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.**

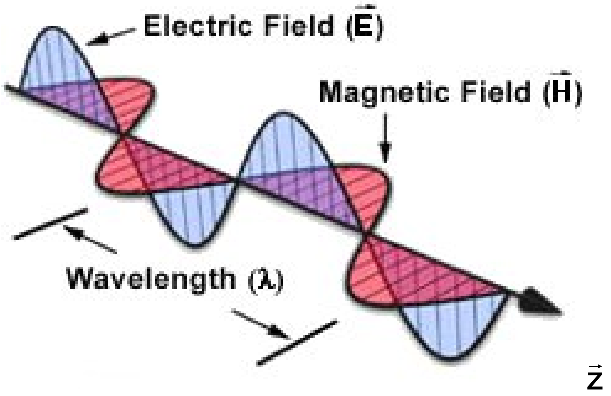


Figure 1.1 A schematic view of an electromagnetic wave propagating along the $\vec{z}$ axis. The electric $\vec{E}$ and magnetic $\vec{H}$ fields oscillate in the x-y plane and perpendicular to the direction of propagation.

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

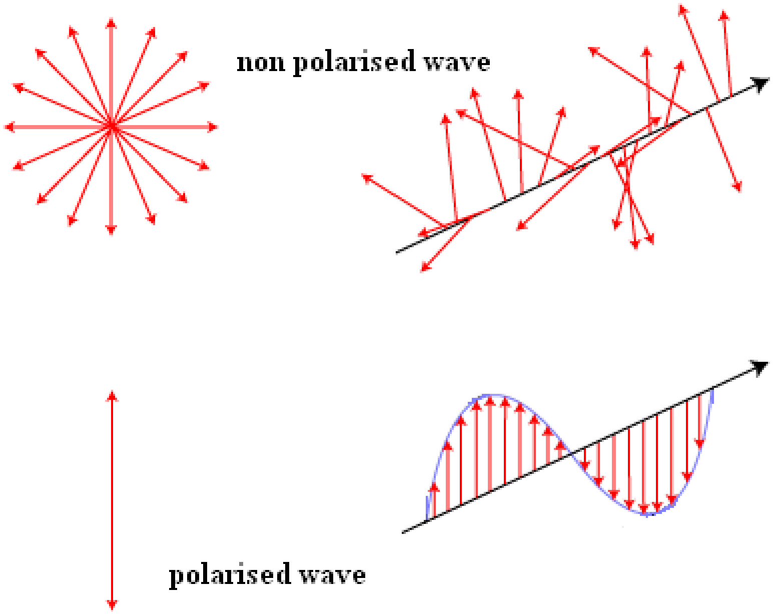


Figure 1.2 Electric field $\vec{E}$ orientation for polarized and non polarized electromagnetic waves.

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

$$\vec{S} = c^2 \varepsilon_0 \vec{E} \times \vec{H} \qquad [1.1]$$

here c is the speed of light in vacuum (c = 2.9979x10^8 m/s ≅ 3.00x10^8 m/s) and ε_0 is vacuum permittivity (or dielectric constant). $\vec{S}$ is in units of energy per unit time per unit area (e.g., W m^{-2})

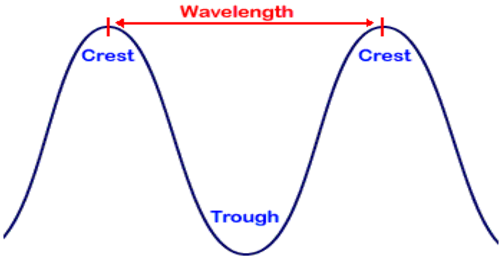
NOTE: $\vec{E} \times \vec{H}$ means a **vector product** of two vectors.

- $\vec{S}$ is often called **instantaneous Poynting vector**. Because it oscillates at rapid rates, a detector measures its average value <*S*> over some tome 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 λ).



Relation between λ and $\tilde{\nu}$: $\boxed{\lambda\ \tilde{\nu} = c}$ [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 ν):

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

UNITS:

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;

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

NOTE: Conversion from the wavelength to wavenumber:

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

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

Table 1.1 Frequency units

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

- **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:

$$\boxed{\mathcal{E}_{\text{photon}} = h\,\tilde{\nu} = h\,c/\lambda = hc\nu} \qquad [1.5]$$

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

- Eq. [1.5] relates energy of each photon of the radiation to the electromagnetic wave characteristics ($\tilde{\nu}$ and λ).
- 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 μm. 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.

