Remote Sensing for Agricultural Applications: Principles and Techniques (2023-2024)

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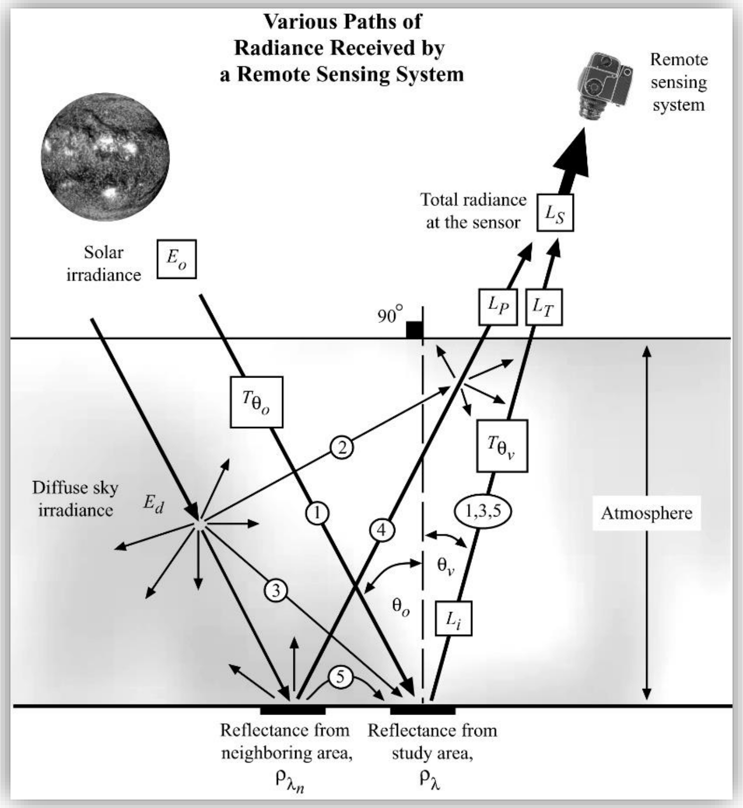
Lecture 2: Principles of electromagnetic radiation

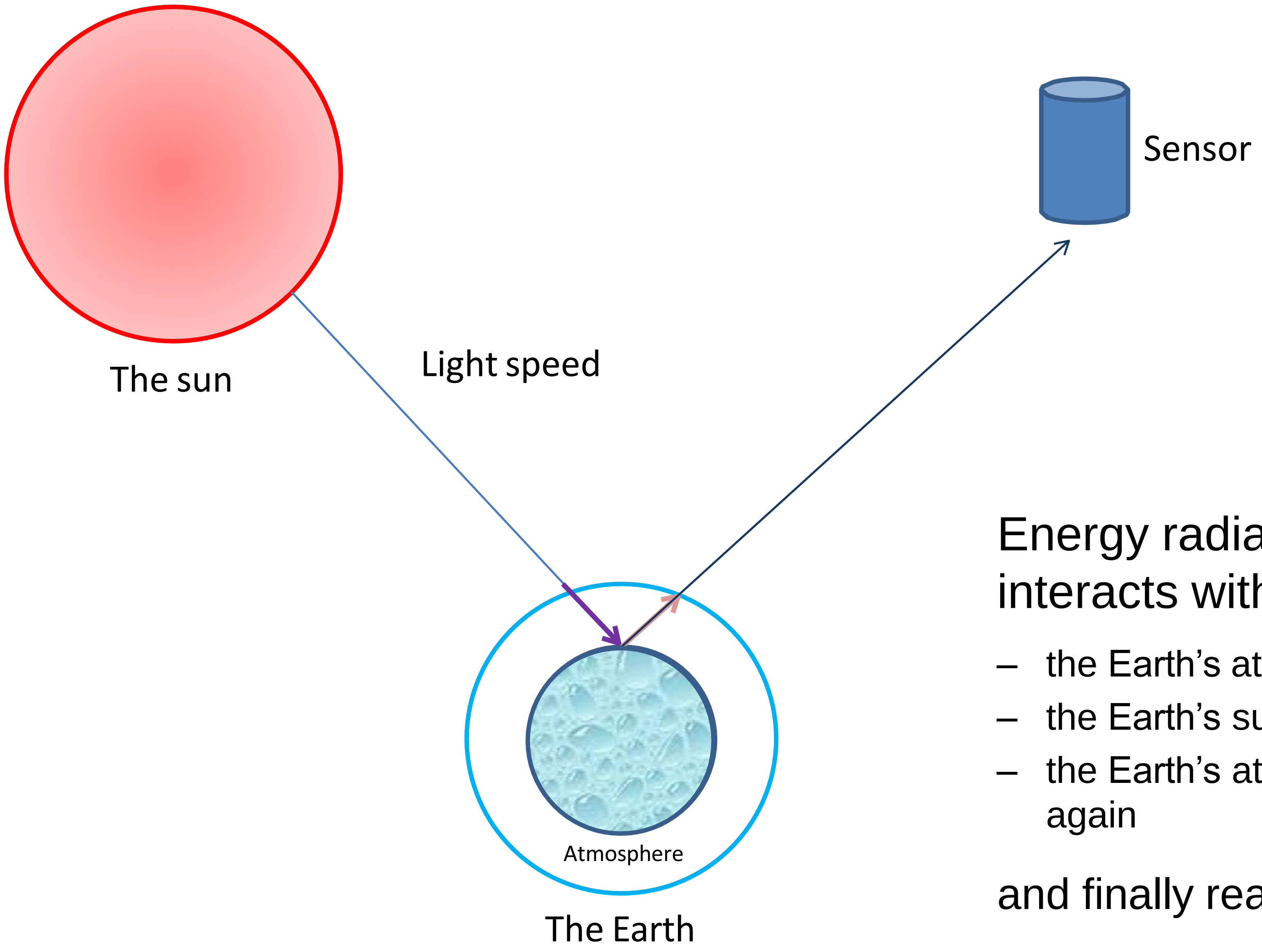


October 18, 2023

Outline

- Concepts:
  - Electromagnetic (EM) radiation
  - Atmospheric scattering
  - Absorption and reflectance
  - Irradiance and radiance
  - Signals received at the sensor
- Objectives:
  - To figure out how remote sensing works
  - To understand the atmospheric attenuation of EM signals

Electromagnetic Energy Interactions

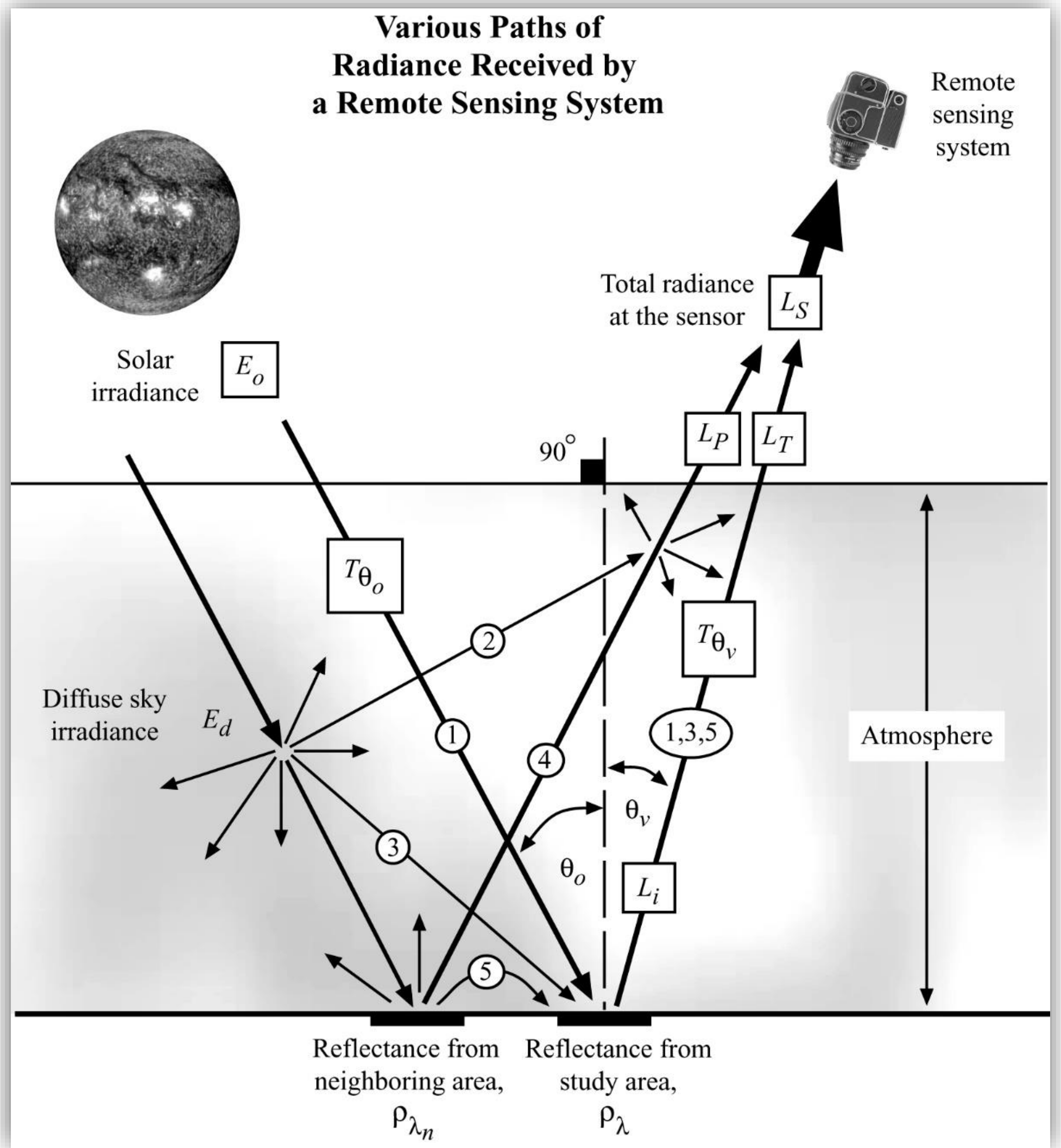


Energy radiated from the sun interacts with:

- the Earth's atmosphere
- the Earth's surface
- the Earth's atmosphere again

and finally reaches the sensor.

In detail

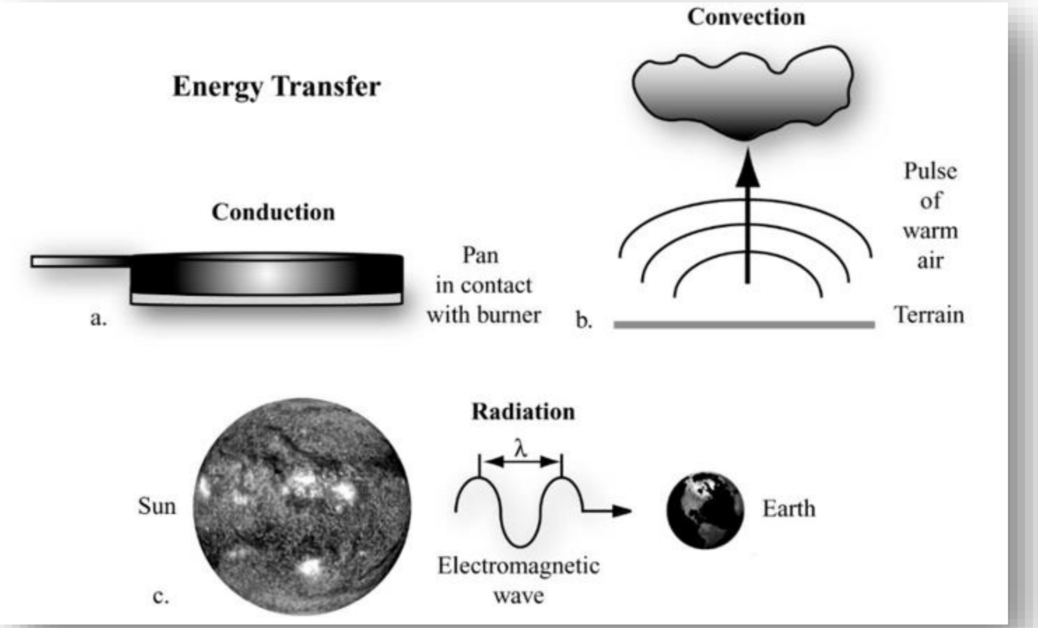


Energy-matter interactions in the atmosphere, over the study area, and at the remote sensor.

How to sort it out?

Jensen (2006)

How is energy transferred?



