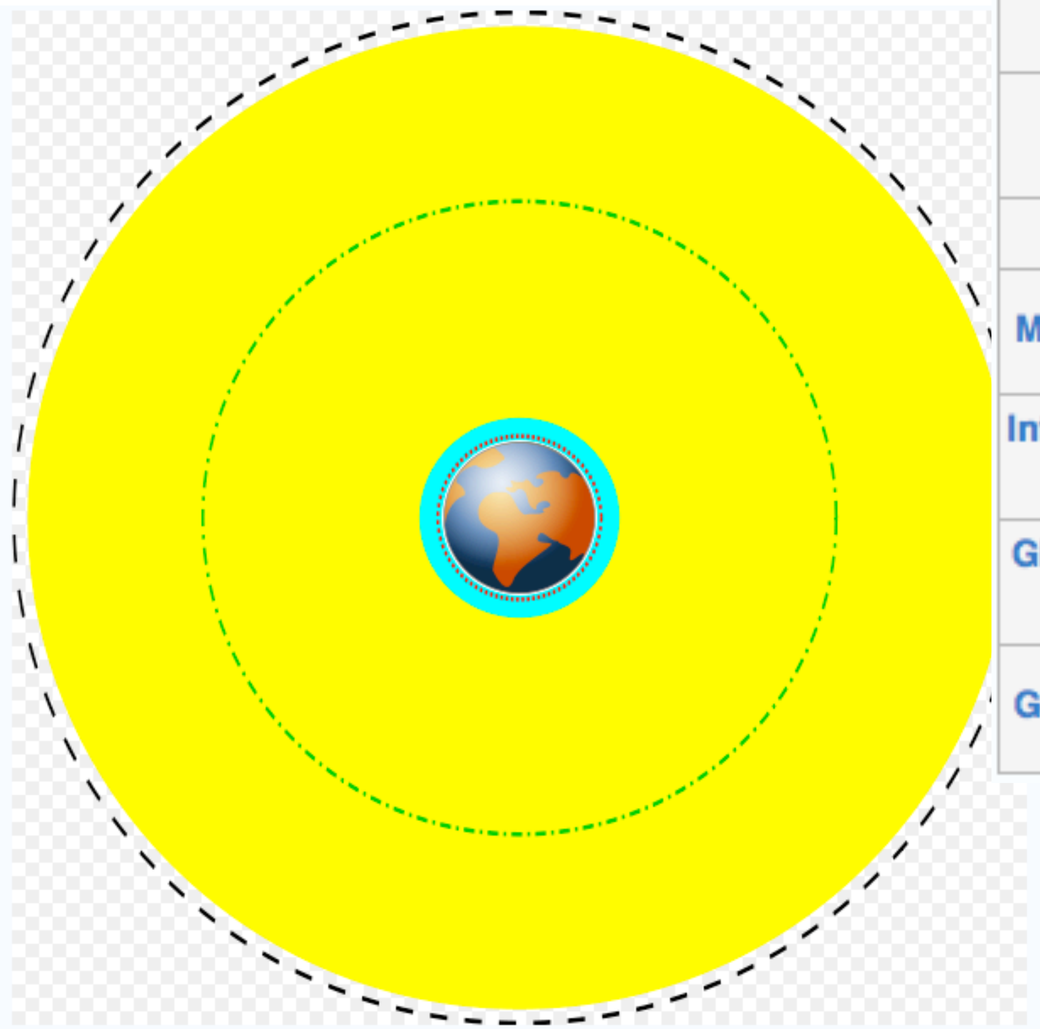
Orbital altitudes



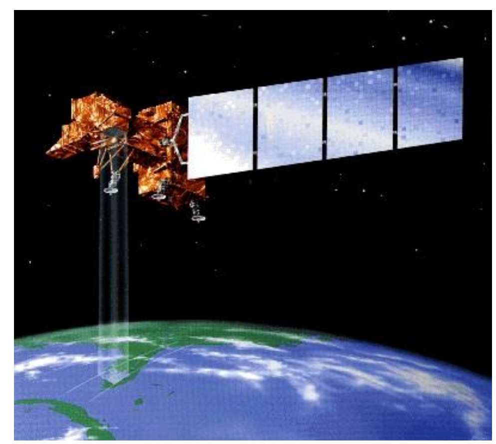
English	Marker	Distance above earth (km)
Earth	Blue/brown image	0
Low Earth Orbit (LEO)	Cyan area	160 to 2,000
Medium Earth Orbit (MEO)	Yellow area	2,000 to 34,780
International Space Station (ISS)	Red dotted line	500
Global Positioning System (GPS) satellites	Green dash-dot line	20,230
Geostationary Orbit (GEO)	Black dashed line	35,794

van Allen belts: 2000 to 5000 km
& 13000 to 19000 km

Source: Wikipedia, 2009

Satellite Remote Sensing
SIO 135/SIO 236

Electromagnetic Radiation and Polarization



Electromagnetic Radiation

- The first requirement for remote sensing is to have an **energy source to illuminate the target**. This energy for remote sensing instruments is in the form of electromagnetic radiation
- Remote sensing is concerned with the measurement of EM radiation returned by Earth surface features that first receive energy from (i) the sun or (ii) an artificial source e.g. a radar transmitter.
- Different objects return different types and amounts of EM radiation .
- Objective of remote sensing is to detect these differences with the appropriate instruments.
- Differences make it possible to identify and assess a broad range of surface features and their conditions

Electromagnetic Radiation (EMR)

- EM energy (radiation) is one of many forms of energy. It can be generated by changes in the energy levels of electrons, acceleration of electrical charges, decay of radioactive substances, and the thermal motion of atoms and molecules.

- All natural and synthetic substances above absolute zero (0 Kelvin, -273°C) emit a range of electromagnetic energy.

- Most remote sensing systems are passive sensors, i.e. they relying on the sun to generate all the required EM energy.

- Active sensors (like radar) transmit energy in a certain direction and records the portion reflected back by features within the signal path.

Electromagnetic Radiation Models

★ To understand the interaction that the EM radiation undergoes before it reaches the sensor, we need to understand the nature of EM radiation

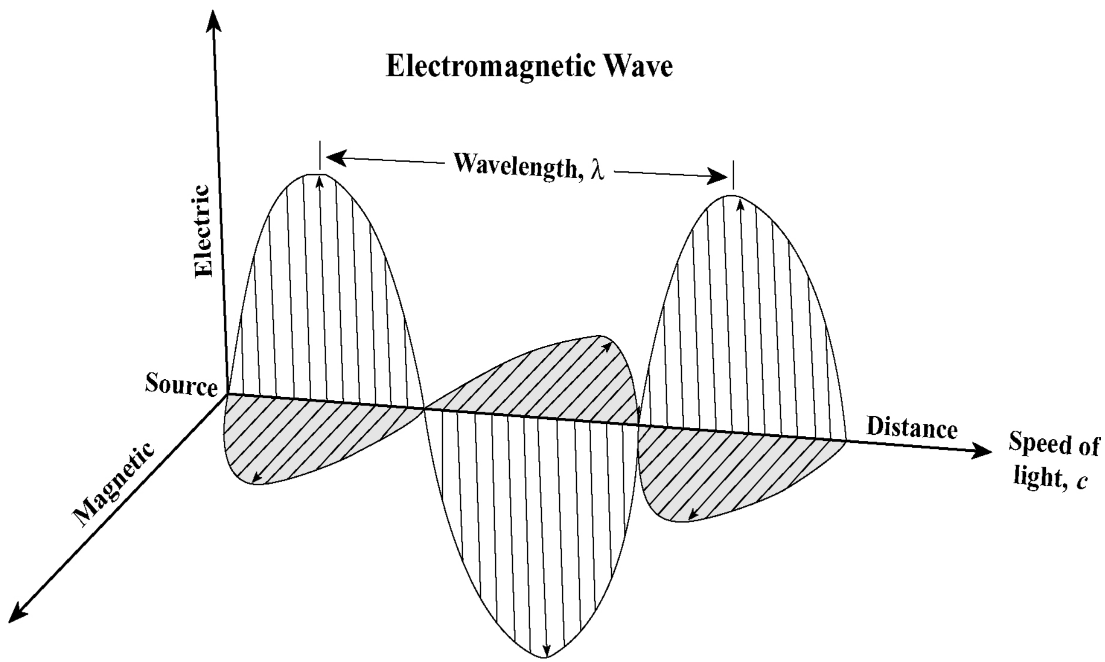
★ To understand how EM radiation is created, how it propagates through space, and how it interacts with other matter, it is useful to consider two different models:

- the *wave* model (today's lecture)
- the *particle* model.

Wave Model of Electromagnetic Radiation

The EM wave consists of two fluctuating fields—one electric (E) and the other magnetic (B).

