RADIOMETRY

Radiometry is concerned with the measurement, analysis, and interpretation of radiant electromagnetic energy. The simplest and most common measurement, made using an instrument called a radiometer, is of received electromagnetic power in a given frequency band. Some instruments, however, analyze the received energy's spectral distribution (spectroradiometers), its polarization (polarimeters), or its angular distribution in space (imaging radiometers). The usual objective of radiometric measurements is the inference from them of the physical and/or chemical state of the material from, or through, which the received electromagnetic energy has been emitted, reflected, or transmitted. Radiometry is therefore a branch of remote sensing and could be considered to include radar. In practice, however, the term *radiometry* is usually used to describe the measurement and characterisation of naturally occurring radiation, or (unlike radar) scattered radiation originating as a narrowband signal. The former, called passive radiometry, deals principally with self-emitted

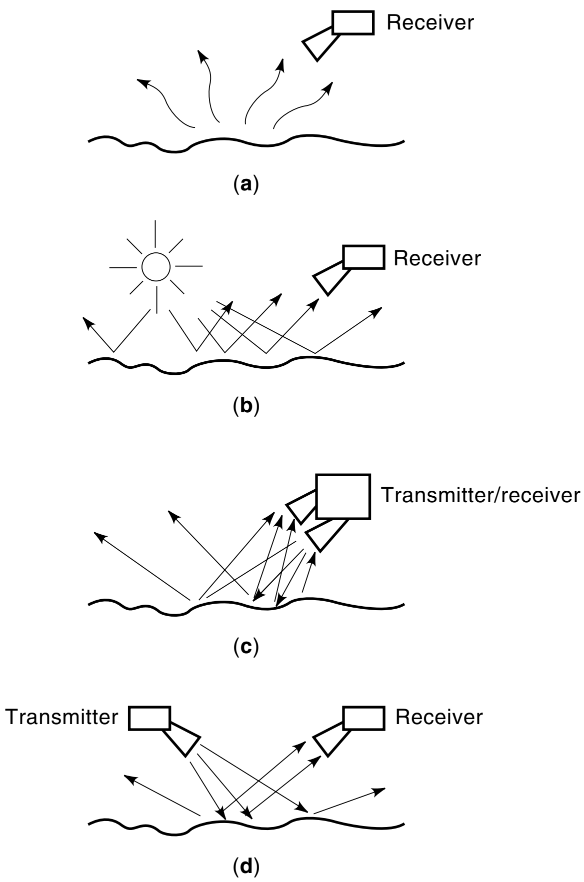

Figure 1. Passive and active radiometry. (a) Passive measurements of self-emitted thermal radiation. (b) Passive measurements of scattered solar radiation. (c) Active (scatterometer) measurements employing monostatic geometry. (d) Active (scatterometer) measurements employing bistatic geometry.

thermal radiation and reflected radiation of solar origin. The latter, called active radiometry, relies on artificial illumination. Figure 1 illustrates these different types of radiometer. Active radiometers are sometimes called scatterometers.

Since all radiometers depend for their operation on the measurement of one or more parameters of electromagnetic radiation, a brief review of such radiation follows.

ELECTROMAGNETIC RADIATION

Whenever charges accelerate (other than those carried by electrons in stable orbits around the nuclei of atoms), or a subatomic particle in an atom makes a transition to a lower energy level, electromagnetic energy is radiated. This energy propagates as a disturbance of the electric and magnetic fields existing in space. An electromagnetic wave propagating in an isotropic, homogeneous, medium has, sufficiently far from its source, an electric field vector, $\boldsymbol{E}$, magnetic field vector, $\boldsymbol{B}$, and unit vector pointing in the direction of wave propagation, $\boldsymbol{u}$, which are mutually perpendicular. Furthermore, the wave front has a curvature that is sufficiently small for it to be considered locally plane. (In a truly plane wave $\boldsymbol{E}$ and $\boldsymbol{B}$ would be constant with respect to position in any plane normal to the direction of propagation.)

For radiation of a single frequency (said to be monochromatic), $\boldsymbol{E}$ and $\boldsymbol{B}$ will vary sinusoidally with time and space. The amplitude (V/m) of such a wave is the peak value of its electric field strength, and its cyclical frequency, f (Hz), is the number of oscillations (or cycles) that the electric field completes, at a given point in space, in one second. [The radian frequency, ω (rad/s), is the phase advance in radians, at a given point in space, that the wave makes in one second and is related to cyclical frequency by $\omega = 2\pi f$.] The phase constant, β (rad/m), is the phase advance in radians that the wave makes, at a given instant of time, over one meter of space in the direction of propagation and is related to wavelength, λ, by $\beta = 2\pi/\lambda$. ($1/\lambda$ and β are therefore the spatial equivalent of cyclical and radian frequency, respectively.)

