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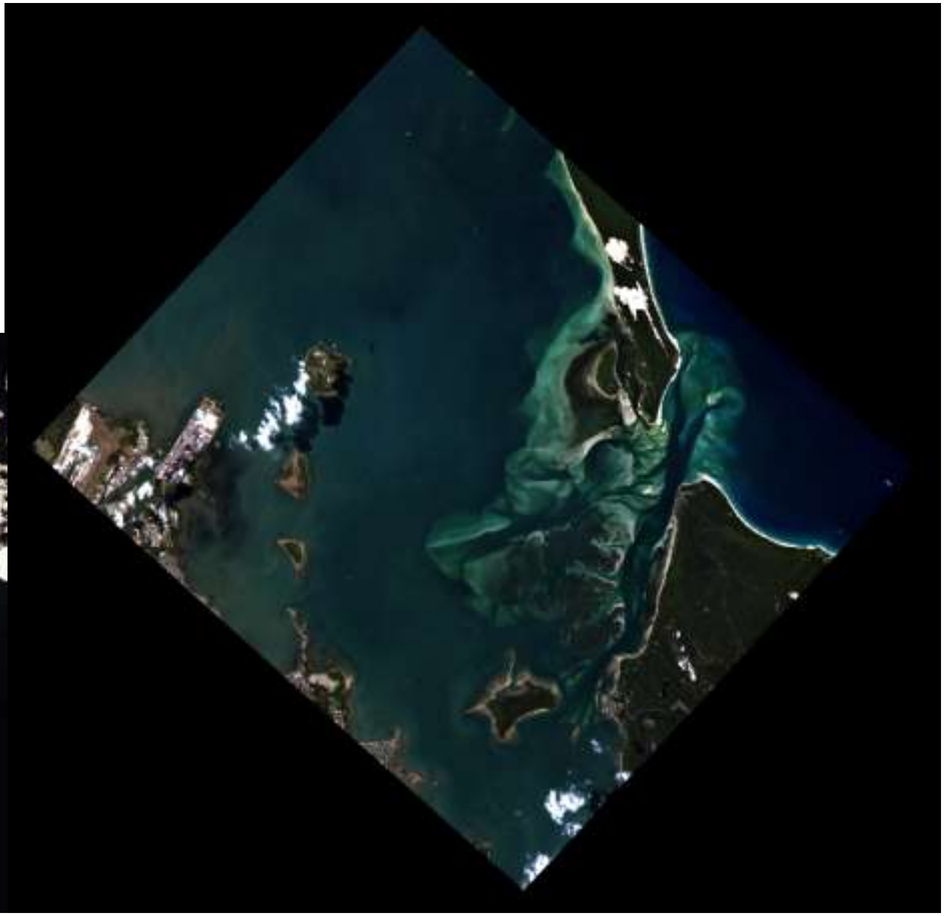

GEO 418 – „Hyperspectral Earth Observation“

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Physics of Optical Remote Sensing

