

## Lecture 1.

### The nature of electromagnetic radiation.

1. Basic introduction to the electromagnetic field:

- Dual nature of electromagnetic radiation
- Electromagnetic spectrum

2. Basic radiometric quantities: intensity and flux.

### Recommended reading:

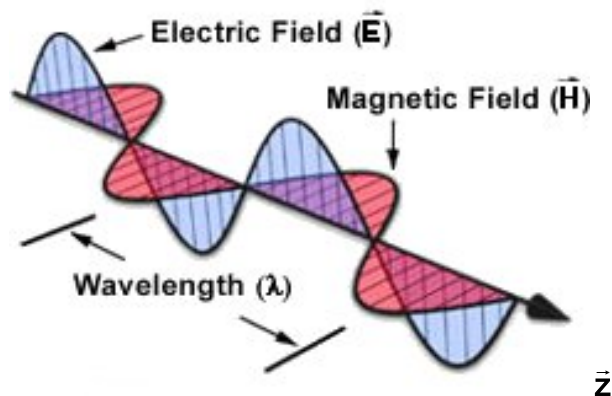
Petty: chapters 2-3

### Basic introduction to electromagnetic field.

**Electromagnetic (EM) radiation** is a form of energy propagated through free space or through a material medium in the form of electromagnetic waves.

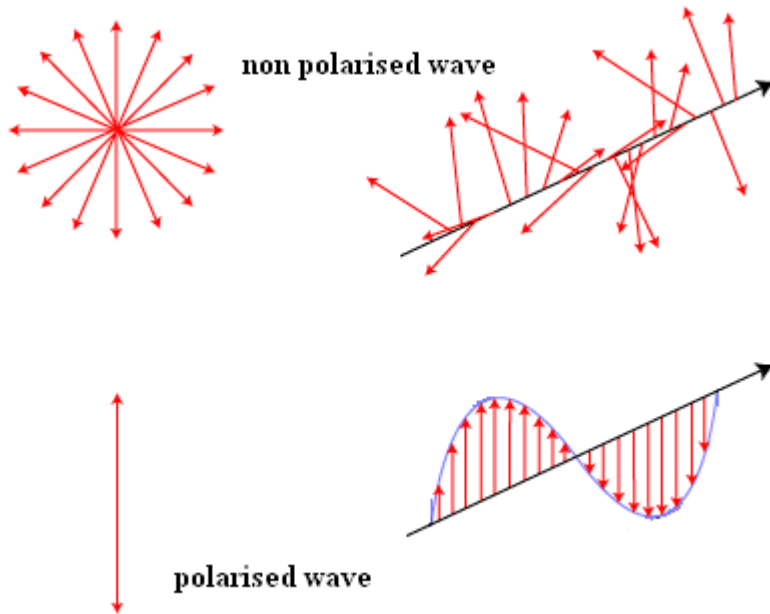
**EM radiation** is so-named because it has electric and magnetic fields that simultaneously oscillate in planes mutually perpendicular to each other and to the direction of propagation through space.

- ✓ Electromagnetic radiation has the **dual nature**:  
its exhibits **wave properties** and **particulate (photon) properties**.
- **Wave nature of radiation:** Radiation can be thought of as a **traveling transverse wave**.



**Figure 1.1** A schematic view of an electromagnetic wave propagating along the  $\vec{z}$  axis. The electric  $\vec{E}$  and magnetic  $\vec{H}$  fields oscillate in the x-y plane and perpendicular to the direction of propagation.

