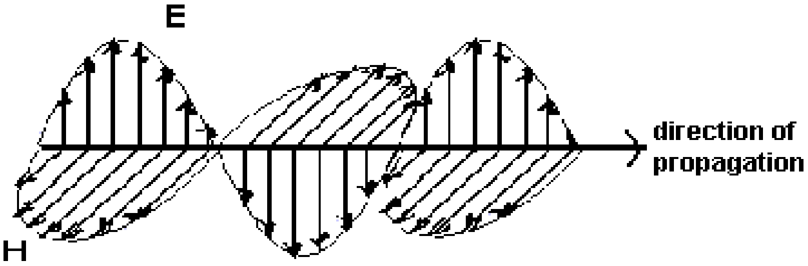
Electromagnetic Wave Propagation

Free space propagation of electromagnetic waves is often called radio-frequency (RF) propagation or simply radio propagation.

The earth's atmosphere, as medium introduces losses and impairments to the signal, which is generally not encountered in vacuum.

A radio wave consists of traveling electric (E) and magnetic (H) fields, with the energy evenly divided between the two types of fields.

"Right-hand rule" - determines the direction of wave propagation. This rule states that if the thumb, forefinger, and middle finger of the right hand are extended so they are mutually perpendicular, the middle finger will point in the direction of wave propagation if the thumb points in the direction of the E field and the forefinger points in the direction of the H field.



Free Space - an idealized wave environment where there are no other transverse electromagnetic (TEM) wave, no gravity, no obstructions, no atmosphere, no celestial events, no terrestrial events, no electrical noise, and no observers. In short, the wave environment is free from everything except the wave itself.
– space that does not interfere with the normal radiation and propagation of waves (epitome of nothingness).

Polarization – orientation of the electric field vector with respect to the earth's surface (ground).
Linear polarization – polarization is constant

- Horizontal polarization – E is propagating parallel to the earth's surface
- Vertical polarization – E is propagating perpendicular to the earth's surface

Circular polarization – the polarization vector rotates 360°as wave moves one wavelength in space and field strength is equal at all angles of polarization

Power density – rate at which energy passes through a given surface area (W/m²)
Field intensity – degree of the electric and magnetic fields of an electromagnetic wave in free space, which can be electric field intensity (V/m) or magnetic field intensity (At/m)

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

$$P = \sqrt{\frac{\mu_O}{\varepsilon_O}} = \sqrt{\frac{1.26\,x\,10^{-6}}{8.854\,x\,10^{-12}}} \approx 120\pi \approx 377\,\Omega$$

$$\mathbf{P} = \mathbf{E}^2/377 = 377\mathbf{H}^2$$

$$\mathbf{H} = \mathbf{E}/377$$

Characteristic Impedance of Free Space

$$Z_S = \sqrt{\frac{\mu_O}{\varepsilon_O}} = \sqrt{\frac{1.26\,x\,10^{-6}}{8.854\,x\,10^{-12}}} \approx 120\pi \approx 377\,\Omega$$

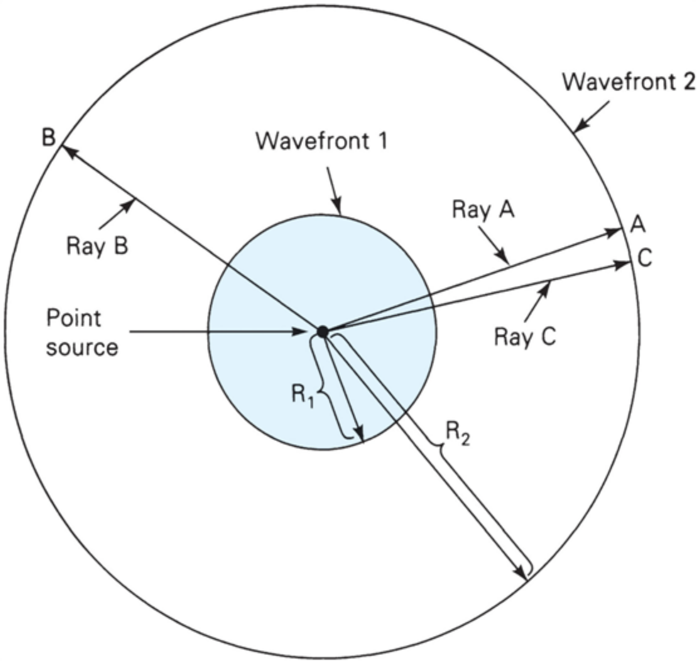
Where: μ_O = magnetic permeability of free space, (H/m)
ε_O = permittivity of free space