Radiation of nonzero bandwidth has an amplitude at a point in space that fluctuates over time as the phase relationships between the constituent (and elemental) monochromatic waves change. The time scale over which this amplitude fluctuation occurs is related to the bandwidth, Δf, of the radiation and is characterized by a coherence time, Δt. Coherence time is defined as the maximum time shift for which the field of the original and time-shifted waves (at a given point in space) are correlated. An equivalent quantity, coherence length, Δl, is defined (for a given instant in time) as the maximum spatial shift for which the fields of original and shifted waves are correlated. For quantitative work the term *correlated* must be interpreted as a correlation value greater than some specified fraction of its maximum. For consistent definitions of bandwidth, coherence length, and coherence time, these quantities are related by

$$\Delta l = c\,\Delta t = \frac{c}{\Delta f} \tag{1}$$

If the tip of the $\boldsymbol{E}$ vector, representing a wave at a single point in space, traces out an elliptical curve, the wave is said to be (fully) polarized. If the curve traced out is random, the wave is said to be unpolarized. A wave with an $\boldsymbol{E}$ vector locus that can be resolved into a deterministic component and a random component is said to be partially polarized. A fully polarized wave having a polarization ellipse with an axial ratio of 1.0, or ∞ is said to be circularly, or linearly, polarized, respectively. A linearly polarized wave therefore has an $\boldsymbol{E}$ vector that traces out a straight line and that, in an isotropic medium, remains in a fixed plane as the wave propagates forward.

The concepts of coherence and polarization are not entirely unrelated since a wave observed on a time scale that is short with respect to its coherence time is always fully polarized. As the observation time increases, the polarization of the wave may gradually change; however, the changes appear random on a time scale large with respect to the wave's coherence time. A wave will remain fully polarized even when observed on a time scale much longer than its coherence time if energy is radiated in one polarization only.

In passive radiometry the received electromagnetic radiation is usually incoherent, spread across a wide band of frequencies, and unpolarized. The useful measurable quantities in this case are power density (W/m^2), radiation intensity (W/sr), power spectral density (W/Hz), and angular/spatial radiation distribution. In radiometry the first three of these quantities are generally referred to as irradiance (E), radiant inten-

Table 1. Radiometric and Photometric Quantities

Quantity	Symbol	SI Unit	Other Common Units	Defining Equation	Comments
Radiant energy	Q_e	J	erg, kWh		Electromagnetic energy
Radiant flux	Φ_e	W	erg/s	$\Phi_e = \frac{dQ_e}{dt}$	Electromagnetic power
Radiant density	w_e	J/m^3	erg/cm^3	$w_e = \frac{dQ_e}{dV}$	Energy density
Irradiance	E_e	W/m^2	W/cm^2	$E_e = \frac{d\Phi_e}{dA}$	Power density (also called radiant flux density)
Radiant excitance	M_e	W/m^2	W/cm^2	$M_e = \frac{d\Phi_e}{dA}$	Power density (also called emittance and radiant flux density)
Radiant intensity	I_e	W/sr		$I_e = \frac{d\Phi_e}{d\Omega}$	Angular concentration of power (also called radiation intensity)
Radiance	L_e	$W\ sr^{-1}\ m^{-2}$	$W\ sr^{-1}\ cm^{-2}$	$L_e = \frac{dI_e}{(dA \cos\psi)}$	Angular concentration of power per unit projected area of source (also called radiometric brightness, especially in microwave applications)
Luminous energy	Q_v	lm s (talbot)	lm h	$\Phi_v = K_m \int_{0.36\,\mu m}^{0.83\,\mu m} \Phi_{e,\lambda}(\lambda)V(\lambda)\,d\lambda$	Photopic definition. Scotopic definition uses primed versions of K_m and $V(\lambda)$.
Luminous flux	Φ_v	lm (lumen)		$\Phi_v = \frac{dQ_v}{dt}$	
Luminous density	w_v	$lm\ s\ m^{-3}$		$w_v = \frac{dQ_v}{dV}$	
Illuminance	E_v	lx (lux)	fc, ph	$E_v = \frac{d\Phi_v}{dA}$	1 lux (lx) = 1 lm/m^2 1 foot-candle (fc) = 1 lm/ft^2 1 phot (ph) = 1 lm/cm^2 Also called illumination
Luminous excitance	M_v	lx		$M_v = \frac{d\Phi_v}{dA}$	Also called luminous emittance
Luminous intensity	I_v	cd (candela)		$I_v = \frac{d\Phi_v}{d\Omega}$	1 candela (cd) = 1 lm/sr
Luminance	L_v	cd/m^2 (nit, nt)	sb, L, fL, asb	$L_v = \frac{dI_v}{(dA \cos\psi)}$	1 stilb (sb) = 1 cd/cm^2 1 lambert (L) = 1 $cd/(\pi\ cm^2)$ 1 foot lambert (fL) = 1 $cd/(\pi\ ft^2)$ 1 apostilb (asb) = 1 $cd/(\pi\ m^2)$ Also called photometric brightness

sity (I), and radiant spectral flux (Φ_f), respectively. In some applications, however (microwave radiometry, for example), different terminologies are also often used (see Table 1).

DEFINITIONS OF RADIOMETRIC QUANTITIES

The commonly used radiometric quantities are as follows:

Radiant energy, Q (J)—The quantity of electromagnetic energy in a specified region of space or associated with a specified process

Radiant flux, Φ (W)—Radiant energy per unit time crossing a specified surface

Radiant density, w (J/m^3)—Radiant energy per unit volume

Radiant flux density, E or M (W/m^2)—radiant flux per unit area normal to a specified direction

Irradiance, E (W/m^2)—radiant flux density arriving at a specified surface

Radiant excitance (or emittance), M (W/m^2)—Radiant flux density leaving a specified surface

Radiant intensity, I (W/sr)—Radiant flux per unit solid angle in a specified direction

Radiance, L ($W\ sr^{-1}\ m^{-2}$)—Radiant intensity in a specified direction per unit projected area of the source normal to the specified direction