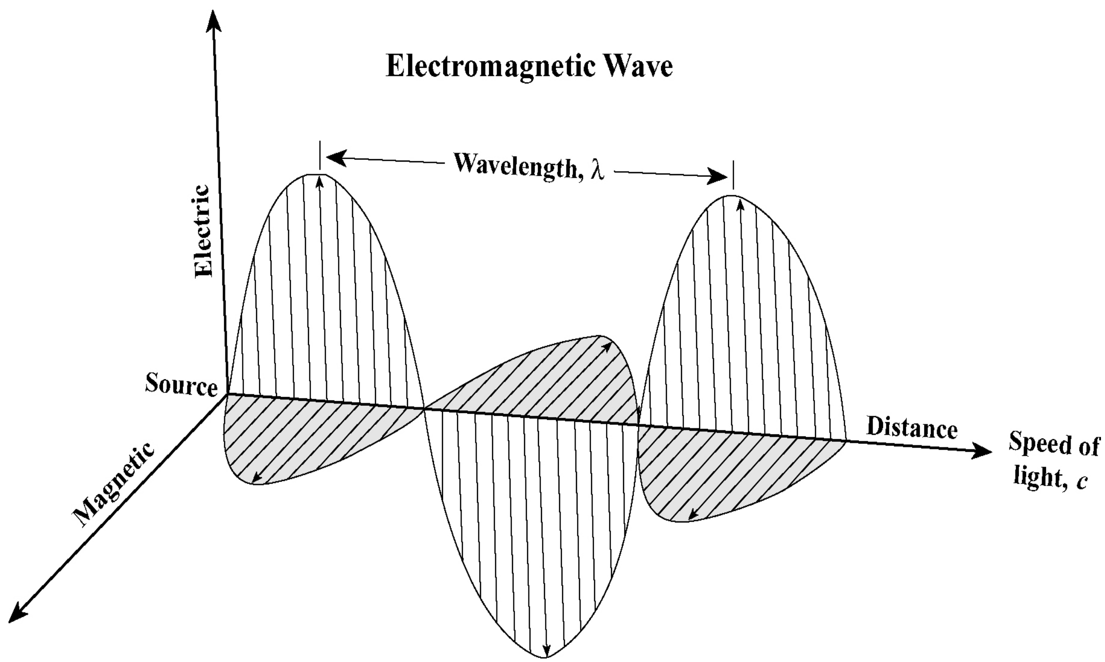
The two vectors are in phase and are at right angles (orthogonal) to one another, and both are perpendicular to the direction of travel.



Wave Model of Electromagnetic Radiation

- EM waves are energy transported through space in the form of periodic disturbances of electric (E) and magnetic (B) fields

- EM waves travel through space at the same speed, c = 2.99792458 x 10^8 m/s, commonly known as the speed of light

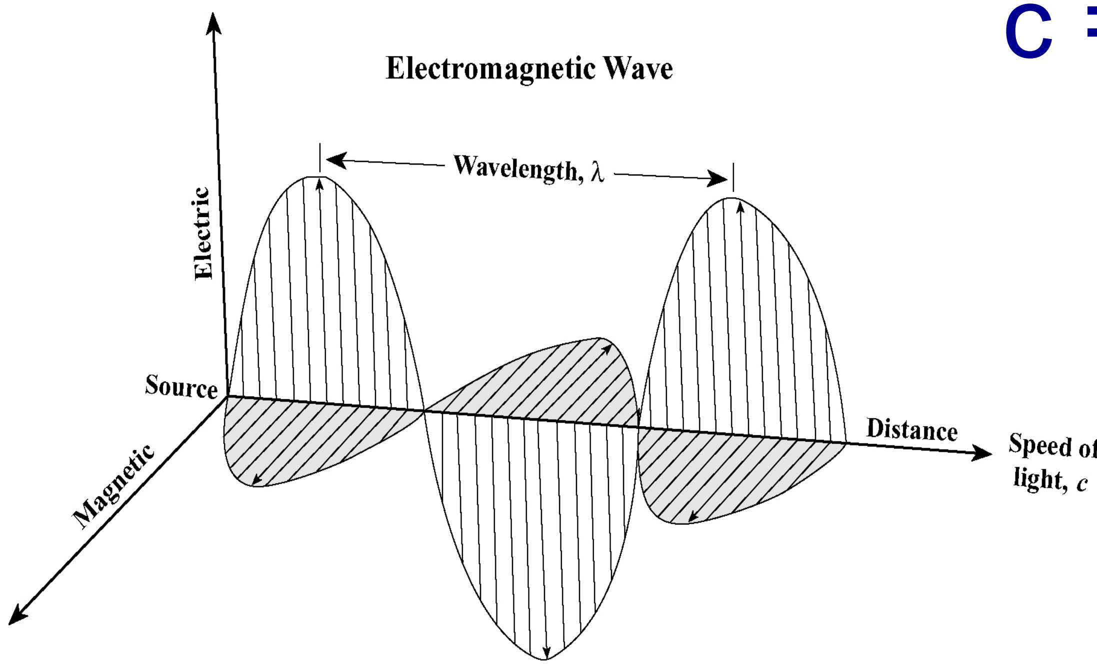


Wave Model of Electromagnetic Radiation

- An EM wave is characterized by a **frequency** and a **wavelength**

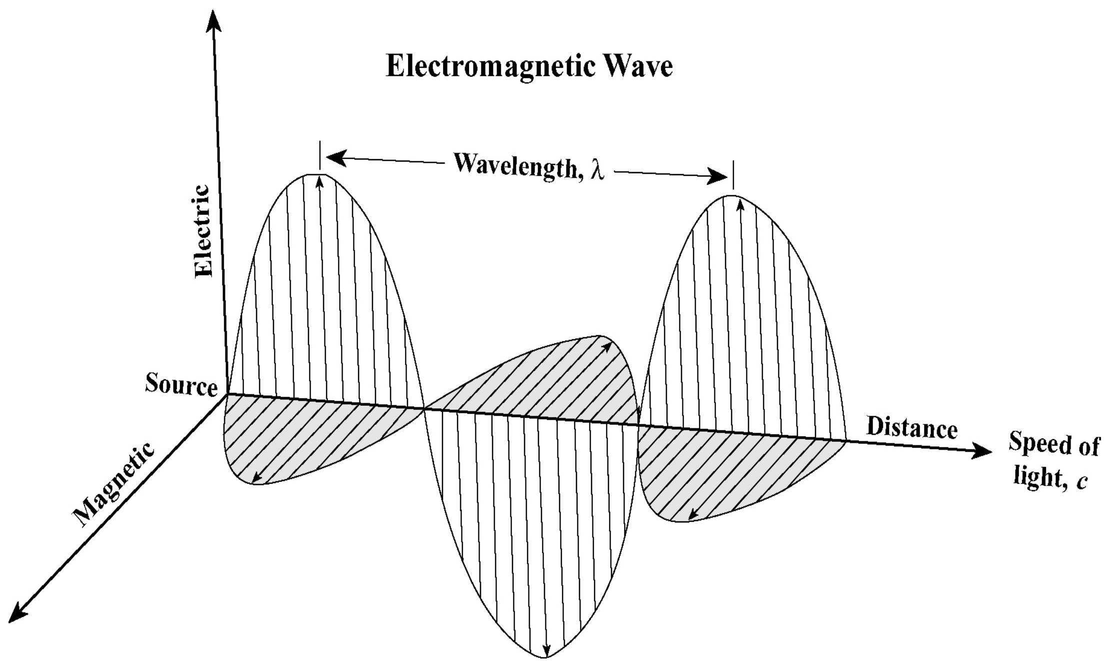
- These two quantities are related to the speed of light by the equation **speed of light = frequency x wavelength**

$$c = f \, . \, \lambda$$



Wave Model of Electromagnetic Radiation

E is perpendicular to direction of propagation
B is perpendicular to direction of propagation
E and B are in phase
E is perpendicular to B
E x B is in direction of propagation
|B| = |E|/c



Electromagnetic (EM) Theory

Electric Field (E)

E is the effect produced by the existence of an electric charge, e.g. an electron, ion, or proton, in the volume of space or medium that surrounds it.

E=F/q F = is the electric force experienced by the particle

q= particle charge

E= is the electric field where the particle is located

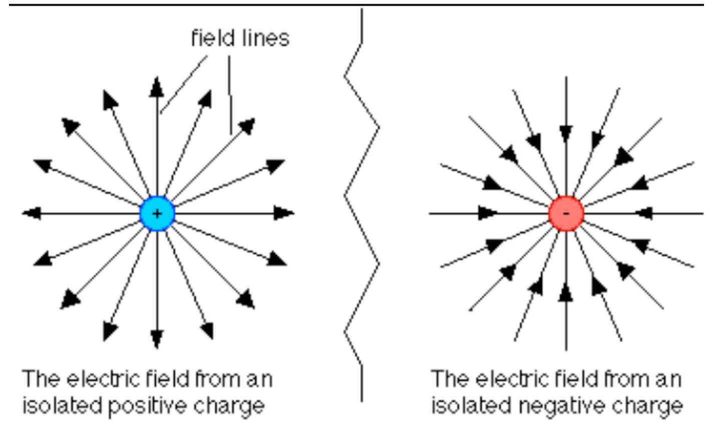
Magnetic Field (B)

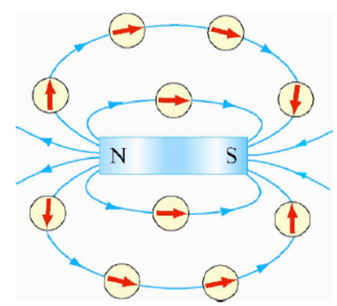
B is the effect produced by a change in velocity of an electric charge q

In a major intellectual breakthroughs in the history of physics (in the 1800s), James Clerk Maxwell came up with the four equations which described all EM phenomena:

➔ MAXWELL'S EQUATIONS

Representation of the electric and magnetic field





A convenient way to represent the magnetic field is with a drawing of "magnetic field lines."
The direction of the lines shows the direction of the magnetic field, while the density of lines shows the strength of the field.

