2

Nature and Properties of Electromagnetic Waves

2-1 FUNDAMENTAL PROPERTIES OF ELECTROMAGNETIC WAVES

Electromagnetic energy is the means by which information is transmitted from an object to a sensor. Information could be encoded in the frequency content, intensity, or polarization of the electromagnetic wave. The information is propagated by electromagnetic radiation at the velocity of light from the source directly through free space, or indirectly by reflection, scattering, and reradiation to the sensor. The interaction of electromagnetic waves with natural surfaces and atmospheres is strongly dependent on the frequency of the waves. Waves in different spectral bands tend to excite different interaction mechanisms such as electronic, molecular, or conductive mechanisms.

2-1-1 Electromagnetic Spectrum

The electromagnetic spectrum is divided into a number of spectral regions. For the purpose of this text, we use the classification illustrated in Figure 2-1.

The radio band covers the region of wavelengths longer than 10 cm (frequency less than 3 GHz). This region is used by active radio sensors such as imaging radars, altimeters, and sounders, and, to a lesser extent, passive radiometers.

The microwave band covers the neighboring region, down to a wavelength of 1 mm (300 GHz frequency). In this region, most of the interactions are governed by molecular rotation, particularly at the shorter wavelengths. This region is mostly used by microwave radiometers/spectrometers and radar systems.

The infrared band covers the spectral region from 1 mm to 0.7 μm. This region is subdivided into subregions called submillimeter, far infrared, thermal infrared, and near infrared. In this region, molecular rotation and vibration play important roles. Imagers, spectrometers, radiometers, polarimeters, and lasers are used in this region for remote
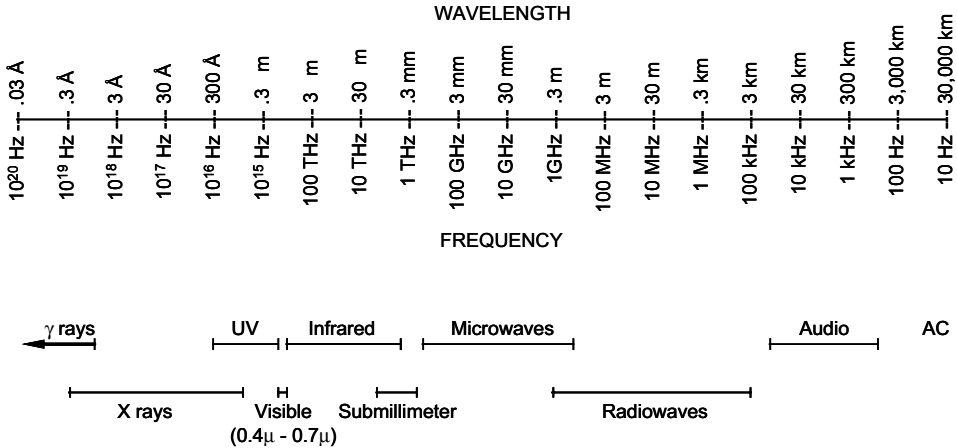
Figure 2-1. Electromagnetic spectrum.

sensing. The same is true in the neighboring region, the visible region (0.7–0.4 μm) where electronic energy levels start to play a key role.

In the next region, the ultraviolet (0.4 μm to 300 Å), electronic energy levels play the main role in wave–matter interaction. Ultraviolet sensors have been used mainly to study planetary atmospheres or to study surfaces with no atmospheres because of the opacity of gases at these short wavelengths.

X-rays (300 Å to 0.3 Å) and gamma rays (shorter than 0.3 Å) have been used to an even lesser extent because of atmospheric opacity. Their use has been limited to low-flying air-craft platforms or to the study of planetary surfaces with no atmosphere (e.g., the Moon).

2-1-2   Maxwell's Equations

The behavior of electromagnetic waves in free space is governed by Maxwell's equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2-1}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \tag{2-2}$$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} \tag{2-3}$$

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E} \tag{2-4}$$

$$\nabla \cdot \mathbf{E} = 0 \tag{2-5}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2-6}$$

where
$\mathbf{E}$ = electric vector
$\mathbf{D}$ = displacement vector

H = magnetic vector
B = induction vector
μ_0, ε_0 = permeability and permittivity of vacuum
μ_r, ε_r = relative permeability and permittivity

Maxwell's concept of electromagnetic waves is that a smooth wave motion exists in the magnetic and electric force fields. In any region in which there is a temporal change in the electric field, a magnetic field appears automatically in that same region as a conjugal partner and vice versa. This is expressed by the above coupled equations.

2-1-3 Wave Equation and Solution

In homogeneous, isotropic, and nonmagnetic media, Maxwell's equations can be combined to derive the wave equation:

$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon_0 \mu_r \varepsilon_r \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \tag{2-7}$$

or, in the case of a sinusoidal field,

$$\nabla^2 \mathbf{E} + \frac{\omega^2}{c_r^2} \mathbf{E} = 0 \tag{2-8}$$

where

$$c_r = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \mu_r \varepsilon_r}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{2-9}$$

Usually, $\mu_r = 1$ and ε_r varies from 1 to 80 and is a function of the frequency. The solution for the above differential equation is given by

$$\mathbf{E} = \mathbf{A} e^{i(kr - \omega t + \phi)} \tag{2-10}$$

where **A** is the wave amplitude, ω is the angular frequency, ϕ is the phase, and k is the wave vector in the propagation medium ($k = 2\pi \sqrt{\varepsilon_r}/\lambda$, λ = wavelength = $2\pi c/\omega$, c = speed of light in vacuum). The wave frequency v is defined as $v = \omega/2\pi$.

Remote sensing instruments exploit different aspects of the solution to the wave equation in order to learn more about the properties of the medium from which the radiation is being sensed. For example, the interaction of electromagnetic waves with natural surfaces and atmospheres is strongly dependent on the frequency of the waves. This will manifest itself in changes in the amplitude [the magnitude of **A** in Equation (2-10)] of the received wave as the frequency of the observation is changed. This type of information is recorded by multispectral instruments such as the LandSat Thematic Mapper and the Advanced Advanced Spaceborne Thermal Emission and Reflection Radiometer. In other cases, one can infer information about the electrical properties and geometry of the surface by observing the polarization [the vector components of **A** in Equation (2-10)] of the received waves. This type of information is recorded by polarimeters and polarimetric radars. Doppler lidars and radars, on the other hand, measure the change in

frequency between the transmitted and received waves in order to infer the velocity with which an object or medium is moving. This information is contained in the angular frequency ω of the wave shown in Equation (2-10). The quantity $kr - \omega t + \phi$ in Equation (2-10) is known as the *phase* of the wave. This phase changes by 2π every time the wave moves through a distance equal to the wavelength λ. Measuring the phase of a wave therefore provides an extremely accurate way to measure the distance that the wave actually travelled. Interferometers exploit this property of the wave to accurately measure differences in the path length between a source and two collectors, allowing one to significantly increase the resolution with which the position of the source can be established.

2-1-4   Quantum Properties of Electromagnetic Radiation

Maxwell's formulation of electromagnetic radiation leads to a mathematically smooth wave motion of fields. However, at very short wavelengths, it fails to account for certain significant phenomena that occur when the wave interacts with matter. In this case, a quantum description is more appropriate.

The electromagnetic energy can be presented in a quantized form as bursts of radiation with a quantized radiant energy Q, which is proportional to the frequency v:

$$Q = hv \tag{2-11}$$

where h = Planck's constant = 6.626×10^{-34} joule second. The radiant energy carried by the wave is not delivered to a receiver as if it is spread evenly over the wave, as Maxwell had visualized, but is delivered on a probabilistic basis. The probability that a wave train will make full delivery of its radiant energy at some place along the wave is proportional to the flux density of the wave at that place. If a very large number of wave trains are co-existent, then the overall average effect follows Maxwell's equations.

2-1-5   Polarization

An electromagnetic wave consists of a coupled electric and magnetic force field. In free space, these two fields are at right angles to each other and transverse to the direction of propagation. The direction and magnitude of only one of the fields (usually the electric field) is sufficient to completely specify the direction and magnitude of the other field using Maxwell's equations.

The polarization of the electromagnetic wave is contained in the elements of the vector amplitude **A** of the electric field in Equation (2-10). For a transverse electromagnetic wave, this vector is orthogonal to the direction in which the wave is propagating, and, therefore, we can completely describe the amplitude of the electric field by writing **A** as a two-dimensional complex vector:

$$\mathbf{A} = a_h e^{i\delta_h} \hat{\mathbf{h}} + a_v e^{i\delta_v} \hat{\mathbf{v}} \tag{2-12}$$

Here, we denote the two orthogonal basis vectors as $\hat{\mathbf{h}}$ for *horizontal* and $\hat{\mathbf{v}}$ for *vertical*. Horizontal polarization is usually defined as the state in which the electric vector is perpendicular to the plane of incidence. Vertical polarization is orthogonal to both horizontal

polarization and the direction of propagation, and corresponds to the case in which the electric vector is in the plane of incidence. Any two orthogonal basis vectors could be used to describe the polarization, and in some cases the right- and left-handed circular basis is used. The amplitudes, a_h and a_v, and the relative phases, δ_h and δ_v, are real numbers. The polarization of the wave can be thought of as that figure that the tip of the electric field would trace over time at a fixed point in space. Taking the real part of Equation (2-12), we find that the polarization figure is the locus of all the points in the h–v plane that have the coordinates $E_h = a_h \cos \delta_h$, $E_v = a_v \cos \delta_v$. It can easily be shown that the points on the locus satisfy the expression

$$\left(\frac{E_h}{a_h}\right)^2 + \left(\frac{E_v}{a_v}\right)^2 - 2\frac{E_h}{a_h}\frac{E_v}{a_v}\cos(\delta_h - \delta_v) = \sin^2(\delta_h - \delta_v) \qquad (2\text{-}13)$$

This is the expression of an ellipse, shown in Figure 2-2. Therefore, in the general case, electromagnetic waves are *elliptically* polarized. In tracing the ellipse, the tip of the electric field can rotate either clockwise, or counterclockwise; this direction is denoted by the *handedness* of the polarization. The definition of handedness accepted by the Institute of Electrical and Electronics Engineers (IEEE), is that a wave is said to have *right-handed* polarization if the tip of the electric field vector rotates *clockwise* when the wave is viewed receding from the observer. If the tip of the electric field vector rotates *counterclockwise* when the wave is viewed in the same way, it has a *left-handed* polarization. It is worth pointing out that in the optical literature a different definition of handedness is often encountered. In that case, a wave is said to be right-handed (left-handed) polarized when the wave is view approaching the observer, and tip of the electric field vector rotates in the clockwise (counterclockwise) direction.

