RADIOWAVE PROPAGATION CONCEPTS

An advantage of electronic communication is that an artificial link (e.g., transmission line, cable, or waveguide) is not necessarily required between the signal source and the receiver. Indeed, the term "wireless" is used in many parts of the world in preference to "radio", and even in the United States "wireless" is often used to describe commercial personal communi-

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Table 1. Frequency Band Designations

Band Designation	Abbreviation	Frequency Range	Free-Space Wavelength Range
Ultralow frequency	ULF	<3 Hz	>100 Mm
Extremely low frequency	ELF	3 Hz to 3 kHz	100 Mm to 100 km
Very low frequency	VLF	3 kHz to 30 kHz	100 km to 10 km
Low-frequency	LF	30 kHz to 300 kHz	10 km to 1 km
Medium-frequency	MF	300 kHz to 3 MHz	1 km to 100 m
High-frequency	HF	3 MHz to 30 MHz	100 m to 10 m
Very high frequency	VHF	30 MHz to 300 MHz	10 m to 1 m
Ultrahigh frequency	UHF	300 MHz to 3 GHz	1 m to 10 cm
Super high frequency	SHF	3 GHz to 30 GHz	10 cm to 1 cm
Extremely high frequency	EHF	30 GHz to 300 GHz	1 cm to 1 mm
Submillimeter		300 GHz to 1 THz	1 mm to 300 μm

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cation by radio. Although radio waves also propagate in waveguides, cables, and transmission lines, the term "radiowave propagation" is used generally, and specifically in this article, for signal travel between a source and a receiver without guidance by such artificial devices. Examples of such systems are radio and television broadcasting, radio point-to-point communication, radar, radio navigation, and remote sensing.

The concept of radiowave propagation allows dividing the total system problem into three separate parts: the transmitter or signal source, the receiver, and propagation. Thus propagation is defined as what happens between the source and the receiver. For this concept to be valid, the distances must be such that far-field criteria for the antennas are satisfied; this allows separating antenna effects from propagation effects. In radar two propagation paths are involved: from the transmitter to the target and from the target to the receiver.

Much has been learned about radiowave propagation since Hertz first demonstrated wireless transmission from one room to another. Now radiowave propagation is considered a moderately mature science, yet new understanding continues to emerge. This article presents an overview of radiowave propagation concepts. More detailed information will be found in articles on specific topics in radiowave propagation.

THE INFLUENCE OF FREQUENCY AND ENVIRONMENT

Frequency

The spectrum of useful electromagnetic waves covers an extraordinarily wide range of frequencies from as low as 70 Hz to X rays at approximately 10 EHz (10^{19} Hz). For convenience, the lower part of the spectrum has been divided into frequency bands as shown in Table 1. The VLF to SHF band designations have been adopted as an international standard. The others are commonly used, but not all authors adhere to those definitions. Because the propagation behavior of radio waves does not change abruptly with frequency, the band designations are often used somewhat loosely with respect to radiowave propagation. For example, a system operating in the range 200 MHz to 500 MHz might be described as a UHF system. In the microwave region of the spectrum, frequency bands are often denoted by letter codes originally applied to radar systems. These are given in Table 2.

Environment

The most important environmental influences on terrestrial propagation are those of the troposphere, the ionosphere, and the ground. The troposphere is the lower region of the atmosphere where ionization is too small to affect radio waves appreciably. Tropospheric effects are caused by refractive index variations, absorption of energy by atmospheric gases, and absorption and scattering by precipitation. The ionosphere is the region of the atmosphere where free electrons produced by ionization strongly affect radio waves in the frequency ranges below about 30 MHz to 50 MHz. The lower altitudinal limit of the ionosphere is in the range of 60 km to 70 km. The term ground designates the surface of the earth, including bodies of water. Local structures, such as buildings, may also have important effects.