with contributions by

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Image Chain

„Way of a **photon**

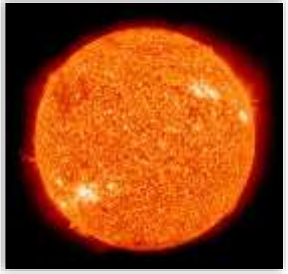
from the **sun**

through **atmosphere**

to **earth**

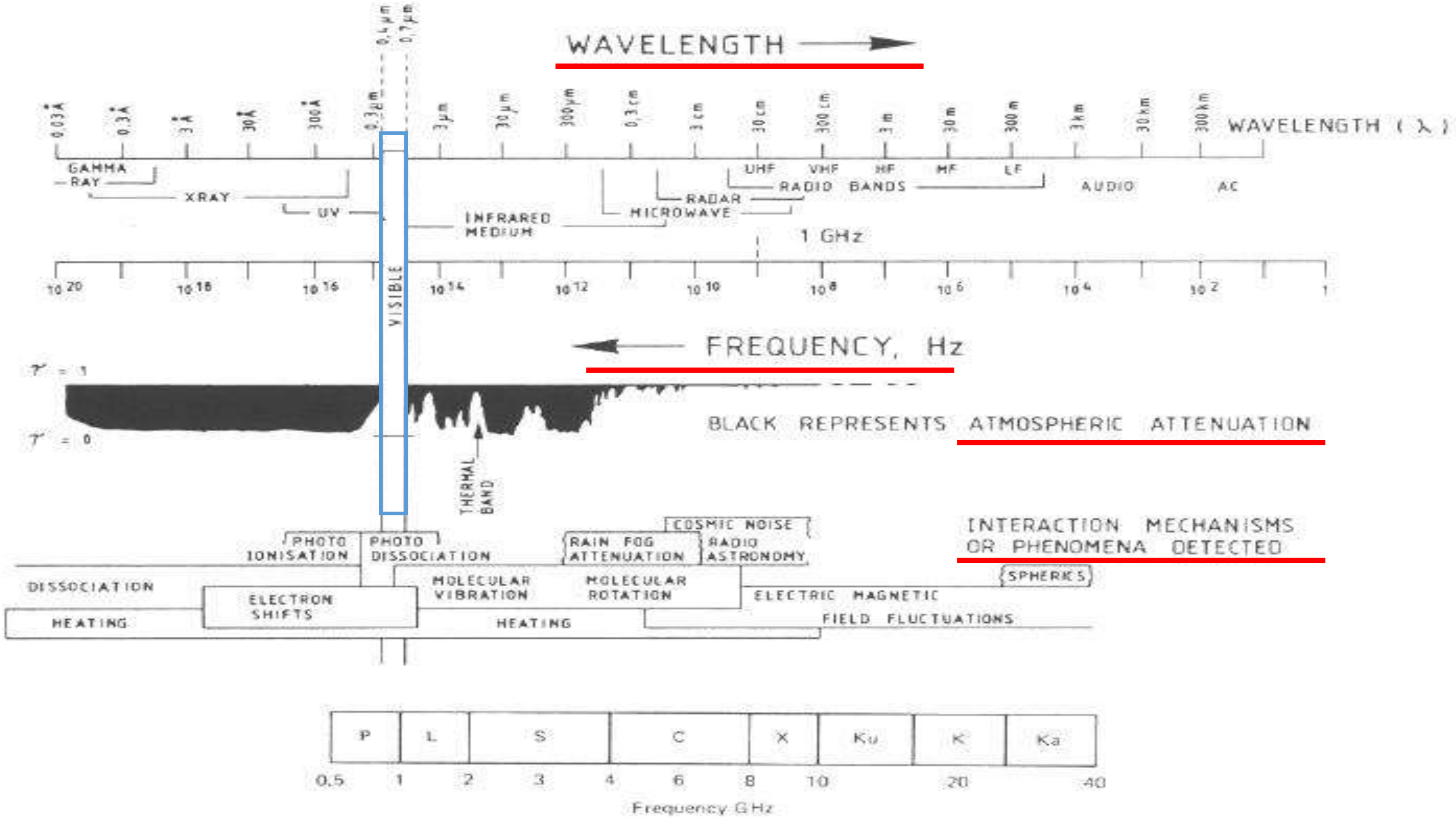
to **EO sensor**

to **image**“

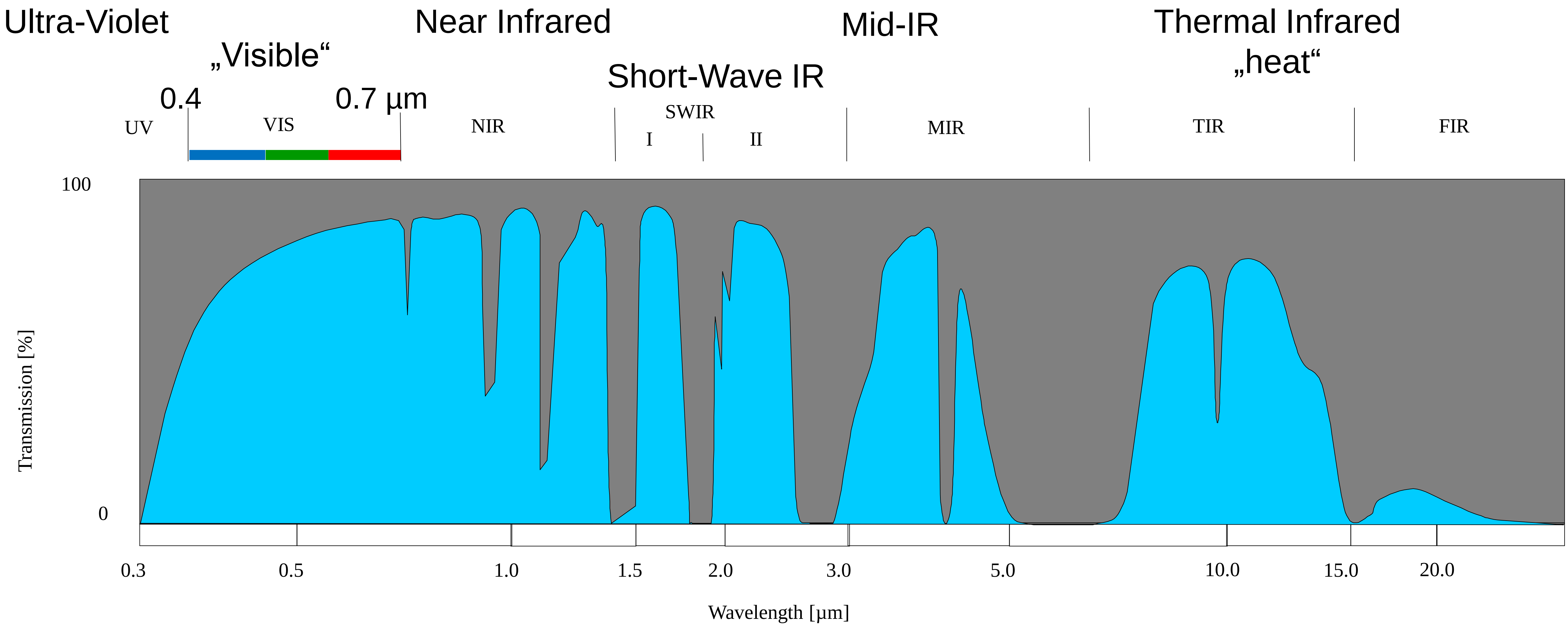


1st: Radiation Source

The electro-magnetic spectrum

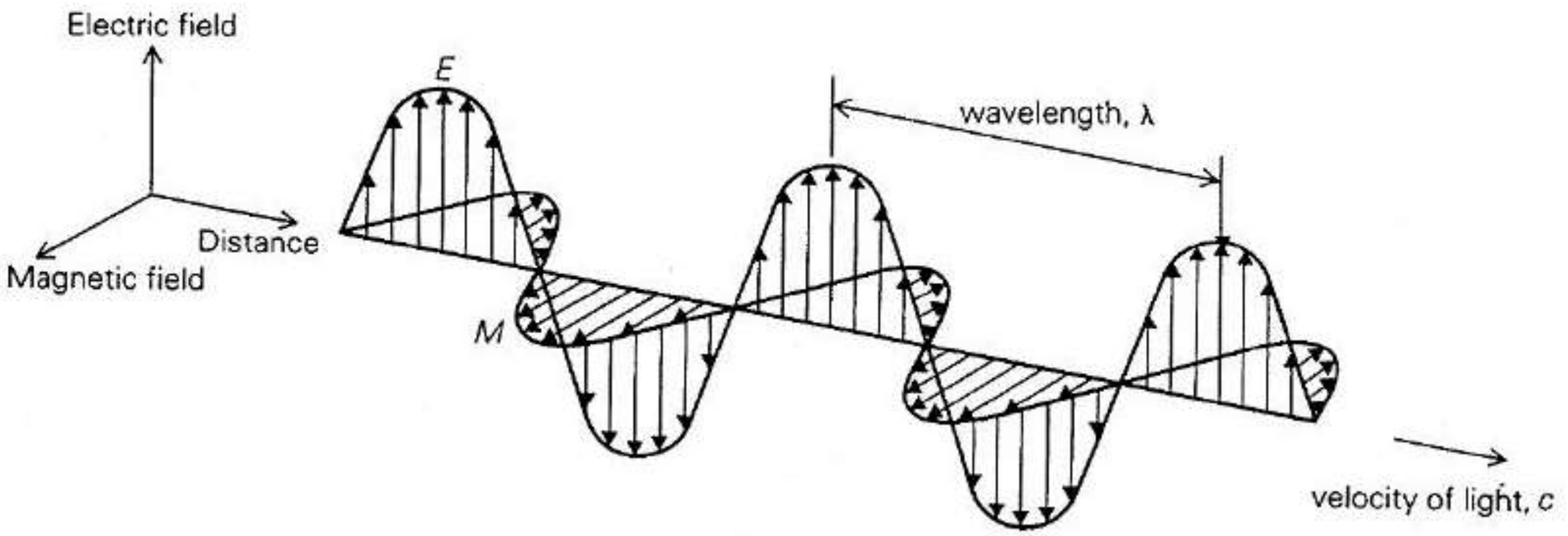


The electro-magnetic spectrum



Physical Basics

Every object is emitting **electro-magnetic radiation**

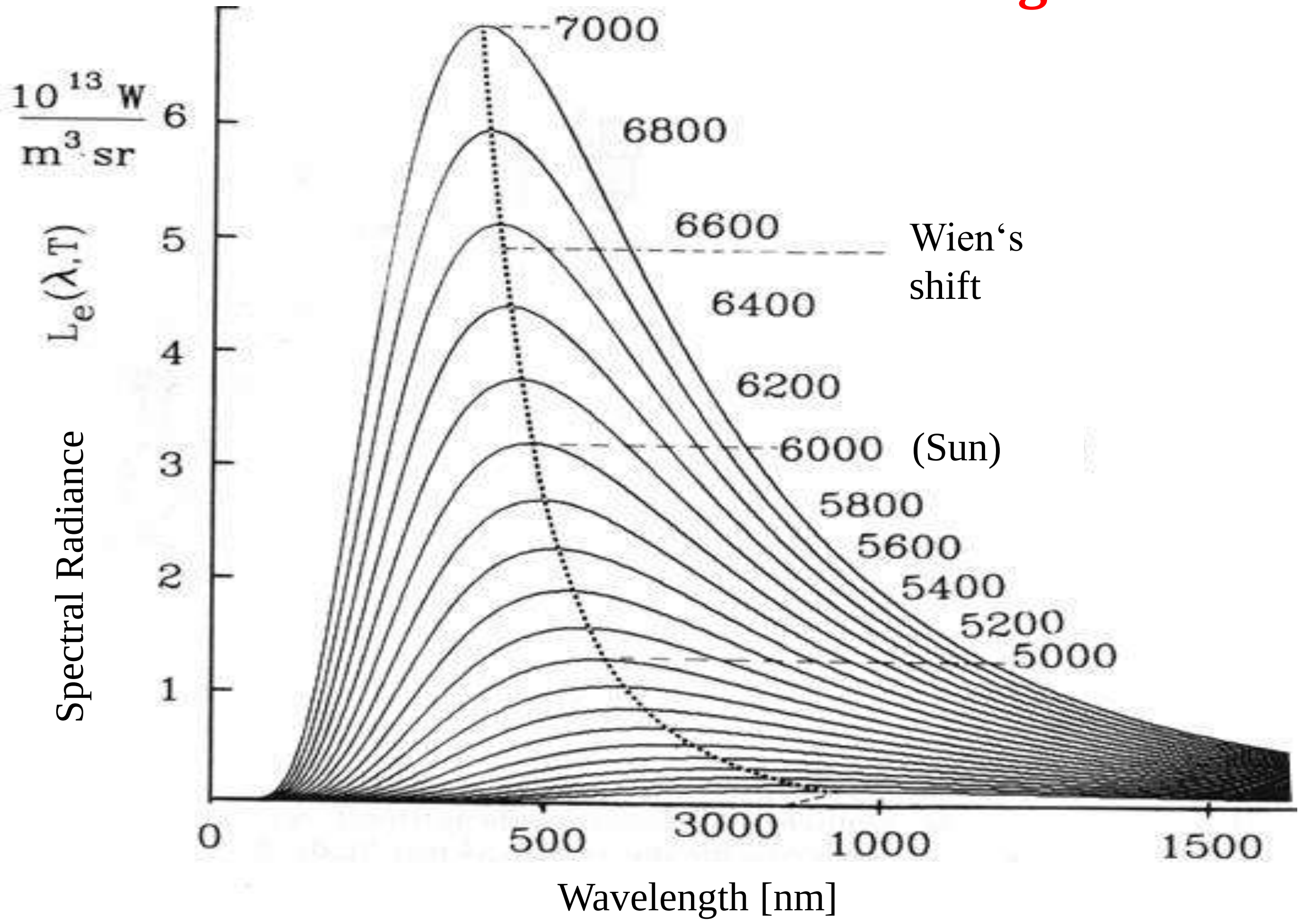


Lillesand & Kiefer (2000)

Physical Basics

Every object is emitting **electro-magnetic radiation**

according to its temperature.



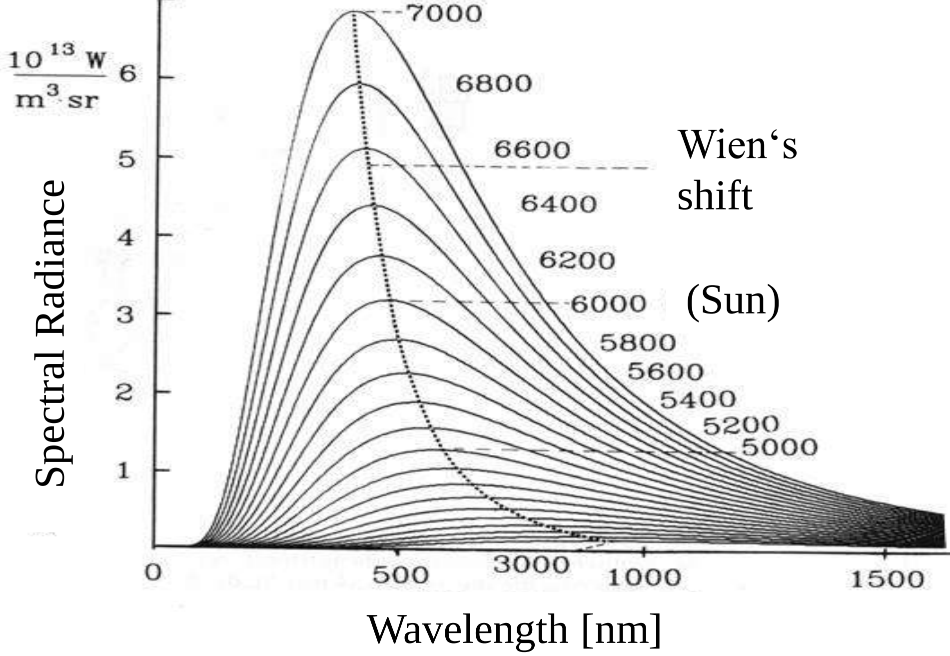
Earth:

~300k average surface temp.

L_{max} at 10 µm (=10.000nm)

Werner Schmidt: Optische Spektroskopie – Eine Einführung. Wiley-VCH Weinheim, 2. Auflage 2000

Physical Basics



- Planck:

  Emittance M = f (λ, T)

- Boltzmann:

  $M_{blackbody} = \sigma\ T^4$ [W m^{-2}] $\sigma = 5.67 * 10^{-8}$ W m^{-2} K^{-1}

  In general: $M = \varepsilon T^n$

  n…property of material, ~4

- Wien:

  The higher the temperature (T) the shorter the wavelength (λ_{max}) of maximal energy emittance

  $\lambda_{max} = 2898 / T$

Physical Basics

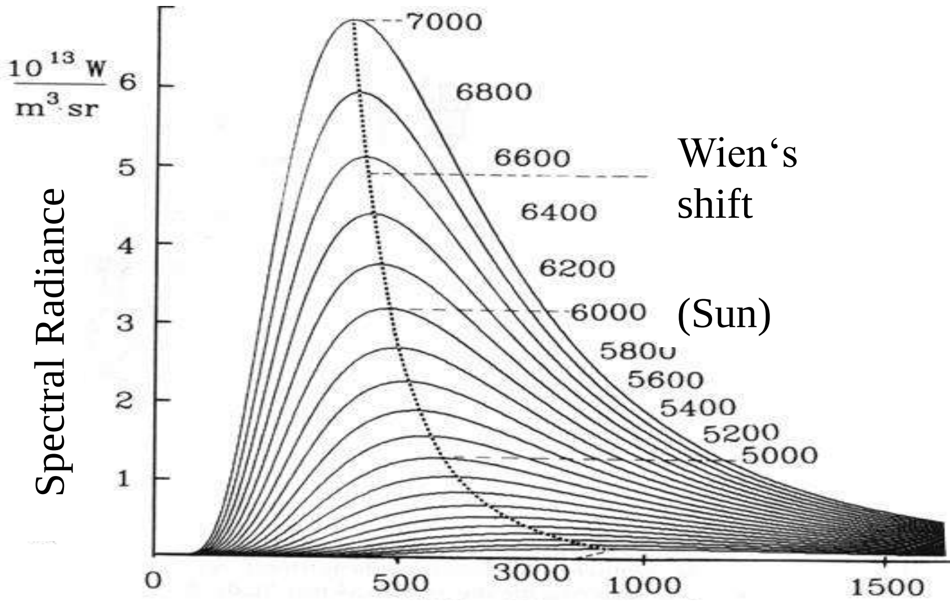
- Electromagnetic wave (Maxwells Equation)

  Electric perpendicular to magnetic
  $c = \lambda * v$ c…Lightspeed in vacuum $3*10^{8}$ m s^{-1}
  v…Frequency

- Energy $q = h * v$
  h: Planck's Constant: $6.63* 10^{-34}$ [J s]
  => Higher energy per photon with shorter wavelength

- Energy pro Photon: green 0.55 µm => $3.61 * 10^{-19}$ J
  TIR 12.00 µm => $1.66 * 10^{-20}$ J

  => 22times higher energy!



Physical Basics

- Example for Planck- and Wien-Equations: surface temperature of stars

B	A	...	G	...	M	Spektral class

Colour Impression

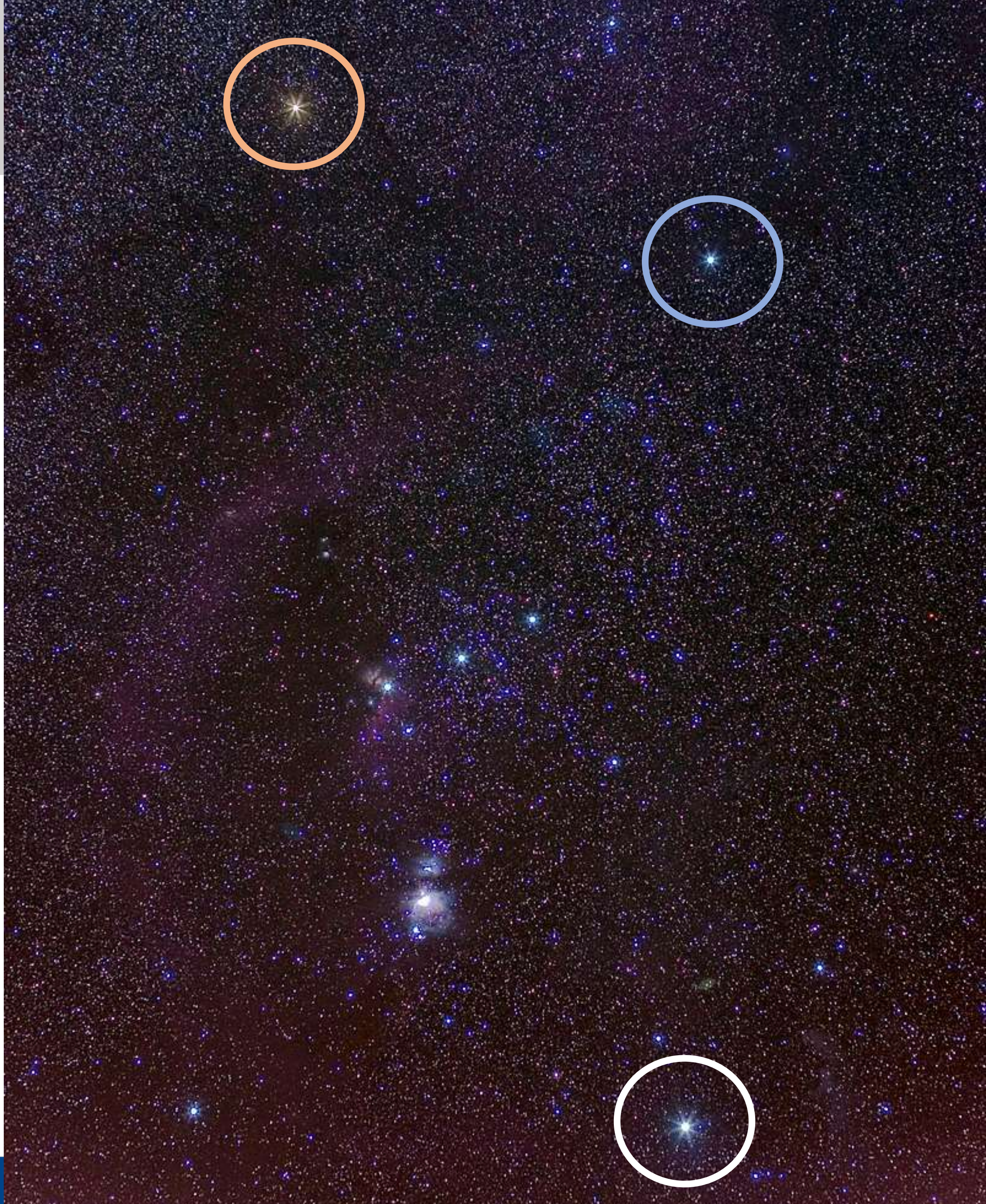
T=25000 K	T=10000 K	T=5800 K	T=2900 K
L(max) at 116 nm	L(max) at 290 nm	L(max) at 500 nm	L(max) at 1000 nm