Radiation consisting of electromagnetic power distributed over a continuum of frequencies has infinitesimally small power at any single frequency. Each of the preceding quantities can be characterized at a single frequency, however, by considering the quantity to be measured within a small bandwidth Δf (centered on frequency f), dividing by Δf, and taking the limit as $\Delta f \to 0$. The result is a spectral density having those units of the original quantity per hertz. (An obvious variation on this definition uses radian frequency instead of cyclical frequency.) At optical frequencies spectral densities are usually expressed as quantities per meter of wavelength rather than per hertz of frequency. A spectral density is typically indicated by preceding the quantity with the word *spectral* and adding a subscript f, ω, or λ to the appropriate symbol. Spectral irradiance, for example, can be expressed in any of the following ways:

$$E_f(f) = \lim_{\Delta f \to 0} \left[\frac{\text{power density contained in frequency band } f - \frac{\Delta f}{2} \text{ to } f + \frac{\Delta f}{2}}{\Delta f} \right] \tag{2}$$

$$E_\omega(\omega) = \lim_{\Delta \omega \to 0} \left[\frac{\text{power density contained in frequency band } \omega - \frac{\Delta \omega}{2} \text{ to } \omega + \frac{\Delta \omega}{2}}{\Delta \omega} \right] \tag{3}$$

$$E_\lambda(\lambda) = \lim_{\Delta \lambda \to 0} \left[\frac{\text{power density contained in wave band } \lambda - \frac{\Delta \lambda}{2} \text{ to } \lambda + \frac{\Delta \lambda}{2}}{\Delta \lambda} \right] \tag{4}$$

The relationship between these various expressions is summarized by

$$E_f(f) = E_\omega\left(\frac{\omega}{2\pi}\right) 2\pi = E_\lambda\left(\frac{c}{\lambda}\right) \frac{c}{f^2} \tag{5}$$

Spectral densities may be a function of frequency and, if so, may be measured by a spectroradiometer to yield information about the source of the radiation, material through which it has passed, or a surface from which it has been reflected. Often, however, spectral densities are constant with frequency (at least over the frequency band of interest). In this case they are referred to as white and are characterized by a single value.

Related Photometric/Luminous Quantities

Radiometric quantities relate to objective measures of energy and power carried by electromagnetic radiation of any wavelength. Photometric (or luminous) quantities relate to the subjective visual impact that these quantities have on an observer (1). In practice, photometric quantities are usually measured objectively but in such a way as to reflect the visual sensation experienced by a normal human observer. This is achieved by using detectors that mimic the response of the human eye/brain system and is called physical photometry. The definition of photometric quantities therefore involves the visual response of a (hypothetical) standard observer (2). In fact two standard responses, $V(\lambda)$ and $V'(\lambda)$, called the photopic and scotopic spectral luminous efficiencies, are defined (Fig. 2). These responses correspond closely to those of human observers under conditions of high (nominally daytime) and low (nominally nighttime) illumination, respectively. (The principal reason for the difference in these two responses is that different types of retinal receptors dominate under the two conditions; cones in the former case and rods in the latter case.)

Spectral luminous efficiencies are used to define a photometric/luminous quantity corresponding to each radiometric quantity, the same symbol usually being used for both. When confusion between the two is possible, the radiometric version is identified using a subscript e and the luminous version using a subscript v. For photopic vision, luminous flux, Φ_v, for example, is related to the radiometric quantity, radiant spectral flux $\Phi_{e,\lambda}(\lambda)$, by

$$\Phi_v = K_m \int_0^\infty \Phi_{e,\lambda}(\lambda) V(\lambda)\, d\lambda \tag{6}$$

[Note that since $V(\lambda)$ is zero outside the range 0.36 μm to 0.83 μm, the limits of the integral in Eq. (6) can be replaced with these values.] The coefficient K_m (= 683.002 lm/W) in Eq. (6) is a conversion factor that changes radiometric units of watts (represented by the integral) into photometric units of lumens (lm). The scotopic version of Eq. (6) has identical form but is distinguished by primes added to Φ_v, $V(\lambda)$, and K_m. The value of K'_m is 1700.06 lm/W (rods, which are more sensitive than cones, dominate vision under conditions of poor illumination). The curves $K(\lambda) = K_m V(\lambda)$ and $K'(\lambda) = K'_m V'(\lambda)$, called the photopic and scotopic spectral luminous efficiencies, (Fig. 3), intersect at a wavelength of 0.555 μm (540 × 10^{12} Hz), for which $V(\lambda)$ is a maximum (unity). At this frequency, therefore, the luminous efficiency is 683 lm/W under all illumination conditions. At other frequencies the luminous efficiency

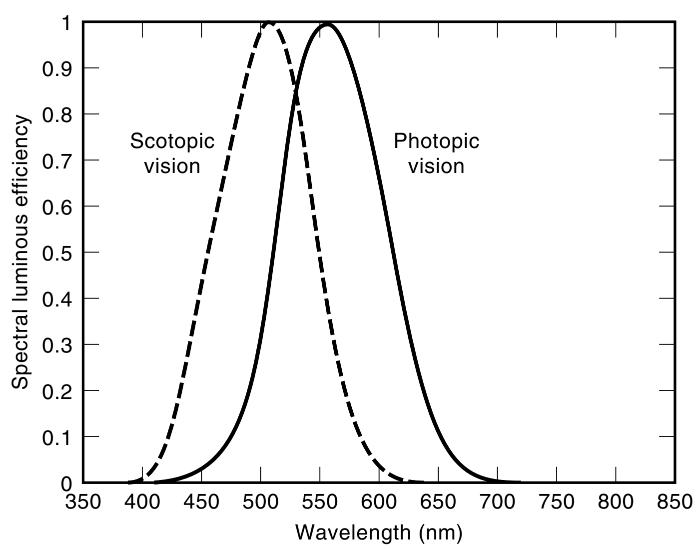

Figure 2. Spectral luminous efficiencies: photopic, $V(\lambda)$, and scotopic, $V'(\lambda)$.