Maxwell's Equations

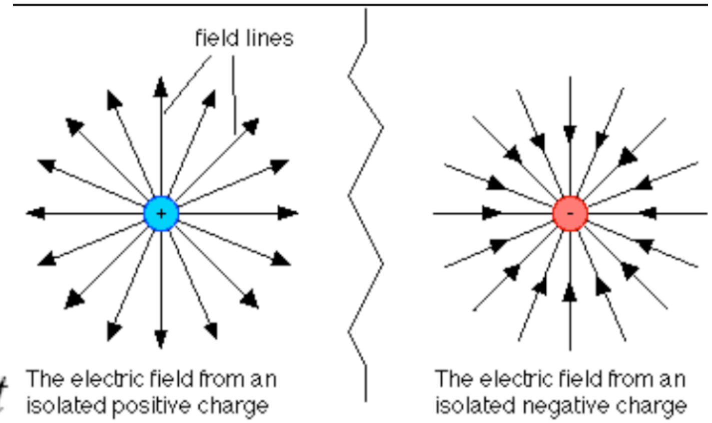
Gauss's law: $$\oint \mathbf{E} \cdot d\mathbf{A} = q / \varepsilon_0$$

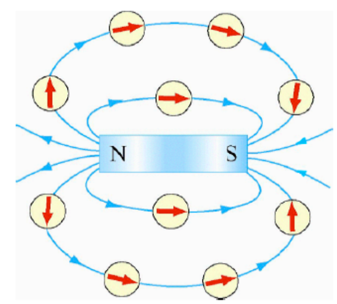
Gauss's law for magnetism: $$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

Maxwell's Faraday rotation: $$\oint \mathbf{E} \cdot d\mathbf{S} = -d\Phi_{\mathbf{B}} / dt$$

Ampere's circuital law: $$\oint \mathbf{B} \cdot d\mathbf{S} = \mu_0 i + \mu_0 \varepsilon_0 d\Phi_{\mathbf{E}} / dt$$

Representation of the electric and magnetic field





A convenient way to represent the magnetic field is with a drawing of "magnetic field lines."
The direction of the lines shows the direction of the magnetic field, while the density of lines shows the strength of the field.

E = electric field (vector)

B = magnetic field (vector)

q = electric charge density,

μ_o = magnetic permeability of free space,

ε_o = electric permittivity of free space (dielectric constant),

i = electric current,

c =1 /sqrt($\mu_o\varepsilon_o$) ~3x10^8 ms^{-1} (speed of light)

Maxwell's Equations

In the absence of charges or currents:

1 Gauss's law: $\oint \mathbf{E} \cdot d\mathbf{A} = q / \varepsilon_0$

2 Gauss's law for magnetism: $\oint \mathbf{B} \cdot d\mathbf{A} = 0$

3 Maxwell's Faraday rotation: $\oint \mathbf{E} \cdot d\mathbf{S} = -d\Phi_{\mathrm{B}} / dt$

4 Ampere's circuital law: $\oint \mathbf{B} \cdot d\mathbf{S} = \mu_0 i + \mu_0 \varepsilon_0 d\Phi_{\mathrm{E}} / dt$

1: The electric flux through a Gaussian surface is equal to the charge contained inside the surface.

2: B field lines aren't created (there are no magnetic monopoles), but they form loops, with no start or stop.

3: Changing B makes E

4: Electric currents create magnetic fields; changing electric fields create magnetic fields.

Maxwell's Equations

Differential form in the absence of magnetic or polarizable media:

1 Gauss's law:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} = 4\pi k \rho$$

2 Gauss's law for magnetism:

$$\nabla \cdot B = 0$$

3 Maxwell's Faraday rotation:

$$\nabla x\, E = -\frac{\partial B}{\partial t}$$

4 Ampere's circuital law:

$$\nabla\, x\, B = \frac{4\pi k}{c^2} J + \frac{1}{c^2}\frac{\partial E}{\partial t}$$

$$= \frac{J}{\varepsilon_0 c^2} + \frac{1}{c^2}\frac{\partial E}{\partial t}$$

$$k = \frac{1}{4\pi\varepsilon_0} = \text{Coulomb's constant} \qquad c^2 = \frac{1}{\mu_0 \varepsilon_0}$$

Maxwell's Equations

Differential form in free space:

1 Gauss's law: $\nabla . E = 0$

2 Gauss's law for magnetism: $\nabla . B = 0$

3 Maxwell's Faraday rotation: $\nabla \times E = -\partial B/\partial t$

4 Ampere's circuital law: $\nabla \times B = \mu_o \varepsilon_o \partial E/\partial t$

Solution to Maxwell's equations

The harmonic plane wave $E_x = E_o \cos(\omega t - kz)$; $E_y = 0$; $E_z = 0$

$B_x = 0$; $B_y = E_o/c \cos(\omega t - kz)$; $B_z = 0$

satisfies Maxwell's equations

wave speed $c = f \cdot \lambda = \omega/k = 1/\sqrt{\varepsilon_o \mu_o}$

ω is the angular frequency, k is the wave number

$\omega = 2\pi f$

$k = 2\pi/\lambda$

Wave Model of Electromagnetic Radiation

- EM waves propagate at the speed of light, c, and consists of an electric field E and a magnetic field B.
- E varies in magnitude in the direction perpendicular to the traveling direction; B is perpendicular to E.
- E is characterized by: frequency (wavelength), amplitude, polarization, phase.

Wave equation:

