

ElectroMagnetic Radiation (EMR)

Lecture 2-3

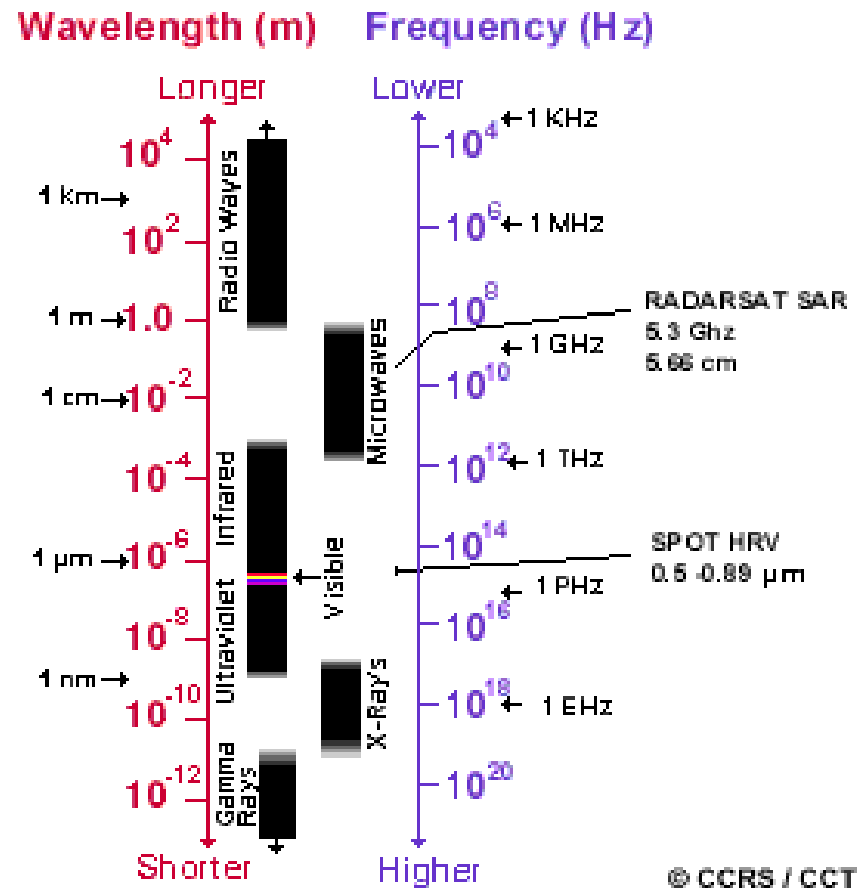
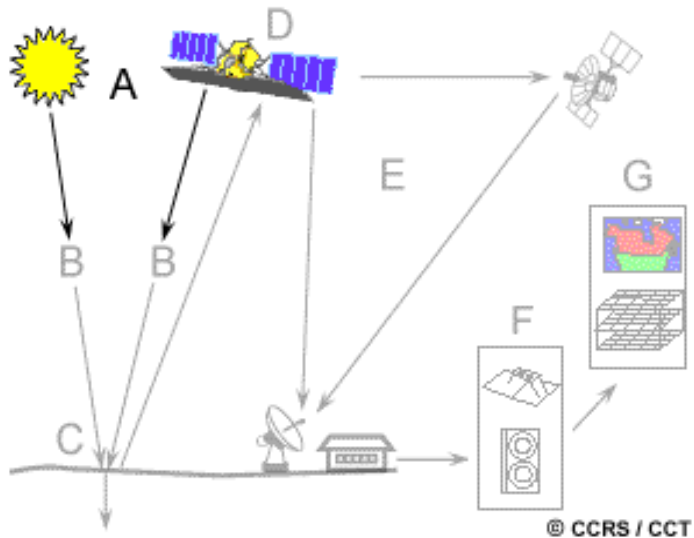
August 29 and 31, 2005

Ways of Energy Transfer

Energy is the ability to do work. In the process of doing work, energy is often transferred from one body to another or from one place to another. The three basic ways in which energy can be transferred include **conduction**, **convection**, and **radiation**.

- Most people are familiar with **conduction** which occurs when one body (molecule or atom) transfers its kinetic energy to another by colliding with it (physical contact). This is how a pan gets heated on a stove.
- In **convection**, the kinetic energy of bodies is transferred from one place to another by physically moving the bodies. A good example is the convectational heating of air in the atmosphere in the early afternoon (less dense air rises).
- The transfer of energy by **electromagnetic radiation** is of primary interest to remote sensing because it is the only form of energy transfer that can take place in a vacuum such as the region between the Sun and the Earth.

Remote sensing and EMR



- remote sensing needs an **energy source to illuminate the target** (unless the sensed energy is being emitted by the target). This energy is in the form of **electromagnetic radiation**

MGS TES
6 – 50 μm

c. Wavelengths detected by common remote sensing systems

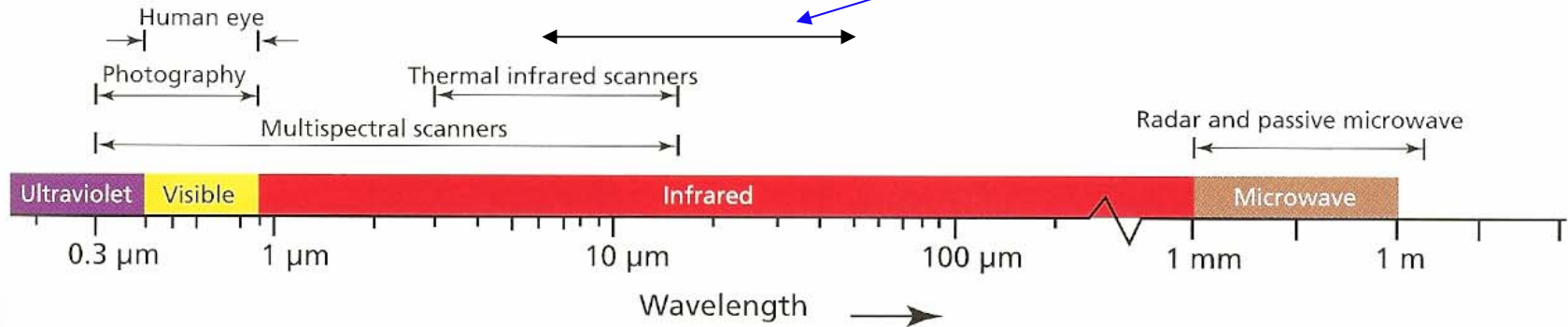


Figure 3.5 Remote sensing in the electronic spectrum. (a) Energy emission. (b) Atmospheric windows important for remote sensing.

(c) Range of wavelengths detected by common remote sensing systems.

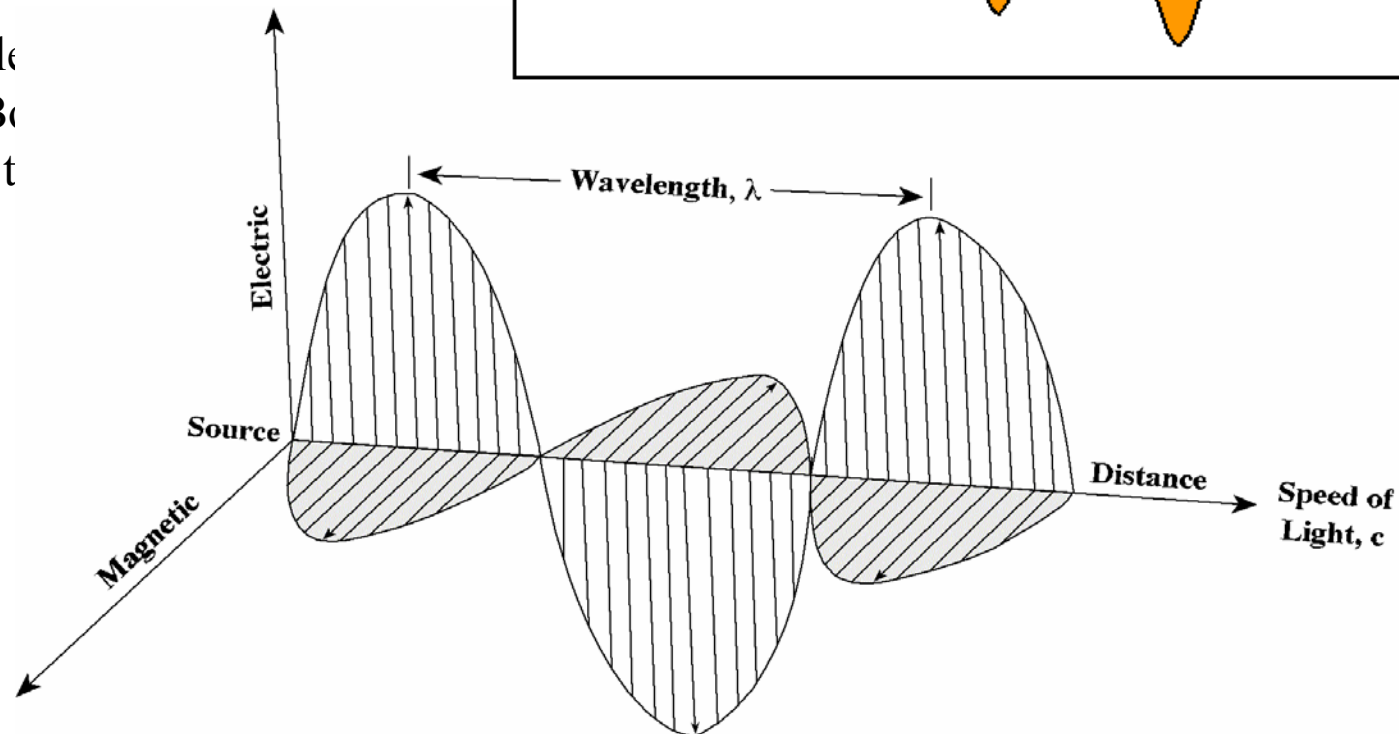
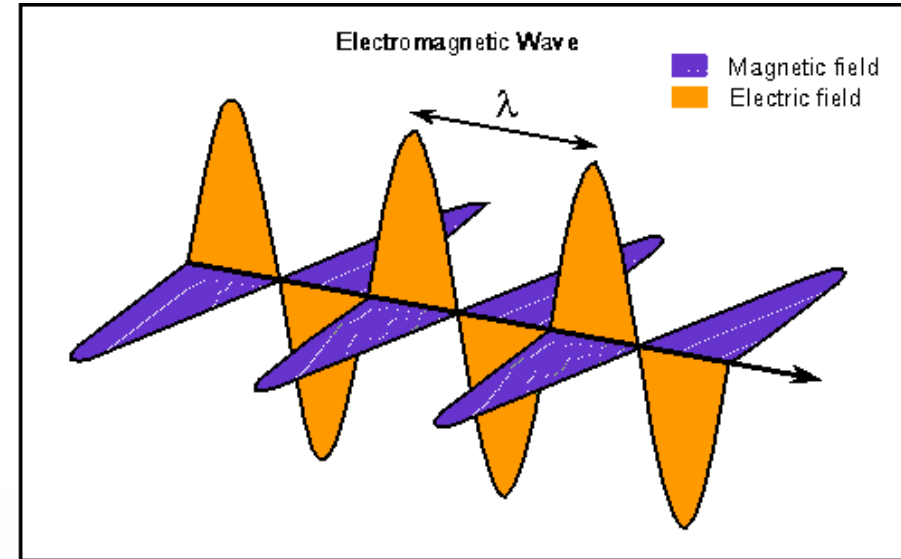
Source: *Remote sensing and image interpretation*, 2nd. ed. by T. M. Lillesand and R. W. Kiefer. © 1987 John Wiley and Sons, Inc. Reprinted with permission of John Wiley and Sons, Inc.