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



**Figure 1.2** Electric field  $\vec{E}$  orientation for polarized and non polarized electromagnetic waves.

**Poynting vector** gives the flow of radiant energy and the direction of propagation as (in the cgs system of units)

$$\vec{S} = c^2 \epsilon_0 \vec{E} \times \vec{H} \quad [1.1]$$

here  $c$  is the speed of light in vacuum ( $c = 2.9979 \times 10^8 \text{ m/s} \cong 3.00 \times 10^8 \text{ m/s}$ ) and  $\epsilon_0$  is vacuum permittivity (or dielectric constant).  $\vec{S}$  is in units of energy per unit time per unit area (e.g.,  $\text{W m}^{-2}$ )

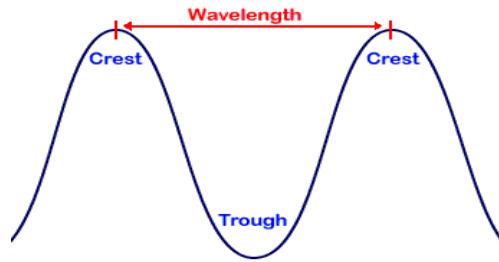
**NOTE:**  $\vec{E} \times \vec{H}$  means a **vector product** of two vectors.

- $\vec{S}$  is often called **instantaneous Poynting vector**. Because it oscillates at rapid rates, a detector measures its average value  $\langle S \rangle$  over some time interval that is a characteristic of the detector.

- **Waves** are characterized by **frequency, wavelength, speed** and **phase**.

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

**Wavelength** is the distance between two consecutive peaks or troughs in a wave (symbolized by the  $\lambda$ ).



**Relation between  $\lambda$  and  $\tilde{\nu}$  :**  $\lambda \tilde{\nu} = c$  [1.2]

- Since all types of **electromagnetic radiation** travel at the speed of light, short-wavelength radiation must have a high frequency.
- Unlike speed of light and wavelength, which change as electromagnetic energy is propagated through media of different densities, frequency remains constant and is therefore a more fundamental property.

**Wavenumber** is defined as a count of the number of wave crests (or troughs) in a given unit of length (symbolized by  $\nu$ ):

$$\nu = \tilde{\nu} / c = 1/\lambda \quad [1.3]$$

**UNITS:**

**Wavelength units:** length  
 Angstrom (A) :  $1 \text{ A} = 1 \times 10^{-10} \text{ m}$ ;  
 Nanometer (nm):  $1 \text{ nm} = 1 \times 10^{-9} \text{ m}$ ;  
 Micrometer ( $\mu\text{m}$ ):  $1 \mu\text{m} = 1 \times 10^{-6} \text{ m}$ ;

**Wavenumber units:** inverse length (often in  $\text{cm}^{-1}$ )

**NOTE:** Conversion from the wavelength to wavenumber:

$$\nu[\text{cm}^{-1}] = \frac{10,000 \text{ cm}^{-1} \mu\text{m}}{\lambda[\mu\text{m}]} \quad [1.4]$$

**Frequency units:** unit cycles per second 1/s (or s<sup>-1</sup>) is called hertz (abbreviated Hz)

Table 1.1 Frequency units

Unit	Frequency, (cycles/sec)
Hertz, Hz	1
Kilohertz, KHz	10 <sup>3</sup>
Megahertz, MHz	10 <sup>6</sup>
Gigahertz, GHz	10 <sup>9</sup>

➤ **Particulate nature of radiation:**

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

The energy of a **photon** is given as:

$$\mathcal{E}_{\text{photon}} = h \tilde{\nu} = h c/\lambda = h c \nu \quad [1.5]$$

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

- Eq. [1.5] relates energy of each photon of the radiation to the electromagnetic wave characteristics ( $\tilde{\nu}$  and  $\lambda$ ).
- Photon has energy but it has no mass and no charge.

**NOTE:** The quantized nature of light is most important when considering absorption and emission of electromagnetic radiation.