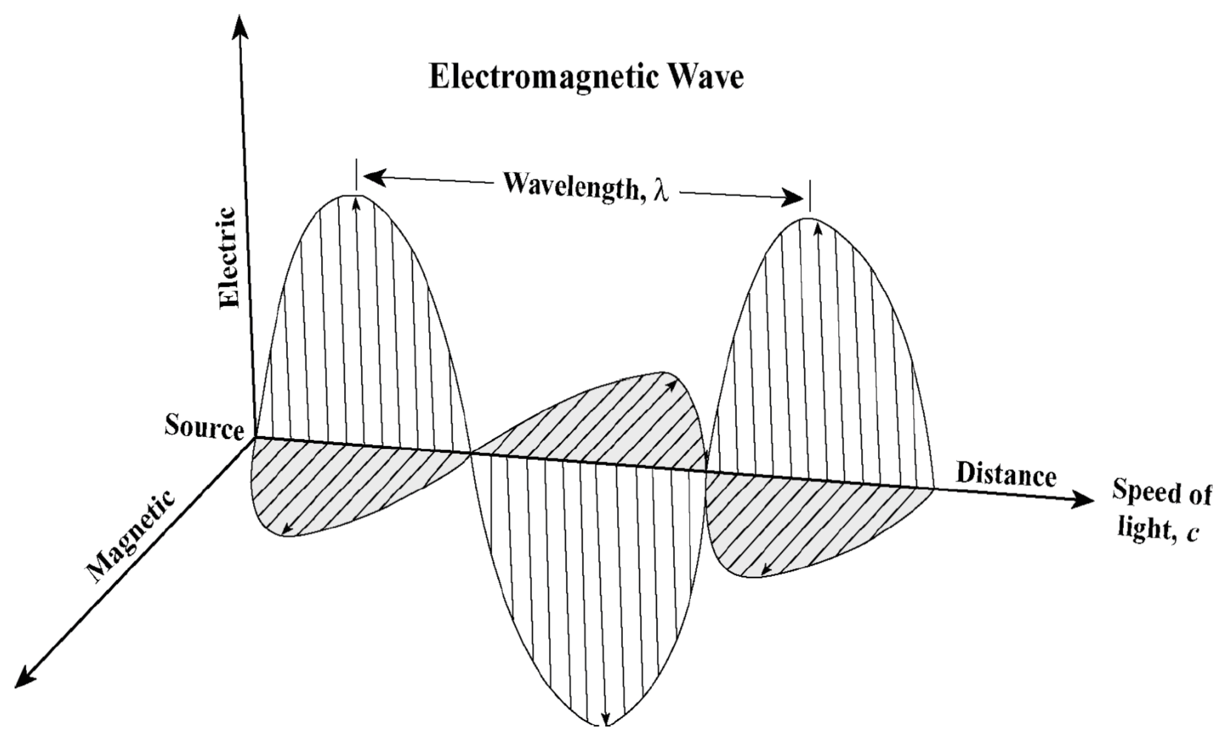
$$E_x = E_o \exp i(\omega t - kz)$$

$k = 2\pi/\lambda$ = wave number

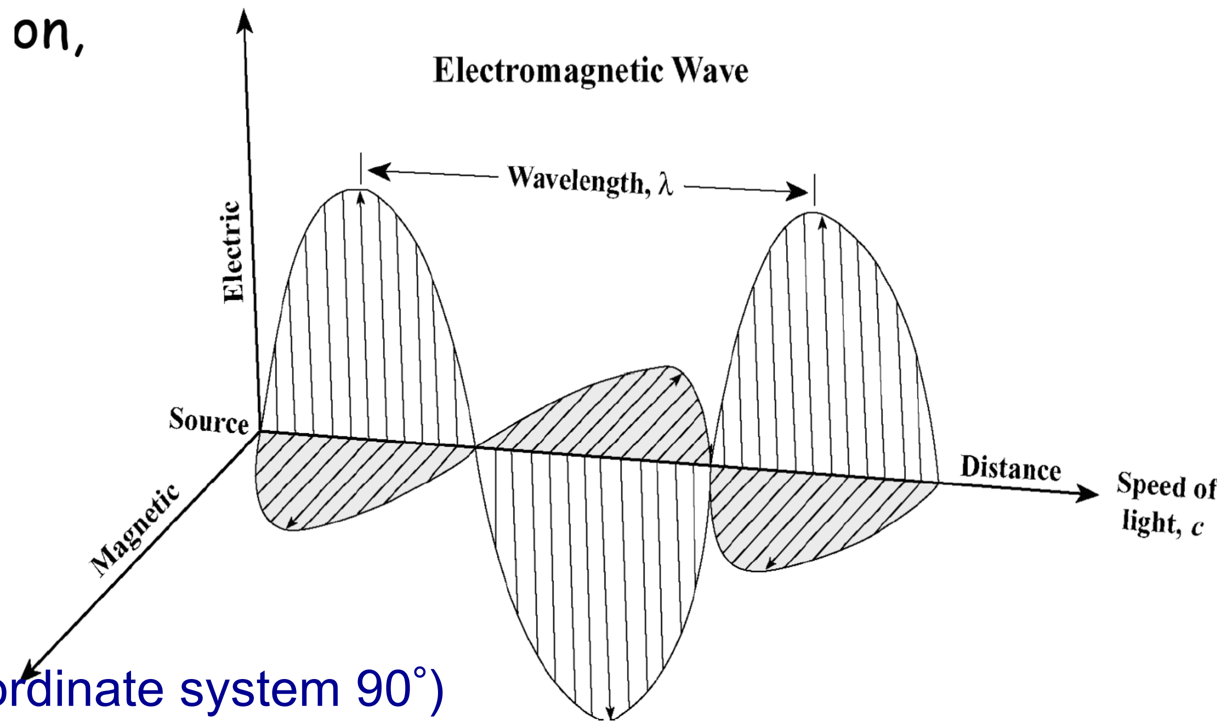
$\omega = 2\pi f$ =angular frequency

f = frequency

Φ =phase



Wave Model of Electromagnetic Radiation



Wave equation:

$$E_x = E_o \cos(\omega t - kz)$$

$k = 2\pi/\lambda$ = wave number

$\omega = 2\pi f$ =angular frequency

f = frequency

Φ =phase

Consider a second wave (rotate coordinate system 90˚)

$E_y = E_o \cos(\omega t - kz)$

Now add these two waves & give them different amplitudes & phases:

$$E_x = E_{ox} \cos(\omega t - kz - \Phi_x)$$
$$E_y = E_{oy} \cos(\omega t - kz - \Phi_y)$$
$$E_z = 0$$

Values of E_x , E_x. Φ_x *and* Φ_y determine how the E field varies with time (polarization)

Light is a traveling EM wave

So…Maxwell's equations tell us that the velocity of EM wave is equal to the speed of light ⇨ i.e. light travels as an EM wave.

$\lambda = c / f$

λ = wavelength (m)

c = speed of light (m/s)

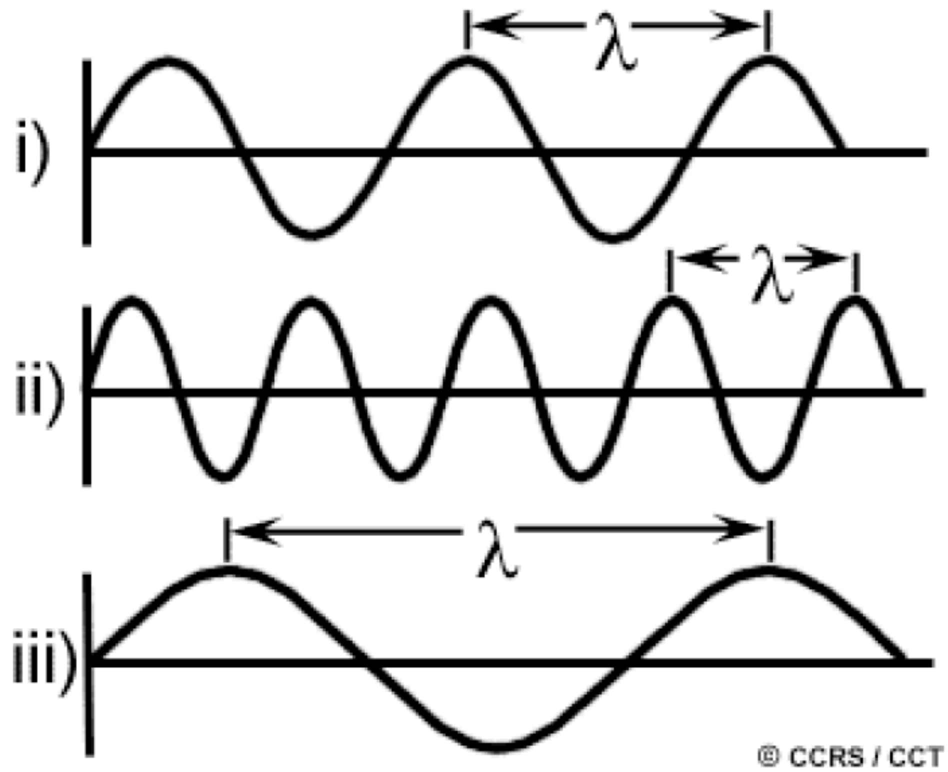
f = frequency (hz or s-1)

c = 300,000 km/s

f = 5.6 GHz; λ = 5.6 cm

f = 1.2 GHz; λ = 24 cm.

λ = 0.4 mm; f = 750 GHz.



Light is a traveling EM wave

Maxwell's equations also tell us that EM waves don't carry any material with them. They only transport **energy**:

$E = h f = h c / \lambda$

c = speed of light (m/s)

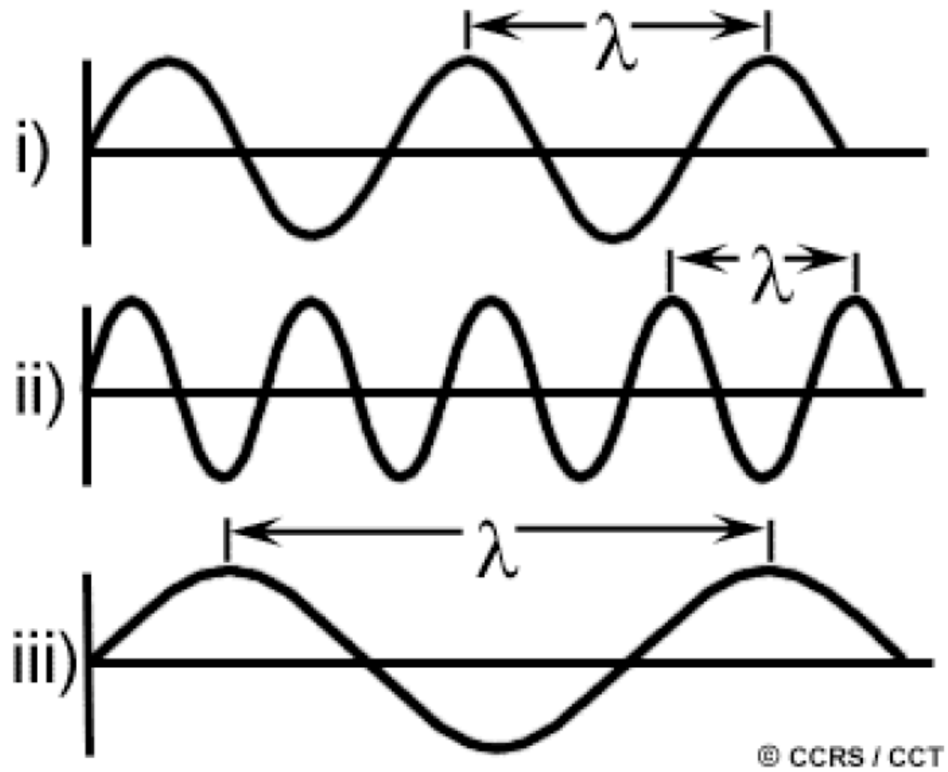
h = Planck's constant.

f = frequency (hz or s^{-1})