Colour impression: continuum & relative strengths of spectral lines in the VIS

Physical Basics

The color of a star is determined by its temperature, according to Wien's law. In the constellation of Orion, one can compare

Betelgeuse ($T \approx 3300$ K, upper left) orange
Rigel ($T = 12100$ K, bottom right) white
Bellatrix ($T = 22000$ K, upper right) blue



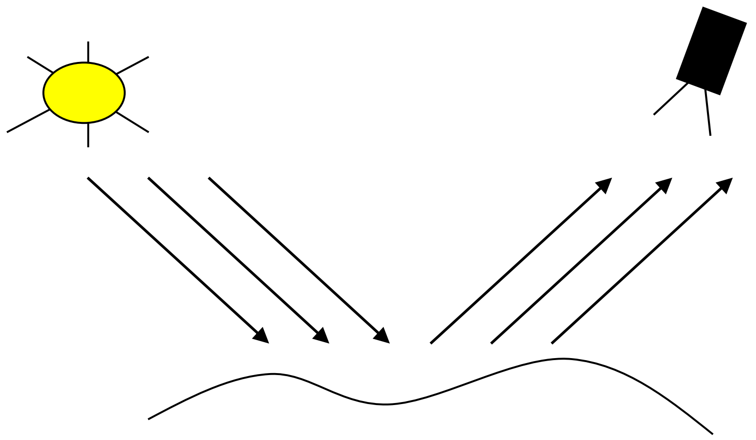
Source (modified):
https://en.wikipedia.org/wiki/Wien%27s_displacement_law

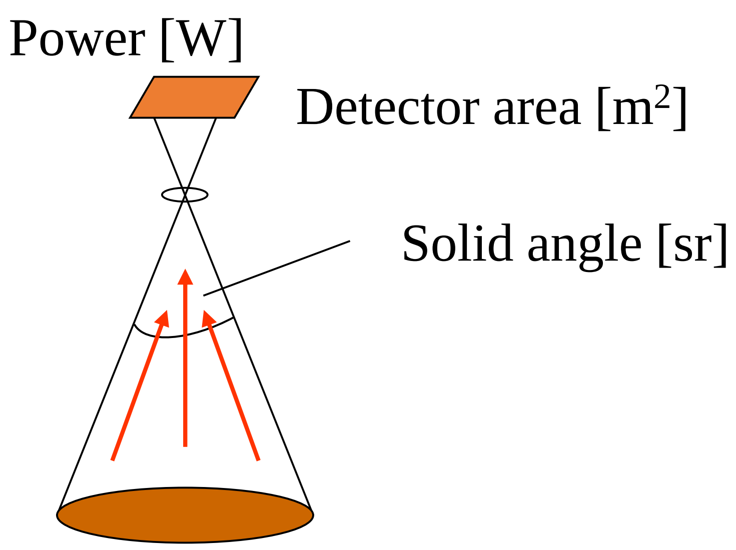
Physical Basics

- The sensor detects:

  Radiance, At-Sensor Radiance L [W m^{-2} sr^{-1}]

  => Unit after system correction, described as L1B product

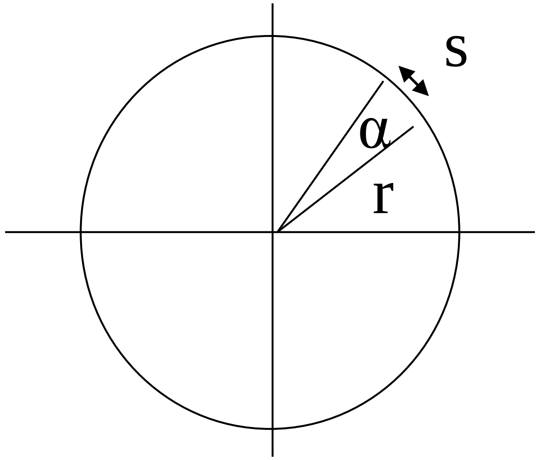




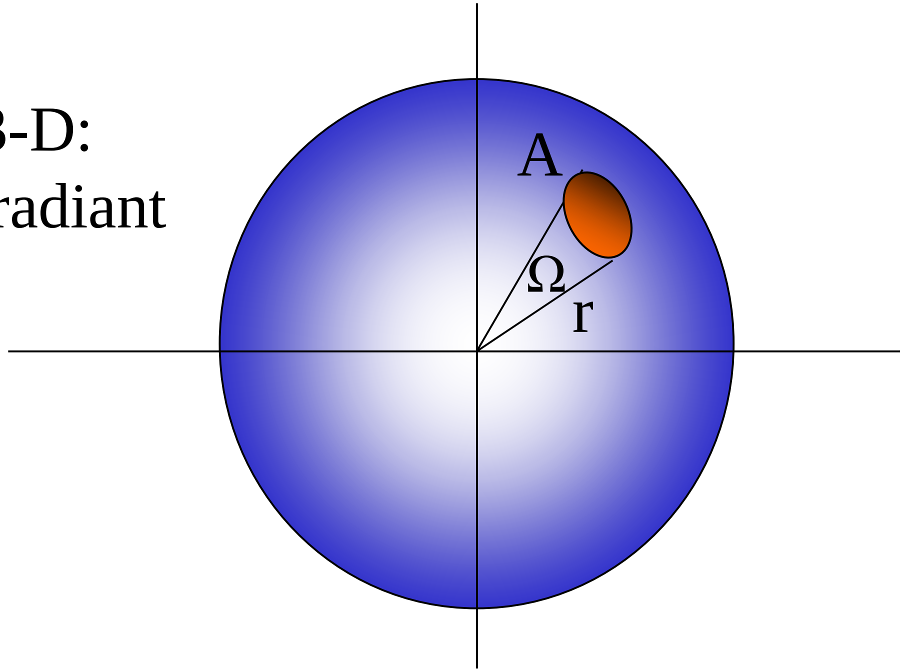
Physical Basics

- Solid Angle Ω (Raumwinkel) steradiant = area / radius2
- Sphere = 4π r2 / r2 = 4 π [sr]
- Sky = 2 π [sr]

In 2-D:
Radiant



In 3-D:
Steradiant



Physical Basics

- **Radiant Energy** Q [J]
  Strahlungsenergie

  i.e. Energy

- **Radiant flux**, or: photon flux Φ [W] = dQ/dt
  Strahlungsfluß Theta, d.h. Energie pro Zeiteinheit

  i.e. Energy per time interval

- **Radiant flux density** [W m^{-2}]
  E: irradiance // M: emittance
  Strahlungsflußdichte, d.h. Energie pro Erfassungsfläche

  i.e. Energy per detector area

- **Radiant intensity** I [W sr^{-1}]
  Strahlungsintensität

  i.e. Energy per solid angle

- **Radiance L** [W m^{-2} sr^{-1}]
  Strahldichte, d.h. Energie pro Zeit, Fläche, Raumwinkel

  i.e. Energy per time, detector area, solid angle

- **When considering spectral measures: additional integration over wavelength interval [μm^{-1}]**

  i.e., Spectral Radiance L in [mW cm^{-2} sr^{-1} μm^{-1}] or [W m^{-2} sr^{-1} μm^{-1}]
  „ATCOR“ „Landsat-8“

- Conversion of Radiance L to other radiance units:

$L = dQ / (dT\, dA\, d\Omega) = (d2\, \Phi) / (dA\, d\Omega \cos \Theta) = (dE) / (d\Omega \cos \Theta) = (dI) / (dA \cos \Theta)$

Radiant Energy Q	Radiant Flux Φ	Irradiance E / Emittance M	Radiant Intensity I
Strahlungsenergie	Strahlungsfluß	Strahlungsflußdichte	Strahlungsintensität I

=> Energy, integrated over dT TIME, dA AREA, dΩ SOLID ANGLE

Physical basics

For EO applications, measure should be

- Independent of incoming radiation (power and geometry)
- Independent of sensor properties (detector characteristics)
- Independent from atmospheric conditions

  => material property only !

Thus more suitable measure: **reflection ρ**

- No unit, but [%]
- Independent from illumination & sensor
- (Almost) independent from geometry & atmosphere

Physical basics

Note there‘s a big difference between TOA Top-Of-Atmosphere **ρ** and BOA Bottom-Of-Atmosphere **ρ**

- TOA Reflectance

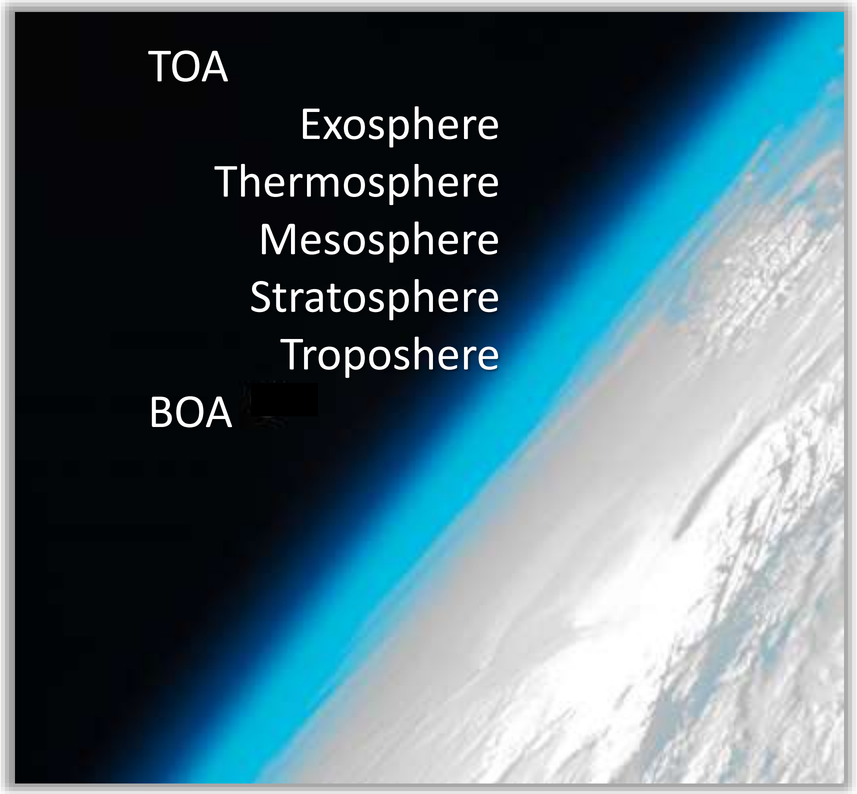
$$\rho_{TOA} = \frac{\pi\ L\ d^2}{E0\ cos\theta_s}$$

d: Earth-Sun distance (astro. units)
E0: Extraterr. solar irradiance
θ_s: Solar zenith angle