**PROBLEM:** A light bulb of 100 W emits at 0.5  $\mu\text{m}$ . How many photons are emitted per second?

**Solution:**

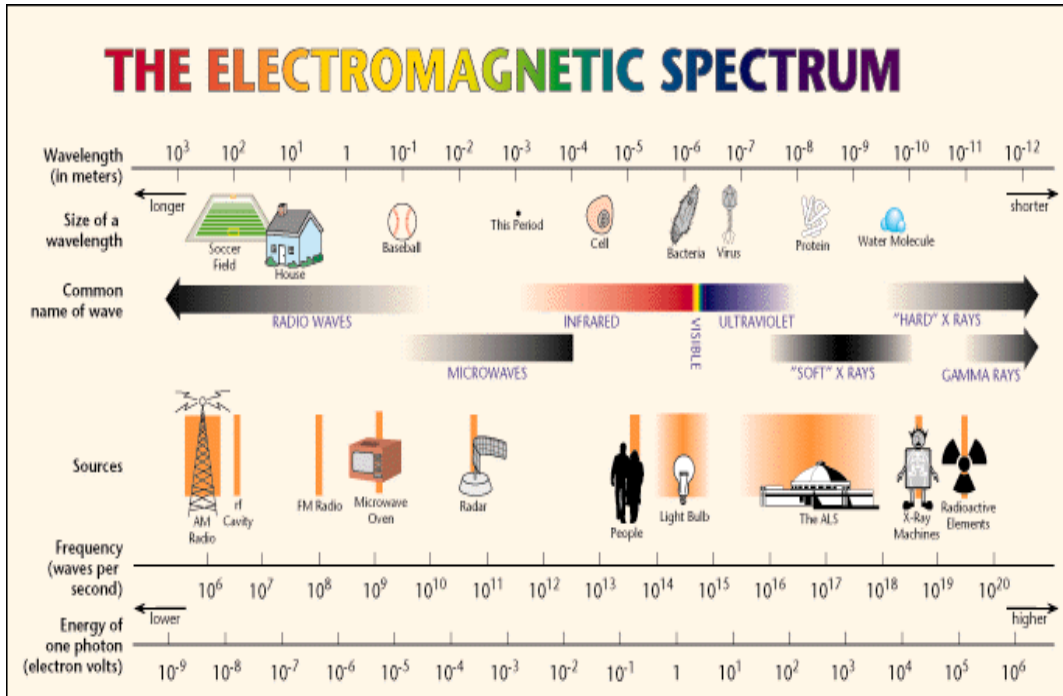
Energy of one photon is  $\mathcal{E}_{\text{photon}} = hc/\lambda$ , thus, using that 100 W = 100 J/s, the number of photons per second, N, is

$$N(s^{-1}) = \frac{100(Js^{-1}) \lambda(m)}{h(Js) c(ms^{-1})} = \frac{100 \times 0.5 \times 10^{-6}}{6.6256 \times 10^{-34} \times 2.9979 \times 10^8} = 2.517 \times 10^{20}$$

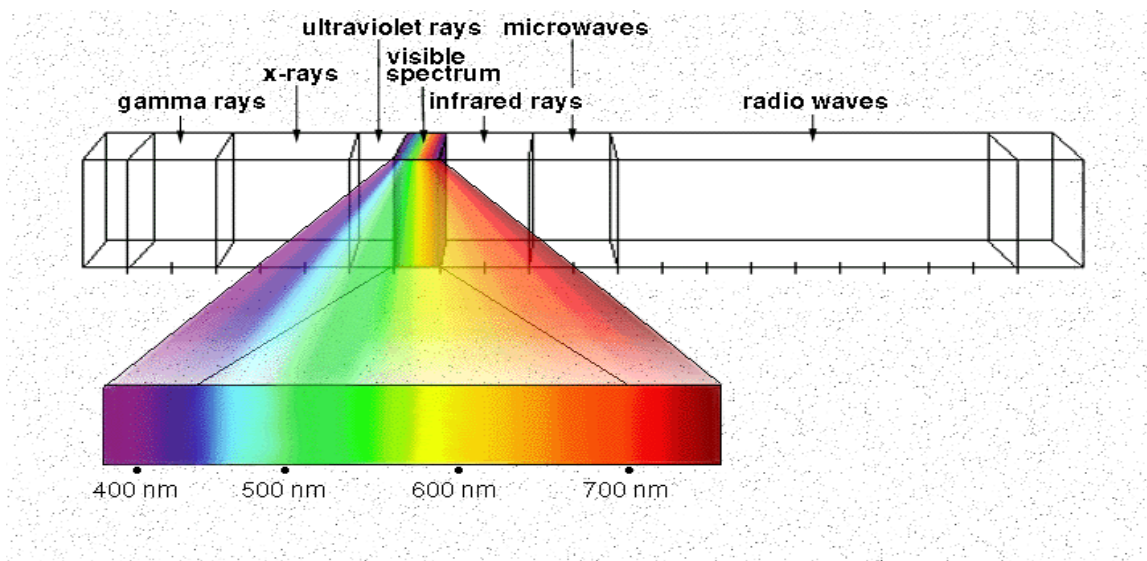
**NOTE:** Large number of photons is required because Plank's constant **h** is very small!!!