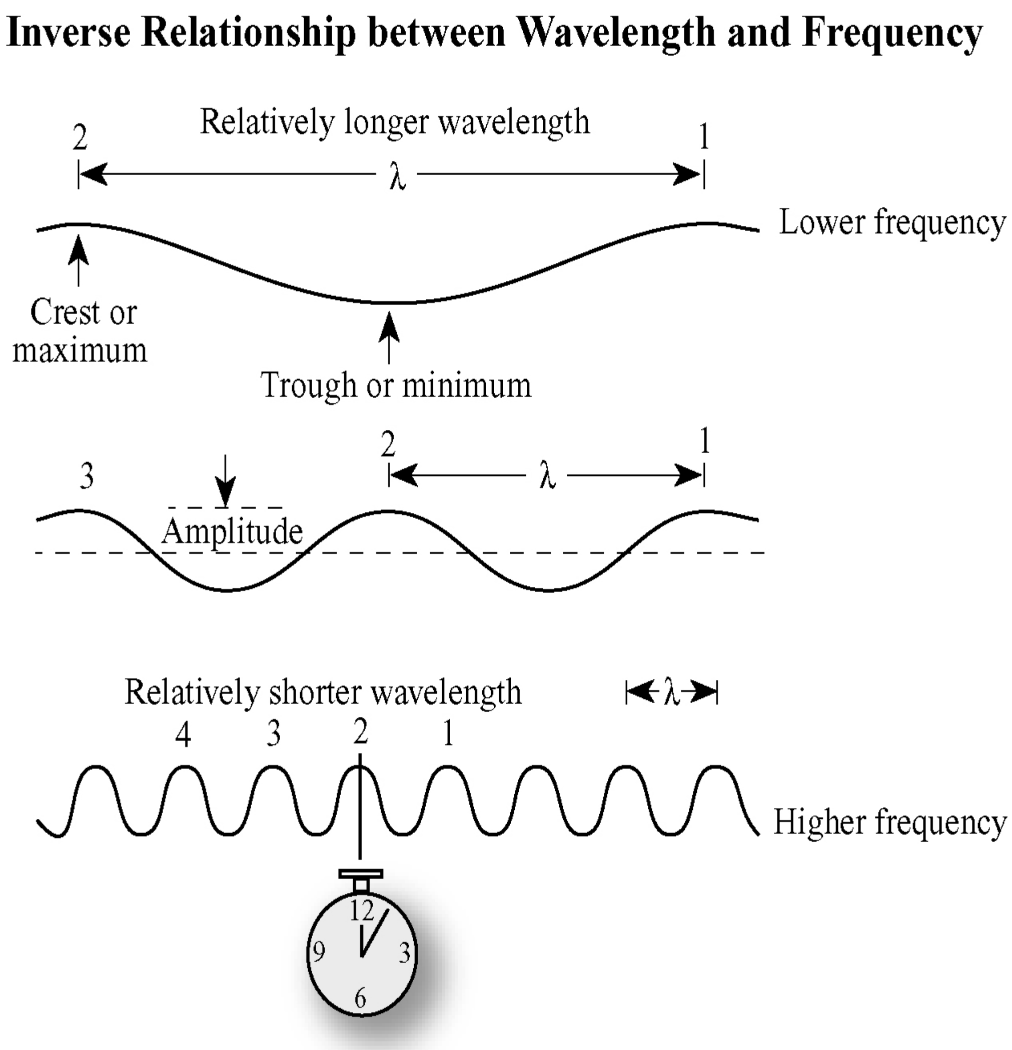
λ=wavelength

High-frequency electromagnetic waves have a short wavelength and high energy;

Low-frequency waves have a long wavelength and low energy



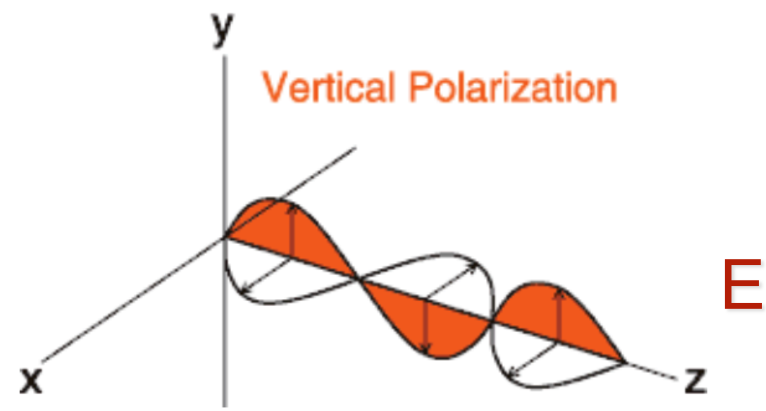
Wave Model of Electromagnetic Radiation



- This cross-section of an EM wave illustrates the inverse relationship between wavelength (λ) & frequency (ν). The longer the wavelength the lower the frequency; the shorter the wavelength, the higher the frequency.
- The amplitude of an EM wave is the height of the wave crest above the undisturbed position.
- Frequency is measured in cycles per second, or hertz (Hz).

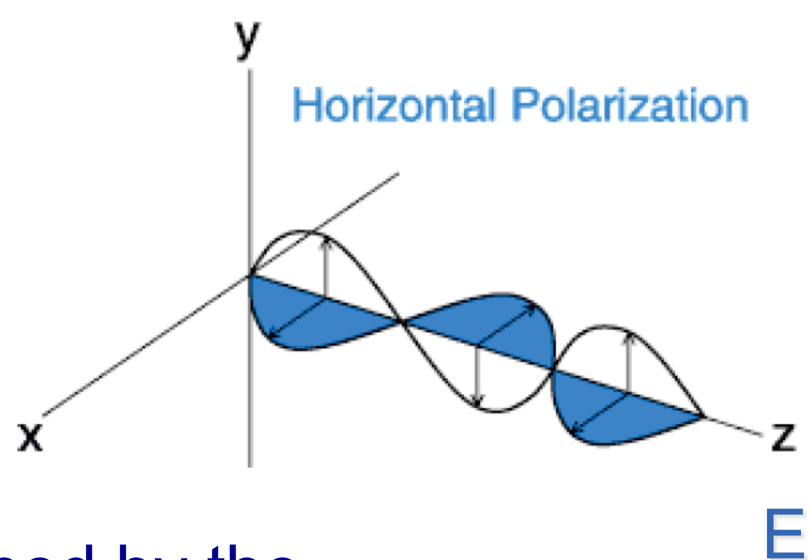
Polarization

Refers to orientation of the electric field **E**



If both **E** and **B** remain in their respective planes, the radiation is called "**plane or linearly polarized**":

Vertically polarized (E is parallel to the plane of incidence)

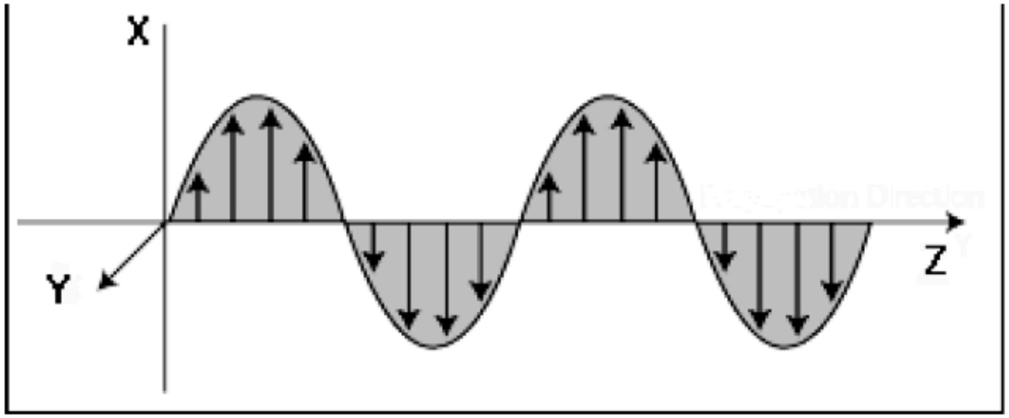


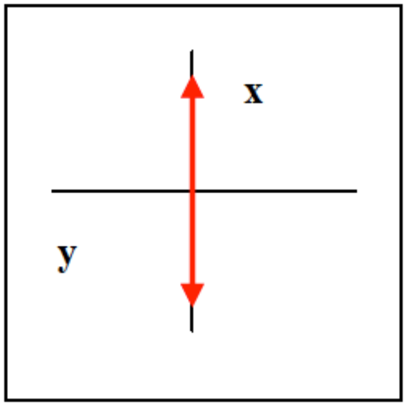
Horizontally polarized (E is perpendicular to the plane of incidence)

Plane of incidence = the plane defined by the vertical and the direction of propagation

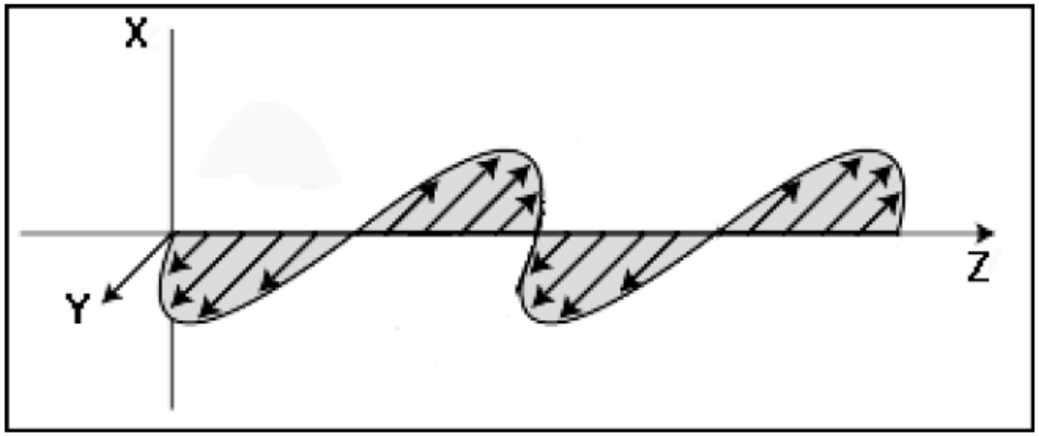
Polarization

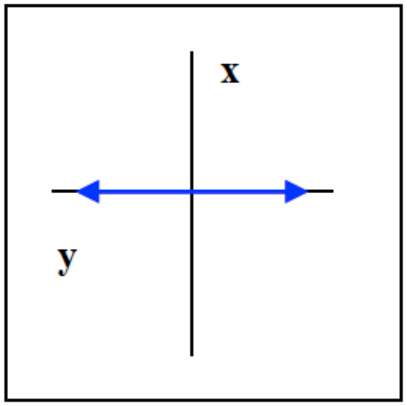
Vertically polarized wave is one for which the electric field lies only in the x-z plane.





