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IEEE Standard Definitions of Terms for Radio Wave Propagation

Sponsor

Wave Propagation Standards Committee
of the
Antennas and Propagation Society

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Abstract: Terms and definitions used in the context of electromagnetic wave propagation relating to the fields of telecommunications, remote sensing, radio astronomy, optical waves, plasma waves, the ionosphere, the magnetosphere, and magnetohydrodynamic, acoustic, and electrostatic waves are supplied.
Keywords: electromagnetic wave propagation, terminology

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Introduction

(This introduction is not part of IEEE Std 211-1997, IEEE Standard Definitions of Terms for Radio Wave Propagation.)

This is the third revision of the original IEEE Std 211-1969, following those of 1977 and 1990. It is indeed true, as noted in previous Forewords, that the "need for revising a definitions standard transcends its publication date and is essentially continuous." Therefore, as this standard goes to print, work on the fourth revision is already in progress, consisting of adding new terms, refining or deleting old ones, and improving the overall consistency of the standard. This voluntary effort is carried out by the Wave Propagation Standards Committee (WPSC) Subcommittee on Definitions, which meets once or twice a year at conferences sponsored by the IEEE Antennas and Propagation Society and occasionally at college campuses. Increasingly, the meetings have been replaced by e-mail, expanding the opportunity for international participation, although substantial contributions also continue to be made on postcards. The chair of the Subcommittee presenting this revision is Wolfhard J. Vogel, who took the baton from George H. Hagn who in turn was preceded by chairs John M. Kelso, C. H. Liu, and Kurt Toman. Both George H. Hagn, the Subcommittee Chair responsible for the second revision, and Walter A. (Bud) Flood, Chair of the WPSC during most of this revision cycle, have been extremely supportive of the current Subcommittee Chair, thus preserving the momentum of the revision effort and adding greatly to its substance. The individuals with primary responsibility for this third revision as well as those who contributed or made useful comments are acknowledged below. An invitation is extended to the users of this standard to contribute to the fourth revision whenever they see deficiencies or have ideas for an improvement by communicating with the WPSC chair via e-mail to Wolf_Vogel@mail.utexas.edu.

Within the IEEE, the work has been coordinated with the APS Antenna Standards Committee and the following societies: EMC, COM, and Instrumentation and Measurements. It has also been coordinated with Study Groups 1, 5, and 6 of the International Telecommunication Union (ITU-R) and the U. S. National Body of the International Electrotechnical Commission (IEC).

The fields covered by this standard include the following where pertinent to electromagnetic wave propagation: radio astronomy, optical waves, plasma waves, ionosphere, magnetosphere, and magnetohydrodynamic, acoustic, and electrostatic waves.

This standard was prepared by the Wave Propagation Standards Committee (WPSC) Subcommittee on Definitions. The Subcommittee was composed of the following membership:

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IEEE Standard Definitions of Terms for Radio Wave Propagation

absorption: The process of converting electromagnetic energy to heat.

absorption band: A band of frequencies for which a medium is considered to be absorbing.

absorption coefficient (κ_a): (of a medium). The rate of decrease of power density of a wave per unit distance, due to absorption. For a homogeneous medium with relative complex permittivity ε_r and the permeability of free space μ_0:

$$\kappa_a = -4\pi \mathrm{Im}\{\sqrt{\varepsilon_r}\}/\lambda_0$$

where

λ_0 is the free-space wavelength
$\exp(+j\omega t)$ is the time factor

Note: For inhomogeneous media *See also:* **extinction coefficient.**

absorption cross-section (σ_a): (of a lossy body). The ratio of power absorbed by the body, P_a, to the power density of an incident plane wave, S_i:

$$\sigma_a = P_a/S_i$$

See also: **extinction cross-section.**

acoustic-gravity wave. In the atmosphere, a low-frequency wave whose restoring forces are compressional, gravitational, and buoyant.

active sounding: The remote sensing of atmospheric or ionospheric parameters by transmission and reception of radio signals.

adiabatic atmosphere of refraction: *See:* **refractive index gradient.**

albedo: (A) In astronomy (where the sizes of the objects/surfaces are extremely large in comparison to a wavelength), the ratio of the total radiation reflected (scattered) from an object to the total incident power. **(B)** In transport theory or particle scattering (where the size of the object is not extremely large), the ratio of the total scattering cross-section to the sum of the scattering and absorption cross-sections.

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amplitude: The maximum or peak value of a periodically varying quantity. *Note:* Sometimes the term complex amplitude is used to denote a phasor. *See also:* **magnitude.**

angel echoes: Radar returns caused by atmospheric inhomogeneities, refractive index discontinuities, insects, birds, or unknown sources. *Note:* Originally, when some physical target could not be identified through direct visual observation, echoes from such unknown causes were designated as "angels."

angle of arrival: (of a wave). The angle between the negative of the propagation vector and a reference direction.

angle of incidence: At a point on a surface, the angle between the negative of the incident propagation vector and the outward normal to this surface.

angular frequency (ω): (of a sinusoidal wave). 2π times the frequency. *Synonym:* **radian frequency.**

angular power spectrum: Constituted by the mean squared magnitudes of the plane wave spectrum of an electromagnetic field as a function of the direction cosines k_x/k and k_y/k. *Note:* The angular power spectrum and the mutual coherence function are Fourier transform pairs. *See also:* **mutual coherence function.**

anisotropic medium: A medium that is not isotropic, i.e., whose constitutive parameters depend on the polarization and direction of wave propagation of the electric and magnetic fields.

antenna temperature: The temperature of a blackbody that, when placed around a matched, loss-free antenna similar to the actual antenna, produces the same available noise power, in a specified frequency range, as the actual antenna in its normal electromagnetic environment. *See also:* **blackbody.**

antipodal focusing: Ionospheric focusing sometimes observed in the vicinity of the antipodal point or region.

aperture averaging: The reduction in output signal variation when the size of the antenna is large compared to the decorrelation distance of the incident field across the aperture. *Note:* The beamwidth of the antenna is much smaller than the angular spectrum of the incoming wave. *See also:* **angular spectrum.**

atmospheric radio duct: A layer in the atmosphere within which radio waves propagate with low attenuation.

atmospherics: Transient bursts of electromagnetic radiation arising from natural electrical disturbances in the lower atmosphere. *Notes:* 1. In the past, the term *static* was used to include atmospherics and other radio noise. The term *sferics* is in current use. 2. Below 1 Hz, noise is primarily of geomagnetic origin; above 1 Hz it is due to lightning.

attenuation: (of an electromagnetic wave). The decrease in magnitude of a field with distance or with changes in the path in excess of the decrease due to a geometrical spreading factor. *See also:* **spreading factor**.

attenuation coefficient: *See:* **attenuation constant.**

attenuation constant (α): The magnitude of the attenuation vector. *Synonym:* **attenuation coefficient.** *See also:* **propagation vector.**

attenuation vector ($\vec{\alpha}$): The imaginary part of the propagation vector, $\vec{k}$. The attenuation vector points in the direction of maximum decrease in magnitude. *See also:* **propagation vector.**

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aurora: Collective name of optical, electrical, and magnetic phenomena, generally at high latitudes, resulting from direct excitation of the upper atmosphere by energetic particles.

auroral absorption: The increased attenuation of radio waves propagating through the D and E regions of the ionosphere when additional ionization is produced by precipitating charged particles usually associated with the visual aurora.

auroral hiss: Audio-frequency electromagnetic noise associated with auroras.

auroral oval: *See:* **auroral zone.**

auroral zone: An annular region situated between approximately 60° and 70° geomagnetic latitude, north or south, in which auroras are frequently present. *Synonym:* **auroral oval.**

backscatter: The scattering of waves back toward the source.

backscattering cross-section: *See:* **monostatic cross-section**.

Beer-Lambert Law: Also called Beer's Law or Bouger's Law, this law, valid for discrete random media, relates the intensity of an electromagnetic wave at one point to the intensity at another point in the direction of propagation. The intensity decreases exponentially with distance and the attenuation coefficient is equal to the product of the concentration of particles and the extinction cross-section per particle. Consequently, the application of Beer's Law is restricted to weakly scattering media.

bistatic scattering coefficient: The scattering coefficient when the transmitter and receiver are not collocated. *See also:* **scattering coefficient.**

blackbody: An ideal material that absorbs all incident radiation. *Note:* Under thermal equilibrium, a blackbody is a perfect emitter with its emissivity and absorptivity equal to unity. The radiation spectrum of a blackbody is given by Planck's radiation law.

Born approximation: A single-scattering approximation in which the exciting field is assumed to be equal to the incident field.

Bragg angles: When an incident plane wave is diffracted by a periodic structure into discrete directions, the angles these directions of travel make with respect to the normal of the mean boundary.

Bragg resonant scattering: Originally described the scattering in discrete directions by spatially periodic boundaries or constitutive parameter(s), where the scattering directions are determined by the resonance condition in which two source-to-scatter-to-receiver path lengths differ by an integer multiple of 2π radians. This same physical mechanism has been found to apply to some randomly rough planar interfaces and random fluctuations of spatially continuous constitutive parameter(s). In these cases, there is a continuum of scattering angles provided there is either a continuous surface roughness or a continuous constitutive parameter fluctuation spectrum that satisfies the proper Bragg resonance condition.

Brewster angle: The angle of incidence of a wave on the planar bounding surface of a lossless medium for which the reflection coefficient for parallel polarization is zero. *Note:* For a lossy medium, the pseudo-Brewster angle is that angle at which the modulus of the reflection coefficient is a minimum.

brightness: *See:* **spectral brightness.**

brightness temperature: For a region or an extended source at a given wavelength, the temperature of an equivalent blackbody radiator that has the same brightness.

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caustic: A point in space where geometric or ray optics theory predicts infinite field strength.

characteristic impedance: (A) For a transmission line, the ratio of the complex voltage between the conductors to the complex current on the conductors, taken at a common reference plane for a single transverse electromagnetic (TEM) propagating wave. **(B)** For a wave guide, the ratio of the complex transverse electric field component at any point in the wave guide to the complex magnetic field component measured perpendicular to the electric field at the same point in the wave guide for a single propagating wave guide mode. **(C)** For an unbounded homogeneous medium, the ratio of the complex transverse electric field component at any point to the complex magnetic field component measured perpendicular to the electric field at the same point. *Note:* For example, for a linearly polarized transverse electromagnetic (TEM) wave propagating in the z-direction of an isotropic medium E_x/H_y is the characteristic impedance.

characteristic wave: A wave that propagates in a homogeneous anisotropic medium with unchanging polarization. *See also:* **extraordinary wave; ordinary wave.**

circularly polarized wave: An electromagnetic wave for which the locus of the tip of the instantaneous electric field vector is a circle in a plane orthogonal to the wave normal. This circle is traced at a rate equal to the angular frequency of the wave with a left-hand or right-hand sense of rotation. *See also:* **left-hand polarized wave; right-hand polarized wave.**

classical maximum usable frequency*: *See:* **maximum usable frequency.**

*Deprecated

coherence: The correlation between electromagnetic fields at points separated in space, time, or both.

coherence function $[R(\overrightarrow{\Delta r},\tau)]$**:** The expected value of the product of a component of the complex field (F_x) at a given location $(\overrightarrow{r})$ and time (t) and the complex conjugate of that field component (F_x^*) at a different location $(\overrightarrow{r} + \overrightarrow{\Delta r})$ and time $(t + \tau)$:

$$R(\overrightarrow{\Delta r},\tau) = E\{F_x(\overrightarrow{r},t)F_x^*(\overrightarrow{r} + \overrightarrow{\Delta r},t + \tau)\}$$

Notes: 1. This definition assumes that the statistics of the field are homogeneous and stationary. 2. The normalized coherence function, also called the mutual coherence function, is the coherence function divided by the expected value of the square of the magnitude of the field.

coherence length: The distance between two wavefronts of an electromagnetic wave, measured in the direction of propagation, over which the phase of these wavefronts remains sufficiently correlated to result in observable interference between them.

coherence time (τ_0)**:** The time over which the mutual coherence function has decreased to $1/e$ at a given location.

coherent bandwidth: *See:* **frequency selective bandwidth.**

coherent field: In situations where the magnitude, phase, and/or vector direction of an electromagnetic field are random variables, the result of averaging the field over all random characteristics. Also called the mean or average field.

collision frequency: In a plasma, the average number of collisions per second of a particle of a given species with particles of another or of the same species.

completely polarized wave: A wave with no randomly polarized content.

