Fundamentals of RF Propagation in Electronic Warfare

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RF PROPAGATION

Propagation characteristics of RF energy are profoundly affected by the earth's surface and atmospheric conditions. Any analysis of radar performance must take into account the propagation phenomena associated with RF radiation in a “real world” environment. The most important propagation phenomena include refraction, anomalous propagation (ducting), and attenuation.

a. In a vacuum, RF waves travel in a straight line. However, RF waves propagating within the earth's atmosphere do not travel in a straight line. The earth's atmosphere bends, or refracts, RF waves. One impact of the atmospheric refraction of RF waves is an increase in the line of sight (LOS) of the radar. This increase in radar LOS effectively extends the range of the radar system

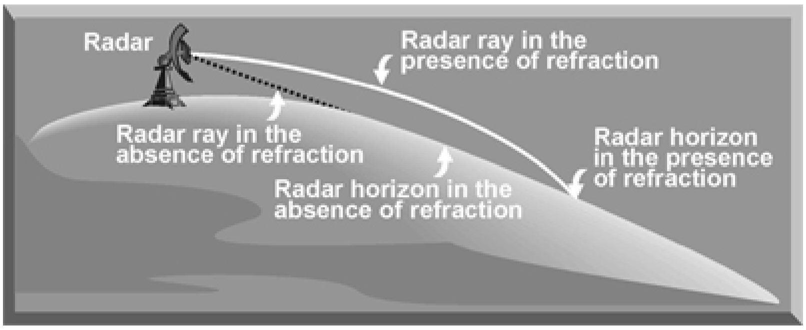

Figure 1-1. Impact of Refraction on RF Propagation

Atmospheric refraction of RF energy can also induce elevation measurement errors in radar systems (Figure 1-2).

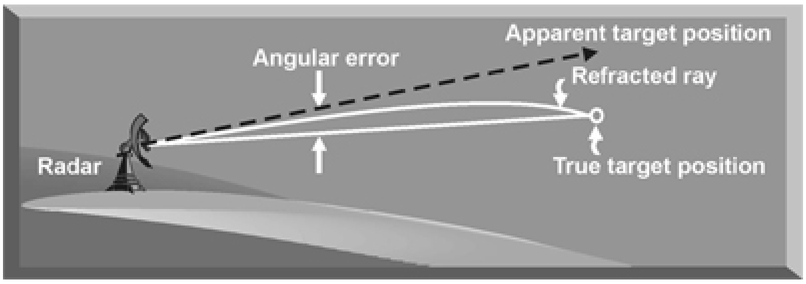

Figure 1-2. Impact of Refraction on Target Elevation Determination

(1) The refraction of RF waves in the atmosphere is caused by the variation in the velocity of propagation with altitude. The index of refraction (n) is used to describe this velocity variation and is defined by Equation 1-1.

$$\text{Index of Refraction } (n) = \frac{\text{Velocity of Propagation in a Vacuum}}{\text{Velocity of Propagation in the Atmosphere}}$$

Equation 1-1. Index of Refraction

(2) The term refractivity (N) is used for predicting the impact of refraction on RF wave propagation. Refractivity is a “scaled up” expression for the index of refraction and is used by radar designers to calculate the impact of refraction on actual radar systems. At normal radar operating frequencies, the refractivity for air containing water vapor can be computed using Equation 1-2.

$$\text{Refractivity } (N) = (n-1) \times 10^6 = \frac{77.6\,p}{T} + \frac{3.75 \times 10^5 e}{T^2}$$

n = index of refraction
e = partial pressure of water vapor
p = barometric pressure
T = absolute temperature (degrees K)

Equation 1-2. Refractivity of RF Waves (Normal Radar Frequencies)

(3) As altitude increases, the barometric pressure and water vapor content decrease rapidly. At the same time, the absolute temperature decreases slowly based on the standard lapse rate. Using Equation 1-2, it can be seen that the refractivity of the atmosphere decreases with increasing altitude. This decrease in refractivity means that the velocity of RF waves increases with altitude. The result is a downward bending, or refraction, of RF waves as depicted in Figure 1-1. RF wave refraction primarily affects ground-based radar systems at low antenna elevation angles, especially at or near the horizon. For most radar applications, refraction is not a factor at elevation angles above 5 degrees.

b. The term anomalous, or nonstandard, propagation is used to describe atmospheric conditions that extend the propagation of RF waves and increase radar range. The most common anomalous propagation phenomena are called superrefraction, or ducting.

