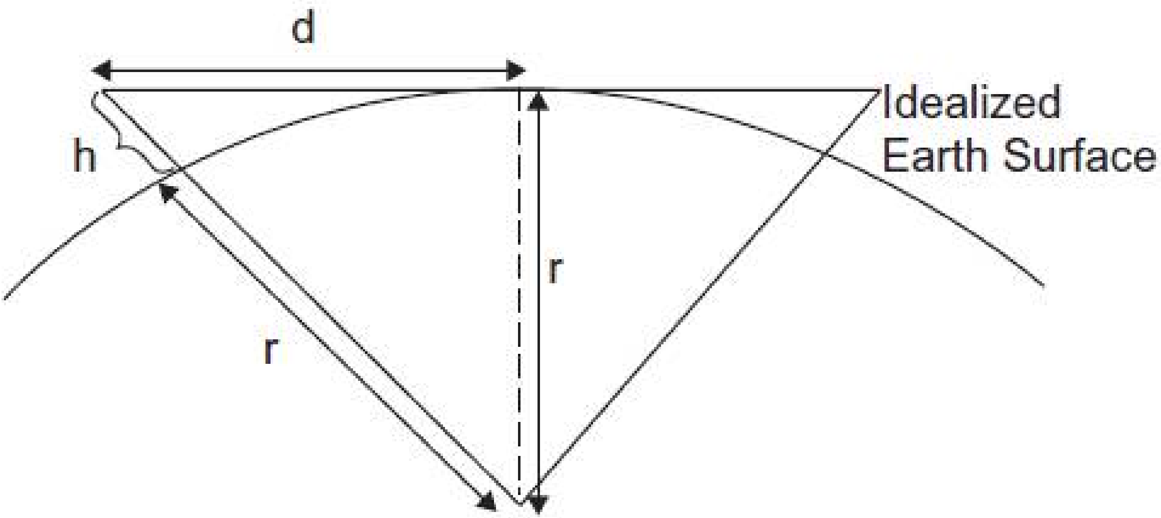
7. terrain diffraction



Line-of-Sight Propagation and the Radio Horizon

In free space, electromagnetic waves are modeled as propagating outward from the source in all directions, resulting in a spherical wave front. Such a source is called an isotropic radiator and in the strictest sense, does not exist. As the distance from the source increases, the spherical wave (or phase) front converges to a planar wave front over any finite area of interest, which is how the propagation is modeled. The direction of propagation at any given point on the wave front is given by the vector cross product of the electric (**E**) field and the magnetic (**H**) field at that point. The *polarization* of a wave is defined as the orientation of the plane that contains the **E** field. This will be discussed further in the following chapters, but for now it is sufficient to understand that the polarization of the receiving antenna should ideally be the same as the polarization of the received wave and that the polarization of a transmitted wave is the same as that of the antenna from which it emanated.*

$$\mathbf{P} = \mathbf{E} \times \mathbf{H}$$



When considering line-of-sight (LOS) propagation, it may be necessary to consider the curvature of the earth (Figure 1.1). The curvature of the earth is a fundamental geometric limit on LOS propagation. In particular, if the distance between the transmitter and receiver is large compared to the height of the antennas, then an LOS may not exist. The simplest model is to treat the earth as a sphere with a radius equivalent to the equatorial radius of the earth.

From geometry

$$d^2 + r^2 = (r + h)^2$$

So

$$d^2 = (2r + h)h$$

Non-LOS Propagation

There are several means of electromagnetic wave propagation beyond LOS propagation. The mechanisms of non-LOS propagation vary considerably, based on the operating frequency. At VHF and UHF frequencies, indirect propagation is often used. Examples of indirect propagation are cell phones, pagers, and some military communications. An LOS may or may not exist for these systems. In the absence of an LOS path, diffraction, refraction, and/or multipath reflections are the dominant propagation modes. *Diffraction* is the phenomenon of electromagnetic waves bending at the edge of a blockage, resulting in the shadow of the blockage being partially filled-in. *Refraction* is the bending of electromagnetic waves due to inhomogeniety in the medium. *Multipath* is the effect of reflections from multiple objects in the field of view, which can result in many different copies of the wave arriving at the receiver.

1.2.2.1 Indirect or Obstructed Propagation While not a literal definition, indirect propagation aptly describes terrestrial propagation where the LOS is obstructed. In such cases, reflection from and diffraction around buildings and foliage may provide enough signal strength for meaningful communication to take place. The efficacy of indirect propagation depends upon the amount of margin in the communication link and the strength of the diffracted or reflected signals. The operating frequency has a significant impact on the viability of indirect propagation, with lower frequencies working the best. HF frequencies can penetrate buildings and heavy foliage quite easily. VHF and UHF can penetrate building and foliage also, but to a lesser extent. At the same time, VHF and UHF will have a greater tendency to diffract around or reflect/scatter off of objects in the path. Above UHF, indirect propagation becomes very inefficient and is seldom used. When the features of the obstruction are large compared to the wavelength, the obstruction will tend to reflect or diffract the wave rather than scatter it.

1.2.2.2 Tropospheric Propagation The troposphere is the first (lowest) 10 km of the atmosphere, where weather effects exist. Tropospheric propagation consists of reflection (refraction) of RF from temperature and moisture layers in the atmosphere. Tropospheric propagation is less reliable than ionospheric propagation, but the phenomenon occurs often enough to be a concern in frequency planning. This effect is sometimes called *ducting*, although technically ducting consists of an elevated channel or duct in the atmosphere.

Propagation Effects as a Function of Frequency

The very low frequency (VLF) band covers 3–30 kHz. The low frequency dictates that large antennas are required to achieve a reasonable efficiency. A good rule of thumb is that the antenna must be on the order of one-tenth of a wavelength or more in size to provide efficient performance. The VLF band only permits narrow bandwidths to be used (the entire band is only 27 kHz wide). The primarily mode of propagation in the VLF range is ground-wave propagation. VLF has been successfully used with underground antennas for submarine communication.

The low-(LF) and medium-frequency (MF) bands, cover the range from 30 kHz to 3 MHz. Both bands use ground-wave propagation and some sky wave. While the wavelengths are smaller than the VLF band, these bands still require very large antennas. These frequencies permit slightly greater bandwidth than the VLF band. Uses include broadcast AM radio and the WWVB time reference signal that is broadcast at 60 kHz for automatic ("atomic") clocks.

The high-frequency (HF), band covers 3–30 MHz. These frequencies support some ground-wave propagation, but most HF communication is via sky wave. There are few remaining commercial uses due to unreliability, but HF sky waves were once the primary means of long-distance communication.

The very high frequency (VHF) and ultra-high frequency (UHF) cover frequencies from 30 MHz to 3 GHz. In these ranges, there is very little ionospheric propagation, which makes them ideal for frequency reuse. There can be tropospheric effects, however, when conditions are right. For the most part, VHF and UHF waves travel by LOS and ground-bounce propagation. VHF and UHF systems can employ moderately sized antennas, making these frequencies a good choice for mobile communications. Applications of these frequencies include broadcast FM radio, aircraft radio, cellular/PCS telephones, the Family Radio Service (FRS), pagers, public service radio such as police and fire departments, and the Global Positioning System (GPS). These bands are the region where satellite communication begins since the signals can penetrate the ionosphere with minimal loss.

The super-high-frequency (SHF) frequencies include 3–30 GHz and use strictly LOS propagation. In this band, very small antennas can be employed, or, more typically, moderately sized directional antennas with high gain. Applications of the SHF band include satellite communications, direct broadcast satellite television, and point-to-point links. Precipitation and gaseous absorption can be an issue in these frequency ranges, particularly near the higher end of the range and at longer distances.

The extra-high-frequency (EHF) band covers 30–300 GHz and is often called *millimeter wave*. In this region, much greater bandwidths are available. Propagation is strictly LOS, and precipitation and gaseous absorption are a significant issue.

VLF and LF (10 to 200 kHz)	Waveguide mode between Earth and D-layer; ground wave at short distances
LF to MF (200 kHz to 2 MHz)	Transition between ground wave and mode predominance and sky wave (ionospheric hops). Sky wave especially pronounced at night.
HF (2 MHz to 30 MHz)	Ionospheric hops. Very long distance communications with low power and simple antennas. The "short wave" band.
VHF (30 MHz to 100 MHz)	With low power and small antennas, primarily for local use using direct or direct-plus-Earth-reflected propagation; ducting can greatly increase this range. With large antennas and high power, ionospheric scatter communications.
UHF (80 MHz to 500 MHz)	Direct: early-warning radars, aircraft-to satellite and satellite-to-satellite communications. Direct-plus-Earth-reflected: air-to-ground communications, local television. Tropospheric scattering: when large highly directional antennas and high power are used.
SHF (500 MHz to 10 GHz)	Direct: most radars, satellite communications. Tropospheric refraction and terrain diffraction become important in microwave links and in satellite communication, at low altitudes.

Friis Equation Origins

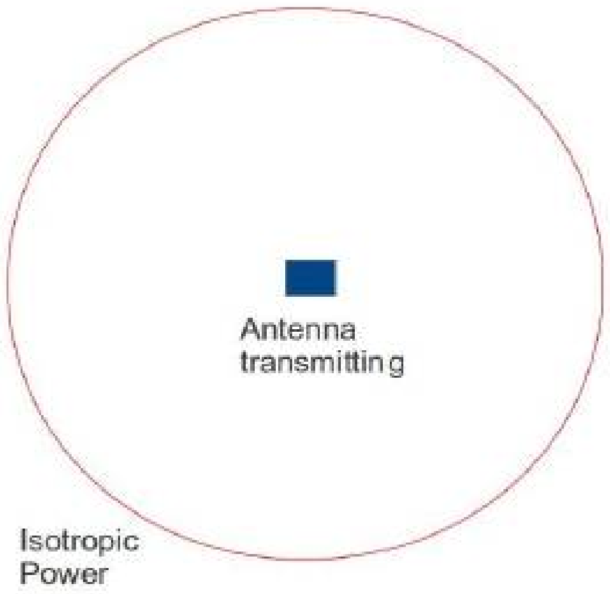
- Derived in 1945 by Bell Labs worker Harald T. Friss
- Gives the amount of power an antenna received under ideal conditions from another antenna
  - Antennas must be in far field
  - Antennas are in unobstructed free space
  - Bandwidth is narrow enough that a single wavelength can be assumed
  - Antennas are correctly aligned and polarized

Simple Form of Friis Equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

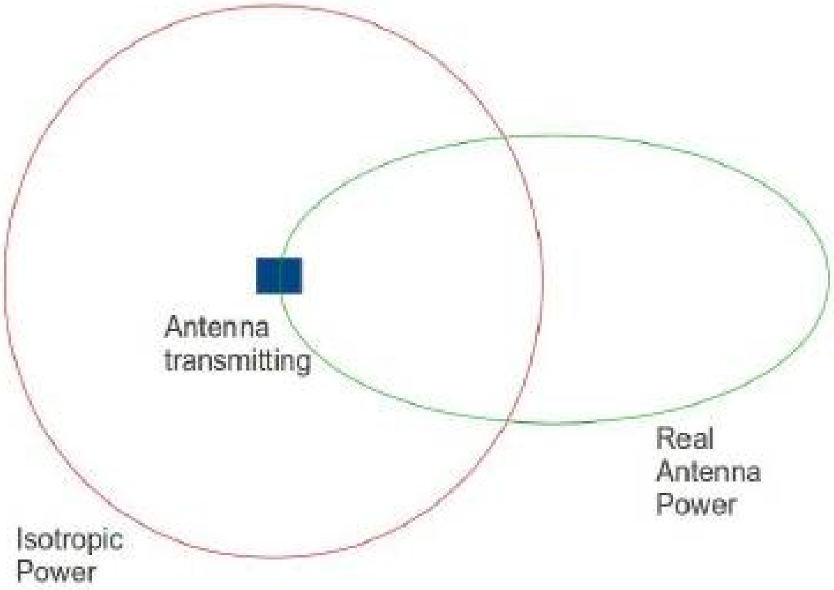
- P_r : Power at the receiving antenna
- P_t : output power of transmitting antenna
- G_t, G_r: gain of the transmitting and receiving antenna, respectively
- λ: wavelength
- R: distance between the antenna

Derivation of equation



- Power from isotropic antenna falls off as r^2
- Power density (p) would be:

$$p = \frac{P_t}{4\pi R^2}$$



Multiplying by gain of the transmitting antenna gives a real antenna pattern

$$p = \frac{P_t}{4\pi R^2} G_t$$

- If receiving antenna has an effective aperture of A_{eff} the power received by this antenna (P_r) is

$$P_r = p\,A_{eff}$$

thus:

$$P_r = \frac{P_t}{4\pi R^2} G_t A_{eff}$$

- The effective aperture of an antenna can be written as

$$A_e = \frac{\lambda^2}{4\pi} G$$

plugging in:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Modifications to Friis equation (Complicated Form)

$$\frac{P_r}{P_t}=G_t(\theta_t,\varphi_t)G_r(\theta_r,\varphi_r)\left(\frac{\lambda}{4\pi R}\right)^2(1-|\Gamma_t|^2)(1-|\Gamma_r|^2)\left|\boldsymbol{a}_t\cdot\boldsymbol{a}_r^*\right|^2 e^{-\alpha R}$$

- G_t , G_r : modifications to gain of antennas in which the antennas “see” each other.
- Γ_t and Γ_t are the reflection coefficients of the antennas
- $\mathbf{a}_t$ and $\mathbf{a}_r$ are the polarization vectors of the antennas
- α is the absorption coefficient of the medium

Communication Systems and the Link Budget

Radio-frequency (RF) planning for networks such as cellular telephone systems or wireless local area networks (LANs) is a key part of network deployment. Insufficient planning can result in overdesign and wasted resources or under design and poor system performance. Prior to planning a network, the parameters controlling the performance of each individual link must be understood. The essential parameters are the received signal strength, the noise that accompanies the received signal, and any additional channel impairments beyond attenuation, such as multipath or interference.

