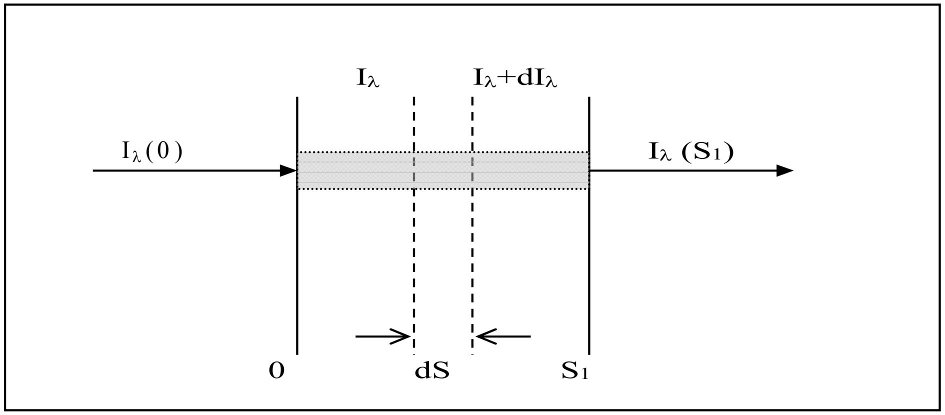
AOSC400-2015
October 1, Lecture # 9

- How is the Beer's Law used?
- To study atmospheric transmissivity
- To study the impact of aerosols
- Introduction to AERONET
- **Rayleigh scattering**

Review of Beer's Law:

Simple Aspects of Radiative Transfer

Tracing a ray from the sun (I_λ (0)) through a medium:



The equation of transfer

Depletion of energy takes place when the light beam goes through the medium:

$$I_\lambda \rightarrow I_\lambda + dI_\lambda$$

$$dI_\lambda \propto \rho I_\lambda ds$$

$$dI_\lambda \propto \rho I_\lambda ds$$

$$dI_\lambda = -k_\lambda \rho I_\lambda ds$$

where k_λ: mass extinction cross section

Therefore, the overall change of intensity:

$$dI_\lambda = -k_\lambda \rho I_\lambda ds$$

Assume, above term is zero (no emission or scattering contribution).

$$\frac{dI_\lambda}{k_\lambda \rho ds} = -I_\lambda$$

where k_λ: mass absorption cross section/absorption coefficient

$$I_\lambda(s_1) = I_\lambda(0)\exp\left(-\int_0^{s_1} k_\lambda \rho ds\right)$$

If the medium is homogeneous and k_λ is independent of distance, can be put in front of integral:

$$\tau = u = \int_0^{s_1} \rho\, ds$$

$$I_\lambda(s_1) = I_\lambda(0)\exp\left(-k_\lambda u\right)$$

Beer's Law

determines attenuation of radiant energy by scattering and/or absorption passing through atmosphere.

Monochromatic transmissivity T_λ

$$T_\lambda = I_\lambda(s_1)/I_\lambda(0)$$

$$T_\lambda = \exp(-k_\lambda u)$$

Since:

$$I_\lambda(s_1) = I_\lambda(0)\exp(-k_\lambda u)$$

$$I_\lambda(s_1) = I_\lambda(0)\exp(-k_\lambda u)$$

$$I_\lambda(s_1) = I_\lambda(0)$$

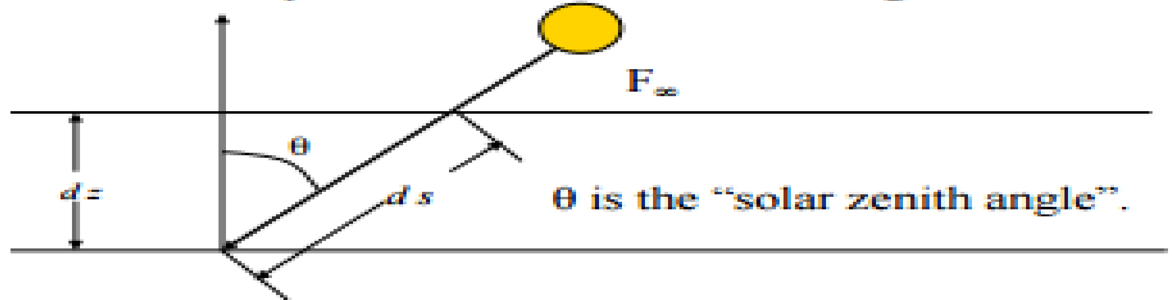
T_λ

Also Beer's Law.

This slides explain better where the cosθ comes from.

$$dF = -\rho \ k \ F \, ds$$ (same as Beer's law formulation, only uses F)

Now we move to the atmosphere. Consider the following illumination geometry:



For this geometry (plane parallel atmosphere), dz = - cos(θ) ds, and solving we have:

$$\cos(\theta)\, dF/dz = -\rho\, k_{abs}\, F$$

We define the **optical depth** along a vertical path, $\tau = \int_z^\infty \rho\, k_{abs}\, dz$, which implies the $d\tau = -\rho\, k_{abs}\, dz$, so we can write:

$$\cos(\theta)\, dF/d\tau = -F$$

solving:

$$F = F_\infty \exp(-\tau/\cos(\theta))$$

Remember τ here is defined as the vertical optical depth. F_∞ is the downward flux density at the top of the atmosphere. The incident flux thus decays exponentially along the slant path ds where the optical depth is given by τ/cos(θ).