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

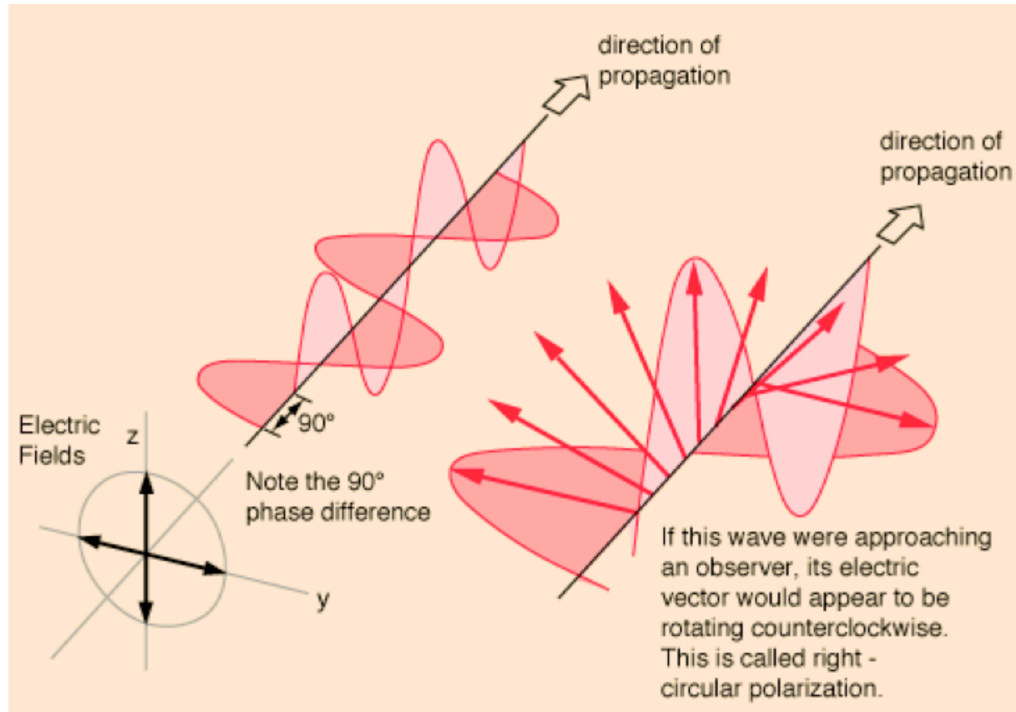




- Horizontal and vertical polarizations are an example of **linear polarization**.

Polarization

If instead of being confined to fixed direction, E rotates in the x-y plane with constant amplitude, it is said to be circularly polarized (either right- or left-hand circular (clockwise/anti-clockwise respectively)



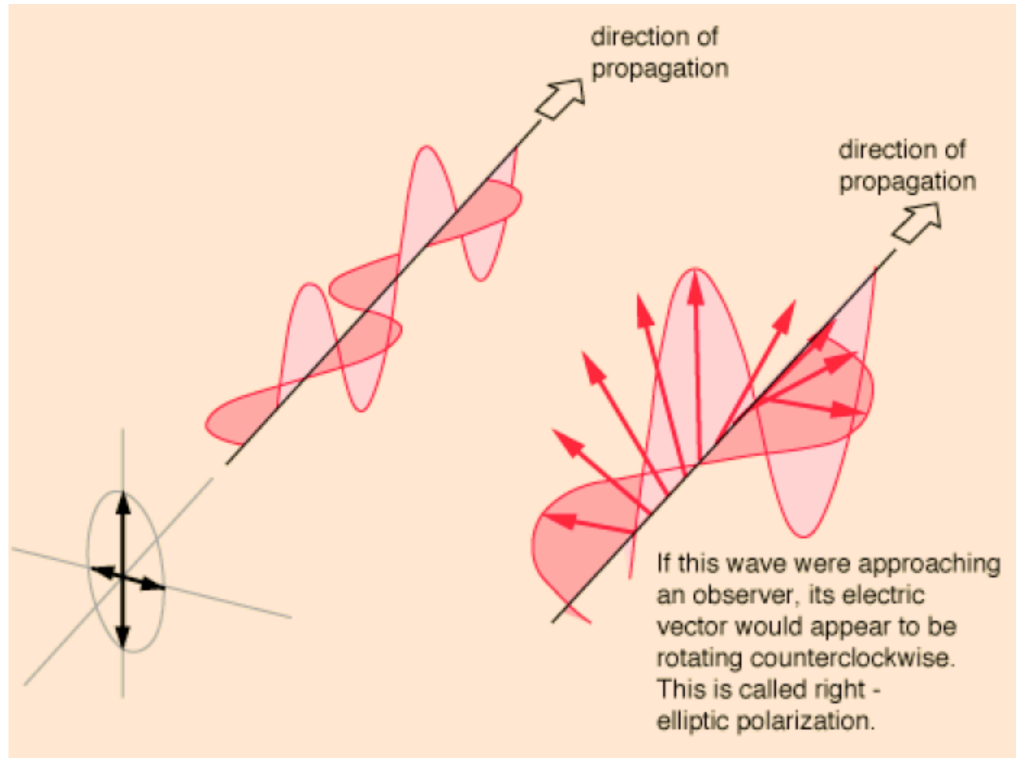
Circularly polarized light consists of two perpendicular EM plane waves of equal amplitude and 90° difference in phase. The light illustrated is right-hand circularly polarized

Radiation from the sun is unpolarized (at random angles)

Polarization

Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90˚

If the thumb of your right hand were pointing in the direction of propagation of the light, the electric vector would be rotating in the direction of your fingers



Right-hand elliptically polarized light

WATCH: https://www.youtube.com/watch?v=8YkfEft4p-w

Stokes parameters

Set of four parameters that describe the polarisation state of EM radiation:

- **S_0** is the intensity **I**
- **S_1** the degree of polarization **Q**
- **S_2** is the the plane of polarization **U**
- **S_3** is the ellipticity **V** (0 for linear, 1 for circle)

$[S_0, S_1, S_2, S_3]$ = Stokes vector

Stokes parameters expressed via amplitudes and phase shift of E_{ox} & E_{oy}

< > means time average

$$S_0 = \langle E_{ox}^2 \rangle + \langle E_{oy}^2 \rangle$$

$$S_1 = \langle E_{ox}^2 \rangle - \langle E_{oy}^2 \rangle$$

$$S_2 = 2E_{ox}E_{oy} \cos(\Delta\phi)$$

$$S_3 = 2E_{ox}E_{oy} \sin(\Delta\phi)$$

Some common Stokes vectors

Linear vertical polarization

$E_{ox} = 0, E_{oy} = 1$

$S_0 = <E_{ox}^2> + <E_{oy}^2> = 1$

$S_1 = <E_{ox}^2> - <E_{oy}^2> = -1$

$S_2 = 2E_{ox}E_{oy} \cos(\Delta\phi) = 0$

$S_3 = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, -1, 0, 0]

Linear horizontal polarization

$E_{ox} = 1, E_{oy} = 0$

$S_0 = <E_{ox}^2> + <E_{oy}^2> = 1$

$S_1 = <E_{ox}^2> - <E_{oy}^2> = 1$

$S_2 = 2E_{ox}E_{oy} \cos(\Delta\phi) = 0$

$S_3 = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, 1, 0, 0]

Normalized so that $S_0 = 1$.

Some common Stokes vectors

Linear at 45°

$\boldsymbol{E_{ox}}$ = *sqrt(1/2)*, $\boldsymbol{E_{oy}}$ = *sqrt(1/2)*

$$\Delta\phi = 0$$

$\mathbf{S_0} = \langle E_{ox}^2 \rangle + \langle E_{oy}^2 \rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2 \rangle - \langle E_{oy}^2 \rangle = 0$

$\mathbf{S_2} = 2E_{ox}E_{oy} \cos(\Delta\phi) = 1$

$\mathbf{S_3} = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, 0, 1, 0]

Linear at -45°

$\boldsymbol{E_{ox}}$ = *sqrt(1/2)*, $\boldsymbol{E_{oy}}$ = *-sqrt(1/2)*

$$\Delta\phi = 0$$

$\mathbf{S_0} = \langle E_{ox}^2 \rangle + \langle E_{oy}^2 \rangle = 1$

$\mathbf{S_1} = \langle E_{ox}^2 \rangle - \langle E_{oy}^2 \rangle = 0$

$\mathbf{S_2} = 2E_{ox}E_{oy} \cos(\Delta\phi) = -1$

$\mathbf{S_3} = 2E_{ox}E_{oy} \sin(\Delta\phi) = 0$

Stokes vector is [1, 0, -1, 0]

Normalized so that $S_0 = 1$.

Some common Stokes vectors

Unpolarized Light [1, 0, 0, 0]

Linear horizontal [1, 1, 0, 0]

Linear vertical [1, -1, 0, 0]

Linear at 45 degrees [1, 0, 1, 0]

Linear at -45 degrees [1, 0, -1, 0]

Right circular [1, 0, 0, 1]

Left circular [1, 0, 0, -1]

Normalized so that $S_0 = 1$.

Stokes parameters

For **unpolarized** light:

$$Q = U = V = 0 \qquad [3.7]$$

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

$$P = (Q^2 + U^2 + V^2)^{1/2} / I \qquad [3.8]$$

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

$$LP = -\frac{Q}{I} \qquad [3.9]$$

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.
Active remote sensing (e.g., radar) commonly uses polarized radiation.