- BOA Reflectance

$$\rho_{BOA} = \frac{\pi\ (\ d^2\ L - L_{path})}{\tau\ E_g}$$

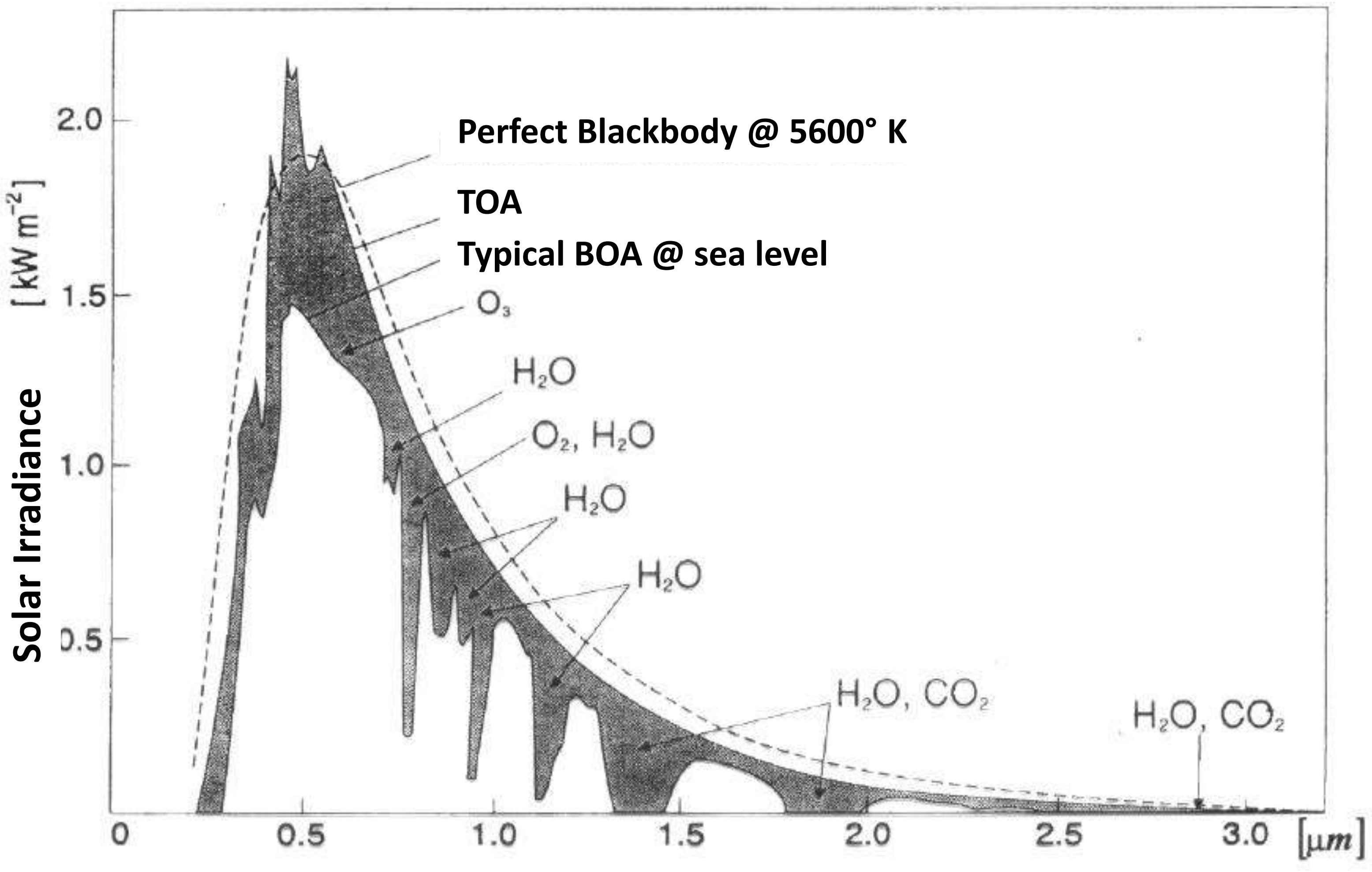
τ: Ground-to-sensor atmospheric transmittance
L_{path}: Path radiance
E_g: Global flux



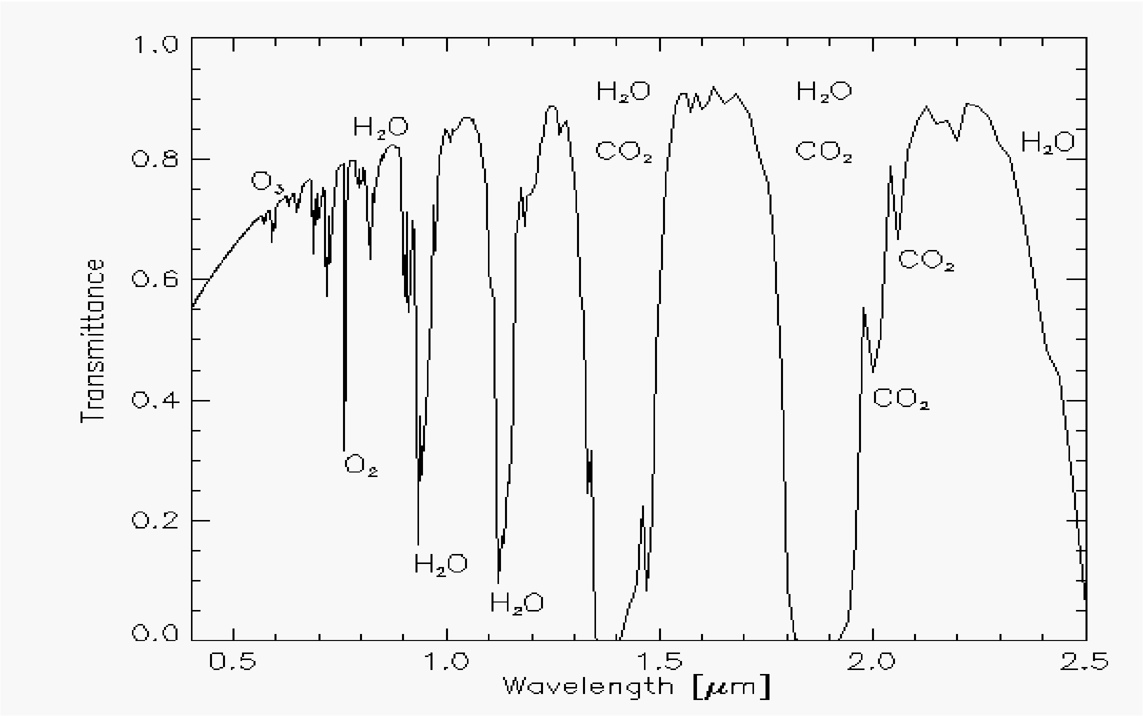
Source: Nasa:GOV ISS030-E-031275

2nd: Atmosphere

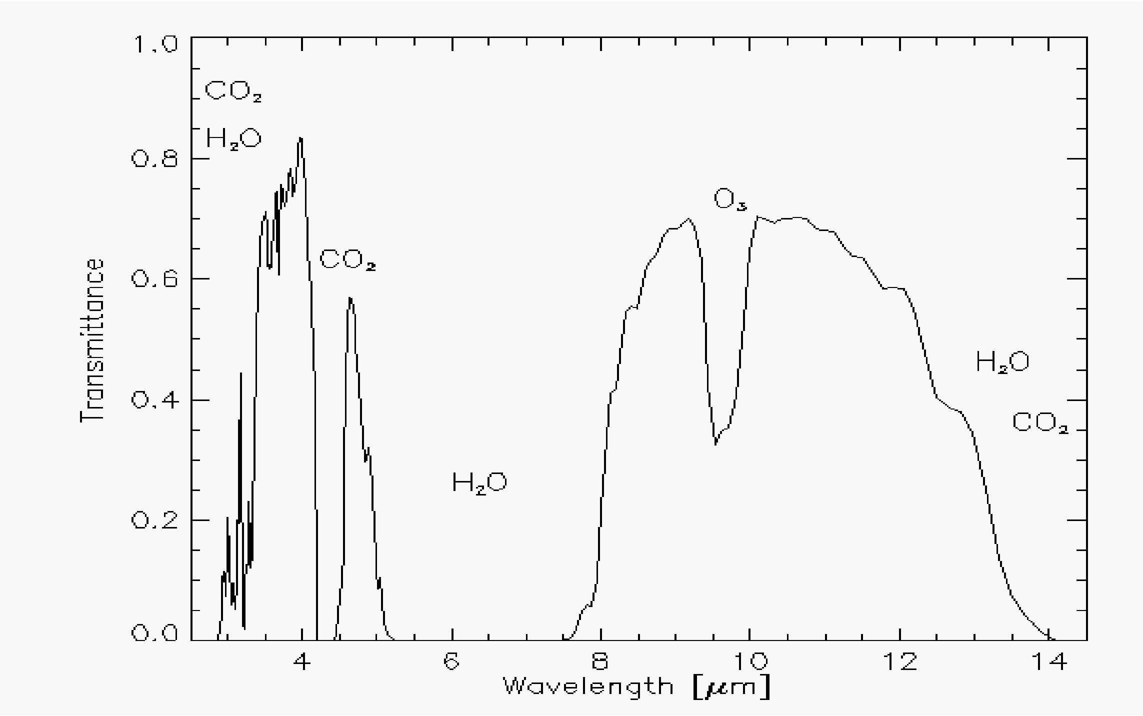
Atmospheric Transmittance



Atmospheric Transmittance



Solar spectral region



Thermal spectral region

Absorption and Scattering

- Major absorbers in the earth‘s atmosphere:

  Water vapor, CO_2, O_2, O_3, CH_4

- Scattering: molecular (Rayleigh, mostly N_2, O_2) and aerosol

  Physical characteristics of aerosols:

  size distribution, refractive index

  Optical characteristics:

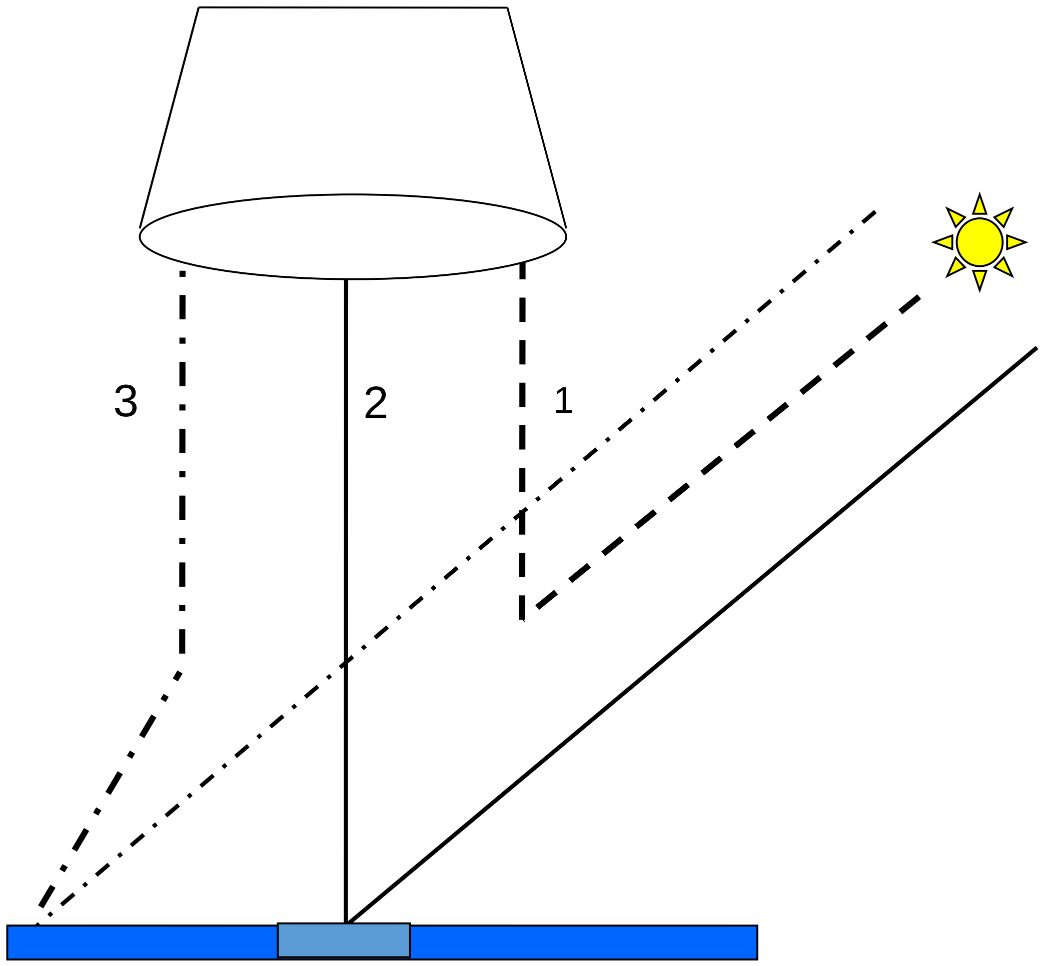
  scattering & extinction coefficient

  scattering phase function

Radiation Components

Assuming flat terrain, the signal sensed consists of the following components:

