ENGO 697

Remote Sensing Systems and Advanced Analytics

Session 3: how to quantify radiation and radiative transfer process

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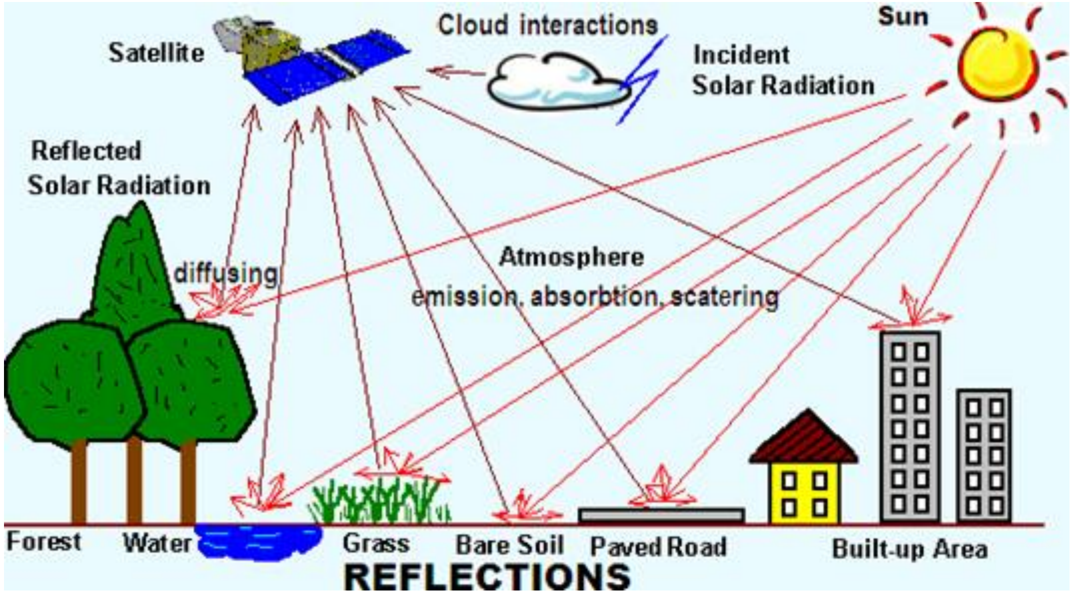
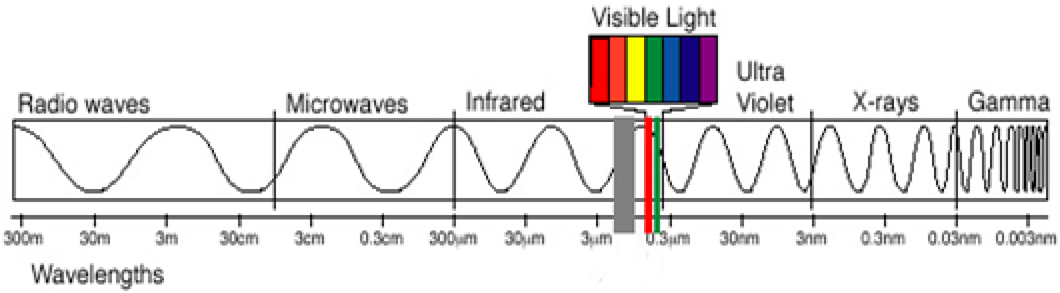
Outline

- ➔ Remote Sensing Radiation
- ➔ Radiation Quantification
- ➔ Radiative Transfer
- ➔ Questions

Radiation in Remote Sensing System



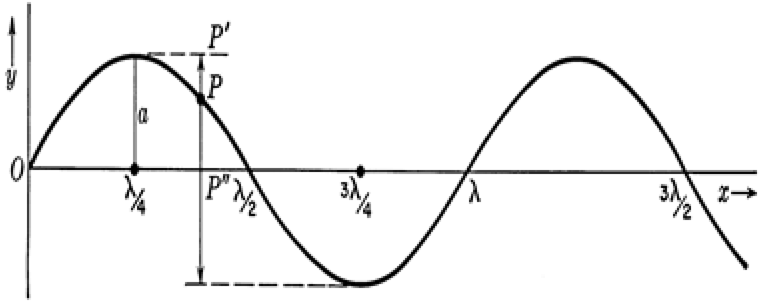


All remote sensing systems measure electromagnetic radiation.

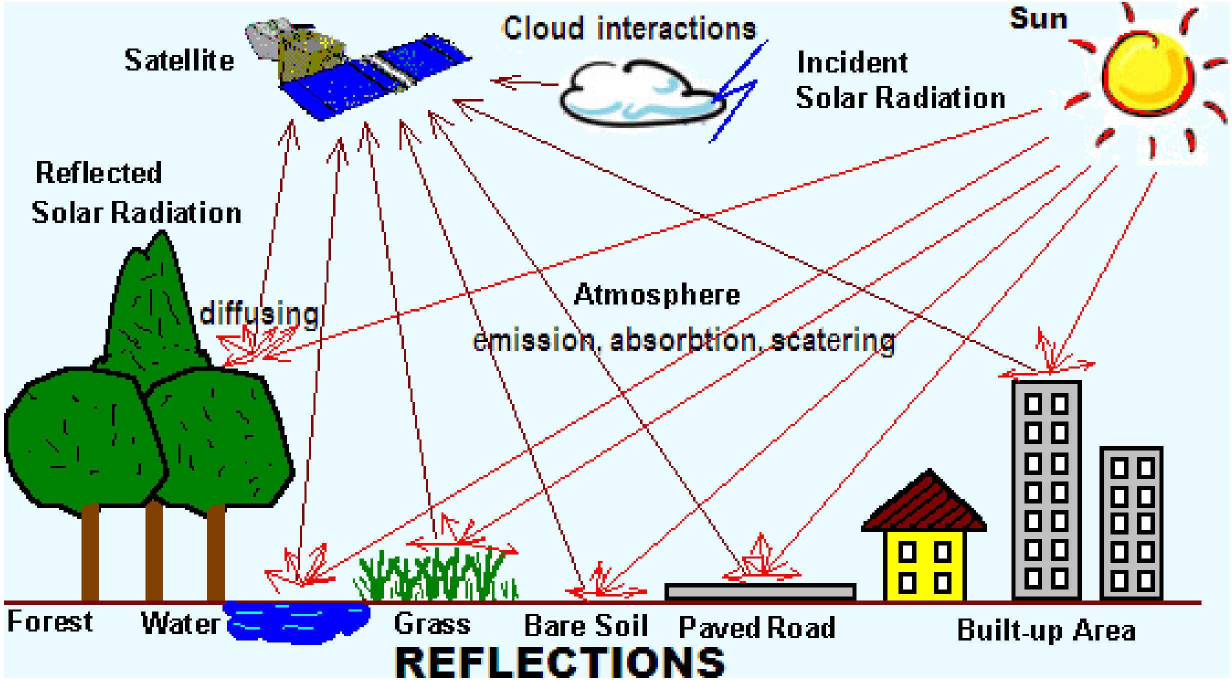
Remote sensing records energy that is reflected and emitted from the target at a certain range within the electromagnetic spectrum.

Electromagnetic radiation can be treated as waves or discrete particles.

In remote sensing, electromagnetic radiation is treated as sinusoidal shaped waves, that are characterized by wavelength and amplitude.



Remote Sensing System Overview



(1) How do you define and quantify radiation received by a sensor unit?

Terminology of radiant energy

Energy dQ (Joules) **from the Earth Atmosphere**

over time is

Flux dQ/dt (Joules/sec = Watts)

at unit ground surface area is

Irradiance dQ/dt/dA (Watts/meter2)

at unit wavelength interval is

Monochromatic Irradiance dQ/dt/dA/dλ (W/m2/micron)

to unit solid angle (detector area) is

Radiance dQ/dt/dA/dλ/dΩ (W/m^2/micron/ster) **observed by satellite radiometer**

is described by **the Planck function** can be inverted to

Brightness temperature

Energy over time is Flux

The rate of energy transfer by electromagnetic radiation is called the radiant flux, which has units of energy per unit time. It is denoted by

$$F = dQ / dt$$

and is measured in joules per second or watts.

For example, the radiant flux from the sun is about 3.90×10^{26} W.

Flux at unit detector area is Irradiance

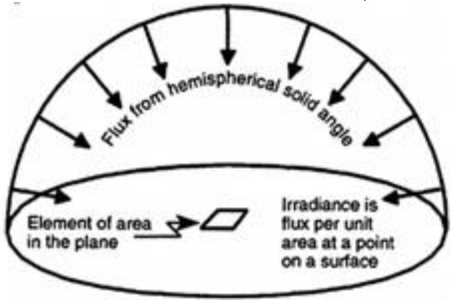
The radiant flux per unit area is called the irradiance (or radiant flux density in some texts). It is denoted by

$$E = dQ / dt / dA$$

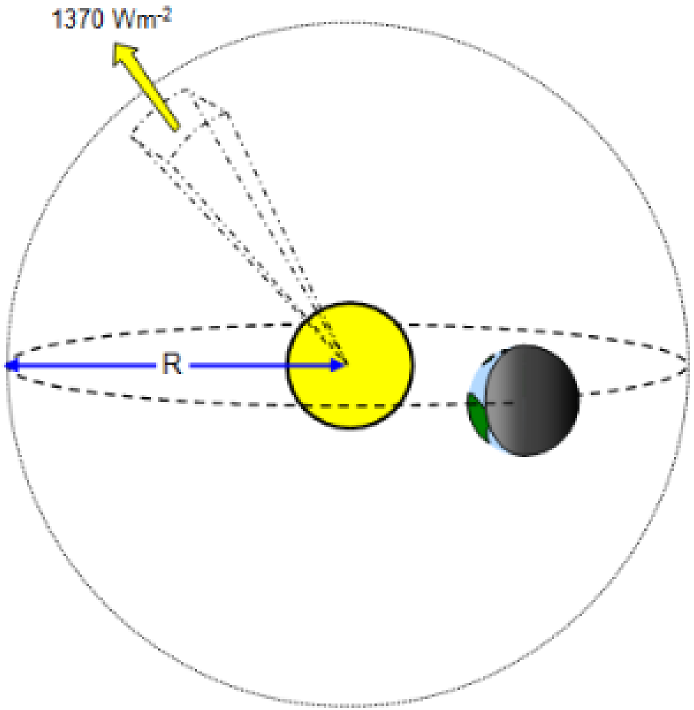
and is measured in watts per square metre.

For example, the irradiance of electromagnetic radiation passing through the outermost limits of the visible disk of the sun (which has an approximate radius of 7×10^8 m) is given by

$$E\ (\text{sun sfc}) = \frac{3.90 \times 10^{26}}{4\pi\,(7 \times 10^8)^2} = 6.34 \times 10^7\ \text{W m}$$



Flux at unit detector area is Irradiance



The solar irradiance arriving at the earth can be calculated by realizing that the flux is a constant, therefore

$$E\ (\text{earth sfc}) \times 4\pi R_{es}^2 = E\ (\text{sun sfc}) \times 4\pi R_s^2,$$

where R_{es} is the mean earth to sun distance (roughly 1.5×10^{11} m) and R_s is the solar radius. This yields

E (earth sfc) $= 6.34 \times 10^7\ (7 \times 10^8 / 1.5 \times 10^{11})^2 = 1370\ \text{W m}^{-2}$.

Irradiance at unit wavelength interval is Monochromatic Irradiance

The irradiance per unit wavelength interval at wavelength λ is called the monochromatic irradiance,

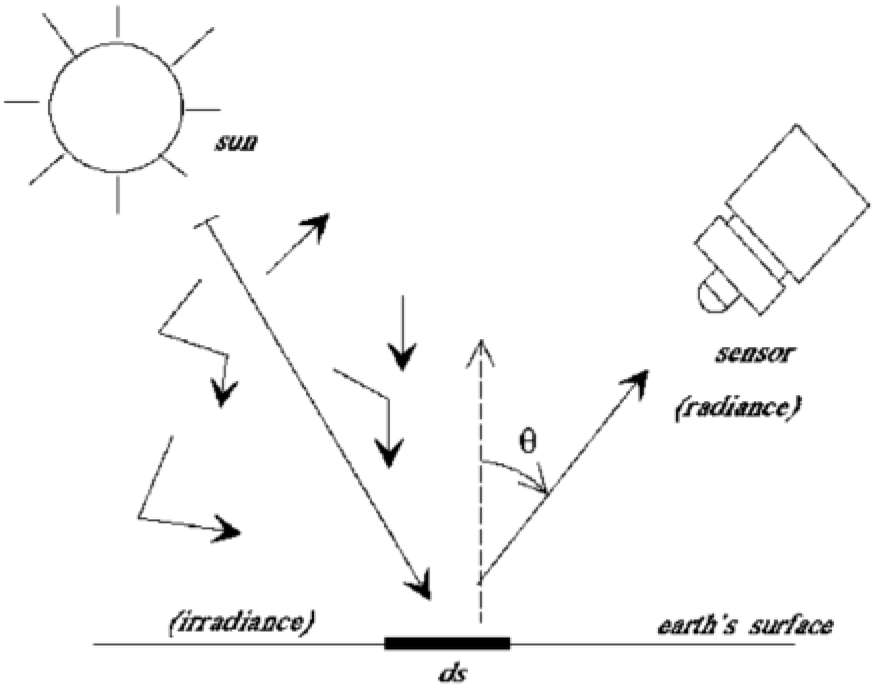
$$E_\lambda = dQ / dt / dA / d\lambda ,$$

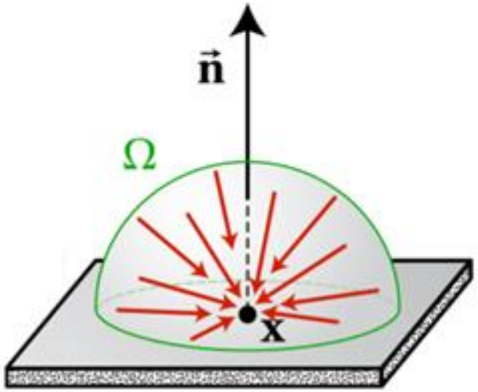
and has the units of watts per square metre per micrometer.

With this definition, the irradiance is readily seen to be

$$E = \int_0^\infty E_\lambda \, d\lambda .$$

Irradiance vs. Radiance

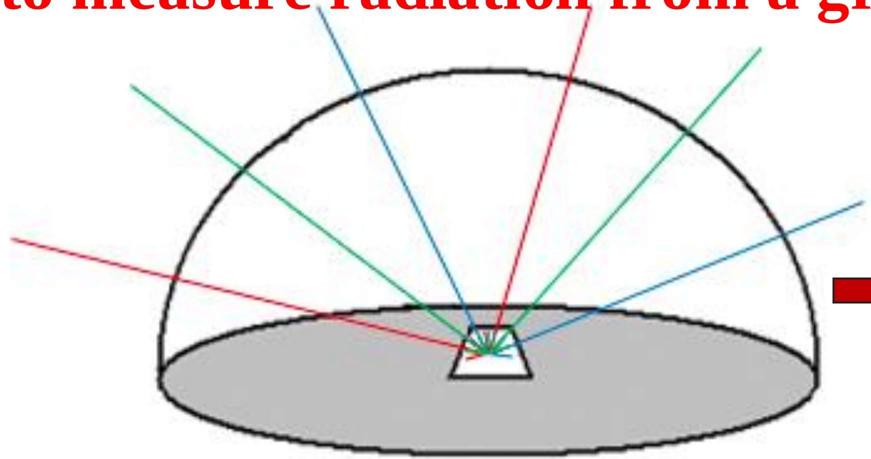




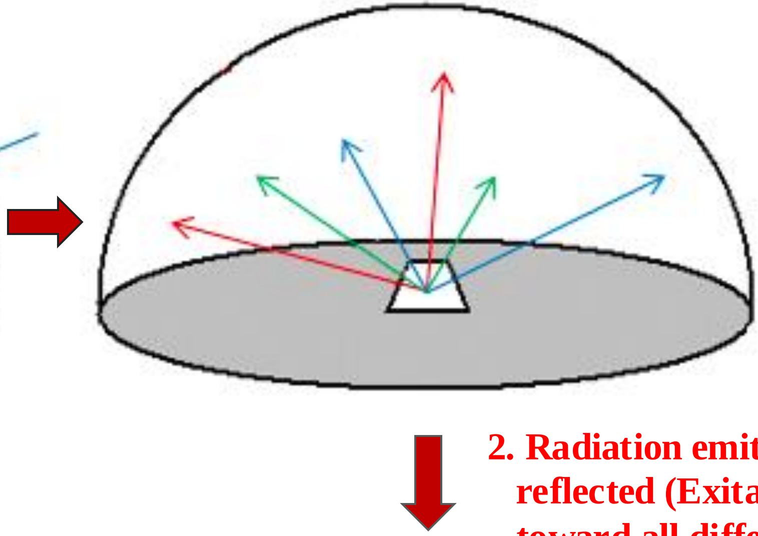
Irradiance of the Earth's surface is mostly caused by the Sun, not only from the direction of the Sun, but also from all directions in the upper hemisphere. This is why we can see clearly along a shady street. Consequently, solar irradiance is the sum of all direct and diffuse irradiance and is therefore hemispheric.