For link planning, a ***link budget*** is prepared that accounts for the transmitter effective isotropically radiated power (EIRP) and all of the losses in the link prior to the receiver

The *link margin* is obtained by comparing the expected received signal strength to the receiver sensitivity or threshold (in satellite systems, the term sensitivity has a different meaning). The link margin is a measure of how much margin there is in the communications link between the operating point and the point where the link can no longer be closed. The link margin can be found using

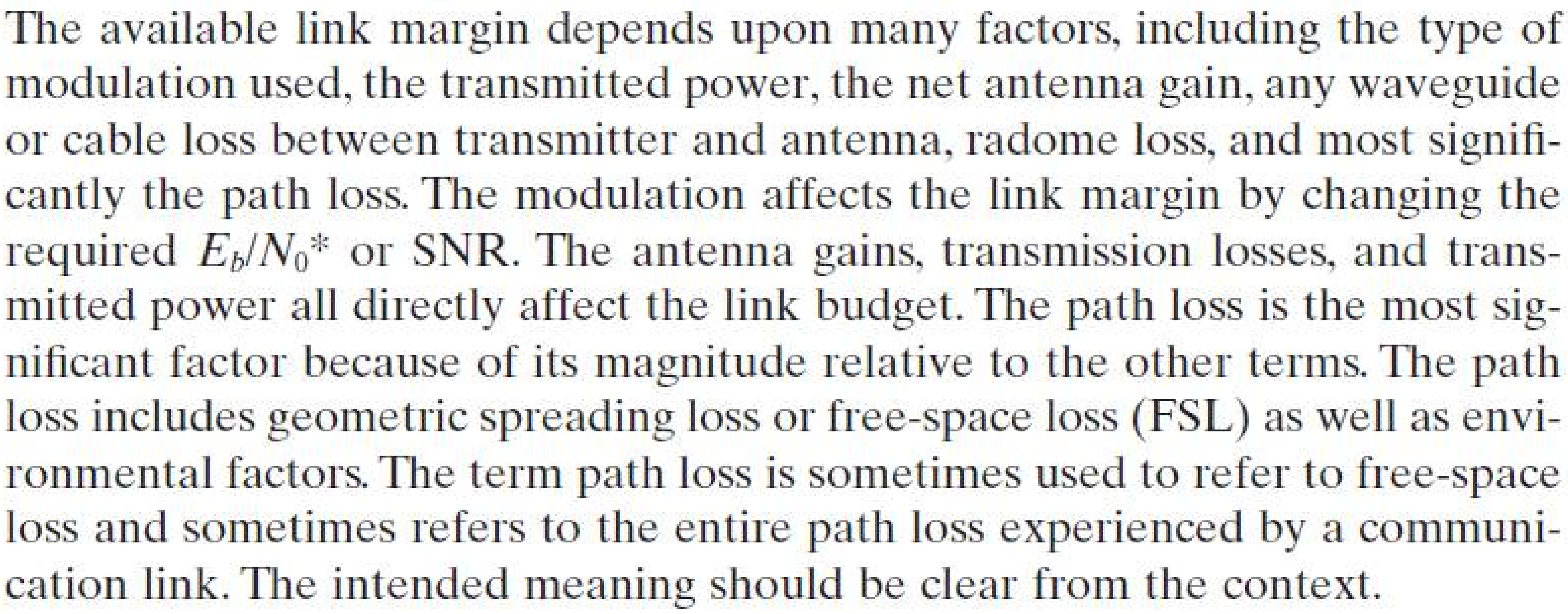
$$\text{Link margin} = \text{EIRP} - L_{Path} + G_{Rx} - \text{TH}_{Rx}$$

EIRP is the effective isotropically radiated power in dBW or dBm

L_{Path} is the total path loss, including miscellaneous losses, reflections, and fade margins in dB

G_{Rx} is the receive gain in dB

TH_{Rx} is the receiver threshold or the minimum received signal level that will provide reliable operation (such as the desired bit error rate performance) in dBW or dBm



The available link margin depends upon many factors, including the type of modulation used, the transmitted power, the net antenna gain, any waveguide or cable loss between transmitter and antenna, radome loss, and most significantly the path loss. The modulation affects the link margin by changing the required E_b/N_0* or SNR. The antenna gains, transmission losses, and transmitted power all directly affect the link budget. The path loss is the most significant factor because of its magnitude relative to the other terms. The path loss includes geometric spreading loss or free-space loss (FSL) as well as environmental factors. The term path loss is sometimes used to refer to free-space loss and sometimes refers to the entire path loss experienced by a communication link. The intended meaning should be clear from the context.

PATH LOSS

Path loss is the link budget element of primary interest in this text as it relates to the topic of RF propagation.The path loss elements include free-space loss, atmospheric losses due to gaseous and water vapor absorption, precipitation, fading loss due to multipath, and other miscellaneous effects based on frequency and the environment.

If the principal path is governed by free-space loss, it is calculated using the Friis free-space loss equation, which can be expressed as

$$L = G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2 \tag{4.1}$$

L is actually a gain (albeit less than unity) rather than a loss.

The antenna gain accounts for the antenna directivity and efficiency, while the inverse distance squared term accounts for the spherical wave-front (geometric) spreading. The dependence on wavelength is an artifact of using the receive antenna gain in the equation rather than the antenna effective area.

The Friis free-space loss equation can be expressed in dB as

$$L_{dB} = -G_{TdB} - G_{RdB} - 20\log(\lambda) + 20\log(d) + 22 \tag{4.2}$$

4.5.1 EIRP

After the first introductory lines of the link budget in 4.4, the next several lines are dedicated to computing the transmitted EIRP. The EIRP is the transmit power plus the antenna gain, minus any waveguide and/or radome losses. Thus

$$\mathrm{EIRP}_{dB} = P_{TxdBm} + G_{TxdB} - L_{WGdB} - L_{R}\mathrm{dBm}$$

4.5.3 Receiver Gain

The receiver gain is equal to the antenna gain less any radome loss, cable or waveguide loss (receiver loss), polarization loss, and pointing loss.

$$G_{RdB} = G_{RxdB} - L_{RadomedB} - L_{WGdB} - L_{Pol} - L_{Pt}$$

The result of a link calculation may be the expected received signal level (RSL), the signal-to-noise ratio (SNR), the carrier-to-noise ratio (CNR), or the bit energy to noise PSD ratio (E_b/N_0). If the RSL is determined, it can be compared to the *minimum detectable signal* (MDS), or the system threshold.

ATMOSPHERIC ATTENUATION

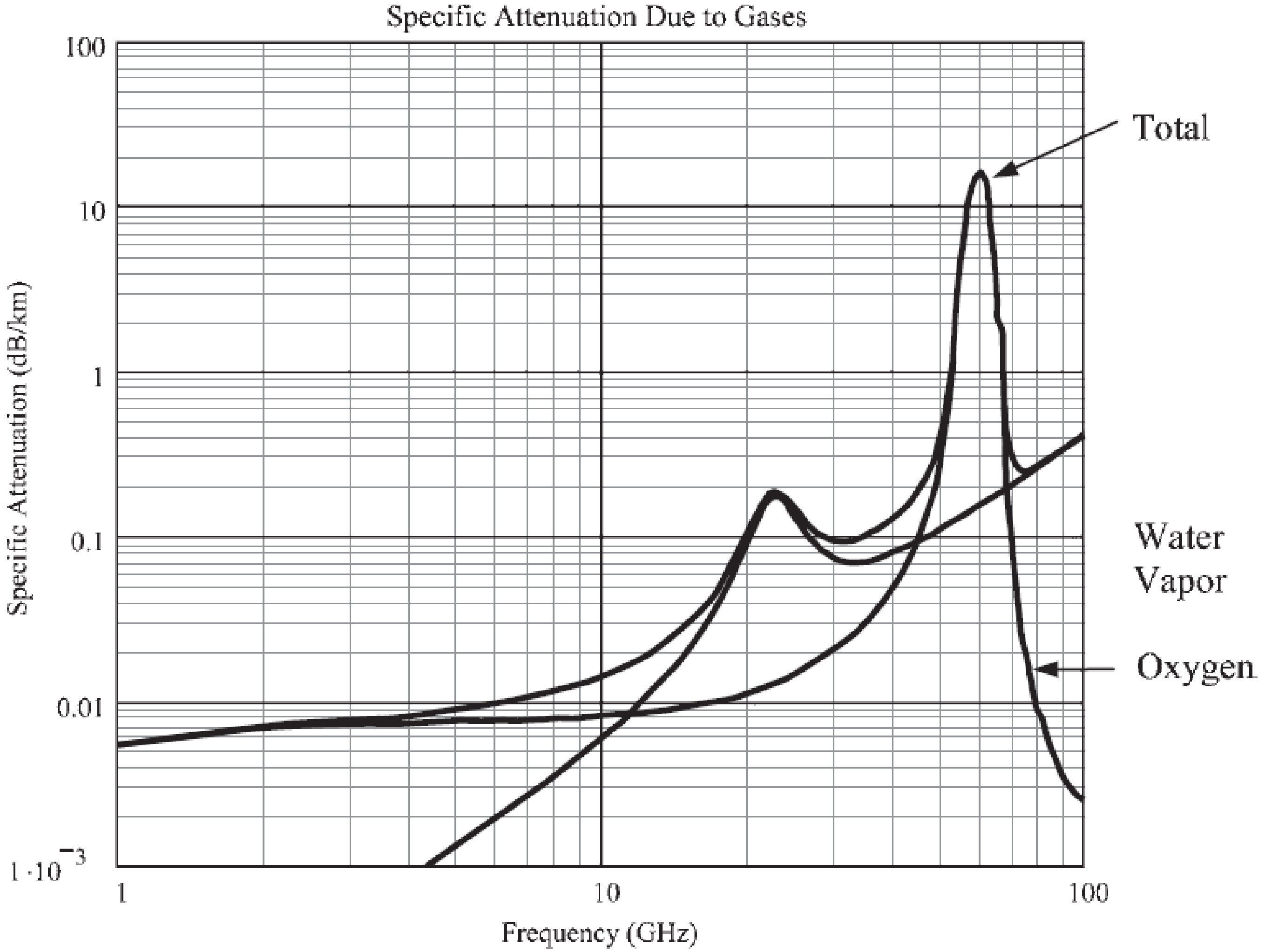
The atmosphere is comprised of gases, which absorb electromagnetic energy at various frequencies. Atmospheric attenuation due to gaseous absorption should not be confused with multipath or rain fades; it is a different mechanism. The gases of primary concern for microwave and millimeterwave systems are oxygen and water vapor. Similar to refraction, atmospheric losses also depend upon pressure, temperature, and water vapor content [12, 13]. For this reason, the effects can vary considerably with location, altitude, and the path slant angle. The atmosphere can be thought of as being comprised of horizontal layers at different altitudes, each having different water vapor and oxygen densities. Therefore, terrestrial links and earth-to-space/air links experience different atmospheric effects and must be modeled differently [12].

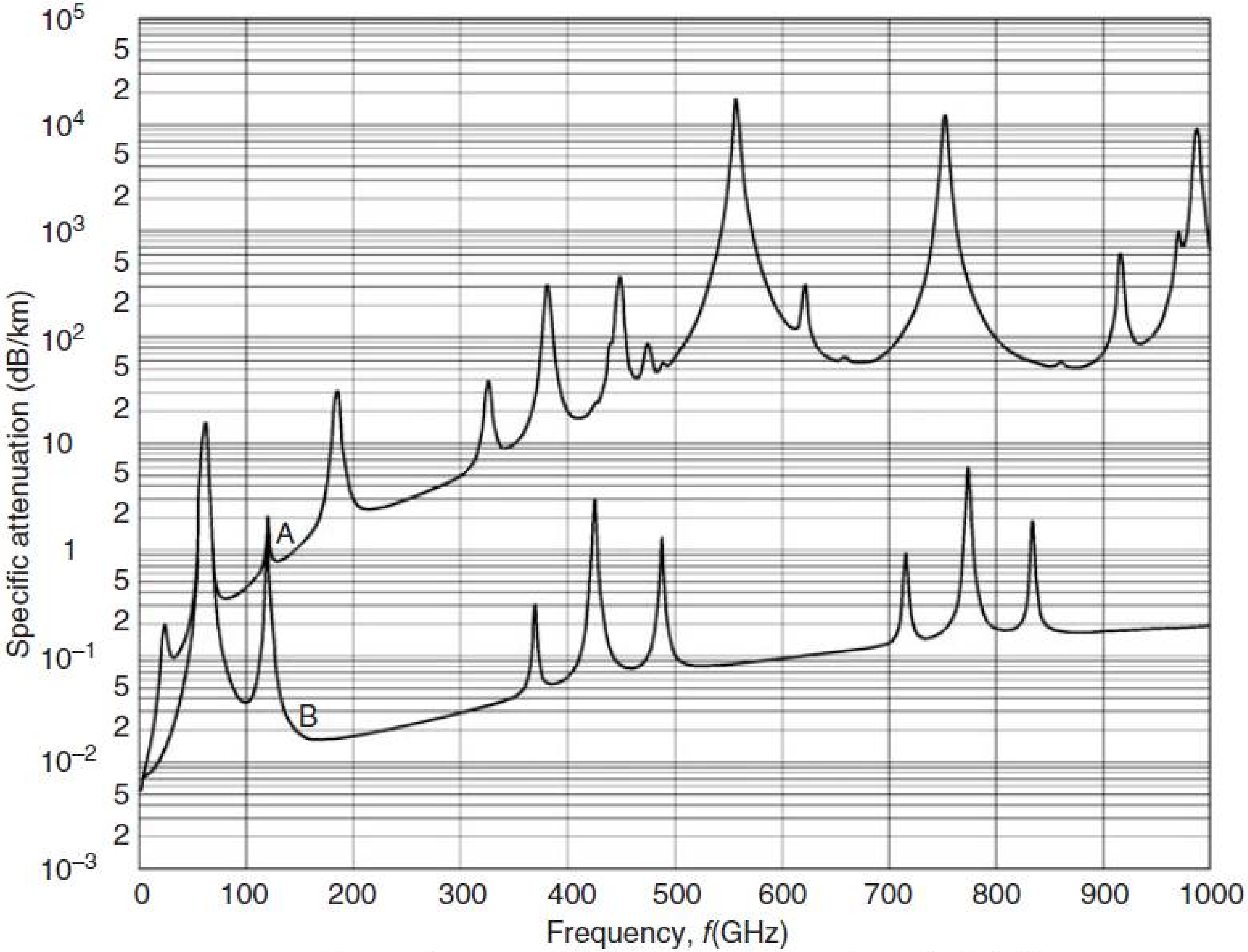
For terrestrial links where both terminals are at or near the same altitude, the atmosphere can be treated as constant over the path. In this case it makes sense to characterize the absorption as a specific attenuation value in dB/km, which can be applied to the path distance to determine the total attenuation.