In the special case in which the ellipse collapses to a line, which happens when $\delta_h - \delta_v = n\pi$ with n any integer, the wave is said to be *linearly* polarized. Another special case is encountered when the two amplitudes are the same ($a_h = a_v$) and the relative phase difference $\delta_h - \delta_v$ is either $\pi/2$ or $-\pi/2$. In this case, the wave is *circularly* polarized.
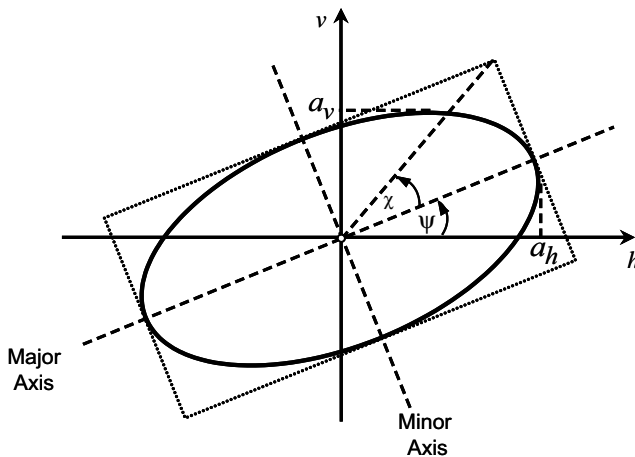

Figure 2-2. Polarization ellipse.

The polarization ellipse (see Fig. 2-2) can also be characterized by two angles known as the ellipse orientation angle (ψ in Fig. 2-2, $0 \leq \psi \leq \pi$) and the ellipticity angle, shown as χ ($-\pi/4 \leq \chi \leq \pi/4$) in Figure 2-2. These angles can be calculated as follows:

$$\tan 2\psi = \frac{2a_h a_v}{a_h^2 - a_v^2} \cos(\delta_h - \delta_v); \qquad \sin 2\chi = \frac{2a_h a_v}{a_h^2 + a_v^2} \sin(\delta_h - \delta_v) \qquad (2\text{-}14)$$

Note that linear polarizations are characterized by an ellipticity angle $\chi = 0$.

So far, it was implied that the amplitudes and phases shown in Equations (2-12) and (2-13) are constant in time. This may not always be the case. If these quantities vary with time, the tip of the electric field vector will not trace out a smooth ellipse. Instead, the figure will in general be a noisy version of an ellipse that after some time may resemble an "average" ellipse. In this case, the wave is said to be *partially* polarized, and it can be considered that part of the energy has a deterministic polarization state. The radiation from some sources, such as the sun, does not have any clearly defined polarization. The electric field assumes different directions at random as the wave is received. In this case, the wave is called *randomly* polarized or *unpolarized.* In the case of some man-made sources, such as lasers and radio/radar transmitters, the wave usually has a well-defined polarized state.

Another way to describe the polarization of a wave, particularly appropriate for the case of partially polarized waves, is through the use of the *Stokes parameters* of the wave. For a monochromatic wave, these four parameters are defined as

$$\begin{aligned} S_0 &= a_h^2 + a_v^2 \\ S_1 &= a_h^2 - a_v^2 \\ S_2 &= 2a_h a_v \cos(\delta_h - \delta_v) \\ S_3 &= 2a_h a_v \sin(\delta_h - \delta_v) \end{aligned} \qquad (2\text{-}15)$$

Note that for such a fully polarized wave, only three of the Stokes parameters are independent, since $S_0^2 = S_1^2 + S_2^2 + S_3^2$. Using the relations in Equations (2-14) between the ellipse orientation and ellipticity angles and the wave amplitudes and relative phases, it can be shown that the Stokes parameters can also be written as

$$\begin{aligned} S_1 &= S_0 \cos 2\chi \cos 2\psi \\ S_2 &= S_0 \cos 2\chi \sin 2\psi \\ S_3 &= S_0 \sin 2\psi \end{aligned} \qquad (2\text{-}16)$$

The relations in Equations (2-16) lead to a simple geometric interpretation of polarization states. The Stokes parameters S_1, S_2, and S_3 can be regarded as the Cartesian coordinates of a point on a sphere, known as the Poincaré sphere, of radius S_0 (see Fig. 2-3). There is, therefore, a unique mapping between the position of a point on the surface of the sphere and a polarization state. Linear polarizations map to points on the equator of the Poincaré sphere, whereas the circular polarizations map to the poles (Fig. 2-4).

In the case of partially polarized waves, all four Stokes parameters are required to fully describe the polarization of the wave. In general, the Stokes parameters are related by $S_0^2 \geq S_1^2 + S_2^2 + S_3^2$, with equality holding only for fully polarized waves. In the extreme
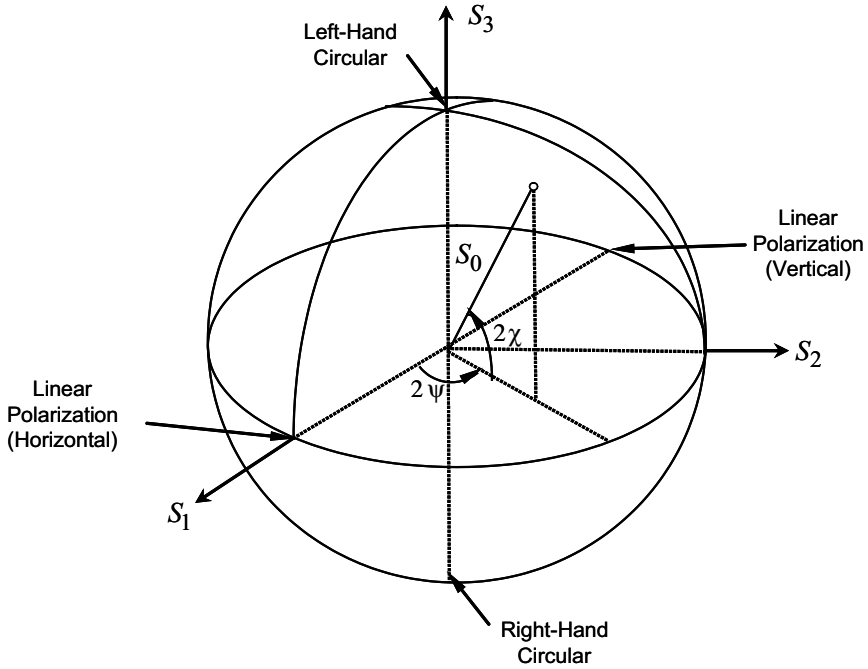
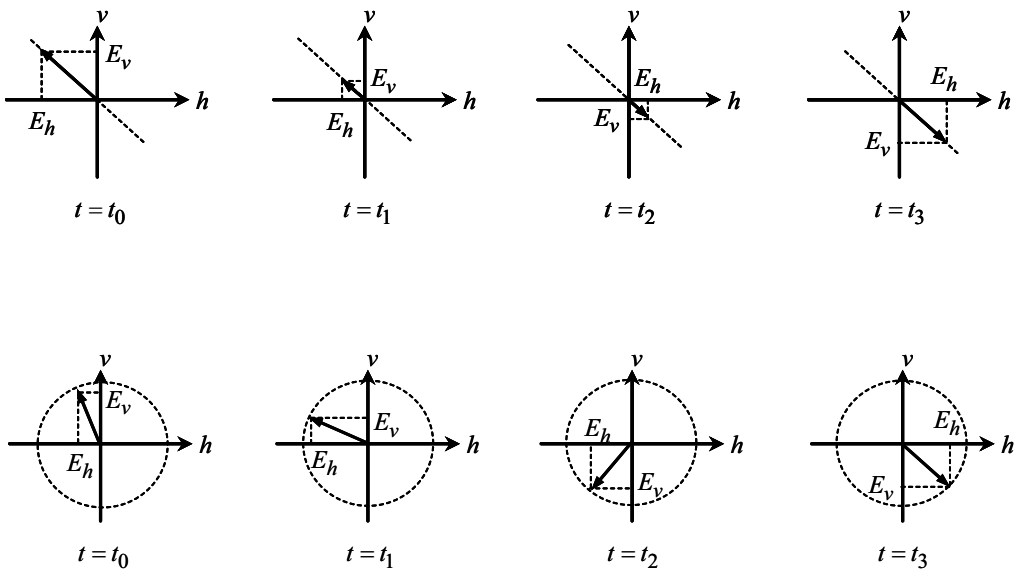**Figure 2-3.** Polarization represented as a point on the Poincaré sphere.

