Lecture 1.

Basic radiometric quantities.

Objectives:

1. Basic introduction to electromagnetic field: Definitions, dual nature of electromagnetic radiation, electromagnetic spectrum.
2. Basic radiometric quantities: energy, intensity, and flux.

Required reading:

L02: 1.1

1. Basic introduction to electromagnetic field.

Electromagnetic radiation is a form of transmitted energy***. Electromagnetic radiation*** is so-named because it has electric and magnetic fields that simultaneously oscillate in planes mutually perpendicular to each other and to the direction of propagation through space. Electromagnetic radiation exhibits the **dual nature**: it has wave properties and particulate properties.

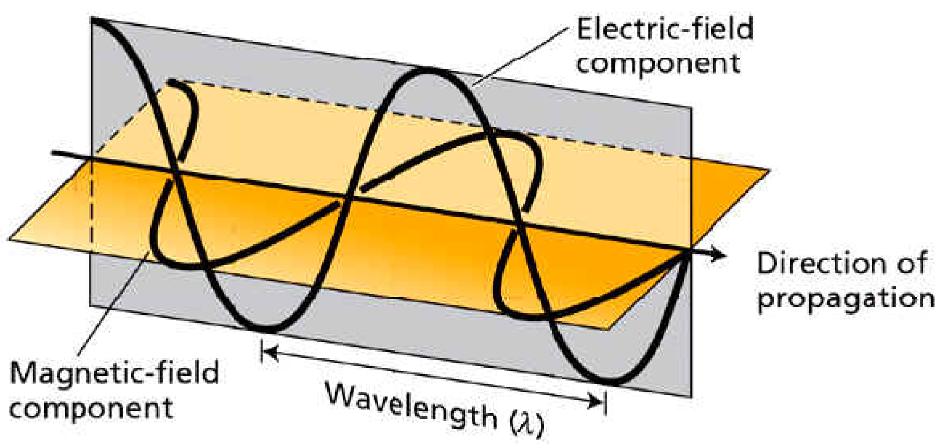


Figure 1.1 Electromagnetic radiation as a traveling wave.

***Wave nature of radiation*:** radiation can be thought of as **a traveling wave** characterized by the **wavelength (or frequency, or wavenumber)** and **speed.**

NOTE: speed of light in a vacuum: $c = 2.9979\text{x}10^8$ m/s $\cong$ $3.00\text{x}10^8$ m/s.

Wavelength, λ, is the distance between two consecutive peaks or troughs in a wave.

Frequency, $\tilde{\nu}$, is defined as the number of waves (*cycles*) per second that pass a given point in space.

Wavenumber, ν, is defined as a count of the number of wave crests (or troughs) in a given unit of length.

Relation between λ, ν **and** $\tilde{\nu}$:

$$\nu = \tilde{\nu}/c = 1/\lambda \qquad [1.1]$$

NOTE: The frequency is a more fundamental quantity than the wavelength

Wavelength units: LENGTH,

Angstrom (A): 1 A = $1\text{x}10^{-10}$ m; Nanometer (nm): 1 nm=$1\text{x}10^{-9}$ m;

Micrometer (μm): 1 μm = $1\text{x}10^{-6}$ m;

Frequency units: unit cycles per second 1/s (or s^{-1}) is called Hertz (abbreviated Hz)

Wavenumber units: LENGTH^{-1} (often in cm^{-1})

- As a transverse wave, EM radiation can be polarized. **Polarization** is the distribution of the electric field in the plane normal to propagation direction.

***Particulate nature of radiation*:**

Radiation can be also described in terms of particles of energy, called **photons**.

The energy of a **photon** is given by the expression:

$$\varepsilon_{\text{photon}} = \boldsymbol{h}\,\tilde{\nu} = \boldsymbol{h}\,c/\lambda = \boldsymbol{h}\,c\nu \qquad [1.2]$$

where $\boldsymbol{h}$ is Plank's constant ($h = 6.6256\text{x}10^{-34}$ J s).

NOTE: Plank's constant $\boldsymbol{h}$ is very small!

- Eq. [1.2] relates energy of each photon of the radiation to the electromagnetic wave characteristics ($\tilde{\nu}$, ν or λ).

- **<u>Spectrum of electromagnetic radiation</u>**

is the distribution of electromagnetic radiation according to energy (or, equivalently, according to the wavelength, wavenumber, or frequency).