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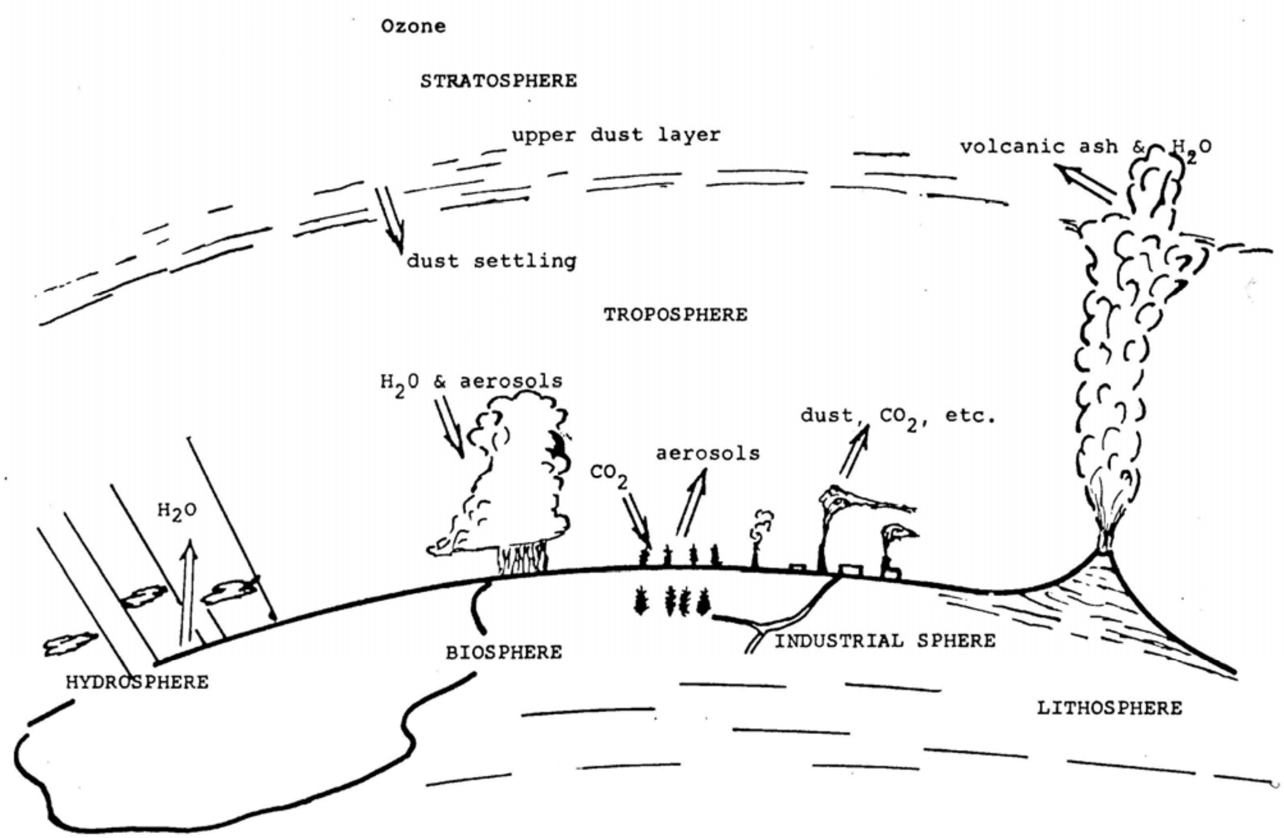
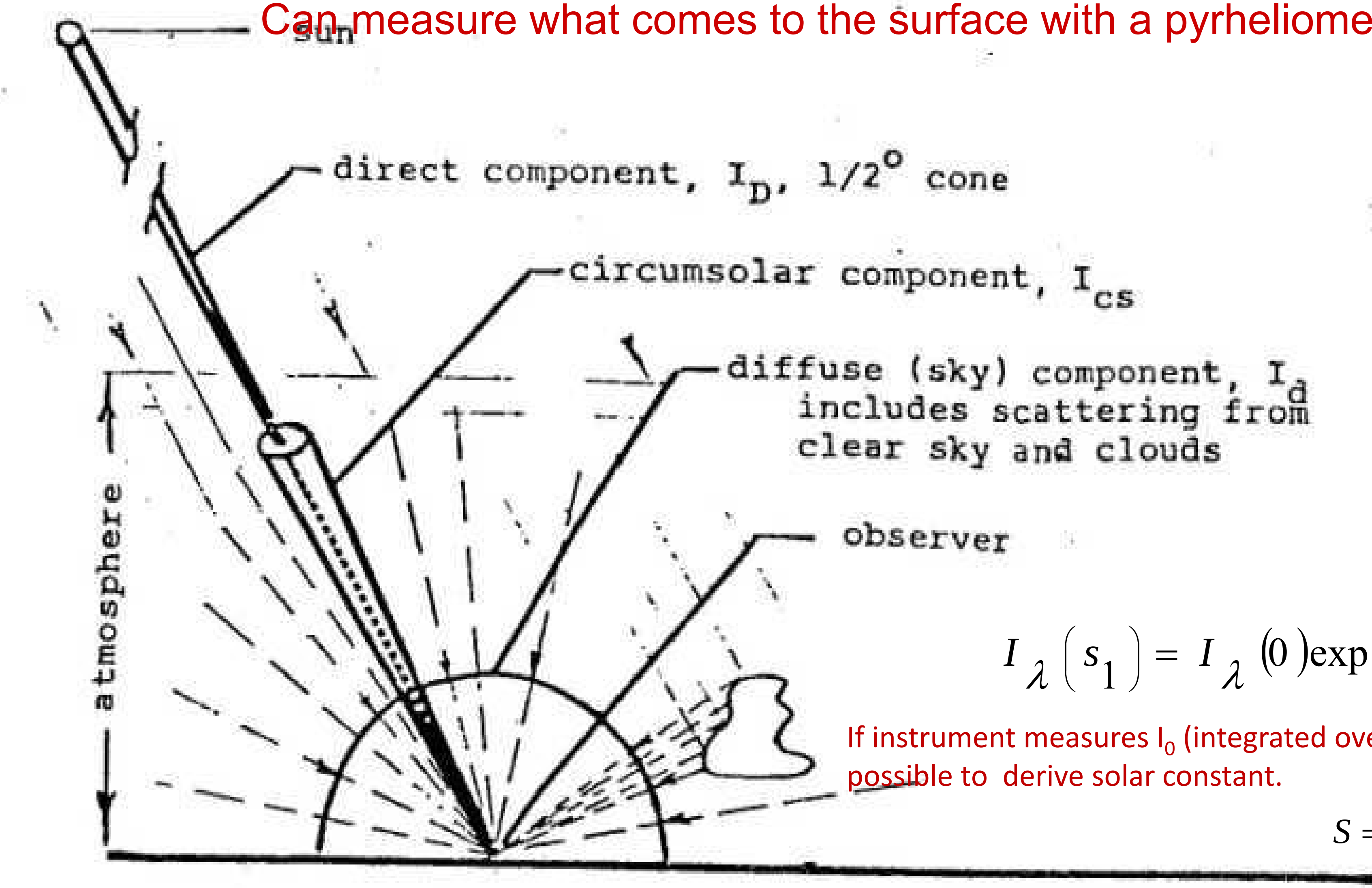
What is in the atmosphere that affects the transfer of radiation?

Possible processes: *Absorption, reflection, scattering*



How can we estimate the total effect of the atmosphere on the radiation from the sun?

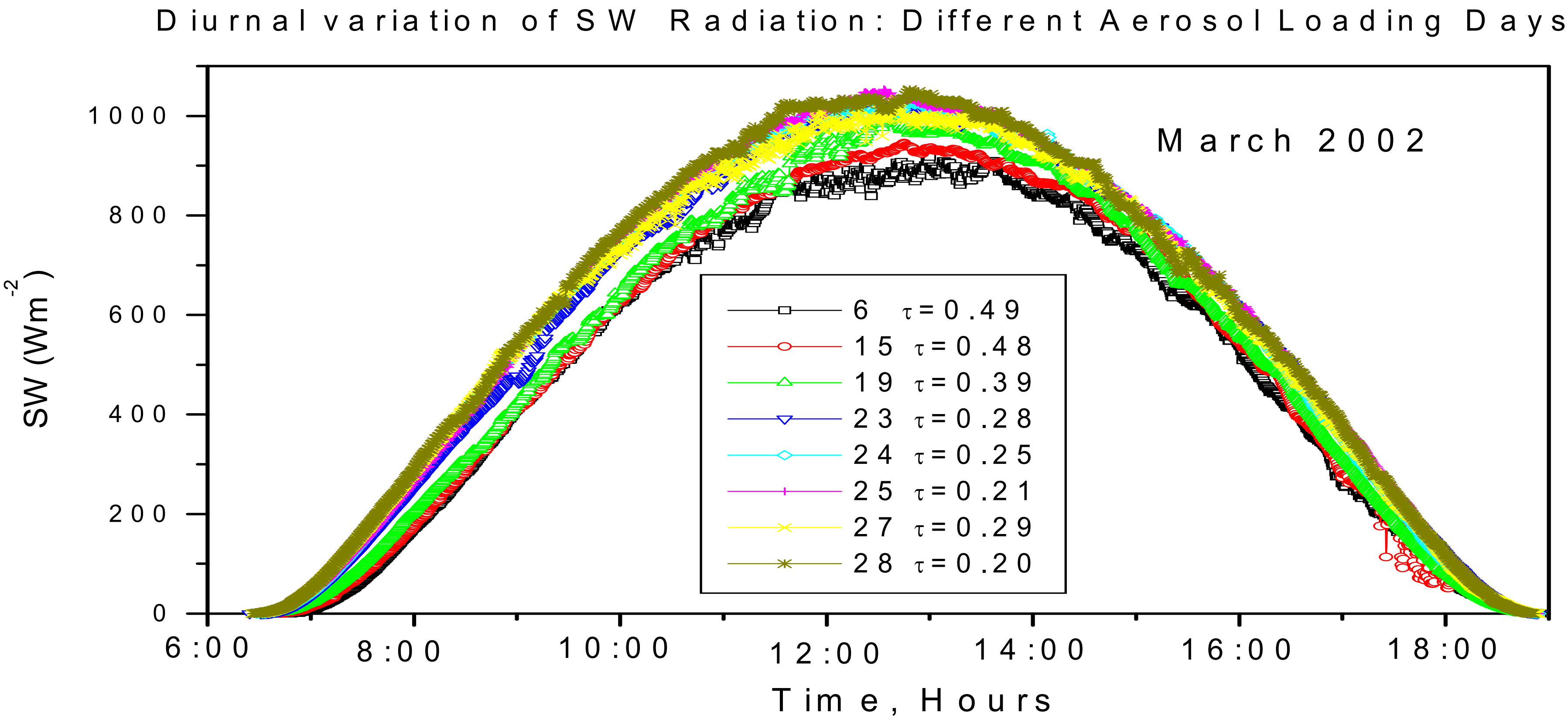
Can measure what comes to the surface with a pyrheliometer.



$$I_\lambda(s_1) = I_\lambda(0)\exp(-k_\lambda u)$$

If instrument measures I_0 (integrated over all wavelengths), possible to derive solar constant.

$$S = I_0 (d/d_m)^2$$



As seen in figure, if the atmosphere is more polluted (higher τ, less radiation reaches the ground.