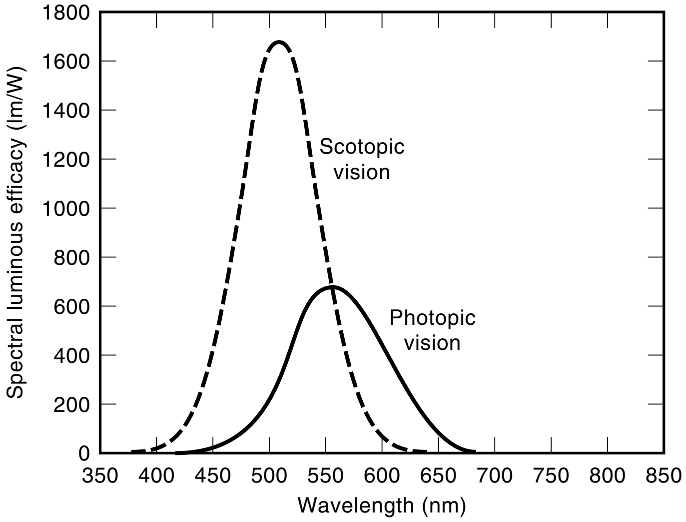

Figure 3. Spectral luminous efficacies: photopic, $K(\lambda)$, and scotopic, $K'(\lambda)$.

is illumination dependent. The wavelength of maximum visual response for scotopic vision is 0.507 μm.

Table 1 summarizes the radiometric and the corresponding photometric quantities.

Photon Flux

At optical and quasi-optical frequencies, the interaction of electromagnetic fields with matter cannot always be explained in terms of smoothly varying field quantities, and recourse must be made to quantum theory. In this description electromagnetic fields are made up of discrete, quantized packets of energy called photons. The energy, Q (joules), carried by each packet, or quanta, is related to the radiation's frequency by $Q = hf$ (J), where $h = 6.626 \times 10^{-34}$ (J·s), is Planck's constant. The probability that the energy carried by a photon will be transferred to a material particle (in a detector, for example) at some specific time and location is proportional to the irradiance (power density) at that time and location. In applications where individual photons may be detected, electromagnetic power is often referred to as a photon flux.

BLACKBODY RADIATION AND EMISSIVITY

A body that absorbs all electromagnetic radiation falling on it (converting the incident radiant energy to thermal energy) and that would therefore appear black at optical frequencies is called a blackbody. Such a body, in thermal equilibrium with its surroundings, must supply precisely as much energy back to, as it receives from, these surroundings. In the absence of conduction and convection the energy transfer mechanism is limited to thermal radiation. The thermal radiant energy emitted by a body can never, therefore, be greater than that emitted by a blackbody of the same size, shape, and physical temperature. The degree of blackness of a body is quantified by its surface emissivity, defined as follows.

Emissivity, ϵ—Ratio of spectral radiant excitance at the surface of a body to the spectral radiant excitance at the surface of a blackbody with the same physical temperature

The maximum value of emissivity, corresponding to that of a blackbody, is therefore unity and the minimum value, corresponding to a surface that reflects all radiant energy falling on it, is zero. A body with an emissivity that is independent of frequency, but less than unity, is called a gray body. Many natural materials have emissivities that are frequency dependent, however, and this dependence, if measured radiometrically, can yield useful information about the material's composition and physical state.

The reflecting, transmitting, and absorbing properties of a material's surface, which can also be inferred from radiometric measurements, are quantified as follows:

Reflectance, ρ—ratio of reflected to incident spectral radiant flux at a surface

Transmittance, τ—ratio of transmitted to incident spectral radiant flux at a surface

Absorptance, α—Ratio of absorbed to incident spectral radiant flux at a surface

It is clear that

$$\rho + \tau + \alpha = 1 \tag{7}$$

The surface of a blackbody has an absorptance of unity and, therefore, a reflectance and transmittance of zero. More generally, for any opaque ($\tau = 0$) material, $\rho = 1 - \alpha$ and emissivity is numerically equal to absorptance (i.e., $\epsilon = \alpha$).

A good model of a blackbody is the surface represented by a small hole drilled in a hollow cavity. Provided that the reflectance of the interior surface of the cavity is not too close to unity, then any radiant energy falling on to the hole is reflected a sufficient number of times inside the cavity for it to be fully absorbed before it can reemerge.