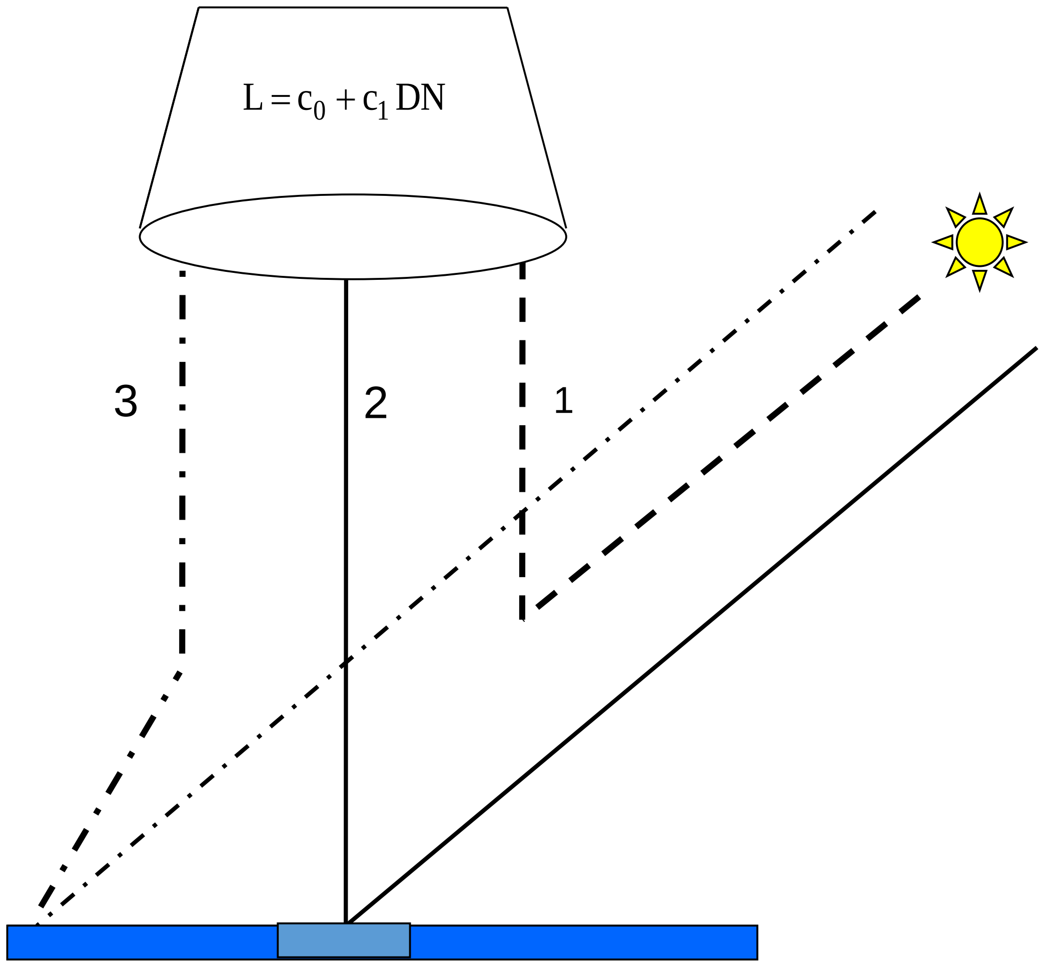
0: sensor calibration & characteristics
1: path radiance (scattered photons)
2: reflected radiance
3: adjacency radiance (reflected & scattered)



Radiation Components

Sensor calibration:

$L_{Sensor} = c_0 + c_1 * DN$



Radiation Components

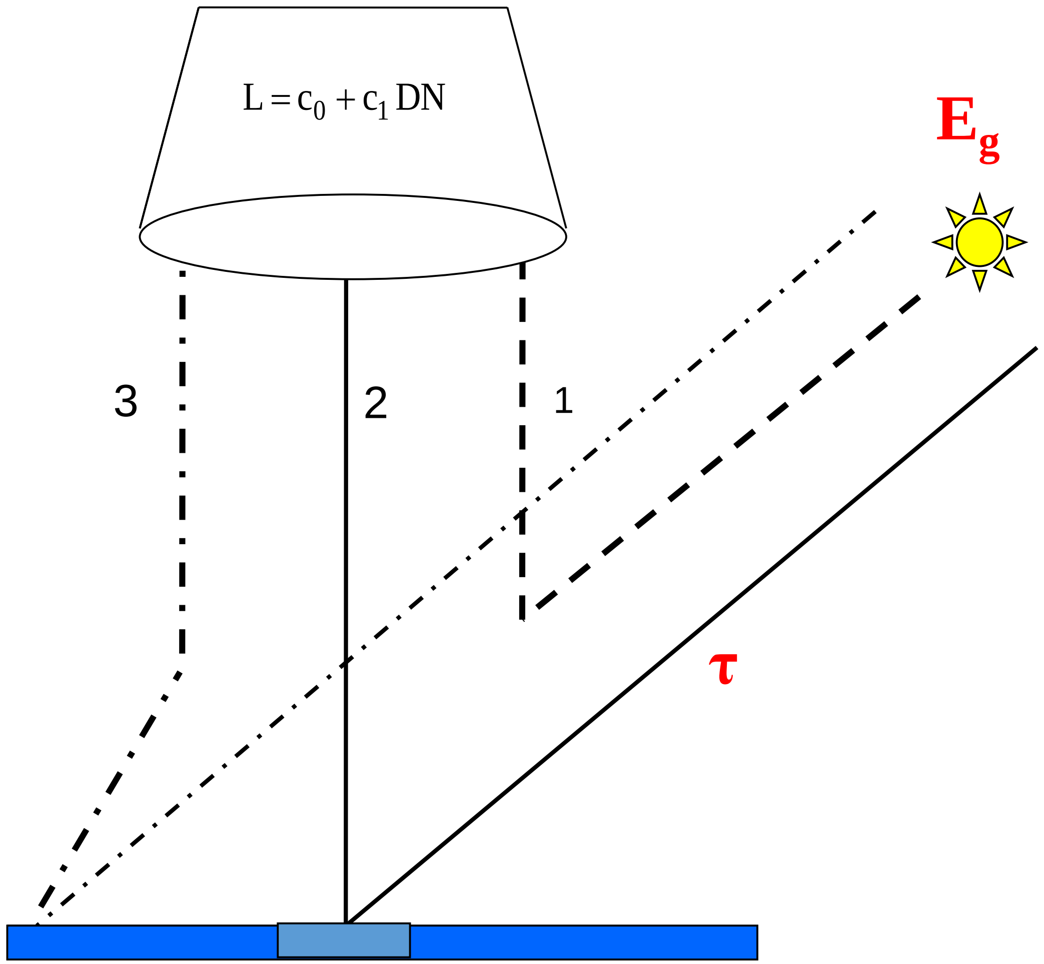
Sensor calibration:

$L_{Sensor} = c_0 + c_1 * DN$

At-sensor radiance:

$L_{Sensor} = L_1 + L_2 + L_3$

$L_{Sensor} = L_{path} + L_{reflected} + L_{adjacency}$



E_g: global flux τ : total atm. transmittance

Radiation Components

Sensor calibration:

$L_{Sensor} = c_0 + c_1 * DN$

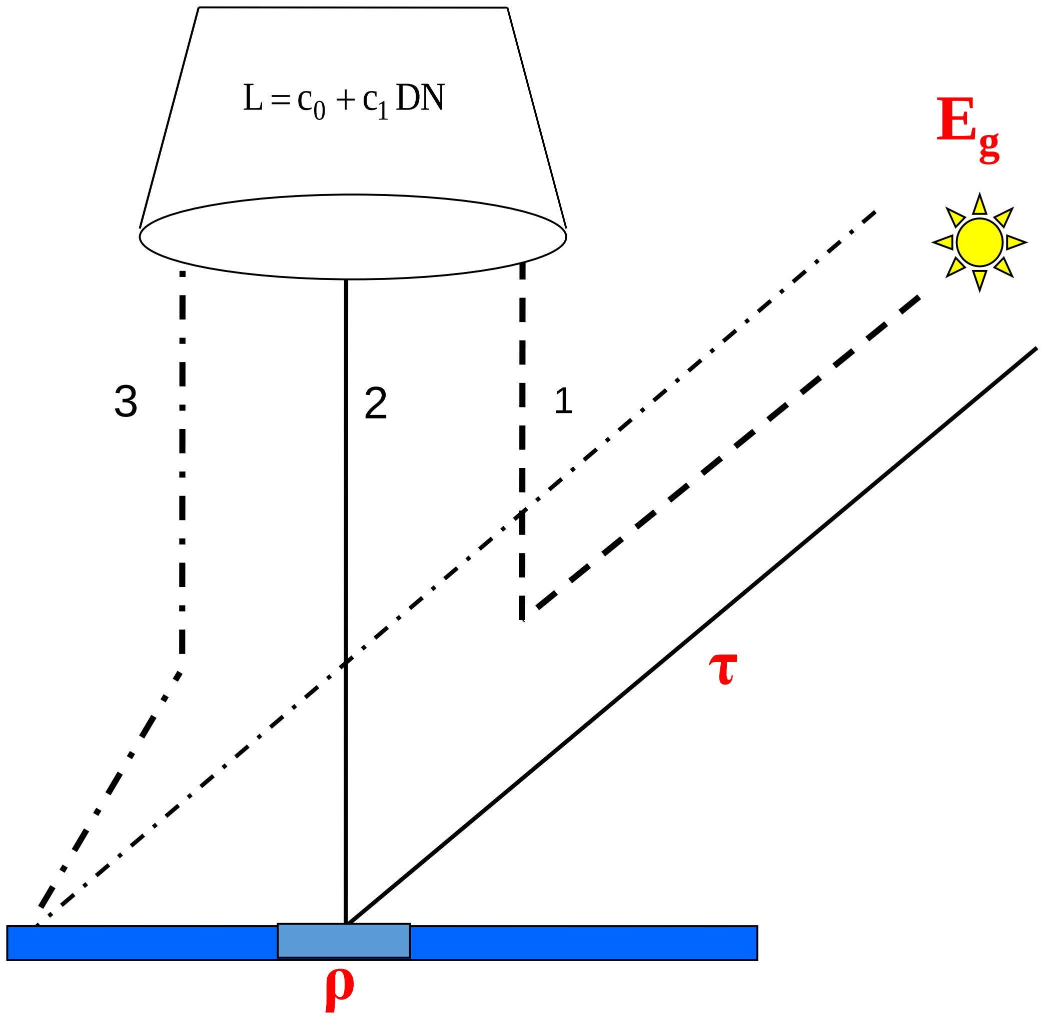
At-sensor radiance:

$L_{Sensor} = L_1 \quad + L_2 \qquad\qquad + L_3$

$L_{Sensor} = L_{path} + L_{reflected} + L_{adjacency}$

Target radiance:

$L_{reflected} = \rho \; E_g * \tau / \pi$



E_g: global flux $\quad$ τ : total atm. transmittance $\quad$ ρ : target reflectance

Radiation Components

When neglecting the adjacency effect:

$$L_{Sensor} = L_{path} + L_{reflected} = L_{path} + \rho \; E_g * \tau / \pi = c_0 + c_1 * DN$$

Radiation Components

When neglecting the adjacency effect:

$L_{Sensor} \quad = \quad L_{path} + L_{reflected} \quad = \quad L_{path} + \rho \; E_g * \tau / \pi \quad = \quad c_0 + c_1 * DN$

Now solving for the target reflectance:

$$\rho = \frac{\pi((c_o + c_1 * DN) - L_{Path})}{\tau * E_g}$$

This means:

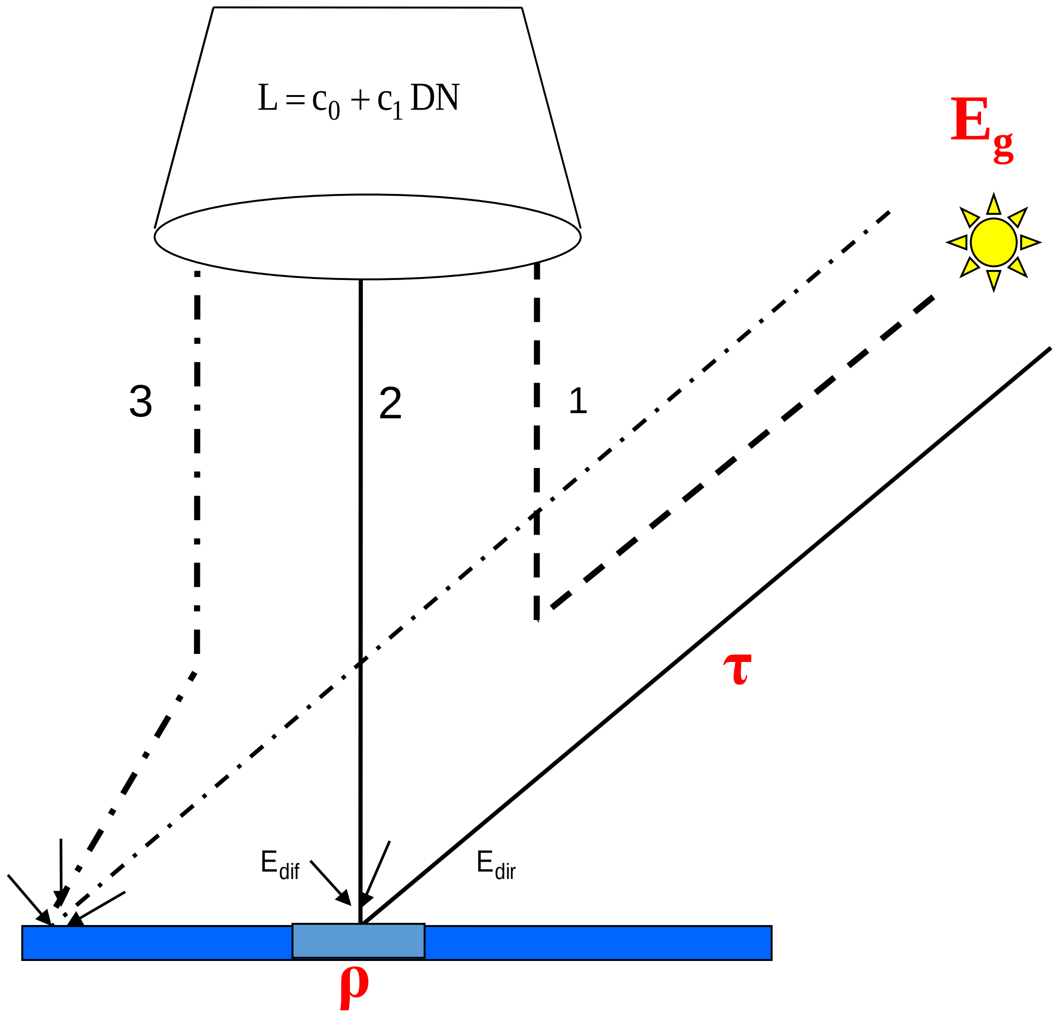
- Estimates of the main atm. parameters (aerosol type, optical thickness and water vapor) required for L_{path}, E_g and τ
- Accurate sensor calibration is mandatory