Pandithurai G., R. T. Pinker, T. Takamura and P. C. S. Devara, 2004. Aerosol Radiative Forcing over a Tropical Urban Site in India (GRL, 2004)

Langley Plots

Possible uses:

Determine extraterrestrial radiation

Calibration of sun-photometers (see slide 16 for definition)

- Effective path length of the air mass = u sec θ_0 = τ
- θ_0 = solar zenith angle; z_1 is the height of the station

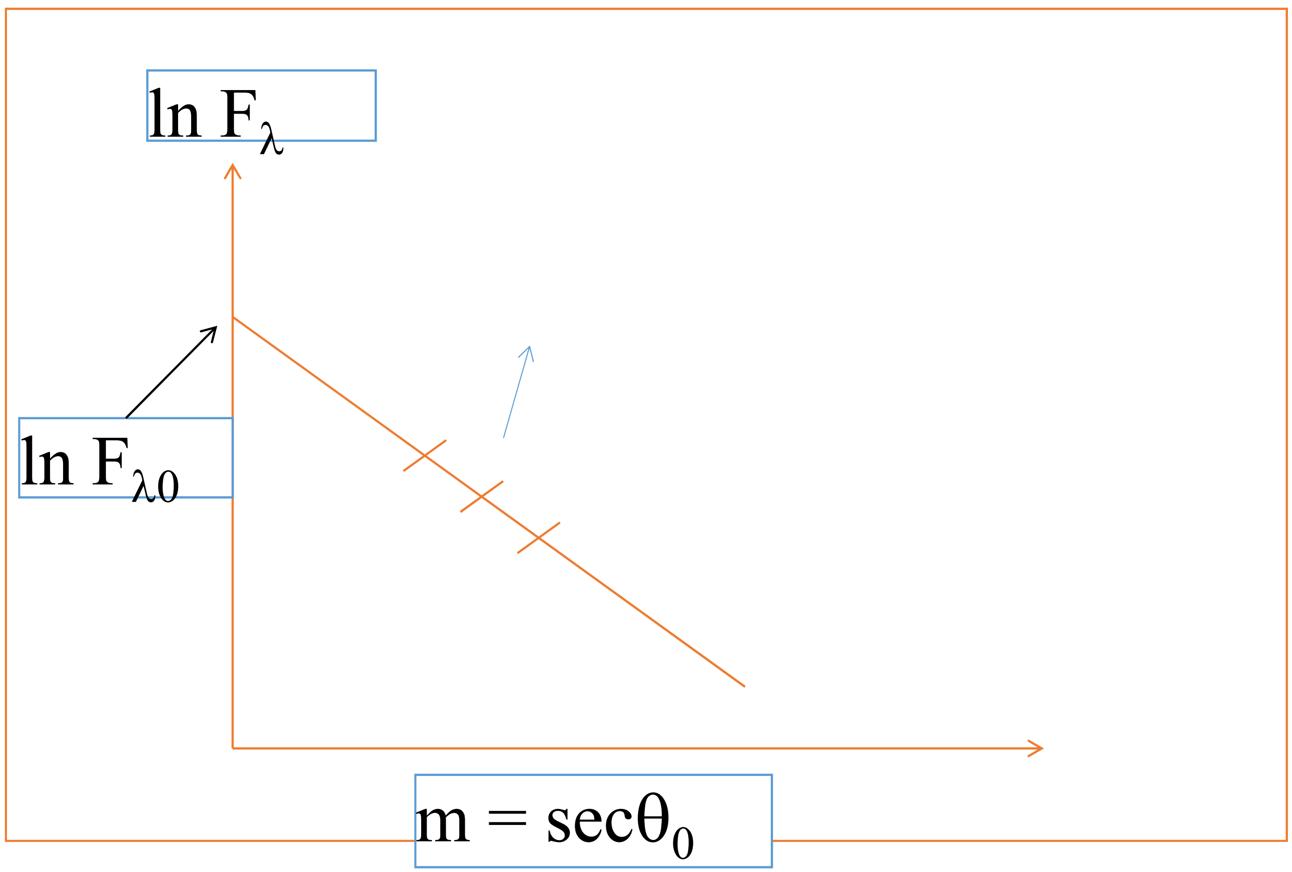
$$\tau = u = \int_{z_1}^{\infty} \rho dz$$

$$F_\lambda = F_{\lambda 0} \exp\left(-k_\lambda u \sec\theta_0\right) = F_{\lambda 0} T_\lambda^m$$

$$\ln F_\lambda = \ln F_{\lambda 0} + m \ln T_\lambda$$

Langley plot

Effective path length of the air mass = u sec θ_0



Other information one can derive from the solar direct beam

Solar direct beam:

$$I = \int_0^{\infty} I_{o\lambda} \exp\left(-\tau_{e\lambda} \sec\theta\right) d\lambda$$

$\sec\theta \approx m_r$ (relative optical mass)

$\tau_{e\lambda}$ = sum of extinctions due to scatter and absorption

$$I = \int^{\infty} I_{0\lambda} \exp\left[-\left(\tau_{R\lambda} + \tau_{oz\,\lambda} + \tau_{wv\,\lambda} + \tau_{D\,\lambda}\right) m_r\right] d\lambda$$

where

$\tau_{R\lambda}$ is due to Rayleigh scattering

$\tau_{oz\lambda}$ is due to ozone absorption

$\tau_{wv\lambda}$ is due to water vapor absorption

$\tau_{D\lambda}$ is due to aerosol extinction

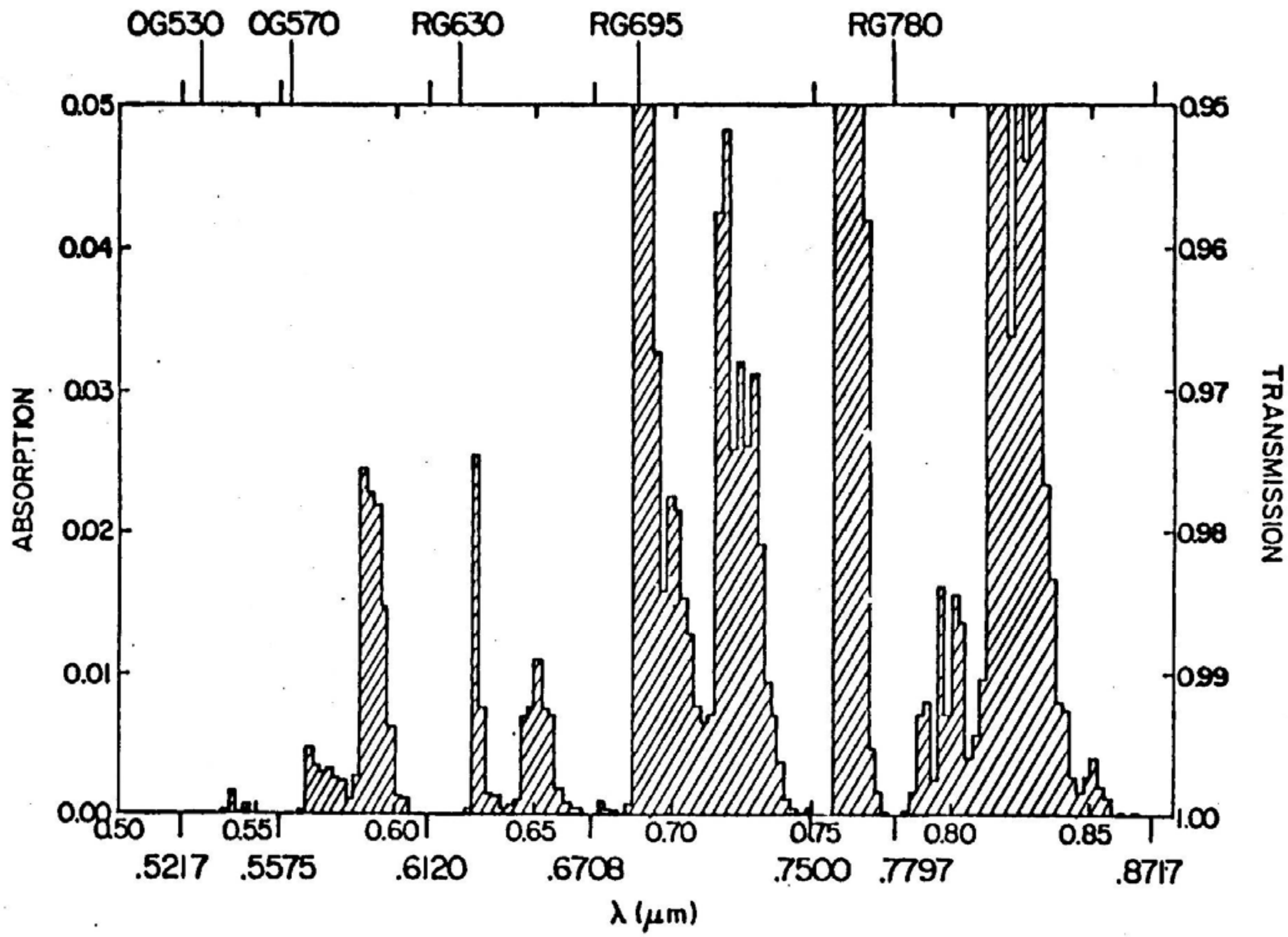
Assuming 3 out of the 4 terms

$$(\tau_{R\lambda} + \tau_{oz\,\lambda} + \tau_{wv\,\lambda} + \tau_{D\,\lambda})$$

are known, the 4th can be estimated.