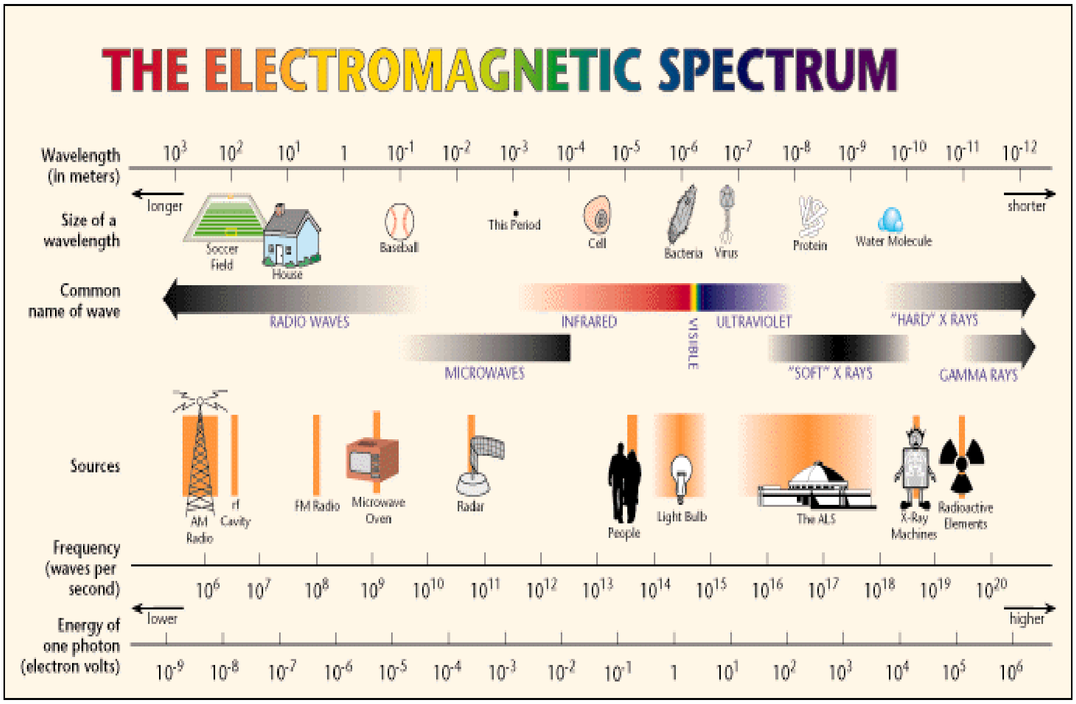


Figure 1.3 Schematic representation of the electromagnetic spectrum.

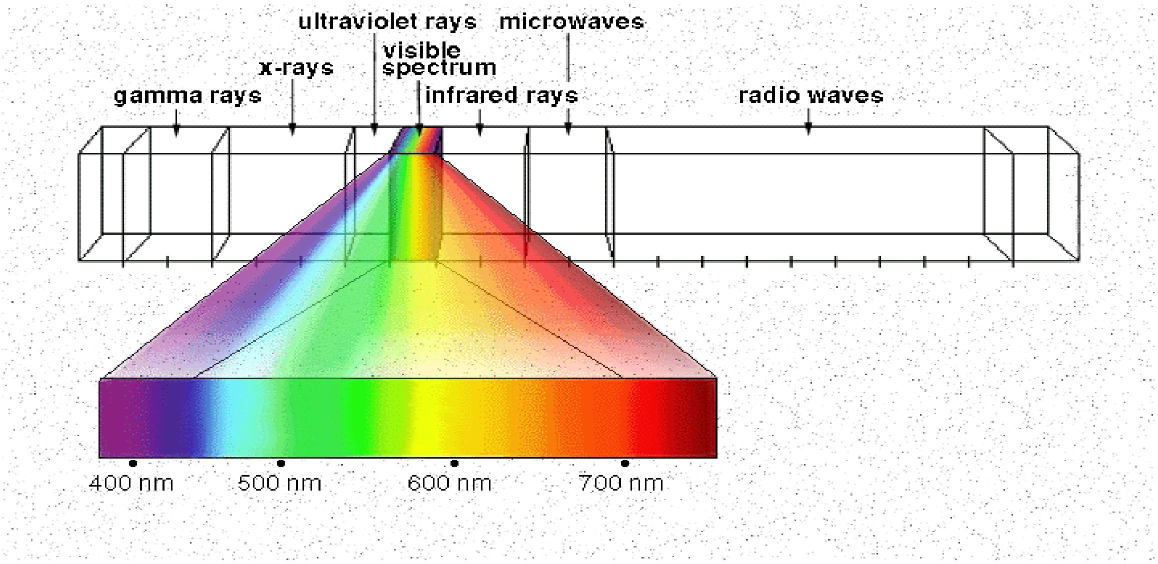


Figure 1.4 Visible region of the electromagnetic spectrum.