Electromagnetic Spectrum

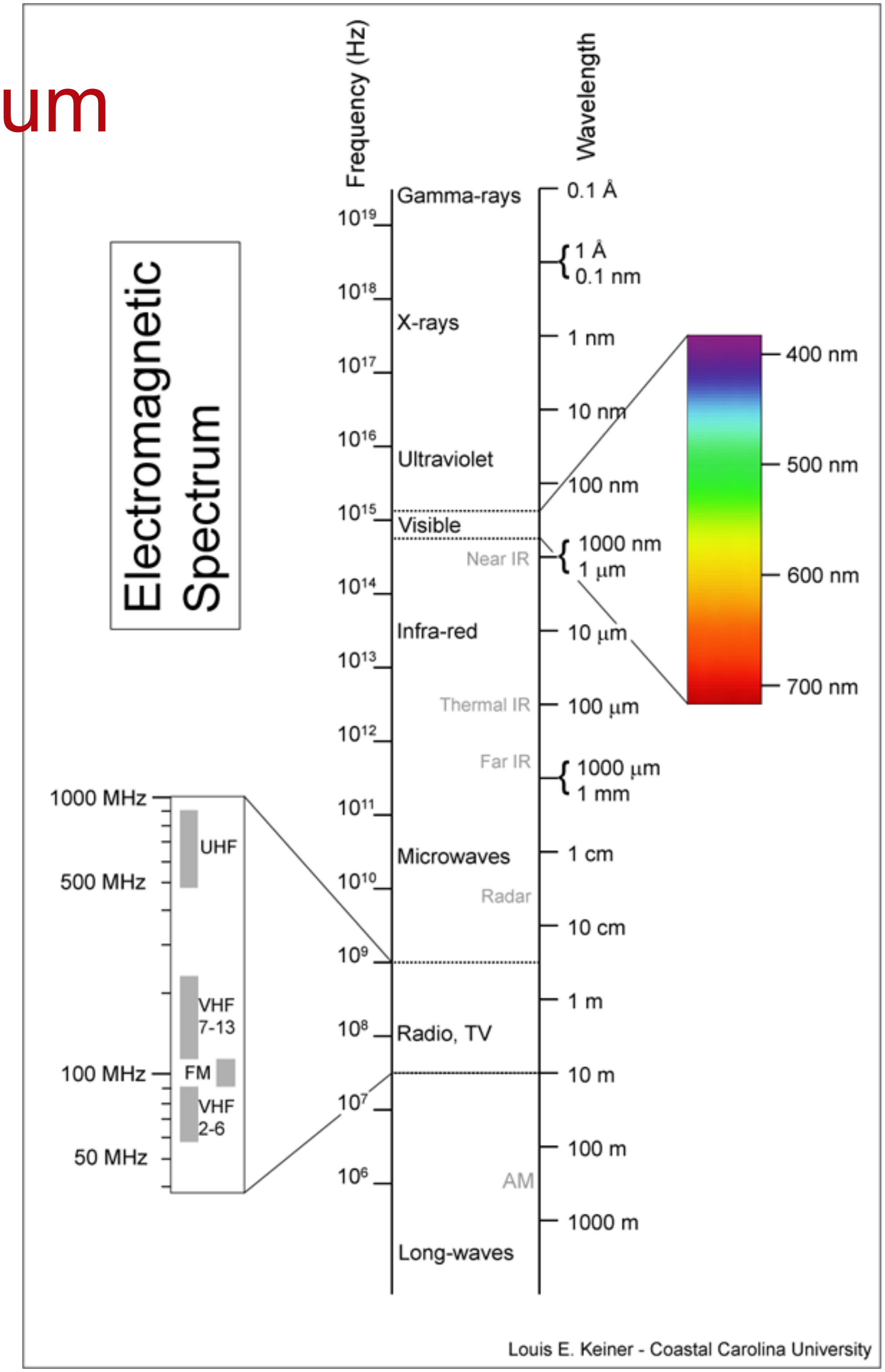
- ★ Frequency (or wavelength) of an EM wave depends on its source.
- ★ There is a wide range of frequency encountered in our physical world, ranging from the low frequency of the electric waves generated by the power transmission lines to the very high frequency of the gamma rays originating from the atomic nuclei.
- ★ This wide frequency range of electromagnetic waves make up the **Electromagnetic Spectrum**.

Electromagnetic Spectrum

- Represents the continuum of electromagnetic energy from extremely short wavelengths (cosmic and gamma rays) to extremely long wavelengths (microwaves).

- No natural breaks in the EMS -- it is artificially separated and named as various spectral bands (divisions) for the description convenience.

- Common bands in remote sensing are visible, infra-red & microwave.

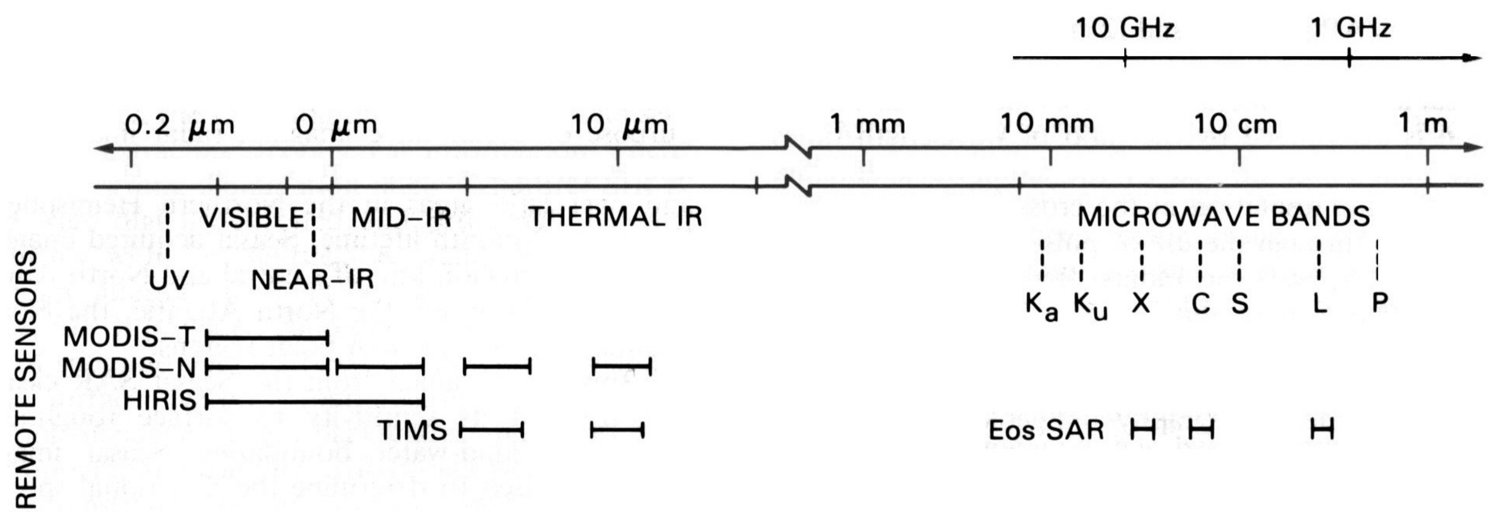


Spectral bands

Three important spectral bands in remote sensing:

- visible light
- infrared radiation
- microwave radiation

Image from NASA 1987. SAR: Synthetic Aperture Radar.
Earth Observing System, Vol. IIf.



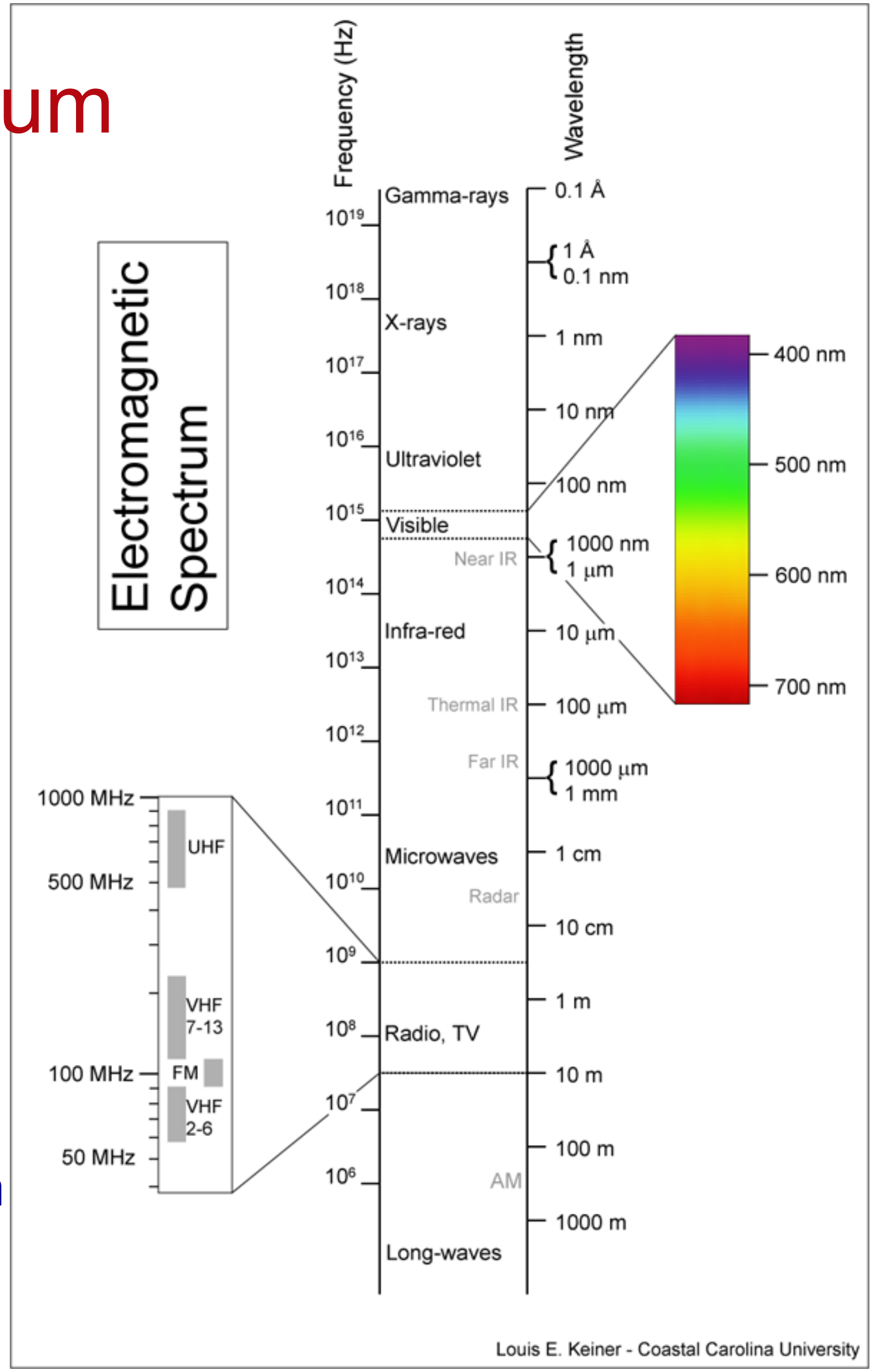
Also see Figure 2.2 in Rees

Electromagnetic Spectrum

Visible: Small portion of the EMS that humans are sensitive to:
blue (0.4-0.5 μm); green (0.5-0.6 μm); red (0.6-0.73 μm)