Most commonly, assumed that the first 3 terms are known and the 4th (aerosol extinction) needs to be estimated.

In principle, it is not necessary to know all of the terms. It is possible to measure the direct beam in spectral intervals where the effect of some of the absorption terms is minimal. Instruments, known as Sun- Photometers of various level of complexity have been build to measure “aerosol optical depth”, namely, extinction due to aerosols. To build a sun photometer, the instrument bands are chosen so that the attenuation by unwanted material is minimal.



One can measure the attenuation of the solar beam in the intervals where absorption is minimal.

Sun photometers

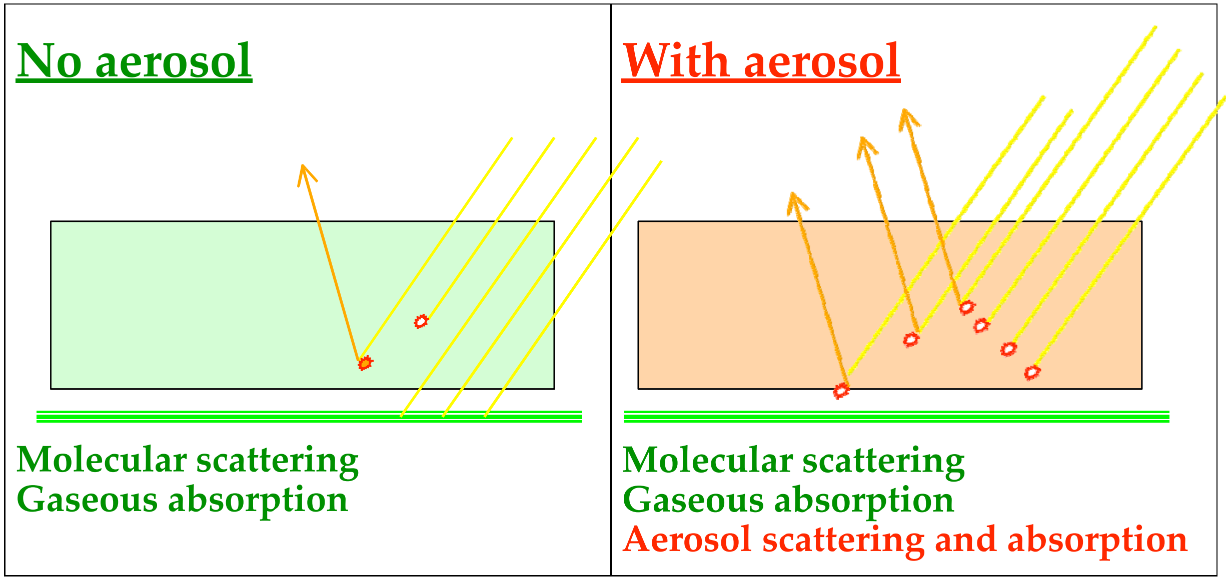
Instruments used to measure aerosol optical depth.

To build a sun photometer, the instrument bands are chosen so that the attenuation by unwanted material is minimal.

What are Aerosols

Stable suspension of solid or liquid particles in a gas. An object of 0.001 µm - 100 µm in diameter that can be kept suspended in a gas for a reasonable period of time. Ash, smoke, dust, fog, mist, drizzle, smog, haze, etc. are aerosols.

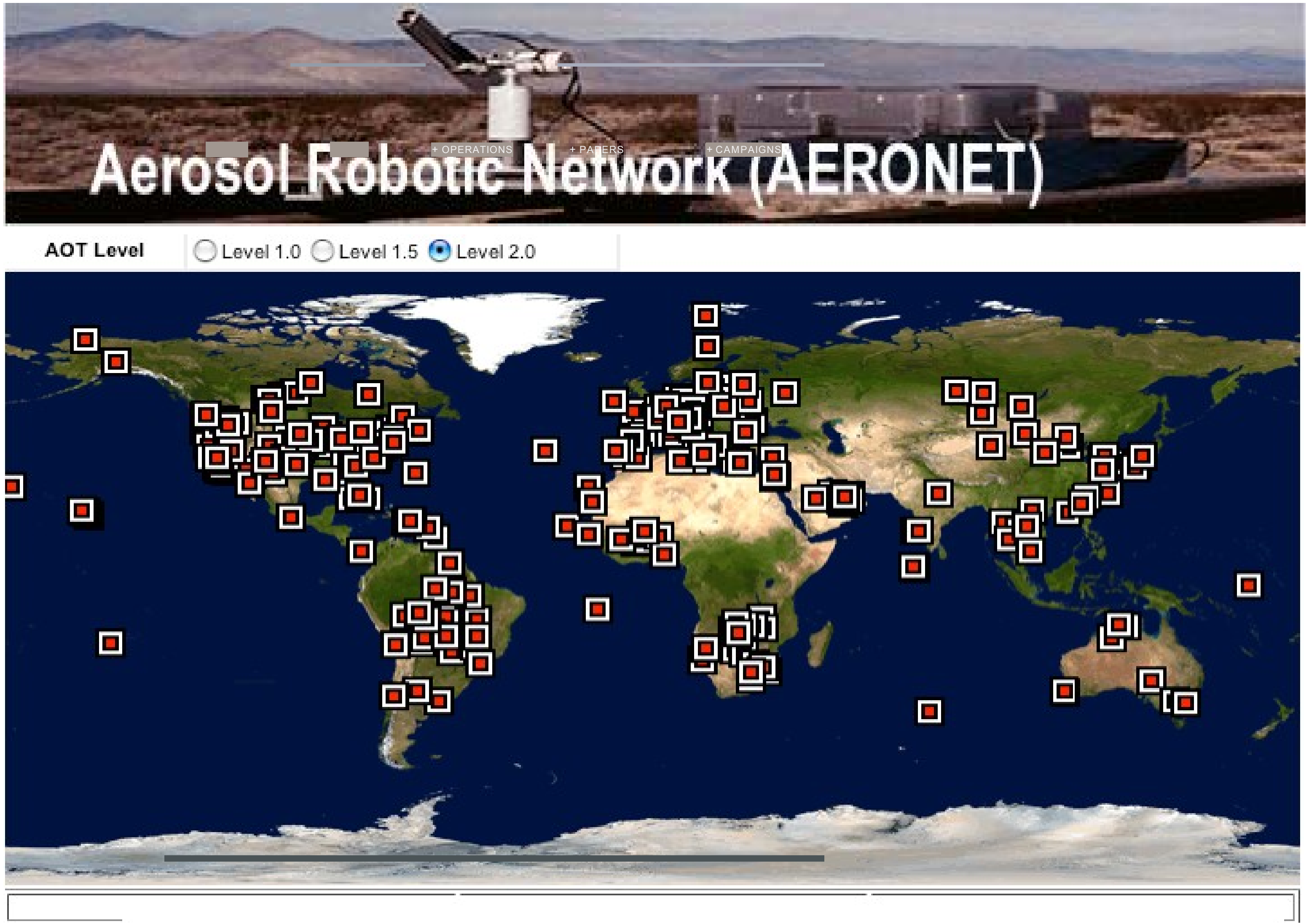
What is radiative forcing of aerosol?



- Aerosol increases atmospheric scattering and absorption
- Aerosol increases reflection of sunlight to space and reduces sunlight reaching the surface
- Aerosol absorption changes the temperature profile in the atmosphere