Radiation Components

Adding some details:

$E_g = E_{direct} + E_{diffuse}$

$\tau = \tau_{direct} + \tau_{diffuse}$



E_g: global flux diffuse + direct τ : total atm. transmittance ρ : target reflectance

Radiation Components

Adding some details:

$E_g = E_{direct} + E_{diffuse}$

$\tau = \tau_{direct} + \tau_{diffuse}$

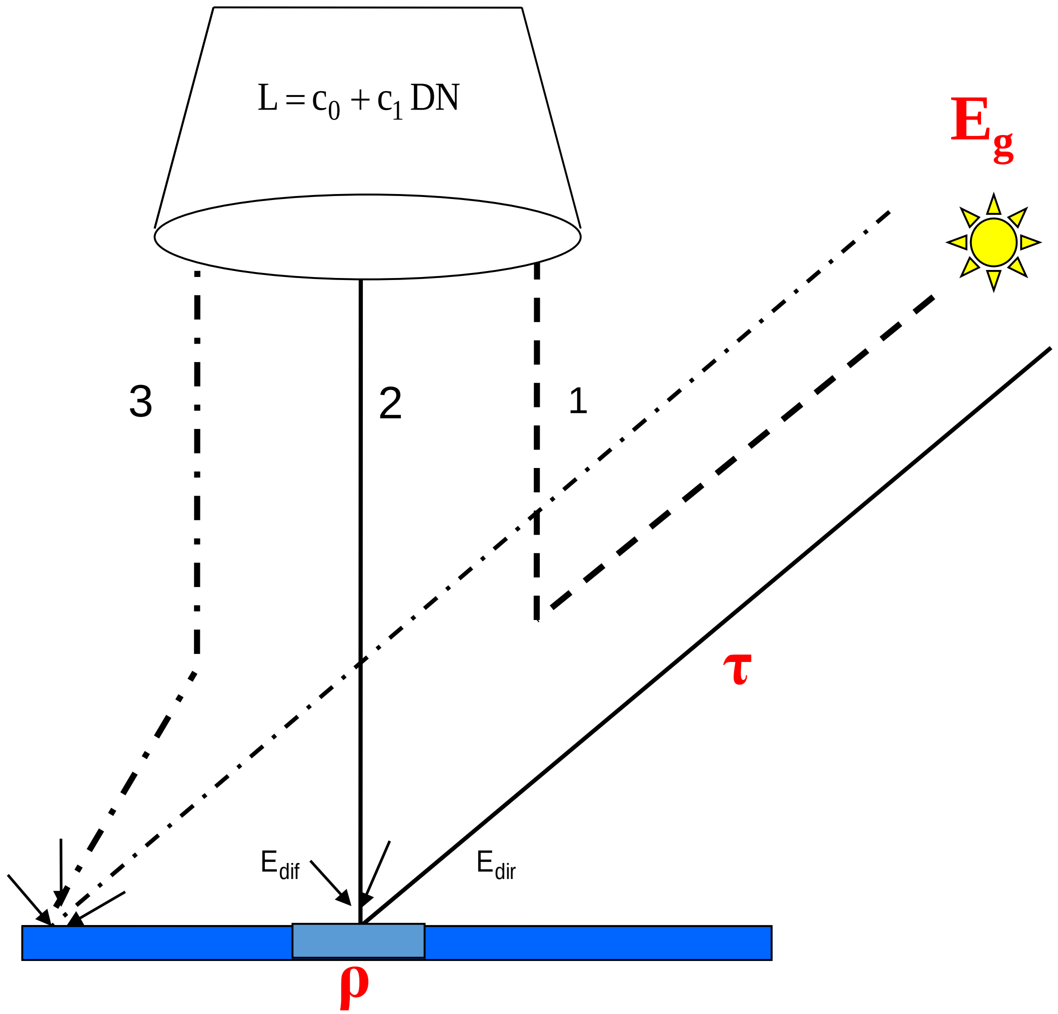
And adding adjacency effects:

$L_{Sensor} = L_{path} + \rho \; E_g \, \tau \; (1/\pi)$ **$* \; (1 / (1- \bar{\rho} \; s))$**

$\bar{\rho}$: background reflection

s: spherical albedo

(atm. backscattering to ground)

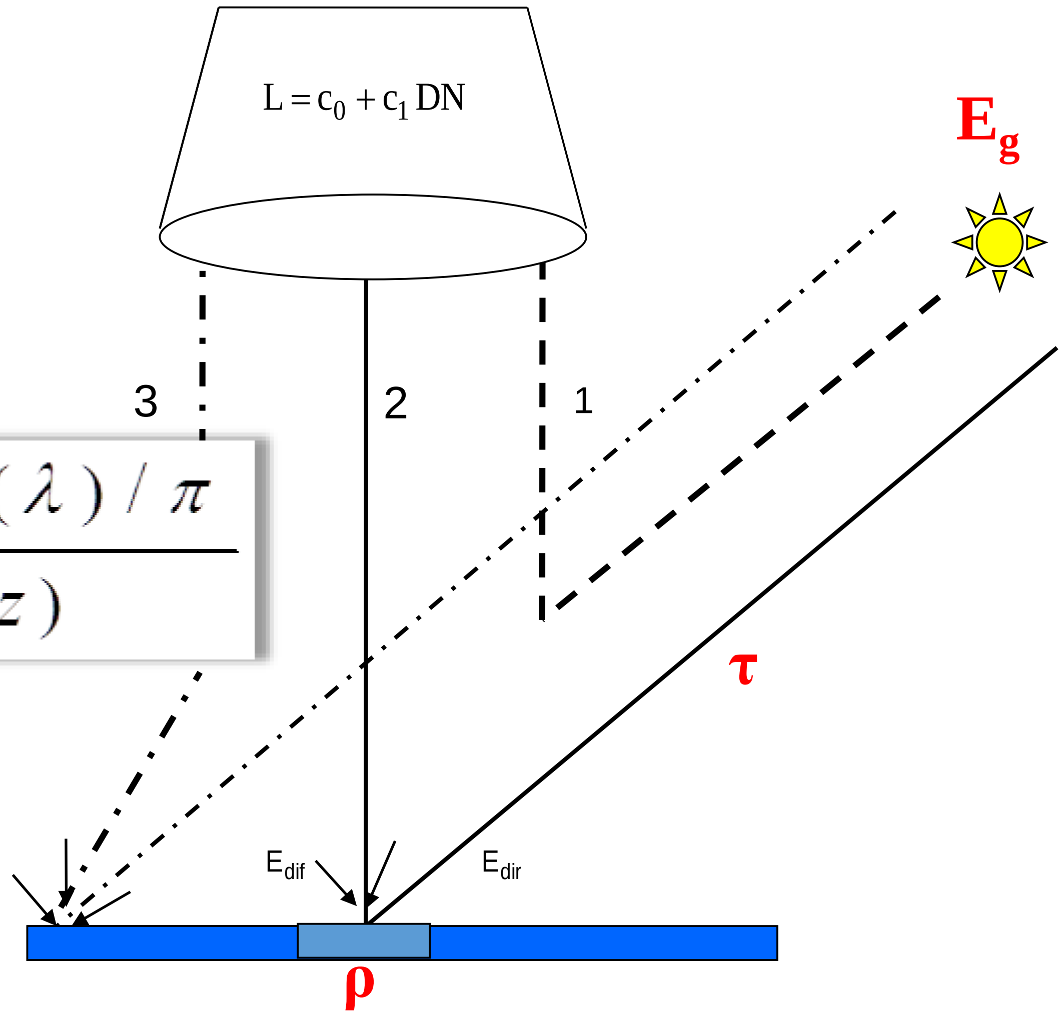


E_g: global flux diffuse + direct τ : total atm. transmittance ρ : target reflectance

Radiation Components

… and all wavelength (λ) & angular (z) dependent:

$$L = L_P(\lambda, z) + \frac{\tau(\lambda, z)\, E_g(\lambda, z)\, \rho(\lambda) / \pi}{1 - \bar{\rho}(\lambda)\, s(\lambda, z)}$$



E_g: global flux τ : total atm. transmittance ρ : target reflectance

Absorption and scattering

Beer's law

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\, x\right]$$

homogeneous path

$\gamma(\lambda)$ **Extinction coefficient (km^{-1})**

x Path length

$$\tau(\lambda, x) = \exp\left[-\int_0^x \gamma(\lambda, x')\, dx'\right]$$

inhomogeneous path

Absorption and scattering

Beer’s law

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\, x\right]$$

homogeneous path

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length

$\xi = \gamma\, x$ **Optical thickness**

Absorption and scattering

Beer's law

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\, x\right]$$

homogeneous path

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length

Extinction = Absorption + Scattering

k ***σ***

$$\gamma(\lambda) = k(\lambda) + \sigma(\lambda)$$

Absorption and scattering

Beer's law

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\, x\right]$$

homogeneous path

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length

Extinction = Absorption + Scattering

$$\gamma(\lambda) = k(\lambda) + \sigma(\lambda)$$

Separate: M = Molecule (Rayleigh)
A = Aerosol

$$\gamma(\lambda) = k_M(\lambda) + k_A(\lambda) + \sigma_M(\lambda) + \sigma_A(\lambda)$$