1. A superrefracting duct is formed when the refractivity of the atmosphere (Equation 1-1) rapidly decreases with altitude. Based on Equation 1-1, this occurs when the temperature increases with altitude and/or the water vapor

content decreases with altitude. An increase in temperature with altitude is called a temperature inversion. To produce a duct, the temperature inversion must be very pronounced

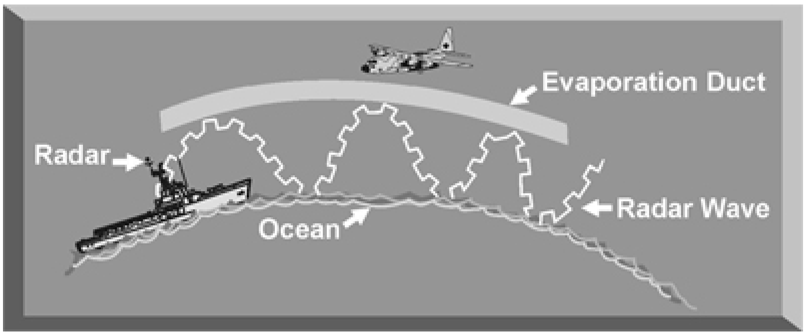

Figure 1-3. Superrefracting Surface Duct

(2) A superrefracting duct acts like a wave guide which traps the RF wave (Figure 2-12). This channels the radar signal and reduces attenuation. In order for an RF wave to propagate within a duct, the angle of the radar signal, in relation to the duct, should be less than one degree. The RF waves trapped by the duct take advantage of the decrease in refractivity and travel much further than normal.

This can greatly extend the range of a radar system.

(3) The extension of radar range inside a duct can result in a reduction of radar coverage outside the duct. The area of reduced radar coverage because of ducting is called a radar hole. Due to radar holes, the extended radar range caused by ducting may result in a decrease in radar coverage along other paths of propagation. These holes can seriously degrade the effectiveness of early warning radar systems. For example, a radar system is taking advantage of a duct formed at the surface to extend low altitude radar range (Figure 2-12). Airborne

targets flying just above the duct would normally be detected, but because of ducting, these targets may be missed.

(4) Water vapor content is a significant factor in producing ducts. Consequently, most ducts are formed over water and in warm climates. Any atmospheric phenomenon that results in a pronounced increase in temperature and/or a decrease in water vapor content as altitude increases can generate a superrefracting duct, of which there are

three types. A superrefracting duct which is formed just above the surface of the earth is referred to as a surface duct. A

surface duct formed just above the surface of the ocean is called an evaporation duct. A duct which is formed well above the surface of the earth is known as an elevated duct.

(a) Surface ducts formed over land are usually a result of the nighttime radiation of heat from the earth. Duct formation is especially prevalent during the summer months when the ground is moist. As the earth loses heat, a temperature inversion is created at the surface coupled with a sharp decrease in the moisture content. These conditions are favorable to the formation of a surface duct. A superrefracting duct can also be produced by the diverging downdraft under a

thunderstorm. The cool air that is dispersed creates a local temperature inversion while the water vapor content decreases due to rain. Surface ducts formed in conjunction with thunderstorms are difficult to predict and normally persist for a short period of time.