1. Describe the EMR

- Wave model
- Particle model

1A. Wave model

- **Electromagnetic wave** consists of an **electrical field** (E) which varies in magnitude in a direction perpendicular to the direction in which the radiation is traveling, and a **magnetic field** (M) oriented at right angle to the electrical field. Both these fields travel at the speed of light (c).



Three characteristics of electromagnetic wave

- **Velocity** is the speed of light, $c=3 \times 10^8$ m/s
- **wavelength** (λ) is the length of one wave cycle, is measured in **metres** (m) or some factor of metres such as

centimetres (cm) 10^{-2} m

micrometres (μm) 10^{-6} m

nanometres (nm) 10^{-9} m

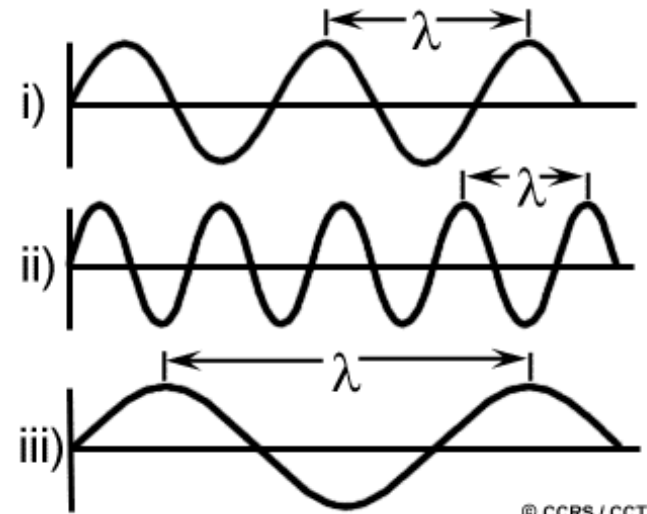
- **Frequency** (ν) refers to the number of cycles of a wave passing a fixed point per unit of time. Frequency is normally measured in **hertz** (Hz), equivalent to **one cycle per second**, and various multiples of hertz. unlike c and λ changing as propagated through media of different densities, ν **remains constant**.

Hertz (Hz) 1

kilohertz (KHz) 10^3

megahertz (MHz) 10^6

gigahertz (GHz) 10^9



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$$c = \lambda \nu$$

where:

λ = wavelength (m)

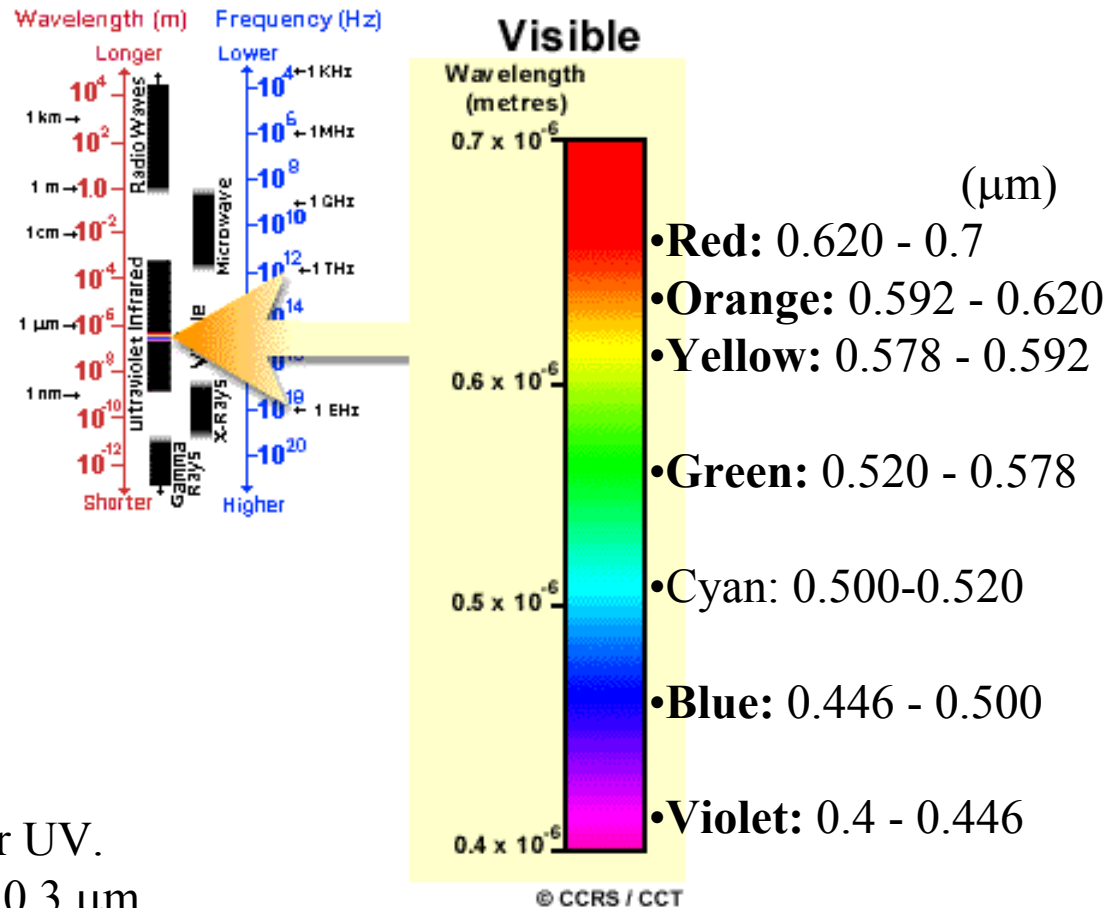
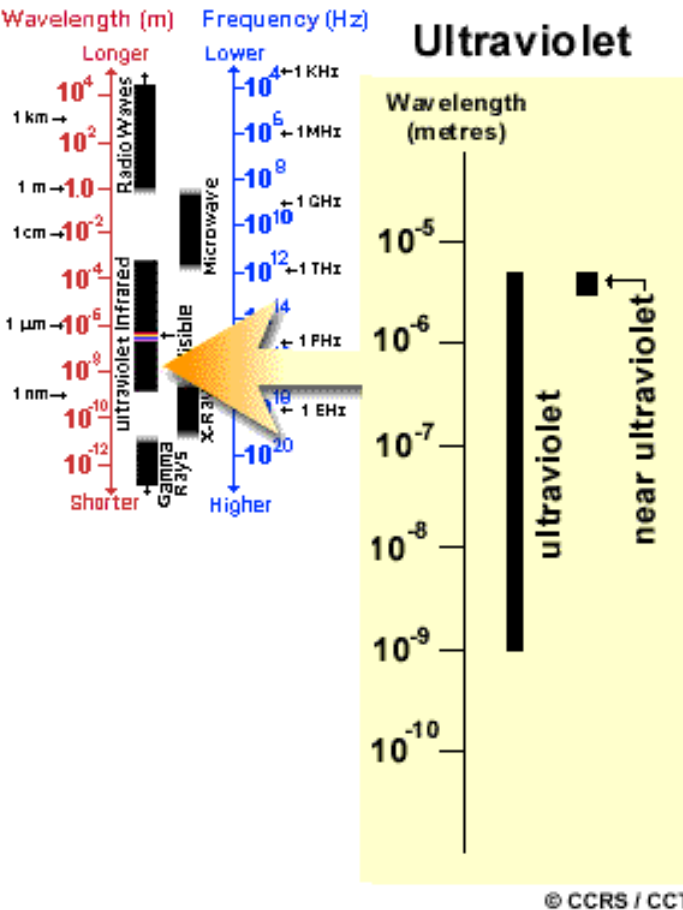
ν = frequency (cycles per second, Hz)

c = speed of light (3×10^8 m/s)

The **amplitude** of an electromagnetic wave is the height of the wave crest above the undisturbed position