Table 2. Standard Radar Frequency-Band Nomenclature

Band Designation	Frequency Range	Approx. Free-Space Wavelength Range
HF	3 MHz to 30 MHz	100 m to 10 m
VHF	30 MHz to 300 MHz	10 m to 1 m
UHF	300 MHz to 1 GHz	1 m to 30 cm
L	1 GHz to 2 GHz	30 cm to 15 cm
S	2 GHz to 4 GHz	15 cm to 7.5 cm
C	4 GHz to 8 GHz	7.5 cm to 3.75 cm
X	8 GHz to 12 GHz	3.75 cm to 2.5 cm
K_u	12 GHz to 18 GHz	2.5 cm to 1.67 cm
K	18 GHz to 27 GHz	1.67 cm to 1.11 cm
K_a	27 GHz to 40 GHz	1.11 cm to 7.5 mm
V	40 GHz to 75 GHz	7.5 mm to 4 mm
W	75 GHz to 110 GHz	4 mm to 2.73 mm
millimeter (mm)[a]	110 GHz to 300 GHz	2.73 mm to 1 mm
submillimeter	300 GHz to 3 THz	1 mm to 100 μm

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[a] The mm designation is sometimes used for the entire frequency range 40 GHz to 300 GHz when general information for this range is to be conveyed.

Interaction of Frequency and Environment

The effect of the environment depends greatly on the system frequency. For example, in frequency ranges below about 30 MHz, the ionosphere is likely to be of prime importance. At VHF and UHF, under certain meteorological conditions, tropospheric layering may form "ducts" which guide waves very efficiently in one frequency band, but not in another. The system frequency is also important with respect to the ground. At microwave frequencies, the wavelength and depth of penetration into the ground are on the order of centimeters; thus the dielectric constant and conductivity at the very surface are important, and even intuitively smooth ground may need to be considered rough if its vertical variations are not small compared to wavelength. In contrast, at VLF the penetration depth is many hundreds of meters; therefore the dielectric constant and conductivity far below the visible surface are important, and the ground may appear smooth even in mountainous areas. As these examples show, it is important to characterize the environment by parametric values appropriate to the system frequency.

The system design also influences the extent to which the environment affects signal propagation. For example, in many satellite communication system calculations the effects of the ground are neglected because the ground station antennas are highly directive and pointed upward. Thus little energy hits the ground on earth-to-space transmission, and little of the energy impinging on the ground is received by the antenna on the space-to-earth path.

The effects of the troposphere, ionosphere, and ground vary with frequency and also with geographic location. In addition, the troposphere and ionosphere vary in time. This variability adds complexity to predicting signal propagation. In many cases, such predictions are limited to statistical estimates.

Noise Considerations

System performance depends on signal strength and also on noise that corrupts the signal. Depending on the system frequency, significant external noise sources may be impulses due to lightning propagated via the ionosphere, emissions from astronomical sources (e.g., the sun, radio stars), or the "blackbody" noise emanating from the transmission medium.

PROPAGATION MECHANISMS AND MODELS

An exact solution of the radiowave propagation problem entails solving Maxwell's equations in the presence of the source and the environment. Such calculations are beyond the state of the art. Instead, approximations based on physical processes are used. For example, the reception of two rays from the transmitter might be considered, one directly and the other via reflection by the ground. Such physically based, mathematical or empirical approximations for calculating signal strength are called propagation models (3). The term "propagation mechanism" is used here for the physical processes which lead to relatively simple propagation models.

In principle, all of the propagation mechanisms discussed later might be considered in every application, but generally one or a few account sufficiently well for the system performance, so that the others are neglected. However, the specific application must be kept in mind. For example, a very small interfering signal may be objectionable, and thus an interference calculation may require including a propagation mechanism that would otherwise be unimportant.

Direct Propagation

The simplest propagation mechanism is direct propagation in which the signal travels from the emitter to the receiver unaffected by any propagation medium, except possibly for attenuation and mild refraction. When attenuation and refraction are absent, propagation occurs as in free space. Direct propagation takes the form of a spherical wave, which can be approximated locally at the receiver as a plane wave.

Although free-space propagation is a highly idealized approximation, it has important applications. Many radars and many satellite communication systems operating in the UHF to C-band frequency range have antennas sufficiently directive to exclude ground effects, and at these frequencies atmospheric effects may generally be neglected. In these cases, the free-space model is applicable. For satellite communications at higher frequencies, atmospheric effects become important, but the direct propagation model is still applicable when attenuation and refractive effects are included. Predictions are very much more complicated if the refractive index is inhomogeneous and time-varying.

In general, the direct propagation model applies when the emitter and receiver are in plain view with respect to one another, provided the effects of other propagation mechanisms are negligible. This situation is most frequently encountered in the atmosphere at UHF to SHF with systems utilizing highly directive antennas.