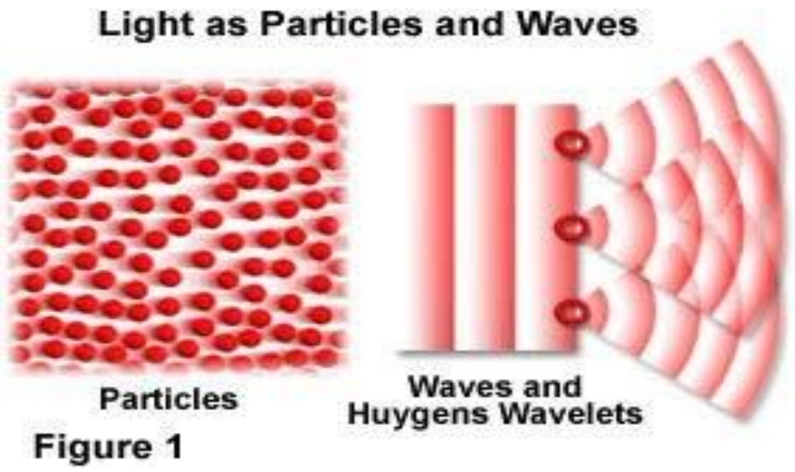
Jensen (2006)

Energy may be transferred in three ways:

- *Conduction:* conducted directly from one object to another in direct physical contact
- *Convection:* movement in the atmosphere caused by warm gas and cold gas
- ***Radiation*: transmitted in the form of electromagnetic (EM) waves that you cannot see**

Electromagnetic radiation models

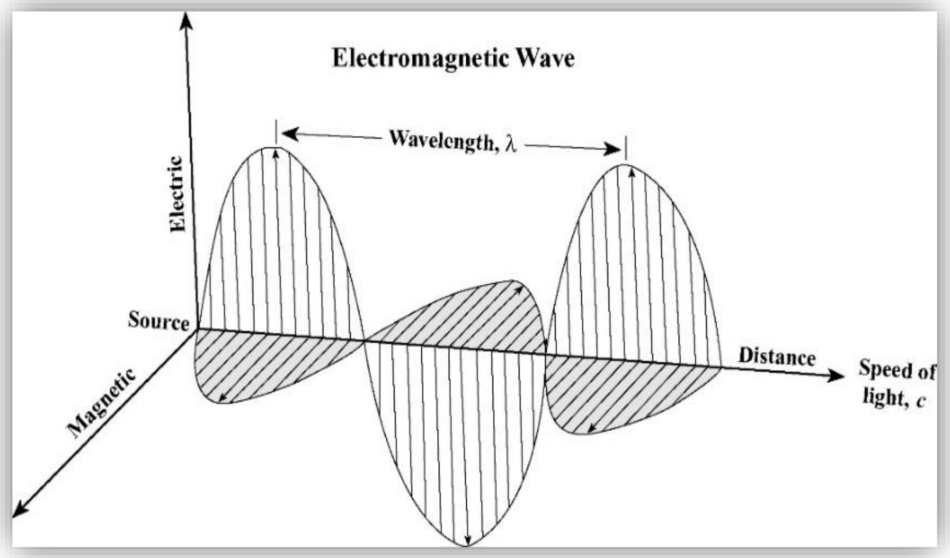
- We can better understand the process of EM radiation using two models:
  - – the ***wave*** model (e.g., wavelength)
  - – the ***particle*** model (e.g., photons interact with leaves)



High school physics: wave-particle duality

Figure from https://www.olympus-lifescience.com.cn/en/

The wave model of EM energy



Jensen (2006)

$$\lambda = \frac{c}{\nu}$$

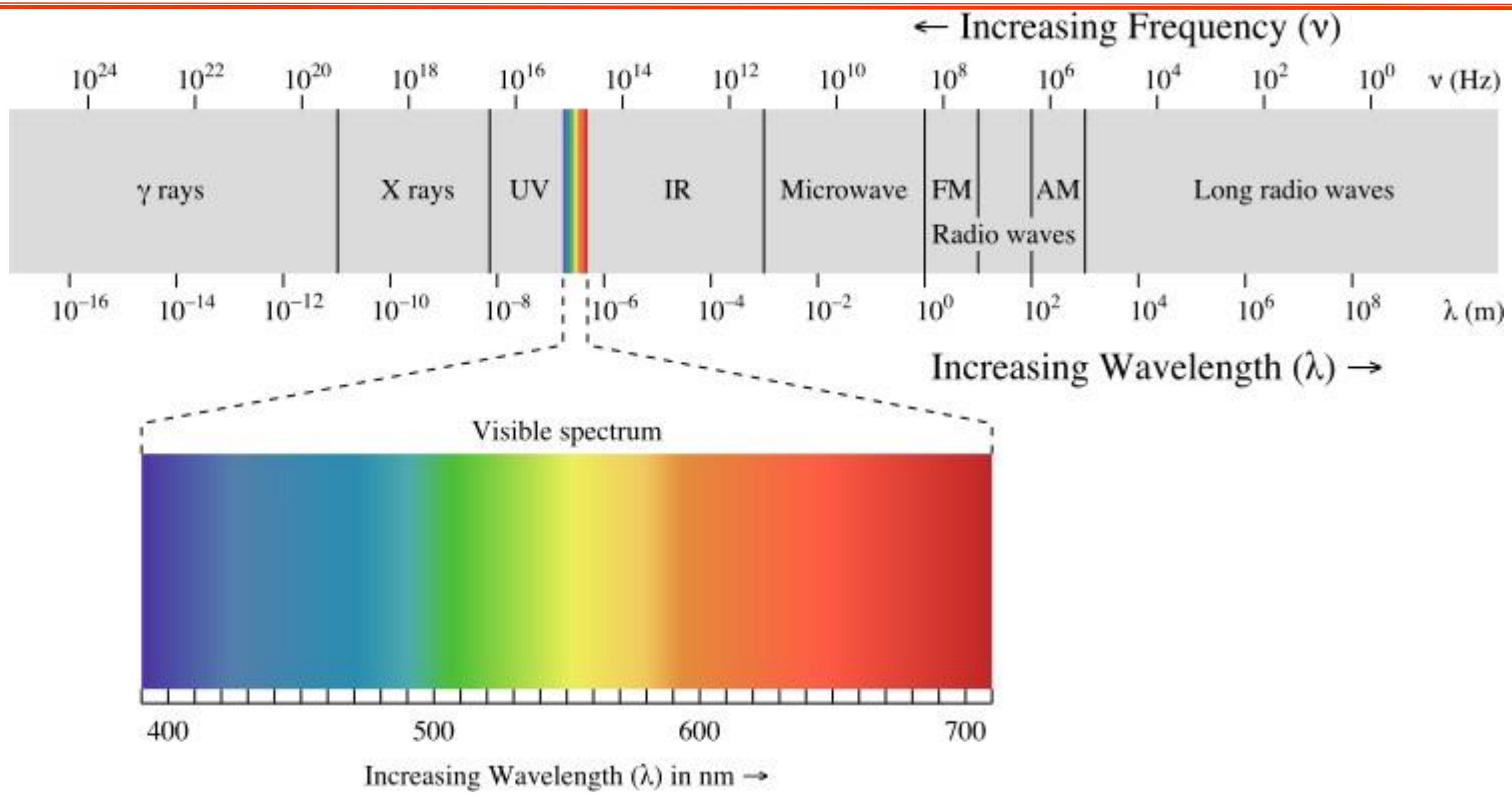
$$\nu = \frac{c}{\lambda}$$

c is the speed of light.

Key concepts:

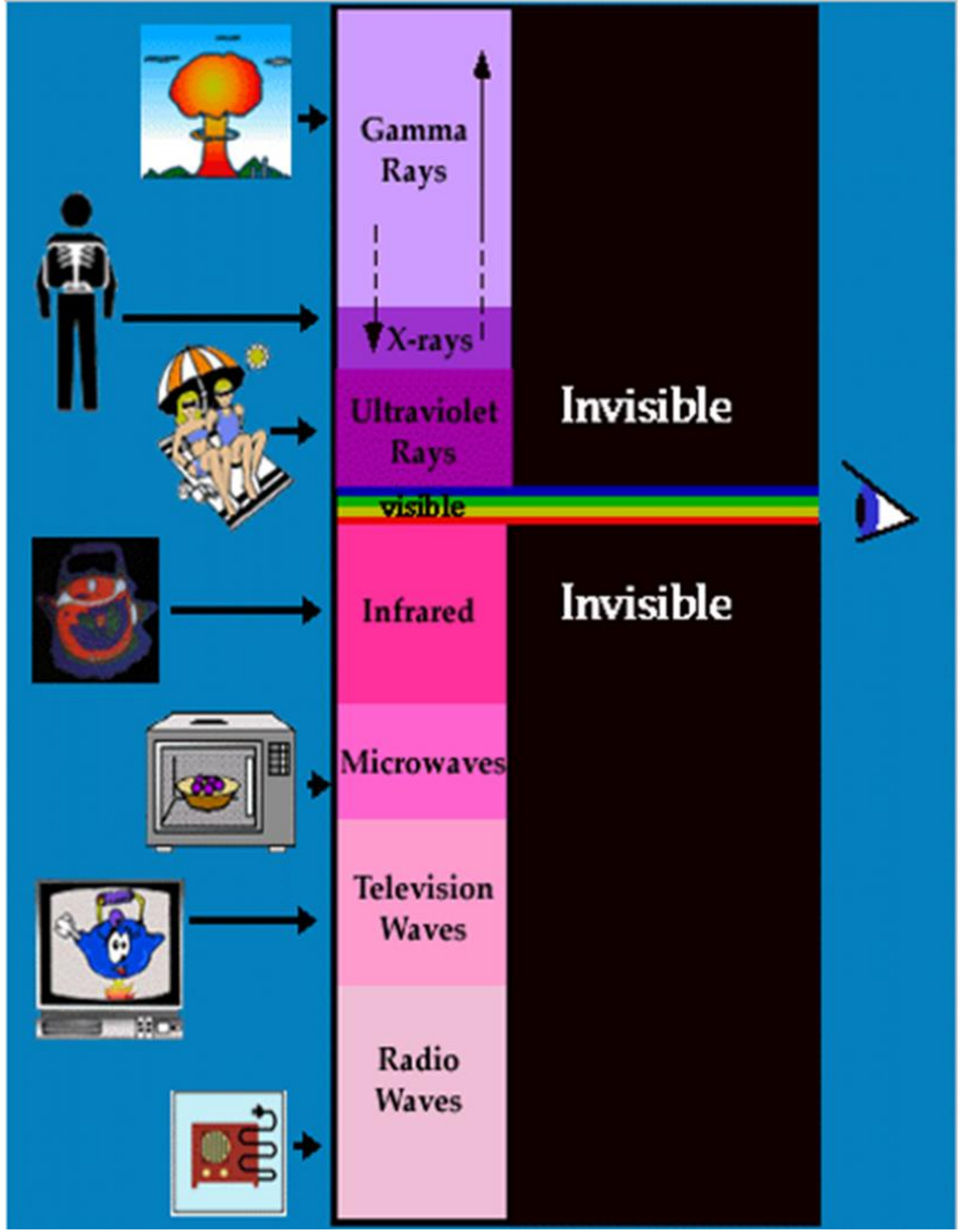
- Wavelength (λ)
  - The mean distance between two consecutive maxima
  - Normally measured in μm or nm
- Frequency (ν)
  - The number of wavelengths that pass a point per unit time
  - Normally measured in Hz
- λ is inversely proportional to ν.

The EM spectrum



A small portion of the EM spectrum

Figure from Wikipedia (http://en.wikipedia.org/wiki/Electromagnetic_radiation)



Q1:
Is any of these names new to you?

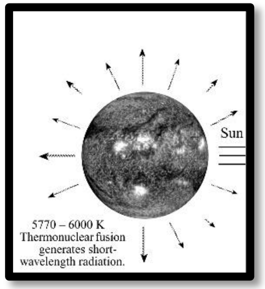
Classification and names of EM waves

Name		Wavelength (nm)
Ultraviolet		10-400
Visible*		400-760
Infrared	Near-infrared*	760-1300
	Shortwave infrared*	1300-3000
	Mid-wave infrared	3000-8000
	Thermal*	8000-14000
	Far infrared	>14000

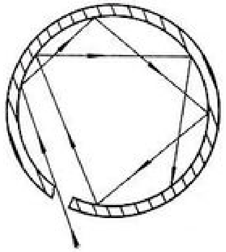
- Note the unit conversion： 1000 nm = 1 μm
- Remember important wave names and learn the RS language.

Blackbody

- Is a ***reference*** for understanding radiation. The Sun and the Earth are approximate blackbodies at 6000 K and 300 K, respectively.