Figure 2-4. Linear (upper) and circular (lower) polarization.

case of an unpolarized wave, the Stokes parameters are $S_0 > 0$; $S_1 = S_2 = S_3 = 0$. It is always possible to describe a partially polarized wave by the sum of a fully polarized wave and an unpolarized wave. The magnitude of the polarized wave is given by $\sqrt{S_1^2 + S_2^2 + S_3^2}$, and the magnitude of the unpolarized wave is $S_0 - \sqrt{S_1^2 + S_2^2 + S_3^2}$. Finally, it should be pointed out that the Stokes parameters of an unpolarized wave can be written as the sum of two fully polarized waves:

$$\begin{pmatrix} S_0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} S_0 \\ -S_1 \\ -S_2 \\ -S_3 \end{pmatrix} \tag{2-17}$$

These two fully polarized waves have orthogonal polarizations. This result shows that when an antenna with a particular polarization is used to receive unpolarized radiation, the amount of power received by the antenna will be only that half of the power in the unpolarized wave that aligns with the antenna polarization. The other half of the power will not be absorbed because its polarization is orthogonal to that of the antenna.

The polarization states of the incident and reradiated waves play an important role in remote sensing. They provide an additional information source (in addition to the intensity and frequency) that may be used to study the properties of the radiating or scattering object. For example, at an incidence angle of 37° from vertical, an optical wave polarized perpendicular to the plane of incidence will reflect about 7.8% of its energy from a smooth water surface, whereas an optical wave polarized in the plane of incidence will not reflect any energy from the same surface. All the energy will penetrate into the water. This is the Brewster effect.

2-1-6   Coherency

In the case of a monochromatic wave of certain frequency v_0, the instantaneous field at any point P is well defined. If the wave consists of a large number of monochromatic waves with frequencies over a bandwidth ranging from v_0 to $v_0 + \Delta v$, then the random addition of all the component waves will lead to irregular fluctuations of the resultant field.

The coherency time Δt is defined as the period over which there is strong correlation of the field amplitude. More specifically, it is the time after which two waves at v and $v + \Delta v$ are out of phase by one cycle; that is, it is given by

$$v\Delta t + 1 = (v + \Delta v)\Delta t \rightarrow \Delta v\Delta t = 1$$
$$\rightarrow \Delta t = \frac{1}{\Delta v} \tag{2-18}$$

The coherence length is defined as

$$\Delta l = c\Delta t = \frac{c}{\Delta v} \tag{2-19}$$

Two waves or two sources are said to be coherent with each other if there is a systematic relationship between their instantaneous amplitudes. The amplitude of the resultant

field varies between the sum and the difference of the two amplitudes. If the two waves are incoherent, then the power of the resultant wave is equal to the sum of the power of the two constituent waves. Mathematically, let $E_1(t)$ and $E_2(t)$ be the two component fields at a certain location. Then the total field is

$$E(t) = E_1(t) + E_2(t) \tag{2-20}$$

The average power is

$$
\begin{aligned}
P \sim \overline{[E(t)]^2} &= \overline{[E_1(t) + E_2(t)]^2} \\
&= \overline{E_1(t)^2} + \overline{E_2(t)^2} + 2\,\overline{E_1(t)E_2(t)}
\end{aligned}
\tag{2-21}
$$

If the two waves are incoherent relative to each other, then $\overline{E_1(t)E_2(t)} = 0$ and $P = P_1 + P_2$. If the waves are coherent, then $\overline{E_1(t)E_2(t)} \neq 0$. In the latter case, we have

$$P > P_1 + P_2 \qquad \text{in some locations}$$

$$P < P_1 + P_2 \qquad \text{in other locations}$$

This is the case of optical interference fringes generated by two overlapping coherent optical beams. The bright bands correspond to where the energy is above the mean and the dark bands correspond to where the energy is below the mean.

2-1-7 Group and Phase Velocity

The phase velocity is the velocity at which a constant phase front progresses (see Fig. 2-5). It is equal to

$$v_p = \frac{\omega}{k} \tag{2-22}$$

If we have two waves characterized by $(\omega - \Delta\omega, k - \Delta k)$ and $(\omega + \Delta\omega, k + \Delta k)$, then the total wave is given by

$$
\begin{aligned}
E(z, t) &= A e^{i[(k-\Delta k)z - (\omega-\Delta\omega)t]} + A e^{i[(k+\Delta k)z - (\omega+\Delta\omega)t]} \\
&= 2A e^{i(kz - \omega t)} \cos(\Delta kz - \Delta\omega t)
\end{aligned}
\tag{2-23}
$$

In this case, the plane of constant amplitude moves at a velocity v_g, called the group velocity:

$$v_g = \frac{\Delta\omega}{\Delta k} \tag{2-24}$$

As $\Delta\omega$ and Δk are assumed to be small, we can write

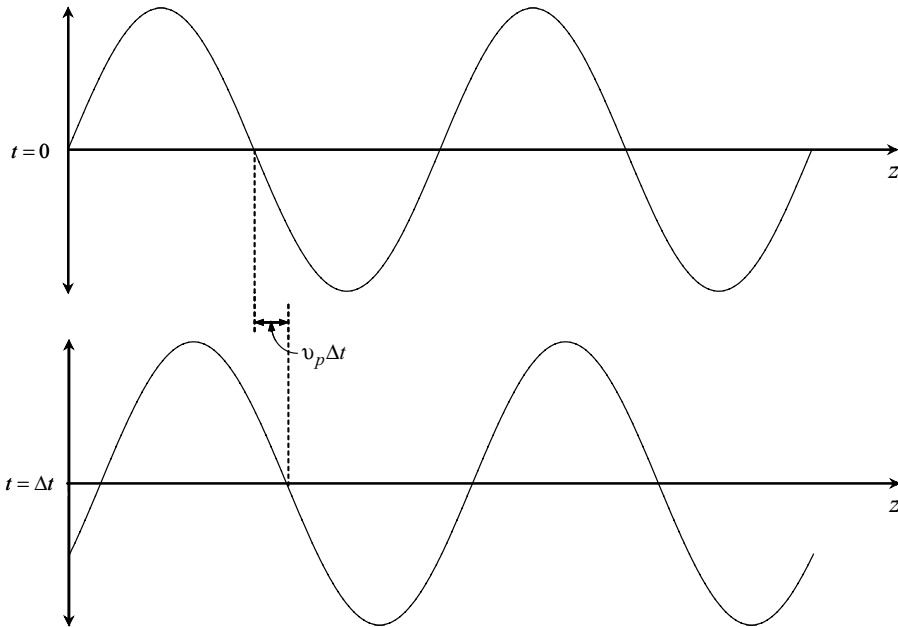$$v_g = \frac{\partial\omega}{\partial k} \tag{2-25}$$

Figure 2-5. Phase velocity.

This is illustrated in Figure 2-6. It is important to note that v_g represents the velocity of propagation of the wave energy. Thus, the group velocity v_g must be equal to or smaller than the speed of light c. However, the phase velocity v_p can be larger than c.

If the medium is nondispersive, then

$$\omega = ck \tag{2-26}$$

This implies that

$$v_p = \frac{\omega}{k} = c \tag{2-27}$$

$$v_g = \frac{\partial \omega}{\partial k} = c \tag{2-28}$$

However, if the medium is dispersive (i.e., ω is a nonlinear function of k), such as in the case of ionospheres, then the two velocities are different.

2-1-8 Doppler Effect

If the relative distance between a source radiating at a fixed frequency v and an observer varies, the signal received by the observer will have a frequency v', which is different than v. The difference, $v_d = v' - v$, is called the Doppler shift. If the source–observer distance is decreasing, the frequency received is higher than the frequency transmitted, lead-
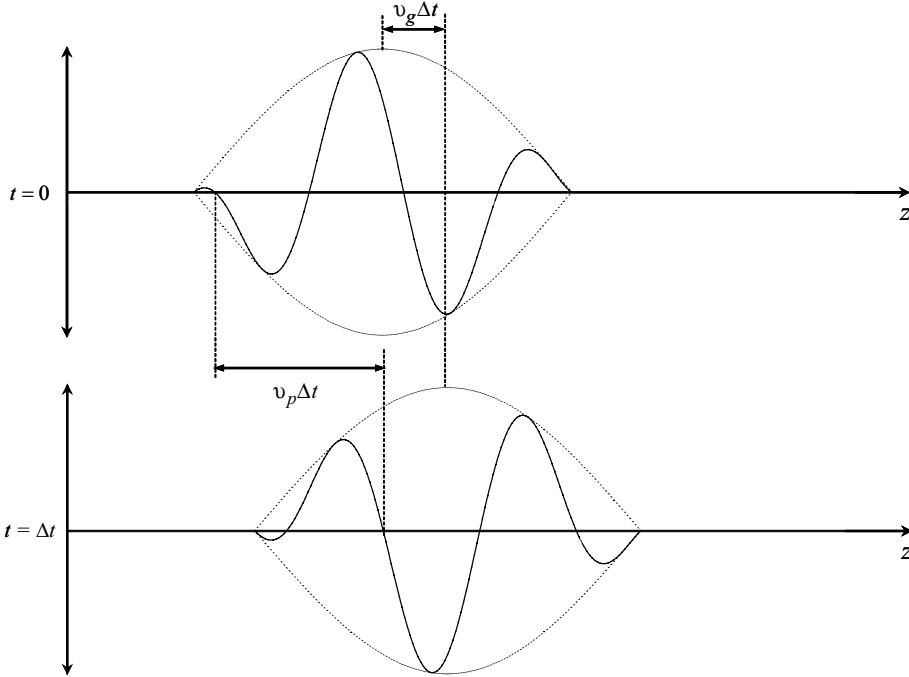
Figure 2-6. Group velocity.

ing to a positive Doppler shift ($v_d > 0$). If the source–observer distance is increasing, the reverse effect occurs (i.e., $v_d < 0$) and the Doppler shift is negative.