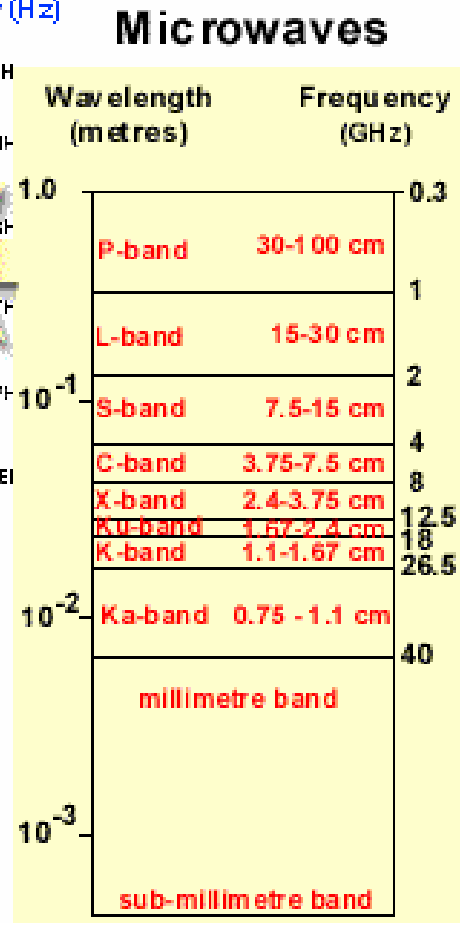
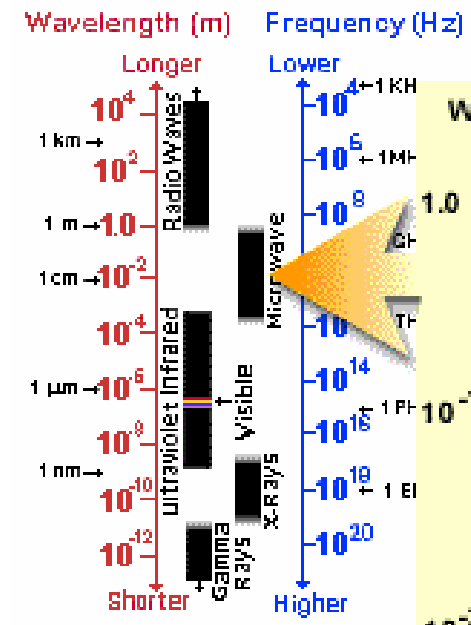
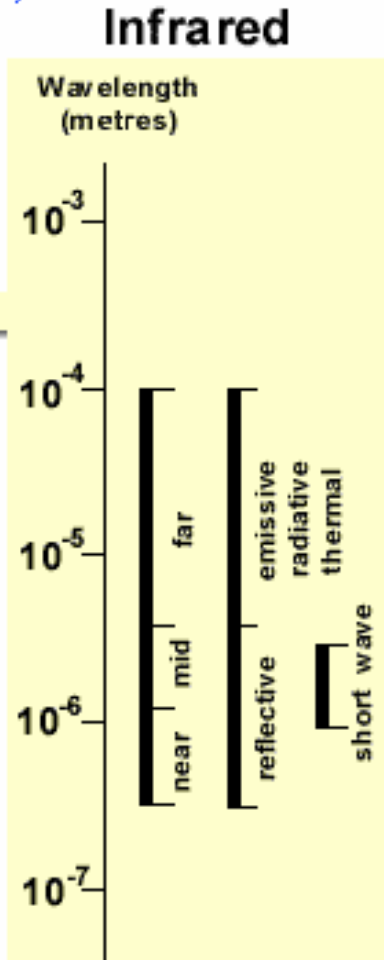
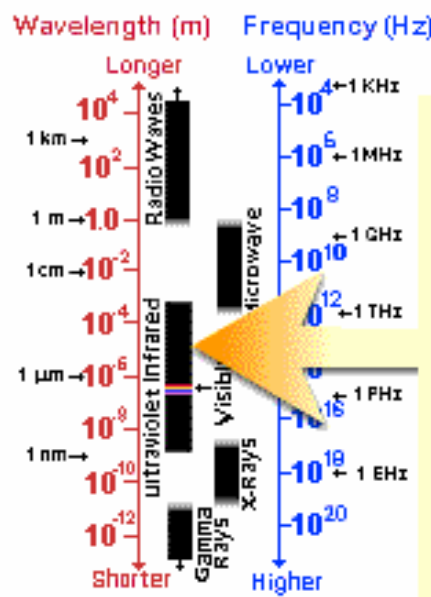
Travel time from the Sun to Earth is 8 minutes

EMR details



Bees and some other insects can see near UV.
The Sun is the source of UV, but only $> 0.3 \mu\text{m}$
(near UV) can reach the Earth.

EMR details (2)



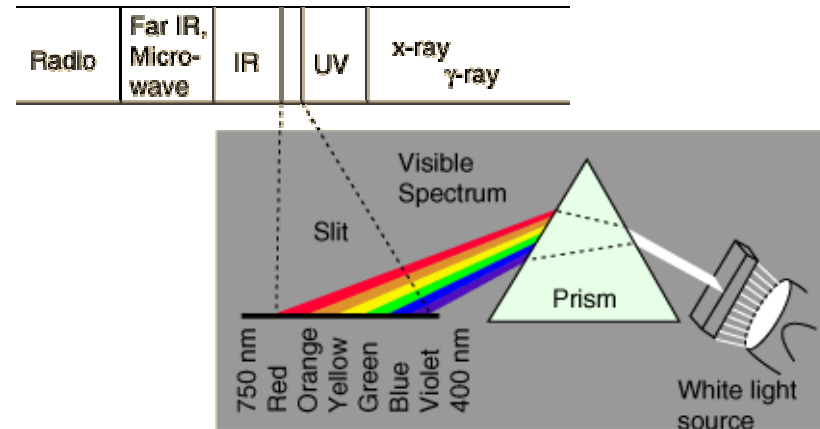
1B. Particle model

- Sir Isaac Newton (1704) was the first person stated that the light had not only wavelike characteristics but also light was a stream of particles, traveling in straight lines.
- Niels Bohr and Max Planck (20's) proposed the **quantum theory** of EMR:

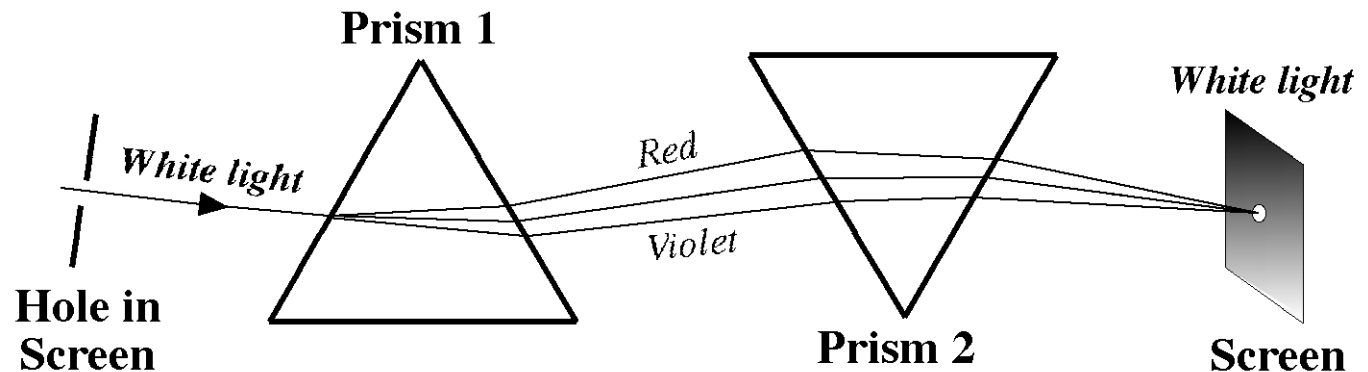
Energy content: Q (Joules) = $h\nu$ (h is the Planck constant 6.626×10^{-34} J s)

$$\lambda = c/\nu = hc/Q \quad \text{or} \quad Q = hc/\lambda$$

- The longer the wavelength, the lower its energy content, which is important in remote sensing because it suggests it is more difficult to detect longer wavelength energy



Newton's experiment in 1666

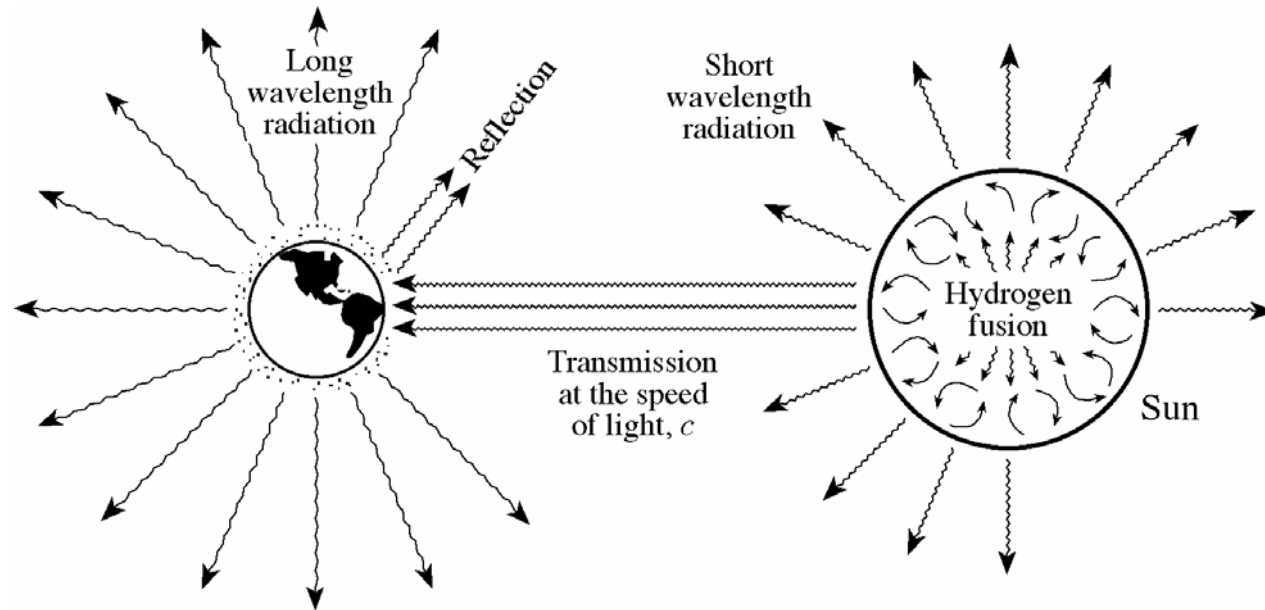


Energy of quanta (photons)