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conductivity (σ)**:** A macroscopic material property that relates the conduction current density (J) to the electric field ($\vec{E}$) in the medium. *Note:* For a monochromatic wave in a linear medium, that relationship is described by the (phasor) equation:

$$\vec{J} = \bar{\bar{\sigma}} \cdot \vec{E}$$

where

$\bar{\bar{\sigma}}$ is a tensor, generally frequency dependent

$\vec{J}$ is in phase with $\vec{E}$

For an isotropic medium, the tensor conductivity reduces to a complex scalar conductivity σ, in which case $\vec{J} = \sigma\vec{E}$.

constitutive parameters: The permittivity and permeability of a medium. *See also:* **permeability; permittivity.**

corner reflector: (A) (antenna). A reflecting object consisting of two or three mutually intersecting conducting flat surfaces. *Note:* Dihedral forms of corner reflectors are frequently used in antennas; trihedral forms are more often used as radar targets. **(B) (radar).** Two (dihedral) or three (trihedral) mutually intersecting conducting surfaces designed to return electromagnetic radiation towards its source. Also used as calibration devices.

correlation length: The direction-dependent distance over which the mutual coherence function for fields or the covariance function for statistical properties of a medium or surface decreases to 1/*e* of its maximum value.

cosmic noise: Noise-like radio waves originating from extragalactic sources.

creeping wave: A wave propagating along a smooth convex surface that has diffracted into the shadow region.

critical frequency: (of an ionospheric layer). The limiting frequency below which a normally-incident magneto-ionic wave component is returned by, and above which it penetrates through, an ionospheric layer.

cross-polarization: The polarization orthogonal to a reference polarization. *See also:* **orthogonal polarization.**

cross-polarization discrimination: The ratio of the power level at the output of a receiving antenna, nominally co-polarized with the transmitting antenna, to the output of a receiving antenna of the same gain but nominally orthogonally polarized to the transmitting antenna.

cross-polarization isolation: The ratio of the wanted power to the unwanted power in the same receiver channel when the transmitting antenna is radiating nominally orthogonally polarized signals at the same frequency and power level.

cyclotron frequency: *See:* **gyro-frequency.**

cylindrical wave: A wave whose equiphase surfaces form a family of coaxial cylinders.

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Debye length (L_D): That distance in a plasma over which a free electron may move under its own kinetic energy before it is pulled back by the electrostatic restoring forces of the polarization (ion) cloud surrounding it. Over this distance, a net charge density can exist in an ionized gas. The Debye length is given by:

$$L_D = 6.9\sqrt{\frac{T_e}{N_e}}$$

where

T_e is the electron temperature

N_e is the electron number density

defocusing: The failure of rays to converge.

degree of polarization: The fraction of the total power in a wave that is completely polarized. *Note*: Sometimes the definition is further restricted to a given polarization state, as in degree of linear polarization.

delay spread: *See:* **time delay spread.**

depolarization: A process by which the polarization state of a wave is altered.

deviative absorption: Occurs when the refractive index is appreciably less than unity (i.e., when the radio ray path is in the process of being bent or "deviated" away from the normal). *Contrast:* **non-deviative absorption.**

dielectric constant*: Relative permittivity (possibly complex).

*Deprecated

diffracted wave: An electromagnetic wave that has been modified by an obstacle or spatial inhomogeneity in the medium by means other than reflection or refraction.

diffraction: The deviation of the direction of energy flow of a wave, not attributable to reflection or refraction, when it passes an obstacle, a restricted aperture, or other inhomogeneities in a medium.

diffuse field: The non-coherent component of the scattered field. *Note:* The diffuse electromagnetic field has a zero average value, (i.e., it is a zero-mean process).

diffuse intensity: Power density associated with the diffuse field.

diffuse reflection: *See:* **diffuse scattering.**

diffuse scattering: The generation of non-coherent (diffuse) fields caused by scattering of an incident electromagnetic wave by a random rough surface or a medium randomly varying with time and/or space.

diffusion approximation: For wave propagation in lossy media, it corresponds to neglecting the displacement current.

direction of polarization: (of an elliptically polarized wave). The direction of the major axis of the electric vector ellipse. *See also:* **elliptically polarized wave.**

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direction of propagation: At any point in a medium, the direction of the time-averaged energy flow. *See also:* **Poynting vector.**

direct wave: A wave propagated over an unobstructed ray path from a source to a point.

Dirichlet boundary condition: A boundary condition applied to the solution of a partial differential equation in which the function is specified as a constant at the boundary. *Note:* When applied to the wave equation for electromagnetic fields, it requires continuity of the tangential field components across the boundary.

dispersion: (of a wave). The variation of the phase velocity with frequency.

dispersive bandwidth: *See:* **frequency selective bandwidth.**

dispersion relation: The functional relationship between the angular frequency, ω, and the wave vector, $\hat{k}$, for waves in a source-free medium. For a dispersionless medium, the components of $\hat{k}$ are linearly proportional to ω.

dispersive medium: A medium in which one or more of the constitutive parameters vary with frequency. *Note:* As a result, the phase velocity of propagating waves in a dispersive medium depends on frequency.

displacement current: The time rate of change of the electric flux density.

distorted Born approximation: *See:* **extended Born approximation.**

Doppler effect: For an observer, the apparent change in frequency of a wave when there is relative motion between the source and the observer.

Doppler spread (σ_λ): The spreading in the frequency domain of the power spectrum of a wave. *Note:* The Doppler spread is inversely related to the decorrelation time (τ_0):

$$\sigma_\lambda = (2\pi\tau_0)^{-1}$$

D region: The region of the terrestrial ionosphere between about 50 km and 90 km altitude. *Note:* The D region is responsible for most of the daytime attenuation of LF, MF and HF radio waves, and it forms the upper boundary of the Earth-ionosphere waveguide for VLF waves.

ducting: Guided propagation of radio waves inside an atmospheric or tropospheric radio duct. *See also:* **atmospheric radio duct.**

edge diffraction: Diffraction by a transverse obstacle with a relatively sharp profile, located between the transmission and reception points. Diffraction over a very sharp profile is frequently called knife-edge diffraction.

effective medium: The replacement of an inhomogeneous medium by an equivalent homogeneous medium having complex constitutive parameters derived from the propagation of the coherent (i.e., mean) field in the actual medium. The equivalent medium describes only the coherent field.

effective radius of the Earth: An effective value for the radius of the Earth that is used in place of the actual radius to correct approximately for atmospheric refraction. *Note:* Under conditions of standard refraction, the effective radius of the Earth is 8.5×10^6 m, or 4/3 the geometrical radius.

EHF: *See:* **extremely high frequency.**

E layer: An ionized layer in the E region. The ionization within the E region is highly correlated with the incident solar flux. Therefore, the normal E layer is present only during daytime.

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electrical length: For a wave of a given frequency, a distance between fieldpoints, expressed in wavelengths of the wave in the medium. *Note:* The electrical length is sometimes expressed in radians or degrees. *See also:* **phase path length.**

electric displacement: *See:* **electric flux density.**

electric field ($\vec{E}$): The electric force that acts on a unit electric charge independent of the velocity of that charge.

electric field integral equation: An integrodifferential equation having the form of a Fredholm integral equation of the first kind for the electric current density and its spatial derivative along the surface *S* of a perfect electric conductor. *Note:* The tangential component of the incident electric field acts as the source for the current, hence the name. The equation is as follows:

$$\hat{n} \times \vec{E}^{i} = \frac{j}{\omega \varepsilon_0} \hat{n} \times \int_{S_0} \{k_0^2 \vec{J}_S g - (\nabla_{S_0} \cdot \vec{J}_S) \nabla_0 g\} dS_0$$

where

$\hat{n}$ is unit normal to S

$\vec{E}^{i}$ is incident electric field

j is $\sqrt{-1}$

k_0^2 is $\omega^2 \mu_0 \varepsilon_0$

$\exp(j\omega t)$ is time convention

g is $\exp[-jk_0|\vec{r} - \vec{r}_0|]/4\pi|\vec{r} - \vec{r}_0|$

∇_0 is gradient evaluated on the surface

∇_{S_0} is gradient in the direction tangential to the surface

electric field strength ($|\vec{E}|$): The magnitude of the electric field vector $\vec{E}$. The units of electric field strength are in volts per meter. *See also:* **field strength permeability.**

electric flux density ($\vec{D}$): A vector quantity related to the charge displaced within the medium by an electric field. The electric flux density is that function whose divergence is the charge density. *Note:* Using phasor notation, the electric flux density is given by:

$$\vec{D} = \bar{\bar{\varepsilon}} \cdot \vec{E}$$

where

$\vec{D}$ is the electric flux density

$\bar{\bar{\varepsilon}}$ is the permittivity in the medium

$\vec{E}$ is the electric field

In an isotropic medium, ε is a scalar and $\vec{D}$ is parallel to $\vec{E}$. In an anisotropic medium, $\bar{\bar{\varepsilon}}$ is a tensor and $\vec{D}$ and $\vec{E}$ are not necessarily parallel. The units of electric flux density are in coulombs per meter squared. *Synonym:* **electric displacement.**

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electromagnetic field: A time-varying field, associated with the electric or magnetic forces and described by Maxwell's equations.

electromagnetic pulse (EMP): An intense transient electromagnetic field. *Note:* EMP is commonly associated with nuclear explosions in or near the Earth's atmosphere; however, electromagnetic pulses can arise from other sources, such as lightning.

electromagnetic spectrum: The spectrum of electromagnetic radiation, as shown in the following table:

Spectral region	Wavelength
Gamma rays	< 0.006 nm
X-rays	0.006–5 nm
Ultraviolet rays	5 nm–0.4 μm
Visible light	0.4–0.7 μm
Infrared	0.7 μm–0.1 mm
Radio	> 0.1 mm

See also: **radio spectrum.**

electromagnetic waves: Waves characterized by temporal and spatial variations of electric and magnetic fields. Electromagnetic waves are known as radio waves, infrared waves, light waves, etc., depending on the frequency.

electrostatic wave: *See:* **longitudinal wave.**

elevated duct: A tropospheric radio duct in which the lower boundary is above the surface of the Earth.

elevation angle: Complement of the angle of incidence. May also refer to the angle of radiation measured above the horizon from a source. *See also:* **grazing angle.**

ELF: *See:* **extremely low frequency.**

elliptically polarized wave: An electromagnetic wave for which the locus of the tip of the electric field vector is an ellipse in a plane orthogonal to the wave normal. This ellipse is traced at the rate in radians equal to the angular frequency of the wave. *See also:* **left-hand polarized wave; right-hand polarized wave.**

emissivity: The ratio of power (per unit surface area, per unit solid angle, over a specified bandwidth) radiated by a material body to the power radiated by a blackbody at the same temperature.

EMP: *See:* **electromagnetic pulse**.

enhanced backscatter: Stronger than expected backscattered signal due to resonant surface or internal waves in the target region.

envelope delay: The time of propagation of the envelope of a wave between two points provided that the envelope is not significantly distorted. *Synonym:* **group delay.** *See also:* **group velocity.**

equiphase surface: Any surface over which the field vectors of a time harmonic wave have the same phase.