The relationship between v_d and v is

$$v_d = v \frac{v}{c} \cos \theta \qquad (2\text{-}29)$$

where v is the relative speed between the source and the observer, c is the velocity of light, and θ is the angle between the direction of motion and the line connecting the source and the observer (see Fig. 2-7). The above expression assumes no relativistic effects ($v \ll c$), and it can be derived in the following simple way.

Referring to Figure 2-8, assume an observer is moving at a velocity v with an angle θ relative to the line of propagation of the wave. The lines of constant wave amplitude are separated by the distance λ (i.e., wavelength) and are moving at velocity c. For the observer, the apparent frequency v' is equal to the inverse of the time period T' that it takes the observer to cross two successive equiamplitude lines. This is given by the expression

$$cT' + vT' \cos \theta = \lambda \qquad (2\text{-}30)$$

which can be written as

$$\frac{c}{v'} + \frac{v \cos \theta}{v'} = \frac{c}{v} \Rightarrow v' = v + v \frac{v}{c} \cos \theta = v + v_d \qquad (2\text{-}31)$$
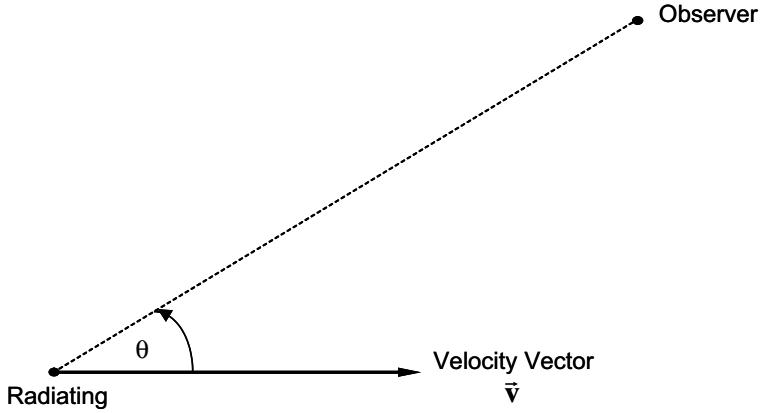
Figure 2-7. Doppler geometry for a moving source, fixed observer.

The Doppler effect also occurs when the source and observer are fixed relative to each other but the scattering or reflecting object is moving (see Fig. 2-9). In this case, the Doppler shift is given by

$$v_d = v\frac{v}{c}(\cos\,\theta_1 + \cos\,\theta_2) \qquad\qquad (2\text{-}32)$$

and if the source and observer are collocated (i.e., $\theta_1 = \theta_2 = \theta$), then

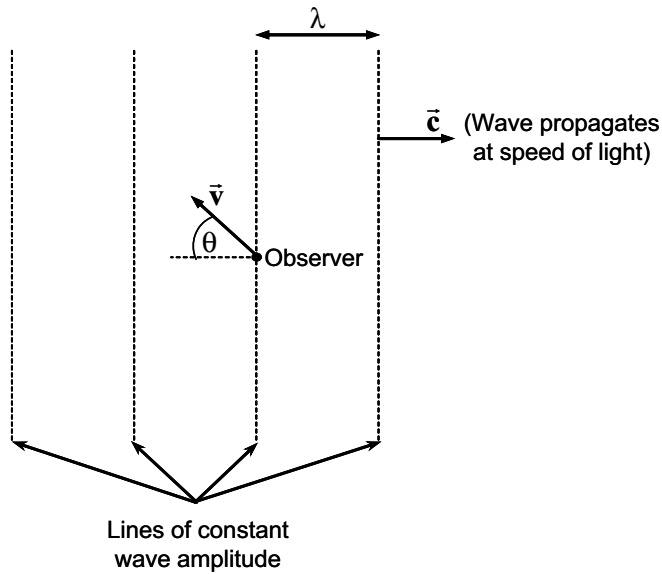$$v_d = 2v\frac{v}{c}\,\cos\,\theta \qquad\qquad (2\text{-}33)$$

Figure 2-8. Geometry illustrating wave fronts passing by a moving observer.
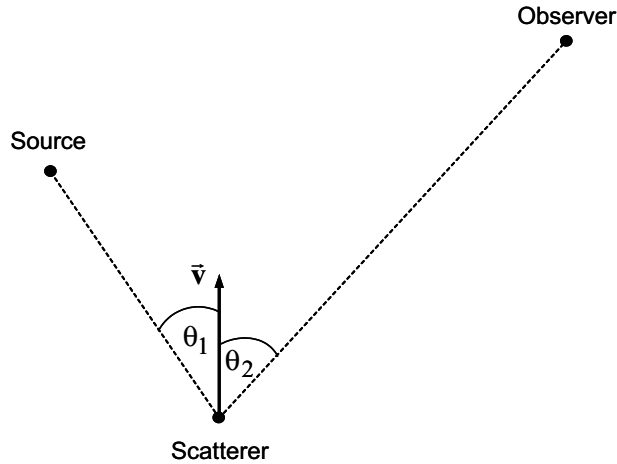
Figure 2-9. Doppler geometry for a moving scatterer with fixed source and observer.

The Doppler effect is used in remote sensing to measure target motion. It is also the basic physical effect used in synthetic-aperture imaging radars to achieve very high resolution imaging.

2-2   NOMENCLATURE AND DEFINITION OF RADIATION QUANTITIES

2-2-1   Radiation Quantities

A number of quantities are commonly used to characterize the electromagnetic radiation and its interaction with matter. These are briefly described below and summarized in Table 2-1.

Radiant energy. The energy carried by an electromagnetic wave. It is a measure of the capacity of the wave to do work by moving an object by force, heating it, or changing its state. The amount of energy per unit volume is called radiant energy density.

Radiant flux. The time rate at which radiant energy passes a certain location. It is closely related to the wave *power,* which refers to the time rate of doing work. The term *flux* is also used to describe the time rate of flow of quantized energy elements such as photons. Then the term *photon flux* is used.

Radiant flux density. Corresponds to the radiant flux intercepted by a unit area of a plane surface. The density for flux incident upon a surface is called irradiance. The density for flux leaving a surface is called exitance or emittance.

Solid angle. The solid angle Ω subtended by area A on a spherical surface is equal to the area A divided by the square of the radius of the sphere.

Radiant intensity. The radiant intensity of a point source in a given direction is the radiant flux per unit solid angle leaving the source in that direction.

Radiance. The radiant flux per unit solid angle leaving an extended source in a given direction per unit projected area in that direction (see Fig. 2-10). If the radiance does not change as a function of the direction of emission, the source is called Lambertian.

A piece of white matte paper, illuminated by diffuse skylight, is a good example of a Lambertian source.

Hemispherical reflectance. The ratio of the reflected exitance (or emittance) from a plane of material to the irradiance on that plane.

Hemispherical transmittance. The ratio of the transmitted exitance, leaving the opposite side of the plane, to the irradiance.

Table 2-1. Radiation Quantities

| Quantity	Usual symbol	Defining equation	Units
Radiant energy	Q		joule
Radiant energy density	W	$W = \dfrac{dQ}{dV}$	joule/m^3
Radiant flux	Φ	$\Phi = \dfrac{dQ}{dt}$	watt
Radiant flux density	E (irradiance) M (emittance)	$E, M = \dfrac{d\Phi}{dA}$	watt/m^2
Radiant intensity	I	$I = \dfrac{d\Phi}{d\Omega}$	watt/steradian
Radiance	L	$L = \dfrac{dI}{dA \cos \theta}$	watt/steradian m^2
Hemispherical reflectance	ρ	$\rho = \dfrac{M_r}{E}$	
Hemispherical absorptance	α	$\alpha = \dfrac{M_a}{E}$	
Hemispherical transmittance	τ	$\tau = \dfrac{M_t}{E}$	
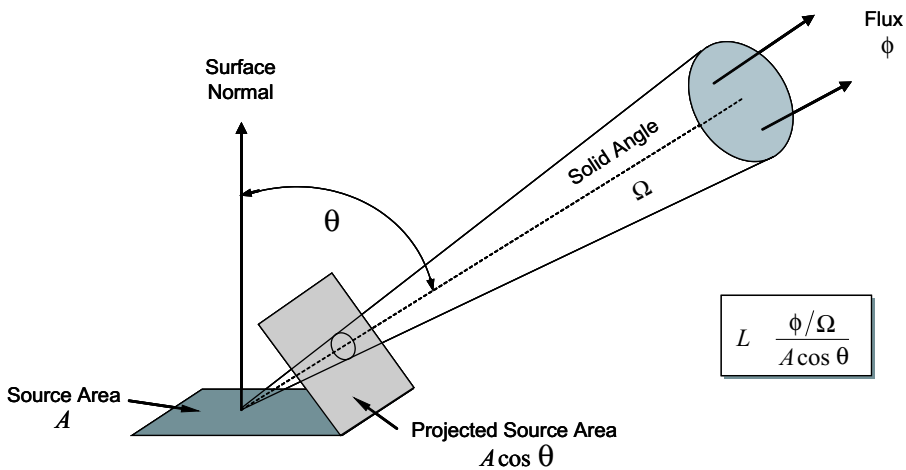
Figure 2-10. Concept of radiance.