(b) A superrefracting surface duct that lies just above the surface of the ocean is a result of evaporated water, thus the term evaporation duct. The air in contact with the ocean is saturated with water vapor, while the air several feet above the ocean contains a much lower level. This rapid decrease in water vapor pressure with an increase in altitude creates an evaporation duct. An evaporation duct exists over the ocean almost all the time. The height of this duct varies from 20 to 100 feet based on the season, time of day, and wind speed. One positive aspect of an evaporation duct is the extended range available to a shipborne

radar system with a properly aligned antenna. This extended range coverage against surface ships and low altitude aircraft is a definite advantage of ducted propagation.

(c) An elevated duct is generally formed by a temperature inversion in the upper atmosphere. To take maximum advantage of the increased radar range inside an elevated duct, both the radar and the target should be inside the elevated duct. In addition, radar systems operating below an elevated duct may also experience enhanced range performance.

(d) The presence of surface ducts and elevated ducts, especially over land, are extremely difficult to predict and may persist for very short periods of time. The atmospheric conditions favorable to duct formation are difficult to predict using conventional weather forecasting techniques.

The attenuation of RF energy in a clear atmosphere is due to the presence of oxygen and water vapor. Attenuation results when a portion of the RF energy strikes these molecules and is absorbed as heat. Figure 2-13 details the RF attenuation loss due to atmospheric gasses based on the frequency of the RF energy.

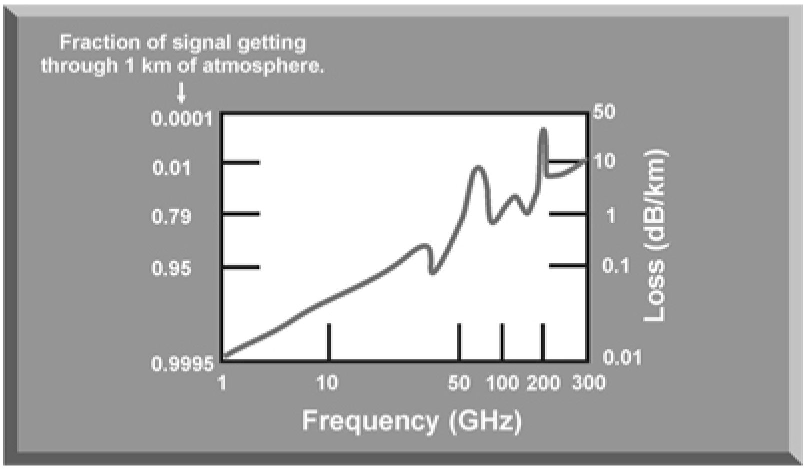

Figure 1-4. RF Atmospheric Attenuation

(1) At frequencies below 1 GHz, the effect of atmospheric attenuation is negligible. Above 10 GHz, atmospheric attenuation increases dramatically. This dramatic signal loss impacts the maximum detection range of radars operating in the millimeter wavelength band.

(2) RF energy attenuation decreases as altitude increases. The RF attenuation experienced by an air-to-air radar will depend on the altitude of the target as well as target range. For a ground-based radar, RF attenuation will decrease as antenna elevation increases.

Electronic Warfare Anomalous Propagation

As EM energy propagates through the atmosphere, it is **attenuated** (i.e., undergoes a loss in overall energy) by absorption and scattering. The major gaseous **absorbers** in the atmosphere are water vapor, carbon dioxide, ozone, and oxygen. Each is selective about what it absorbs, (e.g., oxygen absorbs UV energy), but for most radar, absorption is fairly negligible in terms of its effect on EM propagation. EM energy is also **scattered** by liquids and solids in the atmosphere. This effect is greatly dependent on the size of the particle in relation to the wavelength, but as with absorption, scattering represents a **small** factor in EM propagation.

Changes in **temperature**, **moisture**, and **pressure** in the atmospheric column cause a change in atmospheric density, which in turn causes variations in the speed of EM waves in both the vertical and horizontal. These changes in speed lead to changes in the propagation direction, or bending, of the waves. The bending of EM waves as they pass through the atmosphere is an example of **refraction** (see Figure 1-5). Refraction is always such that the waves turn toward the medium in which they ravel more slowly, as they pass from a faster speed medium into a slower speed medium. This is the case shown in Figure 1, where medium a is the faster speed medium. Refraction causes waves to turn back toward the slower speed medium as they pass from the slower into the faster medium. You can visualize this case if you mentally reverse the arrow directions in Figure 1-5.