Terrain Reflections

When antennas are not highly directional, signals may travel directly from the emitter to the receiver and also by reflection from the ground. In this case, both paths must be considered in evaluating the system performance. Typical examples are ground-to-air, air-to-ground, and air-to-air communication at UHF. In air-to-air communication, the size limitation of aircraft antennas makes it impossible to use highly directive antennas in this frequency range, so that it is not possible to keep the signal from reaching the ground. In practical ground-to-air and air-to-ground communication, the ground station antenna is situated somewhat above the ground and is not sufficiently directive to discriminate against the ground-reflected ray. Thus the propagation model for these systems must include both the direct and the ground-reflection mechanisms.

Ducting

The effects of gravity and meteorological conditions make atmospheric density and humidity functions of altitude. Though the resulting variations of the refractive index are small, significant bending of the signal path in the vertical plane can occur. This refraction may be sufficiently strong to guide the wave along the surface of the earth, a behavior called ducting. Tropospheric ducts are most commonly observed at VHF and UHF. They may also exist at higher frequencies, but the more directional antennas employed at these frequencies are less likely to couple efficiently into a duct. Ducting is much more common at some geographical locations than others because it is closely related to meteorological phenomena. Although ducting is a fairly reliable means of communication in some locations, it is generally more likely to be a source of potential interference.

Terrain Diffraction

When the emitter and receiver are not within plain view of each other at VHF and higher frequencies, diffraction is an appropriate propagation mechanism. When the intervening terrain is hilly or mountainous, the diffracting obstacles are often modeled as cylinders or even as vertical half planes ("knife-edge" diffraction). Diffraction by a conducting sphere is the most common model for relatively flat terrain. More detailed computational models are becoming increasingly available as a result of increased computer power, more theoretical insights, and better algorithms.

Ground Wave

When antennas operate near (in terms of wavelength) and on the ground, it is found that the direct and ground-reflected waves cancel almost completely. In this case, however, it is found that a wave can be excited that travels along the surface and decreases rapidly with altitude. Since efficient transmitting antennas at MF and lower frequencies are necessarily large structures because the wavelength is long, they are generally on or near the ground, and ground-wave propagation is important at these frequencies. It is the dominant mechanism for local standard AM broadcast reception in the 540 kHz to 1.7 MHz band. It is also dominant at LF and VLF for relatively short distances.

Tropospheric Scatter

The troposphere is never truly homogeneous, as common experience with weather indicates. In fact, variations over a wide range of dimensional scales are ever present. These variations can be used to advantage when very reliable wireless point-to-point communications are needed over a path of hundreds of kilometers. When very strong signals are beamed at an atmospheric region within the line of sight of both stations, the relatively small signal scattered out of the beam toward the receiving station may, nevertheless, be sufficient to enable communication at rates on the order of 5 megabits per second over 150 km to 400 km distances at UHF. This technique is useful for communication with communities in arctic regions, where other forms of communication (e.g., satellite communications, ionospheric reflection) are less reliable.

Ionospheric Reflection

In the upper LF, MF, and HF bands, signals give the appearance of traveling in rays that are reflected by the ionosphere above and by the ground below, resulting in a series of "hops". Actually, the rays are bent rather than sharply reflected in the ionosphere, but the effect is essentially the same. Signal transmission by this means is very efficient, and great distances are spanned with modest power and equipment. For these reasons the "short-wave" bands, as they are often called popularly, are utilized for broadcasting, point-to-point communications, and amateur use, and portions of this band of the radio frequency spectrum have become exceedingly crowded.

Waveguide Modes

Ray theory requires that the medium vary slowly with respect to wavelength. Thus it fails for radiowave propagation at frequencies lower than about 100 kHz because the corresponding wavelengths no longer meet the requirement that they be much smaller than the earth-ionosphere distance. Instead, at VLF and ELF the earth-ionospheric space is modeled as a concentrically spherical waveguide with the ground as the lower boundary and the ionosphere as the upper. In the ELF and lower VLF bands only one, or at most a few, modes need to be considered. The number of modes and therefore the computational difficulty increases with frequency. Calculations in the LF frequency band are especially laborious, and a combination of ray and mode theory is often used.