Spherical Wavefront

A point source that radiates power at a constant rate uniformly in all directions is called an isotropic radiator. It is closely approximated by an omnidirectional antenna. The radiated energy of equal intensity is required by a sphere whose surface area is given by $4\pi r^2$

Power Density at any Point on the Surface of a Spherical Wavefront

Spherical wavefront from an isotropic source



$$P_D = \frac{P_{rad}}{4\pi R^2}$$

Where: P_{rad} = total power radiated in watts

R = radius of the sphere

Since: $P_D = E^2/377$

$$P_D = \frac{P_{rad}}{4\pi R^2} = \frac{E^2}{377}; \quad \overline{E}^2 = \frac{377 P_{rad}}{4\pi R^2}; \quad \overline{E} = \frac{\sqrt{30 P_{rad}}}{R}$$

Wave Attenuation and Absorption

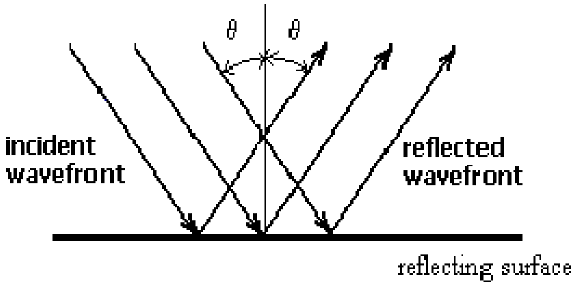
Wave attenuation - reduction in power density (power loss) with distance. The reduction in power density due to nonfree-space propagation is called absorption.

- Water vapor causes significant attenuation of EM waves at higher frequencies (>20 GHz)
- Effect of rain on EM wave propagation is insignificant below 6 GHz. At higher frequencies, rain attenuates radio transmission severely.

Optical Properties of Radio Waves

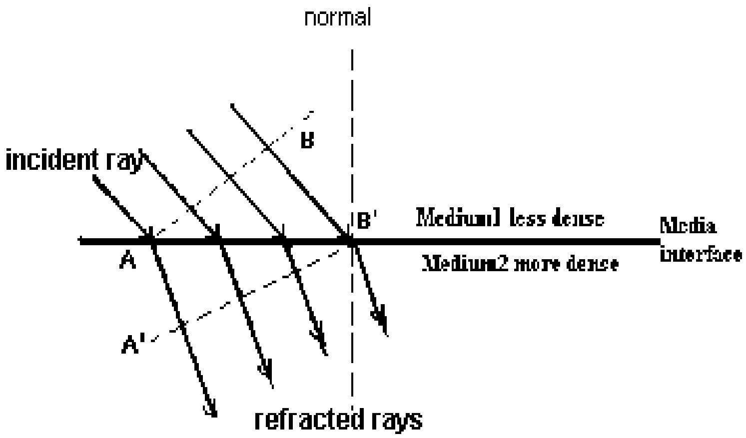
Reflection– the return or change in direction of light, sound radiowaves striking a surface or traveling from one medium to another.

Electromagnetic reflection occurs when an incident wave strikes a boundary of two media and some or all of the incident power does not enter the second material.



Refraction – the bending of a radio wave when it passes obliquely from one medium to another in which the velocity of propagation is different.