The spectral radiant excitance, $M_f(f)$, of a blackbody (Fig. 4), is given by Planck's law (3); that is,

$$M_f(f) = \frac{2\pi h}{c^2}\,\frac{f^3}{\exp(hf/kT) - 1} \tag{8}$$

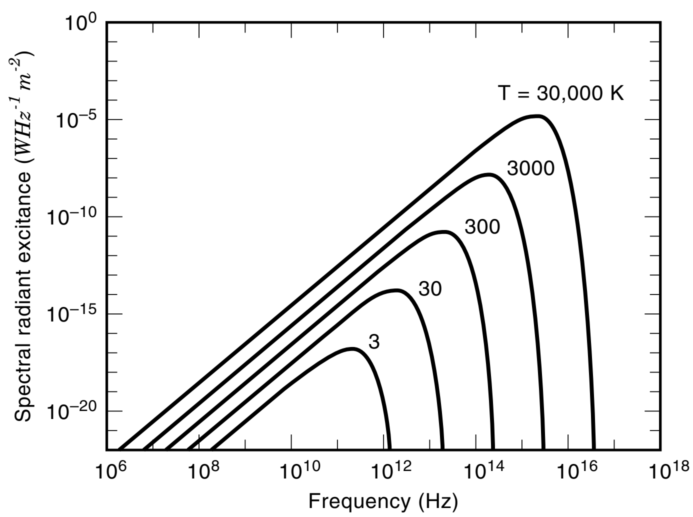

Figure 4. Planck's law for blackbody radiation.

For optical frequencies, where it is traditional to express spectral quantities on a per meter of wavelength, rather than a per hertz of frequency, basis Eq. (8) can be written as

$$M_\lambda(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1} \tag{9}$$

For $hf \ll kT$, which is appropriate for microwave radiometry at all commonly encountered temperatures, Eq. (8) reduces to the Rayleigh–Jeans approximation (Fig. 5). That is,

$$M_f(f) = \frac{2\pi}{c^2} kTf^2 \tag{10}$$

[The Rayleigh–Jeans version of Eq. (9) is $M_\lambda(\lambda) = 2\pi ckT/\lambda^4$.] The spectral radiant excitance of a body with emissivity < 1.0 is therefore given by

$$M_f(f) = \epsilon(f) \frac{2\pi}{c^2} kTf^2 \tag{11}$$

Lambert's Law and Lambertian Radiators

Lambert's cosine law is that the radiant intensity from a blackbody surface is proportional to cos ψ where ψ is the angle between the direction of observation and the surface normal. Any surface (irrespective of its emissivity) that has this distribution of radiant intensity is said to be Lambertian. The radiance of such a surface (being radiant intensity per unit projected area) is independent of ψ. The spectral radiant excitance of an arbitrary surface is related to its spectral radiance by

$$M_f(f) = \int_0^{2\pi} \int_0^{\pi/2} L_f(\psi, f) \cos\psi \sin\psi \, d\psi \, d\gamma \tag{12}$$

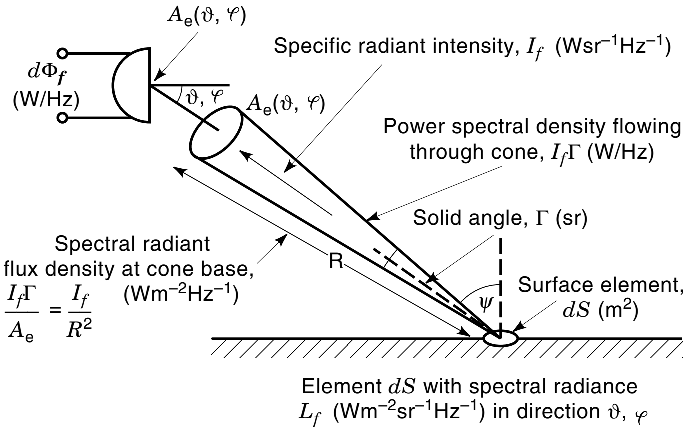

Figure 6. Spectral irradiance at radiometer antenna aperture due to radiating surface element dS.

which, for a Lambertian surface, reduces to

$$M_f(f) = L_f(f)\pi \tag{13}$$

The spectral radiance of a blackbody surface is therefore given by

$$L_f(f) = \frac{2h}{c^2} \frac{f^3}{\exp(hf/kT) - 1} \tag{14}$$

which for $kT \gg hf$ gives the Rayleigh–Jeans approximation

$$L_f(f) = \frac{2kT}{c^2} f^2 = \frac{2kT}{\lambda^2} \tag{15}$$

Radiometric Brightness and Antenna Temperatures

Consider a lossless antenna (i.e., one having an ohmic efficiency of 100%) with effective aperture area $A_e(\theta, \phi)$ receiving radiant energy from a surface S (Fig. 6). If a surface element