Ionospheric Scatter

Signals with a frequency too high to be reflected coherently from the ionosphere may, nevertheless, still be affected by it. One possible effect is the scattering of small amounts of energy out of the beam by local irregularities. This is analogous to the scattering by local irregularities of the troposphere, as discussed previously. Ionospheric scattering is most pronounced in the frequency range immediately above that which supports coherent ionospheric reflections. Ionospheric D-region scatter systems have been operated successfully in the VHF band over 1000 km to 2000 km distances with a bandwidth on the order of 100 Hz.

Meteor Scatter

Meteors are popularly considered rare phenomena, perhaps because our daytime habits and increasingly urbanized existence allow many of us to see them only rarely. Actually, visually observable meteors are not rare by any means, but those too small to observe visually are even more abundant. The number of meteors of a given mass entering the atmosphere approximates an inverse exponential function of the mass. As these meteors enter the atmosphere, they heat and ionize the gas around them, forming trails of ionization. Where this ionization is substantially more intense than that of the ambient ionosphere, the trails reflect signals of a higher frequency than normally reflected from the ionosphere. Meteor-scatter communication systems are operated successfully in the VHF band. Because suitably oriented trails are not always present, such systems must store the information to be transmitted between the occurrence of suitable trails and transmit the information in bursts when such trails are present. This limits the average data rate. Also, a means must be provided for sensing the occurrence of suitable trails. Usually each station continually transmits a pilot signal, and the other station is assured that a trail exists when it receives that signal.

Whistlers

Electromagnetic signals in the ELF/VLF frequency range can propagate through the ionosphere in a peculiar mode in which they closely follow the lines of the earth's magnetic field. It is not easy to launch artificial waves with such very long wavelengths, but lightning generates electromagnetic energy in this frequency range quite effectively. Lightning-generated signals travel along the earth's magnetic field lines, often going out to a distance of several earth radii, and so are guided to the antipode, i.e., the point on the opposite hemisphere where the field line terminates. Part of the signal may be reflected from the antipode along the same field line to the point of origin and may be reflected there again, and so forth. The frequency components of the signal are dispersed in the travel, so that the frequency at the receiver changes with time. When amplified, the resulting audio has a sound reminiscent of whistling; hence the name of the propagation mechanism. Although not useful for information transmission, this propagation mechanism is utilized to obtain information about the upper ionosphere. The same propagation mechanism, but using much stronger artificial magnetic fields, has been investigated for communicating at much higher frequencies through the much denser ion sheath which forms around space vehicles as they reenter the atmosphere.

Nonatmospheric Propagation

The propagation mechanisms discussed so far are those commonly encountered with electromagnetic signal propagation through space or the earth's atmosphere. A different environment prevails when signals propagate through the ocean, through the earth's crust, or through some planetary atmospheres. In the ocean, only signals at ELF or in the visible-light frequency band penetrate to substantial depths. Propagation to substantial depths through the ground also presents difficulties. Nevertheless, radar systems for locating objects, such as water and gas lines at typical shallow depths, are quite successful.

TRANSMISSION LOSS

The most significant question relating to propagation for a radar or telecommunication system is the adequacy of the received signal level. The ratio, usually expressed in decibels (dB), between the power at some point in the transmitting system and a corresponding point in the receiving system is called a loss. Although time delay or phase shift may also be important parameters in some systems, loss is a universal and primary consideration because it relates directly to signal strength. In many cases, the loss varies randomly in time or with location. Then statistical parameters relating to the loss are often the quantities of interest, for example, the median loss.

Several types of losses are defined; see Fig. 1. The usual symbol for loss is L, although A (for attenuation) is also used, and subscripts denote the specific loss under consideration. The loss definitions below follow, with some emendations, those in "The concept of transmission loss for radio links," Recommendation ITU-R P.341-4, of the International Telecommunication Union (4).

Total Loss

The total loss (L_l or A_l) of a link is the ratio between the power supplied by the transmitter and the power supplied to the corresponding receiver under real installation, propagation, and operational conditions. Note: it is necessary to specify the points at which these powers are determined.

System Loss

System loss (L_s or A_s) is the ratio of the RF power input to the transmitting antenna terminals and the resultant RF power available at the receiving antenna terminals. It is expressed in decibels by

$$L_s = 10 \log(p_t/p_a) = P_t - P_a \tag{1}$$

where p_t denotes the RF power input to the transmitter antenna terminals, p_a the available power at the receiving antenna terminals, both measured in the same units, and P_t, P_a are the corresponding power relative to a common reference level (e.g., 1 W) in decibels. Because the system loss is referred to the antenna terminals, it excludes all losses in feeder lines but includes all losses associated with the antenna, for example, antenna-grounding losses, dielectric losses in the antenna, antenna loading-coil losses, and antenna-terminating resistor losses, if applicable.