Radiance is directional, because the sensor receives energy radiated by the source dS along a specific direction.

How to measure radiation from a ground area

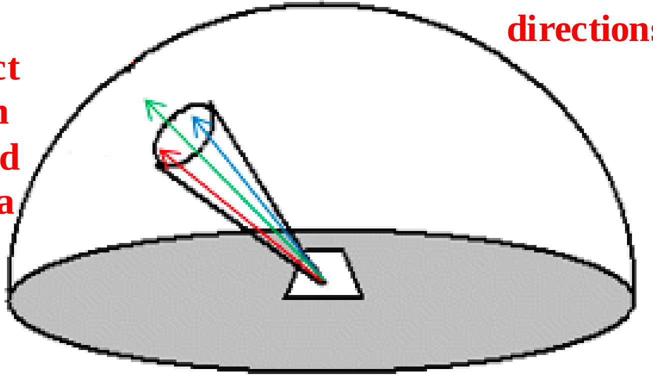


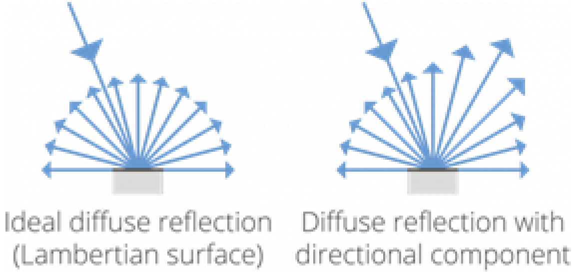
1. Irradiance from all different directions



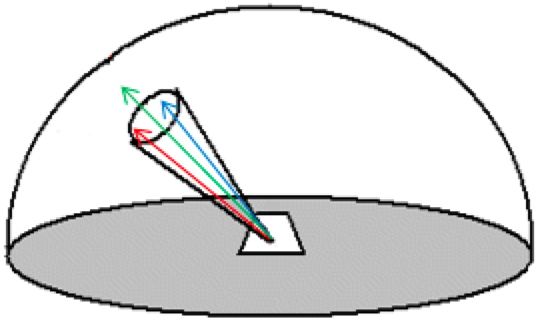
2. Radiation emitted or reflected (Exitance) toward all different directions

3. You can only detect and record radiation over a small projected surface area, within a specific solid angle, which is radiance





What is the solid angle?



A solid angle can be thought of as a cone – in most remote sensing cases this cone is incredibly narrow as it stretches from the observed area to the relevant detecting element in the sensor.

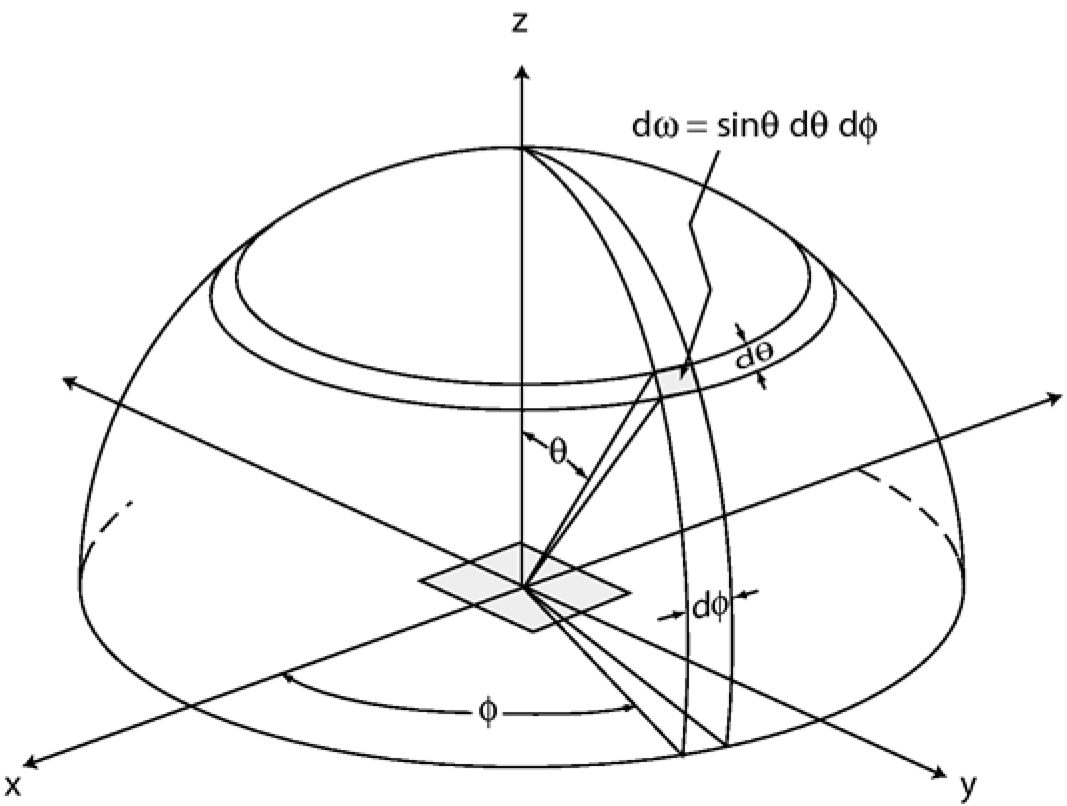


Fig. 2.4: The relationship between solid angle and polar coordinates.

Monochromatic Irradiance from unit solid angle is Radiance

In general, the radiation (exitance) emited or reflected by a surface area **dA** may go toward **an infinity of different directions** over the hemisphere.

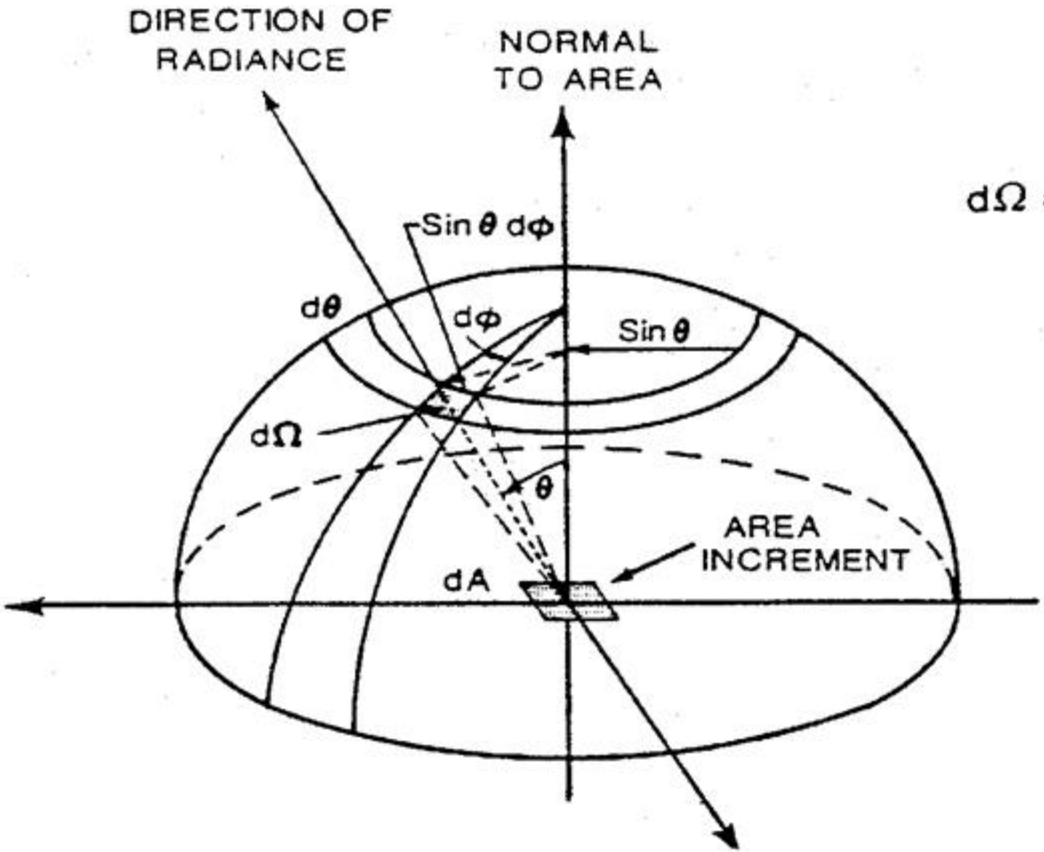
From the sensor perspective, it is necessary to identify the part of the irradiance (emited/reflected by **dA**) that is coming from directions within some **specified infinitesimal arc of solid angle dΩ**. The irradiance per unit solid angle is called the **radiance**,

$$I = dQ \,/\, dt \,/\, dA \,/\, d\lambda \,/\, d\Omega,$$

and is expressed in watts per square metre per micrometer per **steradian**.

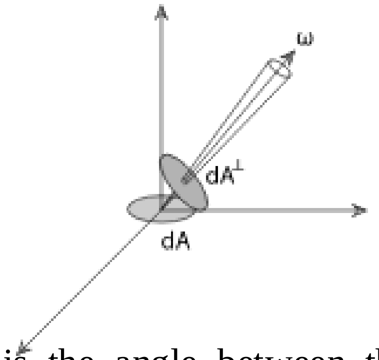
This quantity is often also referred to as **intensity** and denoted by the letter B (when referring to the Planck function).

Irradiance (E) = Integration of Radiance (I) over the entire hemisphere



Spherical coordinates and solid angle considerations

$$d\Omega = \sin\theta \, d\theta \, d\varphi$$



If the zenith angle, θ, is the angle between the direction of the radiation and the normal to the surface, then the component of the radiance normal to the surface is then given by $I \cos\theta$.

The irradiance represents the combined effects of the normal component of the radiation coming from the whole hemisphere; that is,

$$E = \int I \cos\theta \, d\Omega$$

where in spherical coordinates $d\Omega = \sin\theta \, d\theta \, d\varphi$.

Brightness temperature (T) is estimated using Radiance (B) via the Plank's Law

Planck's law describes the spectral density of electromagnetic radiation ***emitted*** by a black body in thermal equilibrium at a given temperature *T*.

Radiation is governed by Planck's Law

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

where λ = wavelengths in um

T = temperature of emitting surface (deg K)

$c_1 = 1.191044 \times 10^{-5}$ ($mW/m^2/ster/cm^{-4}$)

$c_2 = 1.438769$ (cm deg K)

According to Planck law, higher T —--> higher B

Estimate Brightness temperature (T) from Radiance (B)

Planck's law:

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

where λ = wavelengths in um

T = temperature of emitting surface (deg K)

$c_1 = 1.191044 \times 10^{-5}$ (mW/m^2/ster/cm^{-4})

$c_2 = 1.438769$ (cm deg K)

Brightness Temperature

$$T = c_2 / [\lambda \ln(\frac{c_1}{\lambda^5 B_\lambda} + 1)]$$ is determined by inverting Planck function.

Brightness temperature (T) is uniquely related to radiance (B) by inverting Plank function.

Stefan-Boltzmann Law

Planck's Law $B(\lambda,T) = c_1 / \lambda^5 / [e^{c_2/\lambda T} - 1]$ $(W/m^2/ster/um)$

Stefan-Boltzmann Law $E = \pi \int_0^\infty B(\lambda,T)\, d\lambda = \sigma T^4$, where σ = 5.67 x 10-8 W/m2/deg4.

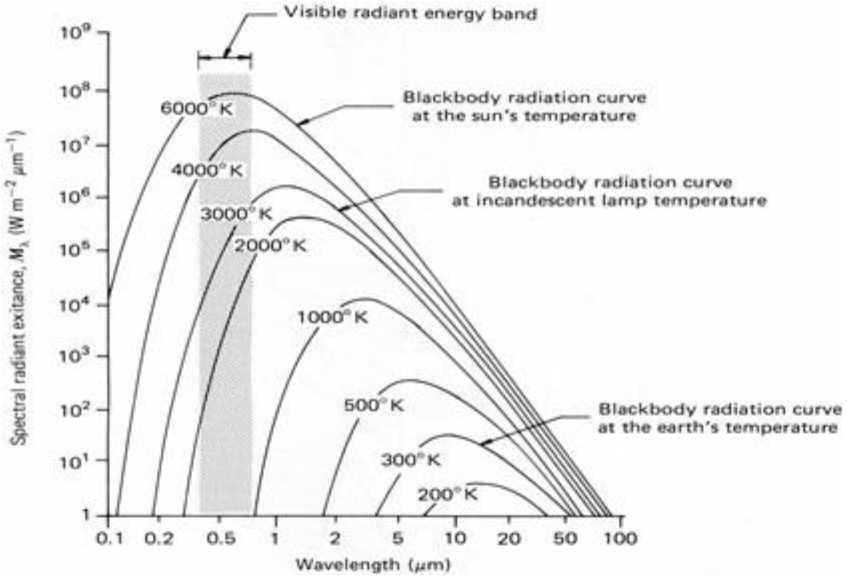
The Stefan Boltzmann law states that **the total energy emitted per unit surface area of a black body** across all wavelengths per unit of time **is directly proportional** to the fourth power of the black body's thermodynamic temperature and emissivity.

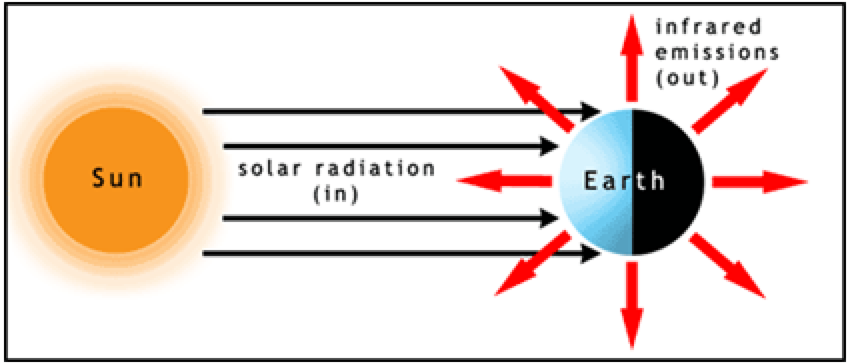
Why higher temperature objects tend to emit shorter-wave radiation?