$$A = \gamma_a d \qquad \text{dB}$$

where d is the line-of-sight distance between the terminals in km and γ_a is the specific attenuation of the atmosphere in dB/km. The specific attenuation of the atmosphere is given by the sum of the specific attenuation due to water vapor and that due to oxygen [12]:

$$\gamma_a = \gamma_o + \gamma_w$$





Curves A: mean global reference atmosphere (7.5 g/m^3)

B: dry atmosphere

Fog and Clouds

The ITU provides a recommended model for fog or cloud attenuation [14] that is valid up to 200 GHz. Application of this model and a few representative design curves for planning are presented in this section. The specific attenuation due to clouds or a fog bank is

$$\gamma_c = K_l M$$

where

γ_c is the specific attenuation of the cloud in dB/km
K_l is the specific attenuation coefficient of the cloud in (dB/km)/(g/m^3)
M is the liquid water density of the cloud in g/m^3

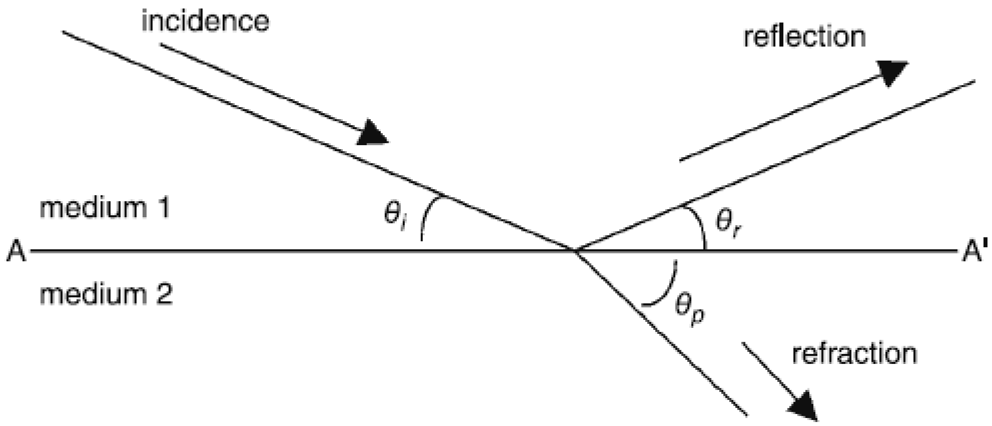
The ITU gives the liquid water density of a cloud or fog as

$$M = 0.05\ \mathrm{g/m^3} \text{ for medium fog (300-m visibility)}$$

$$M = 0.5\ \mathrm{g/m^3} \text{ for dense fog (50-m visibility)}$$

Reflection and scattering from rough surfaces

Radiowaves are reflected by the ground and from objects such as buildings. This can have various effects on radio systems. Reflections from buildings, etc., can permit a radio service to exist where the signal would otherwise be excessively attenuated by shadowing. Conversely, reflections can cause interference where shadowing alone would provide adequate attenuation of an unwanted signal. Reflections are also a major cause of multipath propagation. This can sometimes be exploited, particularly in a mobile radio system using code division multiple access (CDMA). For point-to-point links, on the other hand, ground reflections are generally viewed as an impairment, and every effort is made to minimise their effect.



The line A–A′ is the interface between two media of different electrical properties. Radio energy in medium 1 meets this interface at incidence angle θ_i. Due to the change in wave impedence at the interface, part of the incident energy is reflected, and by geometrical optics this will be at angle θ_r, equal to θ_i. The remainder will penetrate medium 2 at angle θ_p which in general will not equal θ_i. The change in direction of the penetrating ray is referred to as refraction, and the penetrating ray is often referred as the refracted ray. In radiowave propagation studies one of the two media is nearly always air.

6.2.1 The complex reflection coefficient

The reflection coefficient of a surface can be viewed as the transfer function of the reflection process. Since both amplitude and phase changes are possible at the point of reflection, the coefficient is in general complex. Thus if E_i and E_r are the complex values of the incident and reflected phasors immediately before and after the reflection point, we may write:

$$E_r = \rho\, E_i \tag{6.1}$$

where ρ = the complex reflection coefficient.

A reflection coefficient is a function of the electrical properties of the two media, the angle of incidence and of the frequency and polarisation of the incident signal.

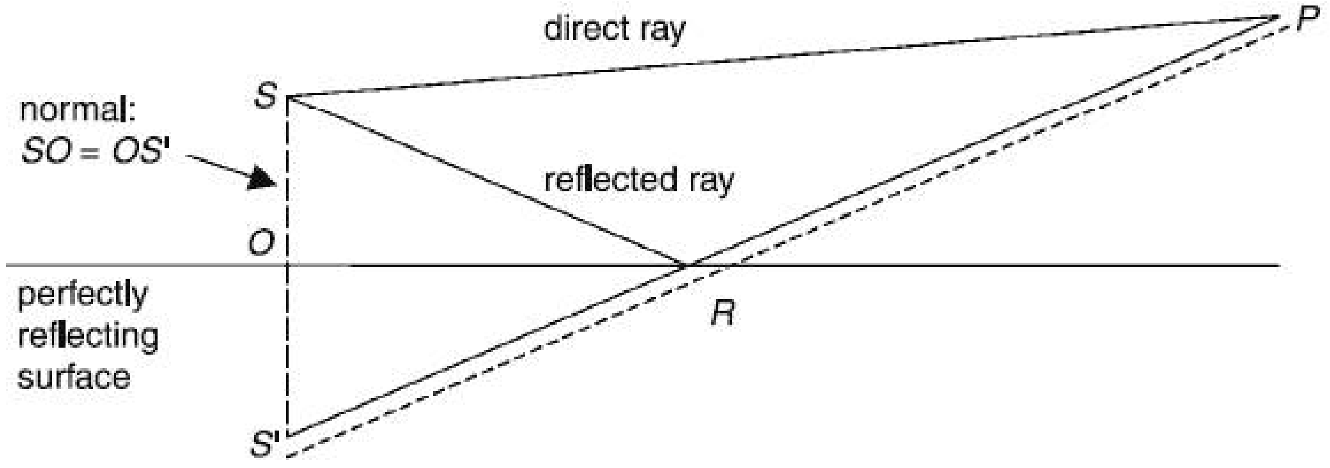
Reflection by perfectly-conducting surfaces

A perfectly-conducting surface is assumed to reflect perfectly, that is, there is no penetration and all of the incident energy is reradiated in the reflected wave. This is based on the principle that the tangential electric vector at a perfectly conducting surface must be zero. This is an idealisation which can only be approximated in reality, but is nevertheless a useful notion.

Before describing perfect reflection for the two incident polarisations it will be useful to introduce the concept of reflection images.

6.3.1 Theory of images

An image is a hypothetical source of radiation which can be useful in practical calculations concerning reflections by plane surfaces.



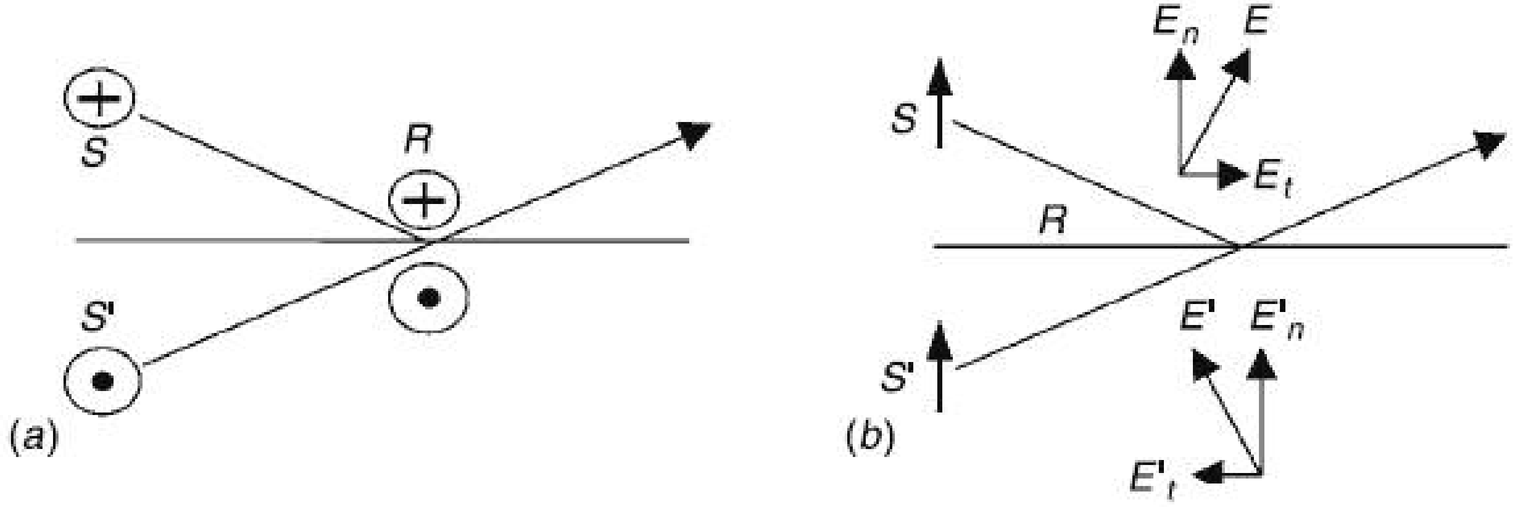


Figure 6.3 Perfect reflection
(a) Perpendicular polarisation
(b) Parallel polarisation

6.3.2 Perfect reflection for perpendicular polarisation

Figure 6.3*a* illustrates reflection from a perfectly-conducting surface for perpendicular polarisation.

The symbol ⊕ at reflection point *R* represents horizontal polarisation with the electric field pointing into the plane of the paper at a particular instance. Since the tangential electric field is zero, the image ray must produce an equi-amplitude opposite-phase field at the same point. This condition is satisfied by an image source having the same amplitude but opposite phase to *S*. Note that this satisfies the condition for all positions of *R*, since the real and image incident path lengths, *SR* and *S′R*, respectively, are equal for all points on the surface.