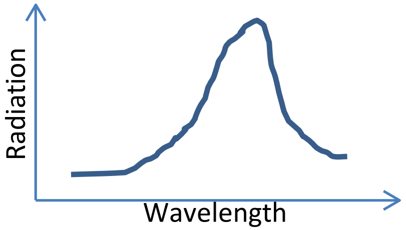
- Has no reflection and transmission. It will absorb all the incoming energy.



- Emits more radiation than any other object under the same temperature.

- Its radiation is dependent on temperature and wavelength (bell-shaped).

Q2:
Why bring in blackbody here?



Stefan-Boltzmann law

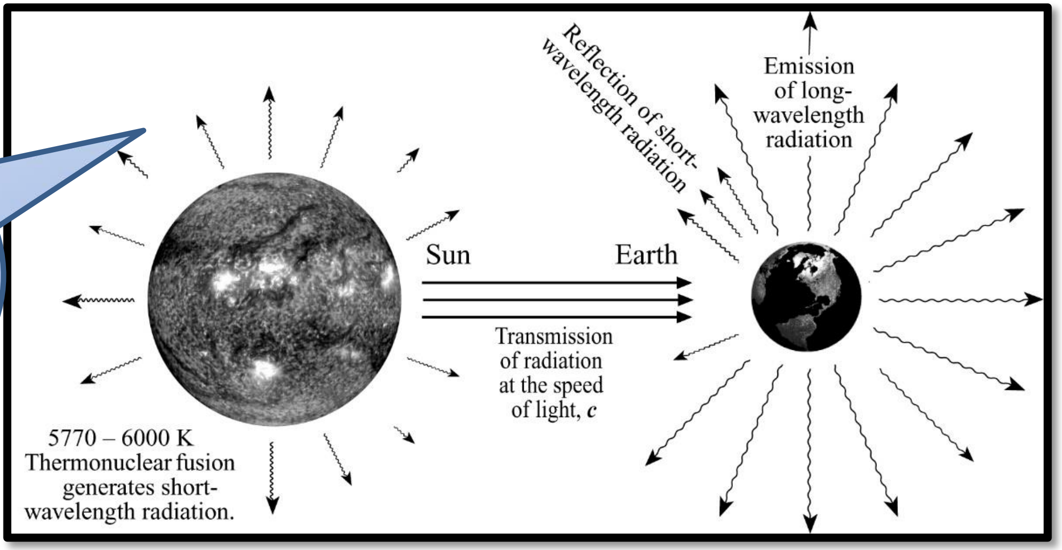
How to quantify the radiation from an object?

- Every object above absolute zero emits EM energy, e.g., water, vegetation, and the surface of the Sun. How different are the emitted energies?

$$\boldsymbol{M_\lambda = \sigma T^4}$$

- The total emitted radiation from a ***blackbody (M_λ)*** is: $\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4}$ (the *Stefan-Boltzmann* constant), *T* is temperature.

Q3:
How is the solar radiation different from the Earth's radiation?



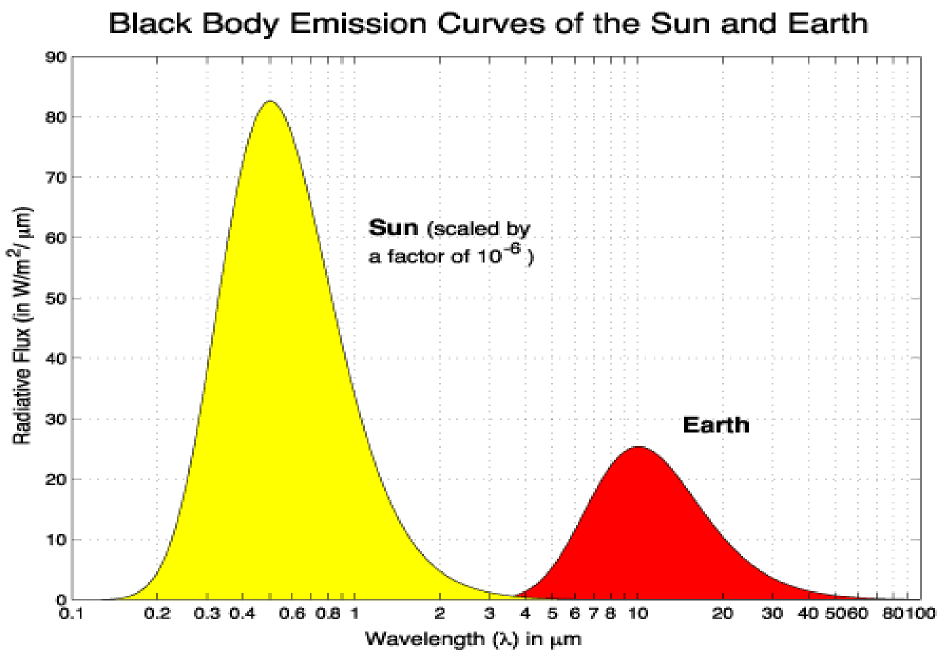
Jensen (2006)

Wien's displacement law

- How to determine the dominant wavelength of emitted energy?

$$\lambda_{max} = \frac{k}{T}$$

λ_{max}: the dominant wavelength, K = 2898 μm K, T is the absolute temperature.



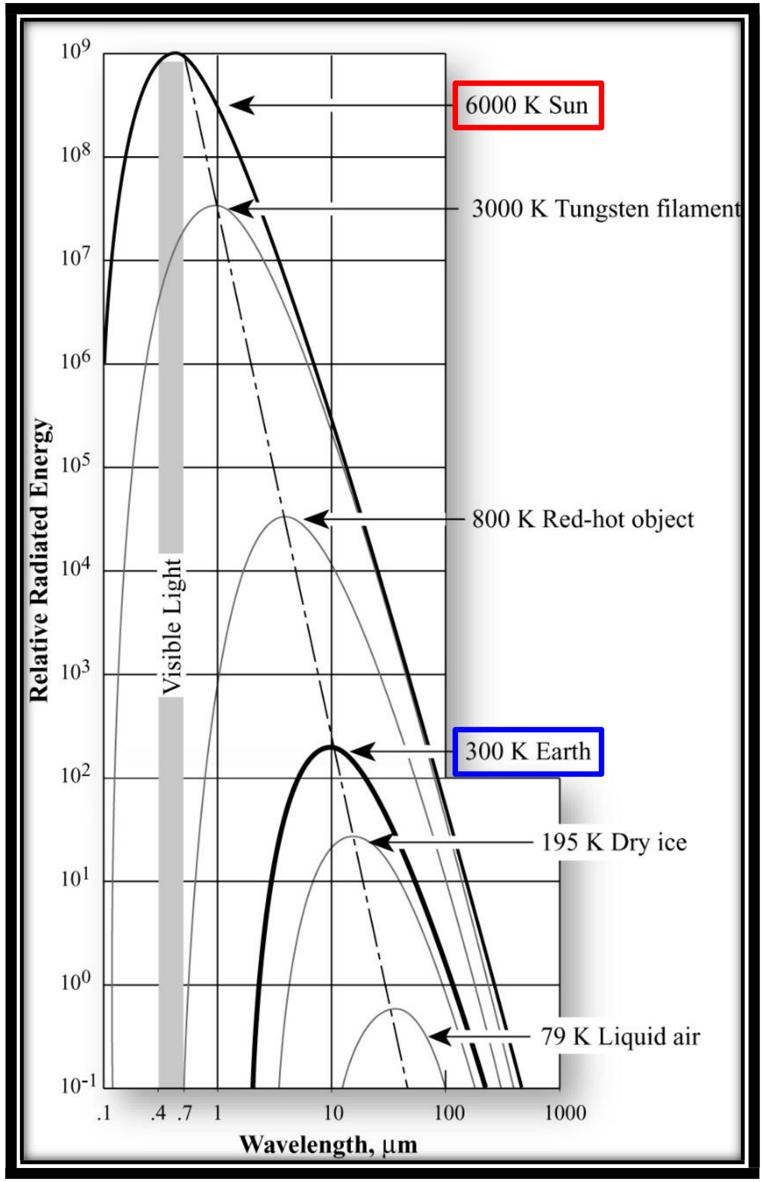
$$\text{The Sun: } \lambda_{max} = \frac{2898\ \mu m\ K}{6000\ K} = 0.48\ \mu m$$

$$\text{The Earth: } \lambda_{max} = \frac{2898\ \mu m\ K}{300\ K} = 9.66\ \mu m$$

Q4:
How is the emitted energy distributed in the EM spectrum?

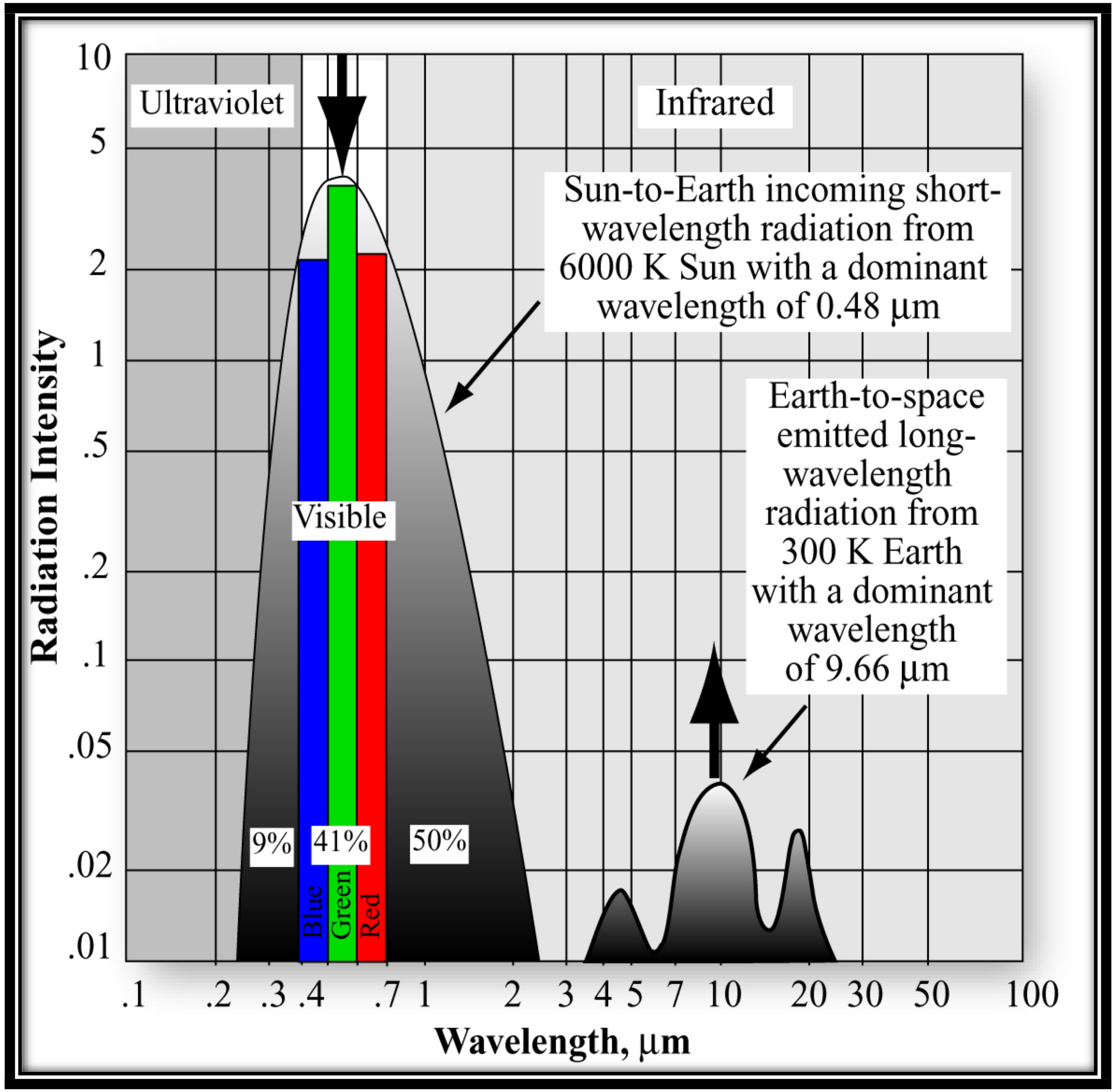
Figure from Columbia EESC 2100

Blackbody radiation curves



- The area under each curve is the total radiated energy for each object.
- The sun produces much EM energy than the Earth because of higher temperature.