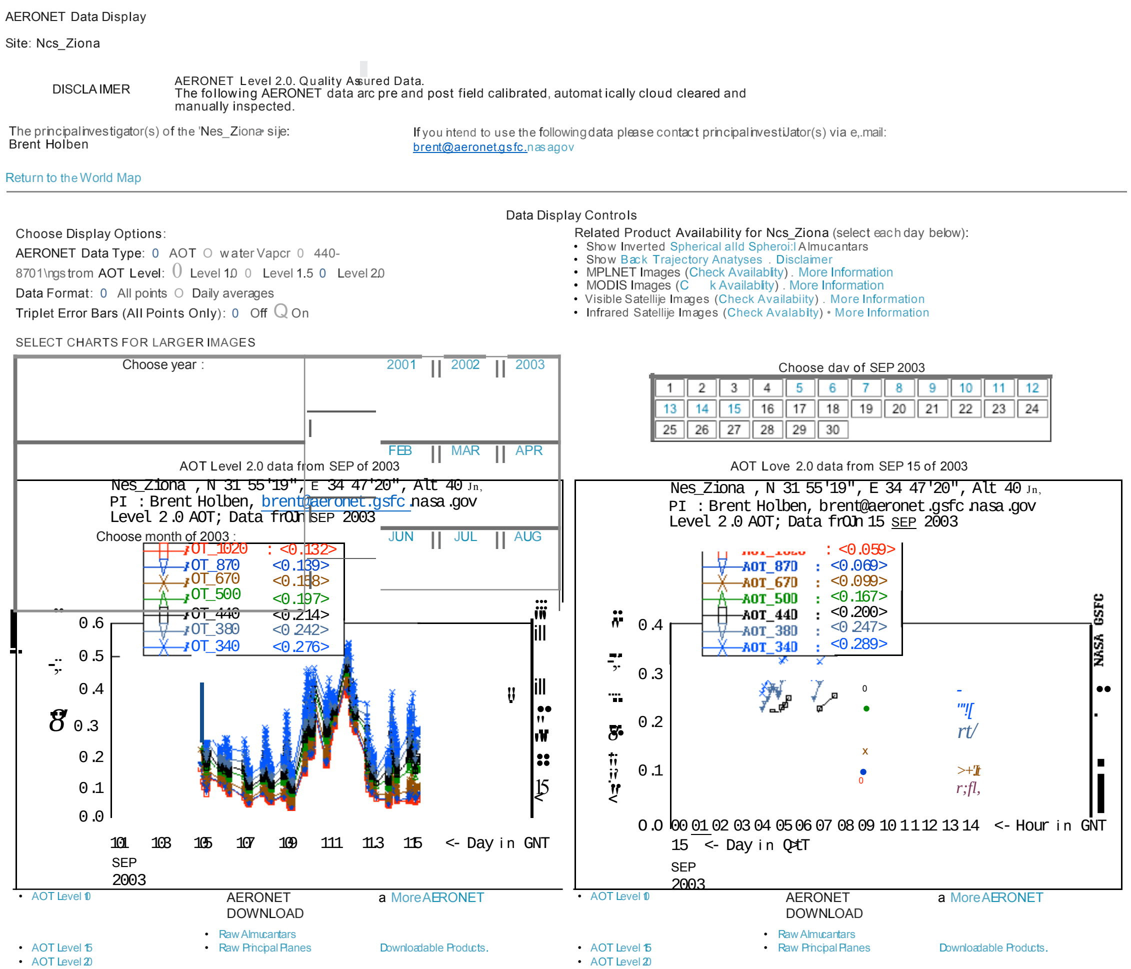
The real world:

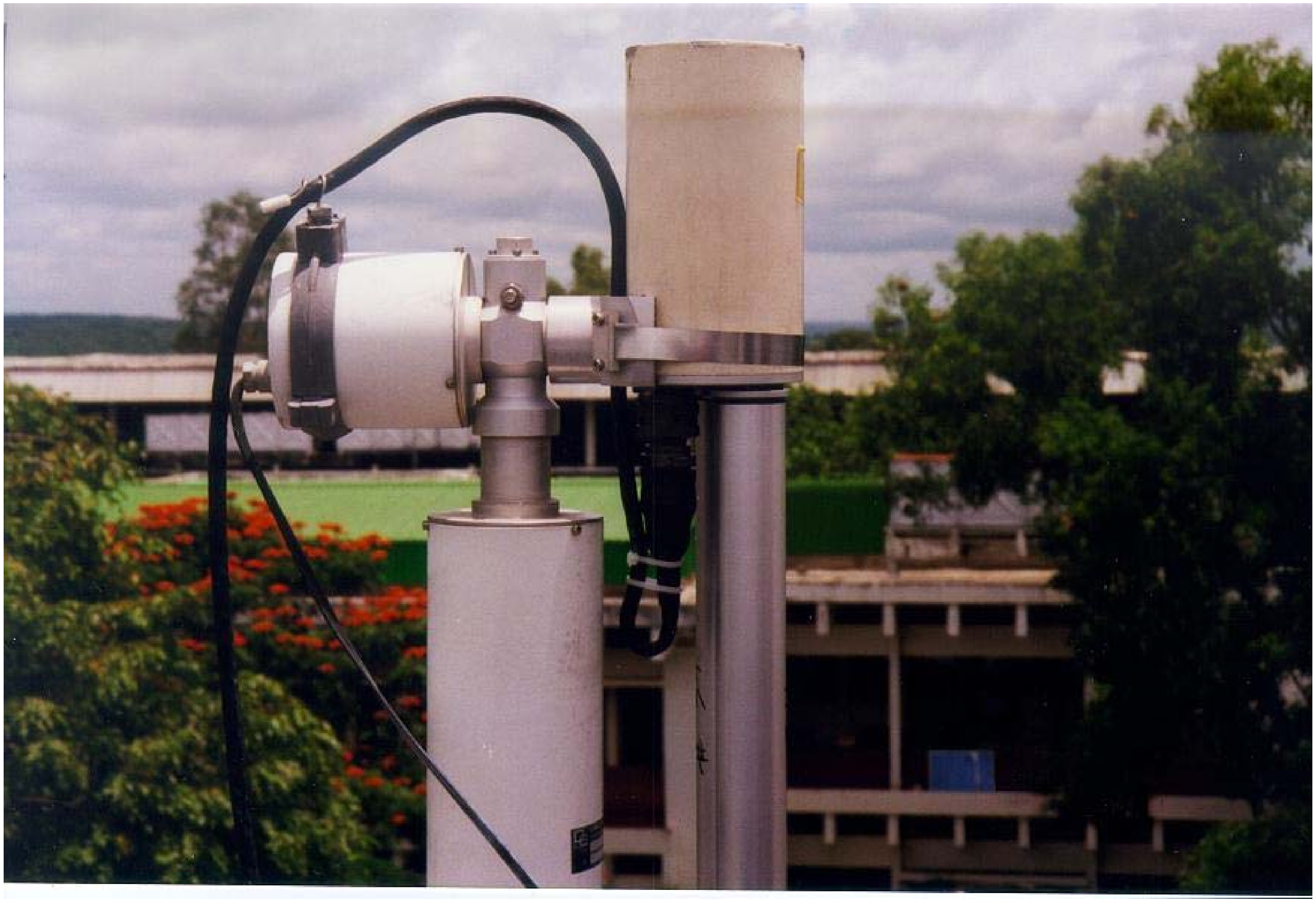
The Aerosol Robotic Network (AERONET) has been established by NASA to measure the effect of aerosol on solar radiation. It is a global network.



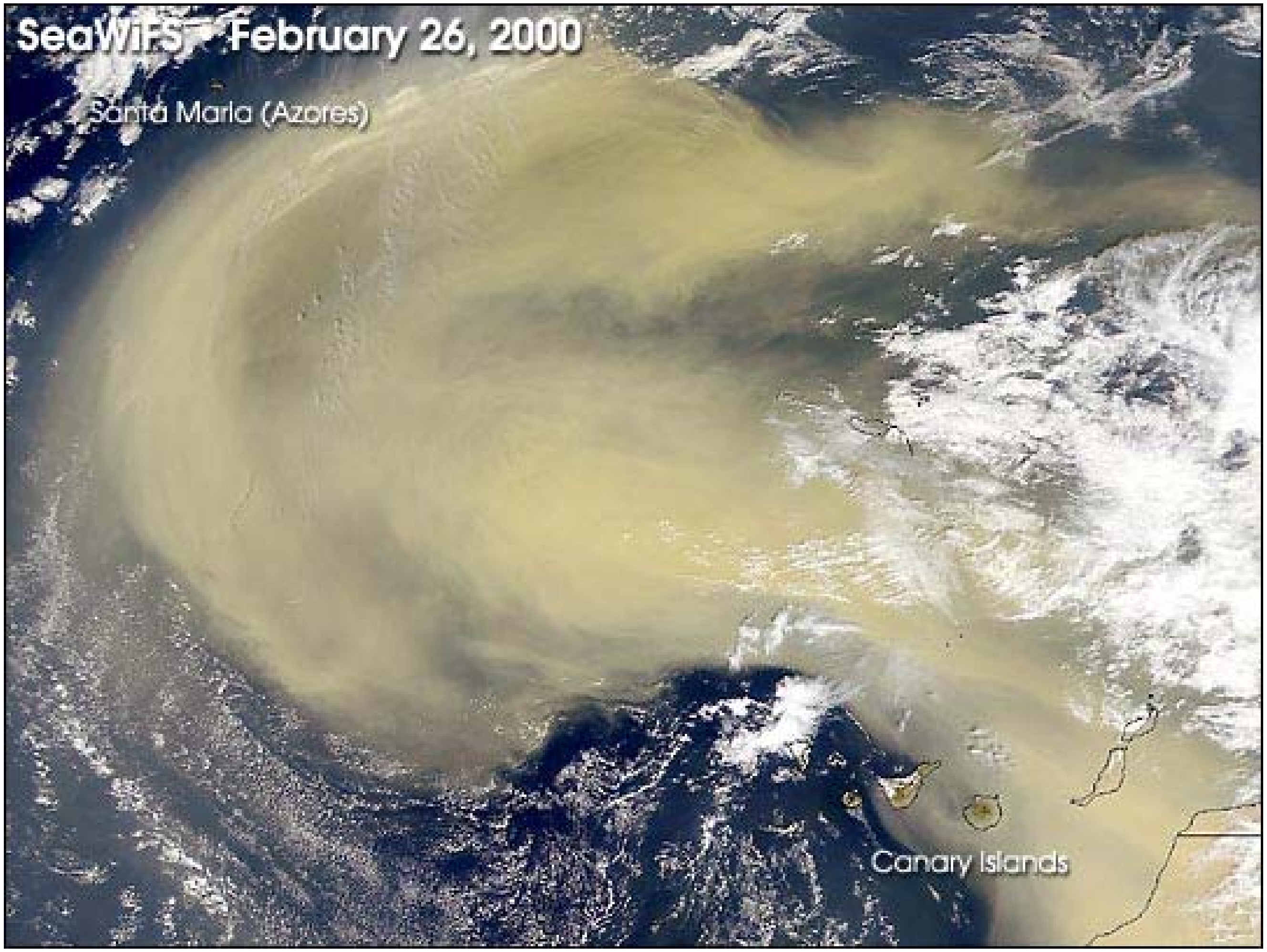
http://aeronet.gsfc.nasa.gov/ http://aeronet.gsfc.nasa.gov/new_web/photo_db/Ilorin.html