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E region: The region of the terrestrial ionosphere between about 90 km and 150 km altitude.

Ergodic hypothesis: For stationary random processes, the equivalence of spatial or temporal average with ensemble average.

Es layer: *See:* **sporadic E layer.**

evanescent field: An electromagnetic field for which, as one moves away from a boundary, the phase is spatially invariant and the magnitude decays exponentially. *Notes:* 1. An evanescent field is a special case of an inhomogeneous plane wave. 2. Fields in a waveguide beyond cutoff are evanescent.

exciting field: The total field responsible for the waves scattered by a particle or elemental surface area. In the case of single scattering, the exciting field consists solely of the incident field. In the multiple scattering case, the exciting field consists of the incident field plus the fields scattered by and among all other particles or elemental surface areas. *See also:* **incident field**.

extended Born approximation: The extended Born approximation takes the exciting field to be the incident field after propagating through the average medium. *Synonym:* **distorted Born approximation.**

extended Huygen's-Fresnel principle: An integral relationship between a scalar wave over one plane in an extended random medium and the wave over a parallel plane located a distance away. In this formulation, the random effects are explicitly represented by the change in log amplitude and phase of a spherical wave propagating between the two planes.

extinction: The decrease of power flux density of an electromagnetic wave due to absorption and scattering.

extinction coefficient (κ_e): (of a medium). The rate of decrease of power density of a wave, per unit distance, due to absorption and scattering.

extinction cross-section (σ_e): (of a body). The ratio of power absorbed (P_a) and scattered (P_s) by the body to the power density of an incident plane wave, S_i:

$$\sigma_e = \frac{(P_a + P_s)}{S_i} = \sigma_a + \sigma_{ts}$$

where

σ_a is the absorption cross-section of the body

σ_{ts} is the total scattering cross-section of the body

extinction matrix ($\bar{\bar{\kappa}}_e$): (of a medium). Vector analog of extinction coefficient for polarized waves propagating in an anisotropic medium.

extragalactic radio waves: Radio waves from beyond our galaxy. *See also:* **cosmic noise**.

extraordinary wave: The magneto-ionic wave component in which the electric vector rotates in the opposite sense to that for the ordinary wave component. *Synonym:* **X wave.** *See also:* **ordinary wave.**

extremely high frequency (EHF): 30–300 GHz. *See also:* **radio spectrum**.

extremely low frequency (ELF): 3 Hz to 3 kHz. *See also:* **radio spectrum**.

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fade depth: The ratio, usually expressed in decibels, of a reference signal power to the signal power during a fade.

fade duration: The time interval during which a signal is below a reference value.

fade slope: The time rate of change of the signal power during a fade, expressed in decibels per second.

fading: The temporal variation of received signal power caused by changes in the transmission medium or path(s).

fading range: The ratio of maximum signal to minimum signal during fading, usually expressed in dB. Often the fading range is specified over a range of percentages. For example, the 5–95% fading range is the ratio of the signal exceeded 5% of the time to that exceeded 95% of the time.

fading rate: The average number of fades occurring per unit time.

Faraday rotation: The rotation of the polarization ellipse of an electromagnetic wave as it propagates in a gyrotropic medium such as a plasma in the presence of a finite magnetic field, in a ferrite, or in some dielectric crystals. *Note:* A gyrotropic material is one in which the permittivity tensor, $\bar{\bar{\varepsilon}}$, or the permeability tensor, $\bar{\bar{\mu}}$, is antisymmetric such that $\varepsilon_{ij} = -\varepsilon_{ji}$ or $\mu_{ij} = -\mu_{ji}$, respectively.

far field region: *See:* **Fraunhoffer region.**

fast wave: An electromagnetic wave propagating close to a boundary or within a bounded medium with a phase velocity greater than that of a free wave which would exist in an unbounded medium with the same electromagnetic properties. *See also:* **slow wave**.

field strength: *See:* **radio field strength**.

finite difference frequency domain (FDFD): A numerical technique for solving partial differential equations by first Fourier transforming the time variable of the equation from the time domain to the frequency domain. Then the resultant partial equation is discretized and solved using the finite difference method.

finite difference time domain (FDTD): A numerical technique for solving a partial differential equation involving time and space variables. The solution is implemented sequentially in the time domain.

finite element frequency domain (FEFD): A numerical technique for solving partial differential equations by first Fourier transforming the time variable of the equation to the frequency domain and then using the finite element method.

finite element time domain (FETD): A numerical technique for solving a partial differential equation directly in the time domain. Discretization of the time variable can be accomplished by the finite difference scheme or by the Galerkin method. *Note:* This method differs from the finite difference time domain (FDTD) method in that the space variable is made discrete by the finite element method rather than the finite difference method. *See also:* **finite difference time domain.**

focusing: The concentration of electromagnetic energy into a smaller region of space. *See also:* **defocusing**.

Foldy's approximation: The approximate solution for the propagation constant of the mean field in a random medium based on the scattering properties of a single particle.

Foldy-Twersky theory: *See:* **Foldy's approximation.**

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F1 layer: The lower of the two ionized layers normally existing in the F region in the day hemisphere. *See also:* **F region.**

forward scattering: Scattering of an electromagnetic wave into directions that are at acute angles to the average direction of propagation of the original wave.

Fraunhoffer region: That region around an electromagnetic radiator or scatterer (maximum dimension D) where the fields can be described in terms of a radial distance and azimuthal and polar angles. *Note:* In this region, the distances of all points to the source's center are larger than $2D^2/\lambda$. *Synonym:* **far field region.**

free space: Space that is free of obstructions and characterized by the constitutive parameters of a vacuum.

free space permeability (μ_0): A scalar constant such that, in vacuum, its product with the magnetic field $\vec{H}$ is equal to the magnetic flux density:

$$\vec{B} = \mu_0 \vec{H}$$

The numerical value of μ_0 is $4\pi \times 10^{-7}$ H/m.

free space permittivity (ε_0): A scalar constant such that in vacuum, the product of ε_0 and the electric field, $\vec{E}$, is equal to the electric flux density:

$$\vec{D} = \varepsilon_0 \vec{E}$$

The numerical value for ε_0 is $8.854{*}10^{-12}$ F/m.

F region: The region of the terrestrial ionosphere from about 150–1000 km altitude. *Notes:* 1. The daytime F region is characterized by an F1 layer and an F2 layer, and at night the lower (F1) layer merges with the upper (F2) layer. 2. The maximum (or peak) of the F2 layer normally occurs in the 300–600 km altitude range.

frequency: (of a periodic oscillation or wave). The number of identical cycles per second, measured in Hertz.

frequency selective bandwidth: The inverse of the product $2\pi\sigma_t$, where σ_t is the time delay spread. *Synonyms:* **coherent bandwidth; dispersive bandwidth.**

frequency selective fading: Fading which alffects unequally the different spectral components of a radio signal.

Fresnel coefficients: (for reflection and transmission). The ratio of the phasor value of the parallel or perpendicular polarization component of the electric field of a reflected or transmitted plane wave to that of the corresponding component of the incident plane wave, evaluated at an infinite planar interface separating two homogeneous media. *Synonyms:* **reflection coefficient; reflection factor.**

Fresnel ellipse: For a ground-reflected ray, the Fresnel ellipse is the locus of points in the ground plane for which the sum of the distances from the two antennas is an integral number of half wavelengths greater than the length of the specularly reflected ray.

Fresnel ellipsoid: The locus of points for which the sum of distances from two antennas is an integral number of half wavelengths greater than the length of the direct ray between the two antennas. The antennas are at the focal points of the set of ellipsoids.

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Fresnel emissivity: The emissivity of an infinite planar interface between two homogeneous media.

Fresnel region: The region around an electromagnetic radiator or scatterer (maximum dimension D) up to a distance of $2D^2$ divided by the wavelength. Outside of this region the dominant part of the fields decay as $1/r$, while inside the region the distance dependence is more complicated.

Fresnel zone: In general, any surface or region bounded by adjacent Fresnel ellipses or ellipsoids. For instance, any plane through both antennas will intersect Fresnel ellipses and define Fresnel zones in that plane. Any plane normal to the ray path between antennas will define a series of circular (annular) Fresnel zones.

Friis transmission formula: The relationship defining the power transfer ratio between two antennas:

$$\frac{P_r}{P_t} = \frac{A_r A_t}{(\lambda d)^2}$$

where

A_r is the effective area of the receiving antenna
A_t is the effective area of the transmitting antenna
λ is the wavelength
d is the separation between the antennas
P_r is the received power
P_t is the transmitted power

Notes: 1. The antennas must be in free space and separated by at least $2D^2/\lambda$, where D is the largest dimension of the larger antenna. 2. The formula accounts for free space propagation loss and antenna gains.

F2 layer: The single ionized layer normally existing in the F region in the night hemisphere and the higher of the two layers normally existing in the F region in the day hemisphere. *See also:* **F region.**

galactic radio waves: Radio waves originating in our galaxy.

geometric optics: The infinitesimal-wavelength limit of processes involved in scattering or propagation, in which case ray-optics apply.

geometric theory of diffraction (GTD): The theory of geometric optics modified to allow for rays propagating into shadow regions. Also includes the development of ray constructs for scattering from edges and removal of "infinities" in optical focusing predictions in inhomogeneous media.

gravity wave: *See:* **acoustic-gravity wave**.

grazing angle: The complement of the angle of incidence for large angles of incidence. *See also:* **elevation angle.**

Green's function: The response of a medium to an incident impulse function.

ground wave: From a source in the vicinity of the surface of the Earth, a wave that would exist in the vicinity of the surface in the absence of an ionosphere. *Note:* The ground wave can be decomposed into the Norton surface wave and a space wave consisting of the vector sum of a direct wave and a ground-reflected wave.

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group delay: *See:* **envelope delay**.

group path length: For a pulsed signal traveling between two points in a medium, the product of the speed of light in vacuum and the travel time of the pulse between the two points, provided the shape of the pulse is not significantly changed.

group velocity: (of a traveling wave). The velocity of propagation of the envelope, provided that the envelope moves without significant change of shape. The magnitude of the group velocity is equal to the reciprocal of the rate of change of phase constant with angular frequency.

guided wave: A propagating wave whose energy is concentrated within or near boundaries between media having different electromagnetic properties.

gyro-frequency (f_H): The lowest natural frequency at which charged particles spiral in a fixed magnetic field. It is given by:

$$f_H = q\frac{|\vec{B}|}{2\pi m}$$

where

q is the charge of the particles
$|\vec{B}|$ is the magnitude of magnetic flux density
m is the mass of the particles.

For a linear medium, the gyro frequency is the same as cyclotron frequency.

height gain: The variation in electromagnetic field strength above a surface, expressed as gain relative to a fixed reference height. *Notes:* 1. This ratio is generally expressed in decibels and may have a negative value. 2. The reference height may be at the Earth's surface.