Absorption and scattering

Beer's law

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\, x\right]$$

homogeneous path

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length

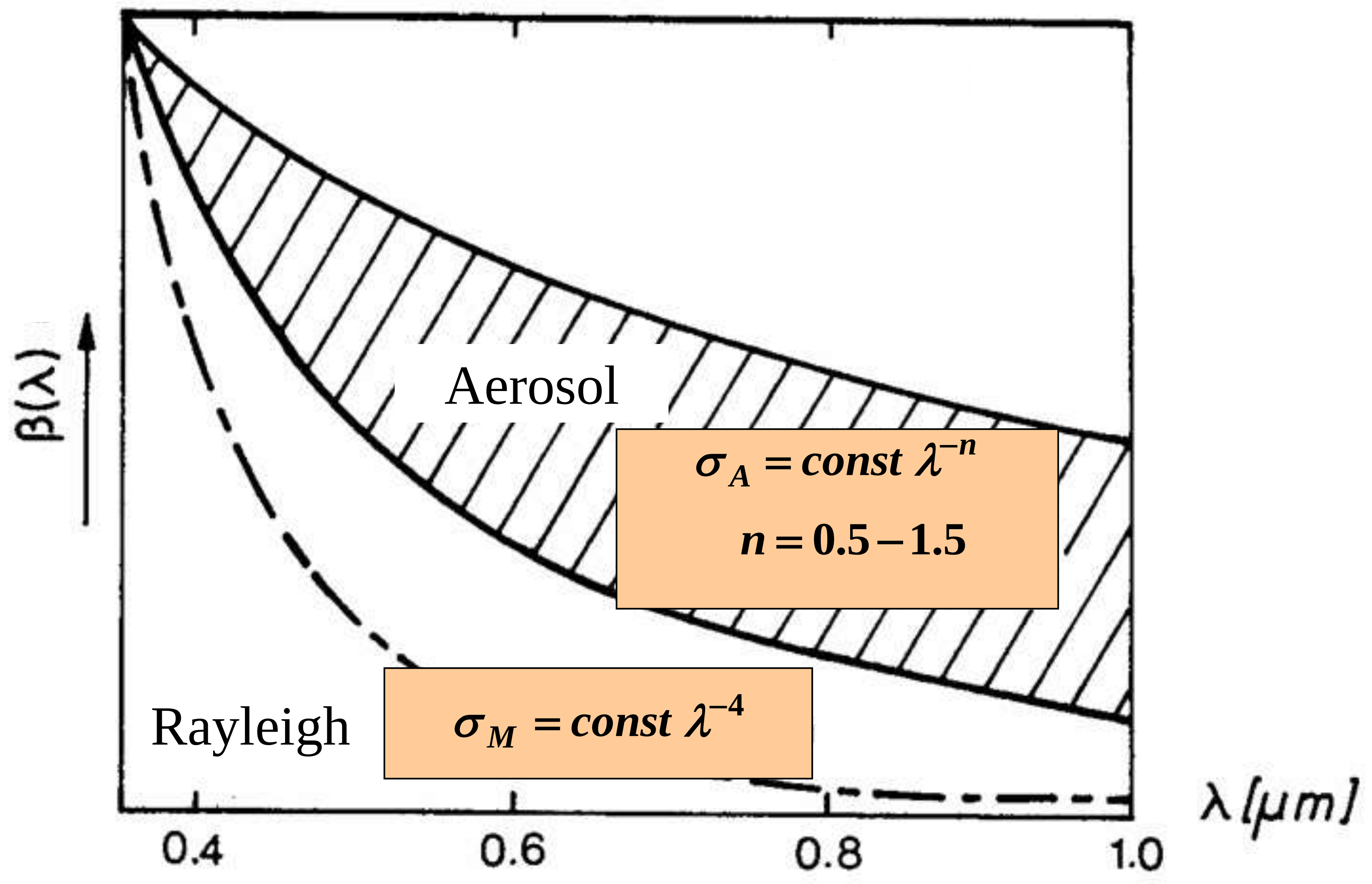
Extinction = Absorption + Scattering

$$\gamma(\lambda) = k(\lambda) + \sigma(\lambda)$$

Single scattering albedo

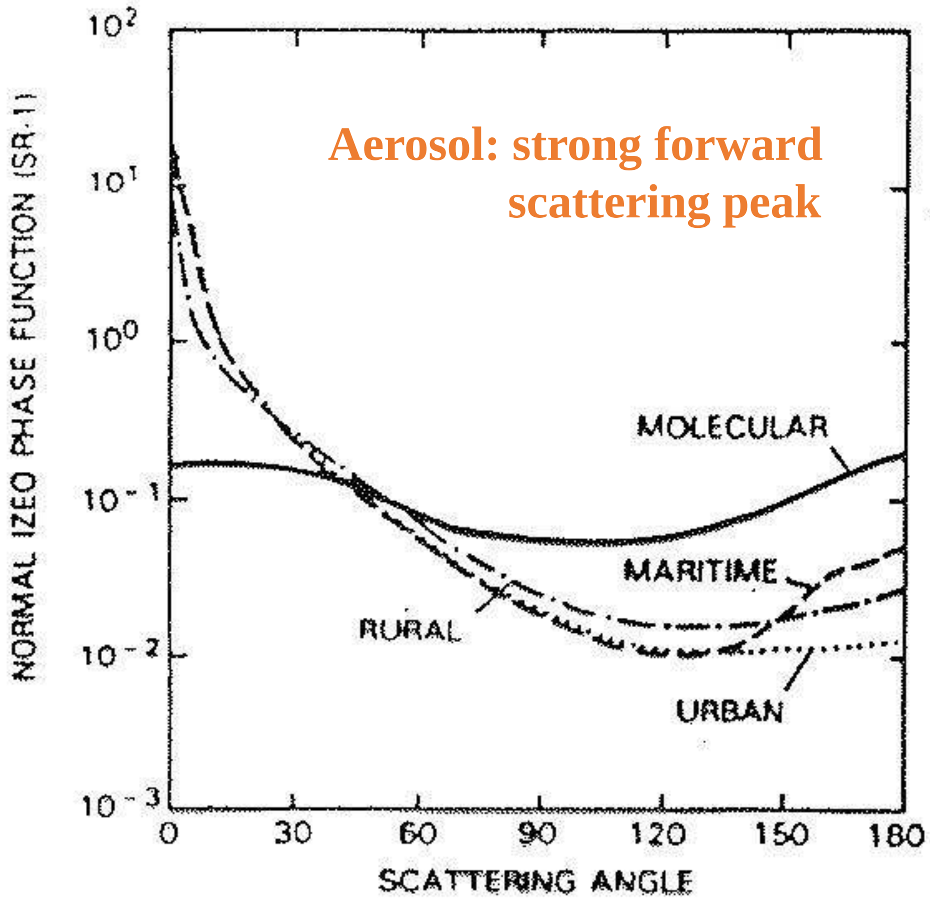
$$\omega(\lambda) = \sigma(\lambda) / \gamma(\lambda)$$

Scattering

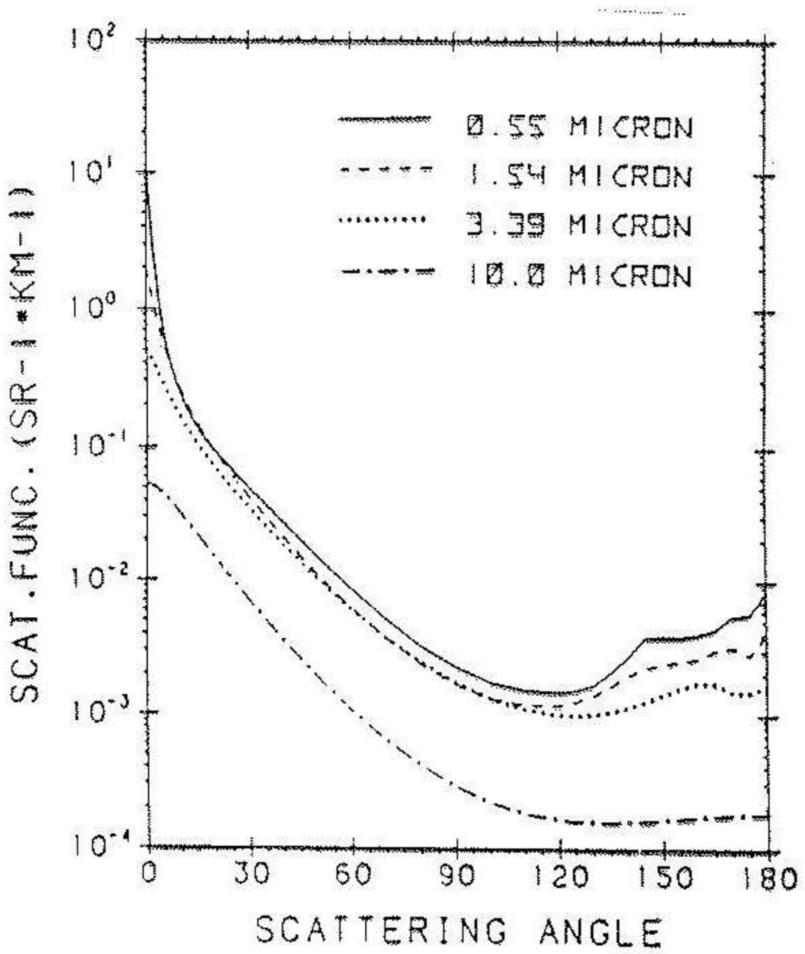


β(λ)
Aerosol
$\sigma_A = const\ \lambda^{-n}$
$n = 0.5 - 1.5$
Rayleigh
$\sigma_M = const\ \lambda^{-4}$
0.4
0.6
0.8
1.0
λ [μm]

Scattering



Rel. humidity = 70% ,
550 nm



Maritime Aerosol,
Rel. humidity=80%

Scattering phase function

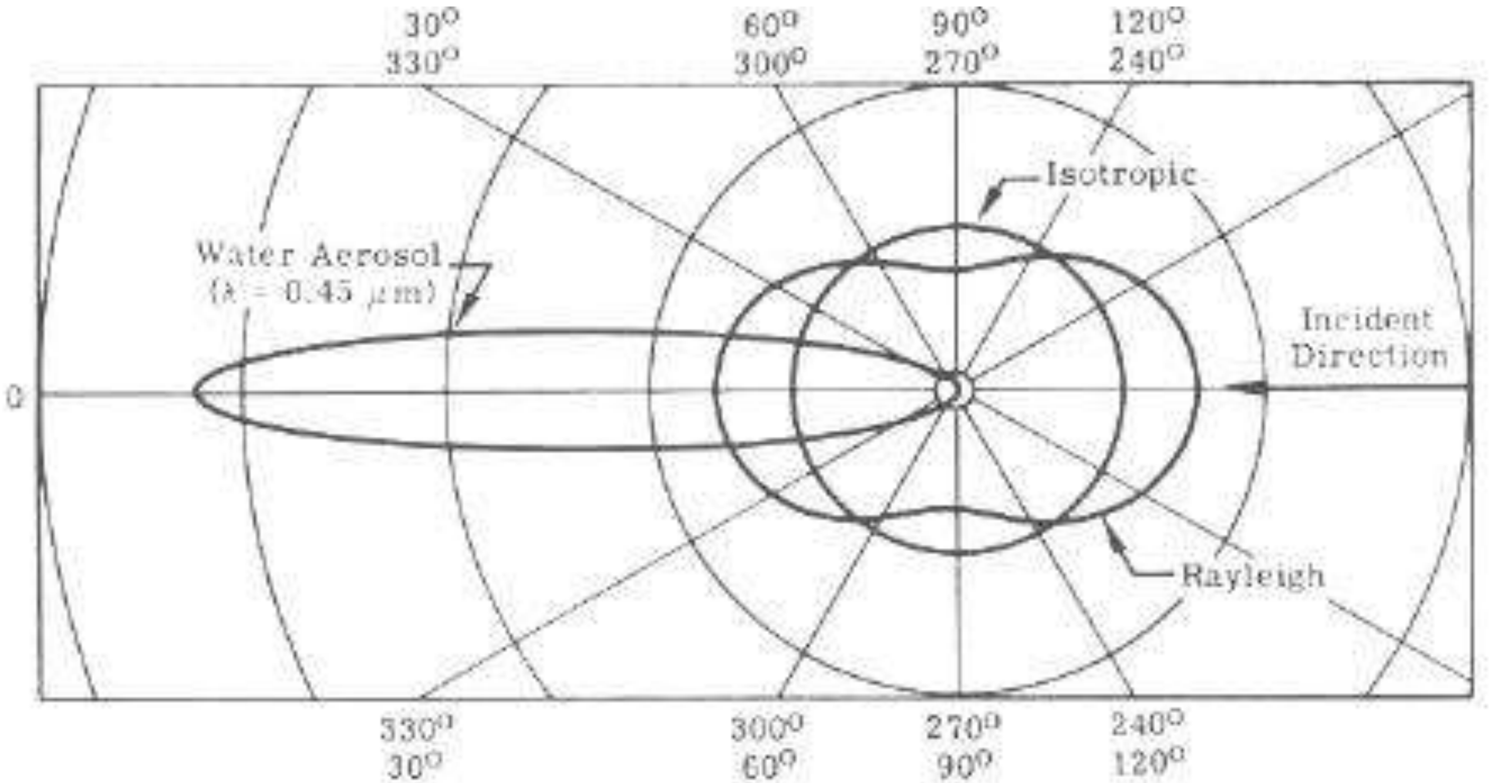


Fig. 8.2 Angular dependence of single-scattering phase functions in any azimuthal plane. The isotropic and Rayleigh functions have been multiplied by 10. (After LaRocca and Turner, 1975.)