Blackbody radiation curves

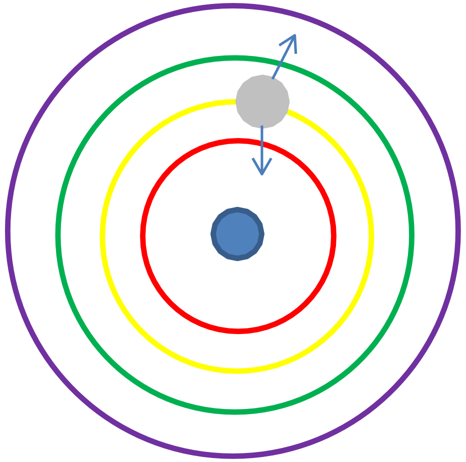


- Our eyes are only sensitive to light in the *visible* region.
- Our remote sensors can be sensitive to light in the *infrared* and *ultraviolet* regions.

Particle model of EM energy

- We can also describe EM energy in terms of particle-like properties using the quantum theory:

$$Q = h\nu \qquad \lambda = \frac{hc}{h\nu} = \frac{hc}{Q}$$



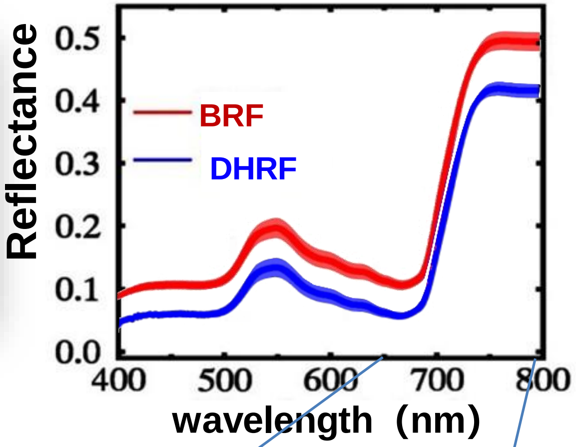
Q is the energy of a quantum
h is the *Planck constant*
$w$is the frequency of the radiation.

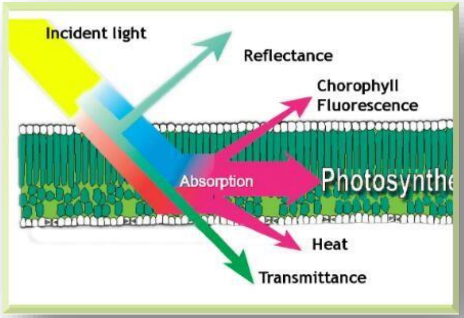
- Note: the longer the wavelength, the lower its energy content.

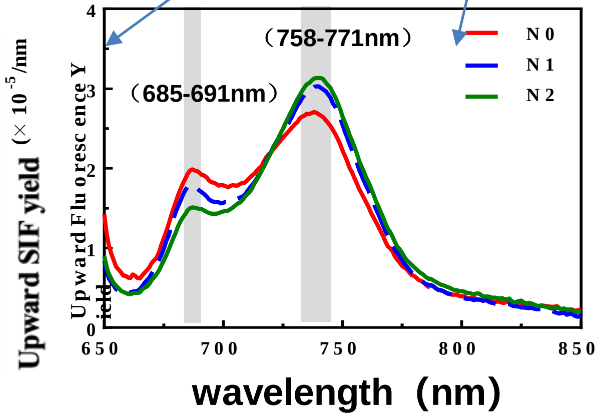
- In remote sensing: it is more difficult to detect longer- wavelength energy emitted at thermal infrared wavelengths than that at shorter wavelengths.

Particle model of EM energy

- **Sun induced chlorophyll fluorescence**







The longer the wavelength，the lower the energy.

Absorbed light in plants =

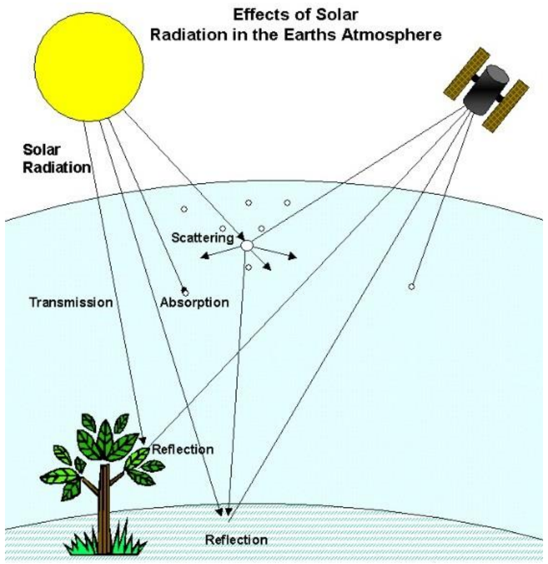
- **Heat dissipation (20%)+**
- **Photosynthesis (78%)+**
- **Fluorescence emission (2%)**

The wavelength with maximum fluorescence emission is greater than those of absorbed red and blue light. It is because photons emit energy with longer wavelengths while leaping to the low-energy level.

Q5:
Why do plants emit fluorescence at longer wavelengths?

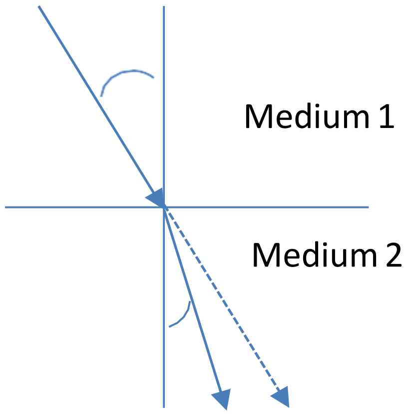
EM energy and atmosphere interactions

- The EM radiation generated by the Sun interacts with the Earth's atmosphere before it reaches the Earth's surface.

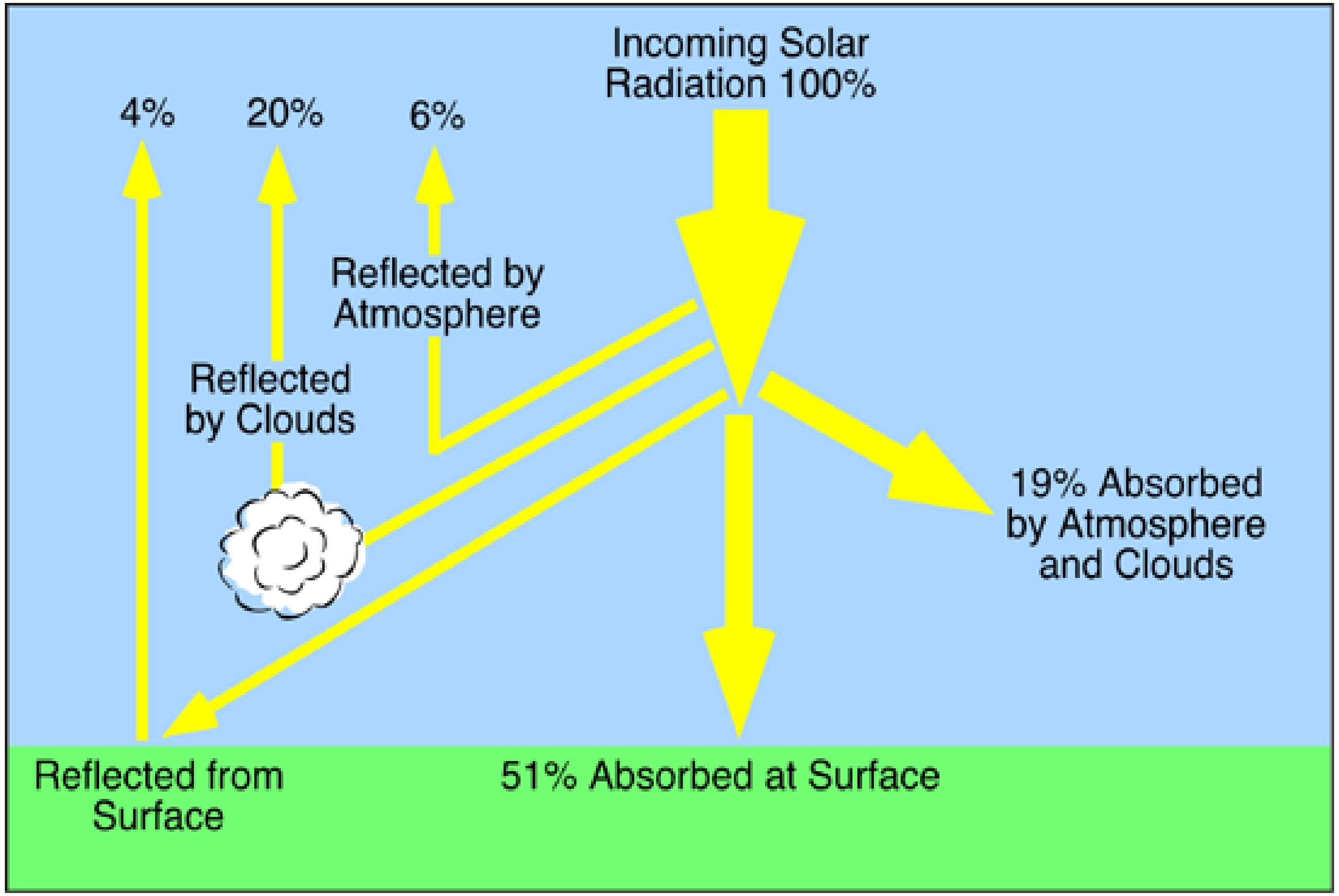


- Refraction, scattering, absorption, reflectance

- Refraction:
  - Occurs due to variation in the speed of EM radiation from one medium to another.



Solar radiation and atmospheric attenuation

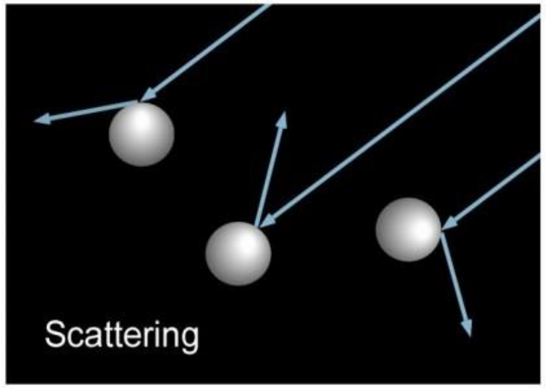


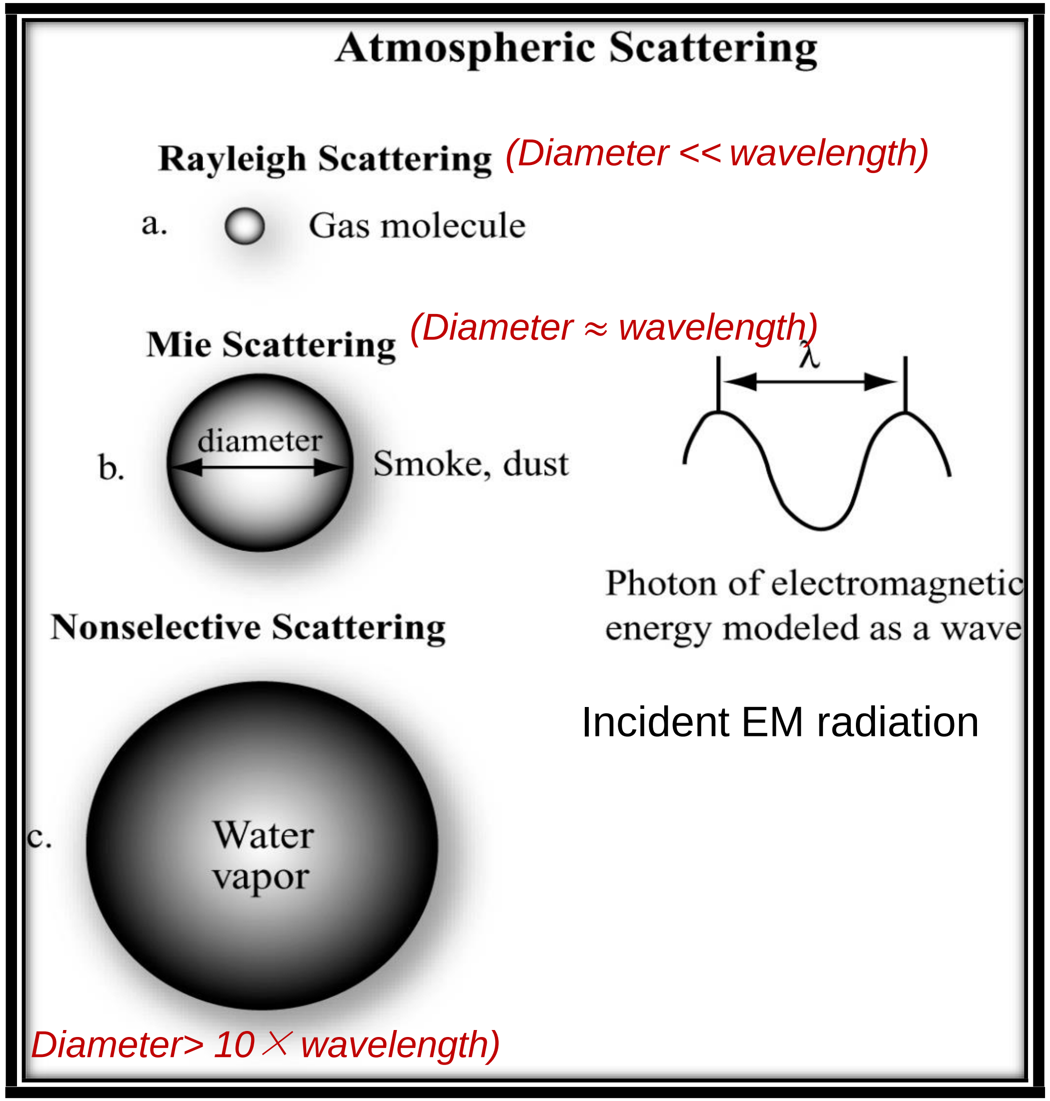
Global modification of incoming solar radiation by atmospheric and surface processes.