Planck's Law $B(\lambda,T) = c_1 / \lambda^5 / [e^{c_2/\lambda T} - 1]$ (W/m²/ster/um)

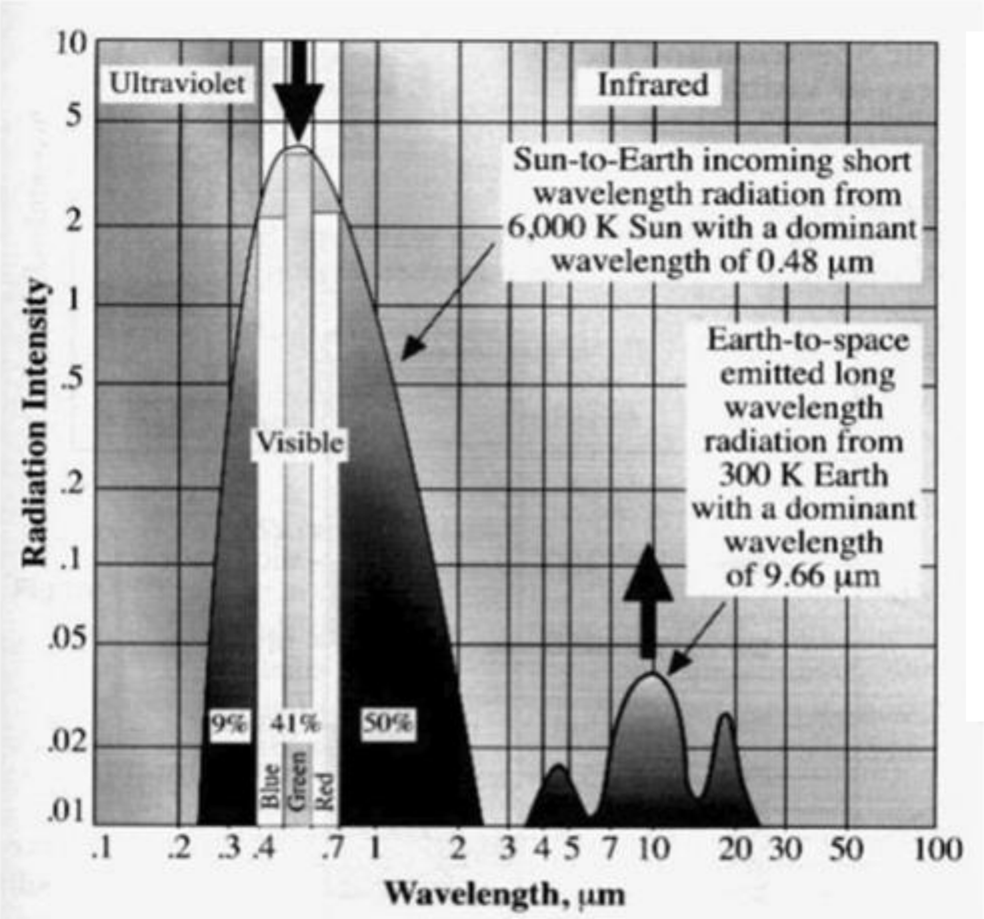
Wien's Law $dB(\lambda_{max},T) / d\lambda = 0$ where $\lambda(max) = 0.2897 / T$

Wien's Law indicates that if temperature T increase, λ(max) decreases. So, objects with higher temperature tend to emit peak energy at shorter wavelengths.





Spectral Distribution – The Sun vs. The Earth

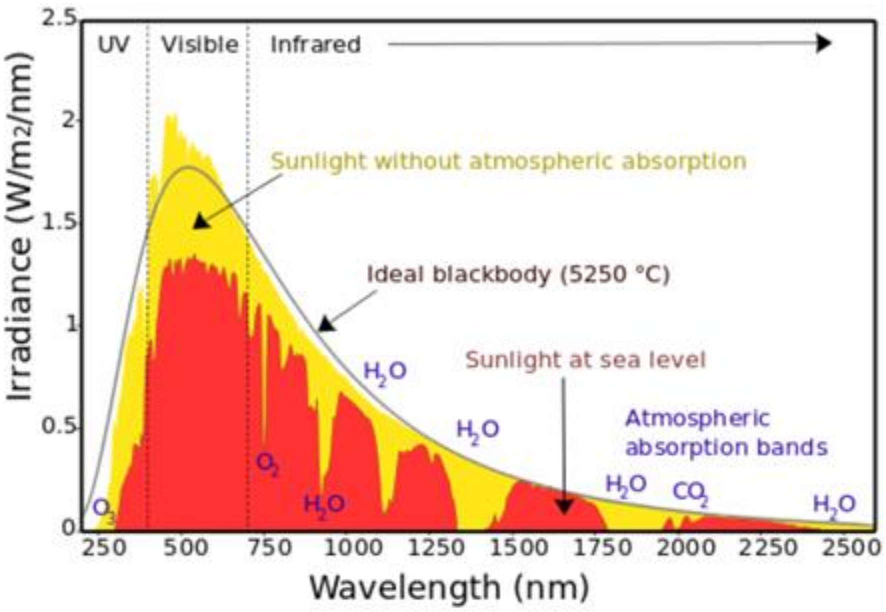


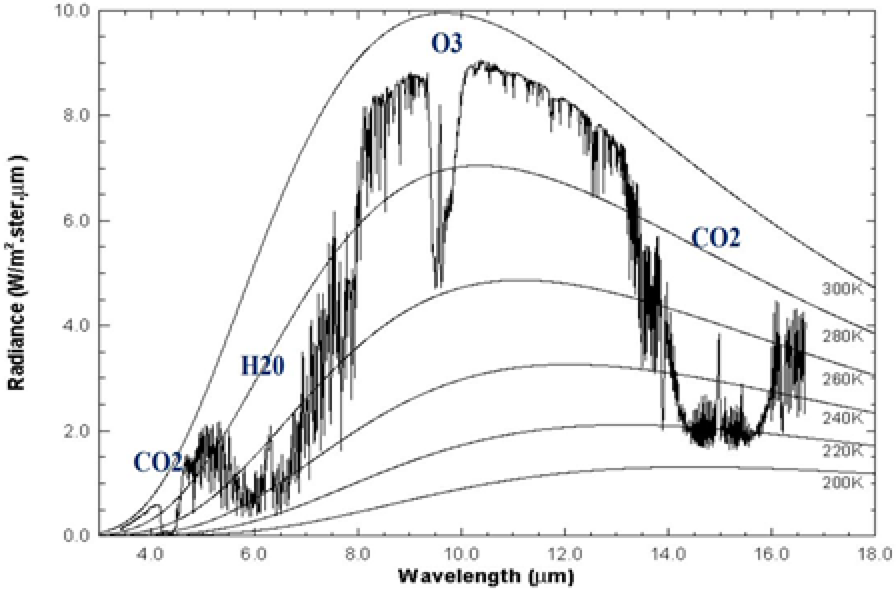
- For terrestrial remote sensing, the most important source is the sun
  Reflected solar energy is used
  0.3 - 2.5 μm
- The Earth is also an energy source
  >6 μm for self-emitted energy

Sun's Radiant Energy Distribution

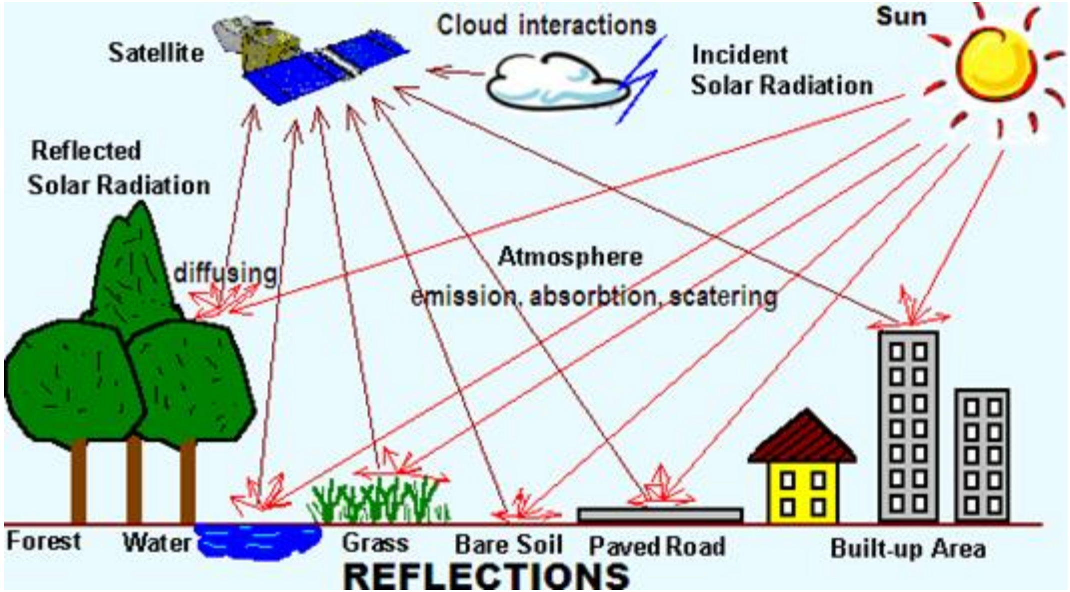
Name of Spectral Region	Wavelength Range, μm	Percent of Total Energy
Gamma and X-rays	< 0.01	Negligible
Far Ultraviolet	0.01 - 0.2	0.02
Middle Ultraviolet	0.2 - 0.3	1.95
Near Ultraviolet	0.3 - 0.4	5.32
Visible	0.4 - 0.7	43.5
Near Infrared	0.7 - 1.5	36.8
Middle Infrared	1.5 - 5.6	12.0
Thermal Infrared	5.6 - 1000	0.41
Microwave	> 1000	Negligible
Radio Waves	> 1000	Negligible

Theoretical vs. actual radiance due to Atmosphere effect





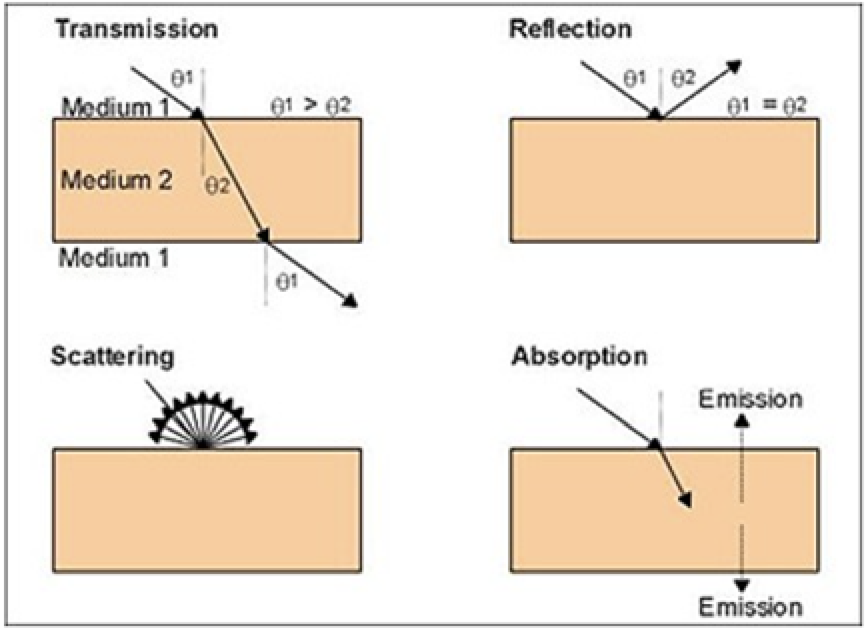
Remote Sensing System Overview



(1) How do you quantify radiation received by Sensor unit?

(2) How to quantify the radiation transfer process?

The fate of incident radiation



Reflectivity, r_λ
(Albedo)

Absorptivity, a_λ

Transmissivity, t_λ
(Transmittance)

$$\boxed{a_\lambda + r_\lambda + t_\lambda = 1}$$

- Radiation incident on a surface is either *reflected, absorbed or transmitted*
- Conservation of energy dictates that the sum of these must be 100% (or 1)
- For opaque objects ➔ negligible transmission ➔ $a_\lambda + r_\lambda = 1$ and $a_\lambda = 1 - r_\lambda$
- If the object is highly reflective, a_λ must be low (e.g., aluminum foil)
- Both a_λ and r_λ depend on the direction of the incident radiation

Blackbody, Perfect-window, Opaque-surface, Emissivity

If a_λ, r_λ, and τ_λ represent the fractional absorption, reflectance, and transmittance, respectively, then conservation of energy says

$$a_\lambda + r_\lambda + \tau_\lambda = 1 \quad .$$

For a blackbody $a_\lambda = 1$, it follows that $r_\lambda = 0$ and $\tau_\lambda = 0$ for blackbody radiation.
For a perfect window $\tau_\lambda = 1$, $a_\lambda = 0$ and $r_\lambda = 0$.
For any opaque surface $\tau_\lambda = 0$, so radiation is either absorbed or reflected $a_\lambda + r_\lambda = 1$, and $a_\lambda = 1 - r_\lambda$, which means that strong reflectors are weak absorbers (i.e., snow at visible wavelengths), and weak reflectors are strong absorbers (i.e., asphalt at visible wavelengths).

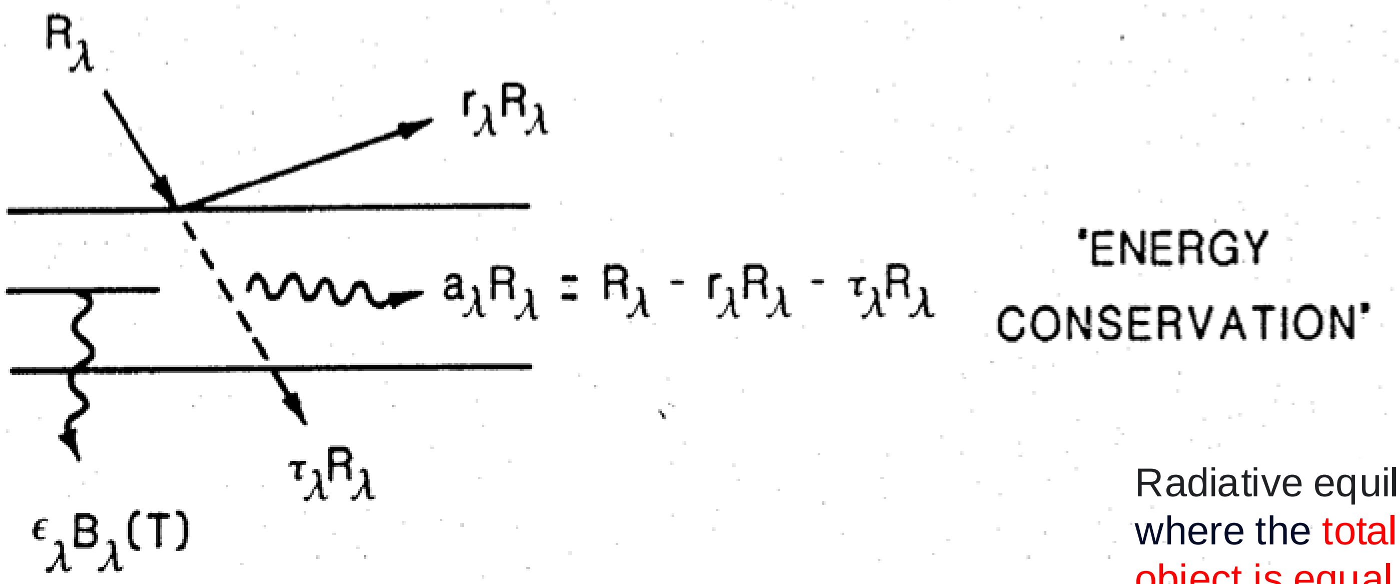
Since a Blackbody does not reflect or transmit energy, and it only emit energy, the radiation B_λ represents the upper limit to the amount of radiation that a real substance may emit at a given temperature for a given wavelength.

