Lecture 3

The nature of electromagnetic radiation.

Objectives:
1. Basic introduction to the electromagnetic field:
   - Definitions
   - Dual nature of electromagnetic radiation
   - Electromagnetic spectrum
2. Main radiometric quantities: energy, flux, and intensity.
3. Concepts of extinction (scattering + absorption) and emission.

Required reading:
G: 2.1, 2.2.1, 2.2.2, 2.3, 2.4, 4.1, Appendix 1.

Additional/advanced reading:
Online tutorial: Chapter 1, Sections 1.2 – 1.3
http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter1/chapter1_1_e.html

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 has the dual nature:
  - it exhibits wave properties and particulate properties.
Wave nature of radiation:

Radiation can be thought of as a traveling transverse wave.

Figure 3.1 A schematic view of an electromagnetic wave propagating along the $\mathbf{z}$ axis. The electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields oscillate in the x-y plane and perpendicular to the direction of propagation.

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

$$\mathbf{S} = c^2 \varepsilon_0 \mathbf{E} \times \mathbf{H}$$  \hspace{1cm} [3.1]

here $c$ is the speed of light in vacuum ($c = 2.9979 \times 10^8$ m/s $\equiv$ 3.00x10$^8$ m/s) and $\varepsilon_0$ is vacuum permittivity (or dielectric constant). $\mathbf{S}$ is in units of energy per unit time per unit area (e.g., W m$^{-2}$).

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

- $\mathbf{S}$ is often called instantaneous Poynting vector. Because it oscillates at rapid rates, a detector measures its average value $\langle \mathbf{S} \rangle$ 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 $\tilde{v}$).

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

![Image of Wavelength Diagram]

**Relation between $\lambda$ and $\tilde{v}$:**

$$\lambda \tilde{v} = c$$  \[3.2\]

- 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 $v$):

$$v = \tilde{v} / c = 1/\lambda$$  \[3.3\]

**UNITS:**

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

- **Wavenumber units:** inverse length (often in cm⁻¹)

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

$$\nu[\text{cm}^{-1}] = \frac{10,000 \text{ cm}^{-1} \mu \text{m}}{\lambda[\mu \text{m}]}$$  \[3.4\]
**Frequency units:** unit cycles per second 1/s (or s⁻¹) is called hertz (abbreviated Hz)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Frequency, (cycles/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hertz, Hz</td>
<td>1</td>
</tr>
<tr>
<td>Kilohertz, KHz</td>
<td>10³</td>
</tr>
<tr>
<td>Megahertz, MHz</td>
<td>10⁶</td>
</tr>
<tr>
<td>Gigahertz, GHz</td>
<td>10⁹</td>
</tr>
</tbody>
</table>

**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:

\[ E_{\text{photon}} = h \nu = h \frac{c}{\lambda} = h c \nu \]  

[3.5]

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

- Eq. [3.5] relates energy of each photon of the radiation to the electromagnetic wave characteristics (\( \nu \) 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 µm. How many photons are emitted per second?

**Solution:**

Energy of one photon is \( E_{\text{photon}} = h \nu = h \frac{c}{\lambda} \), 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.

![Electromagnetic Spectrum](image-url)

**Figure 3.2** The electromagnetic spectrum.

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![Electromagnetic Spectrum](image-url)

**Figure from** [http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html](http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html)
Figure 3.3 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** (will be discussed in Lecture 6-7)

Figure 3.4 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 denote atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't absorbed.
• In this course we study the UV, visible, infrared and microwave radiation.

Table 3.2 Relationships between radiation components.