HF: *See:* **high frequency.**

high frequency (HF): 3–30 MHz. *See:* **radio spectrum.**

homogeneous dense medium: Medium in which the refractive index is significantly different from that of a vacuum. *See also:* **sparse medium**.

homogeneous Helmholtz equation: The wave equation for the electromagnetic potential, Φ, given by:

$$(\nabla^2 + k^2)\Phi = 0$$

where k is the wavenumber in the medium. The homogeneous Helmholtz equation is also the scalar wave equation for a scalar component of the electric field represented by Φ. *Note:* Sometimes k^2 is replaced by $-\gamma 2$, where γ is the propagation constant.

homogeneous medium: A medium whose properties are spatially invariant.

homogeneous plane wave: A wave in which the planes of constant magnitude and constant phase are parallel. *Note:* Homogeneous plane waves are sometimes called uniform plane waves.

horizontally polarized wave: A linearly polarized wave whose electric field vector is perpendicular to the plane of incidence or parallel to the Earth's surface in radio propagation. Same as S-polarization in optics; perpendicular polarization in physics. *See also:* **transverse electric wave.**

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Huygen's principle: Principle proposed by Christian Huygen in 1678 that states that:

— Each point on the wavefront of a light disturbance can be considered to be a new source of secondary spherical waves, and
— The wavefront at any other point in space can be found by constructing the envelopes of the secondary wavelets.

ideal conductor: *See:* **perfect conductor.**

ideal dielectric: *See:* **perfect dielectric.**

improper mode: Refers to a mode of propagation that cannot be excited by a physical source in the absence of other modes, (e.g., Zenneck surface wave).

incidence angle: *See:* **angle of incidence**.

incident field: That component of the exciting field identical to the field that would have been present in the absence of all particles, surfaces, and volumes. *See also:* **exciting field**.

incident wave: A wave that impinges on a discontinuity in refractive index or a medium of different propagation characteristics. The incident wave is the total field in the absence of the discontinuity.

incoherent field: *See:* **diffuse field**.

incoherent scattering: Scattering produced when the wave of an exciting field encounters random fluctuations of complex permittivity or permeability. The fluctuations may be either discrete or continuous (turbid or turbulent in the case of scattering from atmospheric refractive index fluctuations). The scattered fields exhibit random variations in phase and magnitude and thus constitute a zero mean process.

inhomogeneous dense medium: A medium having discrete or continuous spatial variations in its permittivity or permeability, such that multiple scattering must be considered. *See also:* **sparse medium**.

inhomogeneous medium: A medium whose properties are not spatially invariant.

inhomogeneous plane wave: A wave for which the planes of constant magnitude and planes of constant phase are not parallel. Sometimes called a heterogeneous plane wave, but this use is deprecated.

instantaneous frequency: $1/(2\pi)$ times the time rate of change of phase of a wave.

instantaneous Poynting vector $[\vec{P}(t, \vec{r})]$**:** (of an electromagnetic wave). The vector product of the instantaneous electric and magnetic field vectors. The integral of $\vec{P}(t, \vec{r})$ over a surface is the instantaneous electromagnetic power flow through the surface.

integrated precipitable water vapor: The equivalent liquid water height (in centimeters) of a vertical column of water vapor in the atmosphere with 1 cm^2 horizontal cross-section.

intrinsic impedance: For a monochromatic (time harmonic) electromagnetic wave propagating in a homogeneous isotropic medium, the ratio of the complex amplitude of the electric field to that of the magnetic field. *Note:* The intrinsic impedance of a medium is sometimes referred to as the characteristic impedance of the medium.

invariant imbedding: A mathematical technique that can be employed to treat radiative transfer problems in the presence of inhomogeneous profiles of absorption and temperature. In it a boundary-value problem is converted to an initial value problem that incorporates the boundary conditions in the equations themselves. The equations are in the form of first-order ordinary differential equations and can be solved by standard methods of initial value problems.

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ionogram: A record showing the group path delay of ionospheric echoes as a function of frequency.

ionosonde: A swept-frequency or stepped frequency instrument that transmits radio waves vertically or obliquely to the ionosphere and uses the echoes to form an ionogram.

ionosphere: That part of a planetary atmosphere where ions and free electrons are present in quantities sufficient to affect the propagation of radio waves.

ionospheric absorption: The loss of energy from an electromagnetic wave caused by collisions, primarily between electrons and neutral species and ions in the ionosphere.

ionospheric mode of propagation*: Representation of a transmission path by the number of hops between the end points of the path, the ionospheric layers producing the ionospheric reflections being indicated for each hop. For example, 1F + 1E represents a hop with an ionospheric reflection in the F region followed by a reflection at the ground, followed, in turn, by a hop with a reflection from the E region. *Synonym:* **mechanism of propagation.**

*Deprecated

ionospheric wave: *See:* **sky wave.**

isotropic scatterer: A non-physical scatterer that scatters equally in all directions.

Jansky: A unit of spectral power flux density: 10^{-26} times one watt per square meter per Hertz.

junction frequency (JF): The frequency at which the traces seen on an oblique-incidence ionogram corresponding to the low-angle ray and to the high-angle ray respectively, for a given mode, merge together. *Note:* The high-angle ray is also called the Pederson ray.

Kirchhoff approximation: When used in computing electromagnetic scattering from surfaces, this approximation assumes that the surface is locally planar and the field on the surface is equal to the field that would have existed had the surface been a plane tangent to the actual surface at that point. *Notes:* 1. Valid when the local radius of curvature is much greater than a wavelength and multiple scattering can be neglected. 2. Not valid in shadow regions.

Kirchhoff's theory of diffraction: A scalar wave theory, valid when the diffracting aperture has dimensions that are large relative to the wavelength. The diffracted field at any point is found by evaluating an integral involving the field and its derivative over the aperture only, and these quantities are assumed to be the same as they would be were the aperture infinitely large in both directions.

knife-edge diffraction: *See:* **edge diffraction.**

Lambert-Beer Law: *See:* **Beer-Lambert Law.**

Lambertian surface: A surface with a cosine dependence of the scattered power on both the incident and scattering angles and, hence, a cosine squared dependence on angle in the backscatter direction.

lateral wave: A wave, not predicted by geometrical optics, excited at and propagated along the interface of two (possibly lossy) dielectric media. For sufficiently large distances from the source, the magnitude of the field varies as the inverse square of the distance measured along the interface. *Note:* Lateral wave is similar to the component of the radio ground wave when the geometrical-optical component is separated out. *See also:* **Norton surface wave.**

leaky wave: An electromagnetic wave associated with a fast wave guided along a surface. The wave radiates (or "leaks") energy continuously as it travels along the surface and thus decreases exponentially in the direction of propagation. Over a limited region, it may increase with height above the surface. *Note:* Leaky waves may be created by periodic as well as uniform, open guiding structures.

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left-hand polarized wave: A circularly or an elliptically polarized electromagnetic wave for which the electric field vector, when viewed with the wave approaching the observer, rotates clockwise in space. *Notes:* 1. This definition is consistent with observing a counterclockwise rotation when the electric field vector is viewed in the direction of propagation. 2. A left-handed helical antenna radiates a left-hand polarized wave.

LF: *See:* **low frequency.**

limb sounding: A technique for making observations of planetary atmospheres wherein satellite-borne sensors are oriented in a direction tangent to the spherical atmospheric layer of interest, to afford the longest pathlength and highest vertical resolution through the atmosphere.

limiting polarization: The resultant polarization of a wave after it has emerged from a magneto-ionic medium.

linearly polarized wave: An electromagnetic wave for which the locus of the tip of the electric field vector is a straight line in a plane orthogonal to the wave normal.

locally homogeneous medium: A medium in which the changes in electrical properties are small when measured over a distance of a wavelength.

LOF: *See:* **lowest observed frequency.**

longitudinal wave: In a plasma, the type of wave whose restoring force is electrostatic. The associated electric field and particle velocity is in the direction of propagation with accompanying charge density fluctuations.

Lorenz-Mie scattering: *See:* **Mie scattering.**

loss tangent: (of a material). The ratio of the imaginary part of the complex permittivity to the real part.

lowest observed frequency (LOF): In ionospheric sounding, LOF is the lowest frequency for which signals transmitted from a sounder and propagated via the ionosphere are observed on the ionogram, regardless of the precise propagation path involved. *Note:* The LOF is a function of the ionosonde's transmit power, antenna gain, and receiver noise environment.

lowest usable frequency (LUF): The lowest frequency that would permit acceptable performance of a radio circuit by signal propagation via the ionosphere between given terminals at a given time under specified working conditions. *Notes:* 1. The LUF is a system-dependent parameter and is determined by factors such as ionospheric absorption, transmitter power, antenna gain, receiver characteristics, type of service, and noise conditions. 2. LUF is sometimes referred to as lowest usable high frequency. 3. The use of lowest useful frequency for LUF is deprecated.

low frequency (LF): 30–300 kHz. *See also:* **radio spectrum.**

LUF: *See:* **lowest usable frequency.**

magnetic field ($\vec{H}$): For time harmonic fields in a medium with linear and isotropic magnetic properties, the magnetic flux density divided by the permeability of the medium.

magnetic field integral equation: A Fredholm integral equation of the second kind for the electric current density induced on the surface S of a perfect electric conductor. *Note:* The tangential component of the incident magnetic field acts as the source for the current, hence, the name. The equation is as follows:

$$\vec{J}_S = 2\hat{n} \times \vec{H}^i + 2\hat{n} \times \int_{S_0} (\vec{J}_S \times \nabla_0 g) dS_0$$

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where

$\hat{n}$ is unit normal to S

$\vec{H}^{i}$ is incident magnetic field

g is $\exp[-jk_0|\vec{r} - \vec{r}_0|]/4\pi|\vec{r} - \vec{r}_0|$

$\vec{J}_S$ is surface current density

magnetic field strength ($|\vec{H}|$): The magnitude of the magnetic field vector $\vec{H}$. The units of magnetic field strength are in amperes per meter. *Synonym:* **magnetizing force.**

magnetic flux density ($\vec{B}$): A vector field that acts on moving charges (q) such that the force per unit charge ($\vec{F}$) is equal to the vector (cross) product of the velocity ($\vec{v}$) of the particle and $\vec{B}$, the magnetic flux density:

$$\frac{\vec{F}}{q} = \vec{v} \times \vec{B}$$

The units of magnetic flux density are in volt seconds per meter squared.

magnetic induction*: *See:* **magnetic flux density.**

*Deprecated

magnetic loss angle: For a pure sinusoidal wave in a medium with complex permeability μ, the angle defined by the equation

$$f_m = \tan^{-1}\left(\frac{\mu''}{\mu'}\right)$$

where

μ'' is the imaginary part of the complex permeability

μ' is the real part of the complex permeability

magnetic storm: A disturbance of the Earth's magnetic field, generally lasting one or more days and characterized by significant changes in the strength of this field.

magnetizing force: *See:* **magnetic field strength.**

magneto-ionic medium: An ionized gas that is permeated by a fixed magnetic field.

magneto-ionic wave: At a given frequency, either of the two characteristic plane electromagnetic waves that can travel in a homogeneous magneto-ionic medium without change of polarization. *Note:* These characteristic waves are also called the ordinary and extraordinary waves. *See also:* **extraordinary wave; ordinary wave.**

magnetopause: The transition region between the planetary and the interplanetary magnetic fields.

magnetosphere: The region of a planetary atmosphere where the planetary magnetic field, as modified by the solar wind and the interplanetary magnetic field, controls the motions of charged particles. *Note:* The Earth's magnetosphere includes part of the F region of the terrestrial ionosphere up to the magnetopause.

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magneto-telluric current: A current in the Earth associated with time-varying geomagnetic fields.

magneto-telluric fields: Electric and magnetic fields induced in the Earth by external time-varying sources that are usually of ionospheric origin.

magnitude: The real number indicating the maximum or peak value of a periodically varying quantity. *See also:* **amplitude.**

maximum observed frequency (MOF): In oblique-incidence ionospheric sounding, the MOF is the highest frequency for which the signals transmitted from a sounder are observed on the ionogram, regardless of the propagation path involved.

maximum usable frequency (MUF): The highest frequency by which a radio wave can propagate between given terminals, on a specified occasion, by ionospheric refraction alone. *Notes:* 1. Where the MUF is restricted to a particular ionospheric propagation mode, the values may be quoted together with an indication of that mode (e.g., 1E MUF, 2F2 MUF). 2. If the extraordinary component of the wave is involved, then this is noted [e.g., 1F2 MUF (X)]. Absence of a specific response to the magneto-ionic component implies that the quoted value relates to the ordinary wave. 3. It is sometimes useful to quote the ground range for which the MUF applies. This is indicated in kilometers following the indication of the mode type [e.g., 1F2 (4000) MUF (X)].