Not all solar radiation can reach the Earth surface!

Atmospheric scattering

- Scattering
  - A very serious effect of atmosphere
  - Different from reflection, because the direction of scattering is unpredictable.
  - Accomplished by absorption and re-emission of EM radiation in unpredictable directions.
- **Three types of scattering:**
  - **Rayleigh scattering**
  - **Mie scattering**
  - **Nonselective scattering**
- Type of scattering is a function of:
  - The wavelength of the incident radiation
  - The size of atmospheric particle



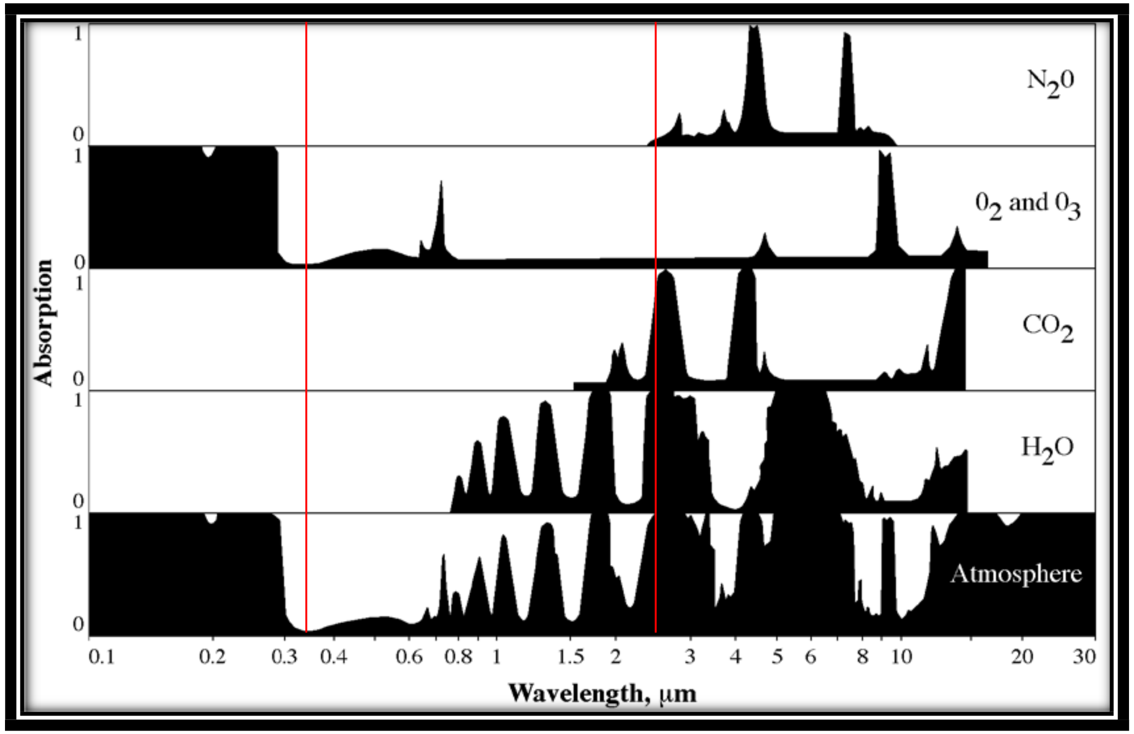


Jensen (2006)

- **Rayleigh scattering:**
  - Molecular scattering
  - the amount of scattering is inversely proportional to the fourth power of the radiation's wavelength
  - Mostly occurs 2-8 km asl.
- **Mie scattering**
  - Non-molecular or aerosol particle scattering
  - Occurs below 4.5 km.
- **Non-selective scattering**
  - All wavelengths of light are scattered, by clouds or fogbanks.
  - Occurs in the lowest portions of the atmosphere.
  - Equal for visible wavelengths.

Atmospheric scattering is a very important factor to be considered in remote sensing. Correction for this effect is crucial for many land applications.

Atmospheric absorption



Jensen (2006)

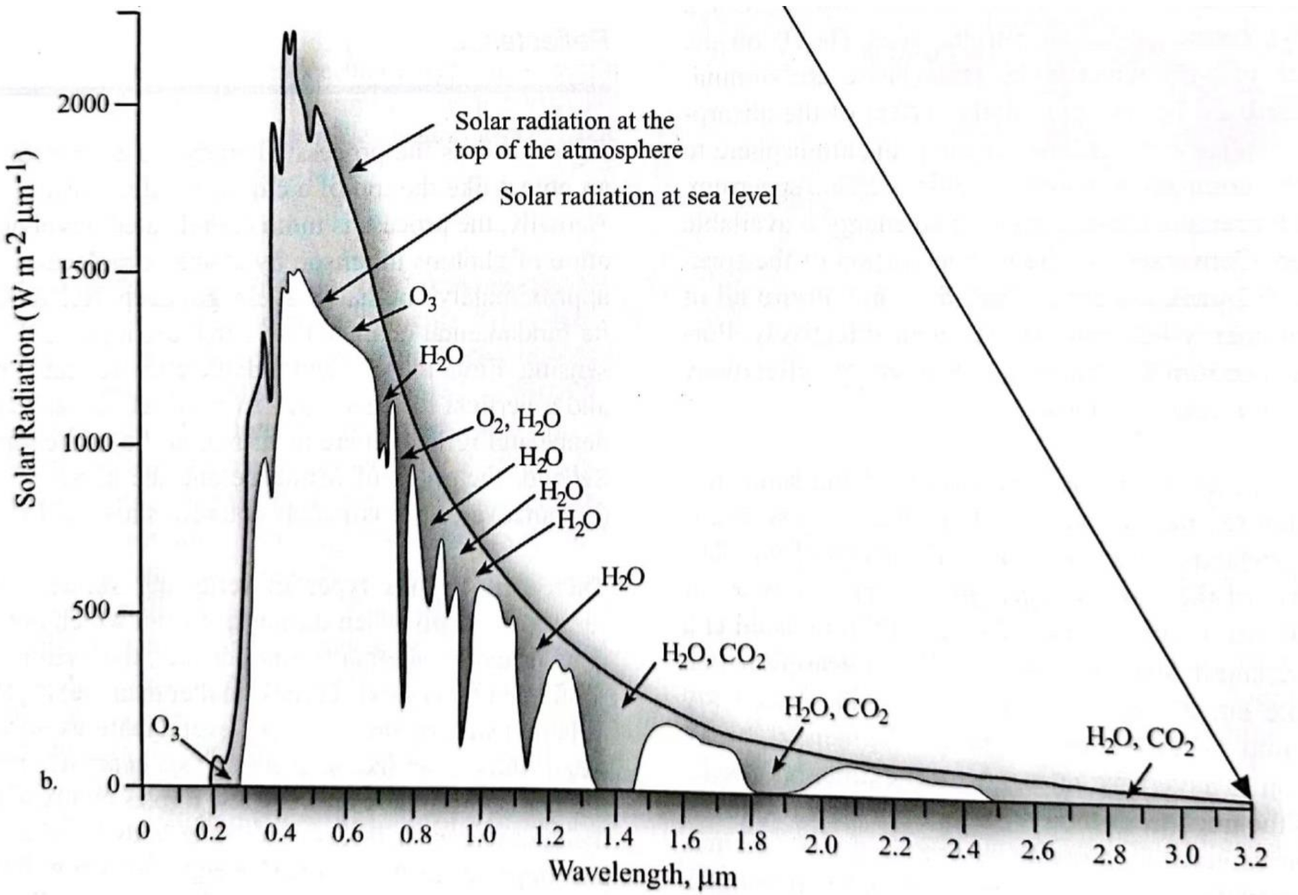
The absorption of the EM energy from the Sun by various gases in the atmosphere.

In the 0.35 – 2.5 um region:

- H_2O is the primary absorber
- O_2 & O_3 have strong absorptions around 0.7 um

- If the energy at a wavelength is strongly absorbed, then we cannot use it for remote sensing.
- The white portions of the spectrum are called *atmospheric windows*. Through these windows, we can sense objects on the Earth.

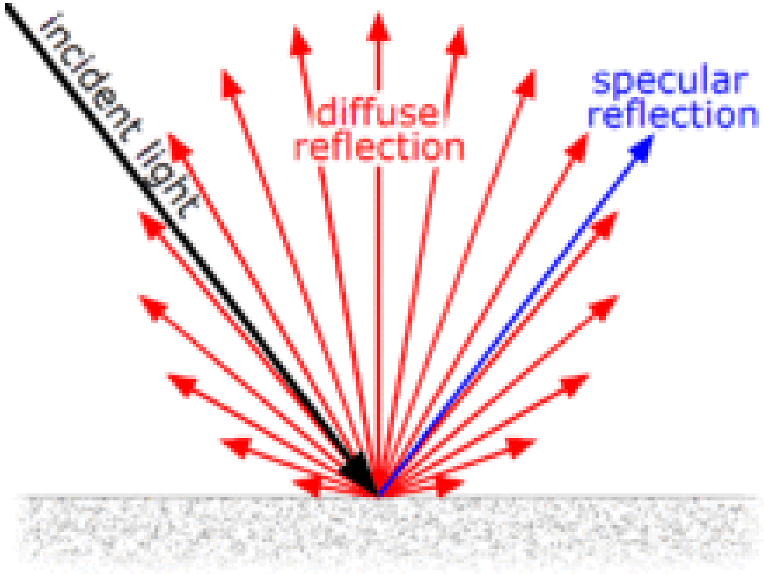
Solar radiation and atmospheric attenuation



- The attenuation of solar radiation from the atmosphere, including scattering, absorption and reflection, can be seen from the comparison between the radiations at the top of the atmosphere and at sea level.

Reflection

- Various types of reflections
  - *Specular reflection*: smooth surfaces, e.g., calm water bodies
  - *Diffuse reflection*: rough surfaces. Radiation can be bounced off in many directions
  - *Lambertian surface*: perfectly diffuse reflection



Q6:
Which type of reflection do you often see in the real world?

Figure from http://en.wikipedia.org/wiki/Diffuse_reflection

The bidirectional reflection

- Bidirectional reflection: The reflectance of an object changes with the directions of incident and reflected light.
- The measured reflectance of an object is a function of incident and viewing directions.

Q7: Why do we care about bidirectional reflection?