How to get data from the network? Go to: http://aeronet.gsfc.nasa.gov/ and click on "Data".



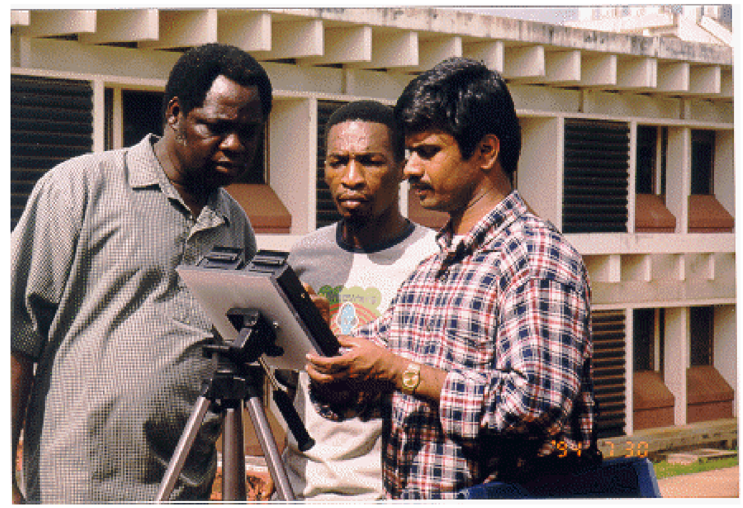


This is how the sun-photometer used by the NASA network looks like.
Ilorin, Nigeria

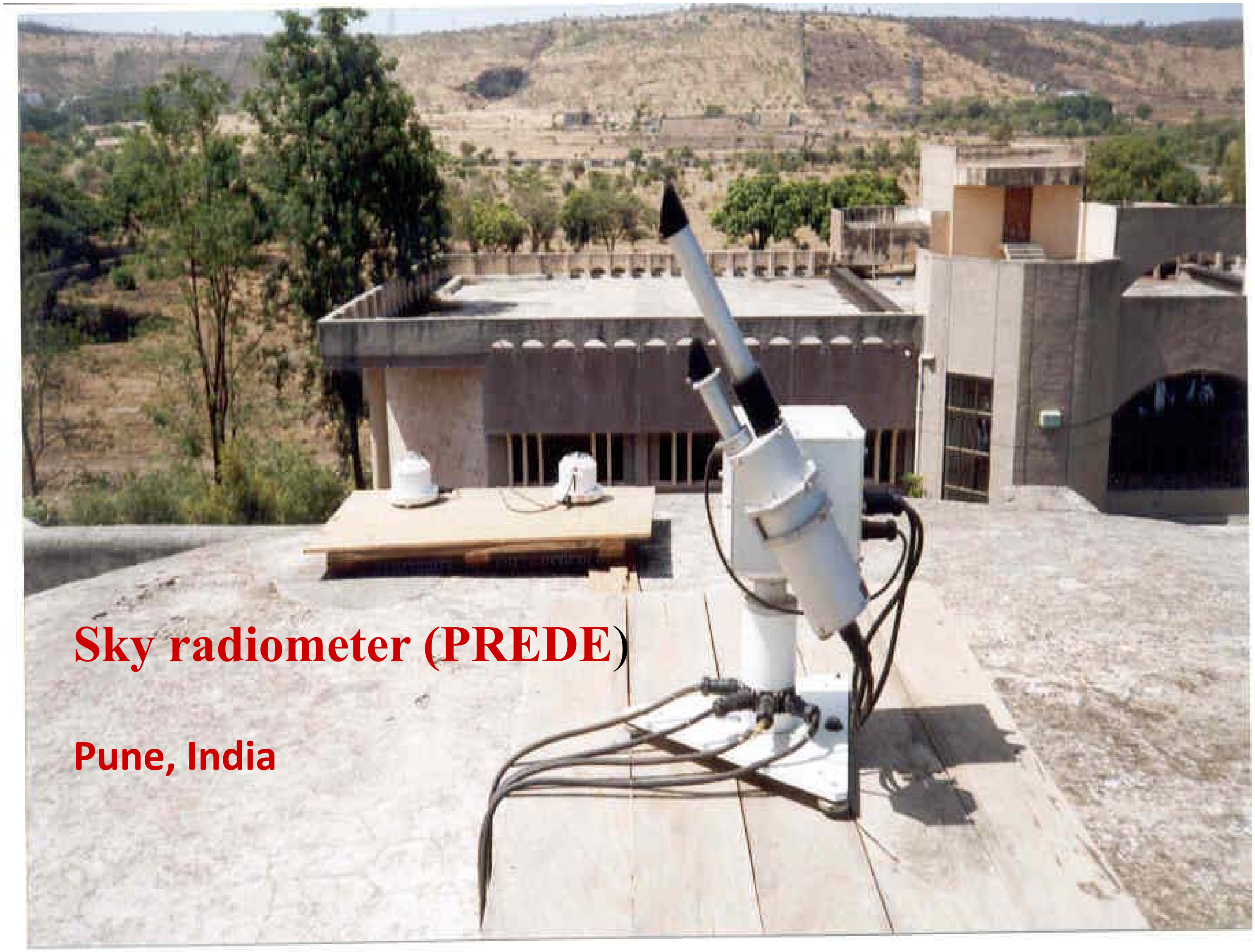


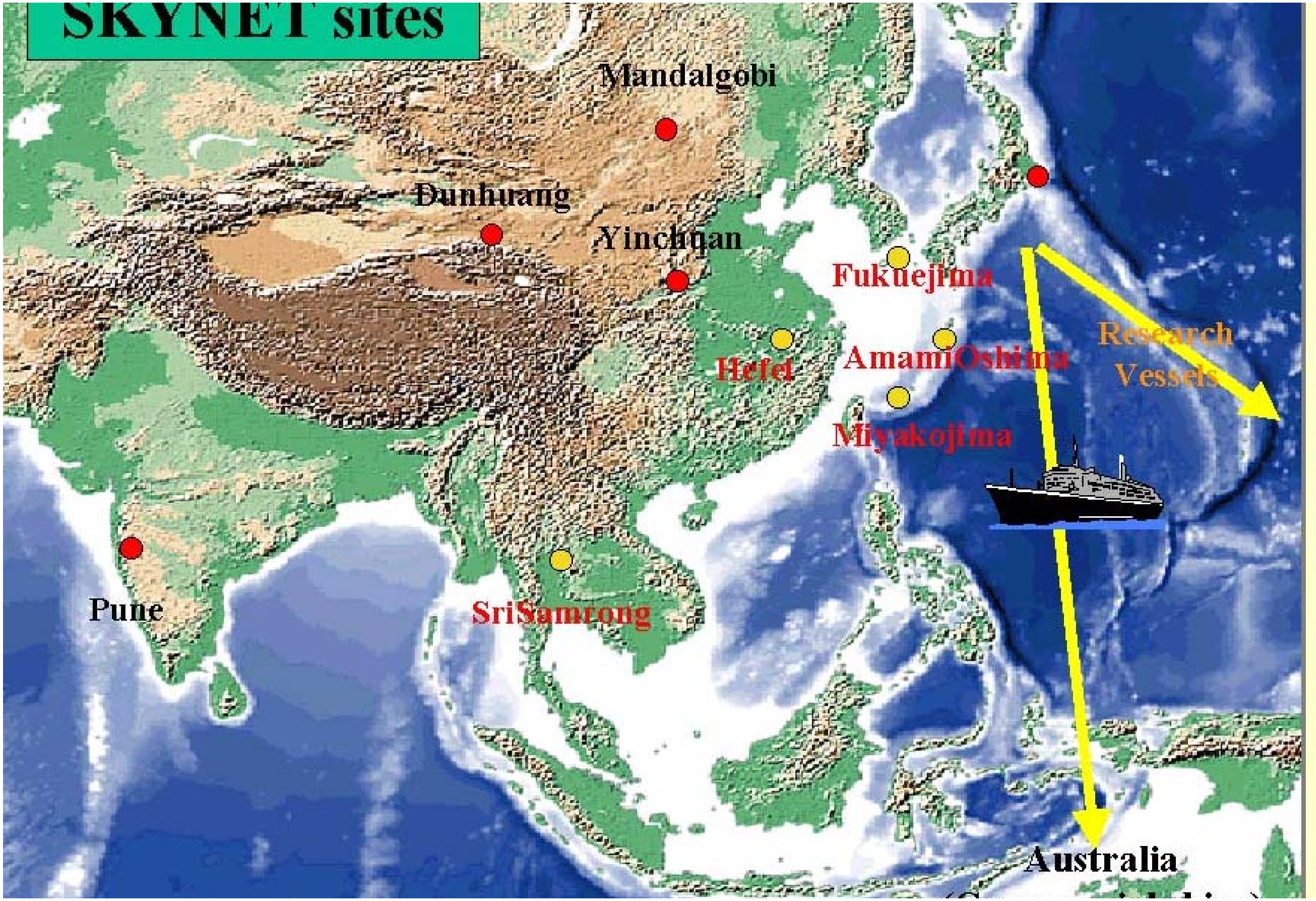
The African site is important because of dust outbreaks from the Sahara.