Refraction can cause waves to bend back toward the slower speed medium as they try to propagate into a faster speed medium. This analogous to the way a car that veers onto a soft sandy shoulder on the side of a road turns toward the sandy area in which it travels more slowly. This bending toward the slow speed medium can lead to **trapping**in which waves are unable to propagate out of the slow speed medium.

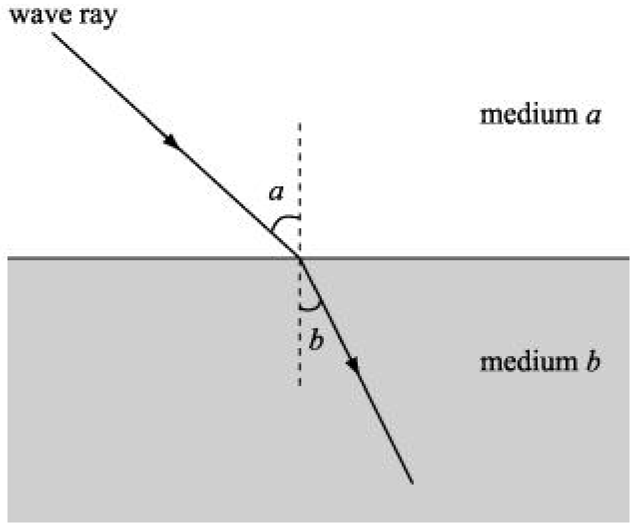

Figure 1-5. RF A simple refraction

Some amount of refraction is always present in our atmosphere, and is quite normal. However, when the structure of the atmosphere causes abnormal bending of the energy waves, **anomalous propagation** (AP) occurs. AP takes place when an unusual, other-than-normal vertical distribution of **temperature**, **moisture**, and**pressure** exists within the atmosphere. Figure 1-6 shows schematically some examples of normal and anomalous radar heights and ranges. The AP regions indicate the height and range effects of anomalous temperature, moisture, and pressure distributions. Note that AP can greatly extend, or reduce, the height and/or range of radar.

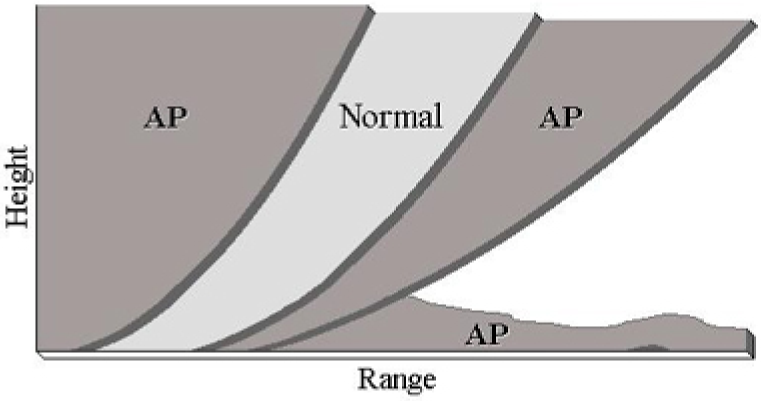

Figure 1-6. RF Anomalous Propagation

AP occurs in many forms. One type of refractive condition can extend the normal detection range of radar and, if conditions intensify, produce false echoes or **ghosting**. Ghosting can cause returning echoes to fool the radar equipment into displaying faraway echoes as though they are much closer than they actually are. This was the case in our first example, and a great deal of time and energy were expended reacting to false echoes.

With another type of refractive condition, AP may produce a **shadow zone**(commonly referred to as a **radar hole**), sometimes allowing an aircraft or ship to approach within visual range but to remain undetected by radar, as in our second example. In this case, the radar equipment operated properly. But one can only imagine the consternation caused within the strike group!