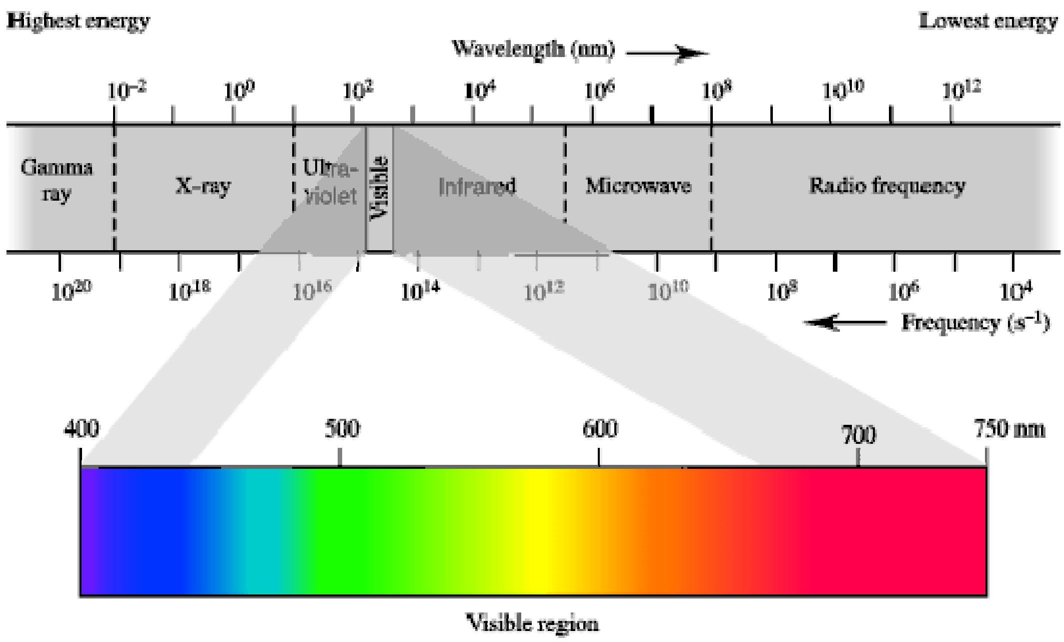


Figure 1.2 The electromagnetic spectrum.

Table 1.1 Relationships between radiation components studied in this course.

Name of spectral region	Wavelength region, µm	Spectral equivalence
Solar	0.1 - 4	Ultraviolet + Visible + Near infrared = Shortwave
Terrestrial	4 - 100	Far infrared = Longwave
Infrared	0.75 - 100	Near infrared + Far infrared
Ultraviolet	0.1 - 0.38	Near ultraviolet + Far ultraviolet = UV-A + UV-B + UV-C + Far ultraviolet
Shortwave	0.1 - 4	Solar = Near infrared + Visible + Ultraviolet
Longwave	4 - 100	Terrestrial = Far infrared
Visible	0.38 - 0.75	Shortwave - Near infrared - Ultraviolet
Near infrared	0.75 - 4	Solar - Visible - Ultraviolet = Infrared - Far infrared
Far infrared	4 - 100	Terrestrial = Longwave = Infrared - Near infrared
Thermal	4 - 100	Terrestrial = Longwave = Far infrared

2. Basic radiometric quantities.

Flux and intensity are the two measures of the strength of an electromagnetic field that are central to most problems in atmospheric sciences.

Intensity (or radiance) is defined as radiant energy in a given direction per unit time per unit wavelength (or frequency) range per unit solid angle per unit area perpendicular to the given direction (see fig. 1.3):

$$dI_{\lambda} = \frac{dE_{\lambda}}{\cos(\theta) d\Omega dt dA d\lambda} \qquad [1.3]$$

I_{λ} is called the **monochromatic** intensity.

- ✓ Monochromatic does not mean at a single wavelengths λ, but in a very narrow (infinitesimal) range of wavelength *d*λ centered at λ.

NOTE: *same name*: intensity = specific intensity = radiance

UNITS: from Eq.[1.3]: (J sec^{-1} sr^{-1} m^{-2} μm^{-1}) = (W sr^{-1} m^{-2} μm^{-1})