- from rare to denser medium it will be refracted towards the normal



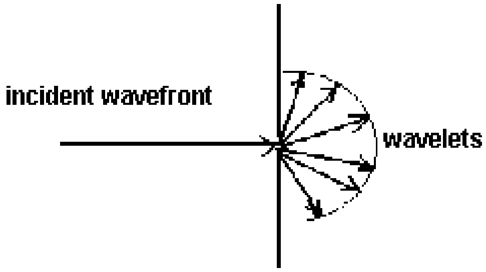
Snell's Law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where: n_1 = refracted index of material 1
n_2 = refracted index of material 2
θ_1 = angle of incidence
θ_2 = angle of refraction

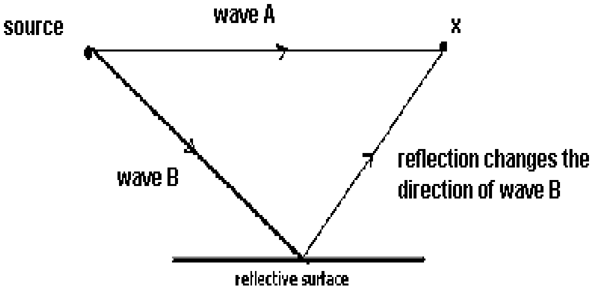
Diffraction – the bending of a wave as it passes the edges of an object or opening.

Diffraction is defined as the modulation or redistribution of energy within a wavefront when it passes near the edge of an opaque object. Diffraction is the phenomena that allows light or radio waves to propagate (peek) around corners.

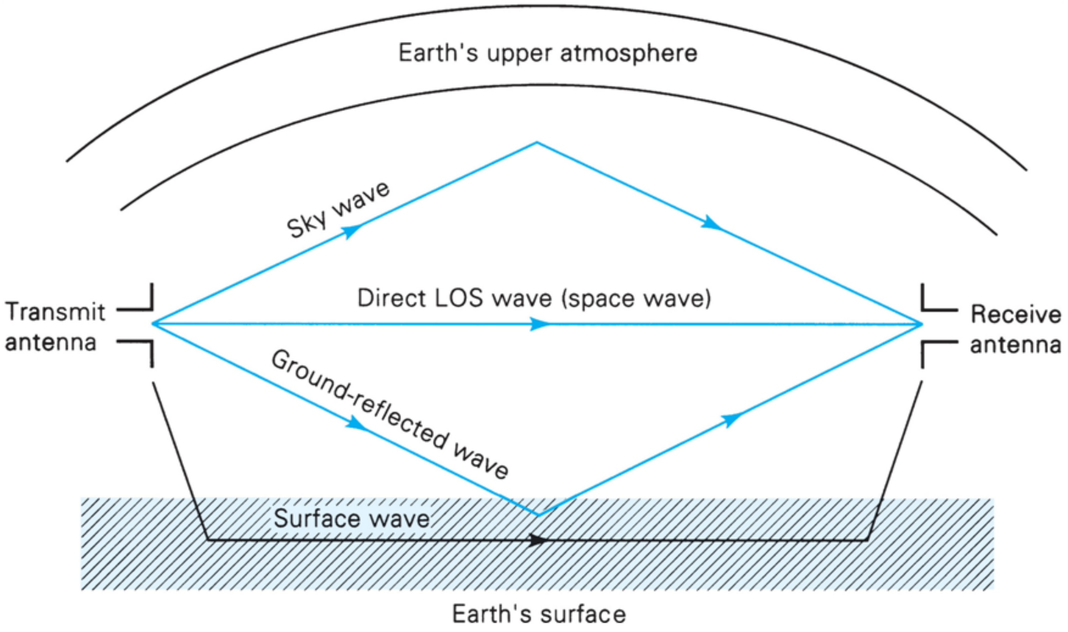


Absorption – the dissipation of energy by radiation passing through a medium.