Another naturally occurring AP feature is known as a **duct**. Simply put, a duct is a region of the atmosphere that **traps** EM waves (prevents them from spreading out), and thus allows them and their energy to propagate over long ranges. Ducts provide significant opportunities to exploit the atmosphere. The challenge in exploiting a duct is to: 1) know it is there, and 2) put a sensor in it! A duct is a transitory feature, and will only trap certain frequencies. The wider the duct, the higher (and, typically, the more useful) the frequency that can be trapped and exploited. The exploitation of ducts is a common tactic, and a very important part of the overall exploitation of the atmosphere.

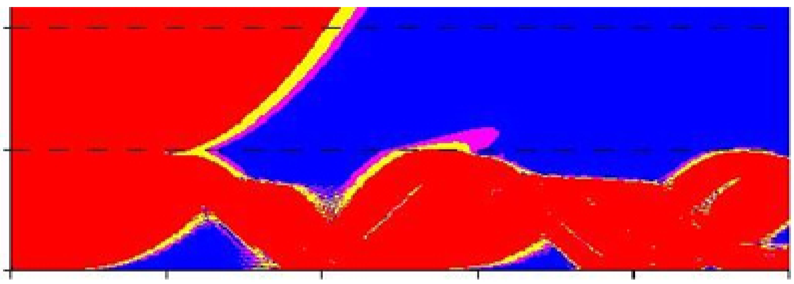

Figure 1-7. Anomalous radar propagation heights and ranges (in red). Vertical axis is height (in ft) and horizontal axis is range (in nm). The extensive area of red between

the surface and 1000 ft indicates trapping in a surface duct leading to long distance propagation of the radar signal.

Anomalous propagation occurs frequently and must be factored into any warfare commander's decision making process. METOC forecasters must:

- Understand the effects of atmospheric variables on radio and radar performance.
- Collect, analyze, and evaluate available data to accurately describe the existing atmospheric propagation condition, and how it will change over time.
- Provide radar operators and operational commanders with this information on a timely basis.

A Little Deeper

Refractive conditions are categorized into four basic classifications: Normal, and (AP) Super-refractive, Trapping, and Sub-refractive (figure 1-8).

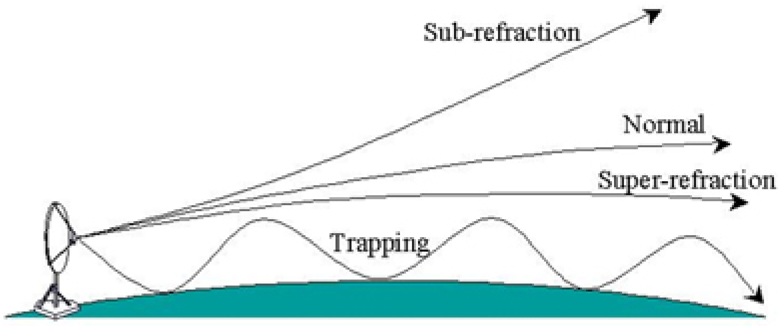

Figure 1-8. Four Classifications of Refraction

Normal Refraction

In free space, an EM wave will travel in a straight line because conditions are uniform and the index of refraction is the same throughout the column. Within Earth's atmosphere, however, the velocity of the wave is less than that of free space. So the propagating wave will be bent downward from a straight line. This is described as **normal** refraction occurs.

Normal refractivity exists in most areas about 50% of the time. AP is not present under normal refractive conditions.

Super-Refraction

In this situation, the vertical distributions of temperature, moisture, and pressure cause the radar waves to bend more toward the surface of Earth than under normal conditions.

As the refractivity gradient continues to decrease, the wave path's curve will approach the radius of curvature of the earth.

Super-refractive conditions can extend radar coverage up to 50% above normal.

Trapping

If the radius of curvature for the wave becomes smaller than Earth's, waves may become **trapped** between two areas: Earth's surface, and the negative gradient causing the downward refraction.