Hemispherical absorptance. The flux density that is absorbed over the irradiance. The sum of the reflectance, transmittance, and absorptance is equal to one.

2-2-2   Spectral Quantities

Any wave can be considered as being composed of a number of sinusoidal component waves or spectral components, each carrying a part of the radiant flux of the total wave form. The spectral band over which these different components extend is called the spectral width or bandwidth of the wave. The manner with which the radiation quantities are distributed among the components of different wavelengths or frequencies is called the spectral distribution. All radiance quantities have equivalent spectral quantities that correspond to the density as a function of the wavelength or frequency. For instance, the spectral radiant flux $\Phi(\lambda)$ is the flux in a narrow spectral width around λ divided by the spectral width:

$$\Phi(\lambda) = \frac{\text{Flux in all waves in the band } \lambda - \Delta\lambda \text{ to } \lambda + \Delta\lambda}{2\Delta\lambda}$$

To get the total flux from a wave form covering the spectral band from λ_1 to λ_2, the spectral radiant flux must be integrated over that band:

$$\Phi(\lambda_1 \text{ to } \lambda_2) = \int_{\lambda_1}^{\lambda_2} \Phi(\lambda)d\lambda \tag{2-34}$$

2-2-3   Luminous Quantities

Luminous quantities are related to the ability of the human eye to perceive radiative quantities. The relative effectiveness of the eye in converting radiant flux of different wavelengths to visual response is called the spectral luminous efficiency $V(\lambda)$. This is a dimensionless quantity that has a maximum of unity at about 0.55 μm and covers the spectral region from 0.4 to 0.7 μm (see Fig. 2-11). $V(\lambda)$ is used as a weighting function in relating radiant quantities to luminous quantities. For instance, luminous flux Φ_v is related to the radiant spectral flux $\Phi_e(\lambda)$ by

$$\Phi_v = 680 \int_0^\infty \Phi_e(\lambda)V(\lambda)d\lambda \tag{2-35}$$

where the factor 680 is to convert from radiant flux units (watts) to luminous flux units (lumens).

Luminous quantities are also used in relation to sensors other than the human eye. These quantities are usually referenced to a standard source with a specific blackbody temperature. For instance, standard tungsten lamps operating at temperatures between 3200°K and 2850°K are used to test photoemissive tubes.

2-3   GENERATION OF ELECTROMAGNETIC RADIATION

Electromagnetic radiation is generated by transformation of energy from other forms such as kinetic, chemical, thermal, electrical, magnetic, or nuclear. A variety of transformation
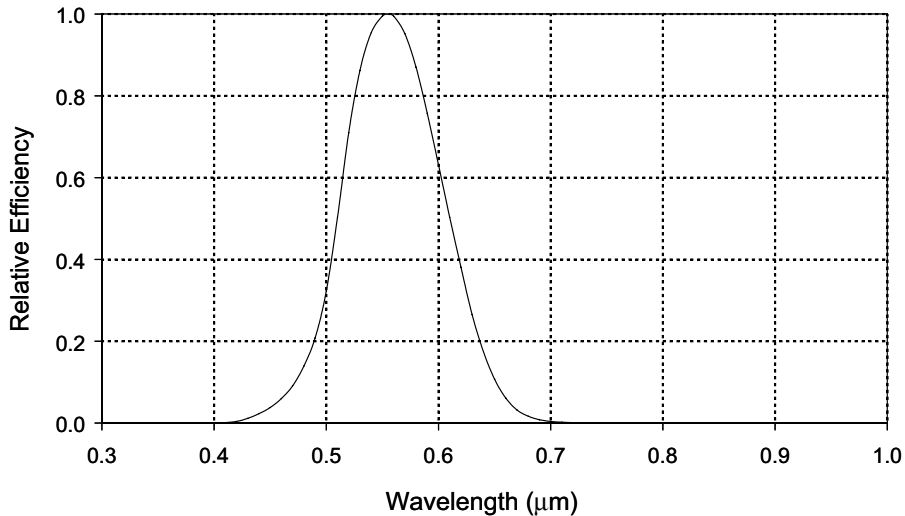
Figure 2-11. Spectral luminous efficiency $V(\lambda)$.

mechanisms lead to electromagnetic waves over different regions of the electromagnetic spectrum. In general, the more organized (as opposed to random) the transformation mechanism is, the more coherent (or narrower in spectral bandwidth) is the generated radiation.

Radio frequency waves are usually generated by periodic currents of electric charges in wires, electron beams, or antenna surfaces. If two short, straight metallic wire segments are connected to the terminals of an alternating current generator, electric charges are moved back and forth between them. This leads to the generation of a variable electric and magnetic field near the wires and to the radiation of an electromagnetic wave at the frequency of the alternating current. This simple radiator is called a dipole antenna.

At microwave wavelengths, electromagnetic waves are generated using electron tubes that use the motion of high-speed electrons in specially designed structures to generate a variable electric/magnetic field, which is then guided by waveguides to a radiating structure. At these wavelengths, electromagnetic energy can also be generated by molecular excitation, as is the case in masers. Molecules have different levels of rotational energy. If a molecule is excited by some means from one level to a higher one, it could drop back to the lower level by radiating the excess energy as an electromagnetic wave.

Higher-frequency waves in the infrared and the visible spectra are generated by molecular excitation (vibrational or orbital) followed by decay. The emitted frequency is exactly related to the energy difference between the two energy levels of the molecules. The excitation of the molecules can be achieved by a variety of mechanisms such as electric discharges, chemical reactions, or photonic illumination.

Molecules in the gaseous state tend to have well-defined, narrow emission lines. In the solid phase, the close packing of atoms or molecules distorts their electron orbits, leading to a large number of different characteristic frequencies. In the case of liquids, the situation is compounded by the random motion of the molecules relative to each other.

Lasers use the excitation of molecules and atoms and the selective decay between energy levels to generate narrow-bandwidth electromagnetic radiation over a wide range of the electromagnetic spectrum ranging from UV to the high submillimeter.

Heat energy is the kinetic energy of random motion of the particles of matter. The random motion results in excitation (electronic, vibrational, or rotational) due to collisions, followed by random emission of electromagnetic waves during decay. Because of its random nature, this type of energy transformation leads to emission over a wide spectral band. If an ideal source (called a blackbody) transforms heat energy into radiant energy with the maximum rate permitted by thermodynamic laws, then the spectral emittance is given by Planck's formula as

$$S(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1} \tag{2-36}$$

where h is Planck's constant, k is the Boltzmann constant, c is the speed of light, λ is the wavelength, and T is the absolute temperature in degrees Kelvin. Figure 2-12 shows the spectral emittance of a number of blackbodies with temperatures ranging from 2000° (temperature of the Sun's surface) to 300°K (temperature of the Earth's surface). The spectral emittance is maximum at the wavelength given by

$$\lambda_m = \frac{a}{T} \tag{2-37}$$

where a = 2898 μm°K. The total emitted energy over the whole spectrum is given by the Stefan–Boltzmann law:

$$S = \sigma T^4 \tag{2-38}$$

where σ = 5.669 × 10^{-8} Wm^{-2}K^{-4}. Thermal emission is usually unpolarized and extends through the total spectrum, particularly at the low-frequency end. Natural bodies are also characterized by their spectral emissivity $\varepsilon(\lambda)$, which expresses the capability to emit radiation due to thermal energy conversion relative to a blackbody with the same temperature. The properties of this emission mechanism will be discussed in more detail in Chapters 4 and 5.

Going to even higher energies, waves in the gamma-ray regions are mainly generated in the natural environment by radioactive decay of uranium (U), thorium (Th), and potassium 40 (^{40}K). The radioisotopes found in nature, ^{238}U and ^{232}Th, are long-lived alpha emitters and parents of individual radioactive decay chains. Potassium is found in almost all surfaces of the Earth, and its isotope ^{40}K, which makes up 0.12% of natural potassium, has a half-life of 1.3 billion years.

2-4   DETECTION OF ELECTROMAGNETIC RADIATION

The radiation emitted, reflected, or scattered from a body generates a radiant flux density in the surrounding space that contains information about the body's properties. To measure the properties of this radiation, a collector is used, followed by a detector.