Emissivity ε_λ is defined as the fraction of emitted radiation R_λ to Blackbody radiation,

$$\varepsilon_\lambda = R_\lambda / B_\lambda \; .$$

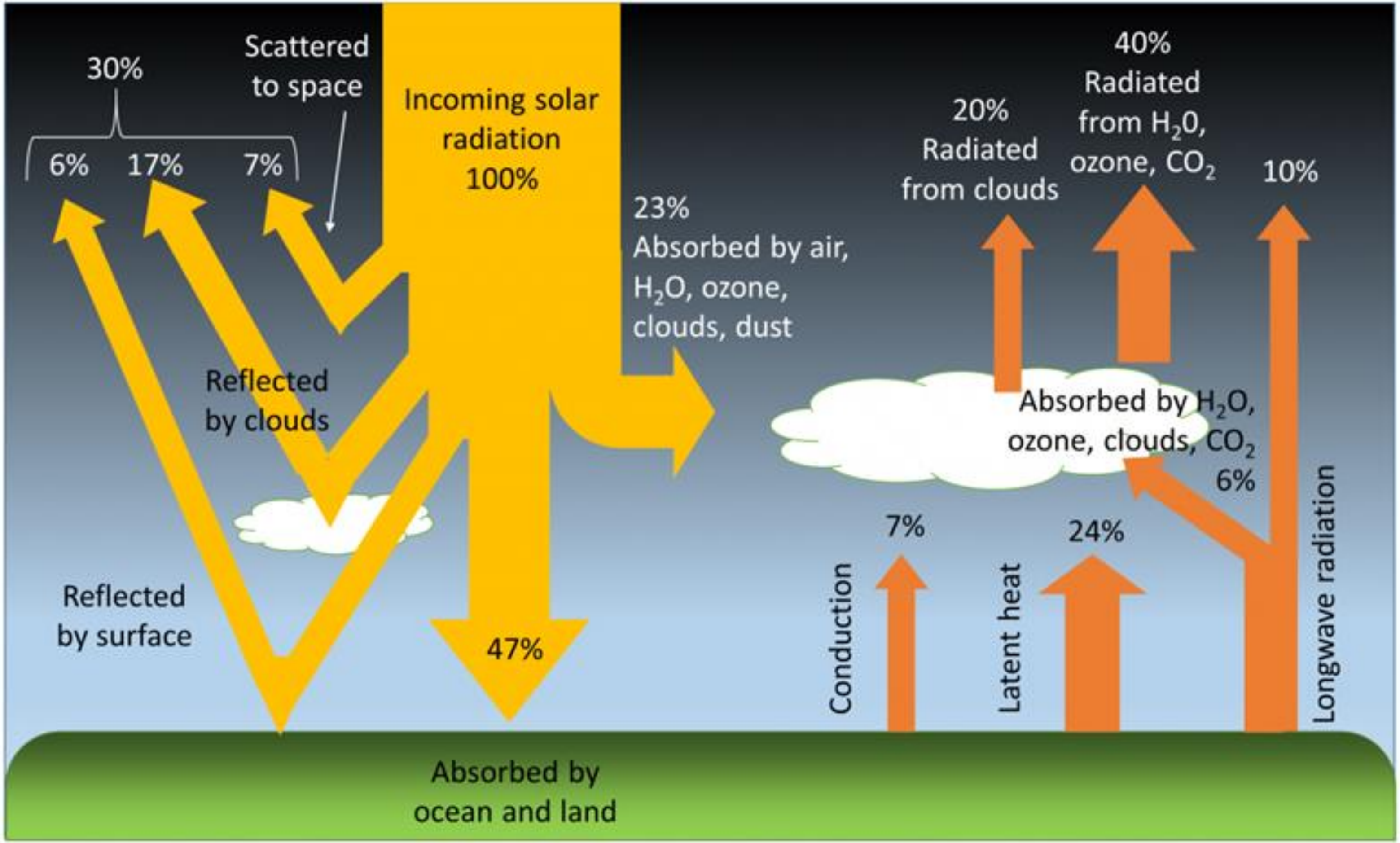
In a medium at thermal equilibrium, what is absorbed is emitted, so $a_\lambda = \varepsilon_\lambda$.

Please describe how does this object reach the **radiative equilibrium condition**

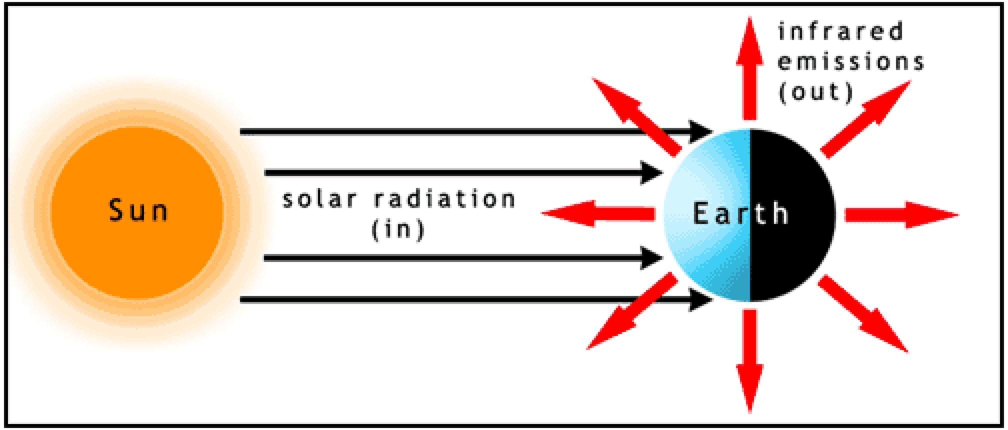


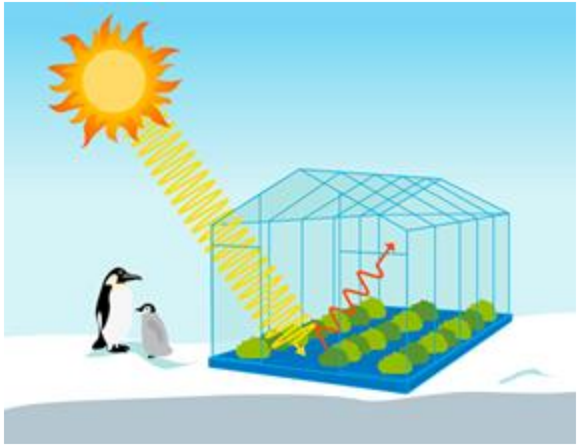
Radiative equilibrium is the condition where the total radiation leaving an object is equal to the total radiation entering it.

How does the Earth achieve balanced heat budget where incoming heat = outgoing heat?



The balance of incoming and outgoing heat on Earth is referred to as its **heat budget**. To maintain constant conditions, the budget must be balanced so that the **incoming heat equals the outgoing heat**.

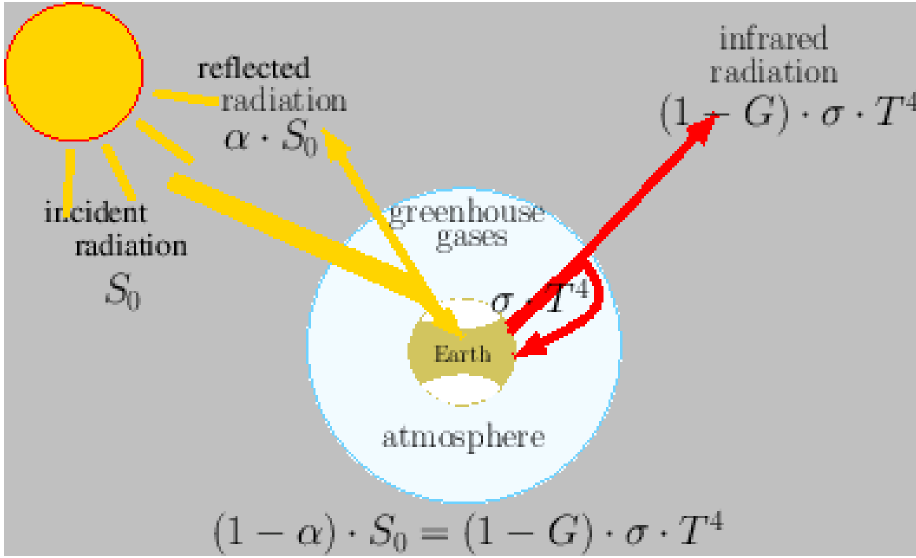




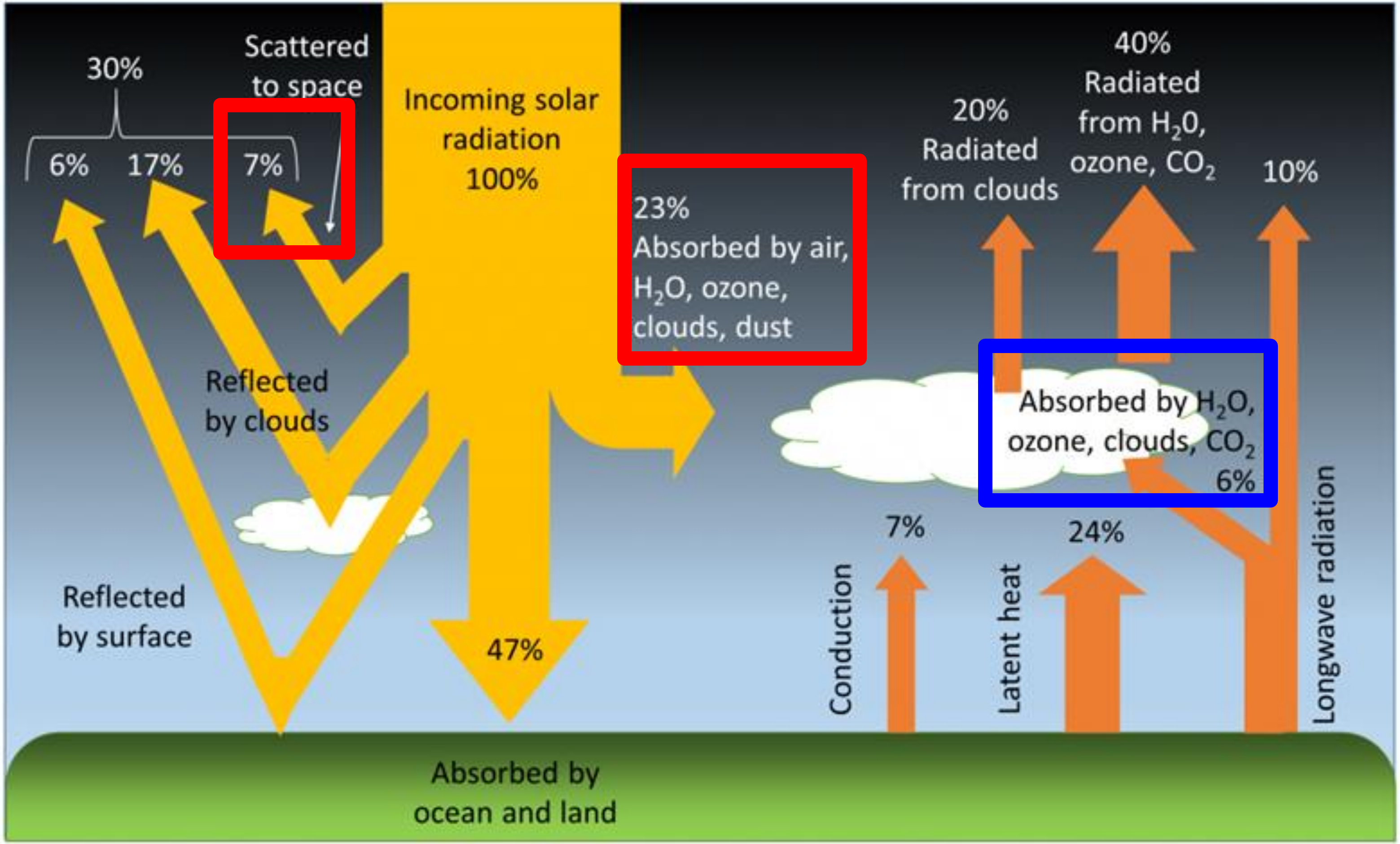
Stefan-Boltzmann Law E = π ∫ B(λ,T) dλ = σT^4,
where σ = 5.67 x 10-8 W/m2/deg4.

G: the absorption of longwave thermal infrared waves emitted by the earth by the greenhouse gas in the atmosphere.

According to the equation, if the solar radiation stays constant, what happens if the value of G is increasing?



Scatter by atmosphere 7%, Absorbed by atmosphere 23% + 6%



The intensity of the scattered radiation in different directions depends strongly on the radiation's wavelength and on the size, shape, and composition of the "particle".

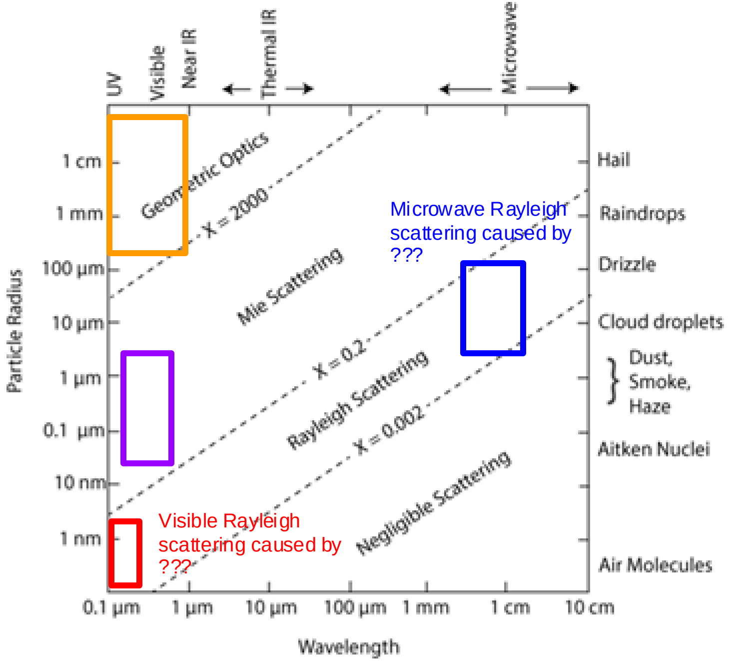
A very important parameter is called the **size parameter**:

$$x \equiv \frac{2\pi r}{\lambda}$$

where *r* is the radius of a spherical particle and *λ* is the radiation's wavelength.

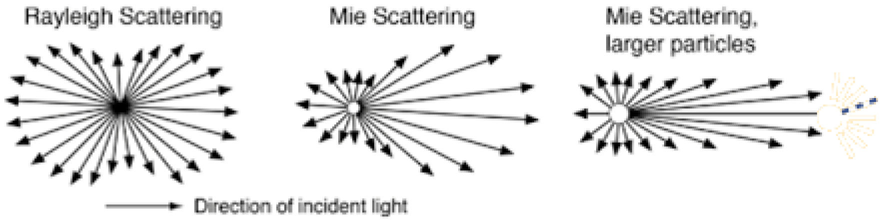
Scattering cross-section (i.e., the ratio of the intensity of radiant energy scattered in a given direction to the incident irradiance) in the Rayleigh regime ($x \ll 1$) is

$$\sigma_s \propto \frac{r^6}{\lambda^4}$$



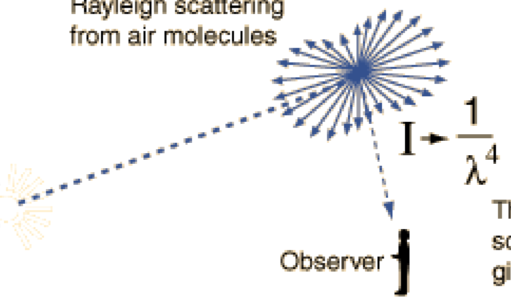
The Various Types of Scattering of Visible Light

TYPE OF PARTICLE	PARTICLE DIAMETER (MICROMETERS, µm)	TYPE OF SCATTERING	PHENOMENA
Air molecules	0.0001 to 0.001	Rayleigh	Blue sky, red sunsets
Aerosols (pollutants)	0.01 to 1.0	Mie	Brownish smog
Cloud droplets	10 to 100	Geometric	White clouds



Scattering Intensity $I = I_0 \frac{8\pi^4 N\alpha^2}{\lambda^4 R^2}(1 + \cos^2\theta)$

Scattering at right angles is half the forward intensity for Rayleigh scattering



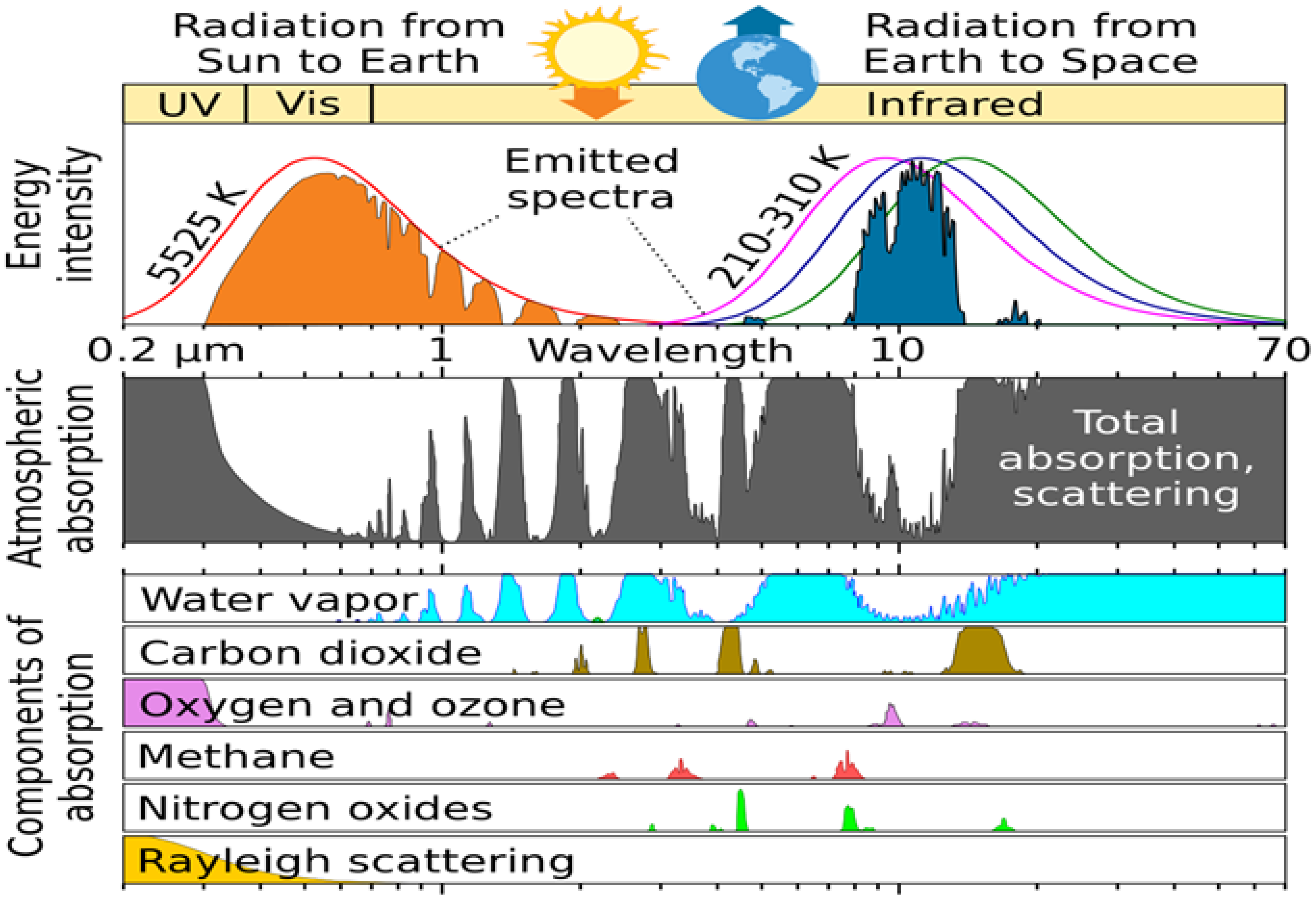
N = # of scatterers

α = polarizability

R = distance from scatterer

The strong wavelength dependence of Rayleigh scattering enhances the short wavelengths, giving us the blue sky.