Entrance to the campus of the University of Ilorin



Another prototype of a sun-photometer used in the Asian SKYNET network




SKYNET sites
Mandalgobi
Dunhuang
Yinchuan
Fukuejima
Hefei
AmamiOshima
Miyakojima
Research
Vessels
Pune
SriSamrong
Australia

Rayleigh scattering

It is assumed that:

- the scattering particle is spherical; the diameter is smaller than 2λ
- the particles scatter independently of one another and the refractive index is close to one
- the scattering is in a peanut shape. Less scattering is in the direction normal to the incident beam.
- θ is the angle between direction of incidence and the direction of scattering and n is the refractive index. Max scattering occurs in the forward and backward direction. There is strong dependence on λ.

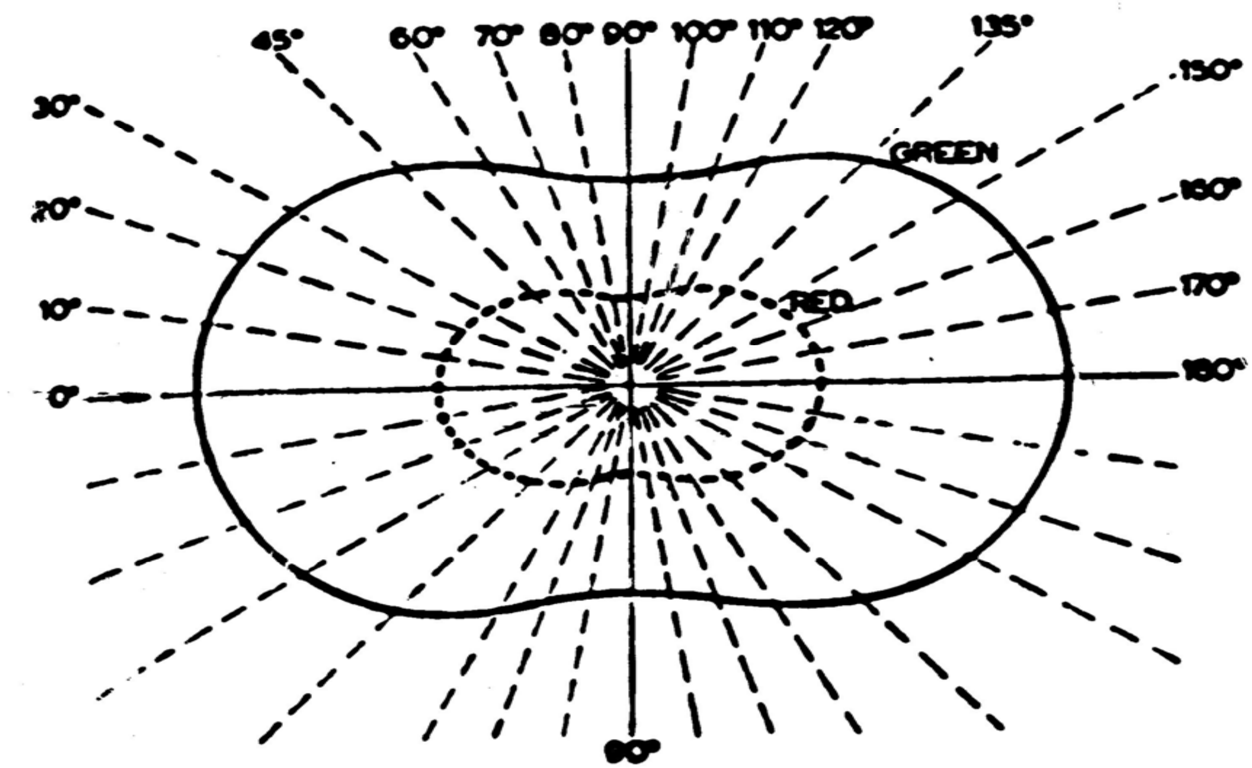
“Small size parameter approximation”

- The size of a scattering particle is parameterized by the ratio *x* of its characteristic dimension *r* and wavelength *λ*:

$$x = 2\pi r/\lambda$$

- Rayleigh scattering can be defined as scattering in the small size parameter regime $x \ll 1$.

Rayleigh scattering



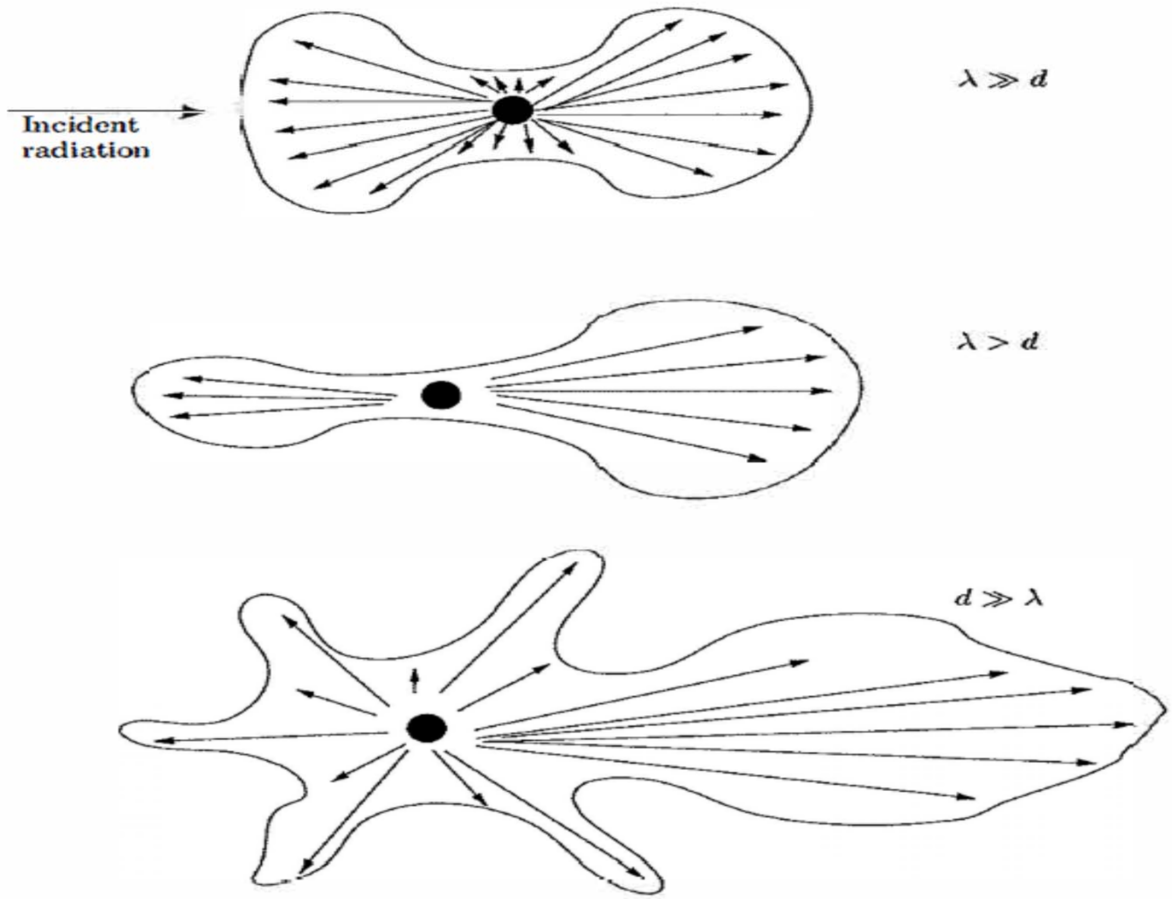
Polar plot of intensity as a function of scattering angle for small particles (r~ 0.025 μm) for green and red light.
Green: 0.5 μm; red 0.7 μm