Maxwell-Garnett mixing formula: Gives the approximate dielectric constant of a medium containing a few small spherical dielectric inclusions, ε_r, as:

$$\varepsilon_r = \varepsilon_1 \frac{1 + 2fy}{1 - fy} \text{ with } y = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}$$

where

ε_1 is the relative dielectric constant of the background medium
ε_2 is the relative dielectric constant of the inclusions
f is the volume fraction of the inclusions

The Maxwell-Garnett mixing formula is valid when f is less than a few percent and the inclusions are small compared to the wavelength.

mean (effective) radiating temperature: For a non-isothermal body or medium:

— The temperature that would give rise to the same total brightness as the actual medium, or
— The temperature that would give rise to the same spectral brightness as the actual medium.

mechanism of propagation: *See:* **ionospheric mode of propagation.**

medium frequency (MF): 300 kHz to 3 MHz. *See also:* **radio spectrum.**

mesopause: The upper boundary of the mesosphere.

mesosphere: That part of the Earth's atmosphere, located above the stratosphere, in which the temperature decreases with increasing height. The mesosphere extends to an altitude of around 85 km, where the temperature reaches a minimum value.

MF: *See:* **medium frequency.**

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micropulsation: Small magnitude fluctuations (usually much less than 10^{-6} of the Earth's magnetic field) with periods on the order of seconds or minutes (f<1 Hz). *Note:* Micropulsations usually result from current fluctuations in the E region.

Mie scattering: Scattering by spherical particles whose diameters are comparable to or greater than a wavelength. *Synonym:* **Lorenz-Mie scattering.**

mixing ratio: (of water vapor). The ratio of the mass of water vapor to the mass of dry air in a given volume of air. This ratio is generally expressed in grams per kilogram.

mixing rules: Various theoretical and often empirical models to predict the effective medium constitutive parameters.

mode of propagation: A form of propagation of guided waves where the transverse field pattern is invariant with range (i.e., as in a waveguide). *Note:* Inappropriate uses of the term mode are common. *Synonym:* **mechanism of propagation.** *See also:* **ionospheric mode of propagation.**

modified index of refraction: In the troposphere, the sum of the refractive index at a given height h above the mean local surface and the ratio of this height to the geometrical mean radius of the Earth.

MOF: *See:* **maximum observed frequency.**

monostatic cross-section: The scattering cross-section of a target in the retro-direction.

monostatic radar: A radar where the transmit and receive antennas are collocated.

Monte Carlo method: A numerical statistical technique that simulates random propagation and scattering processes by repeatedly calculating outcomes using parameters chosen at random from the processes' parameter space.

Mueller matrix: The matrix that relates the Stokes vector of the scattered wave to the Stokes vector of the incident wave. *Synonym:* **Stokes matrix.**

MUF: *See:* **maximum usable frequency.**

multipath transmission: The propagation phenomenon that results in signals reaching the receiving antenna by two or more paths. When two or more signals arrive simultaneously, wave interference results. The received signal fades if the wave interference is time varying or if one of the terminals is in motion.

multiple scatter: A calculation of wave scattering from a surface or a collection of particles for which the field exciting each surface element or particle consists of the incident field plus the fields scattered by all the other surface elements or particles in their many interactions. A full multiple scattering solution is an exact solution to the problem.

M-unit: *See:* **refractive modulus.**

mutual coherence function: The normalized coherence function. *See also:* **coherence function.**

near field: The field of a source at distances that are small compared to the wavelength. *Notes:* 1. The near field includes the quasi-static and induction fields varying as r^{-3} and r^{-2}, respectively, but does not include the radiation field varying as r^{-1}. 2. Often refers to points within the Fresnel region of a large antenna.

Neumann boundary condition: A boundary condition applied to the solution of a partial differential equation in which the derivative of the function, applied in the direction normal to the boundary, is specified as a constant at the boundary.

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non-deviative absorption: Absorption that occurs in regions where the refractive index is close to unity (i.e., when radio ray bending is negligible). *Contrast:* **deviative absorption.**

Norton surface wave: The propagating electromagnetic wave produced by a source over or on the ground. The Norton wave consists of the total field minus the geometrical-optics field. *See also:* **ground wave; lateral wave.**

N-unit (N): A measurement of refractivity, usually in parts per million, where:

$$N = (n - 1) \times 10^6$$

where

n is the refractive index

See also: **refractivity.**

oblique-incidence ionospheric sounding: *See:* **active sounding.**

obstacle gain: The ratio, usually expressed in dB, of the electromagnetic field at a point in the vicinity of the geometrical shadow of an obstacle to the field which would occur in the absence of the obstacle.

operational maximum usable frequency (MUF): The highest frequency that would permit acceptable performance of a radio circuit by signal propagation via the ionosphere between given terminals at a given time under specified working conditions. *Notes:* 1. Acceptable performance may, for example, be quoted in terms of the maximum allowable bit error rate or required signal-to-noise ratio. 2. Specified working conditions may include such factors as antenna type, transmitter power, class of emission, and required information rate. *See also:* **maximum usable frequency.**

optical depth: The value of the integral of the extinction coefficient over a specified path.

optimum working frequency (OWF or FOT): The frequency that is exceeded by the operational maximum usable frequency (MUF) during 90% of the specified period, usually a month. *Note:* The acronym FOT is the French abbreviation of "fréquence optimale de travail."

ordinary wave: That characteristic magneto-ionic wave component deviating the least, in most of its propagation characteristics, from those expected for a wave in a non-magnetized plasma of the same density. *Note:* For vertical incidence, the ordinary wave is reflected near the height at which the plasma frequency is equal to the wave frequency when the effects of collisions are negligible. *Synonym:* **O wave.**

orthogonal polarization: For a given wave, the unique polarization state containing no components of the given wave's polarization. *Notes:* 1. For linear polarization, the (linear) polarization perpendicular to the reference (linear) polarization. 2. For circular polarization, the (circular) polarization with the opposite sense of rotation. 3. For elliptical polarization, the polarization with the same axial ratio, opposite rotation sense and major axis perpendicular to that of the reference polarization.

O wave: *See:* **ordinary wave.**

parabolic approximation: *See:* **parabolic equation.**

parabolic equation: Results when the Helmholtz equation is approximated to emphasize preferred propagation in the axial direction, leading to a differential equation of parabolic form. *Synonym:* **parabolic approximation.**

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parallel polarization: The polarization of a wave for which the electric field vector lies parallel to the plane of incidence. *Note:* Sometimes called vertical or transverse magnetic (TM) polarization. In optics, it is called "p" polarization. In radio propagation, *H* is parallel to the ground. *Synonyms:* **transverse magnetic polarization; vertical polarization.**

paraxial approximation: An approximation in which the waves are constrained to travel predominantly in one direction.

partially polarized wave: A wave with some randomly polarized content.

particle size distribution: The probability density function describing the size distribution of particles in a medium.

Pederson ray: The upper ionospheric ray in oblique-incidence propagation. *See also:* **junction frequency.**

penetration depth: For a given frequency, the depth at which the electric field strength of an incident plane wave, penetrating into a lossy medium, is reduced to 1/e of its value just beneath the surface of the lossy medium. *Note:* The penetration depth, also called the skin depth, is equal to the reciprocal of the attenuation constant in the lossy medium. *Synonym:* **skin depth.**

penetration frequency: (A) (oblique incidence propagation). For a given angle of incidence, the lowest frequency that just penetrates the ionosphere. **(B) (vertical incidence propagation).** *See also:* **critical frequency.**

percent polarized: The degree of polarization expressed in percent. *See also:* **degree of polarization.**

perfect conductor: A medium for which the conductivity is infinite. In a perfect conductor, the total electric and magnetic fields are identically zero regardless of the exciting source. *Synonyms:* **ideal conductor; perfectly conducting medium.**

perfect dielectric: A dielectric medium in which the conductive and dielectric losses are identically zero. See *also:* **ideal dielectric.**

perfectly conducting medium: *See:* **perfect conductor.**

permeability (μ): A macroscopic material property of a medium that relates the magnetic flux density, $\vec{B}$, to the magnetic field, $\vec{H}$, in the medium. For a monochromatic wave in a linear medium, that relationship is described by the (phasor) equation:

$$\vec{B} = \bar{\bar{\mu}} \cdot \vec{H}$$

where

$\bar{\bar{\mu}}$ is a tensor that is generally frequency dependent

For an isotropic medium, the tensor reduces to a complex scalar:

$$\mu = \mu' - j\mu''$$

where

μ' is the real part of the permeability
μ'' accounts for losses

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permittivity (ε): A macroscopic material property of the medium that relates the electric flux density, D, to the electric field, $\vec{E}$, in the medium. For a monochromatic wave in a linear medium, that relationship is described by the (phasor) equation:

$$\vec{D} = \bar{\bar{\varepsilon}} \cdot \vec{E}$$

where $\bar{\bar{\varepsilon}}$, the complex permittivity, is a tensor that is generally frequency dependent. For an isotropic medium, the tensor reduces to a complex scalar:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

where

ε' is the real part of the permittivity
ε'' accounts for losses

perpendicular polarization: The polarization of a wave for which the electric field vector is perpendicular to the plane of incidence. *Note:* Sometimes called horizontal or transverse electric (TE) polarization; in optics, such a wave is said to be "s" polarized.

perturbation technique: An approximate analytical method, the accuracy of which is based on the smallness of one or more characteristics of the medium or interface.

phase constant (β): The magnitude of the phase vector. *See also:* **propagation vector.**

phase function matrix: The matrix that results when the elements of the Mueller matrix are averaged over all scatterer orientations. The phase function matrix relates the average scattered Stokes vector to the incident Stokes vector.

phase path length: For a monochromatic electromagnetic wave, the product of the phase constant and the physical path length. *Note:* In a slowly varying spatially inhomogeneous medium, the path length equals the line integral of the real part of the phase constant along the ray path. *See also:* **electrical length.**

phase vector ($\vec{\beta}$): The real part of the propagation vector, $\vec{k}$. *Note:* The phase vector points in the direction of maximum rate of change of the phase. *See also:* **propagation vector.**

phase velocity: The velocity at which the equiphase planes of a propagating wave travel. *Note:* The minimum phase velocity is in the direction of the wave normal.

phasor notation: For monochromatic fields, the complex notation used in the expressions for field quantities with the exponential time factor $\exp\{j\omega t\}$. For example, for plane waves

$$\vec{\varepsilon}(\vec{r}, t) = \mathrm{Re}\{\vec{E}(\vec{r}, \omega)\exp(j\omega t)\}$$

where

$\vec{\varepsilon}(\vec{r}, t)$ is the instantaneous electric field
Re indicates the real part
$\vec{E}(\vec{r}, \omega)$ is the phasor notation for the electric field

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photo-ionization: Ionization of atoms or molecules caused by infrared, visible, or ultraviolet photons.

physical optics approximation: Estimates the field scattered by a body by considering only the interaction of the incident wave with the local geometry of the body at every point illuminated by the incident wave. The physical optics approximation is the Kirchhoff approximation in the illuminated part of the body and zero in its shadow.