Interference - Radio wave interference occurs when two or more electromagnetic waves combine in such a way that system performance is degraded. It is subject to the principle of linear superposition of electromagnetic waves and occurs whenever two or more waves simultaneously occupy the same point in space.



Terrestrial Propagation of Electromagnetic Waves



Surface wave or ground wave propagation (f < 2 MHz) – an earth-guided EM wave that travels over the surface of the earth

- Attenuation of a ground wave due to absorption depends on the conductivity of the earth's surface and the frequency of the EM wave.

Surface	**Relative Conductivity**
Seawater	Good
Flat, loamy soil	Fair
Large bodies of fresh water	Fair
Rocky terrain	Poor
Desert	Poor
Jungle	Unusable

- Ground waves must be vertically polarized.

Common uses: Ship-to-Ship Communications; Ship-to-Shore Communications; Radio Navigation; Maritime Mobile Communications

Disadvantages of Ground Wave Propagation

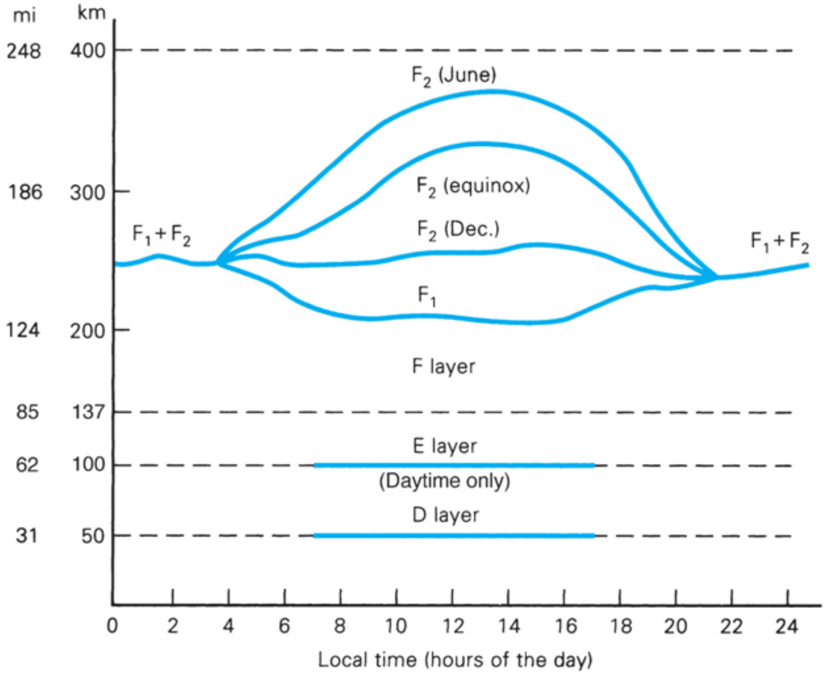
- requires a relatively high transmission power
- limited to VF,LF and MF bands
- ground losses vary considerably with surface material

Advantages of Ground Wave Propagation

- Given enough power, ground waves can be used to communicate between any two locations in the world.
- Ground waves are relatively unaffected by changing atmospheric conditions

Sky Wave Propagation – sometimes called ionospheric propagation

- Takes advantage of the ionosphere (30-250 miles above the earth's surface) that surrounds the earth to provide worldwide communications with reasonably good quality, reliability and moderate power.



Note:

- Almost all HF propagation, and night time long distance MF propagation is by sky wave.
- Above 30 MHZ, waves are more likely to penetrate the ionosphere and continue moving out into space.
- Ionosphere is most dense during time of maximum sunlight
- In general, the lower the frequency, the more easily the signal is refracted.
- In the UHF and SHF bands, a very small percentage of the wave's energy is refracted back to earth
- Since the atmosphere is bombarded by ultraviolet light waves of different frequencies, several ionized layers are formed at different altitudes. The height and thickness of the ionized layers vary, depending on the time of day and even the season of the year.
- When a radio wave is transmitted into an ionized layer, refraction occurs. The amount of refraction that occurs depends on three main factors: (1) the density of ionization of the layer, (2) the frequency of the radio wave, and (3) the angle at which the wave enters the layer.