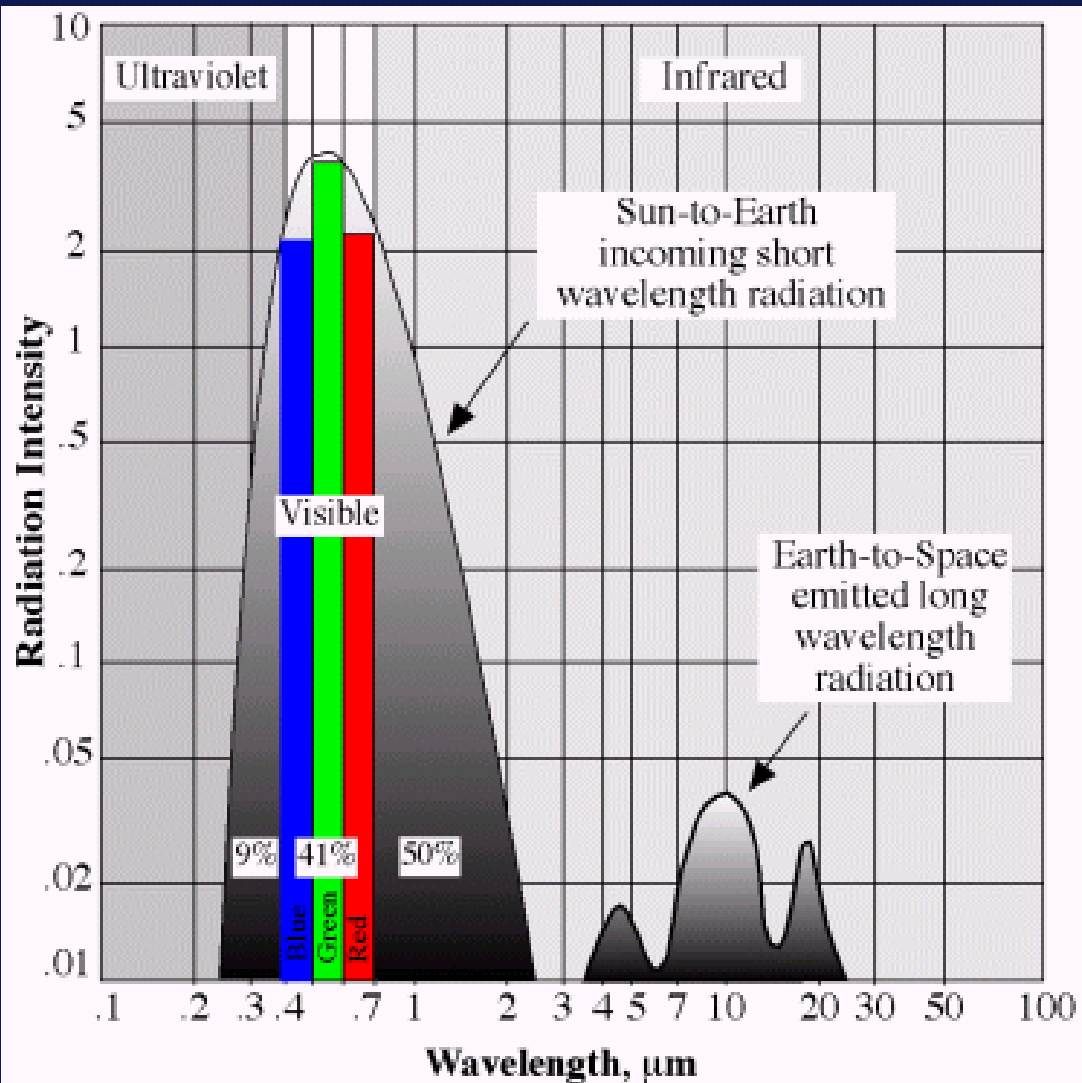
Energy (J)	Frequency (Hz)	Wavelength	Type of radiation	Absorption by atmosphere
10^{-28}	10^3	1000 km	Long radio waves Radio	[Grey shaded area]
10^{-28}	10^4	100 km		
10^{-28}	10^5	10 km		
10^{-27}	10^6	(1 mi) 1 km		
10^{-28}	10^7	100 m		
10^{-28}	10^8	10 m		
10^{-24}	10^9	1 m		
10^{-20}	10^{10}	10 cm		
10^{-18}	10^{11}	(1 in) 1 cm		
10^{-12}	10^{12}	1 mm		
10^{-11}	10^{13}	$\frac{1}{10}$ mm		
10^{-10}	10^{14}	$\frac{1}{100}$ mm		
10^{-18}	10^{15}	$1 \mu\text{m} = 10^{-6} \text{ m}$	Visible	Optical window
10^{-17}	10^{16}	$\frac{1}{10} \mu\text{m}$		
10^{-16}	10^{17}	$\frac{1}{100} \mu\text{m}$	Ultraviolet	[Grey shaded area]
10^{-15}	10^{18}	$10^{-9} \mu\text{m}$		
10^{-14}	10^{19}	10^{-10} m	X ray	[Grey shaded area]
10^{-13}	10^{20}	10^{-11} m		
10^{-12}	10^{21}	10^{-12} m	Gamma ray	[Grey shaded area]

2. Source of EMR

- All objects above absolute zero emit electromagnetic energy, including water, soil, rock, vegetation, and the surface of the Sun. The Sun represents the initial source of most of the electromagnetic energy remote sensing systems (except radar and sonar)
- Total radiation emitted M (Wm^{-2}) = σT^4 (**Stefan-Boltzmann Law**), where T is in degrees K and σ is the “Stefan-Boltzmann” constant, $5.67 \times 10^{-8} \text{ K}^{-4} \text{ Wm}^{-2}$
 - Energy at Sun enormous, $7.3 \times 10^7 \text{ Wm}^{-2}$, reduced to 459 Wm^{-2} by Earth-Sun distance
- Wavelength λ_{max} of peak radiation, in $\mu\text{m} = 2897/T$ (**Wien's Displacement Law**) Examples:
 - Peak of Sun's radiation $\lambda_{\text{max}} = 2897/6000 = 0.48 \mu\text{m}$
 - Peak of Earth's radiation $\lambda_{\text{max}} = 2897/300 = 9.7 \mu\text{m}$



Radiant Intensity of the Sun

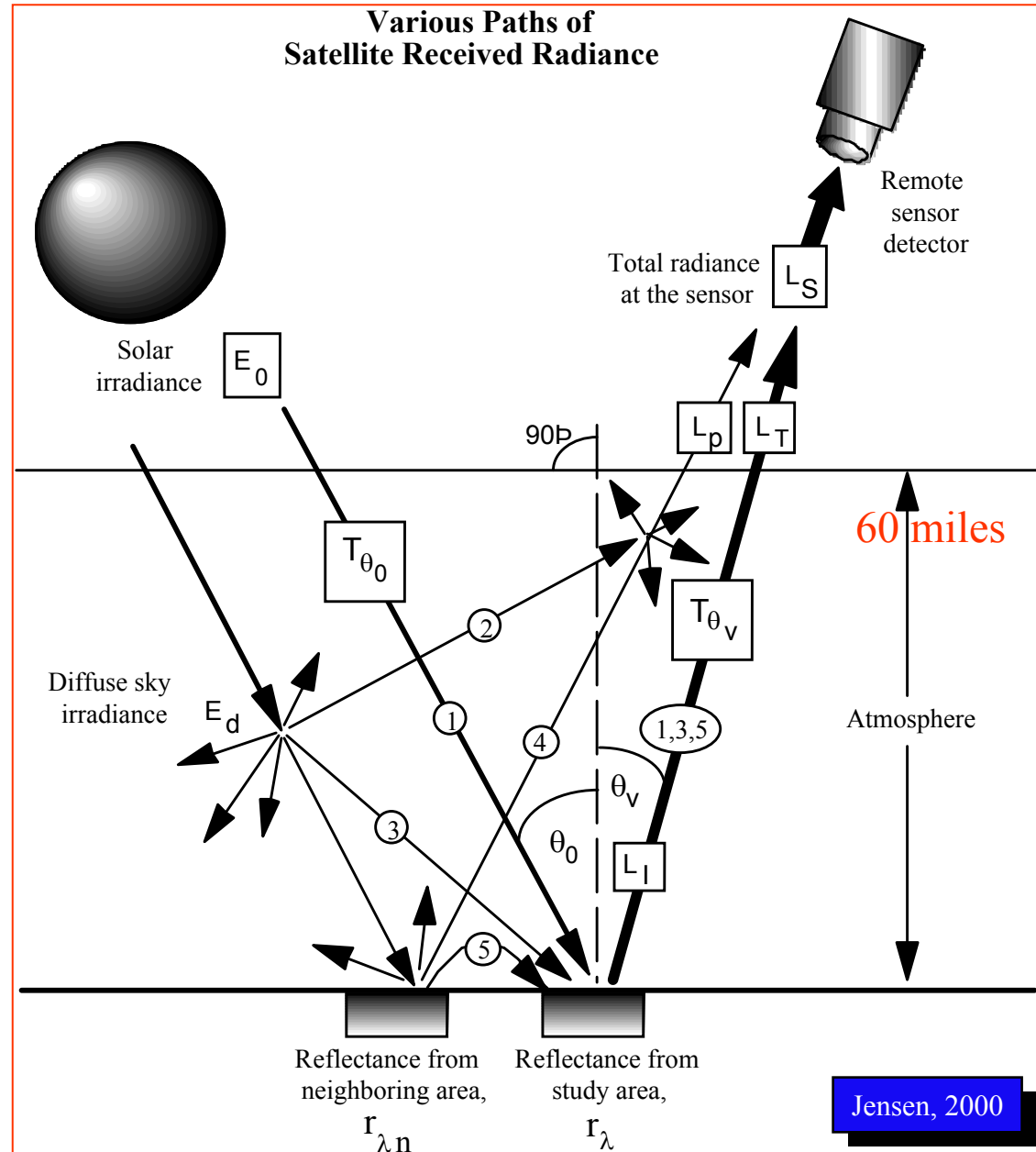


The Sun approximates a 6,000 K blackbody with a dominant wavelength of $0.5 \mu\text{m}$ (green light). Earth approximates a 300 K blackbody with a dominant wavelength of $9.7 \mu\text{m}$. The 6,000 K Sun produces 41% of its energy in the visible region from $0.4 - 0.7 \mu\text{m}$ (blue, green, and red light). The other 59% of the energy is in wavelengths shorter than blue light ($< 0.4 \mu\text{m}$) and longer than red light ($> 0.7 \mu\text{m}$). Eyes are only sensitive to light from the 0.4 to $0.7 \mu\text{m}$. Remote sensor detectors can be made sensitive to energy in the non-visible regions of the spectrum.

3. Paths and Interactions

If the energy being remotely sensed comes from the Sun, the energy:

- is radiated by atomic particles at the source (the Sun),
- propagates through the vacuum of space at the speed of light,
- interacts with the Earth's atmosphere (3A),
- interacts with the Earth's surface (3B),
- interacts with the Earth's atmosphere once again (3C),
- finally reaches the remote sensor where it interacts with various optical systems, filters, emulsions, or detectors (3D).