Atmospheric absorption/scattering and Atmospheric Windows



1. How do different atmosphere components contribute? is it possible to separate water vapor from co2 and methane?

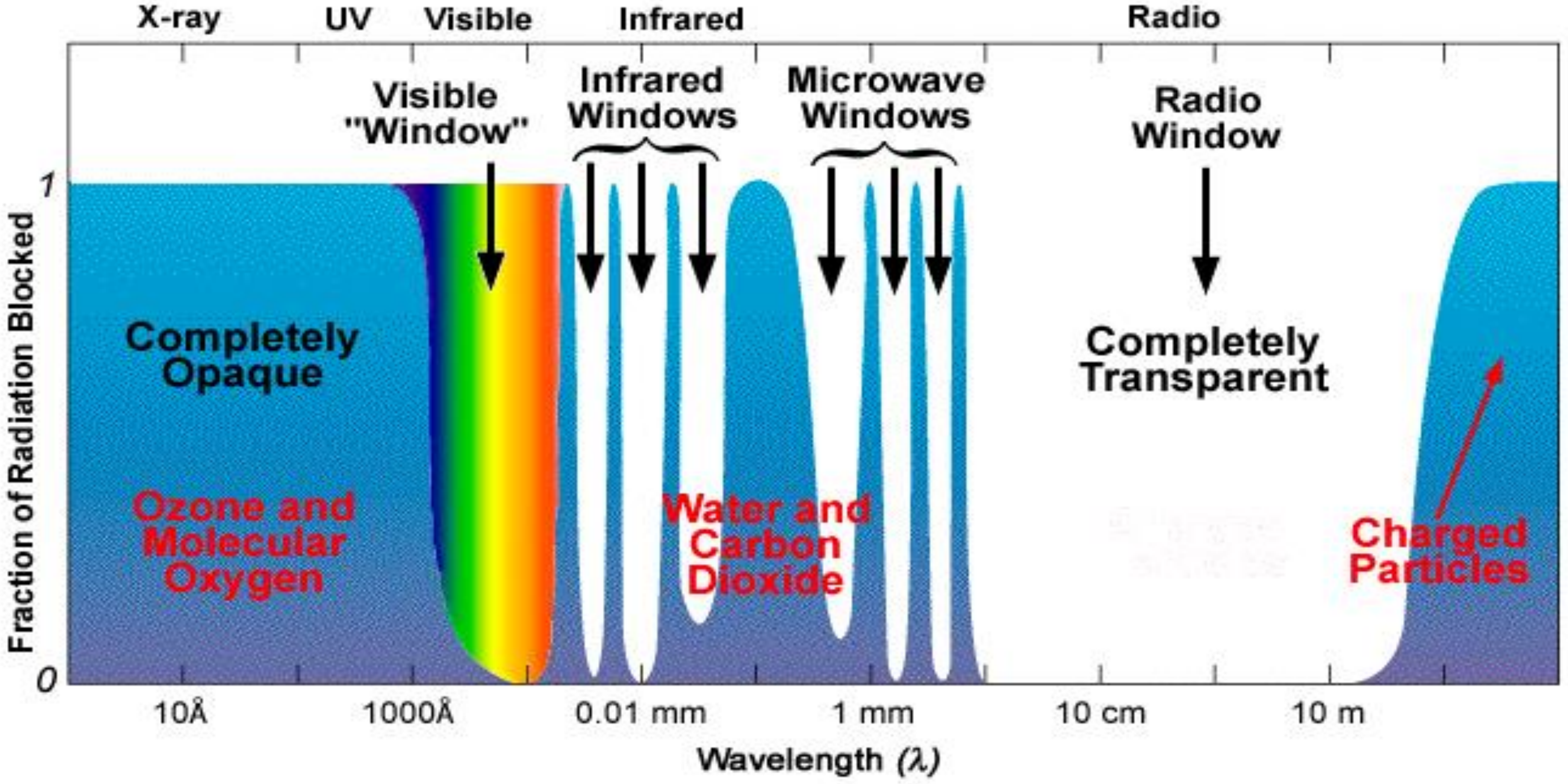
2. Where are atmosphere windows?

3. Why radiations from the Sun and the Earth are not perfect curves?

4. To design a sensor for measuring Earth's temperature, how to choose the spectral range to avoid atmospheric absorption?

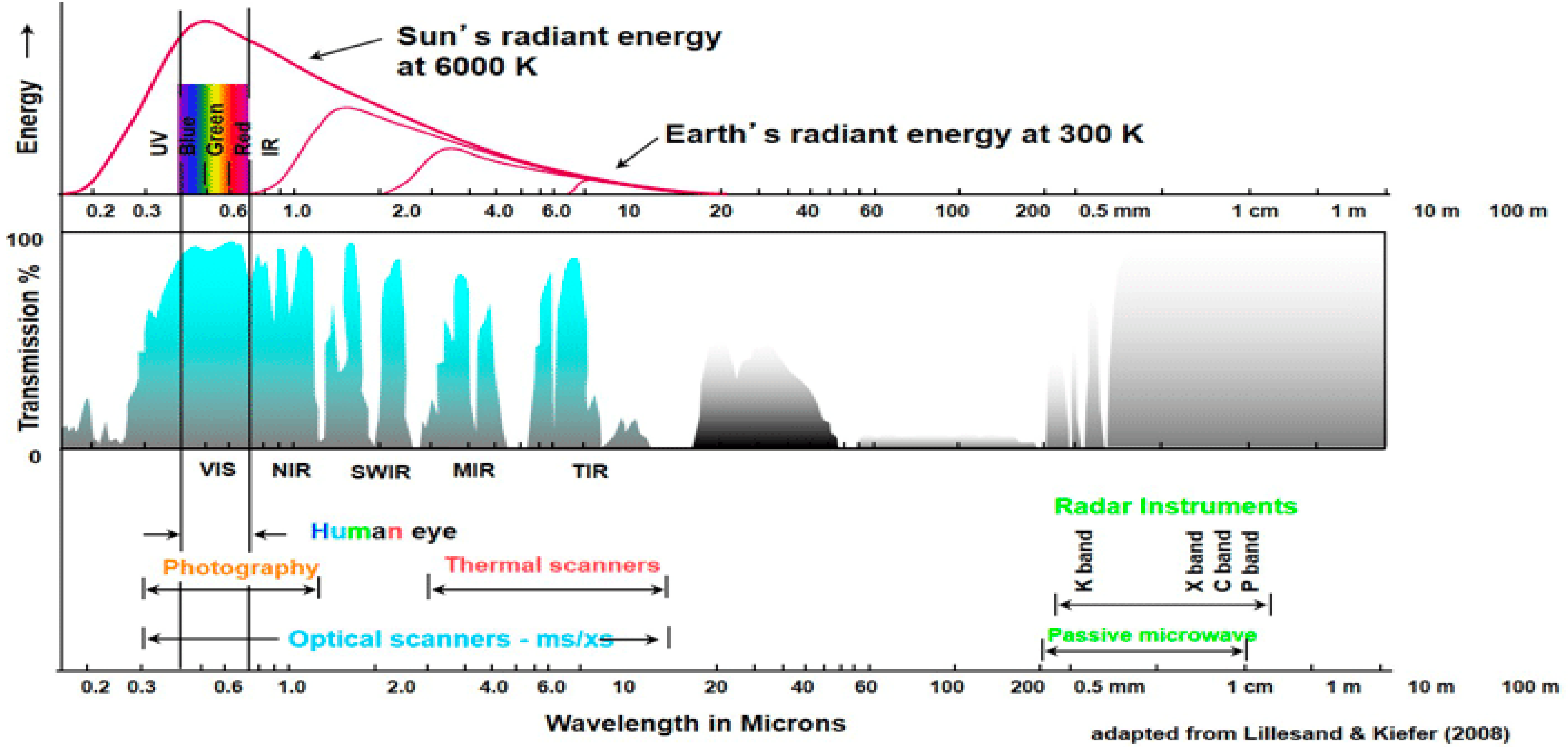
5. To design a sensor for carbon dioxide mapping, how to choose the spectral range to isolate out the contribution of carbon dioxide?

Images from wikipedia, christinatang1992

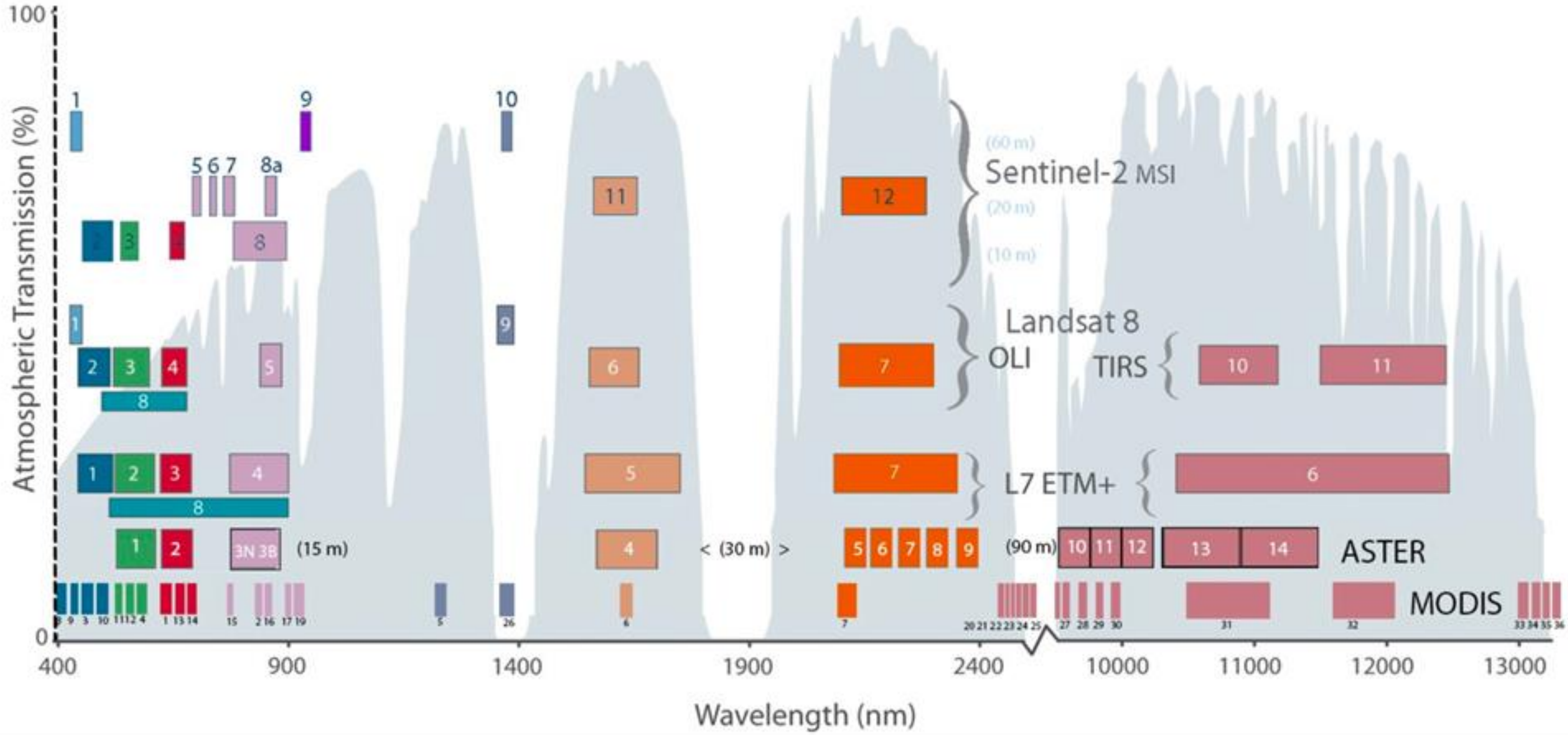


Picture from imagico.de

Which sensors can measure radiation emitted by Earth?

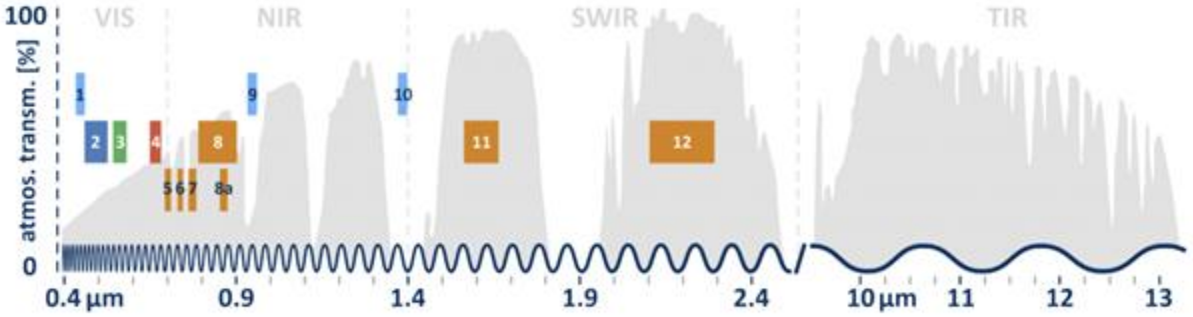


Which sensors can measure Earth temperature? Why Sentinel-2 channel 9 and 10?