Layers of the Ionosphere

D layer - ranges from about 30 to 55 miles. Ionization in this layer is low because it is the lowest region of the ionosphere. This layer has the ability to refract signals of low frequencies. High frequencies pass right through it and are attenuated. After sunset, the D layer disappears because of the rapid recombination of ions.

E layer - limits are from about 55 to 90 miles; also known as the Kennelly-Heaviside layer. The rate of ionic recombination in this layer is rather rapid after sunset and the layer is almost gone by midnight.

This layer has the ability to refract signals as high as 20 MHz. For this reason, it is valuable for communications in ranges up to about 1500 miles.

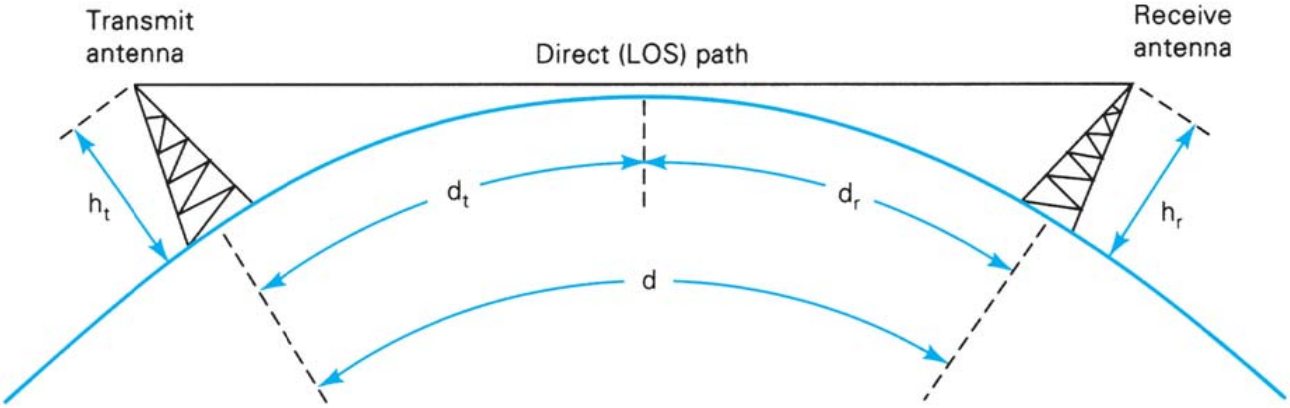
F layer - exists from about 90 to 240 miles. During the daylight hours, the F layer separates into two layers, the F1 and F2 layers. The ionization level in these layers is quite high and varies widely during the day. At noon, this portion of the atmosphere is closest to the sun and the degree of ionization is maximum. The F layers are responsible for high-frequency, long distance transmission.

Space Wave Propagation – commonly called line-of-sight (LOS) transmission

Radio horizon – horizon made by the curvature of the earth

The radio horizon is approximately 4/3 of the optical horizon.

Distance Between Two Antennas



$$d = \sqrt{2h_t} + \sqrt{2h_r}$$

Where: d = total distance (miles)
h_t = transmit antenna height (feet)
h_r = receive antenna height (feet)