<table>
<thead>
<tr>
<th>Name of spectral region</th>
<th>Wavelength region, µm</th>
<th>Spectral equivalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>0.1 - 4</td>
<td>Ultraviolet + Visible + Near infrared = Shortwave</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>4 - 100</td>
<td>Far infrared = Longwave</td>
</tr>
<tr>
<td>Infrared</td>
<td>0.75 - 100</td>
<td>Near infrared + Far infrared</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>0.1 - 0.38</td>
<td>Near ultraviolet + Far ultraviolet = UV-A + UV-B + UV-C + Far ultraviolet</td>
</tr>
<tr>
<td>Shortwave</td>
<td>0.1 - 4</td>
<td>Solar = Near infrared + Visible + Ultraviolet</td>
</tr>
<tr>
<td>Longwave</td>
<td>4 - 100</td>
<td>Terrestrial = Far infrared</td>
</tr>
<tr>
<td>Visible</td>
<td>0.38 - 0.75</td>
<td>Shortwave - Near infrared - Ultraviolet</td>
</tr>
<tr>
<td>Near infrared</td>
<td>0.75 - 4</td>
<td>Solar - Visible - Ultraviolet = Infrared - Far infrared</td>
</tr>
<tr>
<td>Far infrared</td>
<td>4 - 100</td>
<td>Terrestrial = Longwave = Infrared - Near infrared</td>
</tr>
<tr>
<td>Thermal</td>
<td>4 - 100 (up to 1000)</td>
<td>Terrestrial = Longwave = Far infrared</td>
</tr>
<tr>
<td>Microwave</td>
<td>$10^3 - 10^6$</td>
<td>Microwave</td>
</tr>
<tr>
<td>Radio</td>
<td>$&gt; 10^6$</td>
<td>Radio</td>
</tr>
</tbody>
</table>

Table 3.3 Microwave frequency bands used in remote sensing

<table>
<thead>
<tr>
<th>Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Old”</td>
</tr>
<tr>
<td>“New”</td>
</tr>
<tr>
<td>Frequency [GHz]</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>Ku</td>
</tr>
<tr>
<td>K</td>
</tr>
<tr>
<td>Ka</td>
</tr>
</tbody>
</table>

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

\[ \Omega = \frac{s}{r^2} \]  \[\text{[3.6]}\]

**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 = \(4\pi\)

**Example:** What is the solid angle of the Sun from the Earth if the distance from the Sun from the Earth is \(d=1.5\times10^8\) km and Sun’s radius is \(R_s = 6.96\times10^5\) km.

\[ \Omega = \frac{\pi R_s^2}{d^2} = 6.76 \times 10^{-5} \text{sr} \]

**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:

\[ I_\lambda = \frac{dE_\lambda}{ds \cos(\theta)d\Omega d\lambda d\phi} \]  \[\text{[3.7]}\]

\(I_\lambda\) 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.[3.7]:

\((\text{J sec}^{-1} \text{ sr}^{-1} \text{ m}^{-2} \mu\text{m}^{-1}) = (\text{W sr}^{-1} \text{ m}^{-2} \mu\text{m}^{-1})\)
Figure 3.5 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 \(( \mathbf{r} )\), direction \(( \mathbf{\Omega} )\), 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 radiant energy in a given direction per unit time per unit wavelength (or frequency) range per unit area perpendicular to the given direction:

\[
F_\lambda = \frac{dE_\lambda}{dtdsd\lambda}
\]  

[3.8]
UNITS: from Eq.[3.8]:
(J sec\(^{-1}\) m\(^{-2}\) µm\(^{-1}\)) = (W m\(^{-2}\) µm\(^{-1}\))

From Eqs. [3.7]-[3.8], the flux is integral of normal component of radiance over some solid angle

\[ F_\lambda = \int_\Omega I_\lambda \cos(\theta) d\Omega \quad [3.9] \]

- Each detector measures electromagnetic radiation in a particular wavelength range, Δλ. 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:

\[ I_{\Delta \lambda} = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \quad F_{\Delta \lambda} = \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda \quad [3.10] \]

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.

3. The concepts of extinction (scattering + absorption) and emission.
Electromagnetic radiation in the atmosphere interacts with gases, aerosol particles, and cloud particles.

- **Extinction** and **emission** are two main types of the interactions between an electromagnetic radiation field and a medium (e.g., the atmosphere).

*General definition:*

Extinction is a process that decreases the radiant intensity, while emission increases it.