Images from USGS

Sentinel-2 channel design



Sentinel 2 bands

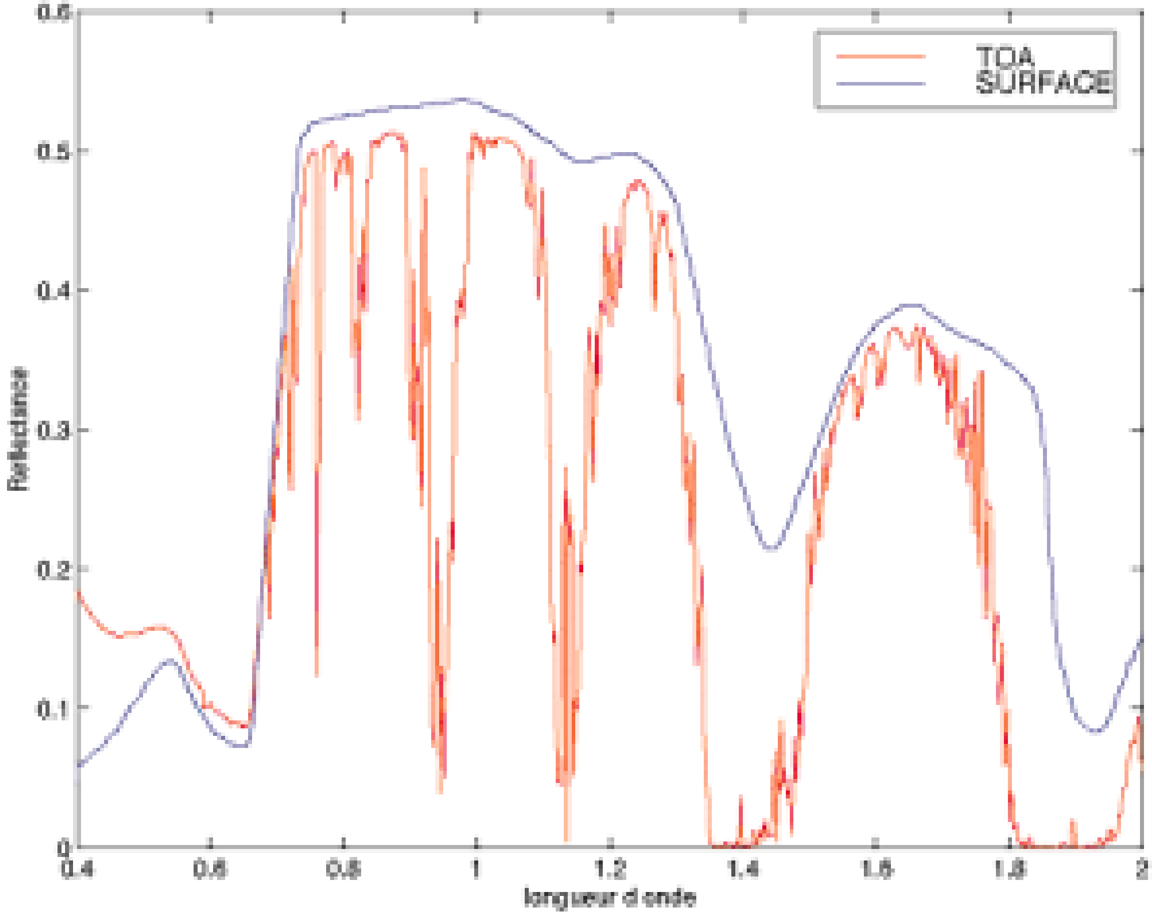
The Sentinel 2 mission is designed to mainly provide information for agricultural and forestry practices and applications. In this context, the three red edge bands (5-7) help to differentiate various plant species by leaf area chlorophyll characteristics. Note: Compared to Landsat, however, the thermal and pan bands are missing.

BAND	SPECTRAL	WAVELEN. [µm]	GEOM. [m]	SENSOR
1	aerosols	0.429 – 0.457	60	MSI
2	blue	0.451 – 0.539	10	MSI
3	green	0.538 – 0.585	10	MSI
4	red	0.641 – 0.689	10	MSI
5	red edge	0.695 – 0.715	20	MSI
6	red edge	0.731 – 0.749	20	MSI
7	red edge	0.769 – 0.797	20	MSI
8	NIR	0.784 – 0.900	10	MSI
8a	narrow NIR	0.855 – 0.875	20	MSI
9	water vapour	0.935 – 0.955	60	MSI
10	SWIR cirrus	1.365 – 1.385	60	MSI
11	SWIR	1.565 – 1.655	20	MSI
12	SWIR	2.100 – 2.280	20	MSI

1. Three red edge bands (5-7) help to differentiate various plant species by leaf area chlorophyll characteristics.

2. Band 10 is effective for detecting high clouds and particularly thin cirrus clouds, because no signal from the ground (except high mountains) can penetrate this spectral range due to strong water vapor absorptions (usually at the lower layers of the atmosphere).

3. Band 9 is used to estimate water vapour content by subtracting band 9 with band 8a, based on the assumption that the surface reflectance for bands 865 and 940 nm is the same (which is quite accurate, even if small variations are possible).

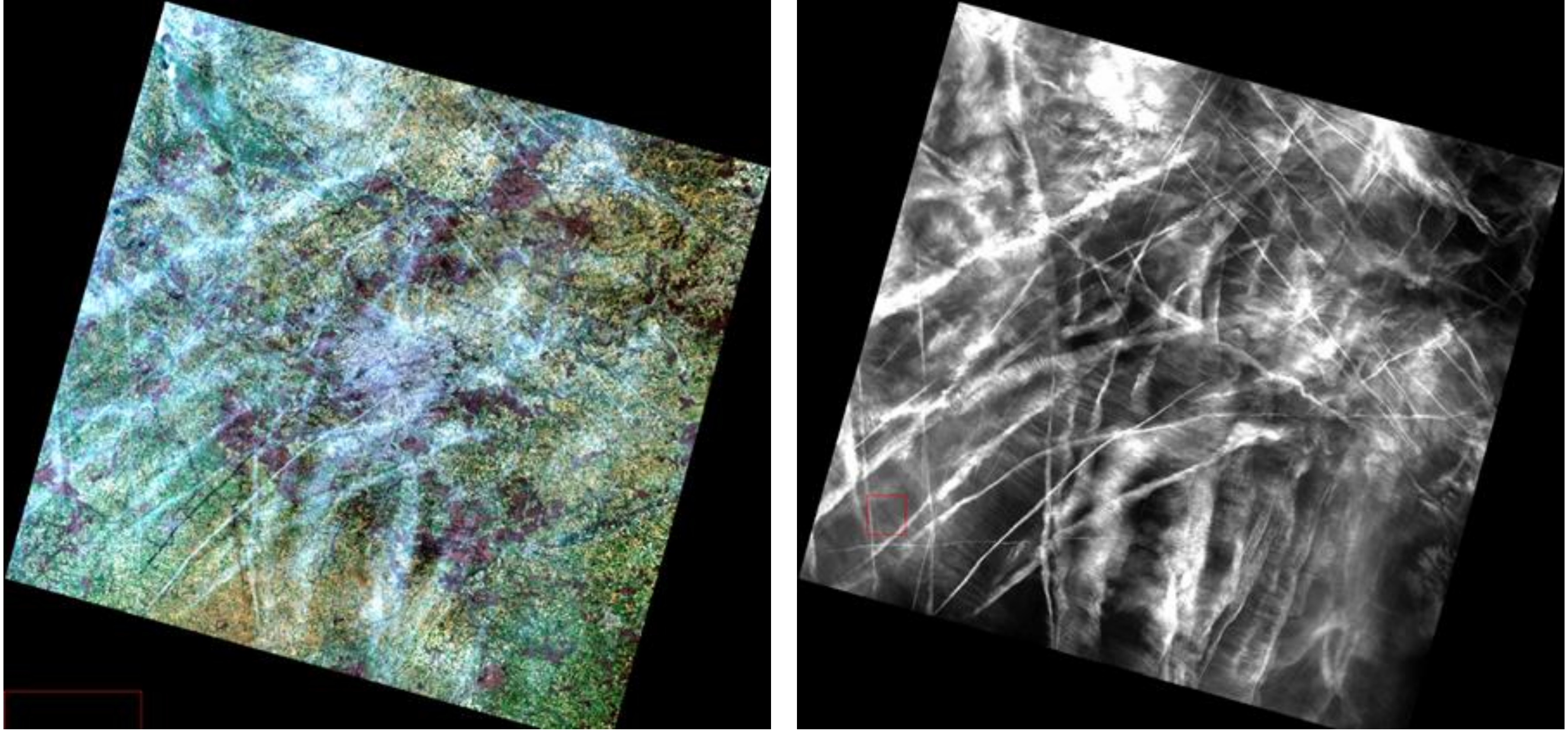


Atmospheric absorption.

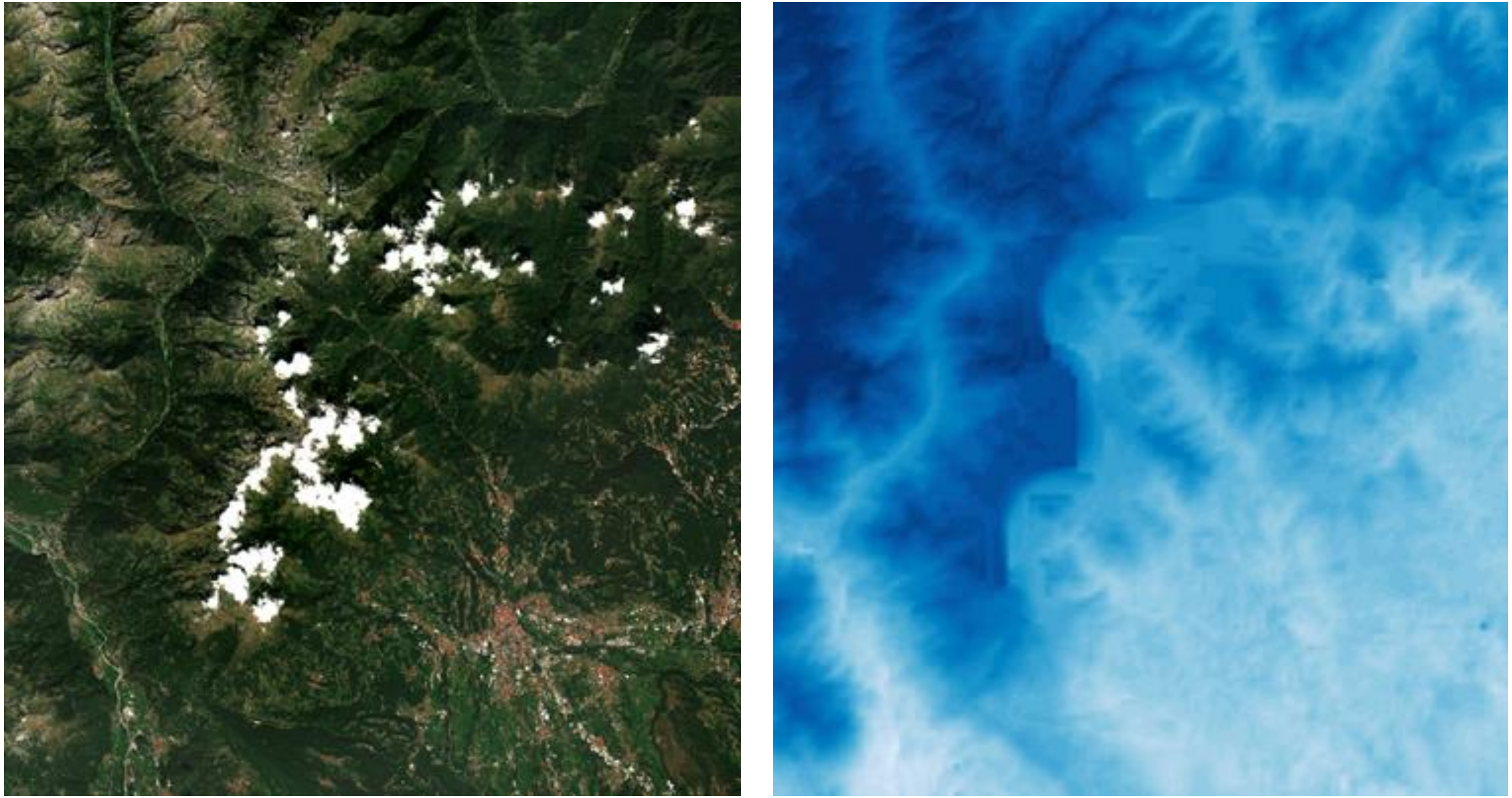
In blue, the surface reflectance for a pixel covered with vegetation, as a function of wavelength.

In red the reflectance at the top of the atmosphere for this same pixel.

At Band 10, i.e., 1.38 µm, water vapor completely absorbs light coming from the surface at sea level.

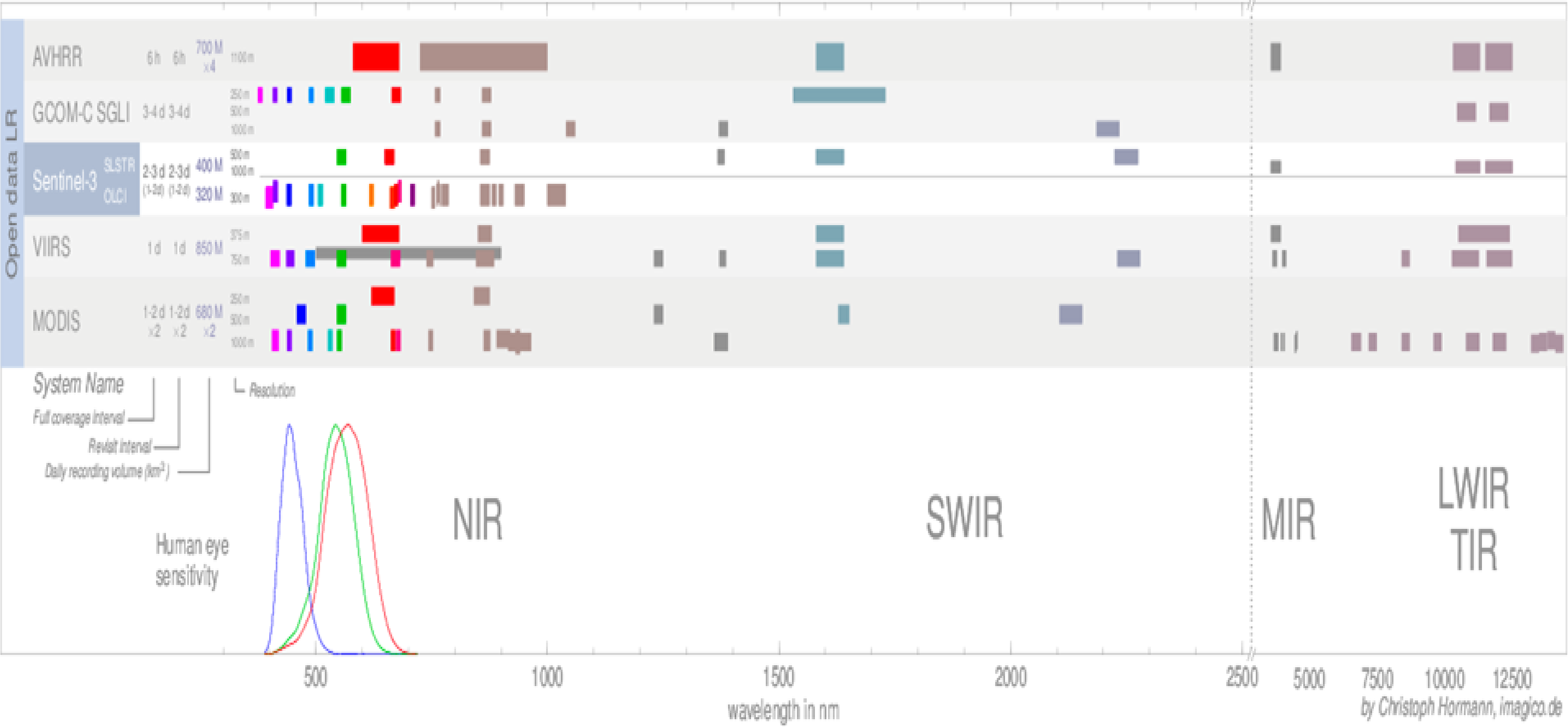


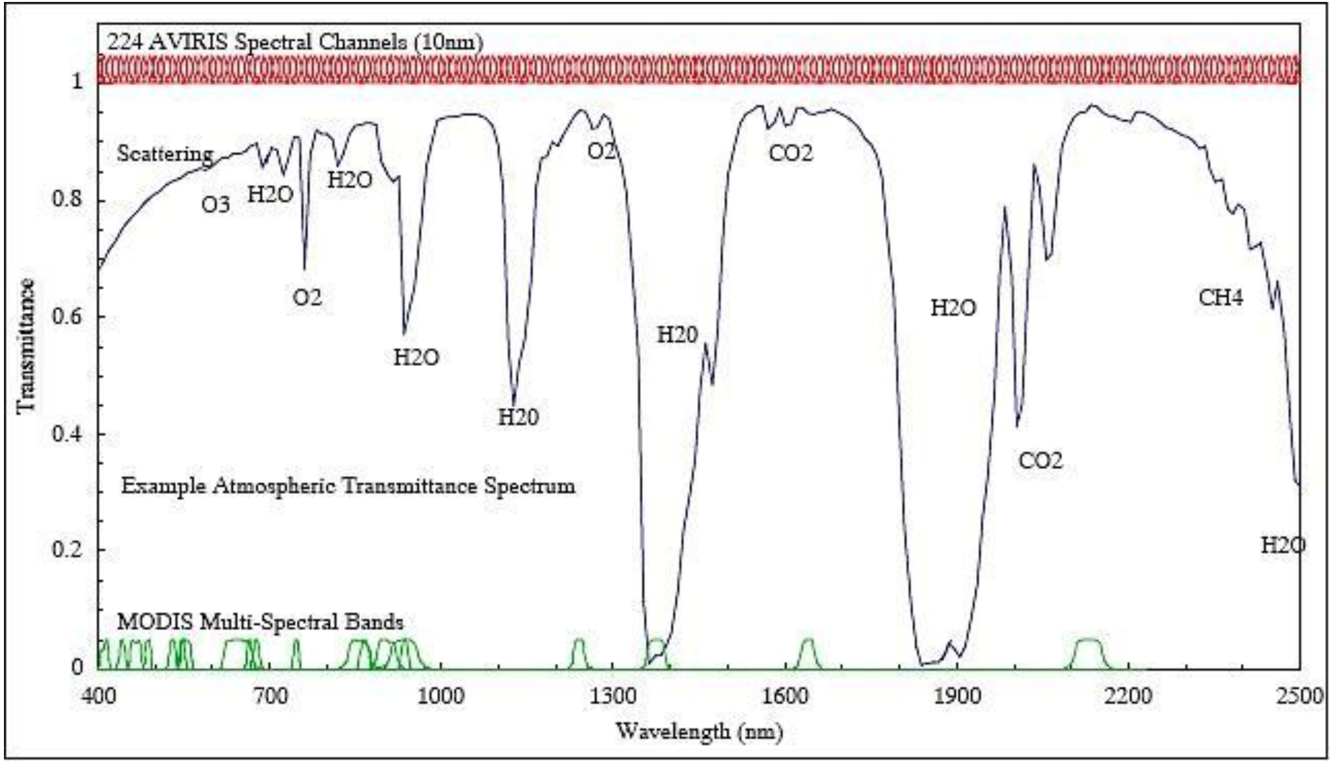
LANDSAT 8 image acquired in Paris on 04/14/2013. On the left, RGB colored composition, on the right, image of the 1.38µm strip. Seeing the number of plane tracks, we say to ourselves that we will have to choose between flying or observing the earth...