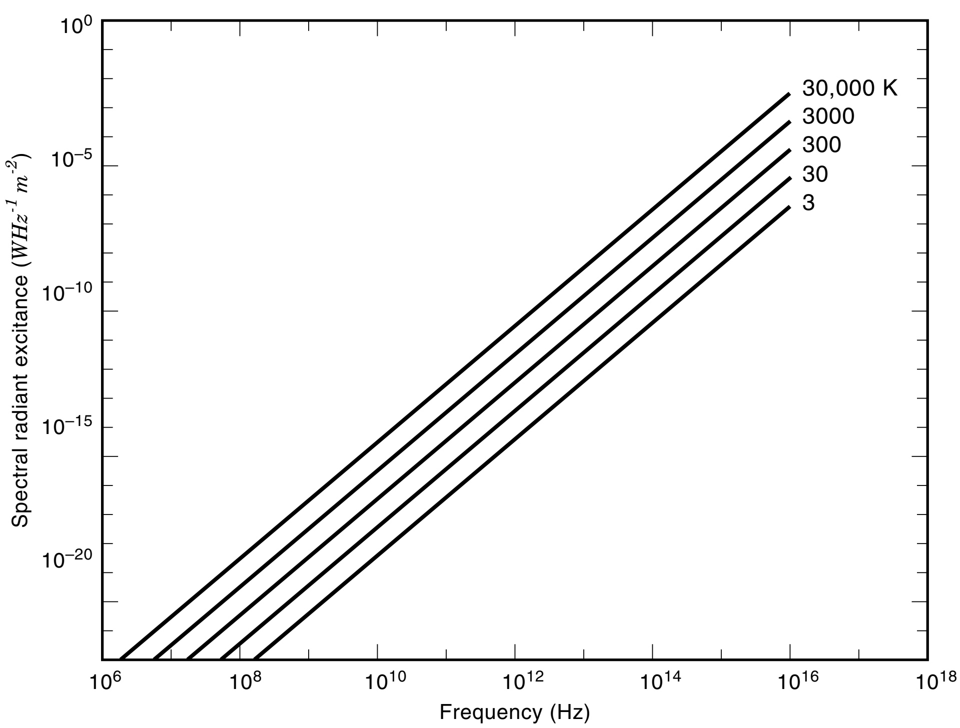

Figure 5. Rayleigh–Jeans approximation for blackbody radiation.

of area dS (m^2) lies at a distance R (m) from the antenna in the direction (θ, ϕ), then the spectral radiant flux density arriving at the antenna due to this element is

$$dE_f = \frac{I_f(\theta,\ \phi)}{R^2} = \frac{L_f(\theta,\ \phi)\,dS\cos\psi}{R^2} \tag{16}$$

The power spectral density (or spectral radiant flux) received by the antenna is therefore

$$d\Phi_f = 0.5A_e(\theta,\ \phi)\,dE_f = \frac{0.5A_e(\theta,\ \phi)L_f(\theta,\ \phi)\,dS\cos\psi}{R^2} \tag{17}$$

(The factor of 0.5 accounts for the fact that the antenna will be polarization matched to only half of the randomly polarized incident energy.) The quantity dS ($\cos\psi$)/R^2 in Eq. (17) can be identified as the solid angle, $d\Omega$, subtended by the surface element at the antenna (Fig. 7). The power spectral density available at the antenna output terminals can therefore be expressed as either a surface, or a solid angle, integral; that is,

$$\begin{aligned}\Phi_f &= 0.5\iint_S \frac{A_e(\theta,\ \phi)L_f(\theta,\ \phi)\cos\psi\,dS}{R^2}\\ &= 0.5\iint_\Omega A_e(\theta,\ \phi)L_f(\theta,\ \phi)\,d\Omega\end{aligned} \tag{18}$$

The power, or radiant flux, received within a band of frequencies f_{min} to f_{max} is then given by

$$\Phi = \int_{f_{min}}^{f_{max}} \Phi_f(f)\,df \tag{19}$$

Since Eq. (18) is a power spectral density, an antenna aperture temperature, T_a, may be defined such that the noise power measured by a noiseless radiometer (i.e., one that has a noise figure of 0 dB), with a lossless antenna, is kT_aB_N (where B_N is the radiometer noise bandwidth and k is Boltzmann's constant). For small B_N, such that $\Phi_f(f)$ can be considered white, $T_a = \Phi/kB_N = \Phi_f/k$ and

$$T_a = \frac{0.5}{k}\iint_\Omega A_e(\theta,\ \phi)L_f(\theta,\ \phi)\,d\Omega \tag{20}$$

In a lossless antenna, effective area is related to antenna directivity by $A_e(\theta,\ \phi) = D(\theta,\ \phi)\lambda^2/4\pi$ (4), where $D(\theta,\ \phi)$ is the antenna directivity pattern. Equation (20) may therefore be written as

$$T_a = \frac{0.5}{k}\frac{\lambda^2}{4\pi}\iint_\Omega D(\theta,\ \phi)L_f(\theta,\ \phi)\,d\Omega \tag{21}$$

The quantity (0.5 $\lambda^2/k)L_f(\theta,\ \phi)$ is usually referred to as a radiometric brightness temperature, $T_B(\theta,\ \phi)$, allowing Eq. (21) to be written as

$$T_a = \frac{1}{4\pi}\iint_\Omega D(\theta,\ \phi)T_B(\theta,\ \phi)\,d\Omega \tag{22}$$

(In microwave radiometry the term *brightness* is often used as a synonym for spectral radiance.) The radiometric brightness temperature of a body is related to the body's physical temperature, T, by the body's emissivity; that is,

$$T_B(\theta,\ \phi) = \epsilon(\theta,\ \phi)T(\theta,\ \phi) \tag{23}$$

[The emissivity's dependence on ψ is not shown explicitly in Eq. (23) but is implied in its θ, ϕ dependence. The frequency dependence is suppressed only for clarity.] The first step in conventional radiometer data analysis usually requires that the radiometric brightness temperature of a particular region be estimated from a measurement of an antenna noise temperature, T_A, defined by

$$T_A = \frac{\Phi_R}{kB_N} \tag{24}$$

where Φ_R is the power supplied to the radiometer by the antenna. If the antenna has nonzero ohmic loss, the measured antenna noise temperature will comprise an attenuated aperture temperature (the aperture temperature being the temperature measured by a lossless antenna) and a thermal contribution from the physical antenna structure itself. For an antenna with ohmic (or radiation) efficiency, η_Ω (expressed as a per unit, not percent, quantity), and physical structure temperature, T_s, the measured antenna noise temperature will be

$$T_A = \eta_\Omega T_a + (1 - \eta_\Omega)\,T_s \tag{25}$$

If the antenna loss is sufficiently small, then $T_a \cong T_A$. Equation (22) shows, however, that the antenna aperture temperature is a weighted average of the observed brightness temperature in which the weighting function is the antenna directivity pattern. If the antenna has a radiation pattern with low side lobes and a beamwidth that is narrow with respect to the angular rate of change of brightness temperature, then T_a gives the required brightness temperature, in the direction of the main lobe, directly. For an imaging radiometer (which scans a beam over some solid angle, for example, to form an image), with a beam that is not sufficiently narrow,