NOTE: “same name”: extinction = attenuation
Radiation is emitted by all bodies that have a temperature above absolute zero (0 K) (often referred to as thermal emission).

- **Extinction** is due to absorption and scattering.

Absorption is a process that removes the radiant energy from an electromagnetic field and transfers it to other forms of energy.

Scattering is a process that does not remove energy from the radiation field, but may redirect it.

**NOTE:** Scattering can be thought of as absorption of radiant energy followed by re-emission back to the electromagnetic field with negligible conversion of energy. Thus, scattering can remove radiant energy of a light beam traveling in one direction, but can be a “source” of radiant energy for the light beams traveling in other directions.

- **Elastic scattering** is the case when the scattered radiation has the same frequency as that of the incident field. Inelastic (Raman) scattering results in scattered light with a frequency different from that of the incident light.

### 4. Polarization. Stokes parameters.

**Polarization** is a phenomenon peculiar to transverse waves.

- Electromagnetic radiation travels as transverse waves, i.e., waves that vibrate in a direction perpendicular to their direction of propagation.

**NOTE:** In contrast to electromagnetic waves, sound is a longitudinal wave that travels through media by alternatively forcing the molecules of the medium closer together, then spreading them apart.
**Polarization** is the distribution of the electric field in the plane normal to the propagation direction.

**Vertically polarized wave** is one for which the electric field lies only in the x-z plane.

**Horizontally polarized wave** is one for which the electric field lies only in the y-z plane.

- Horizontal and vertical polarization are an example of linear polarization.

**Mathematical representation of a plane wave** propagating in the direction \( z \) is

\[
E = E_0 \cos( k z - \omega t + \varphi_0 )
\]

[3.11]

where \( E_0 \) is the **amplitude**;

\( k \) is the propagation (or wave) constant, \( k = \frac{2\pi}{\lambda} \)

\( \omega \) is the circular frequency, \( \omega = kc = \frac{2\pi}{\lambda} \)

\( \varphi_0 \) is the constant (or initial phase)

\( \varphi = (kz - \omega t + \varphi_0) \) is **the phase of the wave**
Introducing complex variables, Eq.[3.11] can be expressed as

\[ E = E_0 \exp( i \varphi ) \]  \hspace{1cm} [3.12]

**NOTE:** In Eq.[3], we use  \( \exp(\pm i \varphi) = \cos(\varphi) \pm i \sin(\varphi) \)

The electric vector \( \vec{E} \) may be decomposed into the parallel \( E_l \) and perpendicular \( E_r \) components as

\[ \vec{E} = E_l \vec{l} + E_r \vec{r} \]

We can express \( E_l \) and \( E_r \) in the form

\[
E_l = E_{l0} \cos( kz - \omega t + \varphi_{l0} ) \\
E_r = E_{r0} \cos( kz - \omega t + \varphi_{r0} )
\]

Then we have

\[
\frac{E_l}{E_{l0}} = \cos(\zeta) \cos(\varphi_{l0}) - \sin(\zeta) \sin(\varphi_{l0}) \\
\frac{E_r}{E_{r0}} = \cos(\zeta) \cos(\varphi_{r0}) - \sin(\zeta) \sin(\varphi_{r0})
\]

where \( \zeta = k z - \omega t \).

Performing simple mathematical manipulation, we obtain

\[
(\frac{E_l}{E_{l0}})^2 + (\frac{E_r}{E_{r0}})^2 - 2(\frac{E_l}{E_{l0}})(\frac{E_r}{E_{r0}}) \cos( \Delta \varphi ) = \sin^2( \Delta \varphi ) \]  \hspace{1cm} [3.13]

where \( \Delta \varphi = \varphi_{l0} - \varphi_{r0} \) called the **phase shift**.

Eq.[3.13] defines an ellipse => **elliptically polarized wave**.