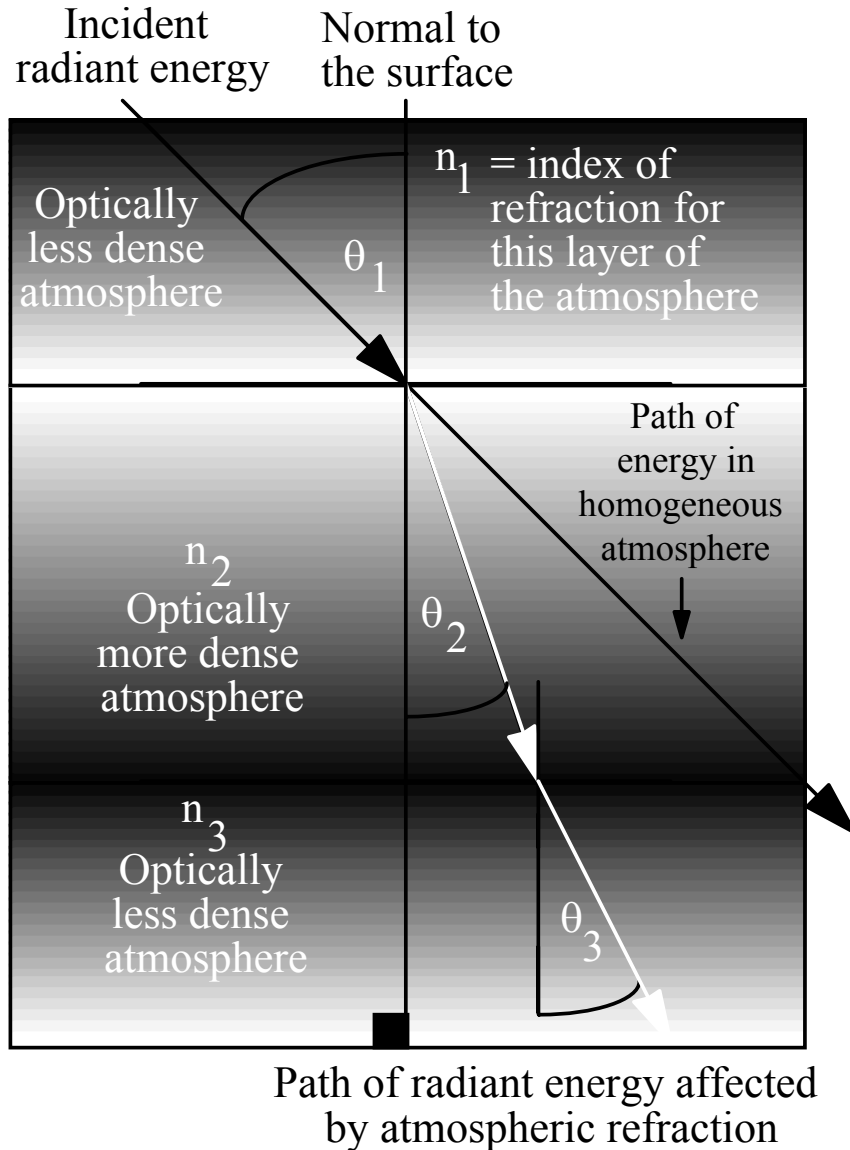


3A. Energy-Matter interactions in the atmosphere

- When the EMR propagated through the Earth's atmosphere almost at the speed of light in a vacuum, unlike a vacuum in which nothing happens, however, the atmosphere (solid, liquid, or gas) may affect not only the **speed** of radiation but also its **wavelength**, its **intensity**, its **direction (refraction)**, **polarization**, and its **phase**. This process called incident radiation.

Atmospheric refraction (transmission)

Atmospheric Refraction



Refraction in three non-turbulent atmospheric layers. The incident radiant energy is bent from its normal trajectory as it travels from one atmospheric layer to another. **Snell's law** ($n_1 \sin \theta_1 = n_2 \sin \theta_2 = n_3 \sin \theta_3$) can be used to predict how much bending will take place based on a knowledge of the angle of incidence and the optical density of each atmospheric level.

$$n_i = c/c_i$$

n_i index of refraction

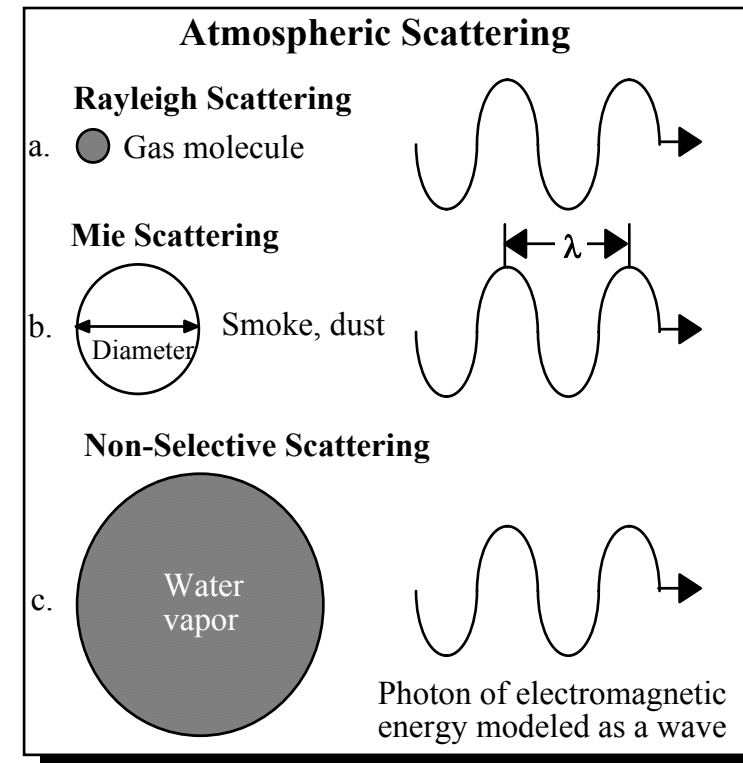
c speed of light in a vacuum

c_i speed of light in a substance

Jensen, 2000

Atmospheric scattering

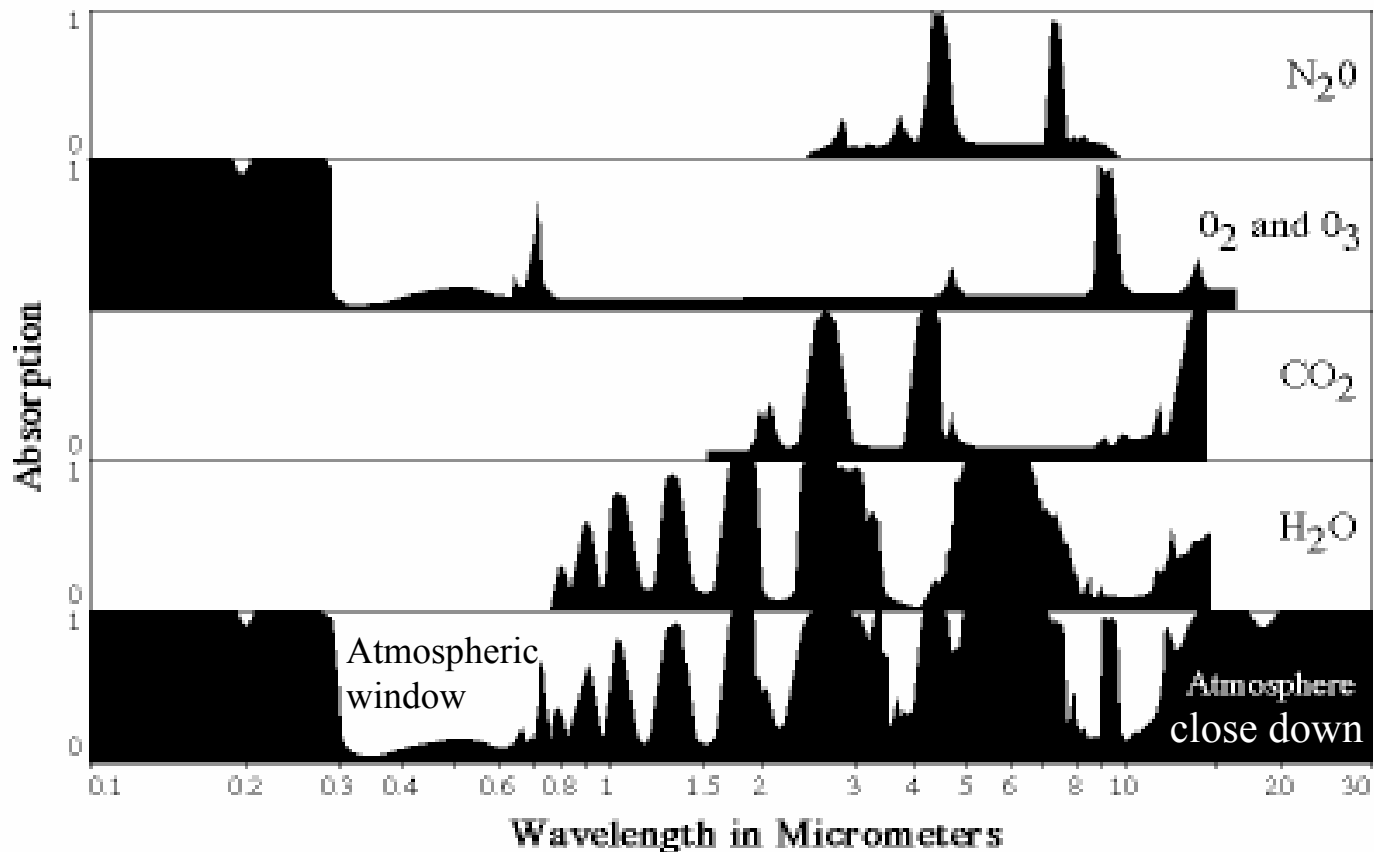
- Direction of scattering is unpredictable.
- Type of scattering is a function of
 - 1) the wavelength of the incident radiant energy and
 - 2) the size of the gas molecule, dust particle, and/or water vapor droplet encountered.
- Scattering severely reduce the contrast of remote sensing images
- **Rayleigh** (gas molecular such as N_2 and O_2) scattering (takes place in the upper 4.5 km), matter diameter is small than 0.1 times γ of the EMR, and the amount of scattering is γ^{-4} , violet and blue are more efficiently scattered (so we can see the blue sky and red sunset, residue of the sunlight)
- **Mie** scattering (smoke and dust in lower 4.5 km), matter diameter is 0.1-10 times the γ of the EMR, the amount of scatter is greater than Rayleigh scatter, violet and blue efficiently scattered, pollution also contributes to beautiful sunsets and sunrises.
- **Non-selective** scattering (water droplets and ice crystals in lowest portion of the atmosphere), matter diameter is larger than 10 times the γ of the EMR. All wavelengths of light are equally scattered, causing the cloud to appear white.



Absorption

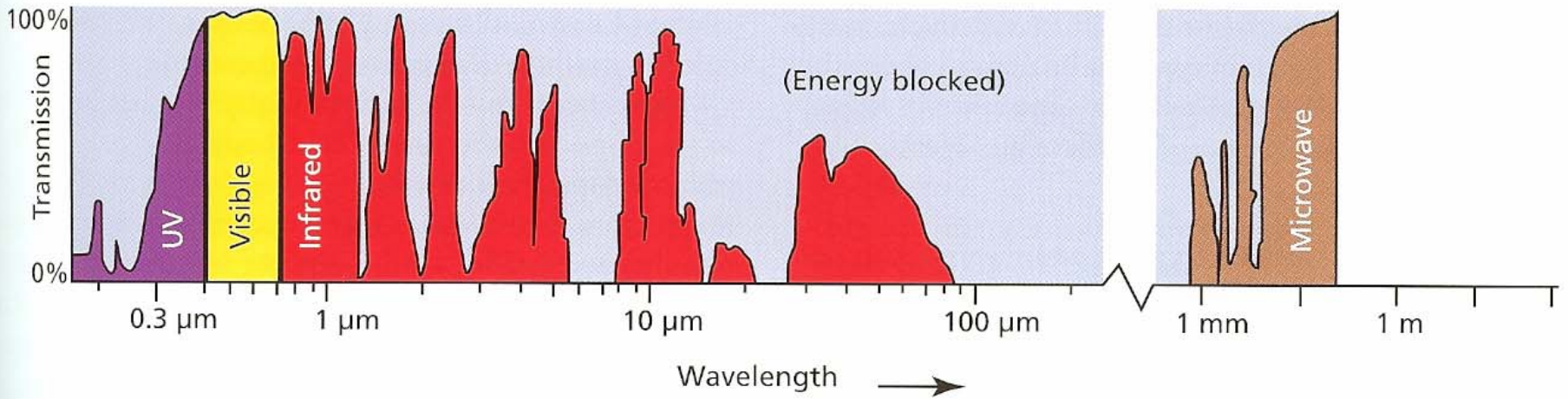
- Absorption is the process by which EMR is absorbed and converted into other forms of energy. The absorption of the incident radiant energy may take place in the atmosphere or on the terrain.
- Absorption occurs when an atom or molecule has a same frequency (resonant frequency) as the incident energy. The incident energy is transformed into heat motion and is then reradiated (emission) at a longer wavelength.
- An absorption band is a range of λ in the EM spectrum within which radiant energy is absorbed by a substance.
- Some wavelengths of radiation are affected far more by absorption than by scattering. Especially in infrared and ultra-violet.
- Absorption plays a very important role in remote sensing, such as Chlorophyll in vegetation absorbs blue and red light for photosynthetic purposes; water is an excellent absorber of energy; many minerals have unique absorption characteristics.