Planck's radiation law: Defines the emission spectrum of a blackbody in terms of its physical temperature.

plane of incidence: The plane containing the normal to the surface of a boundary and the phase vector, $\hat{\beta}$, of the incident wave.

plane wave: A wave whose equiphase surfaces form a family of parallel planes.

plane wave propagation factor: The factor $\exp(-j\hat{k}\cdot\hat{r})$ in the phasor expression for plane wave fields, where $\hat{k}$ is the propagation vector (a constant) and $\hat{r}$ is the position vector.

plasma: A macroscopically neutral assembly of charged and possibly also uncharged particles. *Note:* A plasma is said to be cold if the thermal effects of charged particles on dynamic processes in the plasma can be neglected for the particular problem involved. A plasma is said to be hot (or warm) if the thermal effects are not negligible.

plasma frequency (f_N): A natural frequency of oscillation of charged particles in a plasma given by:

$$(f_N)^2 = (2\pi)^{-2}\frac{Nq^2}{m\varepsilon_0}$$

where

q is the charge per particle
m is the particle mass
N is the particle number density
ε_0 is the permittivity of free space

Note: For electrons, with f_N in Hertz and N in electrons per cubic meter:

$$(f_N)^2 = 80.6N$$

plasmapause: The outer boundary of the plasmasphere, characterized by a steep decrease of the plasma density.

plasmasphere: That ionized region of the topside ionosphere that encircles the Earth around the equator and follows the rotation of the Earth. *Note:* In the equatorial plane, the plasmasphere extends to a distance of 3–7 Earth radii, depending on local time and geomagnetic activity.

plasma sheath: A layer of charged particles, of substantially one sign, that accumulates around a body in a plasma.

plasma waves: Electrostatic waves associated with a "warm" plasma, giving rise to density and velocity fluctuations.

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Poincaré sphere: A tool for graphically displaying the polarization state of a monochromatic wave. For a fully polarized wave, each point on the sphere's surface defines a unique polarization state, with axial ratio and tilt angle mapping into latitude and longitude, respectively.

polar cap: Polar region bounded by the auroral zone.

polar cap absorption (PCA): The intense absorption of radio waves in the polar regions caused by the arrival of high-energy solar protons concentrated in this region by the lines of force of the Earth's magnetic field.

polarimetry: The study of electromagnetic propagation, scattering, and emission that considers the complete polarization state of any arbitrarily polarized wave.

polarization: (of an electromagnetic wave). The locus of the tip of the electric field vector observed in a plane orthogonal to the wave normal. *Notes:* 1. Elliptical polarization is the most general case. 2. The polarization of an electromagnetic wave is defined by the tilt angle, the axial ratio and the sign of the axial ratio, which expresses the sense of rotation of the polarization ellipse. *See also***: circularly polarized wave; elliptically polarized wave; linearly polarized wave; parallel polarization; perpendicular polarization.**

polarization coupling loss: That part of the transmission loss due to the mismatch between the polarization of the incoming wave and the polarization of the receiving antenna.

power density: (of a traveling wave). The time average of the Poynting vector. *Synonym:* **power flux density.** *See also:* **spectral power density; spectral power flux density.**

power flux density: *See:* **power density.**

power reflectance*: *See:* **power reflection coefficient.**

*Deprecated

power reflection coefficient: The squared magnitude of the Fresnel reflection coefficient. *Synonym:* **power reflection factor.**

power reflection factor: *See:* **power reflection coefficient.**

Poynting vector: *See:* **instantaneous Poynting vector; time-averaged Poynting vector.**

precipitation scatter: Electromagnetic scattering caused by precipitating rain, hail, or snow particles.

propagating mode: Refers to a mode where the imaginary part of the propagation constant is much greater than the real part, (i.e., the mode is not cut-off as in a metallic wave guide).

propagation constant (γ): The complex scalar γ in expressions for one-dimensional wave propagation using the exponential factor $\exp(-\gamma z)$.

$$\gamma = jk = \alpha + j\beta$$

where scalar quantity α is the attenuation, scalar quantity β is the phase constant, and k is the wave number. *See also:* **plane wave propagation factor; propagation vector.**

propagation delay: The time required for energy to propagate between two specified points, determined by multiplying the group velocity of the wave by the distance between the two points projected onto the direction of propagation.

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propagation vector (k): The complex vector k in expressions for wave propagation using the exponential factor $\exp[-j(\vec{k} \cdot \vec{r})]$ is:

$$\vec{k} = \vec{\beta} - j\vec{\alpha}$$

where

$\vec{\beta}$ is the phase vector

$\vec{\alpha}$ is the attenuation vector

$\vec{r}$ is a position vector

proper mode: A mode of propagation that can be excited by a physical source.

quasi-crystalline approximation: A formulation used to determine the coherent mean field of a wave propagating in a non-tenuous (dense) random medium; a higher order approximation to Foldy's approximation.

radar astronomy: That branch of astronomy that uses radar to study astronomical objects.

radar backscattering cross-section: Radar scattering cross-section as determined for coincident transmitter and receiver locations. *See also:* **scattering cross-section.**

radar cross-section (RCS): *See:* **scattering cross-section.**

radar reflectivity: A measure of backscattering from an inhomogeneous medium, defined as radar cross section (RCS) per unit volume. Frequently used in radar measurements of meteorological phenomena.

radian frequency: *See:* **angular frequency.**

radiation condition: A condition implying that at large distances from a source, only outgoing waves can exist.

radiative transfer theory: A heuristic formulation for the calculation of the scattered specific intensity based on the conservation of energy.

radio astronomy: The branch of astronomy dealing with the reception and analysis of radio waves from extraterrestrial sources.

radio field strength: The electric or magnetic field strength at a radio frequency. *Synonym:* **field strength.**

radio frequency: A frequency in the radio spectrum. *See also:* **radio spectrum.**

radio horizon: The locus of points at which the direct rays from a point source of radio waves are tangent to the surface of the Earth. *Note:* In general, the radio and geometric horizons differ because of atmospheric refraction.

radio interferometer: A type of radio telescope that uses two or more physically separated collecting elements in order to achieve high angular resolution of the brightness temperature distribution of a radio source.

radio source: In radio astronomy, a celestial object or region that emits radio waves.

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radio spectrum: The radio frequency portion of the electromagnetic spectrum. The frequency ranges are shown in the following table:

Frequency designation	Frequency range
Ultra low frequency (ULF)	< 3 Hz
Extremely low frequency (ELF)	3 Hz to 3 kHz
Very low frequency (VLF)	3–30 kHz
Low frequency (LF)	30–300 kHz
Medium frequency (MF)	300 kHz to 3 MHz
High frequency (HF)	3–30 MHz
Very high frequency (VHF)	30–300 MHz
Ultra high frequency (UHF)	300 MHz to 3 GHz
Super high frequency (SHF)	3–30 GHz
Extremely high frequency (EHF)	30–300 GHz
Submillimeter	300 GHz to 3 THz

radio telescope: An instrument used to detect and collect radio emissions from an object or region in space.

radio wave: An electromagnetic wave of radio frequency. Current usage includes frequencies up to 3 THz. *See also:* **radio spectrum.**

radio wave propagation: The transfer of energy by electromagnetic radiation at radio frequencies.

rainfall rate: *See:* **rain rate.**

rain rate: A measure of the volume of water collected per unit area per unit time due to rain. The common unit is millimeters per hour. *Note:* Precipitation rate may refer to other hydrometeors such as snow, in which case the common units are either millimeters per hour or equivalent rainfall rate in millimeters per hour. *Synonym:* **rainfall rate.**

randomly polarized: Electromagnetic radiation in which the direction of the electric field vector changes randomly in time and/or space.

random medium: A medium in which the spatial variations of permittivity, discrete and/or continuous, are best described in terms of statistical measures.

random surface: A boundary surface, between two different but otherwise homogeneous media, whose height fluctuations are best described in terms of statistical measures.

range of a radio system: The maximum distance for which a radiowave transmitting system, with specified installation and operating conditions, produces a usable signal strength at a specified radio receiver installation.

ray: The path of a wave packet or energy flow in a homogeneous or a slowly varying medium. *Notes:* 1. Energy transport (per unit area) is generally associated with bundles of rays. 2. In isotropic but slowly varying media, the ray path is identical to the path of the wave normal, but this may not be the case in anisotropic media.

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Rayleigh criterion: A criterion that characterizes the roughness of a surface with respect to the reflection of an electromagnetic wave. The degree of roughness is expressed in terms of the quantity:

$$\frac{h\cos\theta}{\lambda}$$

where

h is the rms height of the surface irregularities
θ is the angle of incidence with respect to the mean surface
λ is the wavelength

The surface is considered specular (smooth) if:

$$\frac{h\cos\theta}{\lambda} < \frac{1}{100}$$

The surface is considered rough if:

$$\frac{h\cos\theta}{\lambda} > \frac{1}{10}$$

Rayleigh fading: Signal level variations when the received wave is composed of numerous scattered waves with uniform relative phase distribution.

Rayleigh hypothesis: The Rayleigh hypothesis is an assumption that only outgoing waves exist everywhere above a rough interface, including the trough regions.

Rayleigh scattering: Scattering by dielectric particles much smaller than a wavelength. For the special case of spherical particles in the Rayleigh scattering limit, the scattering cross-section is inversely proportional to the fourth power of the wavelength and directly proportional to the sixth power of the particle diameter.

reciprocity: In wave propagation, the invariance of the complex amplitudes of the received signals to the interchange in location of transmitter and receiver, but not the antennas. *Note:* Reciprocity applies provided that the transmission medium is isotropic and that the antennas remain in place with only their transmit and receive functions interchanged. Reciprocity may not hold when the antennas are in different media.

reference atmosphere for refraction: *See:* **standard atmosphere for refraction.**

reflectance:* *See:* **power reflection coefficient.**

*Deprecated

reflected wave: For two media, separated by a planar interface, that part of the incident wave that is returned to the first medium. The direction of propagation of the reflected wave is given by Snell's law of reflection.

reflection coefficient: *See:* **Fresnel coefficients.**

reflection factor: *See:* **Fresnel coefficients.**

reflectivity: The ratio of reflected to incident power densities of a plane wave incident on a surface and equal to the square of the magnitude of the reflection coefficient.

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refracted wave: For two media, that part of the incident wave that travels from the first medium into the second medium. *Note:* For planar interfaces, the direction of propagation of the refracted wave is given by Snell's law. *Synonym:* **transmitted wave.**

refractive index: A dimensionless complex quantity, characteristic of a medium and so defined that its real part, called the refractive index, n, is the ratio of the phase velocity in free space to the phase velocity in the medium. The product of the imaginary part of the refractive index and the free space propagation constant is the attenuation constant in the medium.

refractive index gradient: The change of the atmospheric refractive index with height. Refraction may be included in propagation calculations by using an effective Earth radius of K times the geometrical radius of the Earth (6375 km) and straight line propagation. The refraction types of the atmosphere and their corresponding refractive index gradients are shown in the following table:

Refraction types	Refractive index gradients		
	dN/dh **(N-Units/km)**	***dM/dh*** **(M-Units/km)**	**K-Factor**
Homogeneous	0	157	1
Adiabatic	–23	134	1.2
Standard	–39.2	118	4/3
Subrefractive	> –39.2	> 118	< 4/3
Extreme subrefractive	> 0	> 157	< 1
Superrefractive	< –39.2	< 118	> 4/3
Ducting threshold	–157	0	∞
Ducting	< –157	< 0	∞

refractive modulus (M): In the troposphere, the excess over unity of the modified index of refraction, expressed in millionths:

$$M = (n + h/a - 1)10^6$$

where

a is the mean geometrical radius of the Earth
n is the refractive index at a height, h, above the local surface and $h/a \ll 1$

refractivity: The amount by which the real part of the refractive index, n, exceeds unity. Refractivity is often measured in parts per million, called N-units, where $N = (n–1) \times 10^6$.

refractivity profile: The height dependence of refractivity in the atmosphere. *See also:* **refractive index gradient.**

refractometer: An instrument used to measure the refractive index of the atmosphere.