➤ **Spectrum of electromagnetic radiation:**

The electromagnetic **spectrum** is the distribution of electromagnetic radiation according to energy or, equivalently, according to the wavelength or frequency.



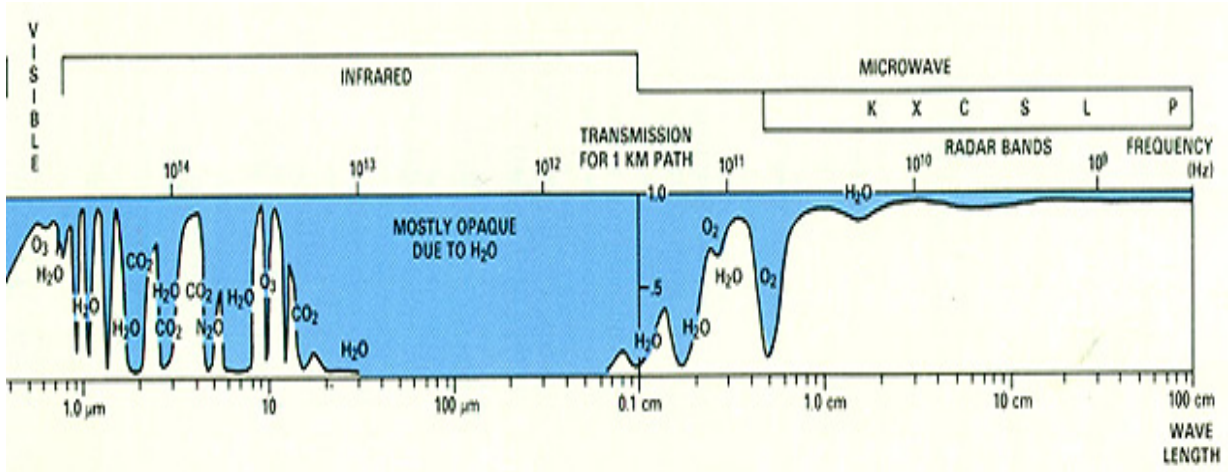
**Figure 1.3** Schematic representation of the electromagnetic spectrum.