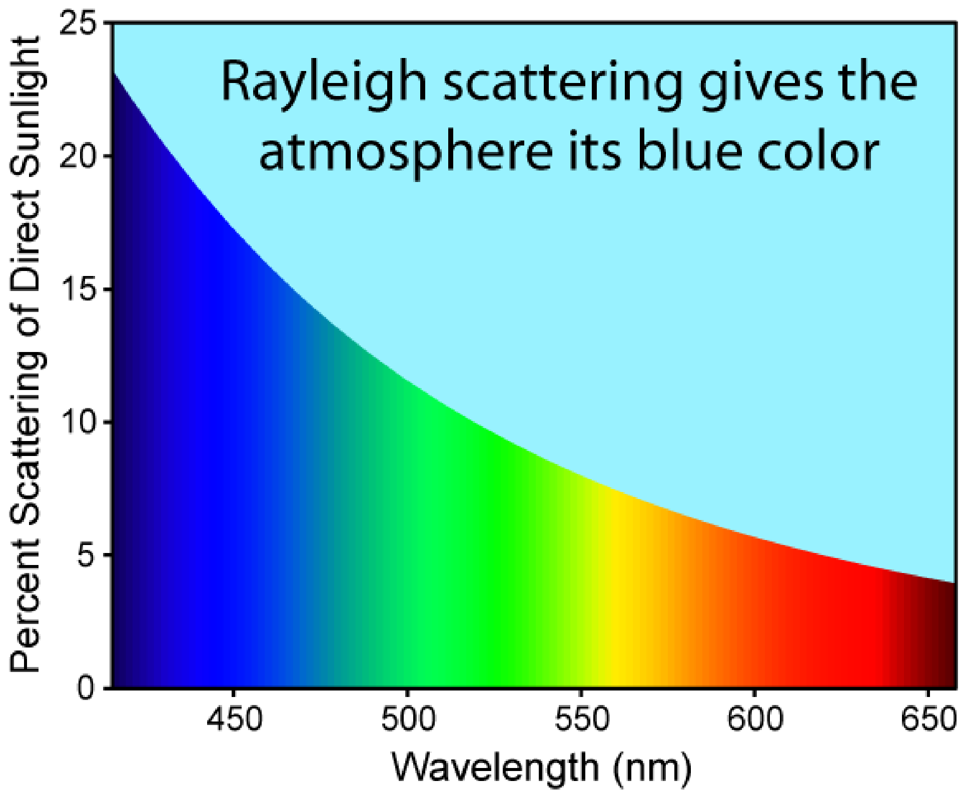
The amount of Rayleigh scattering that occurs for a beam of light depends upon the size of the particles and the wavelength of the light. Specifically, the intensity of the scattered light varies as the sixth power of the particle size, and varies inversely with the fourth power of the wavelength:

$$I_{\lambda}(0) \propto I_{0\lambda}\left(1+\cos^{2}\theta\right)\left(n^{2}-1\right)/\lambda^{4}$$

As shown in your textbook:

58 2 Atmospheric Radiative Transfer





Rayleigh scattering of sunlight in the atmosphere causes diffuse sky radiation, which is the reason for the blue color of the sky and the yellow tone of the sun itself

- A more explicit formulation: the intensity *I* of light scattered by a single small particle from a beam of un-polarized light of wavelength λ and intensity I_0 is given by:
- $$I = I_0 \frac{1+\cos^2\theta}{2R^2}\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2\left(\frac{d}{2}\right)^6$$
- where *R* is the distance to the particle, ϑ is the scattering angle, *n* is the refractive index of the particle, and *d* is the diameter of the particle.
- The Rayleigh scattering coefficient for a group of scattering particles is given as:

- The amount of Rayleigh scattering from a single particle can also be expressed as a cross section σ. For example, the major constituent of the atmosphere, nitrogen, has a Rayleigh cross section of 5.1×10^{-31} m^2 at a wavelength of 0.532 µm (green light). This means that at atmospheric pressure, about a fraction 10^{-5} of light will be scattered for every meter of travel.

$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

For the whole atmosphere

the vertical optical depth $\tau_{R\lambda}$, is given by:

$$\tau_{R\lambda} = \int_0^\infty \kappa_{R\lambda}\rho\, dz = \int_0^\infty \beta_{R\lambda}\, dz$$

where

$\kappa_{R\lambda}$ = Rayleigh mass scattering coefficient

$\beta_{R\lambda}$ = volume scattering coefficient

$$\kappa_{R\lambda}\rho = \beta_{R\lambda}$$

$$\beta_{R\lambda} \propto \frac{(n-1)^2}{N}$$

where n relates to the refractive index and N is the molecular number density of air at STP. Therefore, $\beta_{R\lambda}$ varies with temperature.

As most scatter occurs in the lower atmosphere because the density is largest there, the effect of temperature on the overall optical depth is reduced to the 1% level. The temperature effect can be neglected. The irradiance of the direct beam of the sun at the bottom of a clean dry atmosphere becomes (only molecular scattering):

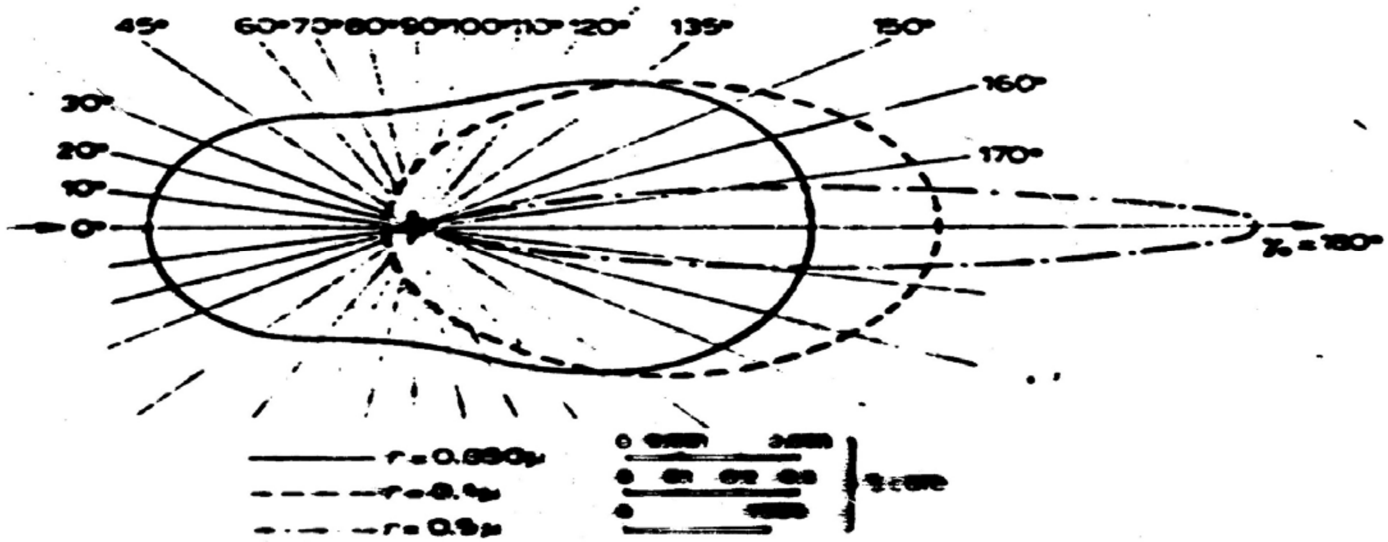
$$I = \int_0^\infty I_{0\lambda} \exp\left[-\left(p_g / p_s\right)\tau_{R\lambda} m_r\right] d\lambda$$

$$\tau_{R\lambda} = 0.00888 \ \lambda^{-4.05}$$

p_s is the standard surface pressure of 1013 mb.

Mie scattering:

For large particle to wavelength ratio. The larger the particle, the more forward scattering is.



Rayleigh scattering is symmetrical with respect to the direction of incidence; the angular scattering by Mie particles - the amount of light scattered in the forward is much larger than in the backward direction .

- For a more rigorous treatment of the concept of scattering read Hansen and Travis (1974) pages: 533-535.

- For a more rigorous treatment of the concept of RAYLEIGH SCATTERING read Hansen and Travis (1974) pages 540-544.