The Sun's absorption spectrum

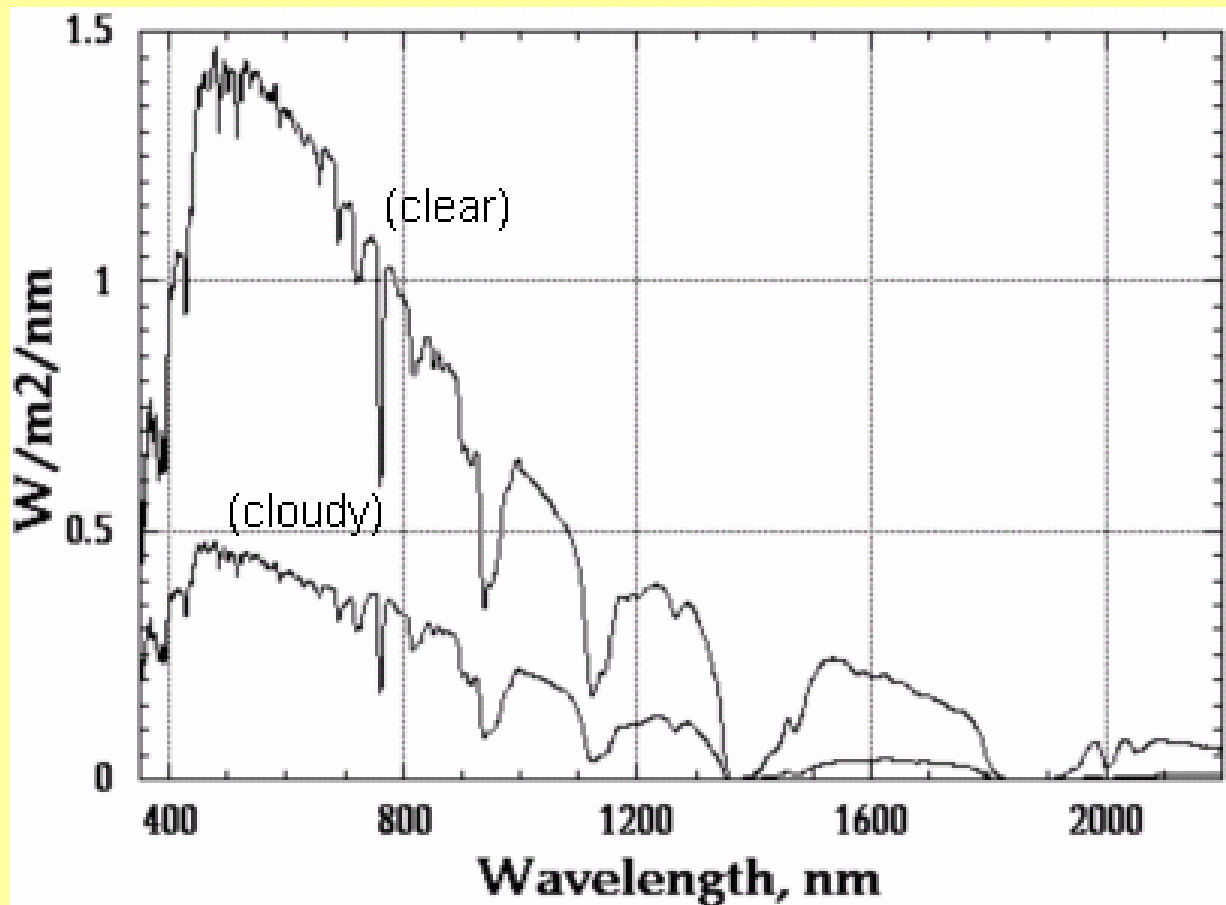


The absorption of the Sun's incident electromagnetic energy in the region from 0.1 to 30 μm by various atmospheric gasses. The first four graphs depict the absorption characteristics of N_2O , O_2 and O_3 , CO_2 , and H_2O . The final graphic depicts the cumulative result of having all these constituents in the atmosphere at one time. The atmosphere essentially closes down in certain portions of the spectrum while there exist "atmospheric windows" in other regions that transmit incident energy effectively to the ground. It is within these windows that remote sensing systems function, including 0.3-2.4, 3-5, 8-14 μm , and > 0.6 cm. Most of these windows become less transparent when air is moist; clouds absorb most of longer wave emitted from the Earth, that is why cloudy nights tend to be warmer than clear nights. Only >0.9 cm can penetrating clouds

b. Atmospheric transmittance



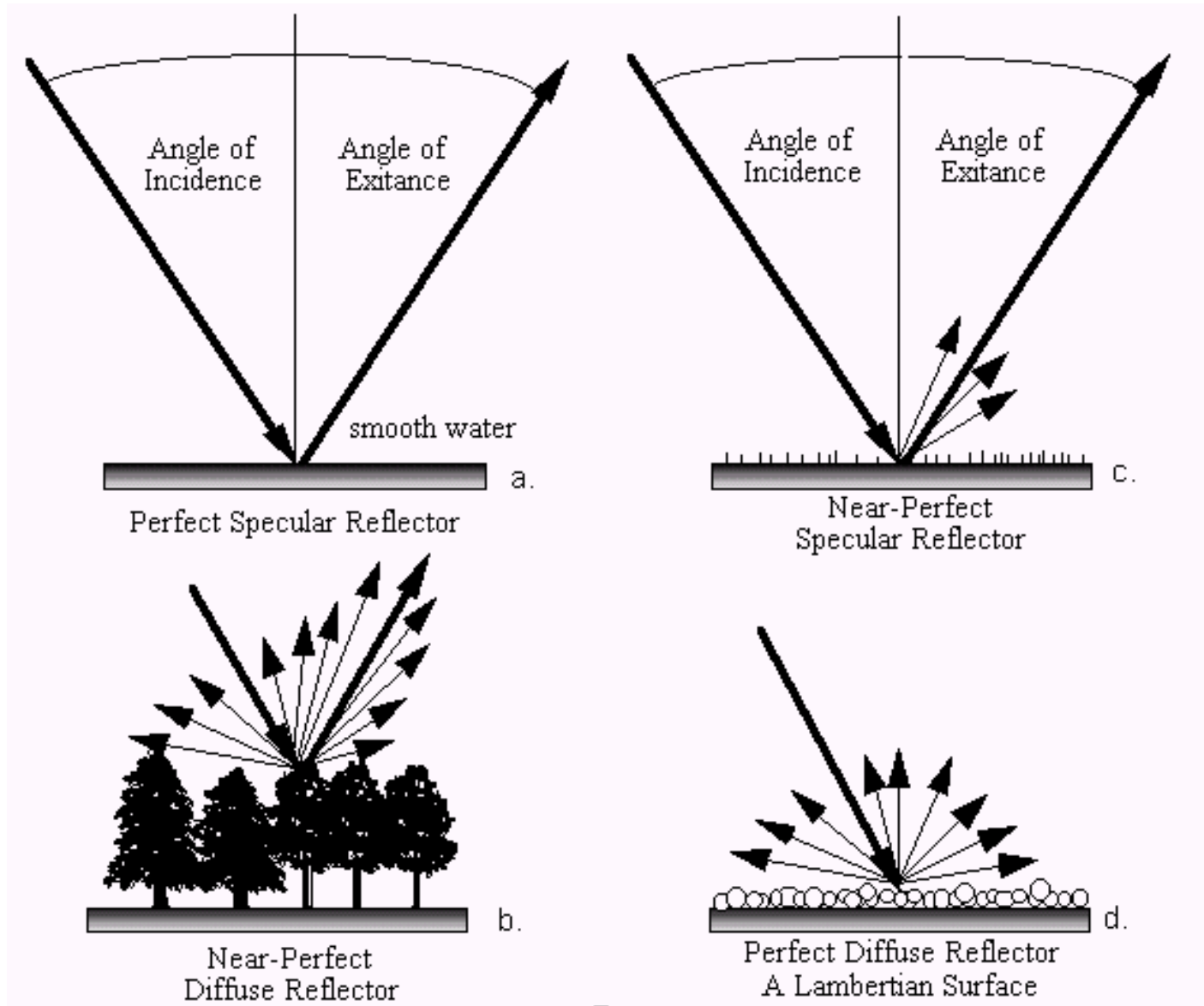
Atmospheric absorption of solar irradiance



Reflectance

- Reflectance is the process whereby radiation “bounces off” an object like the top of a cloud, a water body, or the terrestrial Earth.
- **Two features:**
 - the incident radiation, the reflected radiation, and a vertical to the surface from which the angles of the incidence and reflection are measured all lie in the same plane
 - the angle of incidence and the angle of reflection (exitance) are approximately equal.
- **Two types:**
 - specular reflection
 - diffuse reflection
- A considerable amount of incident radiant flux from the Sun is reflected from the tops of clouds and other materials in atmosphere. A substantial amount of this energy is reradiated back to space.