Trapping produces the greatest extremes in radar performance and can **significantly extend radar ranges**. Radar waves refracting sharply downwards, then reflecting off of Earth's surface, may travel distances well beyond normal. Trapping can occur between the surface and an overlying region of the atmosphere with faster speed characteristics. It can also occur between two layers of the atmosphere that have different characteristics. This is known as an **elevated duct**.

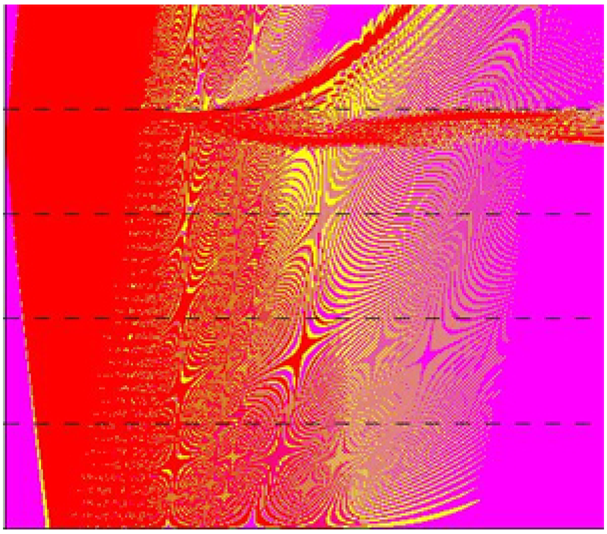

Figure 1-9– Elevated Duct

Sub-refraction

The effects of the fourth type of refraction are significantly different than those of the other three types.

Sub-refractive conditions cause the radar waves to be refracted les than normal and therefore **upward**and **away** from Earth's surface. Waves that are curved upward offer the smallest ranges and worst opportunity for distant detection.

Three Conspiring Amigos:

Moisture, Temperature, and Pressure

Moisture

Of the three atmospheric variables that influence refraction (temperature, moisture, and pressure), **moisture** – or more specifically, **water vapor** – has the greatest effect on refraction. Temperature has the next greatest effects on refraction, followed by pressure. The simple rule of thumb for moisture effects is:

More moisture means more refraction.

Temperature

The simple rule of thumb for temperature effects is:

Higher temperature means less refraction.

Moisture and temperature can (and frequently do) work together to significantly alter refraction.

Pressure

Although pressure is one of the meteorological elements that influences refraction, its effects are small. Pressure variations alone provide **no significant change** in refraction.

So now let us put this all together and examine how moisture, temperature, and pressure affect each type of propagation.

Normal refractive conditions are found in areas with very weak (or no) inversions, deep moisture, moderate to strong winds, and very unstable, well-mixed conditions. There are often showers in the area, and distinct cloud elements (CU/CB, open convective cells, wave clouds, streaks, or convective cloud lines). Synoptic influences include a cyclonic influence, post-frontal or unstable prevailing conditions.

Normal Refraction: Normal refraction occurs under normal (standard) atmospheric conditions in which moisture, temperature, and pressure all decrease with altitude.

In hot, dry areas (temperature > 30°C, RH < 40%), solar heating produces a homogenous surface layer, sometimes hundreds of feet thick. Sub-refractive areas are also formed by warm, moist air moving over a cooler, drier surface, and near warm fronts because of warmer temperatures and an influx of moisture.

Sub-refraction

When the temperature and moisture distribution creates increased refractivity with height, the wave path bends upward and the energy travels away from the surface.

Super-refractive layers are largely associated with temperature and humidity variations near the earth's surface (e.g., surface inversions). Inversions aloft, due to large-scale subsidence, will lead to super-refractive layers aloft. Regardless of where they form, these layers lead to increased radar detection ranges and extensions of the radio horizon.

Super-refraction

Temperature increasing with height and/or rapid moisture decreases with height will cause EM waves to bend downward more than normal.