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

Effects of atmospheric gases:

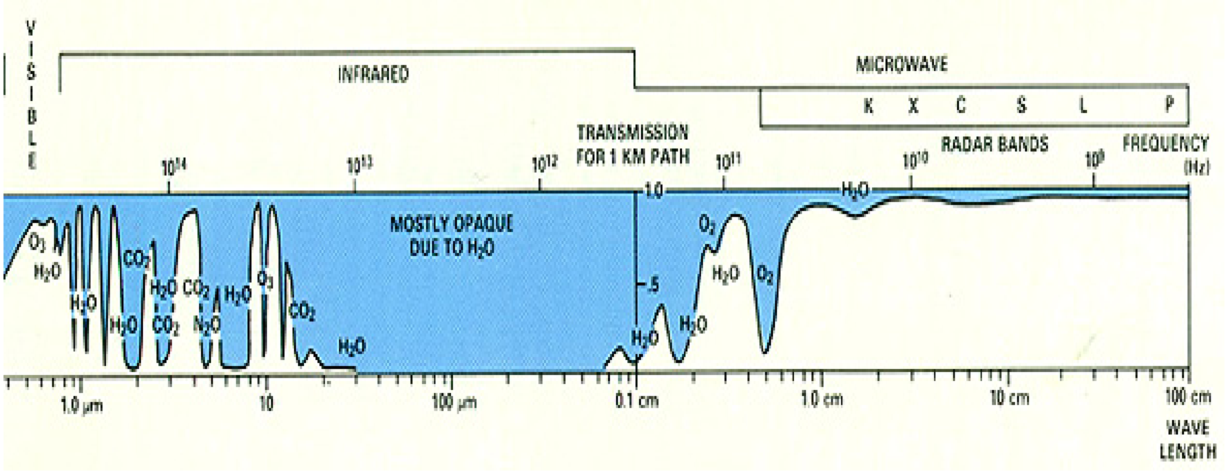
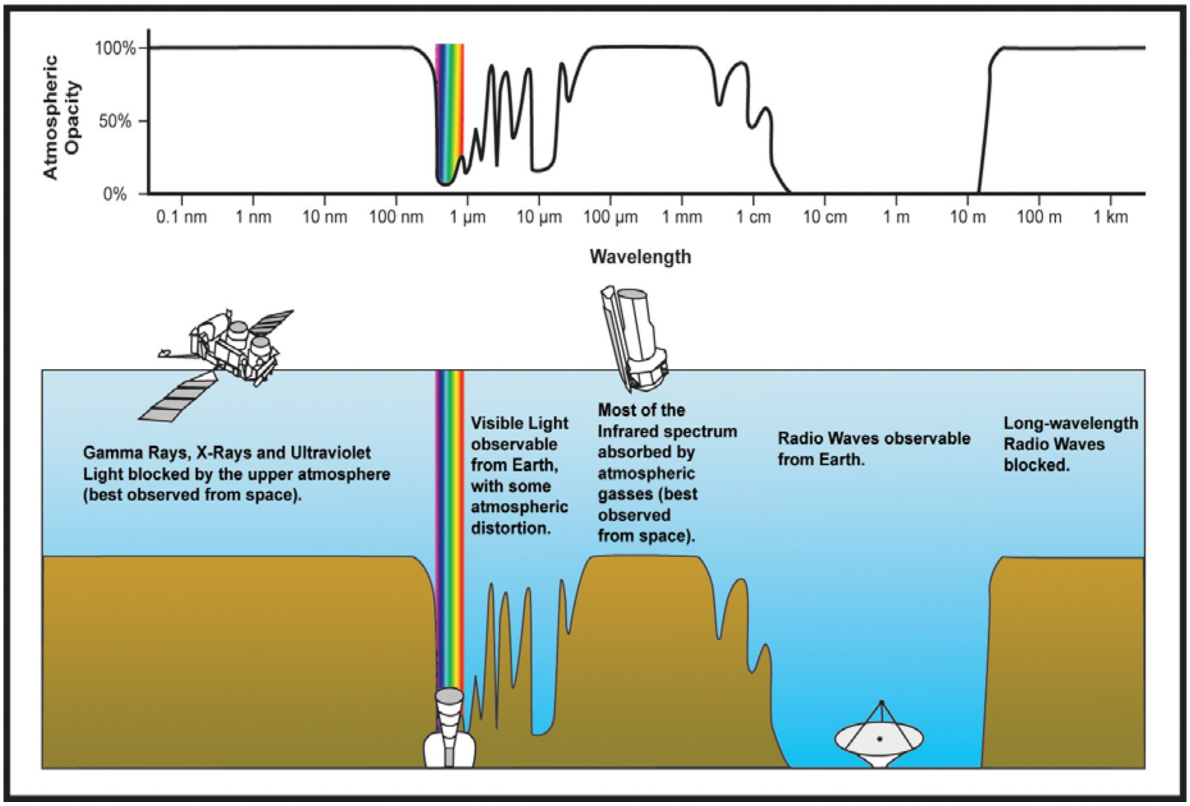


Figure 1.5 A generalized diagram showing relative atmospheric radiation **transmission** at different wavelengths. Blue zones show low passage of incoming and/or outgoing radiation and white areas show atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't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



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

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, 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 (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

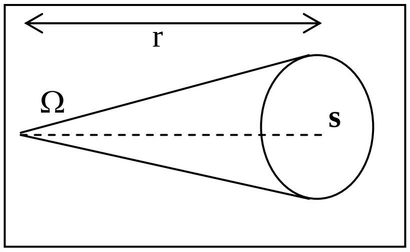
Example: L-band is used onboard American SEASAT and Japanese JERS-1 satellites.