Specular versus diffuse reflectance



3B. Energy-Matter interactions with the terrain

- **Radiant flux** (Φ , in **Watts**): the amount of radiant energy onto, off of, or through a surface per unit time.
- **Radiation budget equation:**

$$\Phi_{i\lambda} = \Phi r_{\lambda} + \Phi \tau_{\lambda} + \Phi \alpha_{\lambda},$$

reflectance: $r_{\lambda} = \Phi r_{\lambda} / \Phi_{i\lambda}$

transmittance: $\tau_{\lambda} = \Phi \tau_{\lambda} / \Phi_{i\lambda}$

absorptance: $\alpha_{\lambda} = \Phi \alpha_{\lambda} / \Phi_{i\lambda}$

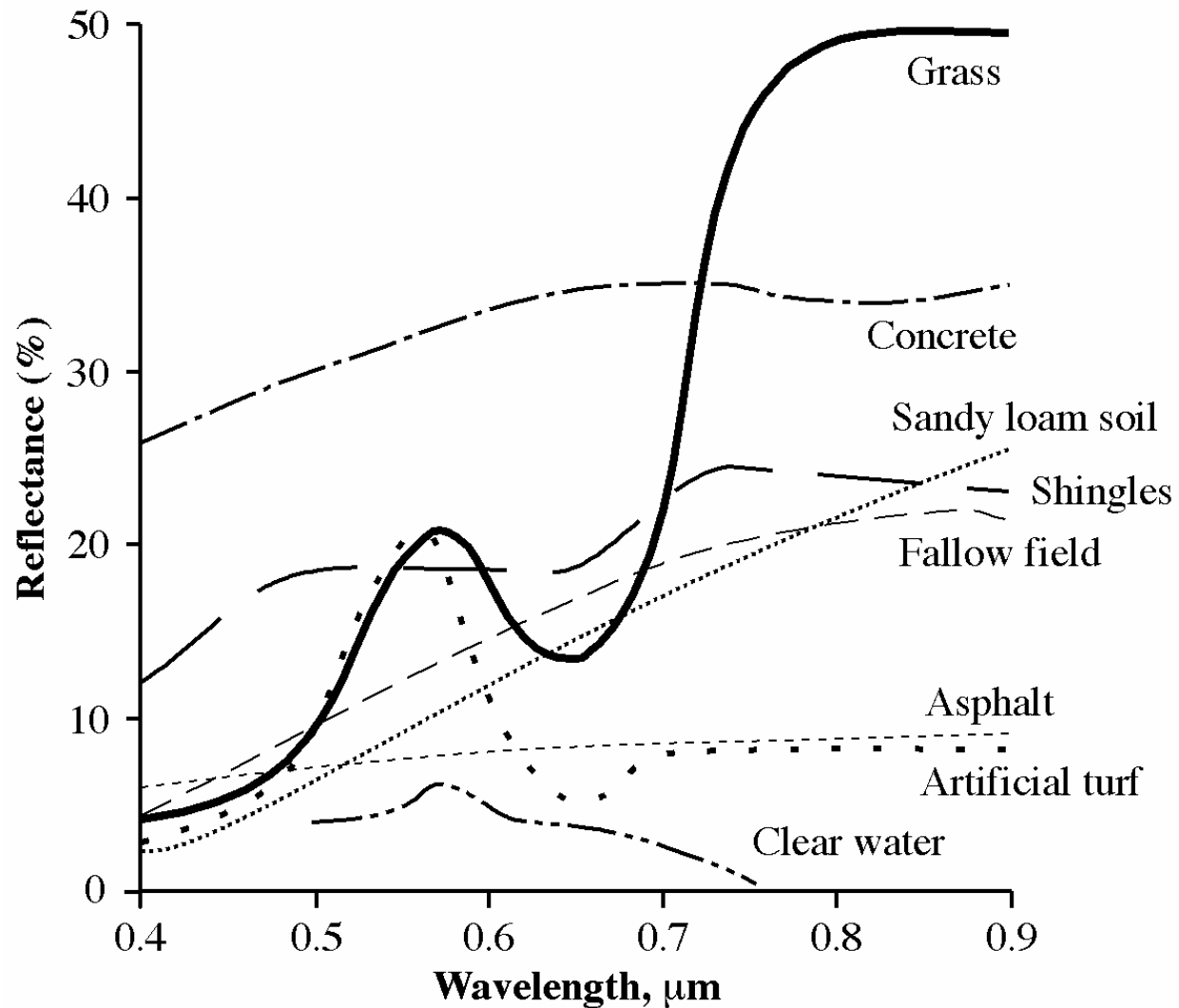
$$1 = r_{\lambda} + \tau_{\lambda} + \alpha_{\lambda}$$

they are based on a hemisphere. Clear glass has high τ_{λ} , so the r_{λ} and α_{λ} should be low; fresh snow has high r_{λ} , so τ_{λ} and α_{λ} are low; fresh asphalt has high α_{λ} , so

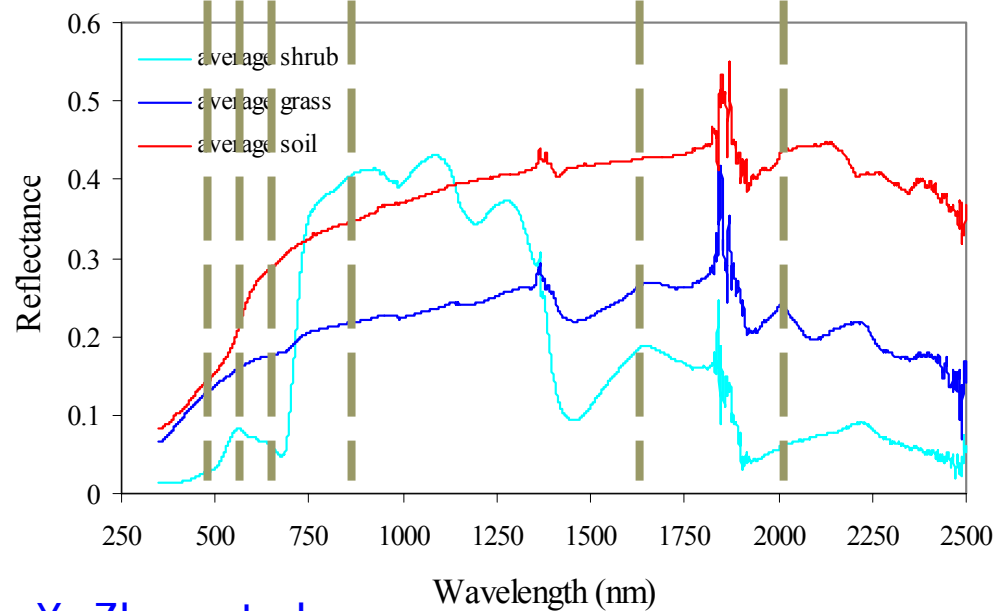
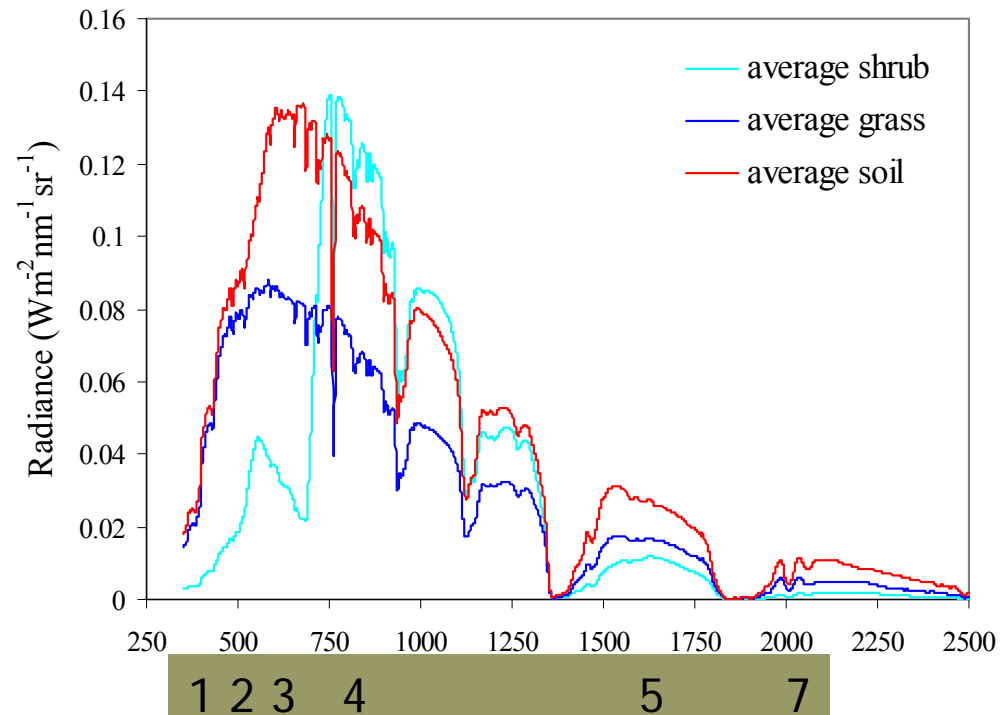
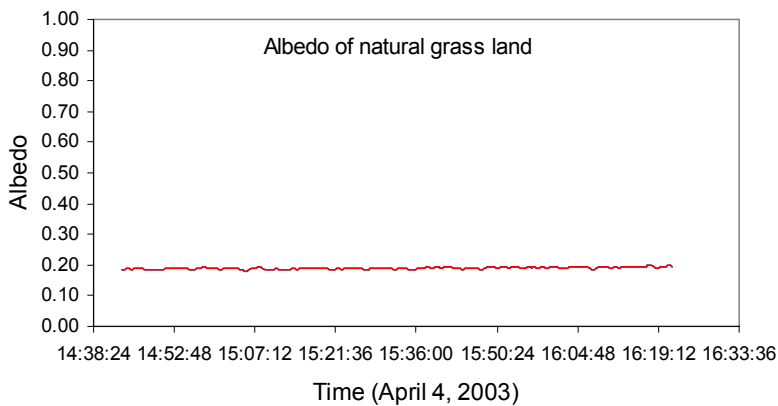
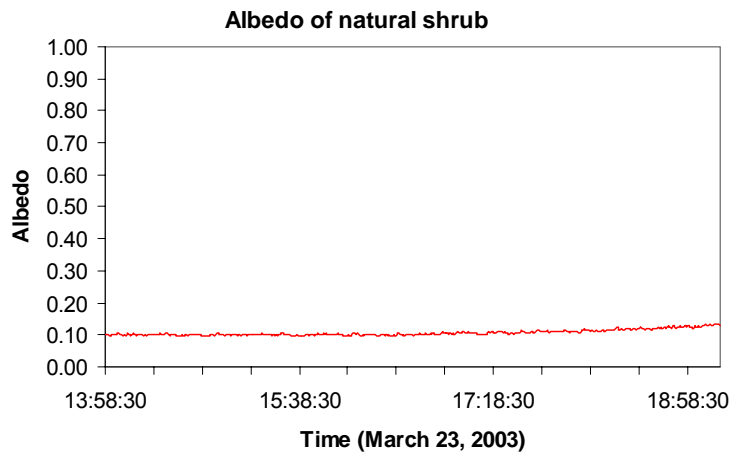
$R_{\lambda} = (\Phi r_{\lambda} / \Phi_{i\lambda}) \times 100$, this is **spectral reflectance** (reflectance at specified wavelength intervals)

- **Albedo** is ratio of the amount of EMR reflected by a surface to the amount of incident radiation on the surface. Fresh Snow has high albedo of 0.8-0.95, old snow 0.5-0.6, forest 0.1-0.2, Earth system 0.35