The collector is a collecting aperture that intercepts part of the radiated field. In the microwave region, an antenna is used to intercept some of the electromagnetic energy. Examples of antennas include dipoles, an array of dipoles, or dishes. In the case of dipoles, the surrounding field generates a current in the dipole with an intensity proportional to the
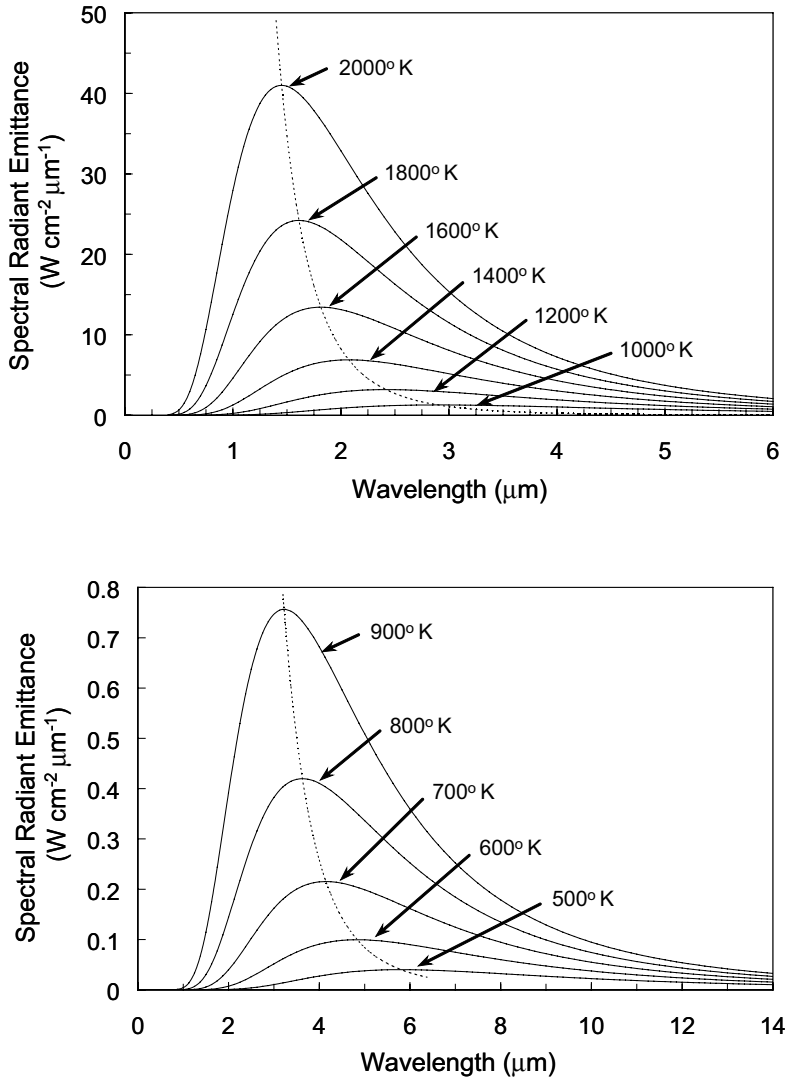
Figure 2-12. Spectral radiant emittance of a blackbody at various temperatures. Note the change of scale between the two graphs.

field intensity and a frequency equal to the field frequency. In the case of a dish, the energy collected is usually focused onto a limited area where the detector (or waveguide connected to the detector) is located.

In the IR, visible, and UV regions, the collector is usually a lens or a reflecting surface that focuses the intercepted energy onto the detector. Detection then occurs by transforming the electromagnetic energy into another form of energy such as heat, electric current, or state change.

Depending on the type of the sensor, different properties of the field are measured. In the case of synthetic-aperture imaging radars, the amplitude, polarization, frequency, and

phase of the fields are measured at successive locations along the flight line. In the case of optical spectrometers, the energy of the field at a specific location is measured as a function of wavelength. In the case of radiometers, the main parameter of interest is the total radiant energy flux. In the case of polarimeters, the energy flux at different polarizations of the wave vector is measured.

In the case of x-ray and gamma-ray detection, the detector itself is usually the collecting aperture. As the particles interact with the detector material, ionization occurs, leading to light emission or charge release. Detection of the emitted light or generated current gives a measurement of the incident energy flux.

2-5 INTERACTION OF ELECTROMAGNETIC WAVES WITH MATTER: QUICK OVERVIEW

The interaction of electromagnetic waves with matter (e.g., molecular and atomic structures) calls into play a variety of mechanisms that are mainly dependent on the frequency of the wave (i.e., its photon energy) and the energy level structure of the matter. As the wave interacts with a certain material—be it gas, liquid, or solid—the electrons, molecules, and/or nuclei are put into motion (rotation, vibration, or displacement), which leads to exchange of energy between the wave and the material. This section gives a quick simplified overview of the interaction mechanisms between waves and matter. Detailed discussions are given later in the appropriate chapters throughout the text.

Atomic and molecular systems exist in certain stationary states with well-defined energy levels. In the case of isolated atoms, the energy levels are related to the orbits and spins of the electrons. These are called the electronic levels. In the case of molecules, there are additional rotational and vibrational energy levels that correspond to the dynamics of the constituent atoms relative to each other. Rotational excitations occur in gases where molecules are free to rotate. The exact distribution of the energy levels depends on the exact atomic and molecular structure of the material. In the case of solids, the crystalline structure also affects the energy level distribution.

In the case of thermal equilibrium, the density of population N_i at a certain level i is proportional to (Boltzmann's law):

$$N_i \sim e^{-E_i/kT} \tag{2-39}$$

where E_i is the level energy, k is Boltzmann's constant, and T is the absolute temperature. At absolute zero, all the atoms will be in the ground state. Thermal equilibrium requires that a level with higher energy be less populated than a level of lower energy (Fig. 2-13).

To illustrate, for $T = 300°K$, the value for kT is 0.025 eV (one eV is 1.6×10^{-19} joules). This is small relative to the first excited energy level of most atoms and ions, which means that very few atoms will be in the excited states. However, in the case of molecules, some vibrational and many rotational energy levels could be even smaller than kT, thus allowing a relatively large population in the excited states.

Let us assume that a wave of frequency v is propagating in a material in which two of the energy levels i and j are such that

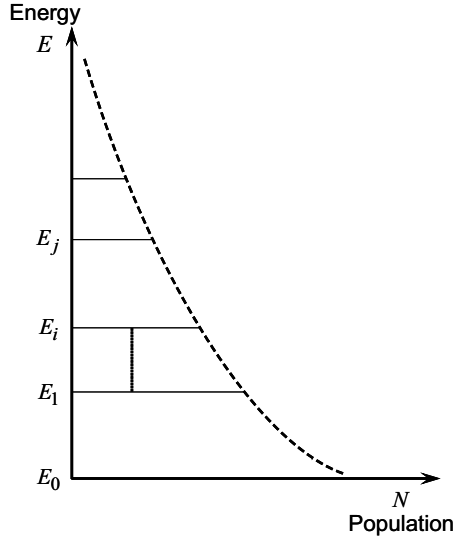$$hv = E_j - E_i \tag{2-40}$$

Figure 2-13. Curve illustrating the exponential decrease of population as a function of the level energy for the case of thermal equilibrium.

This wave would then excite some of the population of level i to level j. In this process, the wave loses some of its energy and transfers it to the medium. The wave energy is absorbed. The rate p_{ij} of such an event happening is equal to

$$p_{ij} = B_{ij}\varepsilon_v \tag{2-41}$$

where ε_v is the wave energy density per unit frequency and B_{ij} is a constant determined by the atomic (or molecular) system. In many texts, p_{ij} is also called transition probability.

   Once exited to a higher level by absorption, the atoms may return to the original lower level directly by spontaneous or stimulated emission, and in the process they emit a wave at frequency v, or they could cascade down to intermediate levels and in the process emit waves at frequencies lower than v (see Fig. 2-14). Spontaneous emission could occur any time an atom is in an excited state independent of the presence of an external field. The rate of downward transition from level j to level i is given by

$$p_{ji} = A_{ji} \tag{2-42}$$

where A_{ji} is characteristic of the pair of energy levels in question.

   Stimulated emission corresponds to downward transition, which occurs as a result of the presence of an external field with the appropriate frequency. In this case, the emitted wave is in phase with the external field and will add energy to it coherently. This results in an amplification of the external field and energy transfer from the medium to the external field. The rate of downward transition is given by
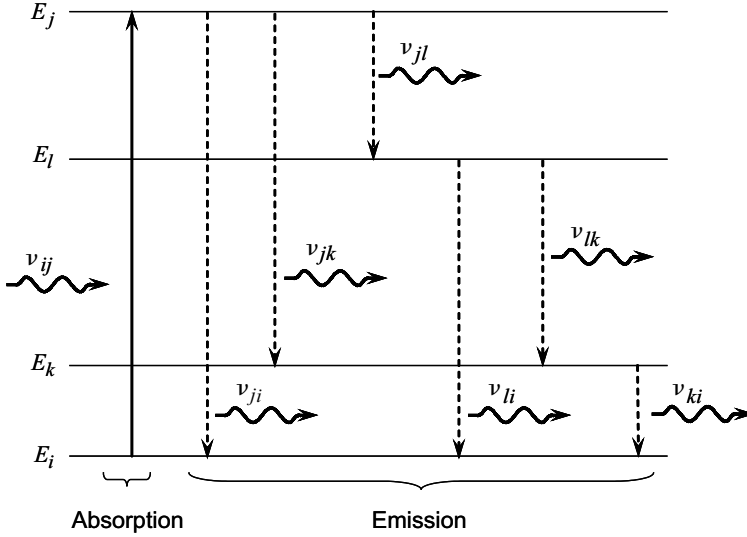
$$p_{ji} = B_{ji}\varepsilon_v \tag{2-43}$$

Figure 2-14. An incident wave of frequency v_{ij} is adsorbed due to population excitation from E_i to E_j. Spontaneous emission for the above system can occur at v_{ij} as well as by cascading down via the intermediate levels *l* and *k*.