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

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

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 = 4π

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

SOLUTION: $\Omega = \frac{\pi R_s^2}{d^2} = 6.76\, x 10^{-5}\, sr$

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:

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

I_λ is referred to as the **monochromatic** intensity.

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

NOTE: _same name_: intensity = specific intensity = radiance

UNITS: from Eq.[1.7]:

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

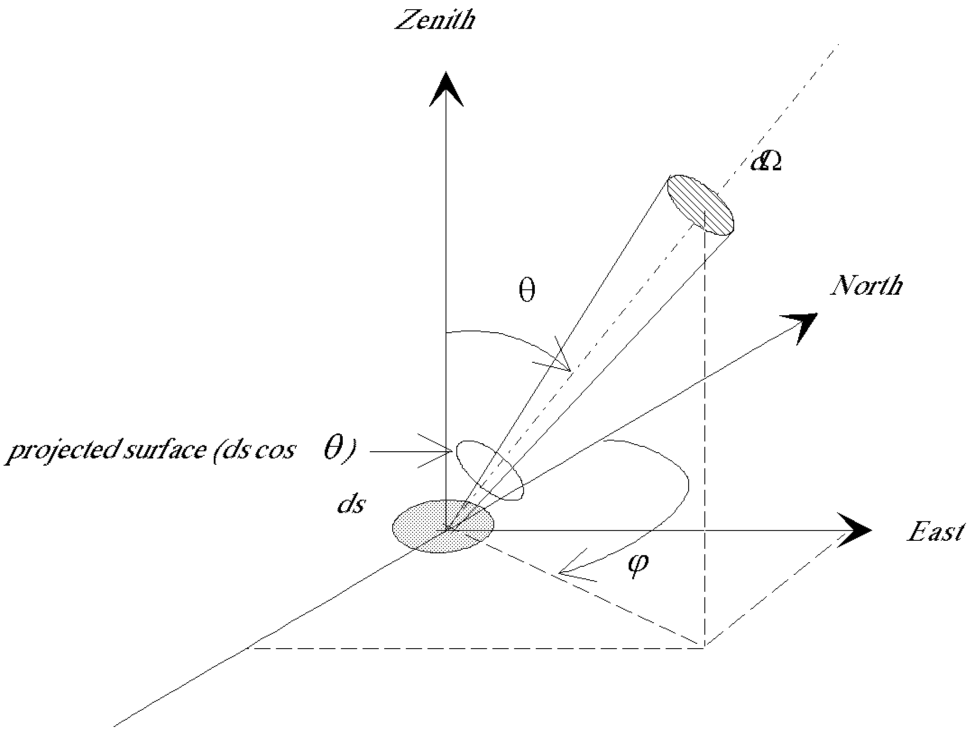


Figure 1.7 Intensity is the flow of radiative energy carried by a beam within the solid angle $d\Omega$.

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:

$$F_\lambda = \frac{d\varepsilon_\lambda}{dt\,ds\,d\lambda} \qquad [1.8]$$

UNITS: from Eq.[1.8]:

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

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

$$F_\lambda = \int_\Omega I_\lambda \cos(\theta)\, d\Omega \qquad [1.9]$$

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 $\boldsymbol{I_{\Delta\lambda}}$ and flux $\boldsymbol{F_{\Delta\lambda}}$ in this range are determined by integrating over the wavelength the monochromatic intensity and flux, respectively:

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

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 µm; IR window: 8 - 12 µm; and total: 0.3 to > 100 µm

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

Table 1.4 MODIS spectral bands

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
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

Cirrus Clouds Water Vapor	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
Cloud Properties	29	8.400 - 8.700	9.58 (300K)	0.05
Ozone	30	9.580 - 9.880	3.69 (250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55 (300K)	0.05
	32	11.770 - 12.270	8.94 (300K)	0.05
Cloud Top Altitude	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:*

[1] *Bands 1 to 19 are in nm; Bands 20 to 36 are in µm*

[2] *Spectral Radiance values are (W/m^{2} -µm-sr)*

[3] *SNR = Signal-to-noise ratio*

[4] *NE(delta)T = Noise-equivalent temperature difference*