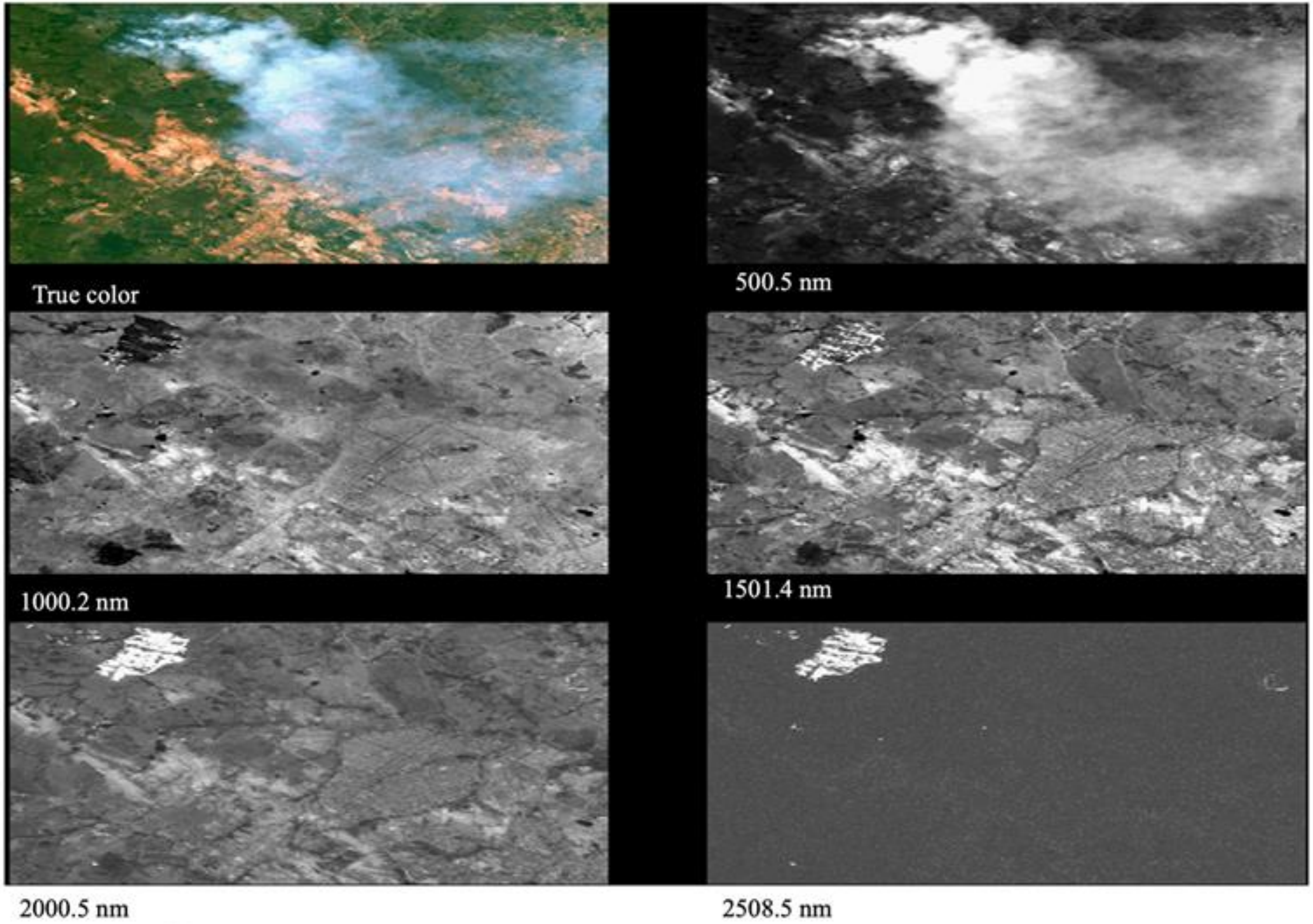
On the left, Sentinel-2 RGB image between Turin and Milan Italy(and zoom on Aosta Valley)
On the right, Corresponding water vapour image,between 0 (dark blue) and 2.5 (white) g/cm2.

Sentinel-3 OLCI/SLSTR in comparison with other low resolution polar orbit systems





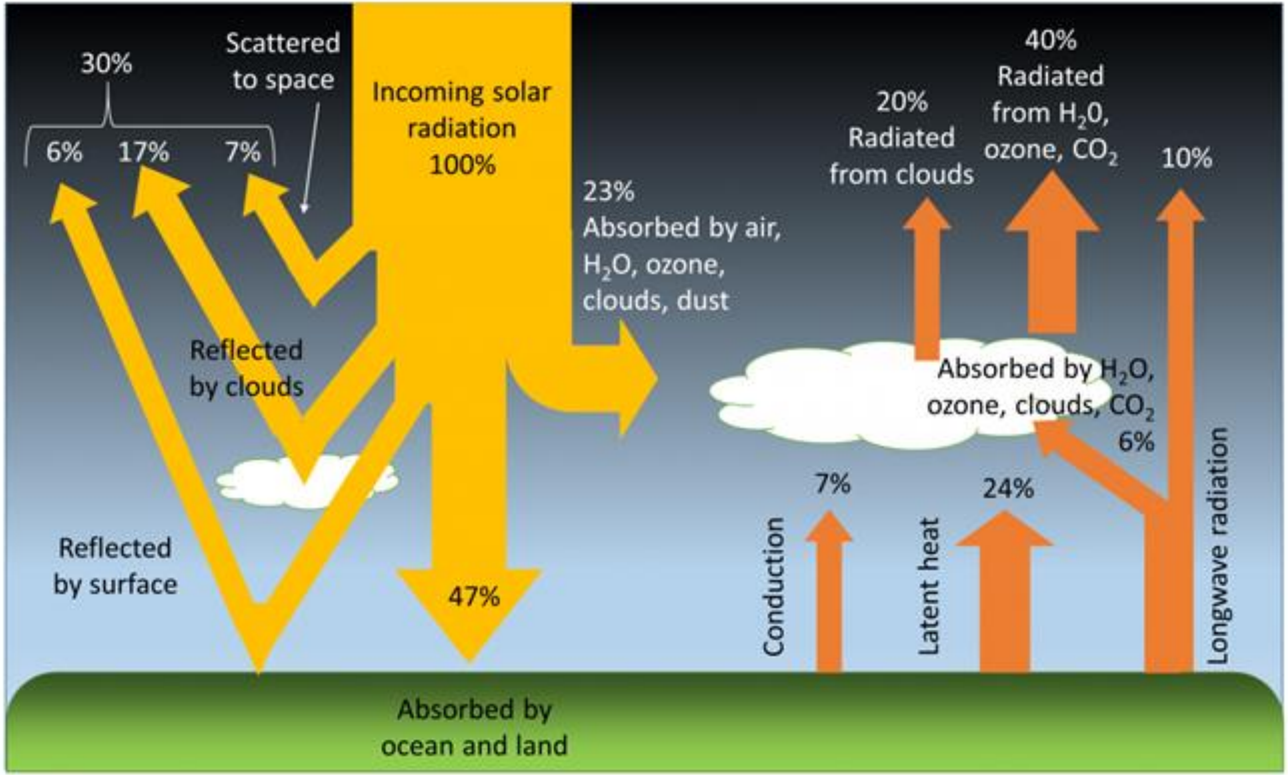
Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) from NASA is the first full spectral range imaging spectrometer and dedicated to Earth Remote Measurement. It is a unique optical sensor that continues to deliver calibrated images of the upwelling spectral radiance in 224 contiguous spectral channels (bands) with wavelengths from 380 to 2510 nanometers.



Cuiaba Brazil mosaic on 25 August 1995 shows a forest clearing fire.

Six of the AVIRIS 224 wavelengths are on display here. Note again how the smoke becomes transparent for wavelengths greater than 1.0 um and the fire signal dominates beyond 2.0 um.

Planetary Albedo



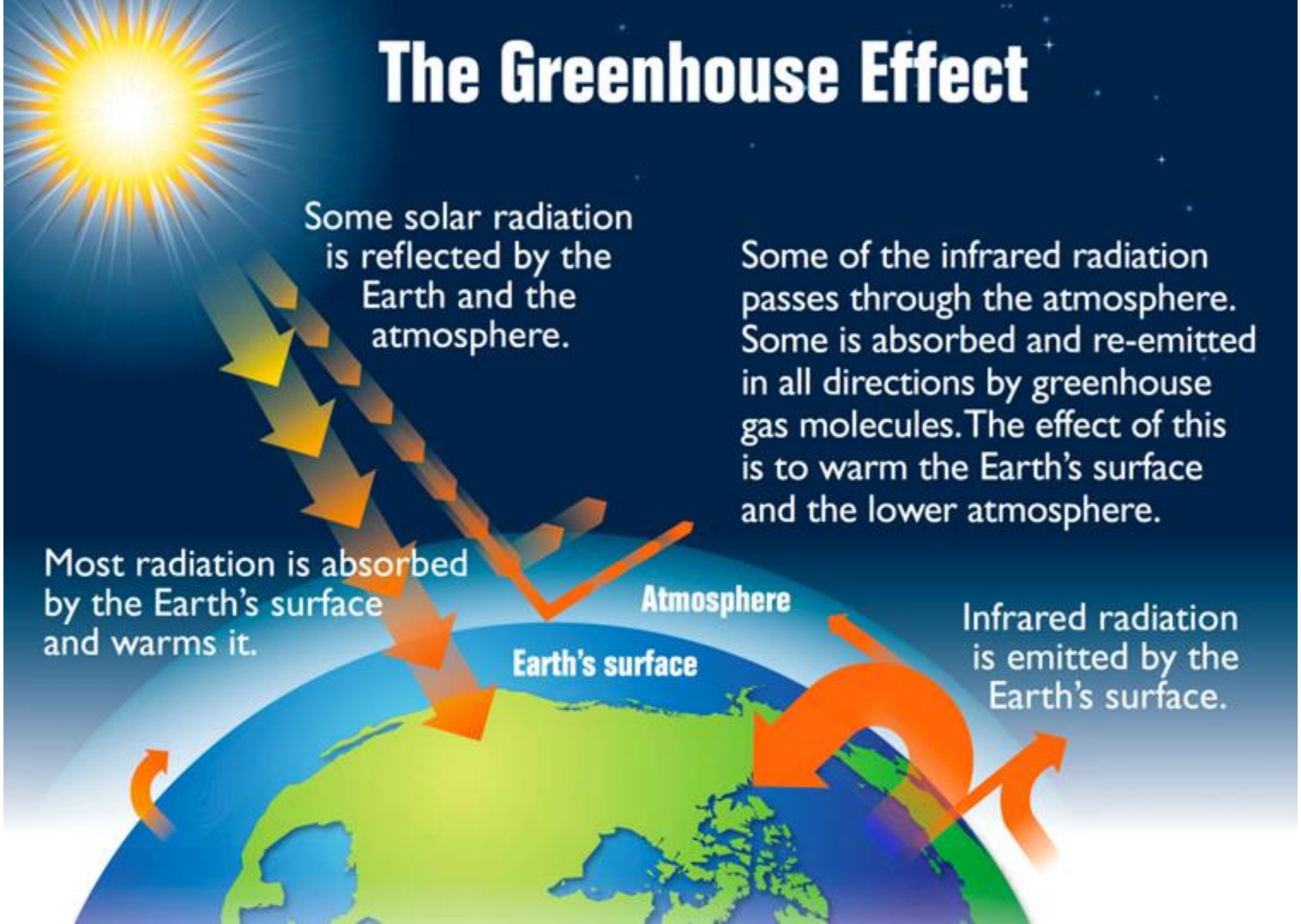
Planetary albedo R is defined as the fraction of the total incident solar irradiance, S, that is reflected back into space.

Radiation balance then requires that the absorbed solar irradiance (E) is given by

$$E = (1 - R)\, S/4.$$

The factor of one-fourth arises because the cross sectional area of the earth disc to solar radiation, πr^2, is one-fourth the earth radiating surface, $4\pi r^2$.

Thus recalling that $S = 1370\ Wm^{-2}$, if the earth albedo is 30 percent, then $E = 241\ Wm^{-2}$.



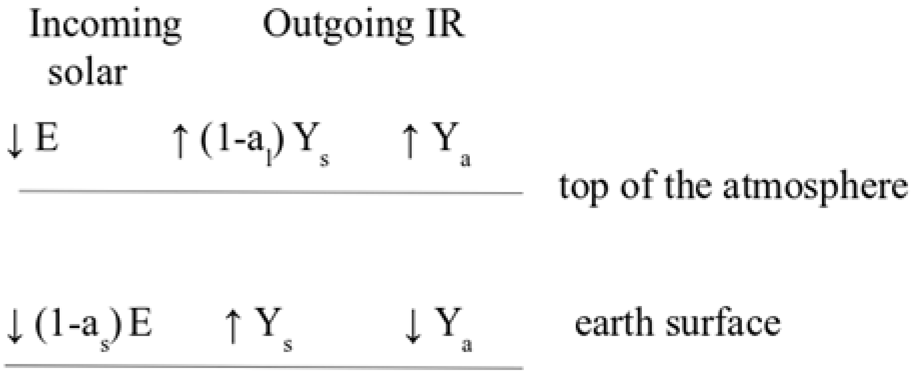
In the greenhouse effect, **the longwave infrared Earth radiation is strongly absorbed** by the atmosphere, particularly **by the greenhouse gases** such as CO2, methane, and water vapor, leading to **higher temperature of the Earth surface** than without these greenhouse gases.

How the Earth surface temperature is increased by the atmosphere – A simple model

Assume that the Earth behaves like a blackbody and that the atmosphere has an absorptivity a_S for incoming solar radiation and a_L for outgoing longwave radiation.
Let E be the solar irradiance absorbed by the earth-atmosphere system, Y_a be the irradiance emitted by the atmosphere (both upward and downward); Y_s the irradiance emitted from the earth's surface. Then, radiative equilibrium requires

$E - (1-a_L)\, Y_s - Y_a = 0$, at the top of the atmosphere,
$(1-a_S)\, E - Y_s + Y_a = 0$, at the Earth's surface.