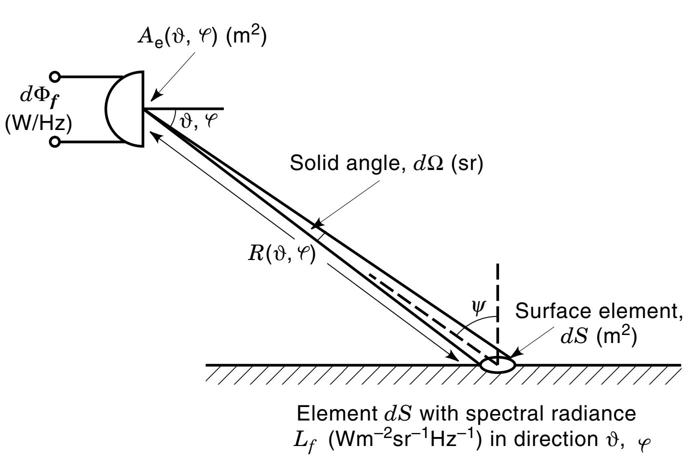

Figure 7. Solid angle subtended at radiometer antenna aperture by radiating surface element dS.

deconvolution of the antenna pattern from the resulting image may be necessary.

Since antenna directivity and gain are related (4) by $G(\theta, \phi) = \eta_\Omega D(\theta, \phi)$, then Eqs. (22) and (25) can be combined and written as

$$T_A = \frac{1}{4\pi} \iint_{4\Omega} G(\theta, \phi) T_B(\theta, \phi)\, d\Omega + (1 - \eta_\Omega) T_s \qquad (26)$$

In the absence of significant atmospheric effects (losses and scattering), Eq. (26) shows that an adequate knowledge of antenna ohmic efficiency and antenna gain pattern will allow the brightness temperature of a surface (with a spatial resolution determined by the antenna beamwidth) to be found from a measurement of antenna noise temperature. [The noise figure of the radiometer must be considered, of course, when making this measurement (5).]

Atmospheric Loss and Scattering

If atmospheric effects cannot be neglected, then the brightness temperature inferred from Eq. (26) must be interpreted as an apparent brightness temperature since it will comprise a contribution from the target surface plus a contribution from the thermal emission of the atmosphere itself. Furthermore, the thermal radiation from each source (i.e., each surface element of the target and each volume element of the atmosphere) will be attenuated by the loss associated with the intervening atmosphere. Since atmospheric thermal emission is essentially isotropic, half of the thermal energy from each element is radiated upward (called upwelling radiation) and half is radiated downward (called downwelling radiation). For a downward-pointing radiometer (such as might be used in planetry-surface remote sensing applications), downwelling radiation may be reflected by the ground back into the antenna's main lobe. The contribution of this ground-scattered radiation will depend on the ground-reflectance and the integrated specific attenuation along the ground-reflected path to the radiometer. An upward-pointing radiometer (such as might be used in terrestrial atmospheric remote sensing applications) observes downwelling radiation from the atmosphere directly. The contribution from ground-scattered downwelling radiation, and ground thermal emission, will now be coupled into the antenna through its downward-pointing side or back lobes. The significance of this radiation will depend on the gain of these lower hemisphere lobes and the brightness temperature of the region within the antenna's main lobe. (If a microwave radiometer with high antenna gain is pointed at high elevation angle into a clear sky, well away from any discrete sources of radiation, then the brightness temperature observed by its main lobe may be as low as a few degrees kelvin. Radiation emitted by, or reflected from, the ground may, under these conditions, be a very significant source of measurement error.)

The preceding description assumes that the atmosphere is an absorbing, but nonscattering, medium. For an atmosphere filled with scattering particles, or more general scattering inhomogeneities, this simplified description is inadequate. [The operating wavelength, and the physical size and composition of inhomogeneities, will determine whether they act as significant scatterers or not (6).] In this case more rigorous theories must be used to account for, and interpret, observed radiometric measurements (7).

APPLICATIONS

The most important application of radiometry lies in remote sensing of the earth's surface and its atmosphere (8). Polar ice mapping, for example, is possible using passive microwave radiometers located on earth-orbiting platforms. Microwave radiometry is especially useful for ice mapping because the contrast in emissivity between ice and water is particularly large at microwave frequencies. Furthermore, since passive microwave radiometry depends on self-emitted thermal radiation, and since the earth's atmosphere is essentially transparent at the microwave frequencies used, then data collection does not rely on solar illumination or the absence of cloud cover. (A requirement for solar illumination is particularly problematic in the polar regions, of course, due to the absence of the sun in winter.) Knowledge of annual, and longer term, changes in the extent of the polar ice shelves is important in the field of climatology generally and to recent concerns about possible climate change in particular.

Other surface materials (e.g., water/rock/sand) can be discriminated using microwave radiometers, and soil moisture mapping is also possible (9). Radiometer measurements applied in this area are of obvious interest in climatology, agriculture, and environmental science. Processes of desertification, like changes in the polar ice cover, are of concern in the context of global warming.