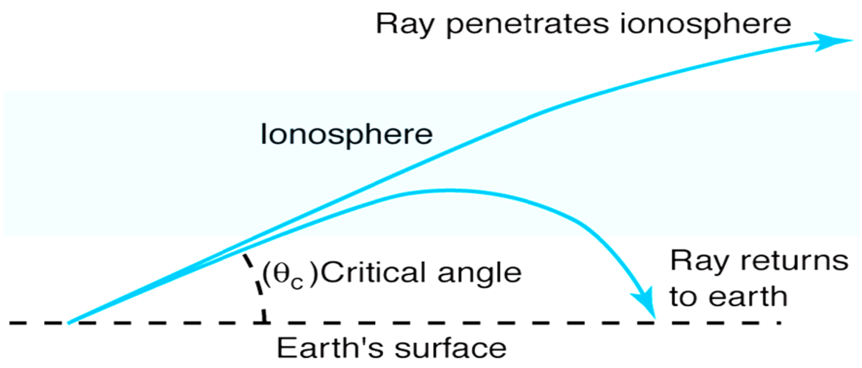
In metric units:

$$d = \sqrt{17h_t} + \sqrt{17h_r}$$

Where: d = total distance (kilometers)
h_t = transmit antenna height (meters)
h_r = receive antenna height (meters)

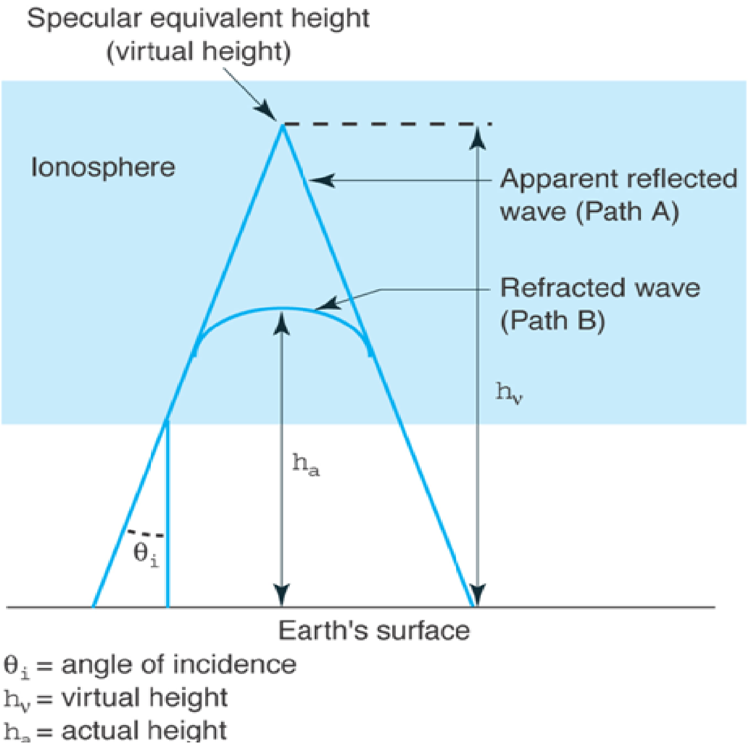
Propagation Terms

Critical frequency – the highest frequency that can be propagated directly upward and still be returned to earth by the ionosphere



Critical angle – maximum vertical angle at which a sky wave can be propagated and still be refracted by the ionosphere.

Virtual Height – height above the earth's surface from which a refracted wave appears to have been reflected.



Maximum Usable Frequency – highest frequency that can be used for sky wave propagation