Solving yields

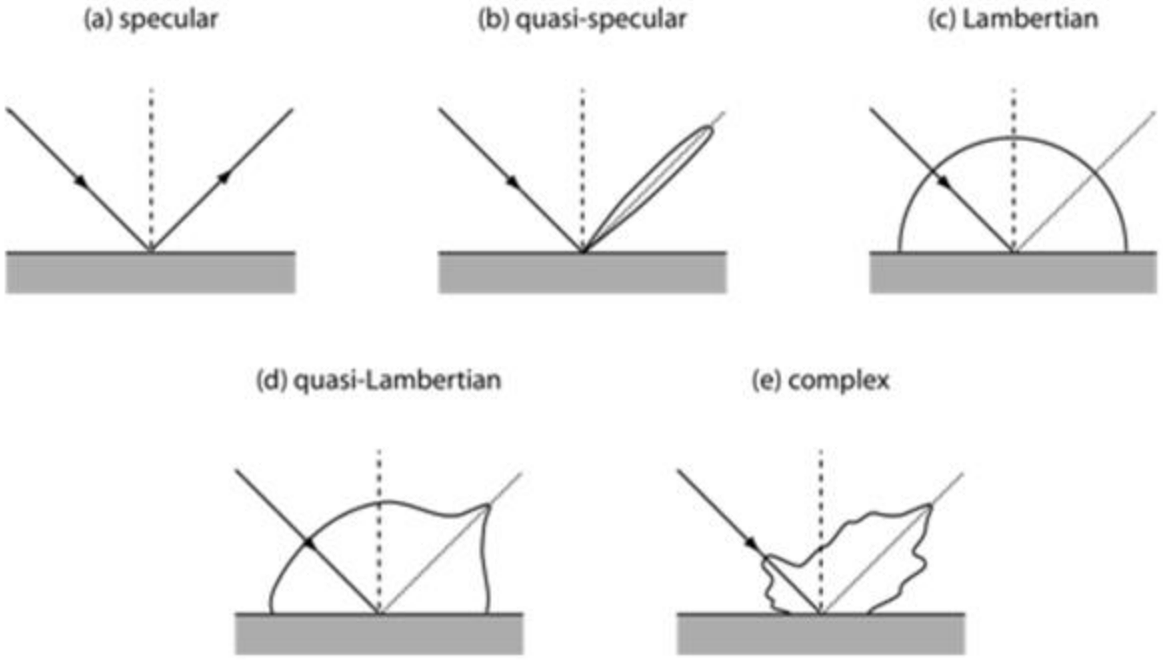


$$Y_s = \frac{(2-a_S)}{(2-a_L)} E = \sigma T_s^4$$

$$Y_a = \frac{(2-a_L) - (1-a_L)(2-a_S)}{(2-a_L)} E$$

If $a_L > a_S$, then $Y_s = E$, and according to Stefans Law, Earth surface temperature will be 255 K. However, since $a_L > a_S$ due to the greenhouse gases (CO_2, methane, and water vapor), $Y_s > E$, and according to Stefans Law, Earth surface temperature will be bigger than 255 K, which means that Earth surface temperature is increased by the presence of the atmosphere. For example, with $a_L = 0.8$ and $a_S = 0.1$ and $E = 241\ Wm^{-2}$, Stefans Law yields a blackbody temperature at the surface of 286 K which is bigger than the 255 K when $a_S = a_L$. The atmospheric gray body temperature Y_a in this example turns out to be 245 K.

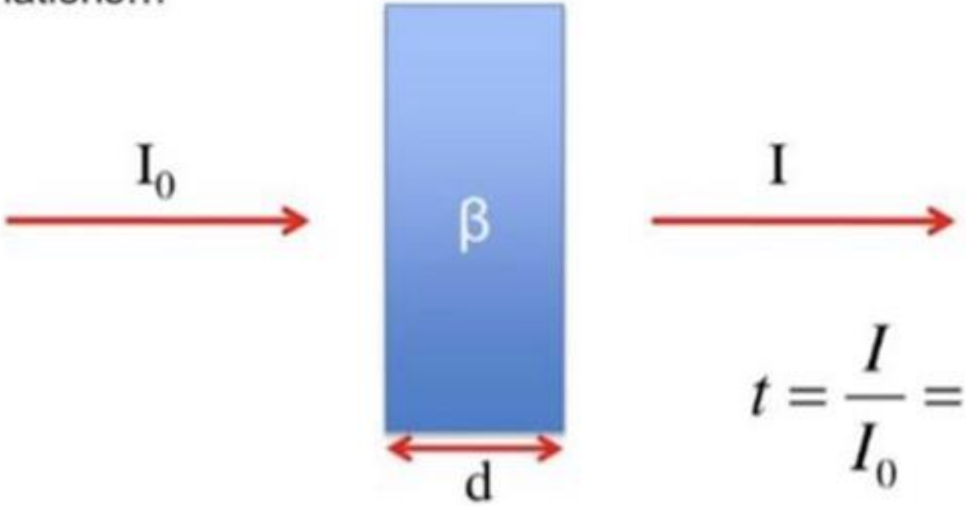
Angular distribution of reflected radiation



- Specular: radiation incident at angle θ reflected away from surface at angle θ
- Lambertian: radiation incident at angle θ reflected equally at all angles

Beer’s law

Also known as the Beer-Lambert Law or the Beer-Bouguer-Lambert Law, or other combinations…



$$t = \frac{I}{I_0} = e^{-\beta d}$$

The law states that there is a logarithmic dependence between the transmission (or transmissivity), *t*, of light through a substance and the product of the absorption coefficient (β) and the distance the light travels through the material, or the path length (d).

Transmittance

Beer's law indicates that transmittance (τ_λ) through an absorbing medium decays exponentially with increasing path length (d), and absorbing coefficient (β_λ)

$$\tau_\lambda (z \rightarrow \infty) = e^{-\beta_\lambda d(z)}$$

where $d(z) = \int_z^\infty \rho \, dz$, with z being a starting point in the depth.

Path length (d) determines the number of intervening absorbing molecules

Absorbing coefficient (β_λ) determines the absorbing power of the molecules

$$\beta_\lambda = \frac{4\pi K}{\lambda}$$

, where K is the extinction/attenuation coefficient (imaginary part of refractive index)

Together, $\beta_\lambda d$ is a measure of the **cumulative depletion capability**, which is often called the **optical depth σ_λ**.

Complex refractive index

$$\tilde{n} = n + i\kappa$$

κ: extinction coefficient

$$n = \frac{1}{\sqrt{2}}\left(\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}}\right)^{\frac{1}{2}}$$

$$\kappa = \frac{1}{\sqrt{2}}\left(-\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}}\right)^{\frac{1}{2}}.$$

Complex dielectric constant

$$n = \sqrt{\varepsilon_r}$$

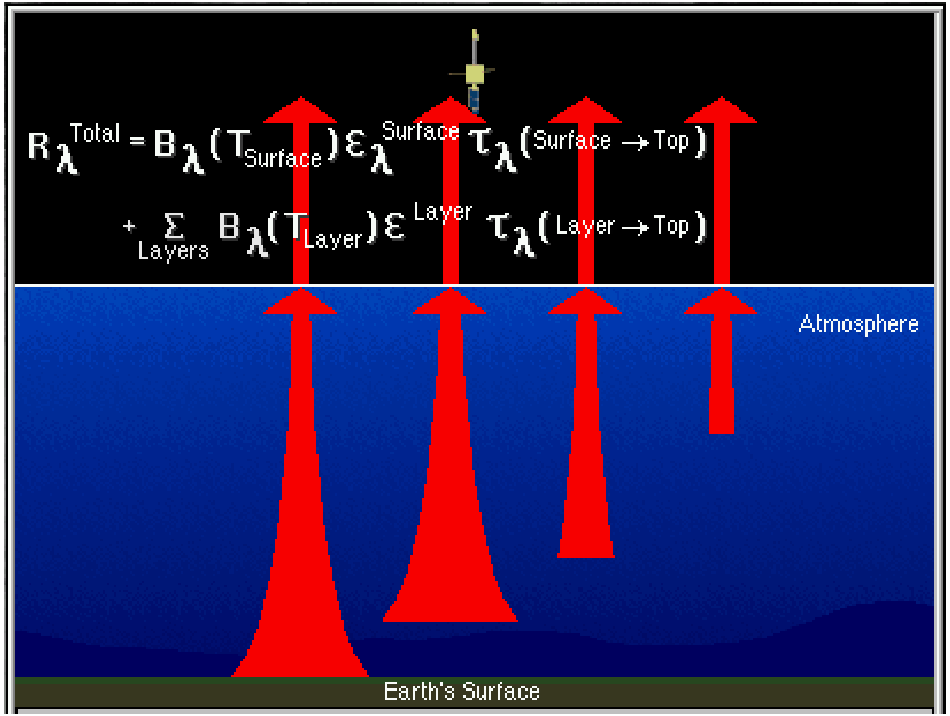
$$\tilde{\varepsilon}_r = \varepsilon_1 + i\varepsilon_2$$

$$\tilde{n}^2 = \tilde{\varepsilon}_r$$

The reflectivity (normal incidence)

$$R = \left|\frac{\tilde{n} - 1}{\tilde{n} + 1}\right|^2 = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}.$$

Radiative Transfer through the Atmosphere



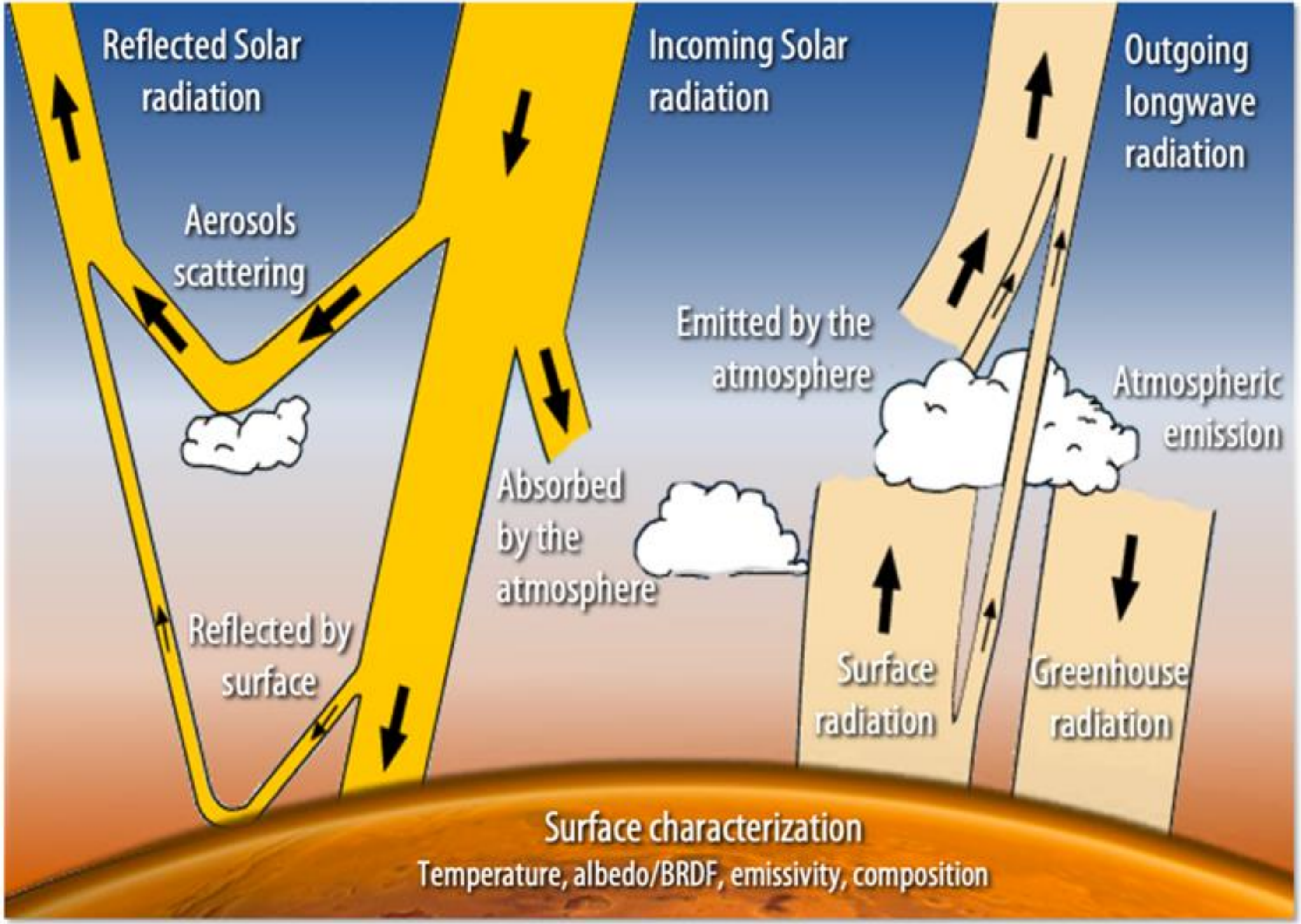
The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer is the sum of radiation emissions from the earth-surface and each atmospheric level that are transmitted to the top of the atmosphere.

Considering the earth's surface to be a blackbody emitter (emissivity equal to unity), the upwelling radiance intensity, I_λ, for a cloudless atmosphere is given by the expression

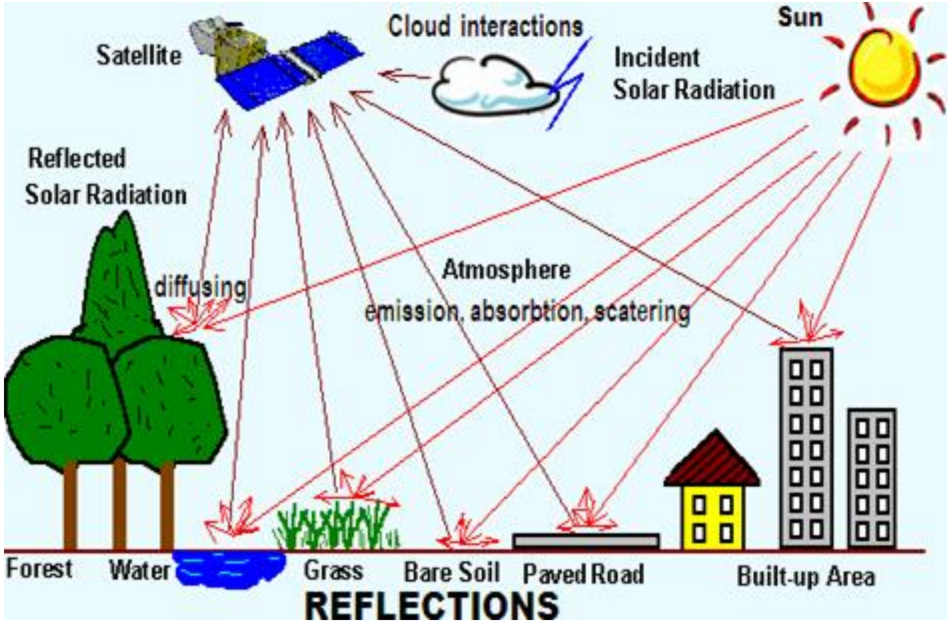
$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top)$$

$$+ \quad \Sigma\, \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

where the first term is the surface contribution and the second term is the atmospheric contribution to the radiance to space.


Reflected Solar radiation
Incoming Solar radiation
Outgoing longwave radiation
Aerosols scattering
Emitted by the atmosphere
Atmospheric emission
Absorbed by the atmosphere
Reflected by surface
Surface radiation
Greenhouse radiation
Surface characterization
Temperature, albedo/BRDF, emissivity, composition

Radiative Transfer through the Atmosphere



The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer:

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top)$$

$$+ \quad \Sigma\, \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

Q: is the above equation a complete forward model? if not, what else elements are missing?

No, because it only considers:
(1) earth surface emission;
(2) atmosphere emissions;

A complete radiative transfer model needs also to address the following factors:
(1) earth surface reflection;
(2) atmosphere reflection;
(3) changing and complex transmittance due to varying atmospheric conditions, e.g., the heterogeneous effect by cloud
(4) the influence of ground target properties (which are usually the properties we want to estimate), e.g., biophysical, biochemical, geophysical, and geochemical parameters, on earth surface reflection and emission;
(5) the geometry among the radiation source, the sensor and the target.

Questions?