The relationships between A_{ji}, B_{ji}, and B_{ij} are known as the Einstein's relations:

$$B_{ji} = B_{ij} \tag{2-44}$$

$$A_{ji} = \frac{8 \pi h v^3 n^3}{c^3} B_{ji} = \frac{8 \pi h n^3}{\lambda^3} B_{ji} \tag{2-45}$$

where *n* is the index of refraction of the medium.

   Let us now consider a medium that is not necessarily in thermal equilibrium and where the two energy levels *i* and *j* are such that $E_i < E_j$. N_i and N_j are the population in the two levels, respectively. The number of downward transitions from level *j* to level *i* is $(A_{ji} + B_{ji}\varepsilon_v)N_j$. The number of upward transitions is $B_{ij}\varepsilon_v N_i = B_{ji}\varepsilon_v N_i$. The incident wave would then lose $(N_i - N_j)B_{ji}\varepsilon_v$ quanta per second. The spontaneously emitted quanta will appear as scattered radiation, which does not add coherently to the incident wave.

   The wave absorption is a result of the fact that usually $N_i > N_j$. If this inequality can be reversed, the wave would be amplified. This requires that the population in the higher level is larger than the population in the lower energy level. This population inversion is the basis of laser and maser operations. However, it is not usually encountered in the cases of natural matter/waves interactions, which form the topic of this text. (*Note:* Natural maser effects have been observed in astronomical objects; however, these are beyond the scope of this text.)

   The transition between different levels in usually characterized by the lifetime τ. The lifetime of an excited state *i* is equal to the time period after which the number of excited atoms in this state have been reduced by a factor e^{-1}. If the rate of transition out of the state *i* is A_i, the corresponding lifetime can be derived from the following relations:

$$dN_i = -A_i N_i \, dt \tag{2-46}$$

$$\Rightarrow N_i(t) = N_i(0)e^{-A_i t} = N_i(0)e^{-t/\tau_i} \tag{2-47}$$

$$\Rightarrow \tau_i = 1/A_i \tag{2-48}$$

If the transitions from i occur to a variety of lower levels j, then

$$A_i = \sum_j A_{ij} \tag{2-49}$$

$$\Rightarrow \frac{1}{\tau_i} = \sum_j \frac{1}{\tau_{ij}} \tag{2-50}$$

2-6   INTERACTION MECHANISMS THROUGHOUT THE ELECTROMAGNETIC SPECTRUM

Starting from the highest spectral region used in remote sensing, gamma- and x-ray inter-actions with matter call into play atomic and electronic forces such as the photoelectric effect (absorption of photon with ejection of electron), Compton effect (absorption of photon with ejection of electron and radiation of lower-energy photon), and pair produc-tion effect (absorption of photon and generation of an electron–positron pair). The photon energy in this spectral region is larger than 40 eV (Fig. 2-15). This spectral region is used mainly to sense the presence of radioactive materials.

In the ultraviolet region (photon energy between 3 eV and 40 eV), the interactions call into play electronic excitation and transfer mechanisms, with their associated spectral bands. This spectral region is used mostly for remote sensing of the composition of the upper layers of the Earth and planetary atmospheres. An ultraviolet spectrometer was flown on the Voyager spacecraft to determine the composition and structure of the upper atmospheres of Jupiter, Saturn, and Uranus.

In the visible and near infrared (energy between 0.2 eV and 3 eV), vibrational and electronic energy transitions play the key role. In the case of gases, these interactions usu-ally occur at well-defined spectral lines, which are broadened due to the gas pressure and temperature. In the case of solids, the closeness of the atoms in the crystalline structure leads to a wide variety of energy transfer phenomena with broad interaction bands. These include molecular vibration, ionic vibration, crystal field effects, charge transfer, and electronic conduction. Some of the most important solid surface spectral features in this wavelength region include the following:

1. The steep fall-off of reflectance in the visible toward the ultraviolet and an absorp-tion band between 0.84 and 0.92 μm associated with the Fe^{3+} electronic transition. These features are characteristic of iron oxides and hydrous iron oxides, collective-ly referred to as limonite.
2. The sharp variation of chlorophyll reflectivity in the neighborhood of 0.75 μm, which has been extensively used in vegetation remote sensing.
3. The fundamental and overtone bending/stretching vibration of hydroxyl (OH) bear-ing materials in the 2.1 to 2.8 μm region, which are being used to identify clay-rich areas associated with hydrothermal alteration zones.
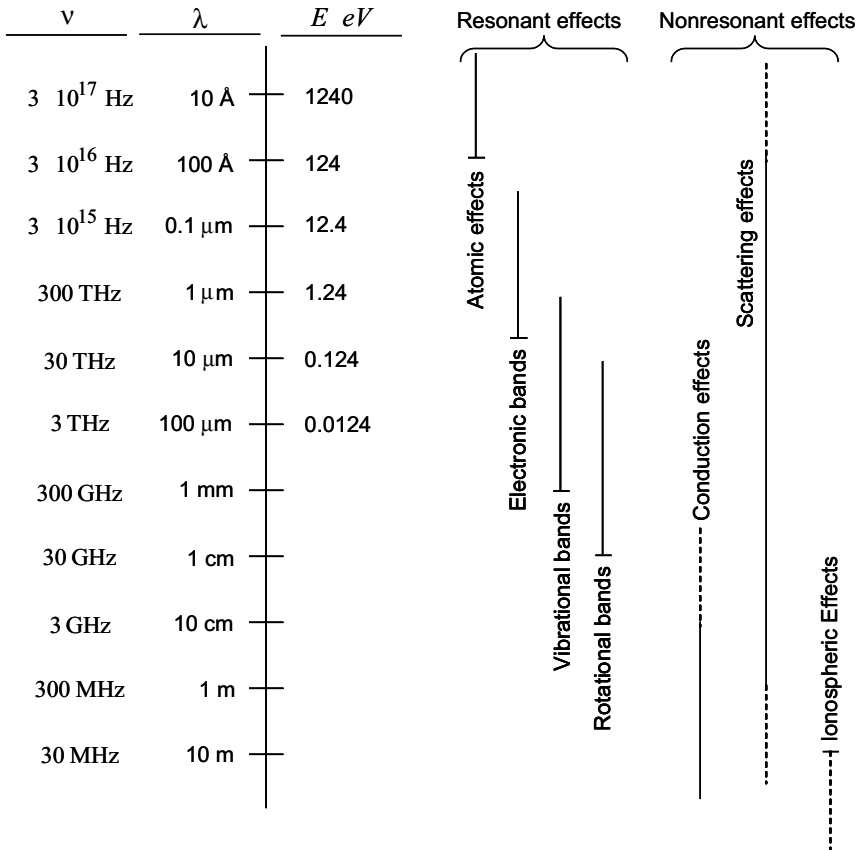
Figure 2-15. Correspondence of spectral bands, photon energy, and range of different wave–matter interaction mechanisms of importance in remote sensing. The photon energy in electron volts is given by $E(eV) = 1.24/\lambda$, where λ is in μm.

In the mid-infrared region (8 to 14 μm), the Si–O fundamental stretching vibration provides diagnostics of the major types of silicates (Fig. 2-16). The position of the restrahlen bands, or regions of metallic-like reflection, are dependent on the extent of interconnection of the Si–O tetrahedra comprising the crystal lattice. This spectral region also corresponds to vibrational excitation in atmospheric gaseous constituents.

In the thermal infrared, the emissions from the Earth's and other planets' surfaces and atmospheres are strongly dependent on the local temperature, and the resulting radiation is governed by Planck's law. This spectral region provides information about the temperature and heat constant of the object under observation. In addition, a number of vibrational bands provide diagnostic information about the emitting object's constituents.

In the submillimeter region, a large number of rotational bands provide information about the atmospheric constituents. These bands occur all across this spectral region, making most planetary atmospheres completely opaque for surface observation. For some gases such as water vapor and oxygen, the rotational band extends into the upper regions of the microwave spectrum.
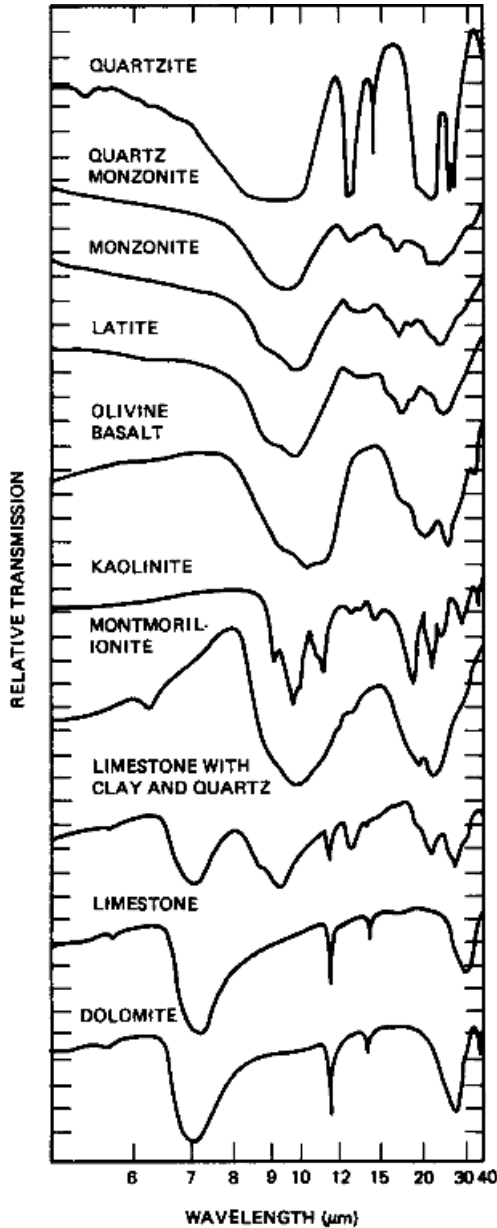
Figure 2-16. Transmission spectra of common silicates (Hunt and Salisbury, 1974).