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relative complex permeability (μ_r): The complex permeability of a medium normalized to the permeability of free space μ_0.

relative complex permittivity (ε_r): The complex permittivity, of a medium normalized to the free space permittivity ε_0.

relative humidity with respect to water (ice): The ratio, expressed as a percentage, of the water vapor pressure in moist air to the saturation vapor pressure with respect to a plane pure water (ice) surface at the same temperature.

resonance: (A) (in an oscillating system). The rapid increase or decrease of the oscillation magnitude as the excitation frequency approaches one of the natural frequencies of the system. **(B)** (of a traveling wave). The change in magnitude as the frequency of the wave approaches or coincides with a natural frequency of the medium (e.g., a plasma frequency).

right-hand polarized wave: A circularly or an elliptically polarized electromagnetic wave for which the electric field vector, when viewed with the wave approaching the observer, rotates counter-clockwise in space. *Notes:* 1. This definition is consistent with observing a clockwise rotation when the electric field vector is viewed in the direction of propagation. 2. A right-handed helical antenna radiates a right-hand polarized wave.

rough surface: An irregular surface separating two media. *See also:* **Rayleigh criterion.**

Rytov approximation: A mathematical approximation for a scalar wave propagating through an inhomogeneous medium in which the unknown field is expressed as $\exp\{X(r)\}$ and various levels of approximation are developed; the lowest order one is based on an assumed slow spatial variability of $X(r)$, (i.e., *grad*[X] = 0).

scalar approximation: The reduction of the vector representation of an electromagnetic field to a scalar description by assuming that the field is identically polarized at every point in space. *Note:* It usually means that cross-polarization effects are ignored.

scalar radiative transfer: A radiative transfer theory in which the vector nature of the fields is ignored. *Synonym:* **scalar radiative transport.**

scalar radiative transport: *See:* **scalar radiative transfer.**

scalar solutions: Solutions of Maxwell's equations where cross-polarization effects are disregarded, i.e., coupling between transverse electric (TE) and transverse magnetic (TM) fields is ignored.

scalar wave equation: *See:* **homogeneous Helmholtz equation.**

scattered wave: An electromagnetic wave that results when an incident wave encounters the following:

— One or more discrete scattering objects
— A rough boundary between two media
— Continuous irregularities in the complex constitutive parameters of a medium

scattering: A process in which the energy of a traveling wave is dispersed in direction by means other than reflection and refraction.

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scattering coefficient: (A) The scattering cross-section per unit illuminated area of a surface expressed in square meters per square meter:

$$\sigma^0_{pq} = \frac{d\sigma_{pq}}{dA}$$

where p and q are polarization indices. **(B)** The scattering cross-section per unit volume of a medium containing discrete scatterers or random variations of refractive index. It is expressed in meters squared per cubic meter and is often designated σ_v. *Note:* The scattering coefficient may be monostatic (backscatter), when the transmitter and receiver are collocated, or bistatic, when they are not. *See also:* **scattering cross-section.**

scattering cross-section: The projected area required to intercept and isotropically radiate the same power as a scatterer (target) scatters toward the receiver. The scattering cross-section is calculated from the relationship:

$$\sigma_{pq} = \lim_{R \to \infty} \left[4\pi R^2 \frac{\left\langle \left| \vec{E}^s_p \right|^2 \right\rangle}{\left\langle \left| \vec{E}^i_q \right|^2 \right\rangle} \right]$$

where

R is the distance between the scatterer and the receiver

$\vec{E}^s_p$ is the p-polarized component of the scattered electric field at the receiver

$\vec{E}^i_q$ is a q-polarized incident electric field at the scatterer.

The incident field is assumed to be planar over the extent of the target.

scattering matrix: A 2 × 2 complex matrix which characterizes the polarized field scattered by a given object.

scattering pattern: *See:* **scattering phase function.**

scattering phase function: The angular spectrum of a scatterer when illuminated by a plane wave. *Synonym:* **scattering pattern.**

scintillation: The phenomenon of fluctuation of the amplitude of a wave caused by irregular changes in the transmission path or paths with time. *Note:* The term scintillation is sometimes used to describe fluctuations of phase and angle of arrival. *See also:* **fading.**

scintillation index: The ratio of the second moment to the first moment squared of the intensity.

selective fading: *See:* **frequency selective fading.**

sferics: *See:* **atmospherics.**

shadow region: The region in space that, because of an intervening obstacle, cannot be reached by an incident geometric-optic ray.

SHF: *See:* **super high frequency.**

short-wave fade-out: *See:* **sudden ionospheric disturbance.**

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silent zone: Part of the skip zone at a distance greater than the range of the ground wave.

single scatter approximation: An approximation used in the calculation of wave scattering by a surface, volume or a collection of particles. In this approximation, the field that excites the surface element or particle, the exciting field, is assumed to be the same field that would have been present in the absence of all other surface or volume elements or particles, (i.e., the exciting field is equal to the incident field). *See also:* **Born approximation.**

skin depth: *See:* **penetration depth.**

skip distance: For a given frequency, the minimum distance at which the sky wave is returned to the Earth. *Note:* Given frequency is the maximum usable frequency for the skip distance.

skip distance focusing: Ionospheric focusing observed in the vicinity of the skip distance.

skip zone: An area of the surface of the Earth surrounding a transmission point bounded by the skip distance in all directions.

sky radiometric temperature: The observed brightness temperature of the sky, caused by emissions from the Earth's atmosphere as well as cosmic and galactic radiation.

sky wave: A radio wave propagated obliquely toward, and returned from, the ionosphere. *Note:* This term has sometimes been called an ionospheric wave but that term is intended to connote internal waves in ionospheric plasmas.

slow wave: An electromagnetic wave propagating close to a boundary with a phase velocity less than that which would exist in an unbounded medium having the same electromagnetic properties. *See also:* **fast wave.**

small-perturbation method: An approximate technique for estimating the scattering from a perturbed boundary or from perturbations in the constitutive parameter(s) of a medium applicable when the perturbation is small compared to a reference parameter or scale such as the wavelength in the boundary case.

Snell's law: The relationship between angles of incidence, reflection and transmission, and material constitutive parameters, for a plane wave incident on a planar boundary between media of differing electromagnetic constitutive parameters. Often expressed as:

$$\theta_i = \theta_r$$

and

$$n_i \sin\theta_i = n_t \sin\theta_t$$

where

θ_i is the angle of incidence
θ_r is the angle of reflection
θ_t is the angle of transmission
n_i is the real part of the refractive index of the material in which the wave is incident
n_t is the real part of the refractive index of the other material

solar activity: The emission of electromagnetic radiation and particles from the sun, including slowly varying components and transient components caused by phenomena such as solar flares.

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solar activity center: A region on the sun containing the sources of variable electromagnetic and corpuscular radiation.

solar activity index: A number characterizing solar activity. Examples are international relative sunspot number, twelve-month running mean sunspot number, and monthly mean solar radio-noise flux.

solar cycle: The magnitude of slowly varying components of solar activity as a function of time. The solar cycle has a period of approximately 11 years. *Note:* The cycle is not symmetrical. It rises to a maximum in approximately 4 years and declines to a minimum in approximately 7 years.

solitary wave: A propagating wave disturbance where the effects of media dispersion and non-linearity compensate one another to produce a self-preserving wave shape. *Synonym:* **soliton.**

soliton: *See:* **solitary wave.**

sparse medium: A medium with a low volume fraction of discrete objects, typically less than 1%. In such a medium, multiple scattering is negligibly small. *See also:* **homogeneous dense medium; inhomogeneous dense medium.**

specific intensity (*I*): A positive real quantity I, in general a function of position r, direction s, frequency f, and time t, representing the quantity of power dP flowing outward through an elemental area dA at a particular location r, within an elemental solid angle $d\Omega$ containing a particular direction s, within a frequency interval $(f, f+df)$:

$$dP = I(r, s, f, t)s\ dA\ d\Omega\ df$$

speckle: The random distribution of intensity in space.

spectral brightness: (of an object). The total power radiated by an object per unit solid angle per unit projected area per unit bandwidth. *Note:* In radiative transfer theory it is called the spectral specific intensity. In infrared radiometry it is called the spectral radiance

spectral power density: Power per unit bandwidth, in watts per Hertz.

spectral power flux density: The power density per unit bandwidth in watts per square meter per Hertz

specular reflection: The process by which all or part of a wave, incident on a smooth surface, is returned to the original medium, in accordance with Snell's law of reflection.

specular surface: (A) A surface, smooth enough that all energy is reflected from it or transmitted across it in those directions specified by Snell's law. **(B)** A planar interface separating two media.

spherical diffraction (propagation): Transhorizon propagation due to diffraction by the spherical surface of the Earth, or more generally by any rounded obstacle which is extremely large in relation to the wavelength.

spherical propagation function: The function given by:

$$f(r) = \frac{e^{-jkr}}{r}$$

where

r is the range from the source
jk is the propagation constant of the medium

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spherical wave: A wave with equiphase surfaces that form a family of concentric spheres.

sporadic E layer: An ionospheric layer of the E region which is thin, transient and of limited geographical extent. *Note:* An equatorial sporadic E layer occurs regularly during the day in association with the equatorial electrojet. *Synonym:* **Es layer.**

sporadic ionization: Ionization of the upper atmosphere, irregularly distributed in space and time, and abnormally high relative to the average ionization level of the region in which it is produced.

spread F: A phenomenon observed on ionograms displaying a wide range of delays of echo pulses, near the F region critical frequencies. *Notes:* 1. The echoes usually are spread in the frequency and virtual height domains on an ionogram. 2. Spread F commonly occurs at night at low latitudes (e.g., near the magnetic dip equator) and at high latitudes.

spreading factor: For propagation in isotropic unbounded media, that amplitude factor that accounts for geometric spreading of the field intensity. *Note:* In the far field region of plane, cylindrical, and spherical waves this factor is 1, $r^{-1/2}$, and r^{-1} respectively, where r is the distance from the source to the observation point.

spreading loss: The decrease in power or power density due to divergence of the outward energy flow of cylindrical and spherical waves.

standard atmosphere for refraction: An atmosphere for which the refractivity is determined by the equation:

$$N(h) = 315\exp(-0.136h)$$

where h is the altitude in kilometers above mean sea level. *Note:* The standard atmosphere for refraction is almost identical to the standard radio atmosphere up to a height of one kilometer. *Synonym:* **reference atmosphere for refraction.** *See also:* **refractive index gradient.**

standard maximum usable frequency*: *See:* **maximum usable frequency.**

*Deprecated

standard M gradient: *See:* **refractive index gradient.**

standard N gradient: *See:* **standard refractive index gradient.**

standard propagation: The propagation of radio waves over a smooth spherical Earth of uniform dielectric constant and conductivity, under conditions of standard refraction in the atmosphere. *See also:* **refractive index gradient.**

standard radio atmosphere: An atmosphere whose vertical refractivity gradient is equal to the standard refractive index gradient. *See also:* **refractive index gradient.**

standard radio horizon: The radio horizon corresponding to propagation through the standard radio atmosphere. *See also:* **refractive index gradient.**

standard refraction: See: **refractive index gradient.**

standard refractive index gradient: A standard value of vertical gradient of refractivity, namely 39.2 N-Units/km, used in studies of the refraction of radio waves in the troposphere. *Note:* This value corresponds, approximately, to the median value of the gradient in the first kilometer of altitude in temperate regions. *Synonym:* **standard N gradient**. *See also:* **refractive index gradient.**

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standard refractive index modulus gradient: *See:* **refractive index gradient.**

standing wave: A wave formed by the interference of two oppositely traveling plane waves having the same frequency and polarization.

stationary phase approximation: A technique for evaluating or estimating integrals whose integrands have rapid variations in phase everywhere except near stationary phase points.

stationary phase point: Point in space near which the phase of a function is slowly varying.

statistically homogeneous: Having statistical characteristics that are independent of the specific locations at which those characteristics are measured.

statistically isotropic: Having statistical characteristics that are independent of the directions along which those characteristics are measured.