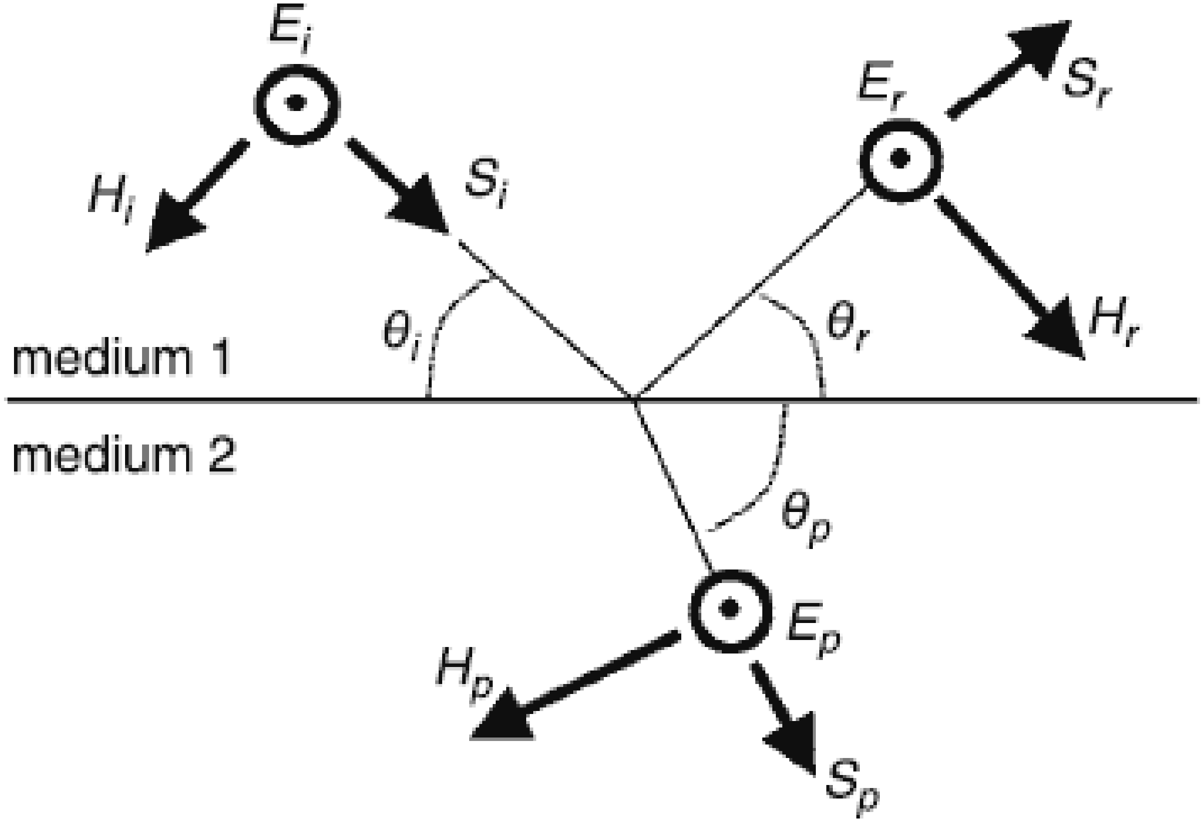
6.3.3 *Perfect reflection for parallel polarisation*

Figure 6.3*b* illustrates the same principle applied to parallel polarisation. In this case only the components of the electric fields tangential to the reflecting surface need to be considered.

The real incident electric field E at reflection point R can be resolved into its components normal and tangential to the reflecting surface, E_n and E_t, respectively. The tangential component E_t will be cancelled if the image source is of equal amplitude and in phase with S. The image tangential component E'_t will then be equal and opposite to E_t, and again this will be true for any point on the surface.

6.3.4 *Discussion of perfect-reflection results*

The above results suggest that for a perfect conductor the reflection coefficient will be $-1 + j.0$ for perpendicular polarisation and $1 + j.0$ for parallel polarisation. In fact, as shown in the following section of this Chapter, for small incidence angles (relative to the surface) reflection coefficients tend in practice to be close to -1 for both polarisations.


E_i
H_i
S_i
E_r
S_r
H_r
θ_i
θ_r
medium 1
medium 2
θ_p
E_p
H_p
S_p

We can now derive general reflection coefficients. The derivation will be given for perpendicular polarisation, and an expression simply stated for parallel polarisation.

Figure 6.6 shows the incident, reflected and refracted rays, with the *E* phasors pointing out of the paper, and the *H* vectors parallel to the paper as required for the direction of power transmission *S* for each ray.

From the continuity of tangential electric fields:

$$E_i + E_r = E_p \tag{6.10}$$

From the continuity of tangential magnetic fields and noting that $\theta_i = \theta_r$:

$$(H_i - H_r)\sin\theta_i = H_p \sin\theta_p \tag{6.11}$$

which is equivalent to:

$$(E_i - E_r)\sin\theta_i/Z_1 = E_p \sin\theta_p \,/\, Z_2 \tag{6.12}$$

where Z_1 and Z_2 are the impedances of medium 1 and 2, respectively.

Assuming that $\mu_1 = \mu_2$:

$$(E_i - E_r)\sin\theta_i \sqrt{\varepsilon_{r1}} = E_p \sin\theta_p \sqrt{\varepsilon_{r2}} \tag{6.13}$$

Combining Eqns. 6.11 and 6.13 to eliminate E_p:

$$\frac{E_r}{E_t} = \frac{\sin\theta_t\sqrt{\varepsilon_{r1}} + \sin\theta_t\sqrt{\varepsilon_{r2}}}{\sin\theta_t\sqrt{\varepsilon_{r1}} - \sin\theta_t\sqrt{\varepsilon_{r2}}} \tag{6.14}$$

It may be noted here that, if medium 1 is air or a vacuum, $\theta_p > \theta_t$ and thus E_r always has the opposite sign to E_t.

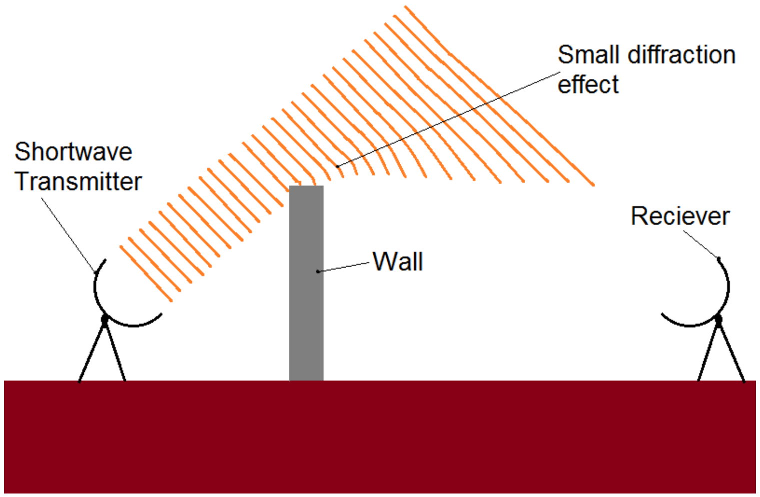
Using Snell's law (Eqn. 6.3) to write θ_p in terms of θ_t:

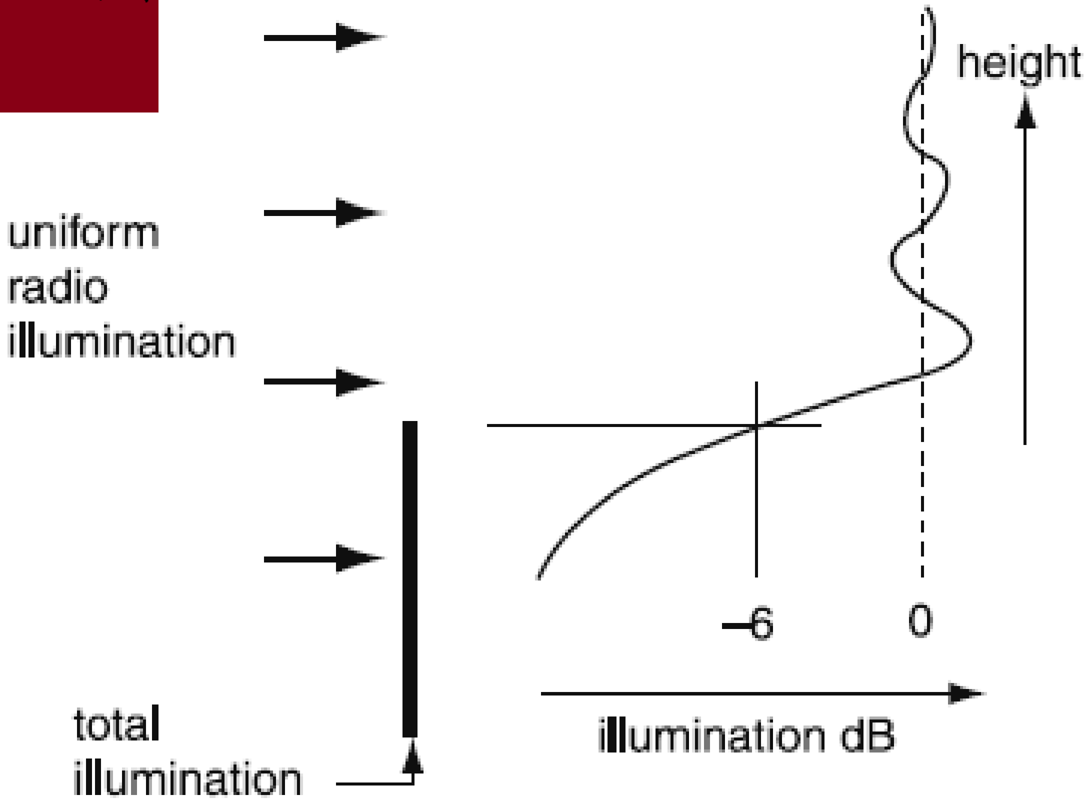
$$\frac{E_r}{E_t} = \frac{\varepsilon_{r1}\sin\theta_t - \sqrt{\varepsilon_{r2} - \varepsilon_{r1}\cos^2\theta}}{\varepsilon_{r1}\sin\theta_t + \sqrt{\varepsilon_{r2} - \varepsilon_{r1}\cos^2\theta}} \tag{6.15}$$

If medium 1 is air or vacuum, for which $\varepsilon_{r1} = 1$, this can be simplified to:

$$\frac{E_r}{E_t} = \frac{\sin\theta_t - \sqrt{\varepsilon_{r2} - \cos^2\theta}}{\sin\theta_t + \sqrt{\varepsilon_{r2} - \cos^2\theta}} \tag{6.16}$$

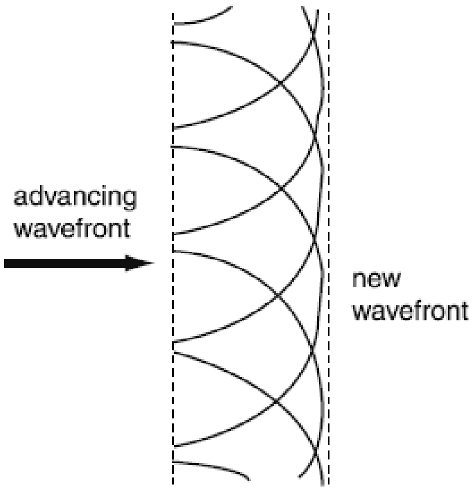
Introduction to diffraction

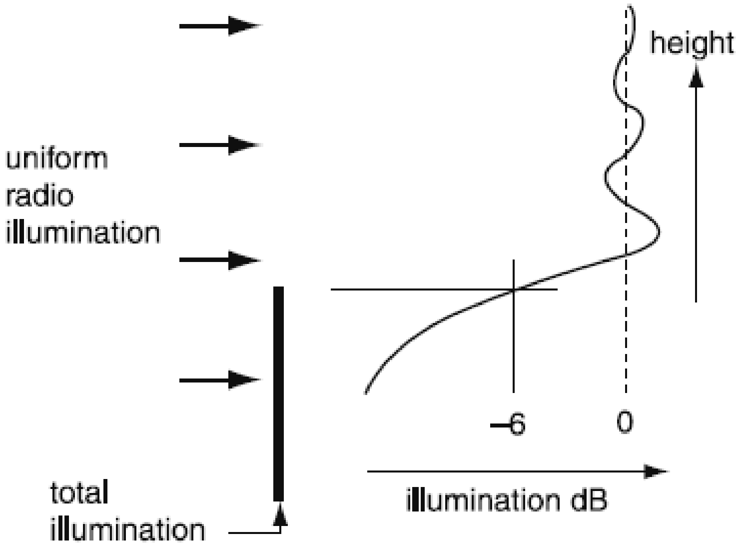




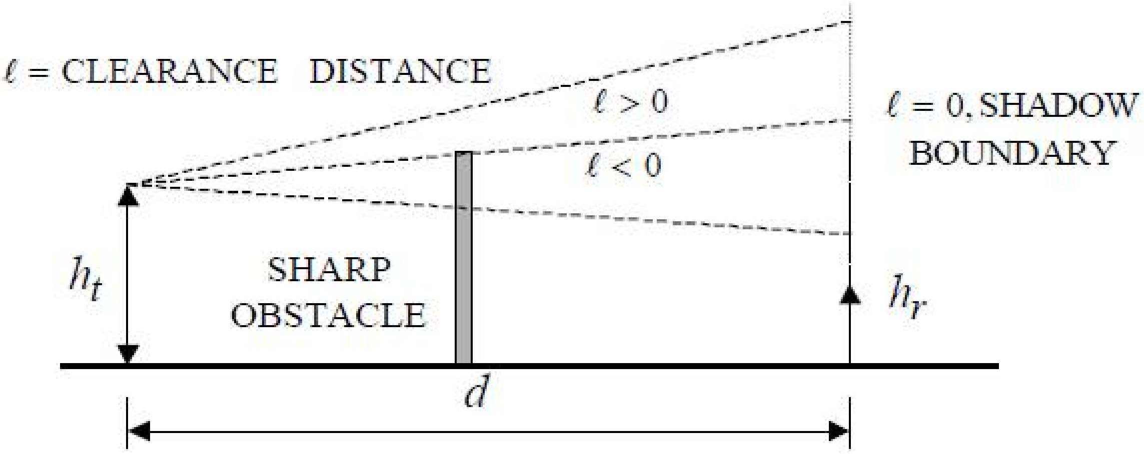
Radio energy does not simply travel in straight lines. As an example, Figure 8.1 shows the variation of illumination at the edge of a radio shadow. On the left a plane radio wavefront travelling to the right is obstructed up to a certain height by a thin totally absorbing obstruction. The graph on the right shows the variation of signal level in dB (horizontal scale) against height (vertical scale) at a point beyond the obstruction.