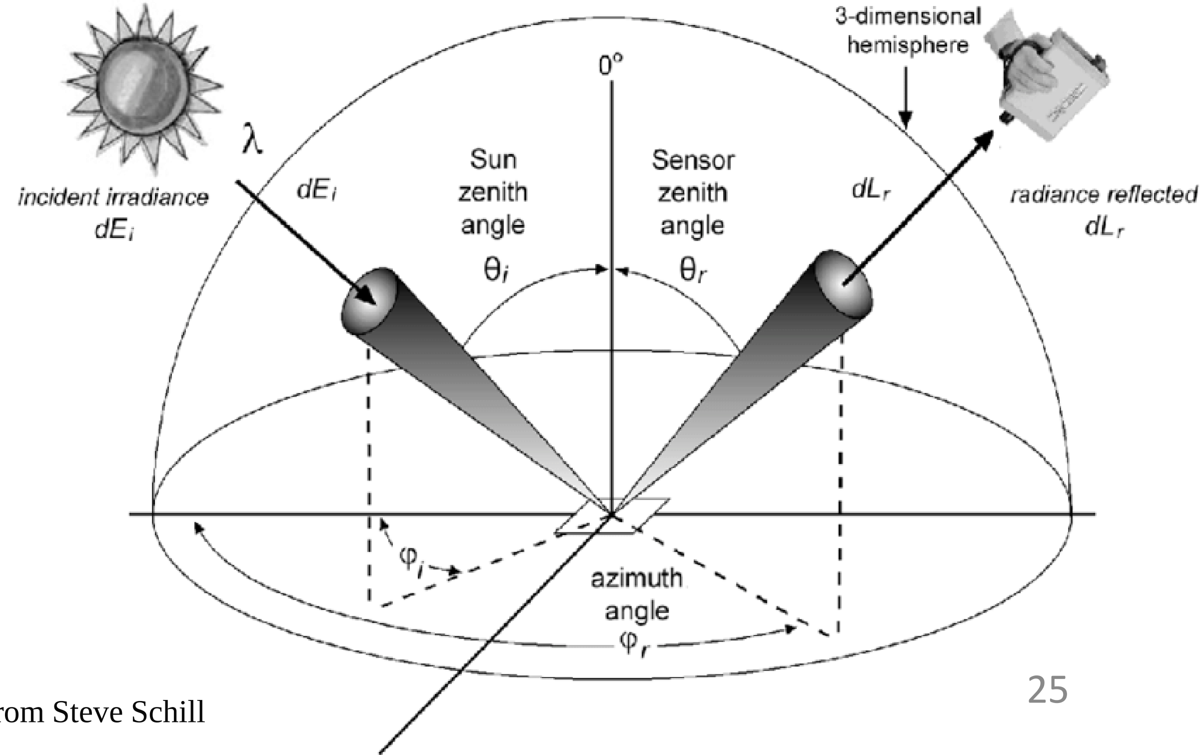


Figure from Steve Schill

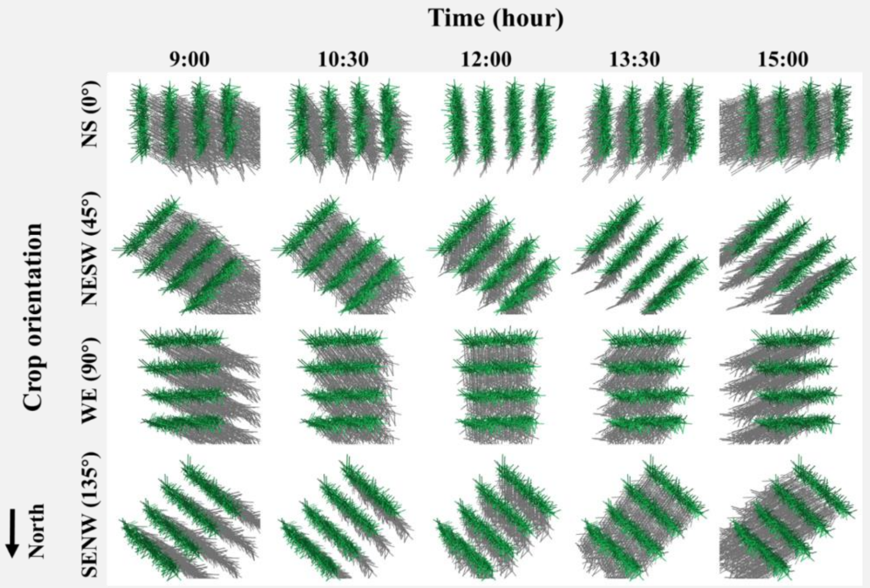
The bidirectional reflection

- Different viewing directions during data collection

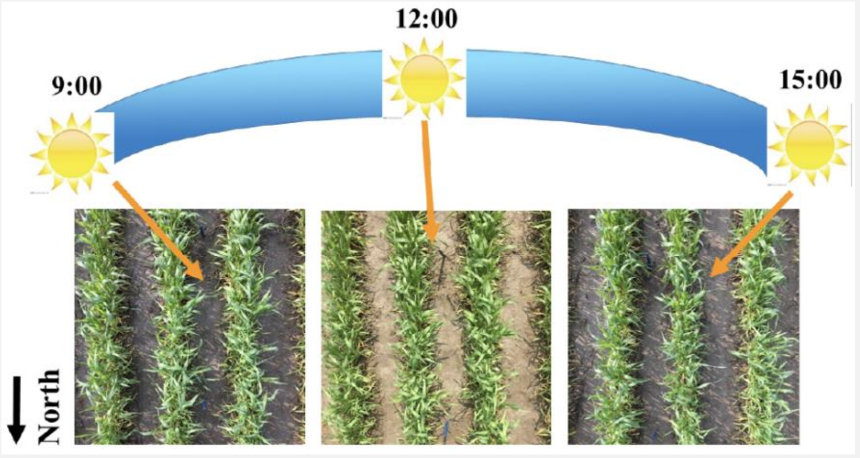
Anthesis stage of winter wheat

The bidirectional reflection

- Different solar incident directions during data collection



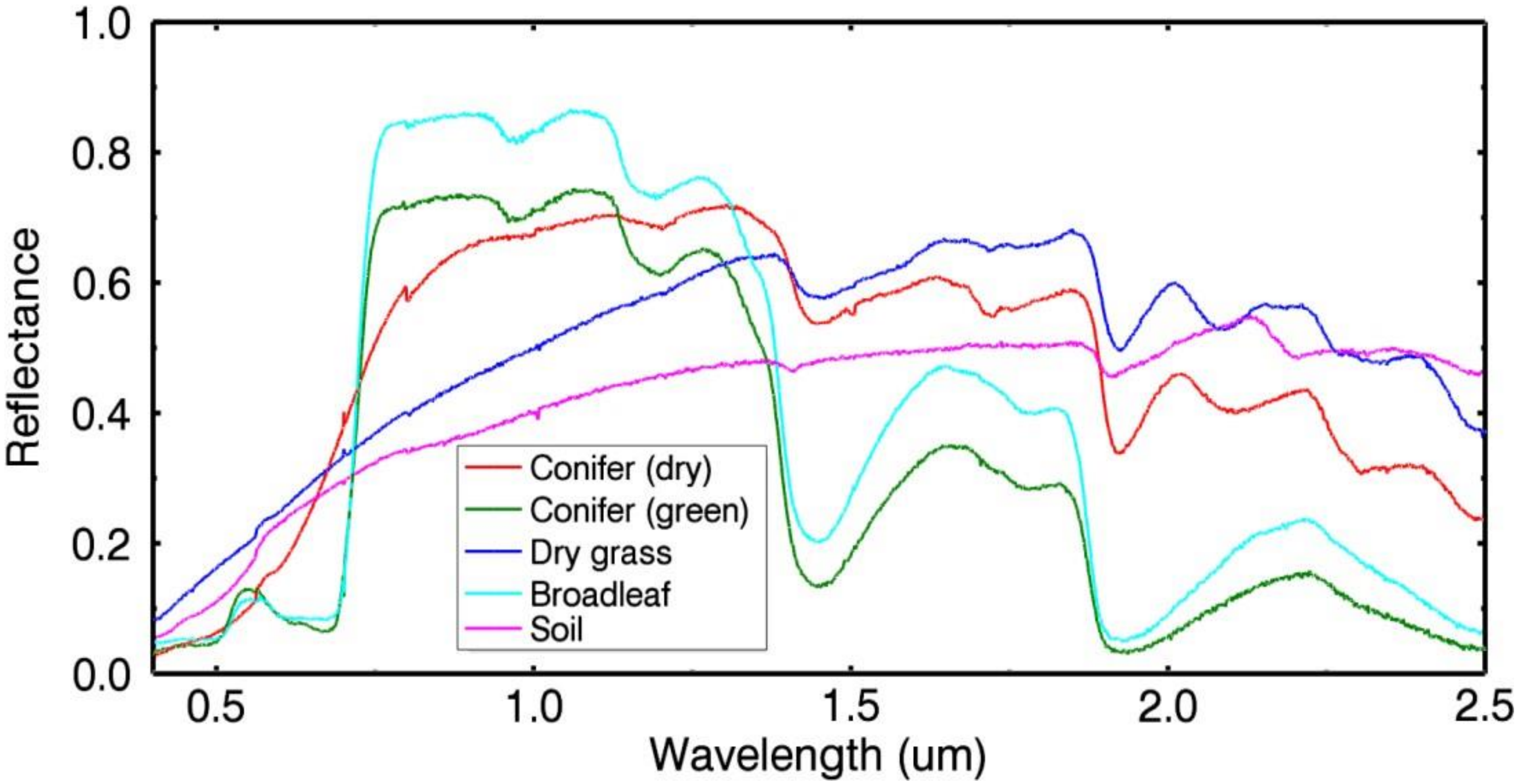
Conceptual diurnal variations of the shaded soil fraction in row crops for the four orientations. Simulated for Rugao, 03/15/2018.



Field photos with different shaded soil fraction in row crops at 9:00, 12:00 and 15:00 in Rugao, 03/22/2018.

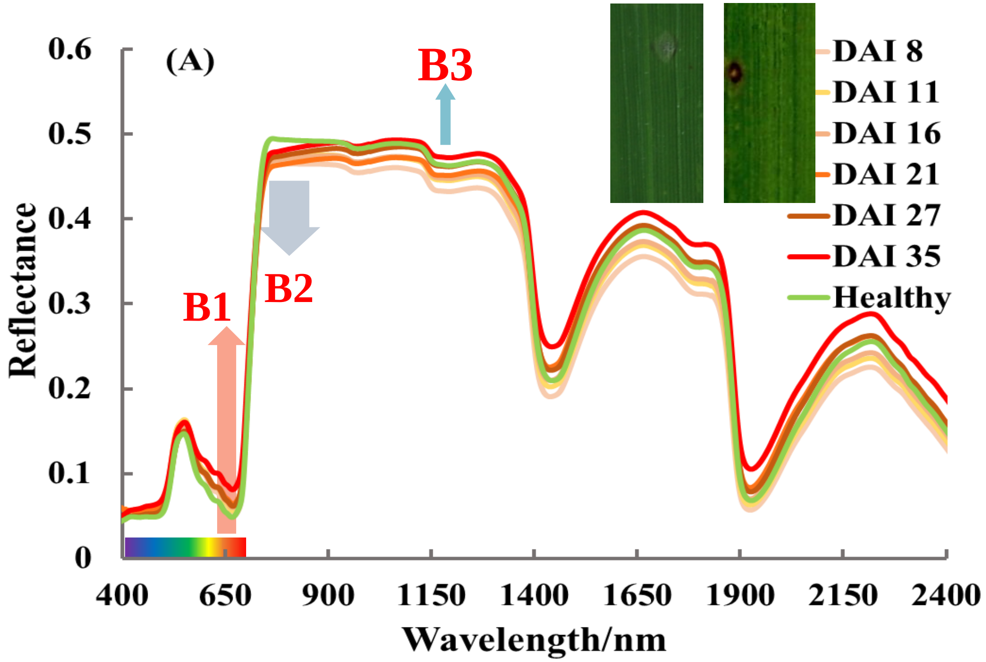
Q8: Is it good to acquire spectral data in the field at off-noon times?