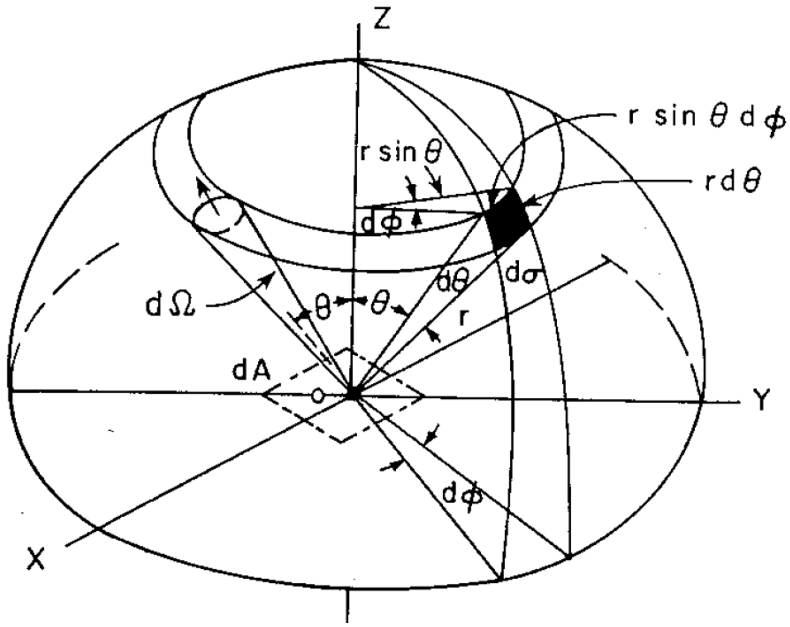
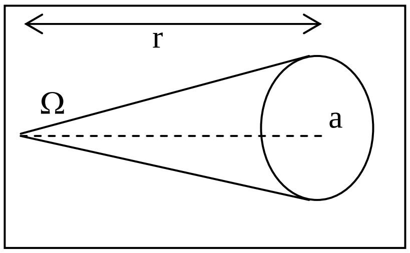


Figure 1.3 Illustration of differential solid angle in spherical coordinates (see L02, fig.1.3)

Solid angle is the angle subtended at the center of a sphere by an area on its surface numerically equal to the square of the radius

$$\Omega = \frac{a}{r^2}$$

UNITS: of a solid angle = steradian (sr)



A differential solid angle can be expressed as

$$d\Omega = \frac{da}{r^2} = \sin(\theta)d\theta d\phi \,,$$

using that a differential area is

$d\alpha = (r\ d\theta)\ (r \sin(\theta)\ d\phi)$

EXAMPLE: Solid angle of a unit sphere = 4π

EXAMPLE: What is the solid angle of the Sun from the Earth if the distance from the Sun to the Earth is d=1.5x10^8 km and Sun's radius is R_s = 6.96x10^5 km:

$$\Omega = \frac{\pi R_s^2}{d^2} = 6.76\,x10^{-5}\,sr$$

Properties of intensity:

- ✓ In general, the intensity is a function of the coordinates ($\vec{r}$), direction ($\vec{\Omega}$), wavelength (or frequency), and time. Thus, it depends on seven independent variables: three in space, two in angle, one in wavelength (or frequency) and one in time.
- ✓ Intensity, as a function of position and direction, gives a complete description of the electromagnetic field.
- ✓ If intensity does not depend on the direction, the electromagnetic field is said to be **isotropic.** If intensity does not depend on position the field is said to be **homogeneous**.

Flux (or irradiance) is defined as radiant energy in a given direction per unit time per unit wavelength (or frequency) range per unit area perpendicular to the given direction:

$$dF_\lambda = \frac{dE_\lambda}{dtdAd\lambda} \qquad [1.4]$$

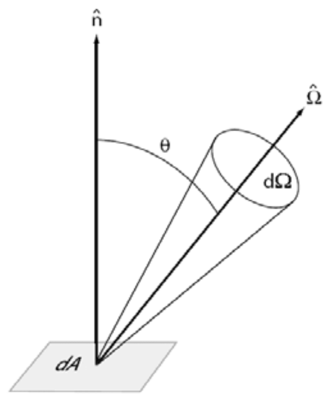
UNITS: from Eq.[1.4]: (J sec^{-1} m^{-2} μm^{-1}) = (W m^{-2} μm^{-1})

From Eqs. [1.3]-[1.4]:

$$F_\lambda = \int_\Omega I_\lambda \cos(\theta) d\Omega \qquad [1.5]$$

Monochromatic **flux** is the integration of normal component of monochromatic **intensity** over a certain solid angle.