In Figure 8.1 the dB scale is relative to the signal level that would exist if the obstruction were absent; it is clearly not the sharp-edged shadow we are used to with light. Just above the obstruction the signal level oscillates; at the edge of the physical obstruction the signal is at –6 dB, not the half-power value of –3 dB as might be assumed, and the signal level does not immediately fall to zero behind the obstruction.

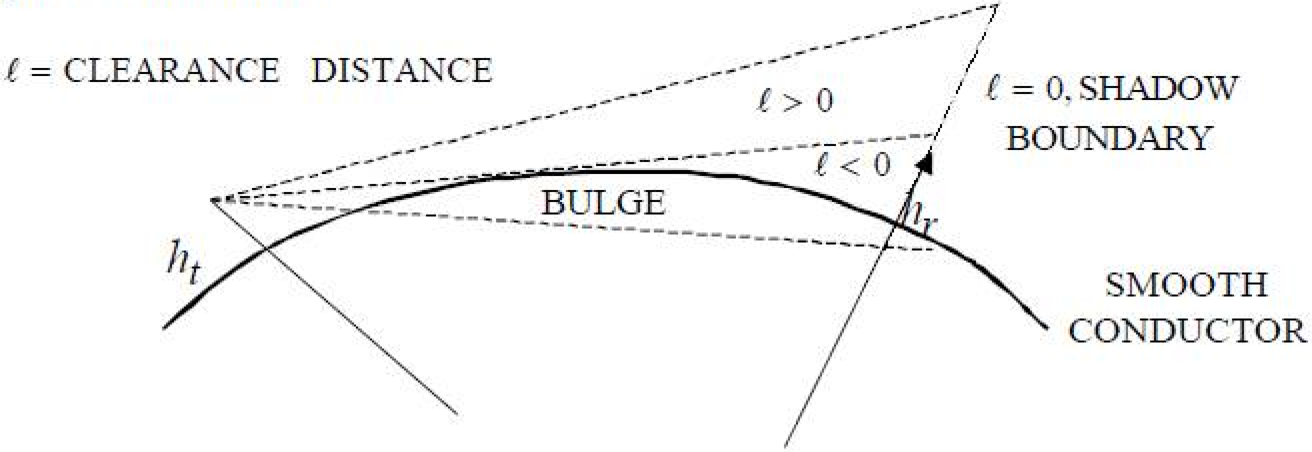




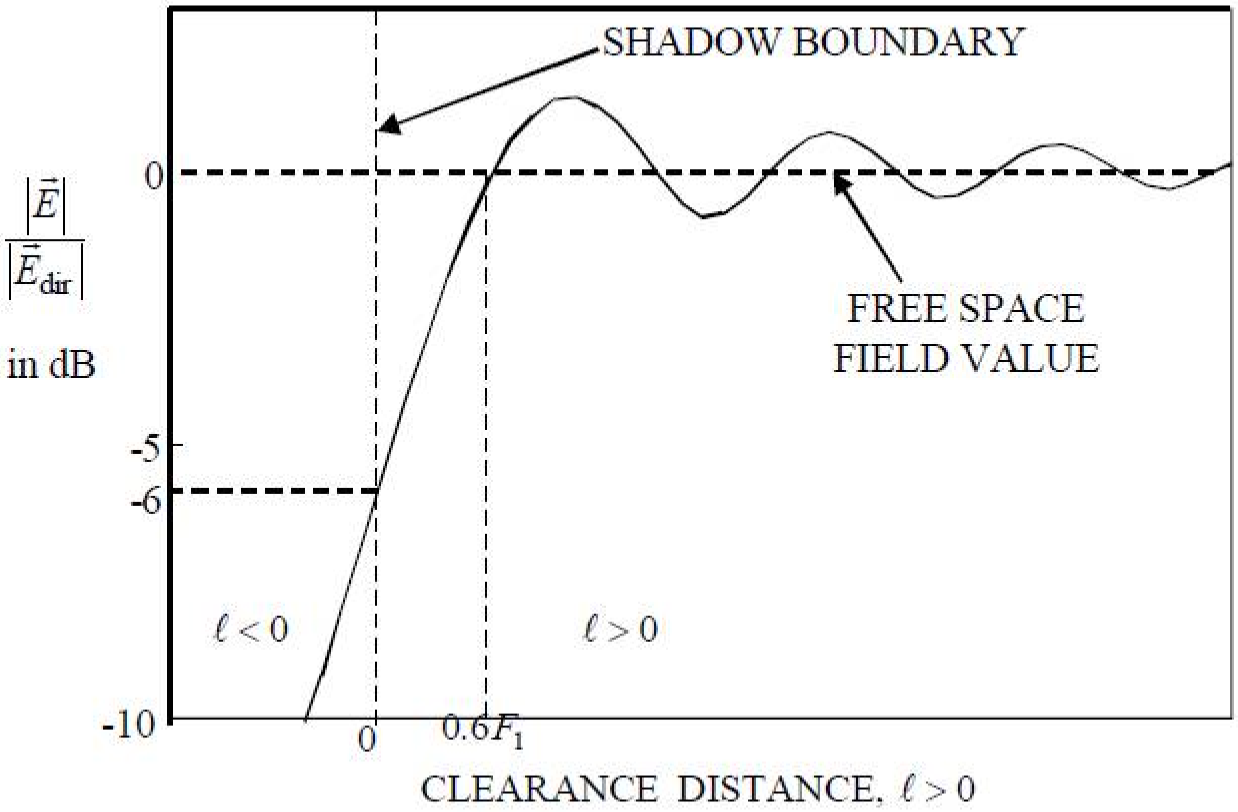
Knife edge diffraction



Smooth sphere diffraction

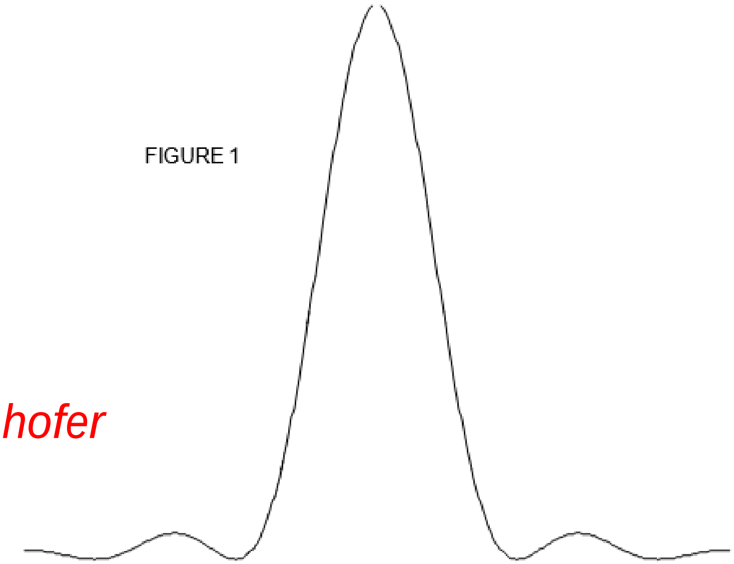


A plot of $\left|\frac{E_{\text{tot}}}{E_{\text{dir}}}\right|$ shows that at $0.6F_1$ the free space (direct path) value is obtained.



If a parallel beam of light from a distant source encounters an obstacle, the shadow of the obstacle is not a simple geometric shadow but is, rather, a diffraction pattern. For example, it is well known that the diffraction pattern formed by a slit looks like the function shown in Figure 1.

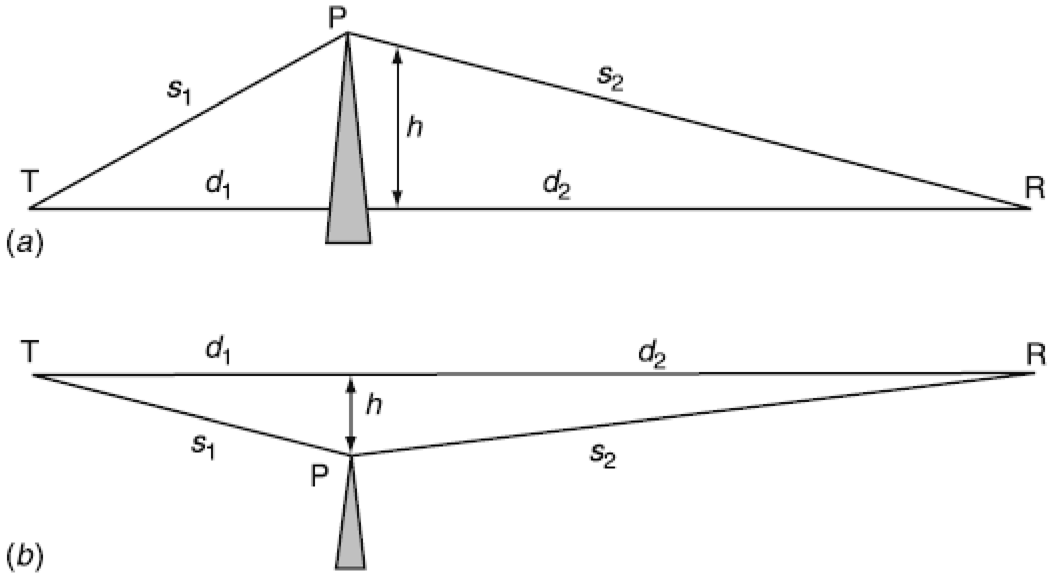
FIGURE 1



Such diffraction is called *Fraunhofer diffraction.*

If, however, the source of light is not distant, but is close to the diffracting obstacle so that the incident waves are not plane waves, the diffraction pattern will look somewhat different. Such diffraction is called *Fresnel diffraction*, and its theory is, unsurprisingly, a little more difficult than the theory for Fraunhofer diffraction.

Fresnel knife-edge diffraction



The diffraction caused by a thin screen obstructing part of an advancing wavefront is referred to as knife-edge diffraction. One of the simplest diffraction analysis methods uses Fresnel diffraction, which is based on a set of assumptions. Some of these concern geometry as illustrated in Figure 8.3. This shows a thin knife-edge obstacle between transmitter T and receiver R which has its edge at height h above the line of sight from T to R. Note that h can be negative. Fresnel diffraction theory applies when $h \ll d_1$, $h \ll d_2$, $\lambda \ll d_1$ and $\lambda \ll d_2$.

The Fresnel method integrates contributions from an advancing wavefront taking into account only the phase differences arising from the differences in path length, for example, the differences between the slope and direct distances s and d, respectively, as shown in Figure 8.3. When this is done for a uniformly illuminated plane wavefront the resulting phasor diagram can be represented by a double spiral known as the Cornu spiral. This is illustrated in Figure 8.4.

On the left of Figure 8.4 five rays from wavefront AA′ converge at point B. These originate from equally spaced points, and thus they represent equal magnitudes. On the right the resulting phasors are summed graphically by placing them in tandem. The phasor from the central point 0 is arbitrarily oriented parallel to the real axis. The phasors from the other points will be at phase angles determined by the additional path lengths compared to the central point. Since $h \ll d$ for each point, the additional path length can be approximated by $h^2/2d$, the angle of each phasor will be proportional to the square of h, and the two arms of the phasor summation for the upper and lower parts of the wavefront will thus curve into spirals. This leads to the shape shown in Figure 8.5.