If the phase shift \( \Delta \varphi = n \pi \) \((n=0, +/-1, +/-2,...)\), then

\[
\sin( \Delta \varphi ) = 0 \text{ and } \cos( \Delta \varphi ) = \pm 1, \text{ and Eq.[3.13] becomes}
\]

\[
\left( \frac{E_l}{E_{l0}} \pm \frac{E_r}{E_{r0}} \right)^2 = 0 \quad \text{or} \quad E_r = \pm \frac{E_{r0}}{E_{l0}} E_l 
\]  \hspace{1cm} [3.14]

Eq.[3.14] defines straight lines => **linearly polarized wave**.
If the phase shift $\Delta \varphi = n \pi / 2$ (n = +/-1, +/-3,…) and $E_{i0} = E_{r0} = E_0$, then

$$\sin(\Delta \varphi) = \pm 1 \text{ and } \cos(\Delta \varphi) = 0,$$

and Eq.[3.13] becomes

$$E_t^2 + E_r^2 = E_0^2 \quad [3.15]$$

Eq.[3.15] defines a circle $\Rightarrow$ circular polarized wave

NOTE: The sign of the phase shift gives handedness: right-handed and left-handed polarization

**Unpolarized radiation** (or randomly polarized) is electromagnetic wave in which the orientation of the electrical vector changes randomly.

If there is a definite relation of phases between different scatterers $\Rightarrow$ radiation is called coherent. If there is no relations in phase shift $\Rightarrow$ light is called incoherent

- Natural light is incoherent.
- Natural light is unpolarized.

- The state of polarization is completely defined by the four parameters: two amplitudes, the magnitude and the sign of the phase shift (see Eq.[3.13]). Because the phase difference is hard to measure, the alternative description called a Stokes vector is often used.

**Stokes Vector** consists of four parameters (called Stokes parameters):

- intensity $I$,
- the degree of polarization $Q$,
- the plane of polarization $U$,
- the ellipticity $V$. 
Notation

\[
\begin{pmatrix}
I \\
Q \\
U \\
V
\end{pmatrix}
\quad \text{or} \quad \{I, Q, U, V\}
\]

- **Stokes parameters** are defined via the intensities which can be measured:
  
  I = total intensity
  
  Q = I_0 - I_90 = differences in intensities between horizontal and vertical linearly polarized components;
  
  U = I_{+45} - I_{-45} = differences in intensities between linearly polarized components oriented at +45° and -45°
  
  V = I_{rcl} - I_{lcr} = differences in intensities between right and left circular polarized components.

- **Stokes parameters** can be expressed via the amplitudes and the phase shift of the parallel and perpendicular components

  \[
  I = E_{ro}^2 + E_{lo}^2 \\
  Q = E_{ro}^2 - E_{lo}^2 \\
  U = 2 E_{ro} E_{lo} \cos(\Delta \phi) \\
  V = 2 E_{ro} E_{lo} \sin(\Delta \phi)
  \tag{3.16}
  \]

**EXAMPLE**. Stokes parameters for the vertical polarization:

For this case \( E_l = 0 \)

\[
\begin{pmatrix}
I \\
Q \\
U \\
V
\end{pmatrix} = \begin{pmatrix}
E_{ro}^2 \\
E_{lo}^2 \\
0 \\
0
\end{pmatrix} = E_{ro}^2 \begin{pmatrix}
1 \\
1 \\
0 \\
0
\end{pmatrix}
\]
For a light beam, we have

\[ I^2 \geq Q^2 + U^2 + V^2 \]

For **unpolarized** light:

\[ Q = U = V = 0 \]

The **degree of polarization** \( P \) of a light beam is defined as

\[ P = \left( Q^2 + U^2 + V^2 \right)^{1/2} / I \]

The **degree of linear polarization** \( LP \) of a light beam is defined by neglecting \( U \) and \( V \)

\[ LP = -\frac{Q}{I} \]

**NOTE:** Measurements of polarization are actively used in remote sensing in the solar and microwave regions.

Polarization in the microwave – mainly due to reflection from the surface.

Polarization in the solar – reflection from the surface and scattering by molecules and particulates.