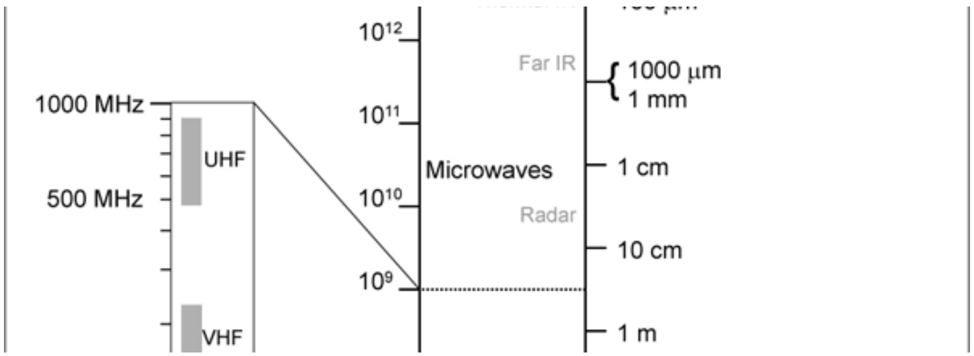
Infrared: Three logical zones:
1. Near IR: reflected, can be recorded on film emulsions (0.7 - 1.3μm).
2. Mid infrared: reflected, can be detected using electro-optical sensors (1.3 - 3.0μm).
3. Thermal infrared: emitted, can only be detected using electro-optical sensors (3.0 - 5.0 and 8 - 14 μm).

Microwave
Radar sensors, wavelengths range from 1mm - 1m (K_a, K_u, X, C, S, L & P)



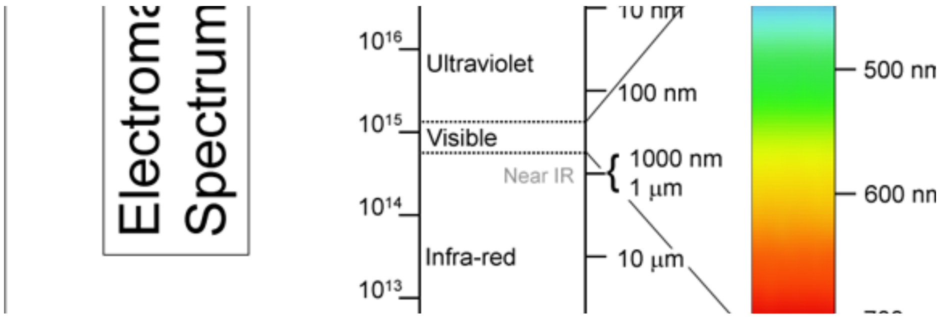
Wavelengths of microwave

- **Microwaves**: 1 mm to 1 m wavelength.
- Further divided into different frequency bands:**(1 GHz = 10^9 Hz)**
- **P band**: 0.3 - 1 GHz (30 - 100 cm)
- **L band**: 1 - 2 GHz (15 - 30 cm)
- **S band**: 2 - 4 GHz (7.5 - 15 cm)
- **C band**: 4 - 8 GHz (3.8 - 7.5 cm)
- **X band**: 8 - 12.5 GHz (2.4 - 3.8 cm)
- **Ku band**: 12.5 - 18 GHz (1.7 - 2.4 cm)
- **K band**: 18 - 26.5 GHz (1.1 - 1.7 cm)
- **Ka band**: 26.5 - 40 GHz (0.75 - 1.1 cm)



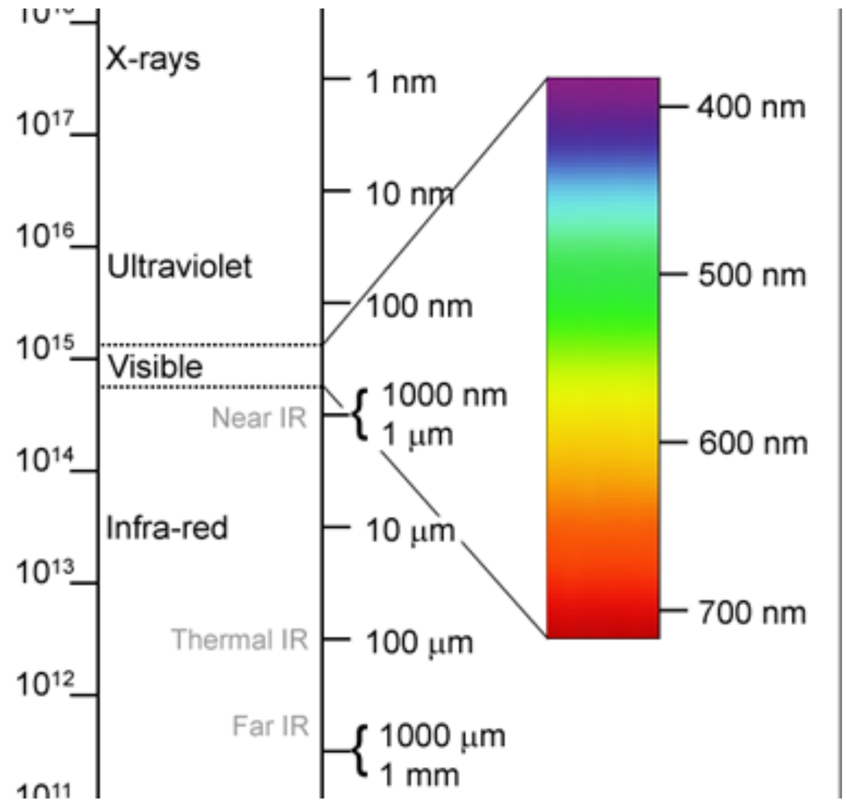
Wavelengths of Infrared

- **Infrared**: 0.7 to 300 µm wavelength. This region is further divided into the following bands:
- **Near Infrared (NIR)**: 0.7 to 1.5 µm.
- **Short Wavelength Infrared (SWIR)**: 1.5 to 3 µm.
- **Mid Wavelength Infrared (MWIR)**: 3 to 8 µm.
- **Long Wavelength Infrared (LWIR)**: 8 to 15 µm.
- **Far Infrared (FIR)**: longer than 15 µm.
- The NIR and SWIR are also known as the **Reflected Infrared**, referring to the main infrared component of the solar radiation reflected from the earth's surface. The MWIR and LWIR are the **Thermal Infrared**.



Wavelengths of visible light

- **Red**: 610 - 700 nm
- **Orange**: 590 - 610 nm
- **Yellow**: 570 - 590 nm
- **Green**: 500 - 570 nm
- **Blue**: 450 - 500 nm
- **Indigo**: 430 - 450 nm
- **Violet**: 400 - 430 nm



Interaction of EMR with matter

Propagation of EMR in a uniform homogenous material depends on two properties of medium:

1) ***relative electric permittivity*** ε_r ***or dielectric constant*** $\varepsilon_r = \varepsilon/\varepsilon_0$

2) ***relative magnetic permeability*** $\mu_r = \mu/\mu_0$

with no absorption, ε_r and μ_r are real, dimensionless numbers

$E_x = E_o \cos(\omega t - kz)$ and $B_y = E_o/c \cos(\omega t - kz)$

wave speed (phase velocity) $\omega/k = c/\mathrm{sqrt}(\varepsilon_r \mu_r)$

The ***refractive index*** $n = (\varepsilon_r \mu_r)^{1/2}$ is a measure of how much the speed of EMR is reduced inside the medium [for free space, n=1]

Complex dielectric constant

For most media we shall need to consider, μ_r = 1 (non magnetic materials)

If the medium absorbs energy from the wave, the dielectric constant becomes complex (real + imaginery)

↑ loss tangent

$\varepsilon_r = \varepsilon' - i\varepsilon''$ or $\varepsilon_r = \varepsilon'(1 - i \tan \delta)$

See page 36 of Rees, arrive at the following wave equation:

➔ $E_x = E_o \exp(-\omega kz/c) \exp(i[\omega t - \omega mz/c])$

Simple harmonic wave whose amplitude decreases exponentially with z
Flux density $F = F_0 \exp(-2\ \omega kz/c)$

➔ Absorption length $l_a = c/2\omega k$