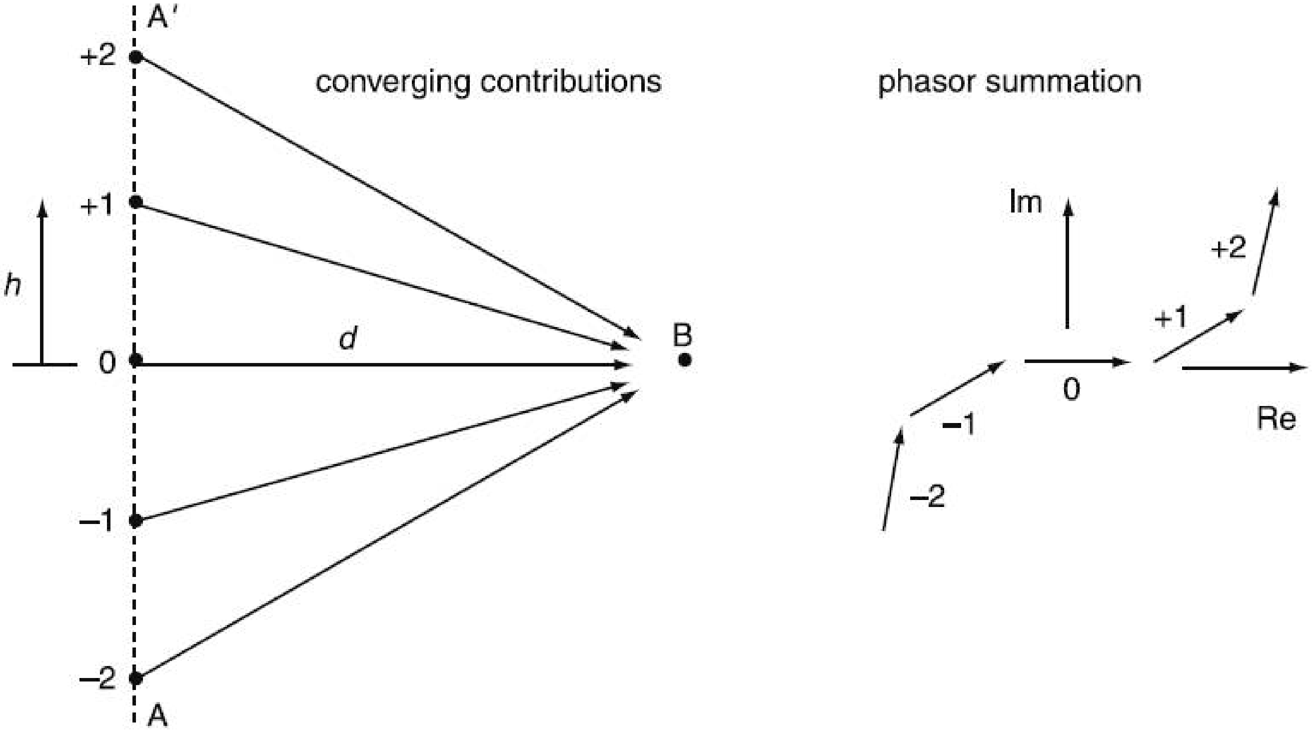
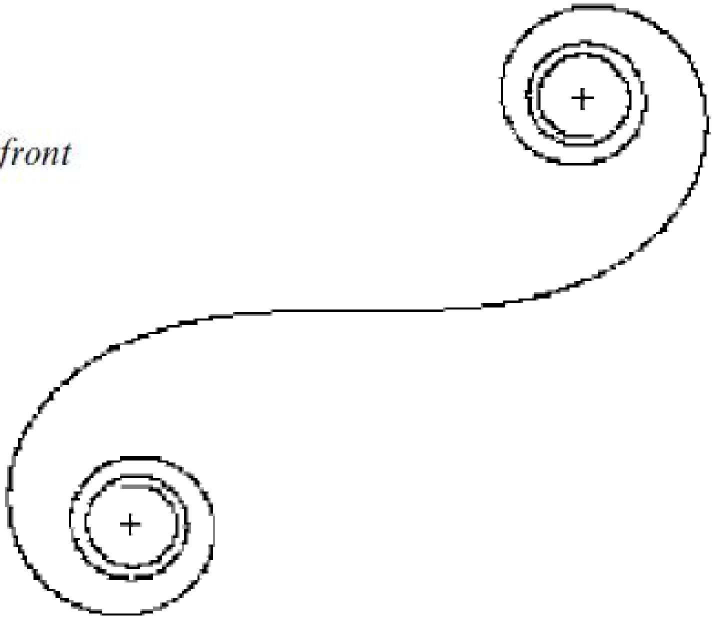
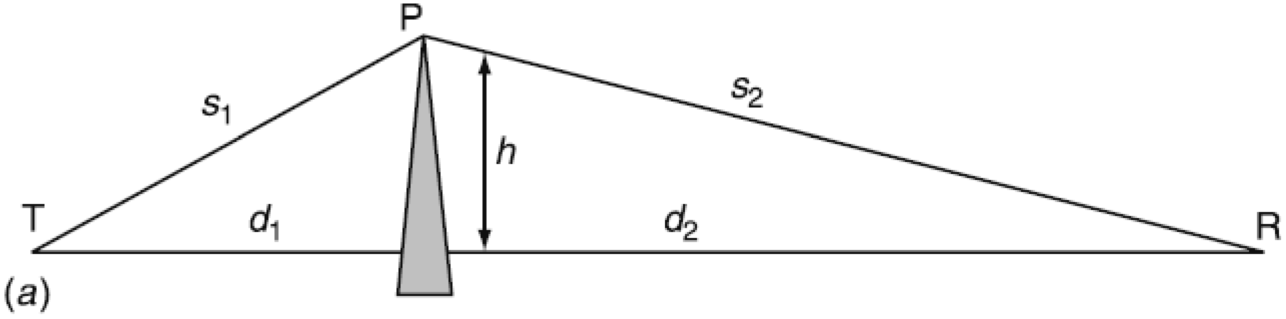


Figure 8.4 Phasor summation of contributions from a wavefront





Direct Ray TR = $d_1 + d_2$

Reflected Ray TPR = $\sqrt{d_1^2 + h^2} + \sqrt{d_2^2 + h^2}$

So the path length difference is

$$\Delta = \sqrt{d_1^2 + h^2} + \sqrt{d_2^2 + h^2} - d_1 - d_2$$

As h<<d_1 and h<<d_2 then using Binomial expansion

$$\sqrt{d_1^2 + h^2} \cong d_1\left(1 + \frac{h^2}{2d_1^2}\right)$$

Hence

$$\Delta = d_1 + d_2 + \frac{h^2}{2d_1} + \frac{h^2}{2d_2} - d_1 - d_2 = \frac{h^2}{2d_1} + \frac{h^2}{2d_2}$$

So corresponding phase difference

$$\emptyset = \frac{2\pi\Delta}{\lambda} = \frac{2\pi}{\lambda} \frac{h^2}{2} \left(\frac{d_1 + d_2}{d_1 d_2}\right)$$

Now Fresnel – Kirchhoff diffraction is used to describe a number called v number as

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

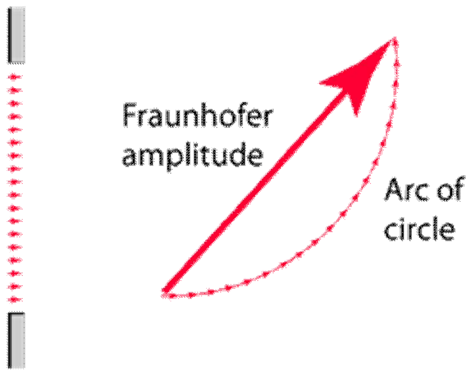
Depending on sign of h, v changes. For zero h this v number is zero.

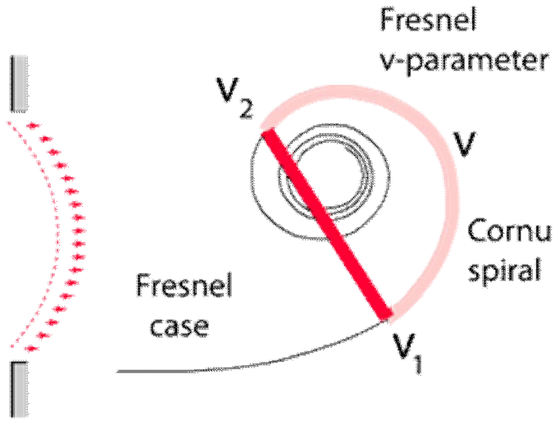
If $\emptyset = n\pi$ then $\Delta = \frac{n\lambda}{2}$ Hence $n\lambda = h^2\left(\frac{d_1+d_2}{d_1 d_2}\right)$

Hence it is clear that increase in distance is added with a square terms.

$$\emptyset = \frac{\pi v^2}{2}$$

The v-parameter in Fresnel diffraction analysis can be thought of as the arc length along the amplitude vector diagram called the Cornu spiral. In the Fraunhofer diffraction case where the source wavefront was assumed to be planar, the different elements of the wavefront had a constant phase difference and the incremental amplitude elements added to form the arc of a circle. In the Fresnel diffraction case where the curvature of the wavefront is included, the relative phase is not constant and the amplitude elements bend into the spiral curve.





Now we need to calculate the total amount of intensity of signal received at point P.

$$\left(\int_0^v \cos\frac{1}{2}\pi u^2 du\right)^2 + \left(\int_0^v \sin\frac{1}{2}\pi u^2 du\right)^2.$$

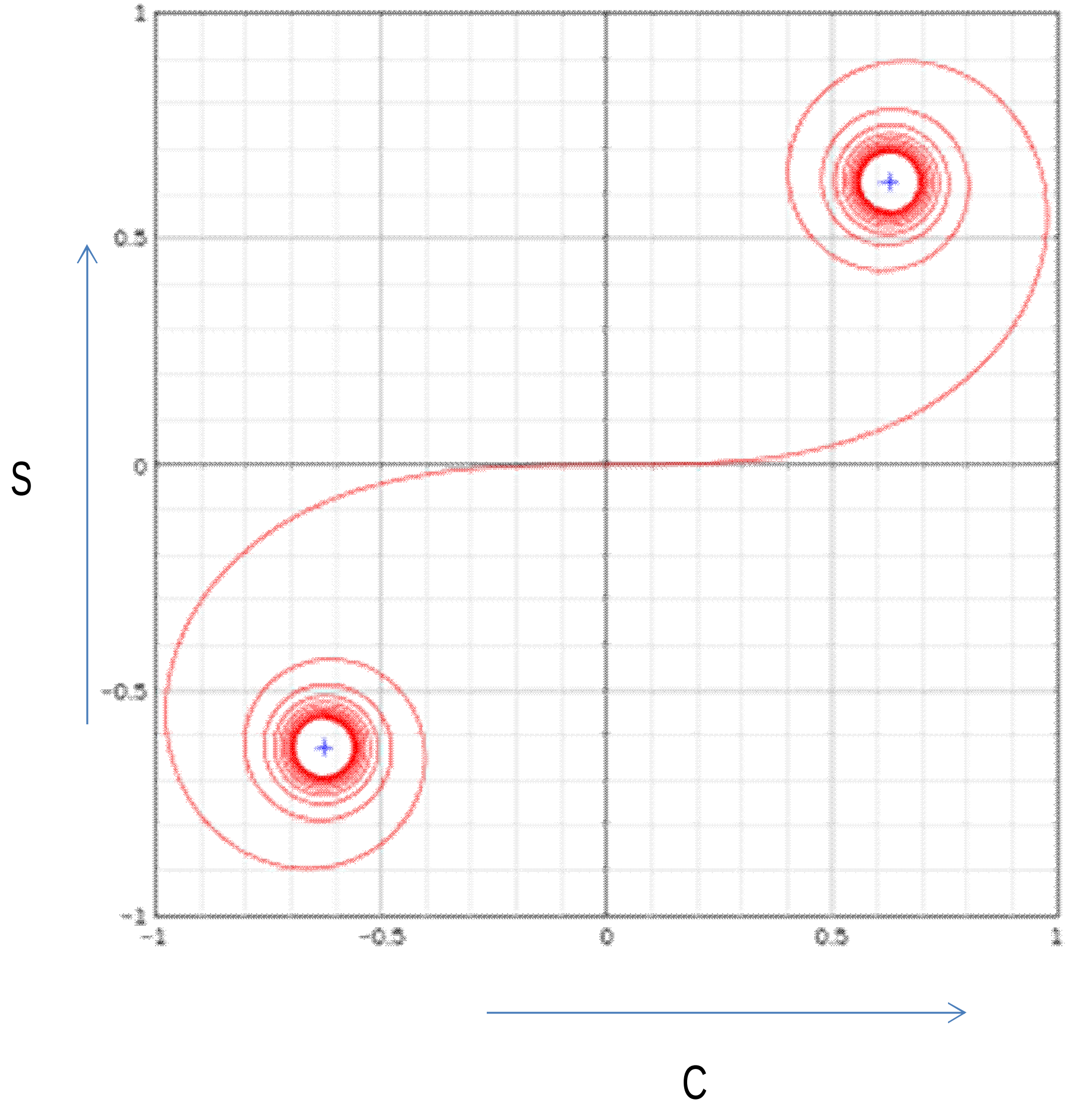
$$C = \int_0^v \cos\frac{1}{2}\pi u^2 du \quad \text{and} \quad S = \int_0^v \sin\frac{1}{2}\pi u^2 du$$

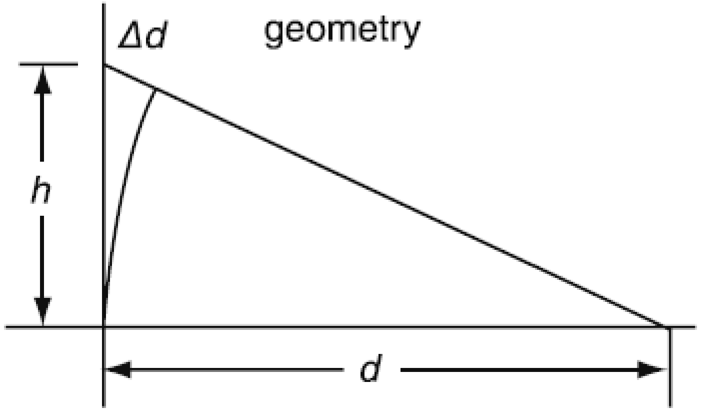
How this integration arrives : This is called Fresnel Integration. Fresnel integration is a term to solve Fresnel / near field diffraction parameter. So if a Electric field E originates from a source and if there are spatial /path variation on a single frame then how to calculate total E field at receiver due to all cumulative variable path diff effects.

In the above expression u is a dummy variable which has been used as integration factor related to height h in v number.