Spectral reflectance of selected materials



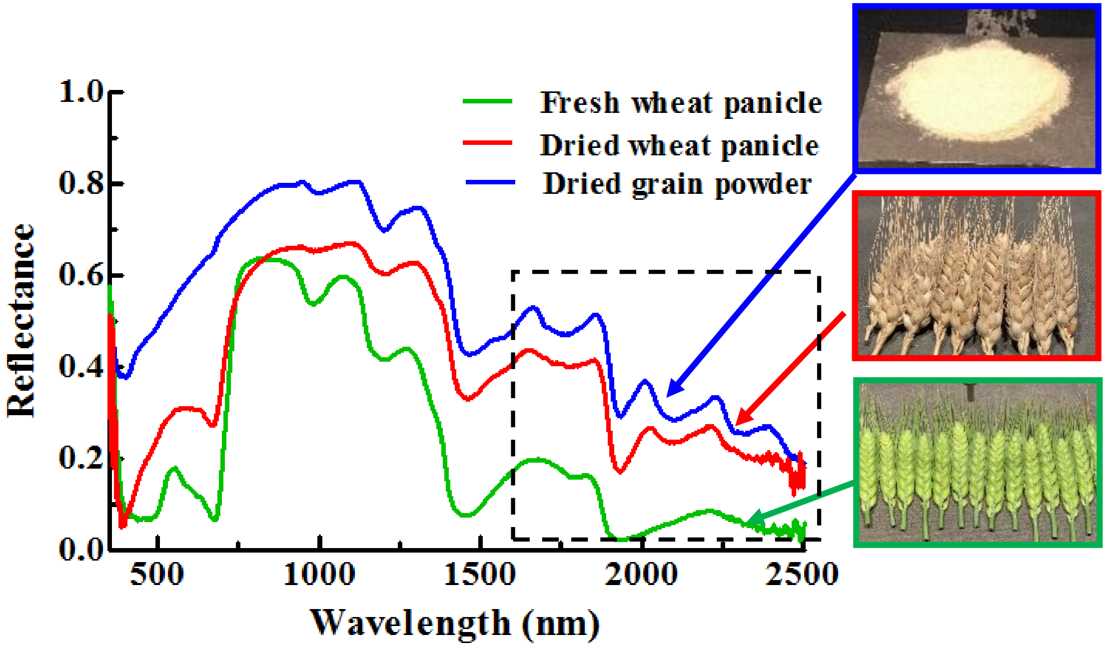
- Reflectance spectra of several ground surface materials

Spectral reflectance of selected materials

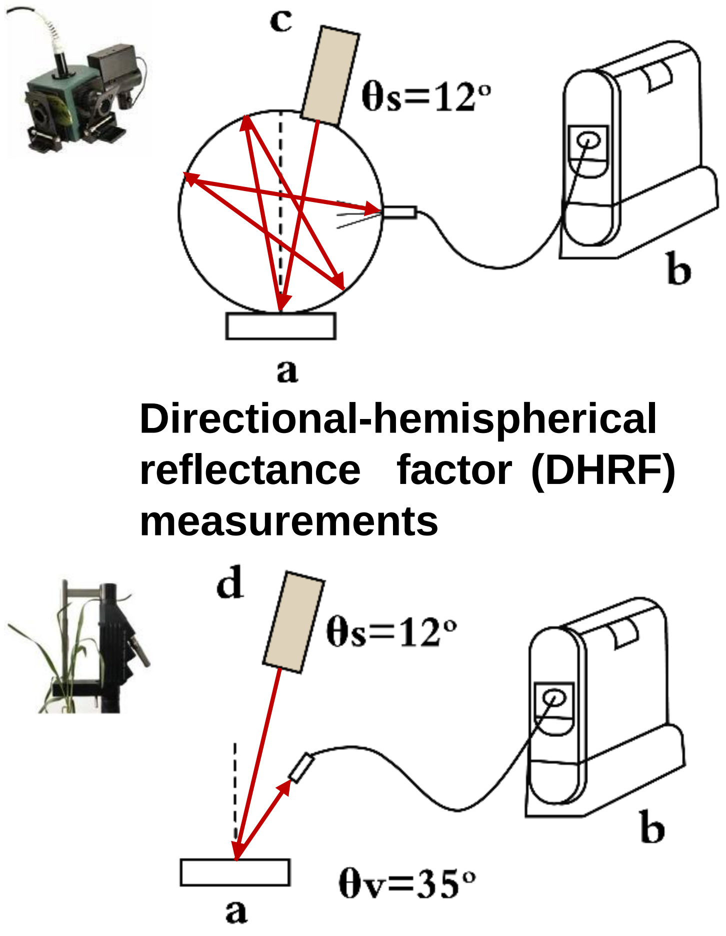


- Reflectance spectra of rice leaves for different days after inoculation of rice leaf blast

- Reflectance spectra of wheat panicles in various status

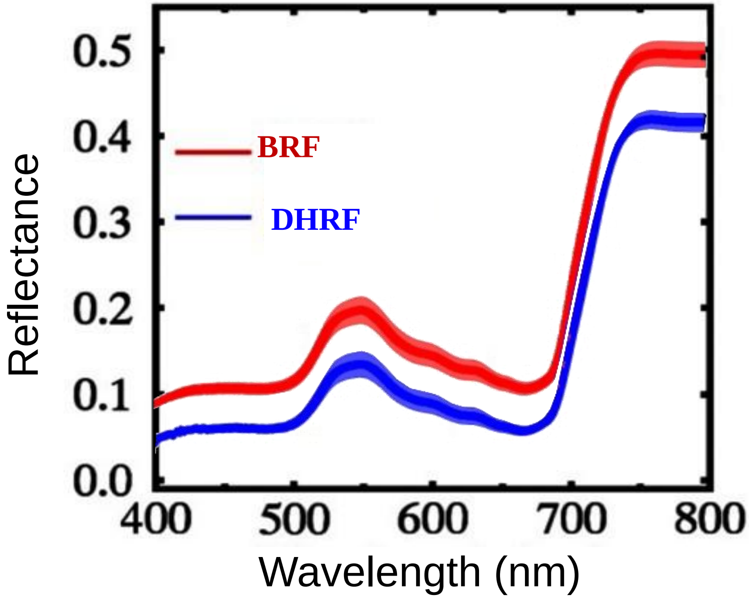


Leaf reflectance



Directional-hemispherical reflectance factor (DHRF) measurements

Bidirectional reflectance factor (BRF) measurements

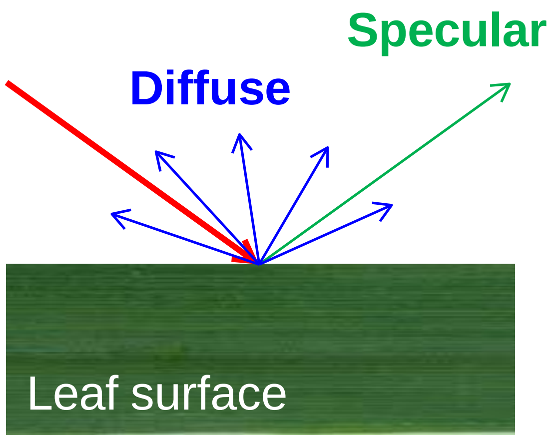


- DHRF and BRF spectra were all collected from the same leaves, but there could be significant differences in magnitude.

Q9: Why was the BRF higher than DHRF?

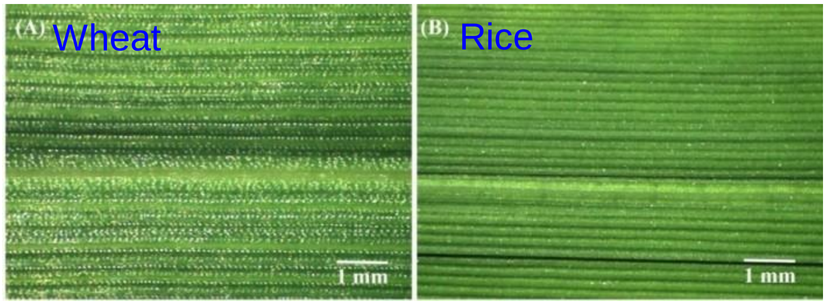
Li, et al. (2019), *Remote Sensing of Environment, 111240*

Leaf reflectance



For the VNIR region and small incident angles

$$\mathrm{BRF}(\lambda) = \mathrm{DHRF}(\lambda) + b$$



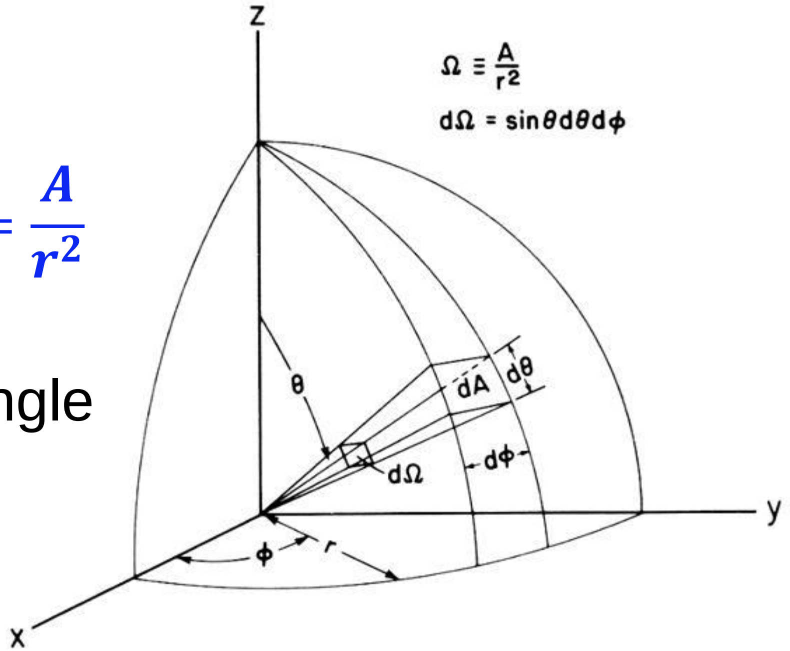
- The wheat leaf is smoother than the rice leaf and exhibits greater specular reflection.

Li et al., (2018), *Remote Sens. Environ.*, *206*, 1-14.

Physical quantities in remote sensing

- Radiant flux Φ_λ(watts, W): Radiant energy (J) passing through a surface in unit time.
- Solid angle $\boldsymbol{\Omega}$ (steradians, sr): given a spherical surface with a radius of *r* and a cone of any shape from the center of the sphere to the sphere, a solid angle is defined as the ratio of the area *(A)* for the intersection of the cone and sphere to the square of the radius.

$$\boldsymbol{\Omega} = \frac{\boldsymbol{A}}{\boldsymbol{r}^2}$$



- The area of a sphere is $4\pi r^2$, and the solid angle of the sphere is 4π.

Radiant flux density

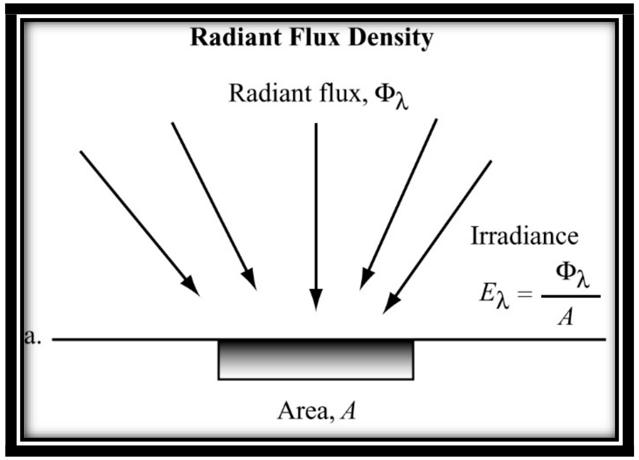
- **Irradiance E_λ**
  - It is the amount of radiant flux *incident* upon a surface per unit area

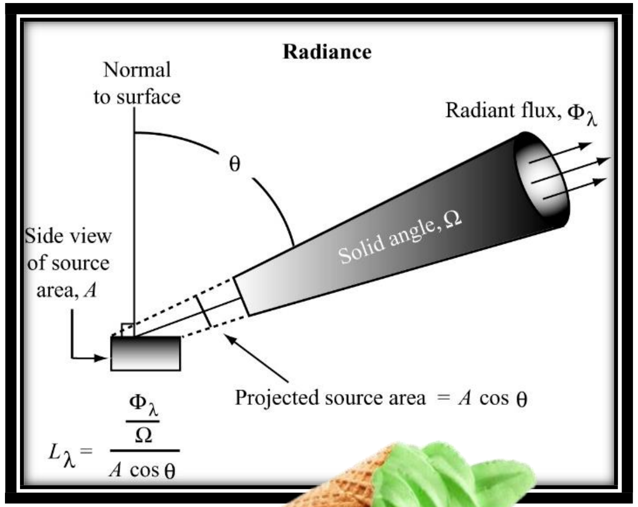
$$E_\lambda = \frac{\Phi_\lambda}{A}\ (Wm^{-2})$$

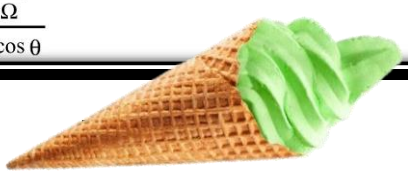
- **Radiance L_λ:**
  - It is the radiant intensity leaving a specific projected source area in a specified direction

$$L_\lambda = \frac{\frac{\Phi_\lambda}{\Omega}}{A\cos\theta}\ (Wm^{-2}sr^{-1})$$

  - Solid angle can be thought of a 3-D cone that funnels radiant flux.