Trapping

As previously described, if the radius of curvature for the wave becomes smaller than Earth's, a trapping layer results. This refractive condition is called trapping because the wave is confined to a narrow region of the atmosphere.

Trapping is an extension of super-refraction because the meteorological conditions for both are the same. The conditions that form a trapping layer are more intense than those that form a super-refractive layer.

Trapping refractive conditions can cause confinement of EM waves to a thin layer of the troposphere. If trapped in this region, EM energy can propagate over great ranges. The confinement region is commonly called a **duct**.

Weather and EM Refraction: The Gouge!

With knowledge of the overall synoptic weather pattern, it is possible to make a**rough determination** of the refractive conditions associated with the high and low pressure areas and associated frontal regions (Figure 6).

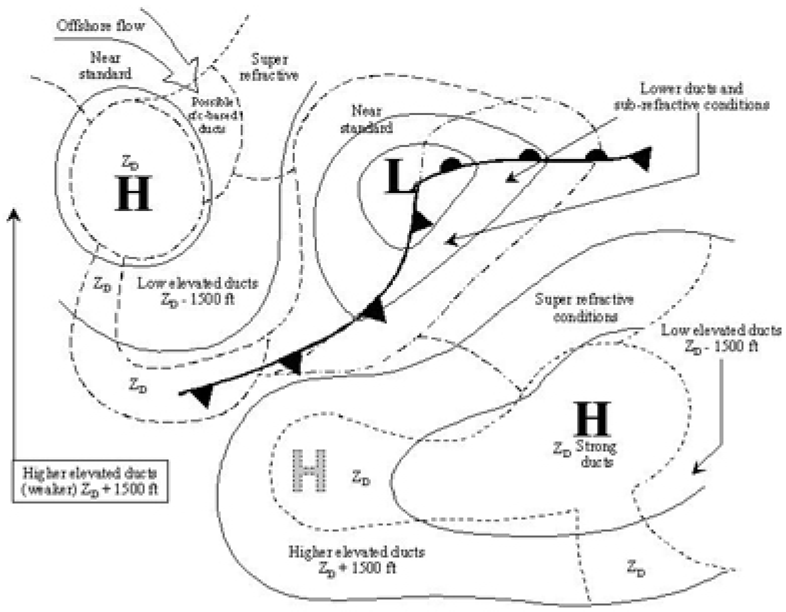

Figure 1-10 - Ducting conditions associated with typical midlatitude synoptic weather situations

SST (C)	SST (F)	Height MSL (Z_D) (m)	Height MSL (Z_D) (ft)
5-7	41-45	1000	3300
8-10	46-50	1200	3900
11-12	51-55	1300	4300
13-15	56-60	1400	4600
16-18	61-65	1500	4900
19-21	66-70	1600	5200
22-24	71-75	1700	5600
25-27	76-80	1800	6200
> 27	> 80	2000	6600

To use the table at left, determine the SST for the region in question, then apply the value of Z_D as specified on the above chart.

Figure 1-11 – Approximate mean elevated duct heights for indicated sea surface temperature (SST) intervals.

SUMMARY

Since all radar operations depend on the transmission and reception of RF energy, a basic knowledge of RF frequency, wavelength, and polarization provides the basis for understanding the more complex radar characteristics.

Since most modern radar systems employ some form of Doppler signal processing, the concept of the Doppler effect is fundamental to understanding modern radar operation. The concepts of refraction, anomalous propagation (ducting), and atmospheric attenuation are key to understanding how RF waves propagate in the atmosphere. The topics in this chapter provide a foundation for understanding radar and jamming system operation.

Determination of refractive conditions can tell you the following and more:

- *How far away enemy sensors will detect friendly assets (missiles, aircraft, ships, boats)*
- *How far away friendly sensors will detect enemy assets*
- *Where reconnaissance platforms need to be placed to exploit the atmosphere and extend friendly detection capability*
- *What altitudes provides aircraft with the greatest weapons stand-off range*
- *From what direction friendly assets should approach the enemy to give the greatest detection advantage*