Cornu Spiral (Eular Spiral) is a plot of S vs C

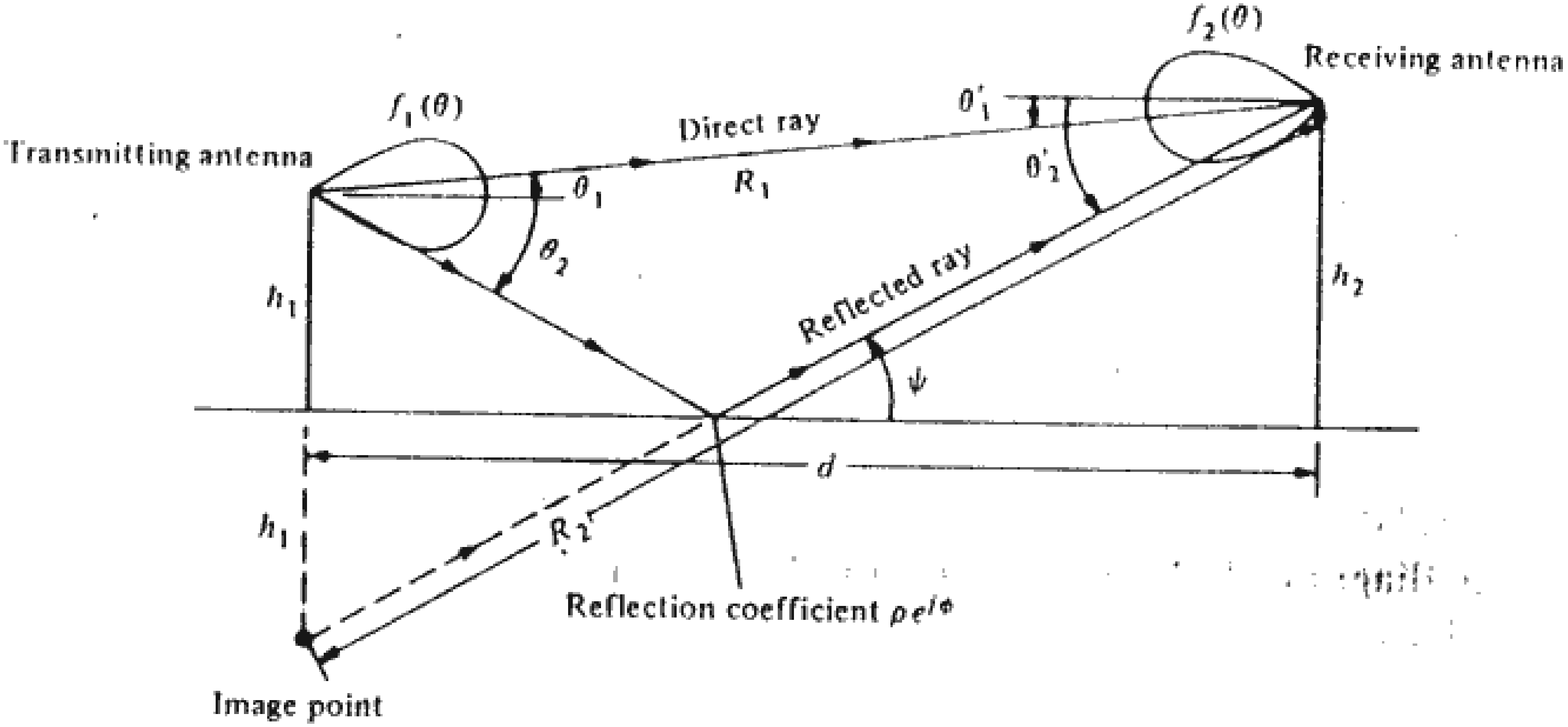
An **Euler spiral** is a curve whose curvature changes linearly with its curve length





ANTENNAS LOCATED OVER A FLAT EARTH

Propagation above 50 MHz with small antenna mounted over any structure
Preferable communication – LOS.
But the problem is interference.



Assume Flat Earth

Direct wave

$$f_1(\theta_1)f_2(\theta_1')\frac{e^{-jk_0R_1}}{4\pi R_1}$$

Ground Reflected Wave

$$f_1(\theta_2)f_2(\theta_2')\rho\, e^{j\phi}\,\frac{e^{-jk_0R_2}}{4\pi R_2}$$

Total Received

$$\left|f_1(\theta_1)f_2(\theta_1')\frac{e^{-jk_0R_1}}{4\pi R_1}\left[1+\rho\, e^{j\phi}\,\frac{f_1(\theta_2)f_2(\theta_2')}{f_1(\theta_1)f_2(\theta_1')}\,e^{-jk_0(R_2-R_1)}\right]\right| = \left|f_1(\theta_1)f_2(\theta_1')\frac{e^{-jk_0R_1}}{4\pi R_1}\right| F \qquad (6.1)$$

The factor F, called the *path-gain factor*, shows how the field at the receiving antenna differs from the value it would have under free-space propagation conditions. When it can be assumed that $f_1(\theta_2) \approx f_1(\theta_1)$ and $f_2(\theta_2') \approx f_2(\theta_1')$, then F can be expressed as

$$F = |1+\rho\, e^{j\phi-jk_0(R_2-R_1)}| \qquad (6.2)$$

The path-gain factor is the array factor associated with the antenna at height h_1 and its image below the surface, with the relative excitation of the image antenna being $\rho\, e^{j\phi}$.

With reference to Fig. 6.1, it can be seen that $R_1 = [d^2 + (h_2 - h_1)^2]^{1/2}$ and $R_2 = [d^2 + (h_1 + h_2)^2]^{1/2}$. When h_1 and h_2 are very small compared with d, a binomial expansion gives

$$R_1 \approx d + \tfrac{1}{2}\frac{(h_2 - h_1)^2}{d} \qquad R_2 \approx d + \tfrac{1}{2}\frac{(h_2 + h_1)^2}{d}$$

from which we obtain

$$R_2 - R_1 = \frac{2h_1 h_2}{d}$$

If $\rho e^{j\phi}$ were equal to -1 then

$$F = |1 - e^{-jk_0 2h_1 h_2/d}| = 2\left|\sin\frac{k_0 h_1 h_2}{d}\right| \tag{6.3}$$

This shows that interference effects can lead to a doubling of the field strength relative to its value under free-space conditions. With reference to Fig. 6.2 we let ψ_0 be the elevation angle given by $\tan\psi_0 = h_2/d$ so that Eq. (6.3) can be written as

$$F = 2|\sin(k_0 h_1 \tan\psi_0)| \tag{6.4}$$

The relationship expressed by Eq. (6.4) is usually plotted in the form of a coverage diagram showing the variation of F with h_2 and d, that is, with ψ_0, for given values of h_1 and λ_0 expressed as a ratio h_1/λ_0. Note that F is a maximum when

$$\tan \psi_0 = \frac{1}{k_0 h_1}\left(\frac{\pi}{2} + n\pi\right) = \frac{\lambda_0}{h_1}\left(\frac{1}{4} + \frac{n}{2}\right) \qquad n = 0, 1, 2, \ldots \qquad (6.5a)$$

and is a minimum when

$$\tan \psi_0 = \frac{\lambda_0}{h_1}\frac{n}{2} \qquad n = 0, 1, 2, \ldots$$

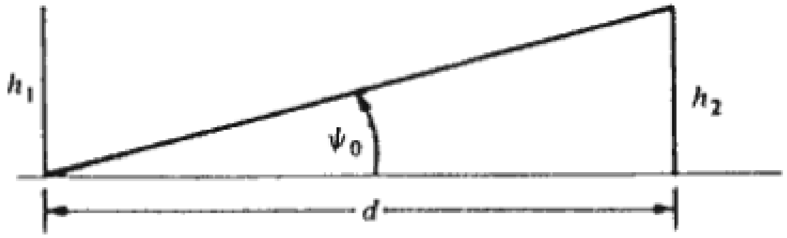
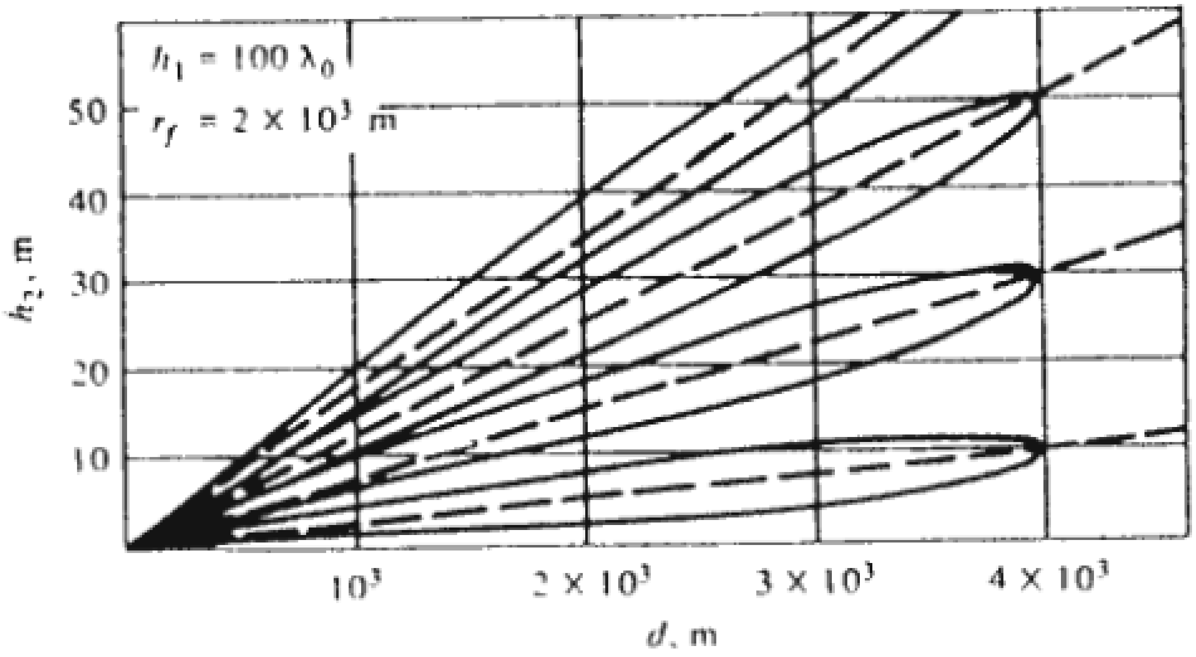


Figure 6.2 Elevation angle ψ_0.

A coverage diagram is a plot of the relative field strength as a function of direction in space from the transmitting antenna. It is analogous to the field-strength radiation pattern of an antenna. In any coverage diagram the fixed parameters are the height h_1 of the transmitting antenna and the wavelength λ_0. The distance d to the location of the receiving antenna and the height h_2 of the receiving antenna are variable parameters, and each pair of values h_2, d determines a point in space.



Ionospheric propagation

The ionosphere, which extends from ~60 km to ~1000 km, significantly affects the propagation of high-frequency (HF) to ultrahigh-frequency (UHF) signals which pass through it. The effects are varied but include refraction, retardation and scintillation. Ground–ground HF communications systems, ground–space communications systems, single frequency GPS (global positioning system), HF over-the-horizon radars, satellite altimeters and space-based radars [1] are examples of radio systems constrained by this medium.

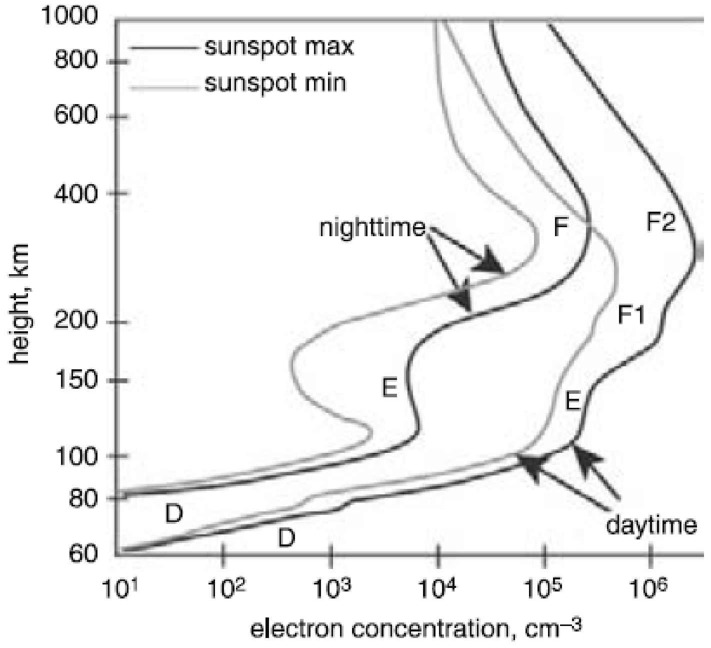


Fig. 8.16

If a gas with molecules having an ionization energy of W J is exposed to a radiation of frequency f Hz, the ionization will occur if

$$hf > W$$

where h is the Planck's constant ($h = 6.626068 \times 10^{-34}$ Js); i.e., the energy contained in the radiation should be higher than that of the ionization energy of the molecule.

It has been observed that the electron density profile (electron density versus height), has regions of maxima as well as regions of constant density (Fig. 8.16). These regions are known as layers of the ionosphere. There are mainly three layers in the ionosphere designated by the letters D, E, and F. The F layer splits into separate layers F_1 and F_2 during day time. The E and F layers, which are present during both day and night times, make long distance communication possible by reflecting radio waves in the frequency range of 3–30 MHz. Radio waves above 30 MHz pass through the ionosphere. The D layer, which is present only during the day time, does not reflect high frequency electromagnetic waves (3–30 MHz), but attenuates the waves passing through it. Even though the D layer reflects lower frequency waves ($<$ 1 MHz), due to the high absorption of the electromagnetic energy by the D layer, the utility of the reflected waves is limited.

Because of the variation in chemical composition of the air with height, and because different gases differ in their ability to absorb solar radiation of different frequencies, there is a tendency for the ionization in the ionosphere to become stratified, so that the curve of electron density as a function of height commonly has several maxima, as shown in Fig. 27. There are two semipermanent "layers" of this character, the *E* and the *F* or F_2 layers, with a third designated as F_1 usually present in the daytime. The height of a particular layer and the maximum electron density in the layer will vary at different times of the day and of the year as the result of variations in the composition and temperature of the air at different heights, and of the radiation received from the sun. The distribution of ionization with height in a typical case is shown schematically in Fig. 27, in which three distinct layers are shown corresponding to typical daytime conditions. It will be noted that the ionization does not drop to zero between the layers, but merely has a value less than the maxima on either side.