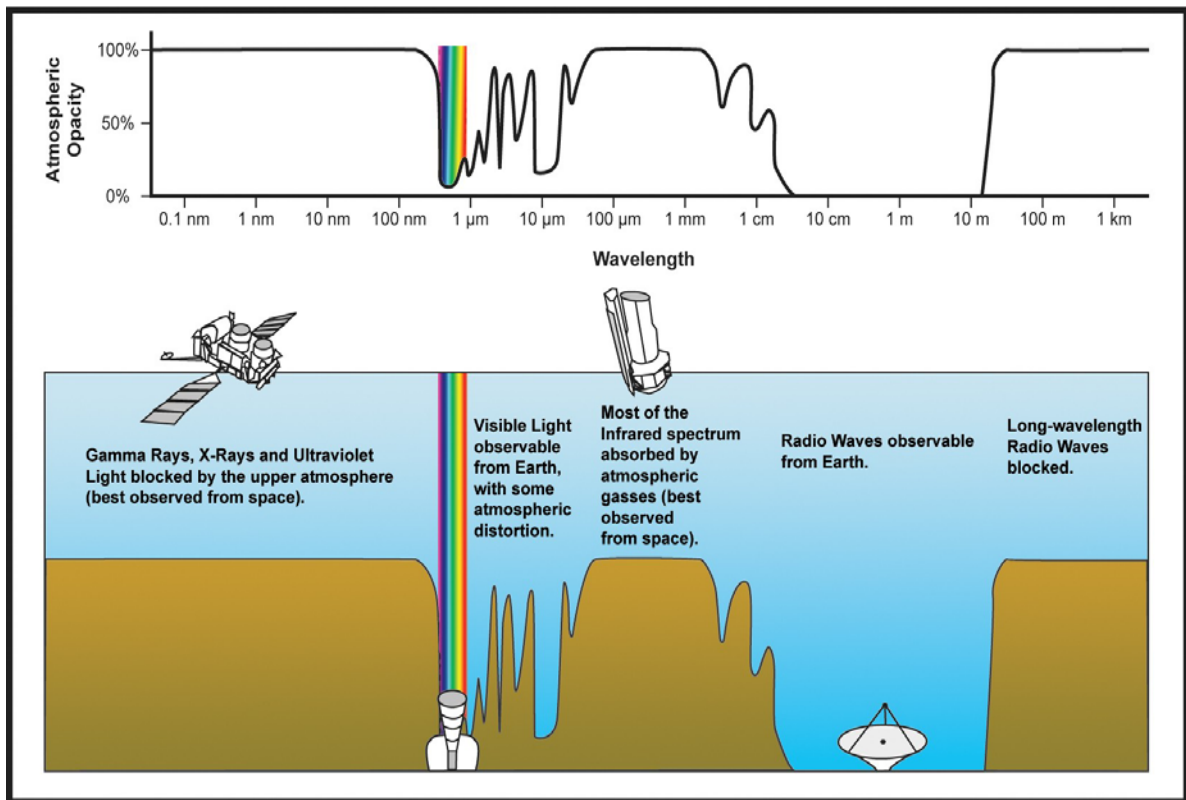
**Figure 1.4** Visible region of the electromagnetic spectrum.

**NOTE:** In remote sensing, sensor's spectral bands in the visible are often called by their color (e.g., blue, green, and red channels)

**Effects of atmospheric gases:**



**Figure 1.5** A generalized diagram showing relative atmospheric radiation **transmission** at different wavelengths. Blue zones show low passage of incoming and/or outgoing radiation and white areas show atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't absorbed.



**Figure 1.6** Schematics showing the role of Earth's atmospheric composition in remote sensing.

Table 1.2 Common names and relationships between radiation components.

Name of spectral region	Wavelength region, $\mu\text{m}$	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 (up to 1000)	Terrestrial = Longwave = Far infrared
Microwave	$10^3 - 10^6$	Microwave
Radio	$> 10^6$	Radio

Table 1.3 Microwave frequency bands used in remote sensing

Bands		Frequency [GHz]
“Old”	“New”	
L	D	1-2
S	E, F	2-4
C	G, H	4-8
X	I, J	8-12
Ku	J	12-18
K	J	18-26
Ka	K	26-40

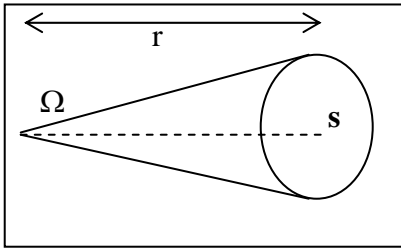
**Example:** L-band is used onboard American SEASAT and Japanese JERS-1 satellites.