Selected reflectance curves

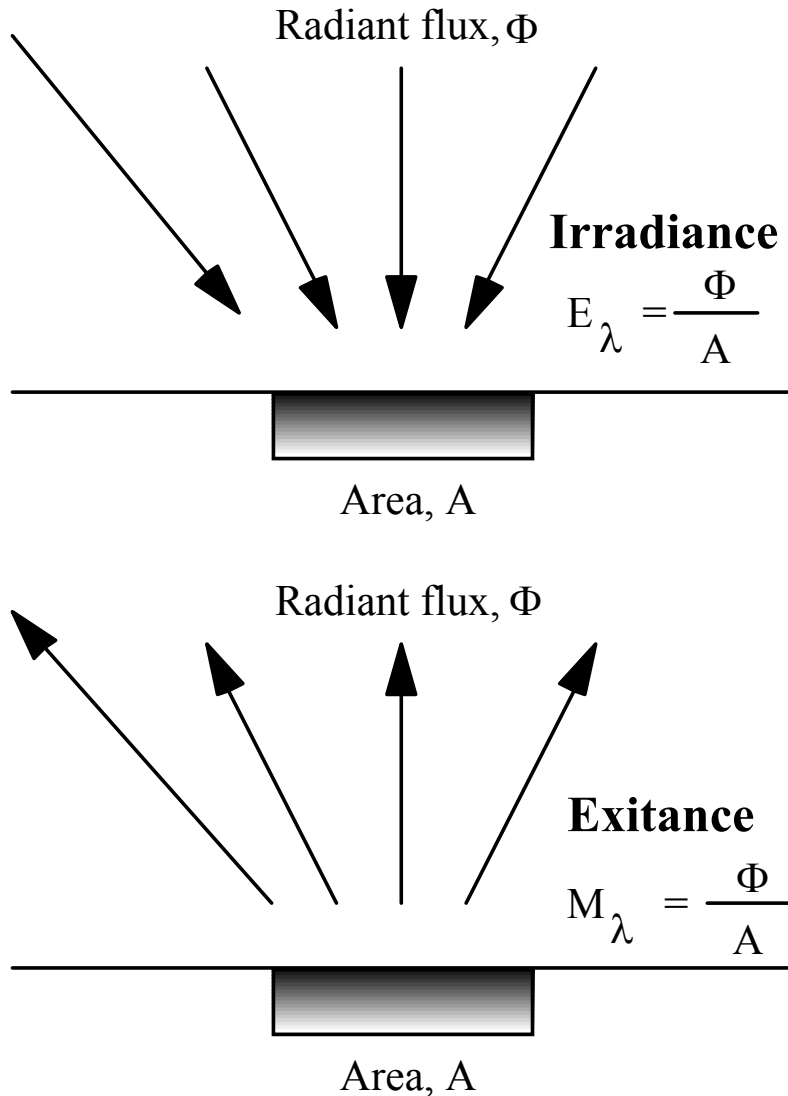


Some Results



Source: X. Zhou et al.

Concept of Radiant Flux Density

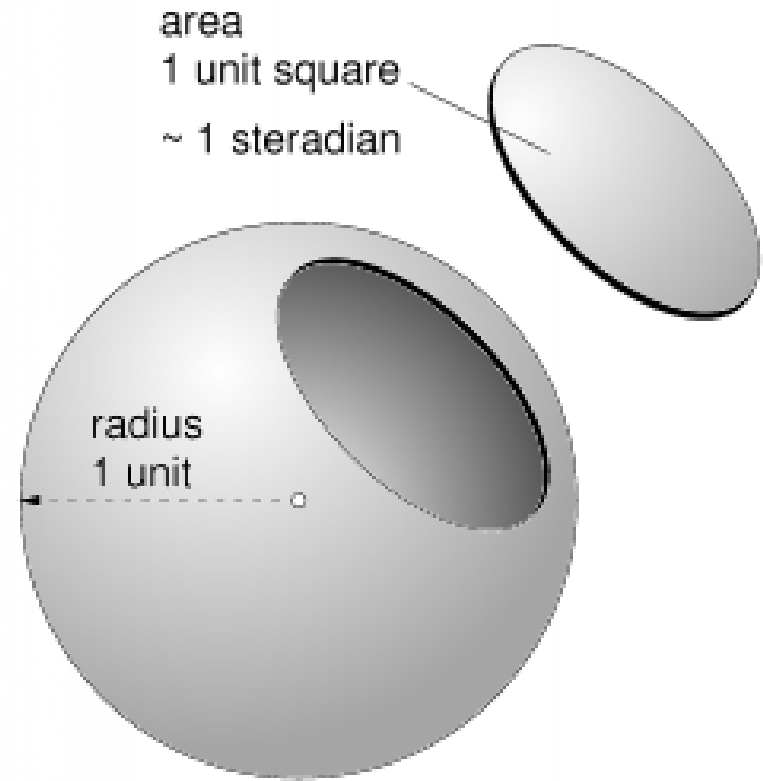


- **Irradiance** is a measure of the amount of incoming energy in **Watts m^{-2}** .
- **Exitance** is a measure of the amount of energy leaving in **Watts m^{-2}**
- **Radiance** (L_{λ}) is the amount of EMR leaving or arriving at a point on a surface, is the most precise remote sensing radiometric measurement. It is measured in Watts per meter squared per steradian (**$W m^{-2} sr^{-1}$**), or it is measure in Watts per meter squared per wavelength per steradian (**$W m^{-2} \mu m^{-1} sr^{-1}$**)

Wavenumber (ν) = $1/\lambda$, λ is wavelength (μm). traditionally, ν is expressed in inverse cm, so $\nu = 10^4/\lambda$ (cm^{-1})

Solid angle

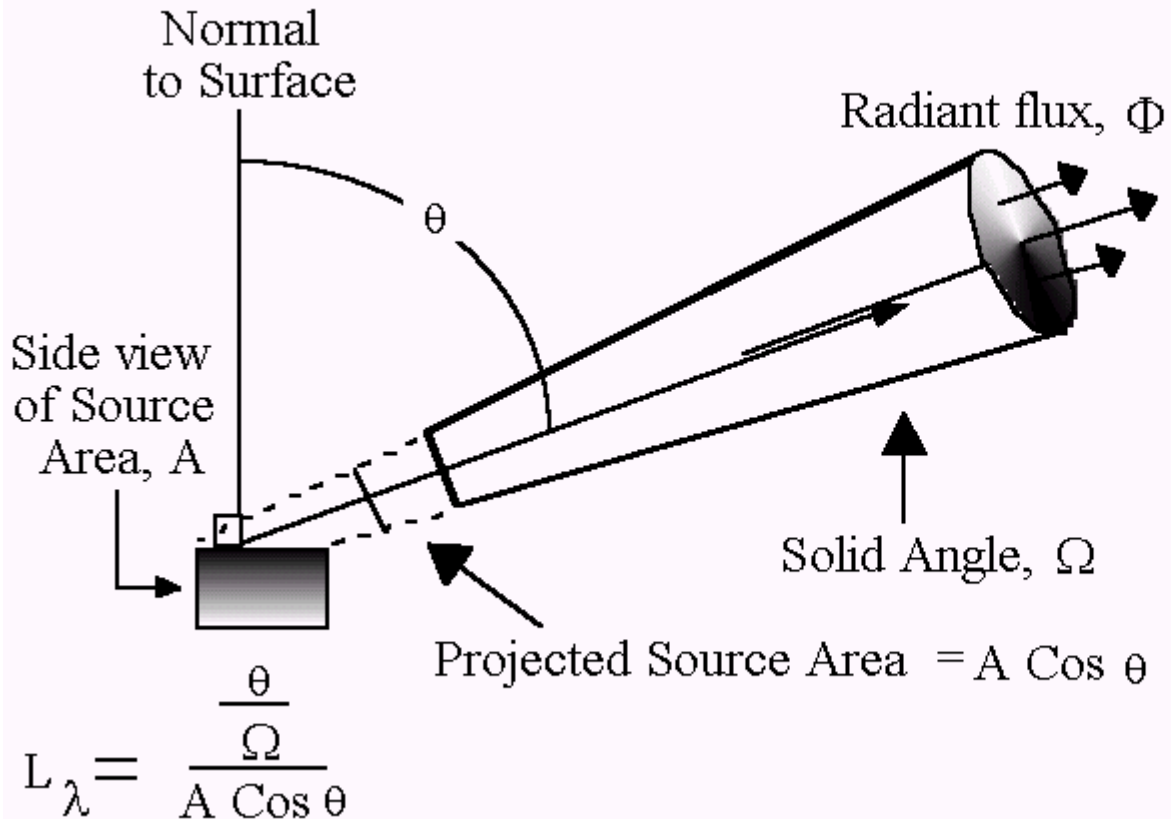
- The angle that, seen from the center of a sphere, includes a given area on the surface of that sphere. The value of the solid angle is numerically equal to the size of that area divided by the square of the radius of the sphere
- The maximum solid angle is ~ 12.57 , corresponding to the full area of the unit sphere, which is 4π .
- Standard unit of a solid angle is the **Steradian (sr)**.
(Mathematically, the solid angle is unitless, but for practical reasons, the steradian is assigned.)



$$\Omega = A / r^2$$

Concept of radiance

Concept of Radiance



The concept of radiance leaving a specific projected source area on the ground, in a specific direction, and within a specific solid angle. This is the most precise radiometric measurement used in remote sensing.

θ is the zenith angle

sr: steradian

3C. Energy-Matter interactions in the atmosphere once again

- The radiant flux reflected or emitted from the Earth's surface once again enters the atmosphere, where it interacts with the various gases, water vapor, and particulates. Thus, the atmospheric scattering, absorption, reflection, and refraction (or transmission) influence the radiant flux once again before the energy is recorded by the remote sensing system.

3D. Energy-Matter interactions in the sensor system

- When the energy finally reaches the remote sensor, the radiance will interact with either the **camera** filter, the optical glass lens, and the film emulsion or optical-mechanical **detector** which record the number of photons in very specific wavelength regions reaching the sensor.
- Ideally, the radiant recorded by remote sensor is the amount of radiance leaving the terrain at a specific solid angle. Unfortunately, other radiant energy from various other paths may also enter the sensor's instantaneous field of view (IFOV). This will introduce noise.
- Various paths and factors for the noise are summarized from path 1 to path 5.

- Path 1: solar irradiance (E_0) and atmospheric transmittance (T)
- Path 2: Diffuse sky irradiance (E_d)
- Path 3: after some scattering, absorption, and/or reemission
- Path 4: radiance from nearby terrain
- Path 5: reflect or scatter from nearby terrain.

Total amount of radiation from study area

$$L_T =$$

Path radiation

$$L_p =$$

Total radiation recorded by the sensor

$$L_s = L_T + L_p$$

- A great deal of research has been done to computer the atmospheric transmission and path radiance, and then remove them. This is a big remote sensing topic.