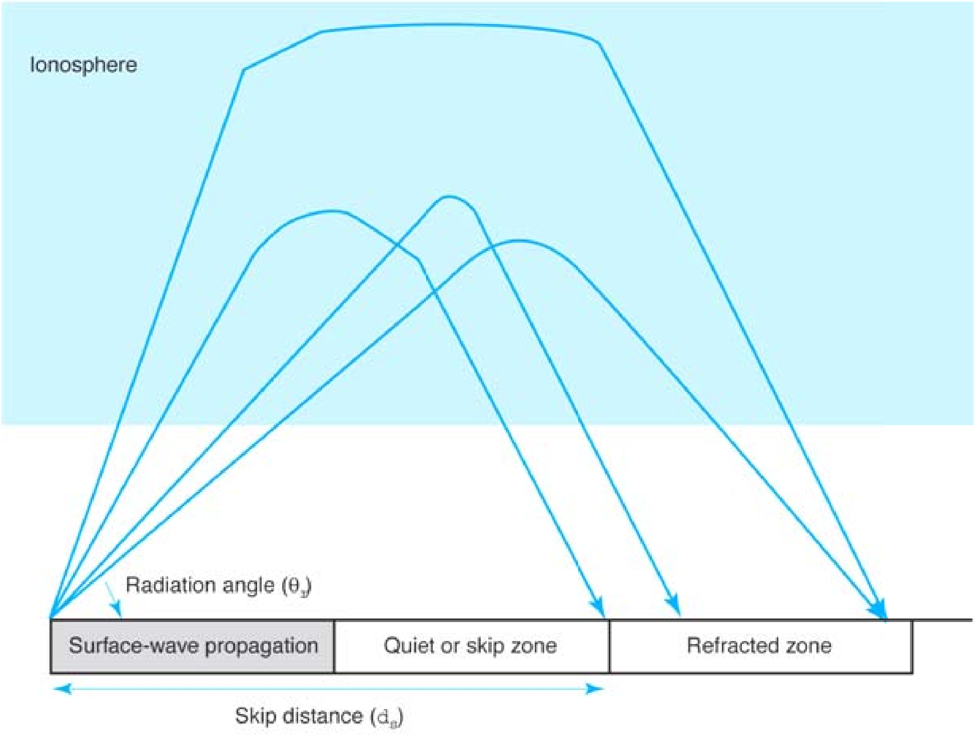
$\text{MUF} = f_c / \cos\theta_i = f_c \sec\theta_i$ ***(secant law of radio wave propagation)***

For more reliable communications:

Optimum Working Frequency (OWF) = 0.85 * MUF

Skip distance – minimum distance from a transmit antenna that a sky wave at a given frequency will be returned to earth. The frequency must be less than the MUF and propagated at its critical angle.

Quiet or skip zone – the area where the surface waves are completely dissipated and the point where the first sky wave returns to earth



Free Space Path Loss - loss incurred by an EM wave as it propagates in a straight line through a vacuum with no absorption or reflection of energy from nearby objects.

$$FSL = 32.4 + 20 \log f_{(MHz)} + 20 \log D_{(km)}$$

or $$FSL = 92.4 + 20 \log f_{(GHz)} + 20 \log D_{(km)}$$

Fading – variation in signal loss mainly caused by weather disturbances

To accommodate temporary fading, an additional loss is added to the normal path loss. This loss is called fade margin.

Barnett-Vignant Reliabilty Equation

$$\mathbf{F_m = 30 \log D + 10 \log (6ABf) - 10 \log (1 - R) - 70}$$

Where: d = distance (km)
f = frequency (GHz)
R = reliability (decimal value)
A = terrain roughness factor (0.25 to 4),
B = factor to convert worst-month probability to annual probability (0.125 to 1 depending on humidity or dryness).

A – roughness factor
= 4 over water or very smooth terrain
= 1 over average terrain
= 0.25 over very rough, mountainous terrain

B- factor to convert worst-month probability to annual probability
= 1 to convert an annual availability to a worst month basis
= 0.5 for hot humid areas
= 0.25 for average inland areas
= 0.125 for very dry mountainous areas

Problems:

1. Determine the power density for a radiated power of 1 kW at a distance 20 km from an isotropic antenna. Determine the electric field intensity at that point.
2. Determine the effect on power density if the distance from a transmit antenna is tripled.
3. Determine the radio horizon for a transmit antenna 100 ft high and a receiving antenna 50 ft high.
4. Determine the MUF for a critical frequency of 10 MHz and an angle of incidence of 45°.
5. Determine the path loss for a frequency of 800 MHz and distance of 0.6 km.
6. Determine the fade margin for the following conditions: distance between sites, D = 40 km, f = 1.8 GHz, smooth terrain, humid climate and a reliability objective of 99.99% Ans: 31.4 dB