**2. Basic radiometric quantities: intensity and flux.**

**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

$$\Omega = \frac{s}{r^2} \quad [1.6]$$

**UNITS:** of a solid angle = steradian (sr)



A differential solid angle can be expressed as

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

using that a differential area is

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

**Example:** Solid angle of a unit sphere =  $4\pi$

**PROBLEM:** What is the solid angle of the Sun from the Earth if the distance from the Sun to the Earth is  $d=1.5 \times 10^8$  km? Sun's radius is  $R_s = 6.96 \times 10^5$  km.

**SOLUTION:**  $\Omega = \frac{\pi R_s^2}{d^2} = 6.76 \times 10^{-5} \text{ sr}$

**Intensity (or radiance)** is defined as radiative 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:

$$I_\lambda = \frac{d\varepsilon_\lambda}{ds \cos(\theta) d\Omega dt d\lambda} \quad [1.7]$$

$I_\lambda$  is referred to as the **monochromatic** intensity.

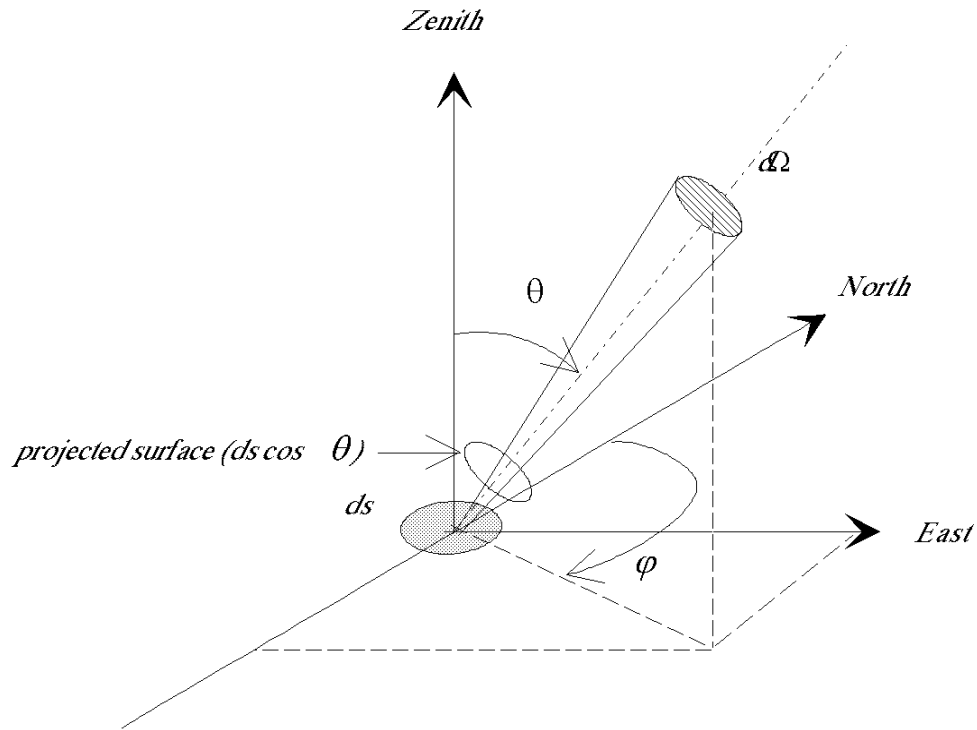
- Monochromatic does not mean at a single wavelengths  $\lambda$ , but in a very narrow (infinitesimal) range of wavelength  $\Delta\lambda$  centered at  $\lambda$ .