Monochromatic **upwelling (upward or outgoing) hemispherical flux** on a horizontal plane is the integration of normal component of monochromatic **intensity** over the all solid angles in the upper hemisphere



$$F_\lambda^\uparrow = \int_{2\pi} I_\lambda^\uparrow(\vec{\Omega}) \vec{n}\vec{\Omega} d\Omega \qquad [1.6]$$

where $\cos(\theta) = \vec{n}\vec{\Omega}$

Eq. [1.6] in spherical coordinates gives

$$F_\lambda^\uparrow = \int_0^{2\pi}\int_0^{\pi/2} I_\lambda^\uparrow(\theta,\varphi)\cos(\theta)\sin(\theta)d\theta d\varphi = \int_0^{2\pi}\int_0^{1} I_\lambda^\uparrow(\mu,\varphi)\mu d\mu d\varphi \qquad [1.7]$$

where ***μ = cos(θ).***

Downwelling (downward) hemispherical flux (i.e., integration over the lower hemisphere)

$$F_\lambda^\downarrow = -\int_0^{2\pi}\int_{\pi/2}^{\pi} I_\lambda^\downarrow(\theta,\varphi)\cos(\theta)\sin(\theta)d\theta d\varphi = -\int_0^{2\pi}\int_0^{-1} I_\lambda^\downarrow(\mu,\varphi)\mu d\mu d\varphi =$$

$$= \int_0^{2\pi}\int_0^{1} I_\lambda^\downarrow(-\mu,\varphi)\mu d\mu d\varphi \qquad [1.8]$$

Monochromatic **<u>net flux</u>** at a horizontal plane is the integration of normal component of monochromatic **intensity** over the all solid angles (over 4π):

$$F_{net,\lambda} = \int_{4\pi} I_\lambda(\vec{\Omega})\vec{n}\vec{\Omega}d\Omega \qquad [1.9]$$

Thus the **net flux** can be expressed as a difference between **upwelling and downwelling hemispherical fluxes**:

$$F_{net,\lambda} = F_\lambda^{\uparrow} - F_\lambda^{\downarrow} = \int_0^{2\pi}\int_{-1}^{1} I_\lambda(\mu,\varphi)\mu d\mu d\varphi \qquad [1.10]$$

NOTE: The net flux is often expressed as

$$F_{net,\lambda} = F_\lambda^{\downarrow} - F_\lambda^{\uparrow}$$

that is determined by a source of EM energy and its direction of propagation.

<u>Actinic flux</u> is the total spectral energy at a point (used in photochemistry):

$$F_{act,\lambda} = \int_{4\pi} I_\lambda(\vec{\Omega})\vec{n}d\Omega \qquad [1.11]$$

<u>Spectral integration:</u>

Radiative quantities may be spectrally integrated (e.g., in energy balance calculations)
For example, the *downwelling shortwave (SW) flux* is

$$F^{\downarrow} = \int_{0.1\mu m}^{4.0\mu m} F_\lambda^{\downarrow} d\lambda \qquad [1.12]$$

and the *upwelling SW flux* is

$$F^{\uparrow} = \int_{0.1\mu m}^{4.0\mu m} F_\lambda^{\uparrow} d\lambda \qquad [1.13]$$

Similarly, the *downwelling and upwelling longwave (LW) fluxes are*

$$F^{\downarrow} = \int_{4\mu m}^{100\mu m} F_\lambda^{\downarrow} d\lambda \qquad [1.14]$$

$$F^{\uparrow} = \int_{4\mu m}^{100\mu m} F_{\lambda}^{\uparrow} d\lambda \qquad [1.15]$$

Photosynthetically Active Radiation (**PAR**) designates the spectral range of solar light from 0.4 to 0.7 μm that photosynthetic organisms are able to use in the process of photosynthesis:

$$F_{PAR}^{\downarrow} = \int_{0.4\mu m}^{0.7\mu m} F_{\lambda}^{\downarrow} d\lambda \qquad [1.16]$$

- ✓ Intensities and fluxes may be *per wavelength* or *per wavenumber*. Since intensity across a spectral interval must be the same, we have $I_{\lambda} d\lambda = I_{\nu} d\nu$ and thus

$$I_{\nu} = I_{\lambda} \left| \frac{d\lambda}{d\nu} \right| = I_{\lambda} \frac{1}{\nu^2} = I_{\lambda} \lambda^2 \qquad [1.17]$$

EXAMPLE: Convert between radiance in *per wavelength* to radiance *per wavenumber* units at λ = 10 μm. Given $\boldsymbol{I_{\lambda}}$ = 9.9 W m^{-2} $sr^{-1}\mu m^{-1}$. What is $\boldsymbol{I_{\nu}}$?

$\boldsymbol{I_{\nu}}$ = (9.9 W m^{-2} $sr^{-1}\mu m^{-1}$) (10 μm) (10^{-3} cm) = 0.099 W m^{-2} $sr^{-1}(cm^{-1})^{-1}$