A radio wave entering the ionosphere from the earth has a tendency to be bent earthward, and if the conditions are favorable, the bending will be sufficient to cause the wave to return to earth as shown in Fig. 27. Upon striking the earth it will then be again reflected upward as shown. This action makes it possible to carry on radio communication over great distances in spite of the earth's curvature. The wave that reaches these distant points as a result of the action of the ionosphere is termed the *sky wave.*

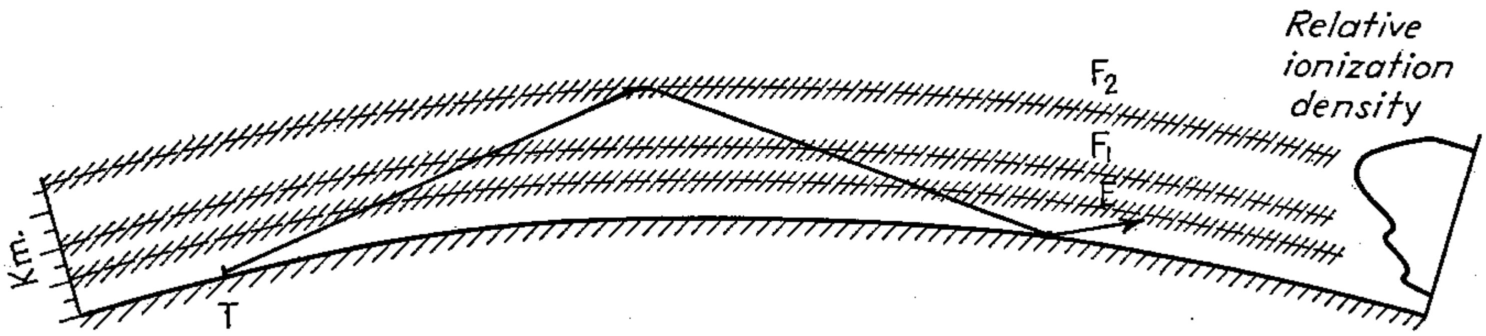


FIG. 27.—Schematic diagram drawn approximately to scale showing location of various ionosphere layers, approximate distribution of ionization, and typical path of a wave refracted from the F_2 layer.

8. Propagation of a Radio Wave in an Ionized Medium. *Fundamental Mechanisms Involved.*—When a radio wave enters the ionosphere the electric field of the wave exerts a force upon the electrons, setting them in vibration at the frequency of the wave.[1] Under conditions where the earth's magnetic field has negligible effect, this vibration is along a line parallel to the electric field of the wave. The velocity of vibration lags 90° behind the electric field, and is inversely proportional to the frequency. Since a moving electron represents a current, each electron set in vibration by the radio wave acts as a miniature parasitic antenna that absorbs energy from the wave and then reradiates this energy in a different phase. The net effect, after the phase difference between the original and reradiated fields is taken into account, is to bend the wave path away from the regions of high electron density toward regions of lower density. The magnitude of this effect varies with the amplitude of the electron vibration, and therefore becomes increasingly great as the wave frequency is lowered.

The electrons in the ionosphere exist in the presence of the earth's magnetic field. Such a magnetic field exerts a force on a moving electron that is proportional to the instantaneous velocity of the electron, and to the component of the magnetic field at right angles to the direction of motion. The direction of this force is at right angles to the direction of motion of the electron, and to the component of the magnetic field producing the deflecting force. The effect of the earth's magnetic field at the higher radio frequencies is to cause each electron to vibrate in an elliptical path, as shown at *a* or *b* in Fig. 28, with the major axis of the ellipse lying in the direction of the electric field of the wave. The ratio of minor axis to major axis increases as the velocity with which the electron vibrates becomes greater, *i.e.*, as the frequency is reduced. This trend continues until at a frequency termed the gyro frequency and having a value of approximately 1.4 mc, the electron vibrates in a spiral path as shown at *c*, in which the velocity becomes increasingly great. At still lower frequencies the electrons vibrate in loops as shown at *d* and *e*, commonly making several loops during each half cycle of the radio wave.

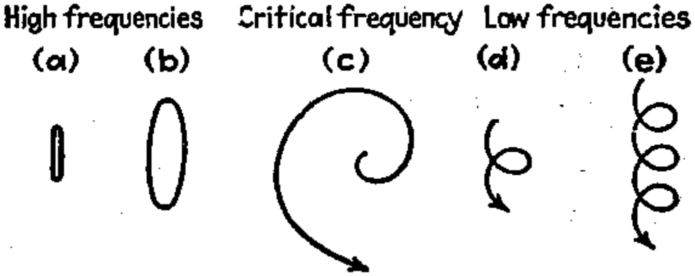
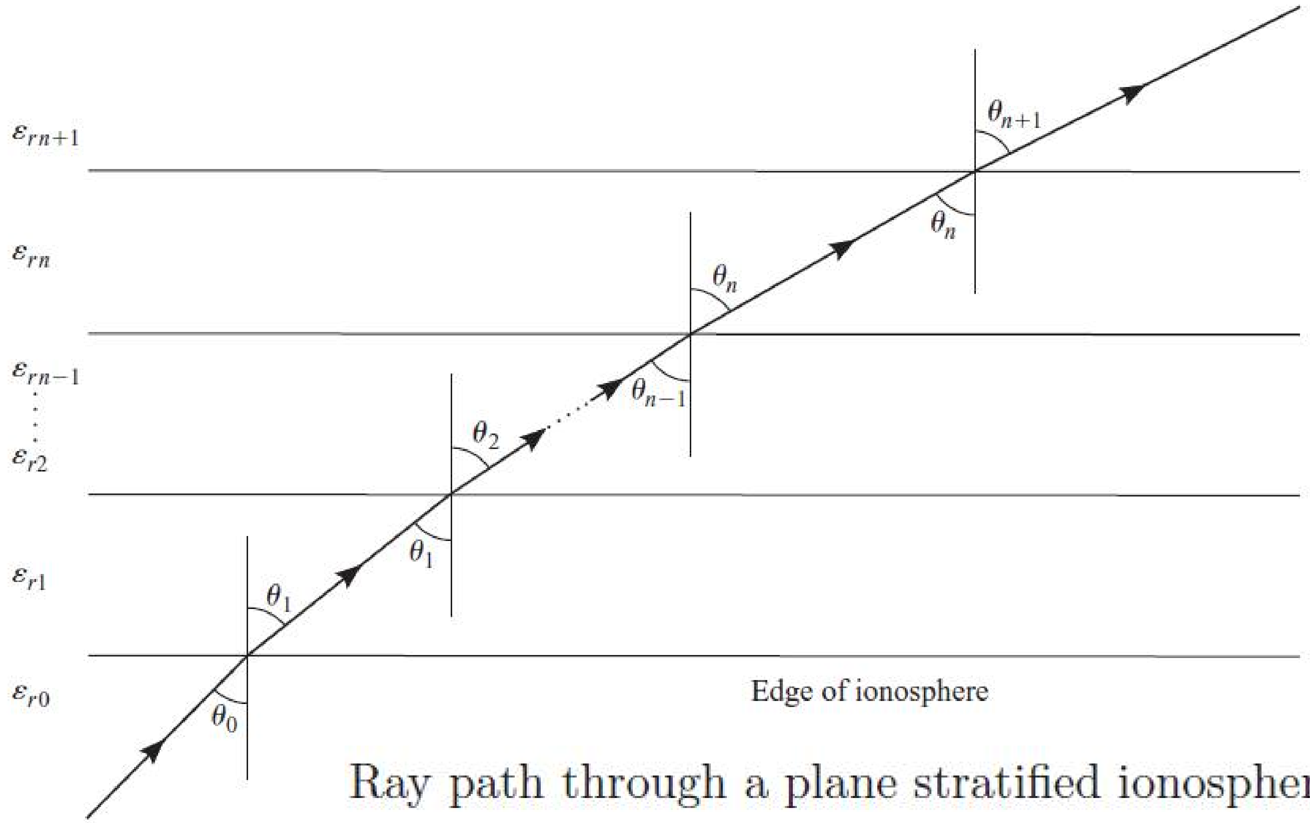
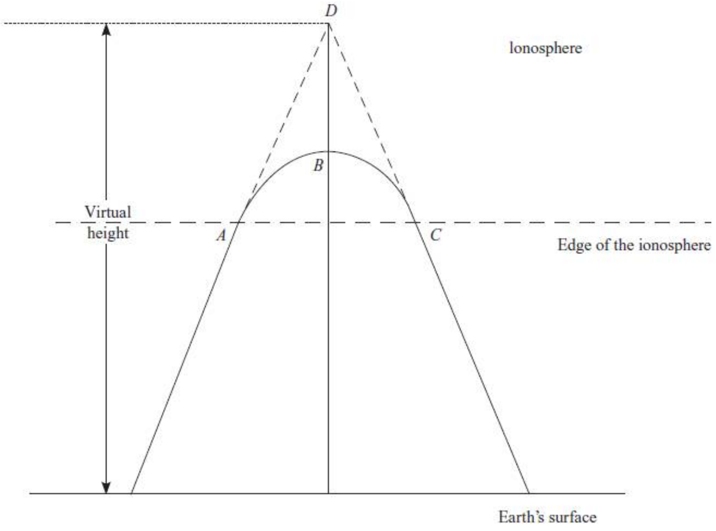
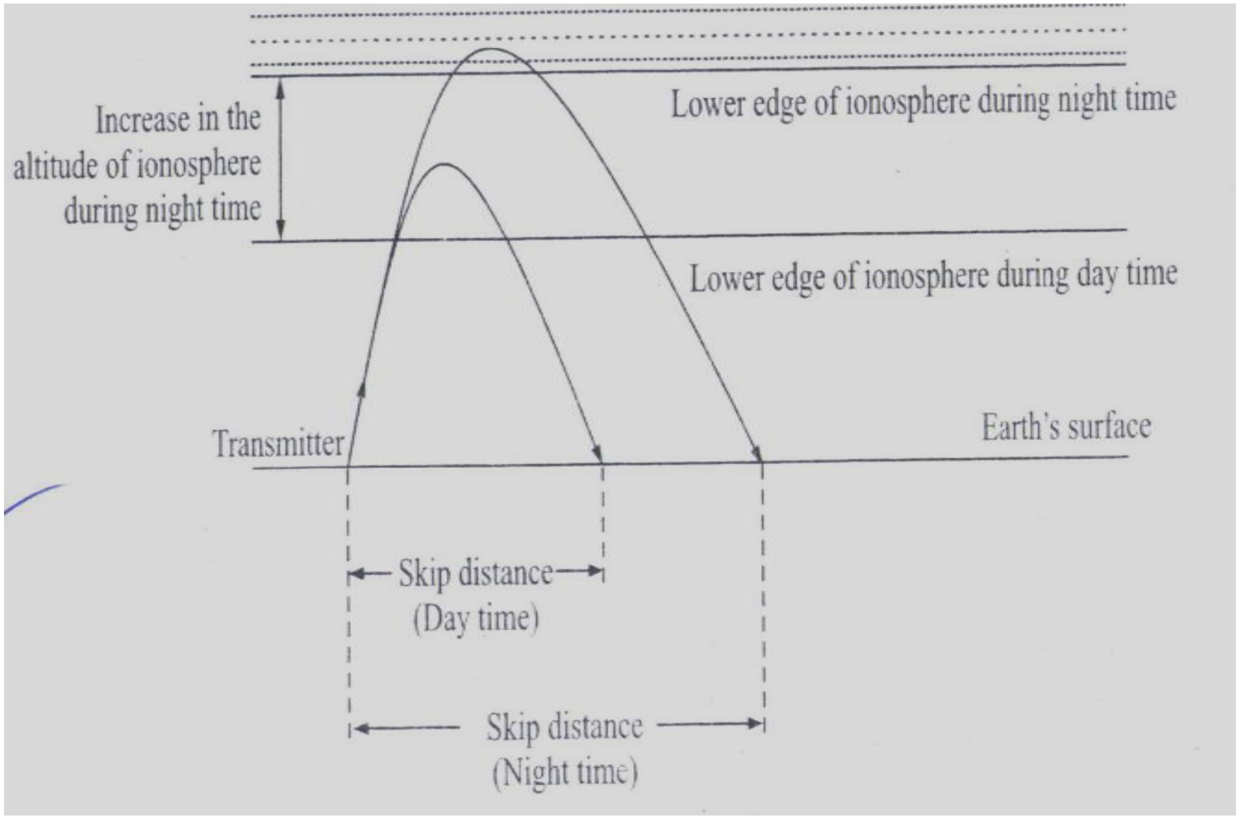


FIG. 28.—Paths followed by an electron when vibrating under the influence of a radio wave, in the presence of the earth's magnetic field. To avoid confusion the paths for the low-frequency cases represent only a half cycle of the vibration that proceeds cyclically.



Ray path through a plane stratified ionosphere


D
Ionosphere
B
Virtual height
A
C
Edge of the ionosphere
Earth's surface


Increase in the altitude of ionosphere during night time
Lower edge of ionosphere during night time
Lower edge of ionosphere during day time
Transmitter
Earth's surface
Skip distance (Day time)
Skip distance (Night time)

Pls note ionosphere required to study
This presentation
From scan note (wave propagation –III)
3,
3.1.
3.2
3.3.1
3.3.2
3.3.3
3.3.4
3.3.9
3.3.10
3.3.11