Transmission Loss

Transmission loss (L or A) is defined as the ratio between the power radiated by the transmitting antenna and the power that would be available at the receiving antenna terminals if this antenna were lossless but its radiation diagram, that is, its directional and polarization characteristics, were unchanged. In Fig. 1 the antenna losses L_{tc} and L_{rc} for transmitting and receiving, respectively, are defined as 10 log (R'/R), where R' is the resistive component of the impedance of the designated antenna and R is its radiation resistance.

Basic Transmission Loss

Basic transmission loss, denoted by L_b or A_i, is the transmission loss that would occur if the antennas were replaced by hypothetical isotropic antennas with the same polarizations in the direction of propagation as the real antennas. The propagation path is retained, but the effects of obstacles close to the antennas are disregarded. The symbols G_t and G_r in Fig. 1 denote the directivity gains of the antennas for the polarization and direction of propagation being considered. The basic transmission loss is the ratio of the equivalent isotropic radiated power (EIRP) of the transmitter system to the available power from a hypothetical isotropic, lossless receiving antenna with the same polarization as that of the real antenna in the propagation direction.

Free-Space Basic Transmission Loss

The free-space basic transmission loss (L_{bf} or A_0) is the transmission loss that would occur if the antennas were replaced with hypothetical isotropic antennas, matched in polarization for maximum power transfer and located in an unbounded, lossless, homogeneous, isotropic environment, retaining the distance between antennas. Free-space basic transmission loss is a function only of the ratio of the distance d between transmitter and receiver to the wavelength λ. It is given in decibels by

$$L_{bf} = 20 \log\left(\frac{4\pi d}{\lambda}\right) \tag{2}$$

where d and λ are measured in the same units.

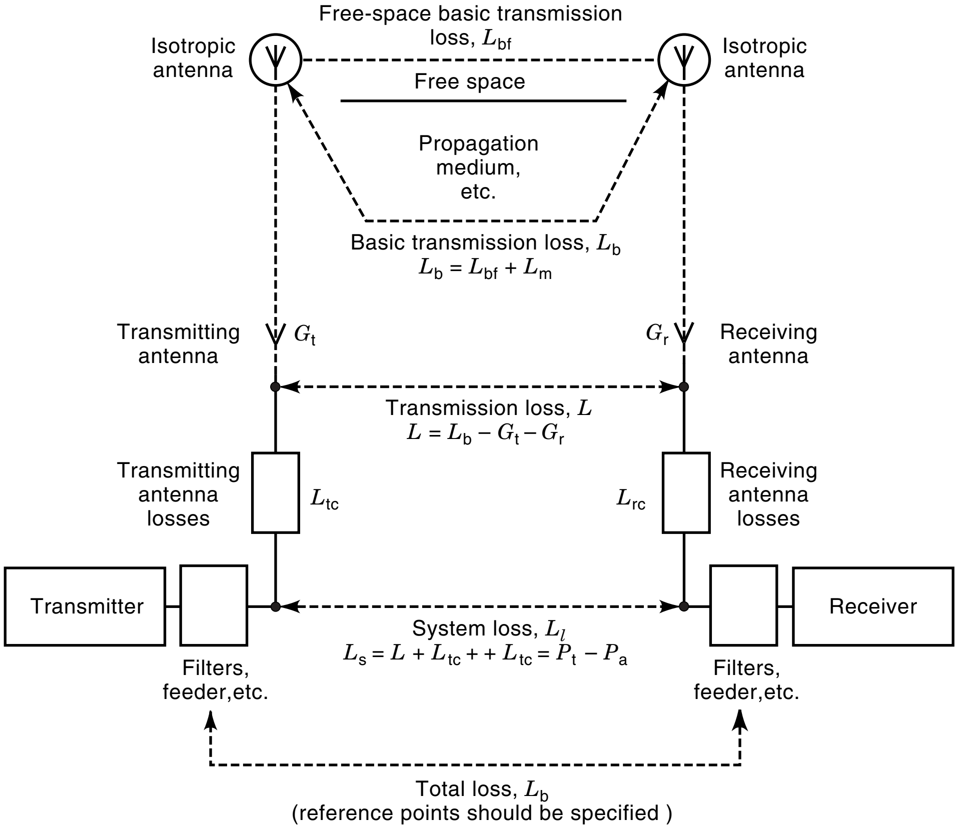

Figure 1. Definitions of losses. Adapted from "The concept of transmission loss for radio links" (Recommendation ITU-R P.341-4), © International Telecommunication Union, 1996, Ref. 4. By permission.