The interaction mechanisms in the lower-frequency end of the spectrum ($v < 20$ GHz, $\lambda > 1.5$ cm) do not correspond to energy bands of specific constituents. They are, rather, collective interactions that result from electronic conduction and nonresonant magnetic and electric multipolar effects. As a wave interacts with a simple molecule, the resulting displacement of the electrons results in the formation of an oscillating dipole that generates an electromagnetic field. This will result in a composite field moving at a speed low-

TABLE 2-2. Wave–Matter Interaction Mechanisms across the Electromagnetic Spectrum

Spectral region	Main interaction mechanisms	Examples of remote sensing applications
Gamma rays, x-rays	Atomic processes	Mapping of radioactive materials
Ultraviolet	Electronic processes	Presence of H and He in atmospheres
Visible and near infrared	Electronic and vibration molecular processes	Surface chemical composition, vegetation cover, and biological properties
Mid-infrared	Vibrational, vibrational–rotational molecular processes	Surface chemical composition, atmospheric chemical composition
Thermal infrared	Thermal emission, vibrational and rotational processes	Surface heat capacity, surface temperature, atmospheric temperature, atmospheric and surface constituents
Microwave	Rotational processes, thermal emission, scattering, conduction	Atmospheric constituents, surface temperature, surface physical properties, atmospheric precipitation
Radio frequency	Scattering, conduction, ionospheric effect	Surface physical properties, subsurface sounding, ionospheric sounding

er than the speed of light in vacuum. The effect of the medium is described by the index of refraction or the dielectric constant. In general, depending on the structure and composition of the medium, the dielectric constant could be anisotropic or could have a loss term that is a result of wave energy transformation into heat energy.

In the case of an interface between two media, the wave is reflected or scattered depending on the geometric shape of the interface. The physical properties of the interface and the dielectric properties of the two media are usually the major factors affecting the interaction of wave and matter in the microwave and radio frequency part of the spectrum. Thus, remote sensing in this region of the spectrum will mainly provide information about the physical and electrical properties of the object instead of its chemical properties, which are the major factors in the visible/infrared region, or its thermal properties, which are the major factors in the thermal infrared and upper microwave regions (see Table 2-2).

In summary, a remote sensing system can be visualized (Fig. 2-17) as a source of electromagnetic waves (e.g., the sun, a radio source, etc.) that illuminate the object being studied. An incident wave interacts with the object and the scattered wave is modulated by a number of interaction processes that contain the "fingerprints" of the object. In some cases, the object itself is the source and the radiated wave contains information about its properties. A part of the scattered or radiated wave is then collected by a collector, focused on a detector, and its properties measured. An inverse process is then used to infer the properties of the object from the measured properties of the received wave.

EXERCISES

2-1. In order to better visualize the relative scale of the waves' wavelength in different regions of the spectrum, assume that the blue wavelength ($\lambda = 0.4$ μm) is ex-
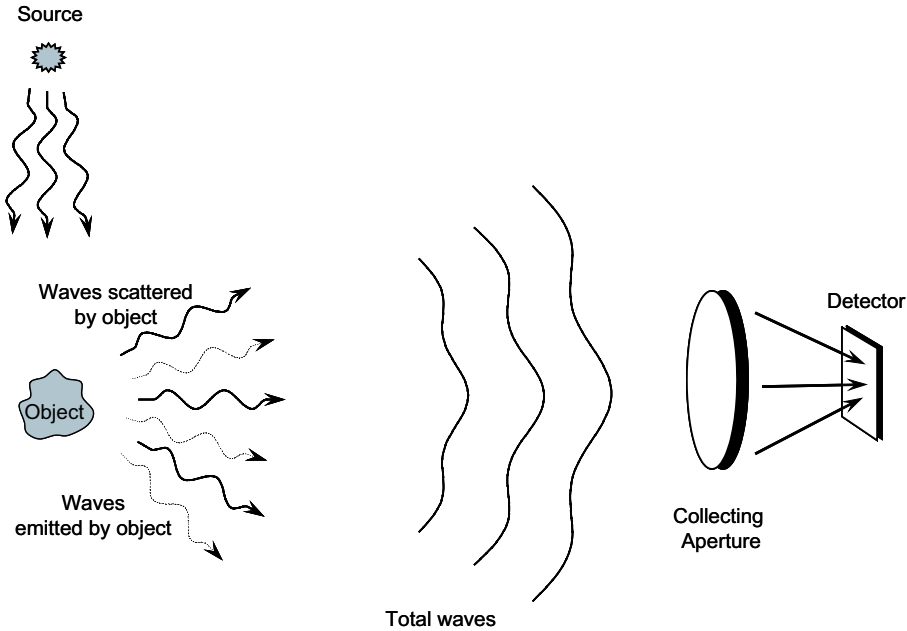
Figure 2-17. Sketch of key elements of a remote sensing system.

panded to the size of a keyhole (1 cm). What would be the wavelength size of other spectra regions in terms of familiar objects?

2-2. The sun radiant flux density at the top of the Earth's atmosphere is 1.37 kilowatts/m^2. What is the flux density at Venus (0.7 AU), Mars (1.5 AU), Jupiter (5.2 AU), and Saturn (9.5 AU)? Express these values in kilowatts/m^2 and in photons/m^2 sec. Assume $\lambda = 0.4$ μm for the sun illumination. (Note that AU = astronomical unit = Earth/sun distance.)

2-3. Assume that the sun emittance spectrum follows exactly Plank's formula:

$$S(\lambda)\frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{ch/\lambda kT}-1}$$

with T = 6000°K. Calculate the percent of solar energy in the following spectral regions:

- In the UV ($\lambda < 0.4$ μm)
- In the visible (0.4 μm $< \lambda < 0.7$ μm)
- In the infrared (0.7 μm $< \lambda < 10$ μm)
- In the thermal infrared and submillimeter (10 μm $< \lambda < 3$ mm)
- In the microwave ($\lambda > 3$ mm)

2-4. The amplitudes of two coexistent electromagnetic waves are given by

$$\mathbf{E}_1 = \hat{\mathbf{e}}_x A \cos(kz - \omega t)$$

$$\mathbf{E}_2 = \hat{\mathbf{e}}_y B \cos(kz - \omega t + \phi)$$

Describe the temporal behavior of the total electric field $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$ for the following cases:

- $A = B$, $\phi = 0$
- $A = B$, $\phi = \pi$
- $A = B$, $\phi = \pi/2$
- $A = B$, $\phi = \pi/4$

Repeat the exercise for $A = 2B$.

2-5. The amplitudes of two coexistent electromagnetic waves are given by

$$\mathbf{E}_1 = \hat{\mathbf{e}}_x A \, \cos\left[\omega\left(\frac{z}{c} - t\right)\right]$$

$$\mathbf{E}_2 = \hat{\mathbf{e}}_y B \, \cos\left[\omega'\left(\frac{z}{c} - t\right)\right]$$

where c is the speed of light in vacuum. Let $\omega' = \omega + \Delta\omega$ and $\Delta\omega \ll \omega$ Describe the behavior of the power $P \sim |\mathbf{E}_1 + \mathbf{E}_2|^2$ of the composite wave as a function of P_1 and P_2 of each individual wave.

2-6. A plasma is an example of a dispersive medium. The wavenumber for a plasma is given by

$$k = \frac{1}{c}\sqrt{\omega^2 - \omega_p^2}$$

where c = speed of light and ω_p = plasma angular frequency.

(a) Calculate and plot the phase and group velocity of a wave in the plasma as a function of frequency.

(b) Based on the results of (a), why is a plasma called a *dispersive* medium?

2-7. A radar sensor is carried on an orbiting satellite that is moving at a speed of 7 km/sec parallel to the Earth's surface. The radar beam has a total beam width of $\theta = 4°$ and the operating frequency is $\nu = 1.25$ GHz. What is the center frequency and the frequency spread of the echo due to the Doppler shift across the beam for the following cases:

(a) a nadir-looking beam

(b) a 45° forward-looking beam

(c) a 45° backward-looking beam

2-8. Repeat Problem 2-7 for the case in which the satellite is moving at a velocity of 7 km/sec but at a 5° angle above the horizontal.

2-9. Plot and compare the spectral emittance of blackbodies with surface temperatures of 6000°K (Sun), 600°K (Venus), 300°K (Earth), 200°K (Mars), and 120 K (Titan). In particular, determine the wavelength for maximum emission for each body.

2-10. A small object is emitting Q watts isotropically in space. A collector of area A is located a distance d from the object. How much of the emitted power is being

intercepted by the collector? Assuming that $Q = 1$ kW, and $d = 1000$ km, what size collector is needed to collect 1 milliwatt and 1 microwatt?

2-11. Two coexistent waves are characterized by

$$E_1 = A \cos(\omega t)$$

$$E_1 = A \cos(\omega t + \alpha)$$

Describe the behavior of the total wave $E = E_1 + E_2$ for the cases where $\alpha = 0$, $\alpha = \pi/2$, $\alpha = \pi$, and $\alpha = $ a random value with equal probability of occurrence between 0 and 2π.

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