Stokes matrix: *See:* **Mueller matrix.**

Stokes parameters: Elements of the Stokes vector. *See also:* **Stokes vector.**

Stokes vector: A 4 × 1 vector of real numbers called the Stokes parameters, representing the polarization state of a propagating wave:

$$\bar{I} = \begin{bmatrix} I_0 \\ Q \\ U \\ V \end{bmatrix} = \frac{1}{2\eta} \begin{bmatrix} |E_v|^2 + |E_h|^2 \\ |E_v|^2 - |E_h|^2 \\ 2\mathrm{Re}\{E_v E^*_h\} \\ 2\mathrm{Im}\{E_v E^*_h\} \end{bmatrix}$$

where

E_v is the vertical electric field component of the wave

E_h is the horizontal electric field component of the wave

η is the intrinsic impedance of the medium

* indicates the complex conjugate

stratopause: The upper boundary of the stratosphere.

stratosphere: That part of the Earth's atmosphere located above the troposphere in which the temperature remains constant or increases slightly with increasing height. The stratosphere extends to a height of around 50 km.

structure constant (C_n^2): A measure of the turbulent fluctuations of the refractive index of the atmosphere.

submillimeter: 300 GHz to 3 THz. *See also:* **radio spectrum.**

sub-refractive atmosphere: *See:* **refractive index gradient.**

sudden ionospheric disturbance (SID): An ionospheric disturbance with a duration of from a few minutes to a few hours, characterized by the sudden increase in the ionization of the D region in the daylight hemisphere as a result of electromagnetic radiation from a solar flare. *Note:* This effect is sometimes called the Mägel-Delinger effect.

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super high frequency (SHF): 3–30 GHz. *See also:* **radio spectrum.**

super-refractive atmosphere: *See:* **refractive index gradient.**

surface duct: An atmospheric radio duct for which the lower boundary is the Earth's surface.

surface impedance: For a monochromatic electromagnetic wave incident on a locally planar boundary, the complex ratio of the total orthogonal electric to magnetic field components tangent to the surface. The surface impedance is taken as having a positive real part.

surface wave: A wave guided by a boundary with a surface impedance whose reactive part exceeds the resistive part. A surface wave is generally characterized as a slow wave having a magnitude that exponentially decreases with distance from the interface but may be modified by curvature.

system loss (L_s): (of a radio system). The ratio of the input power to the terminals of the transmitting antenna to the available output power at the terminals of the receiving antenna. Usually expressed in decibels as a positive number.

tangent-plane approximation: *See:* **Kirchhoff approximation.**

temperature inversion: (in the troposphere). An increase of temperature with height in the troposphere.

TEM wave: *See:* **transverse electromagnetic wave.**

tenuous medium: A medium in which the spatial variations of constitutive parameters, either continuous or discrete, are small relative to their mean values.

thermodynamic equilibrium: A situation in which the net thermal radiation exchanged by members of a system is zero.

thermosphere: That part of the Earth's atmosphere located above the mesosphere in which temperature increases and then remains constant with increasing height and from which there is virtually no further escape of particles to free space. The thermosphere extends to an altitude of 500–600 km.

thin phase screen approximation: An approximation in which the cumulative effects of phase distortion take place in an equivalent thin layer and amplitude effects are neglected.

tilt angle of polarization: Angle of major axis of the polarization ellipse relative to horizontal.

time-averaged Poynting vector ($\vec{\hat{S}}$): Of a periodic electromagnetic wave, the time average of the instantaneous Poynting vector over the wave period. For time harmonic waves, it is equal to:

$$(1/2)\mathrm{Re}(\vec{\hat{E}} \times \vec{\hat{H}}^*)$$

where

Re	indicates the real part
$\vec{\hat{E}}$	is the electric field vector in phasor notation
$\vec{\hat{H}}$	is the magnetic field vector in phasor notation
*	indicates the complex conjugate

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time delay spread (σ_τ): A measure of the differential propagation times due to multipath propagation. Specifically, time delay spread is the rms width of the signal received when a very narrow pulse has been transmitted. *Note:* The time delay spread is inversely proportional to the frequency selective bandwidth (f_τ):

$$\sigma_\tau = (2\pi f_\tau)^{-1}$$

T matrix: Relates the scattered field to the exciting field.

topside ionospheric sounding: Vertical incidence ionospheric sounding made from an artificial Earth satellite above the height of the maximum electron density of the F region.

total electron content (TEC): The total number of free electrons in a tube (generally with a vertical axis) of unit transverse cross-section passing through the ionosphere. *Note:* The units for TEC are 10^{16} electrons/m^2 (or 10^{12} electrons/cm^2).

total scattering cross-section: The average over 4π steradians of the bistatic scattering cross-section for a specific illumination, given by

$$\sigma_t = \frac{1}{4\pi}\int_\Omega \sigma d\Omega$$

transhorizon tropospheric propagation: Tropospheric propagation between two points, the reception point being beyond the radio horizon of the transmission point. Transhorizon propagation includes a variety of possible propagation mechanisms such as diffraction, scattering, ducting, refraction and reflection. *See also:* **tropospheric scatter propagation.**

transmission coefficient: *See*: **Fresnel coefficients.**

transmission factor: *See:* **Fresnel coefficients.**

transmission loss (*L*): (of a radio system). The ratio of the power radiated from the transmitting antenna to the resultant power that would be available from a loss-free (but otherwise identical) receiving antenna.

transmissivity: (A) (of a boundary). The ratio of the normal component of the power density transmitted across the boundary between two media to the normal component of the incident power density. **(B)** (of a layer). The ratio of the normal component of the power density transmitted through the layer to the normal component of the incident power density.

transmissivity matrix: A 4 × 4 matrix of dimensionless real numbers which, when multiplied by the Stokes vector incident upon a boundary or through a medium, yields the Stokes vector that is propagated across that boundary or medium.

transmitted wave: (A) The wave launched by a transmitting antenna. **(B)** *See also:* **refracted wave.**

transverse electric (TE) wave: For waves propagating in homogeneous space, an electromagnetic wave whose electric field is perpendicular to the direction of propagation. For waves incident on a scatterer, the wave whose electric field is perpendicular to the plane of incidence.

transverse electromagnetic (TEM) wave: An electromagnetic wave in which both the electric and magnetic field vectors are everywhere perpendicular to the direction of propagation.

transverse magnetic (TM) polarization: *See:* **parallel polarization.**

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transverse magnetic (TM) wave: For waves propagating in homogeneous space, an electromagnetic wave whose magnetic field is perpendicular to the direction of propagation. For waves incident on a scatterer, the wave whose magnetic field is perpendicular to the plane of incidence.

traveling ionospheric disturbance (TID): A localized disturbance in the electron density distribution propagating in the ionosphere. *Note:* A TID is the signature in the ionosphere of an atmospheric gravity wave (AGW) in the neutral thermosphere.

tropopause: The upper boundary of the troposphere.

troposcatter: *See:* **tropospheric scatter propagation.**

troposphere: The lower part of the Earth's atmosphere, situated immediately above the surface of the Earth and in which the temperature decreases with increasing altitude except in certain local temperature inversion layers. The troposphere extends to an altitude of around 9 km at the poles and 17 km at the equator.

tropospheric layer: An elevated portion of the troposphere having radio propagation properties that are clearly distinguished from those of the surrounding atmosphere. Horizontal dimensions are generally in excess of 100 km, and vertical dimensions are on the order of 1 km.

tropospheric propagation: Propagation within the troposphere.

tropospheric radio duct: *See:* **atmospheric radio duct.**

tropospheric scatter propagation: Propagation of radio waves through the atmosphere caused by scattering from inhomogeneities in the refractive index of the troposphere. *Note:* Troposcatter enables propagation beyond the radio horizon. *Synonym:* **troposcatter.**

tropospheric wave: A radio wave that propagates in the troposphere.

turbulence: Random movements within a liquid or gaseous medium inducing heterogeneous values of certain characteristics of the medium.

turbulence scale: A length representative of the average size of the irregularities of a specified property of a medium subject to turbulence.

two-frequency mutual coherence function: The correlation between two fields at two frequencies measured at the same point in space and time.

UHF: *See:* **ultra high frequency.**

ULF: *See:* **ultra low frequency.**

ultra high frequency (UHF): 300 MHz to 3 GHz. *See also:* **radio spectrum.**

ultra low frequency (ULF): Lower than 3 Hz. *See also:* **radio spectrum.**

uniform plane wave: *See:* **homogeneous plane wave.**

unpolarized: *See:* **randomly polarized.**

vector radiative transport: An attempt to incorporate the vector nature of electromagnetic waves into the energy conserving transport theory. *See also:* **radiative transfer theory.**

vertical polarization: *See:* **parallel polarization.**

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very high frequency (VHF): 30–300 MHz. *See also:* **radio spectrum.**

very low frequency (VLF): 3–30 kHz. *See also:* **radio spectrum.**

VHF: *See:* **very high frequency.**

virtual height: The apparent height of reflection of a radio wave from an ionized layer. It is determined from the time interval between the transmitted pulse and the ionospheric echo at vertical incidence, assuming that the velocity of propagation is the velocity of light (in vacuum) over the entire path.

VLF: *See:* **very low frequency.**

volume fraction: The ratio of the volume of inclusions to the total volume (inclusions plus host material).

volume mixing ratio: The ratio defined by $N(z)/N(\text{air})$ where $N(z)$ is the number density (number of molecules per unit volume) of a particular species and $N(\text{air})$ is the number density of air.

volume scattering: Scattering from inhomogeneities distributed throughout a volume. The inhomogeneities can be discrete particles or structures or continuous spatial variations of refractive index.

waveguide: Metallic or dielectric structures, usually uniform in the longitudinal direction, that are capable of guiding waves.

wave interference: The variation of wave amplitude with distance or time, caused by the superposition of two or more waves of the same (or very nearly the same) frequency. *Note:* If the waves have very nearly the same frequency, they are said to "beat with each other."

wavelength: (of a monochromatic wave). The distance between two points of corresponding phase of two consecutive cycles in the direction of the wave normal. The wavelength, λ, is related to the magnitude of the phase velocity, v_p, and the frequency, f, by the equation:

$$\lambda = v_p / f$$

wave normal: (of a traveling wave). The direction normal to an equiphase surface taken in the direction of increasing phase. *See also:* **direction of propagation.**

wave number (*k*): 2π divided by the wavelength in the medium.

wave tilt: (of a monochromatic electromagnetic wave propagating near the interface between two media). The complex ratio of the electric (or magnetic) field component that is tangent to the interface to that which is normal to the interface, both field components lying in the plane of propagation. *Note:* Wave tilt is generally associated with ground wave propagation over the Earth's surface.

wave vector: *See:* **propagation vector.**

whistler: A form of radio energy in the extremely low frequency/very low frequency portion of the spectrum, usually originating from lightning strokes and characterized by a whistling tone of decreasing pitch that may last for several seconds. *Note:* Propagation of this energy is in the whistler mode, which is strongly guided along the Earth's magnetic field. *See also:* **whistler mode.**

whistler mode: The propagation mode of any right-hand polarized electromagnetic wave propagating along a magnetic field line in a plasma at a frequency less than the electron gyrofrequency but greater than the ion gyrofrequency.

X wave: *See:* **extraordinary wave.**

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