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

**UNITS:** from Eq.[1.7]:

$$(\text{J sec}^{-1} \text{ sr}^{-1} \text{ m}^{-2} \mu\text{m}^{-1}) = (\text{W sr}^{-1} \text{ m}^{-2} \mu\text{m}^{-1})$$





**Figure 1.7** Intensity is the flow of radiative energy carried by a beam within the solid angle  $d\Omega$  .

**Properties of intensity:**

- a) In general, 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.
  - b) In a transparent medium, the intensity is constant along a ray.
- 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 radiative energy in a given direction per unit time per unit wavelength (or frequency) range per unit area perpendicular to the given direction:

$$F_{\lambda} = \frac{d\epsilon_{\lambda}}{dt ds d\lambda} \quad [1.8]$$

**UNITS:** from Eq.[1.8]:

$$(\text{J sec}^{-1} \text{ m}^{-2} \mu\text{m}^{-1}) = (\text{W m}^{-2} \mu\text{m}^{-1})$$

From Eqs. [1.7]-[1.8], the flux is integral of normal component of radiance over some solid angle

$$F_{\lambda} = \int_{\Omega} I_{\lambda} \cos(\theta) d\Omega \quad [1.9]$$

**NOTE:** Many satellite sensors have a narrow viewing angle and hence measure the intensity (not flux). To measure the flux, a sensor needs to have a wide viewing angle.

- Depending on its **spectral resolution**, a detector measures electromagnetic radiation in a particular wavelength range,  $\Delta\lambda$ . The intensity  $I_{\Delta\lambda}$  and flux  $F_{\Delta\lambda}$  in this range are determined by integrating over the wavelength the monochromatic intensity and flux, respectively:

$$I_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} I_{\lambda} d\lambda \quad F_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} F_{\lambda} d\lambda \quad [1.10]$$

**NOTE:** Lecture 2 gives classification of the sensors with respect to their spectral resolution: broad-band, narrow-band, spectral and hyperspectral.

**Examples:**

Broad-band sensor: CERES (Clouds and the Earth's Radiant Energy System)

Three bands (channels): Solar region: 0.3 - 5.0  $\mu\text{m}$ ; IR window: 8 - 12  $\mu\text{m}$ ; and total: 0.3 to > 100  $\mu\text{m}$

Narrow-band sensor: MODIS (Moderate Resolution Imaging Spectroradiometer)

Table 1.4 MODIS spectral bands

Primary Use	Band	Bandwidth <sup>1</sup>	Spectral Radiance <sup>2</sup>	Required SNR <sup>3</sup>
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color Phytoplankton Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250
Surface/Cloud Temperature	20	3.660 - 3.840	0.45 (300K)	0.05
	21	3.929 - 3.989	2.38 (335K)	2.00
	22	3.929 - 3.989	0.67 (300K)	0.07
	23	4.020 - 4.080	0.79 (300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17 (250K)	0.25
	25	4.482 - 4.549	0.59 (275K)	0.25

<b>Cirrus Clouds Water Vapor</b>	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16 (240K)	0.25
	28	7.175 - 7.475	2.18 (250K)	0.25
<b>Cloud Properties</b>	29	8.400 - 8.700	9.58 (300K)	0.05
<b>Ozone</b>	30	9.580 - 9.880	3.69 (250K)	0.25
<b>Surface/Cloud Temperature</b>	31	10.780 - 11.280	9.55 (300K)	0.05
	32	11.770 - 12.270	8.94 (300K)	0.05
<b>Cloud Top Altitude</b>	33	13.185 - 13.485	4.52 (260K)	0.25
	34	13.485 - 13.785	3.76 (250K)	0.25
	35	13.785 - 14.085	3.11 (240K)	0.25
	36	14.085 - 14.385	2.08 (220K)	0.35

\* Footnotes:

<sup>1</sup> Bands 1 to 19 are in nm; Bands 20 to 36 are in  $\mu\text{m}$

<sup>2</sup> Spectral Radiance values are ( $\text{W}/\text{m}^2 \cdot \mu\text{m}\cdot\text{sr}$ )

<sup>3</sup> SNR = Signal-to-noise ratio

<sup>4</sup>  $NE(\Delta T)$  = Noise-equivalent temperature difference