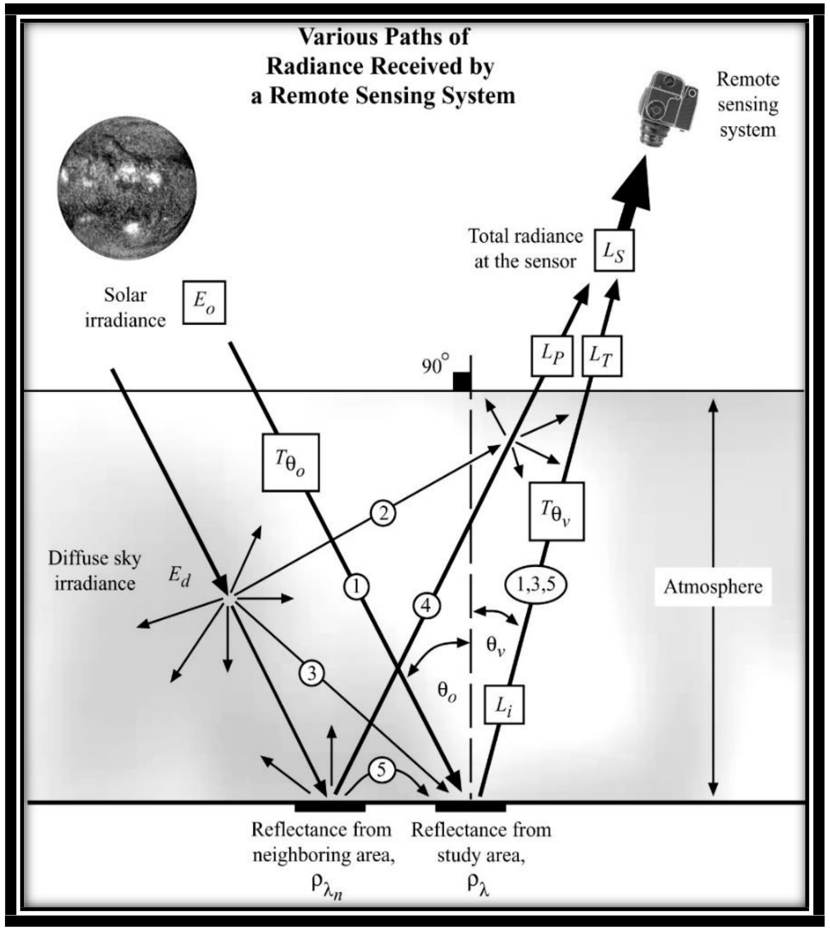






Radiance is the core concept in remote sensing.

From solar irradiance to radiance at the sensor



- Path 1: spectral solar irradiance reaching the target area = $E_{O_\lambda} \times T_{\theta_O} \times cos\theta_O$
- Path 2: upward spectral diffuse sky irradiance E_{du_λ}
- Path 3: downward spectral diffuse sky irradiance E_{dd_λ}
- Path 4 : reflected or scattered spectral irradiance from nearby terrain into the IFOV of the sensor ρ_{λ_π}
- Path 5: reflected or scattered spectral irradiance from nearby terrain onto the study area.

The total incident solar irradiance:

$$E_{g_\lambda} = \int_{\lambda_1}^{\lambda_2} (E_{O_\lambda} T_{\theta_O} cos\theta_O + E_{du_\lambda} + E_{dd_\lambda}) d\lambda$$

Q10: What has the solor radiant flux changed when traveling from the Sun to the sensor?

From solar irradiance to radiance at the sensor

The total radiance exiting from the target area:

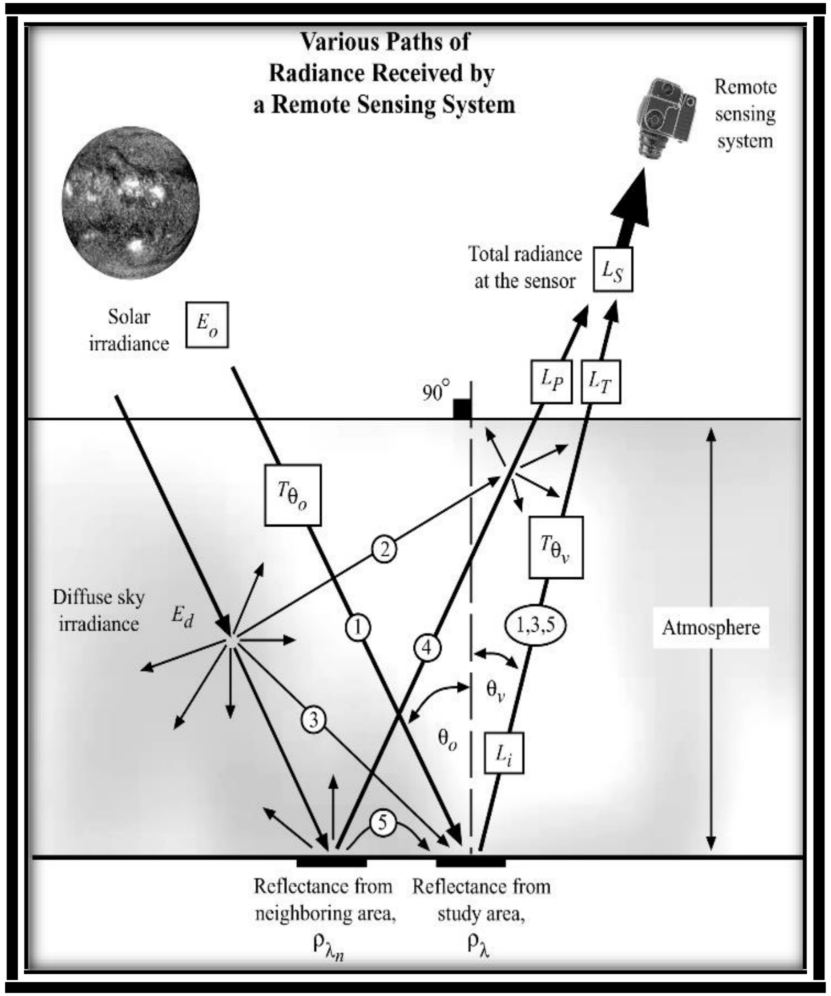
$$L_T = \frac{1}{\pi}\int_{\lambda_1}^{\lambda_2}(E_{O_\lambda} T_{\theta_O} \cos\theta_O + E_{du_\lambda} + E_{dd_\lambda})\rho_\lambda T_{\theta_v} d\lambda$$

π is the projected solid angle of a hemisphere.

The total radiance recorded by the sensor:

$$L_S = L_T + L_P \; (W m^{-2} sr^{-1})$$

Therefore, $L_T \neq L_S$



Q11: Is the radiance leaving the target area the same as that recieved by the sensor?

Path radiance L_P

- A bad (unwanted) component of L_S
- Introduces errors to the data collection process
- Hinders the acquisition of accurate spectral measurements
- Primarily from the diffuse sky irradiance (E_d) from path 2 and $\boldsymbol{\rho}_{\boldsymbol{\lambda}_{\boldsymbol{\pi}}}$ from path 4
- Could be removed from L_S using atmospheric radiative transfer models by atmospheric correction

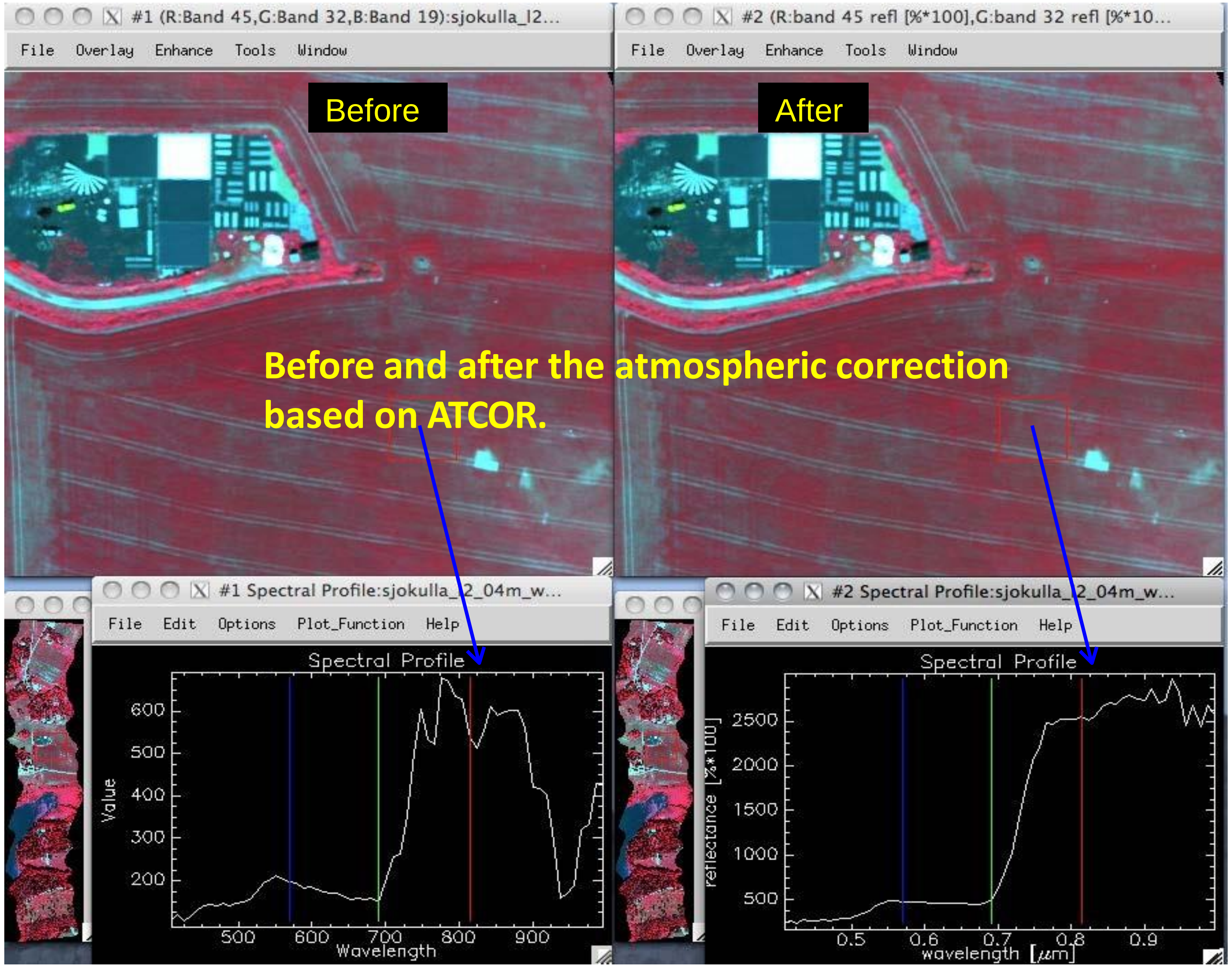
Q12: Why do we have to remove path radiance?

Atmospheric correction

Approaches:

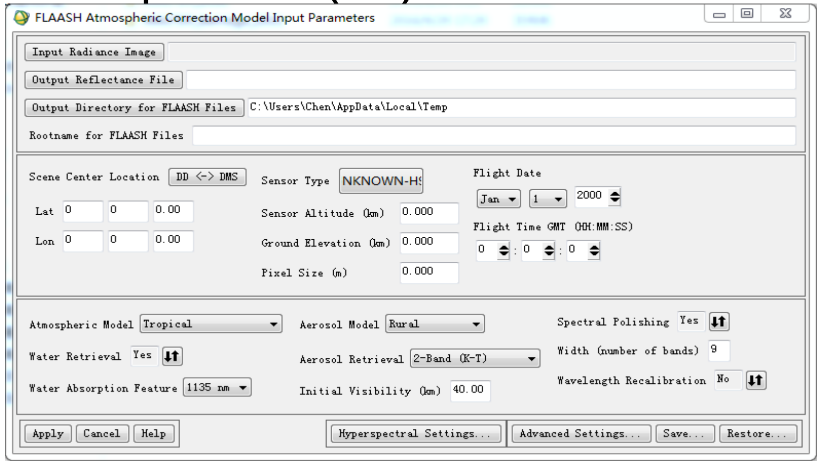
- **MODTRAN**
- **6S**
- **ACORN**
- **ATCOR**
- **…**

The radiance brightness is usually converted into surface reflectance.



How to perform atmospheric correction?

- Necessary for monitoring agronomic parameters
- May not be necessary for land cover classification
- The complex effect can be corrected with professional software packages
- Software packages for atmospheric correction:
  - Second Simulation of the Satellite Signal in the Solar Spectrum (6S)
  - MODTRAN
  - ACORN
  - ATCOR
  - FLAASH
  - …



Further reading

- RSE Chapter 2