Loss Relative to Free Space

Loss relative to free space (L_{m} or A_{m}) is defined as the difference between the basic transmission loss and the free-space basic transmission loss in decibels:

$$L_{\mathrm{m}} = L_{\mathrm{b}} - L_{\mathrm{bf}} \tag{3}$$

Loss relative to free space may be divided into losses of different types, for example, extinction loss, diffraction loss, wave-interference loss, reflection loss, polarization-coupling loss, aperture-to-medium coupling loss. Because these losses are directly connected with propagation mechanisms, the end result of propagation studies is frequently presented in the form of loss relative to free space.

Extinction Loss. Extinction is the total attenuation due to absorption of signal power in the propagation medium and scattering of power out of the beam by the medium. In the troposphere at X-band and higher frequencies, oxygen, water vapor, and precipitation absorb power from a propagating wave. Precipitation also scatters power out of the beam in the frequency range where particle or droplet size is not small compared to the wavelength. In the ionosphere, absorption is caused primarily by collisions between electrons and neutral molecules. In ground-wave propagation, currents in the ground cause absorption losses.

Diffraction Loss. On a propagation path using diffraction by terrain features or by the spherical earth, only a fraction of the power is scattered in a direction useful to the receiver. The resulting decrease in useful power density is considered a diffraction loss.

Wave-Interference Loss. When several rays combine to produce the effective received wave, interference may cause a signal decrease relative to that of the ray directly received. This effect can be characterized as a wave-interference loss, although this terminology is not encountered frequently in practice. Of course, signals may also be enhanced by interference, resulting in a negative wave-interference loss.

Reflection Loss. Several phenomena result in reflection loss. If reflection from the ground occurs at a non-grazing incidence, the amplitude of the effective plane-wave reflection coefficient of the interface is less than unity, resulting in a reflection loss in the reflected ray. If the surface is rough on a scale comparable to the wavelength, energy is reflected in a range of angles about the specular, resulting in an effective specular reflection coefficient less than unity, and hence a reflection loss in the specular direction. If the reflecting surface is curved, the defocusing (or focusing) effect of the curvature decreases (or enhances) the reflected power density in the propagation direction of interest, resulting in a positive (or negative) reflection loss. The concave curvature of the ionosphere, as seen from the ground, causes focusing. The convex curvature of the earth surface, as seen from above, causes defocusing.

Polarization-Coupling Loss. In an isotropic medium, polarization-coupling loss occurs when the receiving and transmitting antenna polarizations are not matched for optimum power transfer. This situation arises most frequently when interfering signals are being considered.

In an anisotropic medium, such as the ionosphere, plane waves of arbitrary polarization are split into two rays of characteristic polarizations. These rays propagate with generally different attenuations and phase shifts, and they recombine into a single plane wave when emerging from the medium or even within the medium. Polarization-coupling loss occurs when the transmitted wave polarization does not match that of a desired characteristic mode and when the receiving antenna does not match the polarization of the wave received.

Aperture-to-Medium Coupling Loss (Antenna-Gain Degradation). For some propagation mechanisms under certain conditions, the free-space directivity gain of the antennas is not realized. Then the directivity gain is said to be degraded, and the resulting signal loss is termed an aperture-to-medium coupling loss. As an example, in tropospheric scatter propagation a highly directive antenna is used to illuminate a region of the turbulent troposphere that is visible from both transmitter and receiver. The receiver utilizes a highly directive antenna to receive the signal scattered from the illuminated region. The part of the region within both the transmitting antenna beam and the receiving antenna beam is called the common volume. Increasing the directivity of each antenna increases the signal level, but the increase is not proportional to the directivity increase because the narrower beams reduce the common volume. Thus the full free-space directivity of the antennas is not realized. The loss in directivity, when considered an antenna effect, is called antenna-gain degradation; when considered as a propagation effect, it is called antenna-to-medium coupling loss. It is most pronounced for antennas with very high directivity.

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