A rather different application of microwave radiometry concerns the development of the worldwide satellite communications network. Since a material's thermal emission and absorption are directly related, a brightness temperature measured at a given frequency can be used to infer the attenuation that an electromagnetic wave of that frequency would experience when propagating along the path observed. Ground-based, upward-pointing microwave radiometers can therefore be used to estimate the expected statistics of earth-space signal attenuation for use in the design of microwave satellite communication systems (10). The dominant mechanism resulting in large attenuation is the presence of precipitation along the path. Measurements of this type can, therefore, also be used in conjunction with appropriate signal attenuation/rain rate models to estimate rainfall intensity statistics for hydrological applications. (In recent years, however, the use of meteorological radar has probably become the preferred rainfall remote sensing tool.)

Active microwave radiometry can, like its passive variant, operate independent of solar illumination and is immune to cloud cover (and, depending on frequency, other meteorological phenomena that may make the atmosphere opaque). Downward-pointing scatterometers, for example, can be used to map surface wind velocities by measuring the effective reflectance of the ocean surface. The technique used in this application depends on the fact that the received signal for a nadir pointing, monostatic scatterometer decreases as the wind speed increases and the water surface becomes rough. This is due to the tendency of the reflected energy to be scattered in many directions by the rough surface, rather than reflected, specularly, back along the illuminating path. The apparent reflectance of the ocean surface can therefore be used as a measure of wind speed. Other reflectance measurements, using forward- and side-looking radiometer beams, allow wind velocity to be inferred since the reflecting facets of the waves have a preferred orientation that depends on wind direction.

Downward-pointing, millimeterwave, spectroradiometer observations of brightness temperature around the absorption/emission lines of a homogeneously mixed atmospheric constituent can be used to estimate the vertical temperature profile of the atmosphere. Oxygen, which has a cluster of closely spaced resonance lines around 60 GHz, is often used for this purpose (11). The basic principle of such temperature measurements is as follows. The brightness temperature observed at any given frequency represents a weighted mean taken over the observed path. The weighting factor at a particular altitude depends on the density of the oxygen at that altitude and on the attenuation of the intervening atmosphere. Thus at high altitudes (near the radiometer) the contribution to total brightness will be small because the density of the gas is low. At low altitudes (far from the radiometer) the contribution to total brightness will also be low because the intervening atmosphere will greatly attenuate this contribution. The observed brightness temperature will therefore be dominated by a region of the atmosphere at some intermediate height. If measurements are made across a band of frequencies coincident with the skirt of an atmospheric constituent's absorption band where atmospheric attenuation changes rapidly with frequency, then the height from which the dominant contribution arises also changes with frequency. In this way a brightness temperature versus frequency profile can be transformed to a brightness temperature versus altitude profile.

In a related area, microwave radiometry has been applied in the estimation, using zenith pointing radiometers, of integrated atmospheric water content (both liquid and gaseous phases). The large specific, and latent, heats of water mean that mapping of this quantity is important in understanding the global energy balance. If spectroradiometer measurements are made across a significant band of frequencies close to the water vapor absorption line at 22 GHz, then the water vapor's density profile can be inferred. The technique here is essentially the same as that described previously in the context of temperature profiling using the 60 GHz oxygen absorption line(s). The temperature profile is first estimated (using the oxygen line, for example), and the brightness temperature versus frequency profile in the skirt region of the water vapor's absorption line is transformed to a brightness temperature versus altitude profile. The water vapor's density at a given altitude is then inferred from the brightness at that altitude. Similar measurement can be used to find vertical profiles of many other atmospheric constituents with applications to environmental monitoring and pollution control.

Infrared radiometry (especially at 4 μm and 11 μm) can be used for ocean surface temperature mapping with obvious applications to meteorology and climatology. In practice, both these frequencies, and at least one other intermediate frequency, are usually required in order to correct for errors introduced by atmospheric water vapor and scattering by atmospheric aerosols. Multifrequency measurements can yield data with accuracies of 1 K.

Chlorophyll, the dominant pigmentation in most species of plants, has absorption lines close to 440 nm and 650 nm corresponding to the blue and red parts of the visible spectrum, thus giving vegetation its predominantly green color. [In fact, there are two distinct varieties of chlorophyll, blue-green and yellow-green, which both have absorption lines located about 10 nm either side of these frequencies (11).] In the near infrared region, however, absorption by chlorophyll is very low and reflectance correspondingly high. Infrared and visible reflectance measurements can, together, yield information about the photosynthetic capacity of selected areas of the biosphere (12). The presence of pigmentation other than chlorophyll can also be detected by spectroradiometric measurements and used to discriminate between different plant species. Furthermore, water absorption lines at 1.45 μm and 1.95 μm allow the water content of plant material to be estimated from infrared measurements. High-resolution, multiband, visible and infrared radiance measurements can thus be used to assess the quantity, variety, health, and photosynthetic vigour of much of the earth's surface vegetation.

Visible multiband measurements of radiance can also be used to gather information about the phytoplankton of the oceans' surface layers. A particular problem associated with these measurements is that upwelling radiation originating in the intervening atmosphere must generally be accounted for. One solution relies on the fact that the oceans do not contribute to upwelling radiance in the red part of the spectrum. Measurements in the red region of the spectrum over the oceans can therefore be used to estimate atmospheric upwelling radiance, which in turn can be used to infer atmospheric contributions at other wavelengths.

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