Visibility, meteorological range

Koschmieder Equation:

$$VIS = \frac{1}{\gamma}\ln\left(\frac{1}{\varepsilon}\right) = \frac{3.912}{\gamma}$$

Visibility, meteorological range

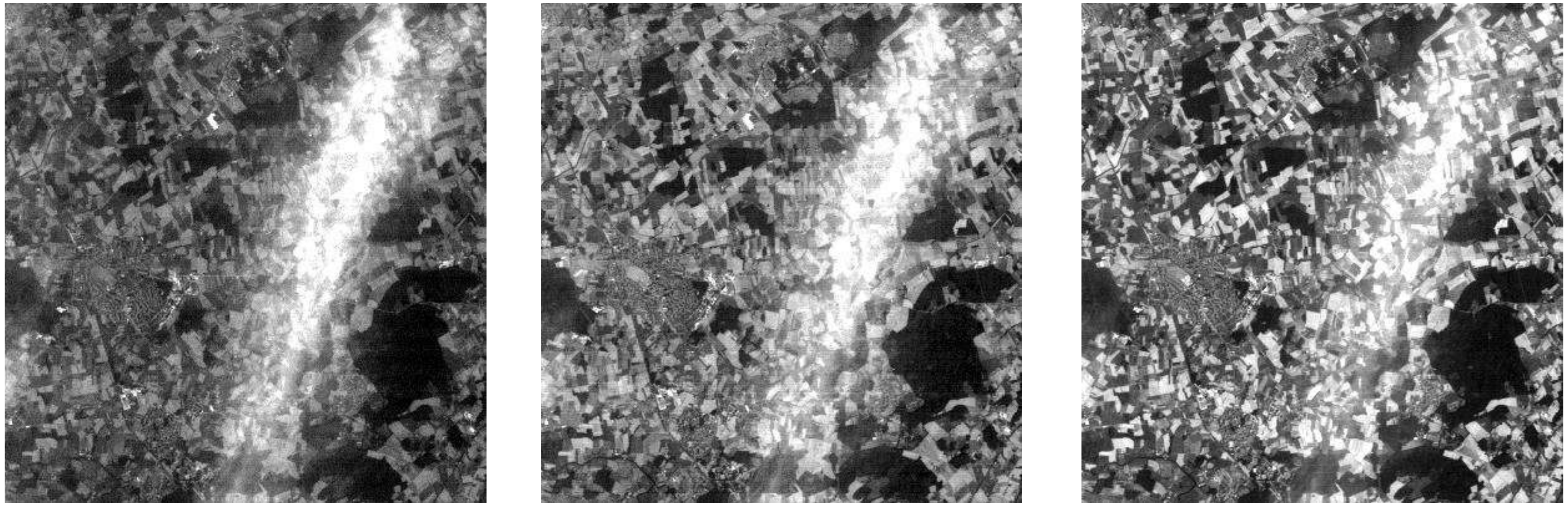
Contrast threshold ε = 0.02

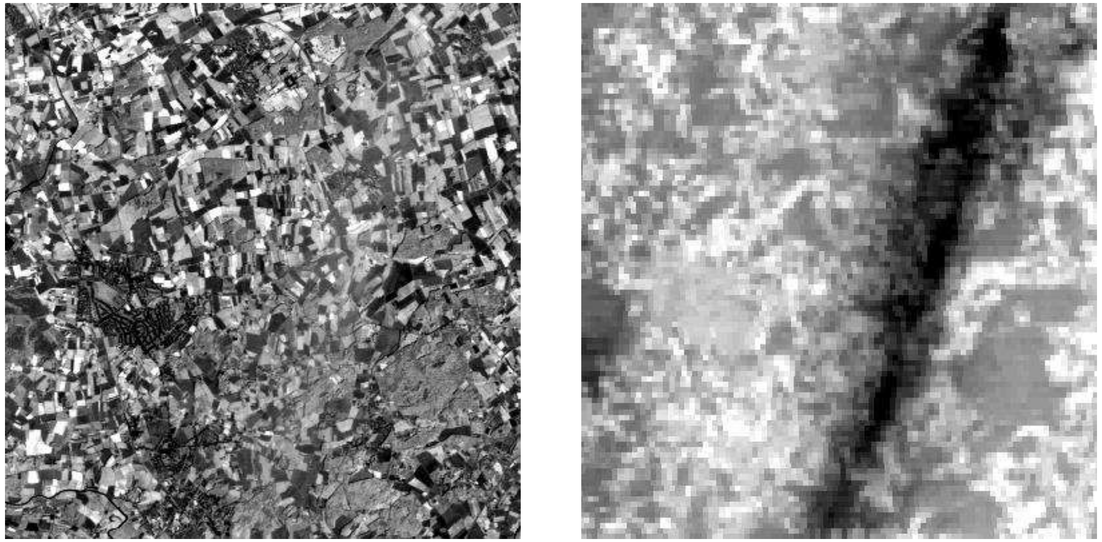
Extinction coefficient (γ at 0.55 µm)

(depends on complex refractive index, particle size & distribution, concentration)

Wavenumber w (cm^{-1}) and wavelength λ (µm) : $w(cm^{-1}) = \frac{10^4}{\lambda(\mu m)}$

Scattering and Absorption





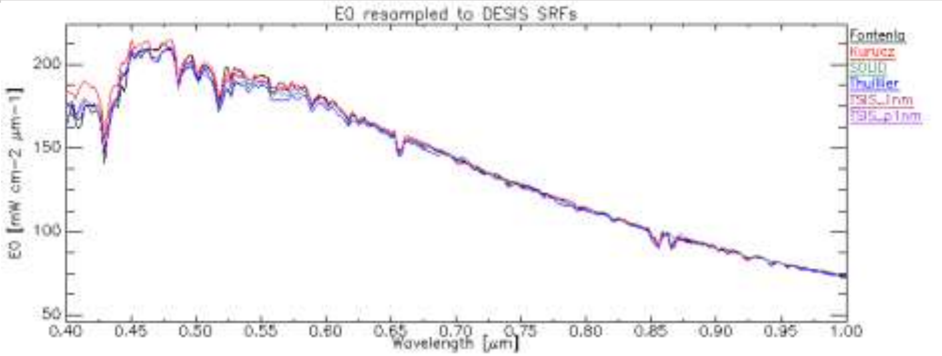
Top: Landsat TM bands 1-3
(480, 560, 660 nm)

Bottom: TM bands 4, 6
(840 nm, 11.5 µm)

Note: TIR affected by WV,
not by dust particles

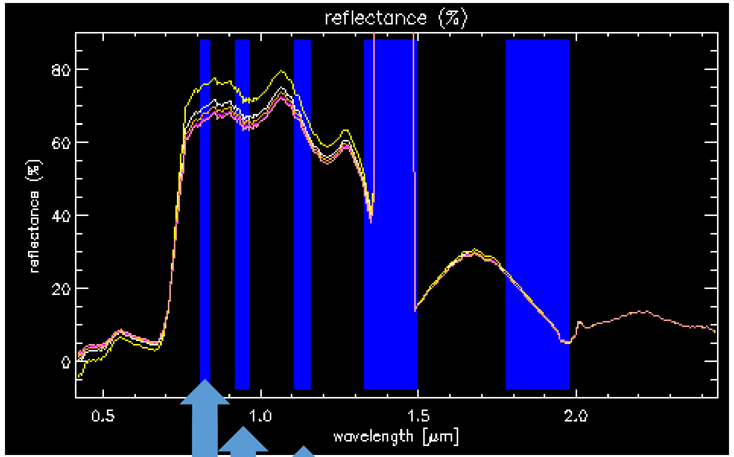
Therefore atm. correction requires

- Solar irradiance (E0)

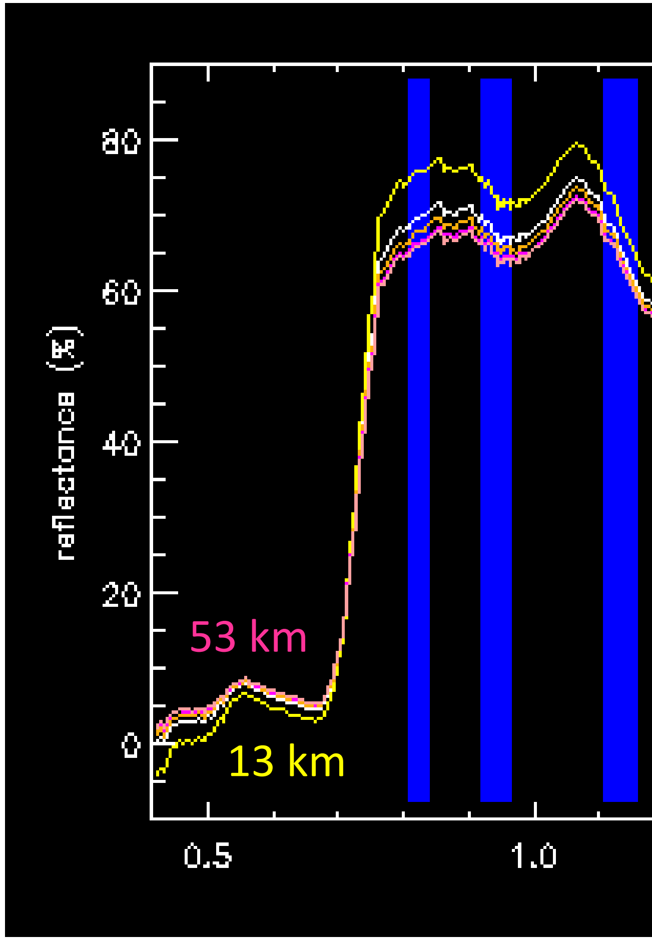


Different E0 models

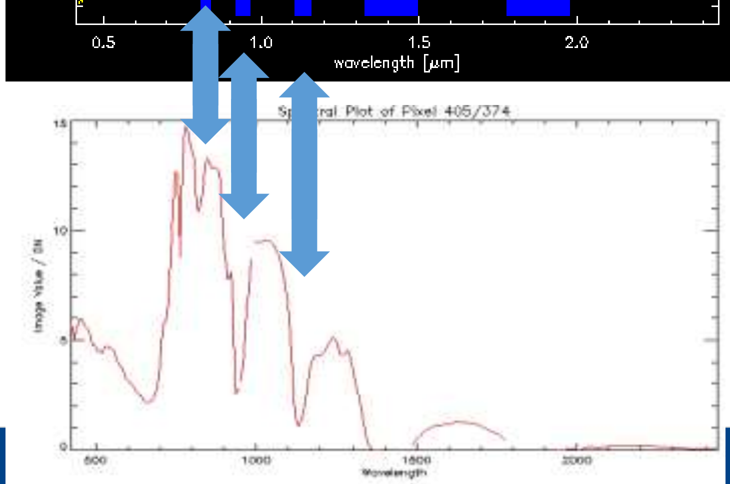
- Aerosol properties



Simulated VIS of 13... 53 km, rural aerosol

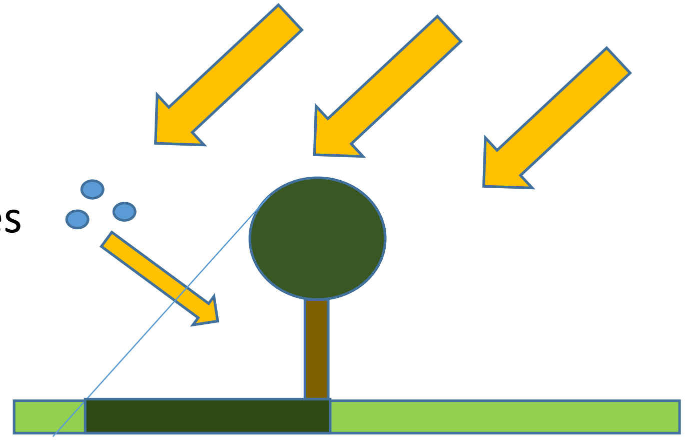


- Water vapor column



- „Blue“ shadows:
  diffuse illumination

Aerosols & molecules
Rayleight



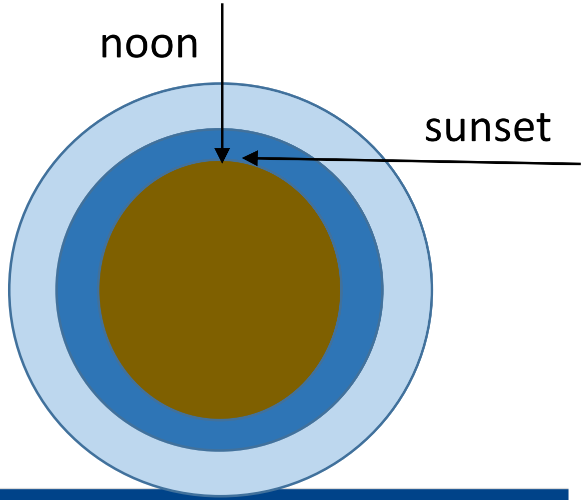
- „Red“ sunset & sunrise: path lengths, rayleigh scattering & refraction

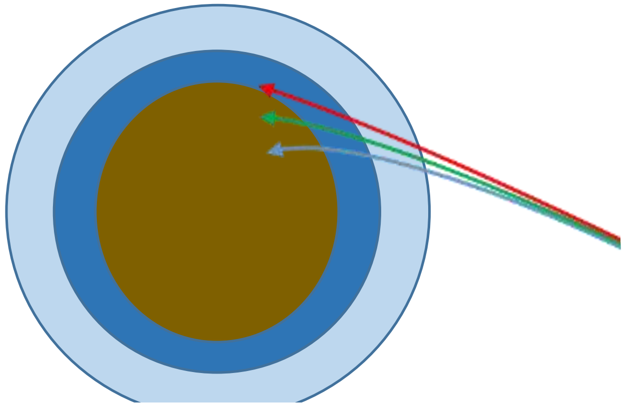
$$\sigma_M = const\ \lambda^{-4}$$ Rayleigh

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\ x\right]$$ Beer's law

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length



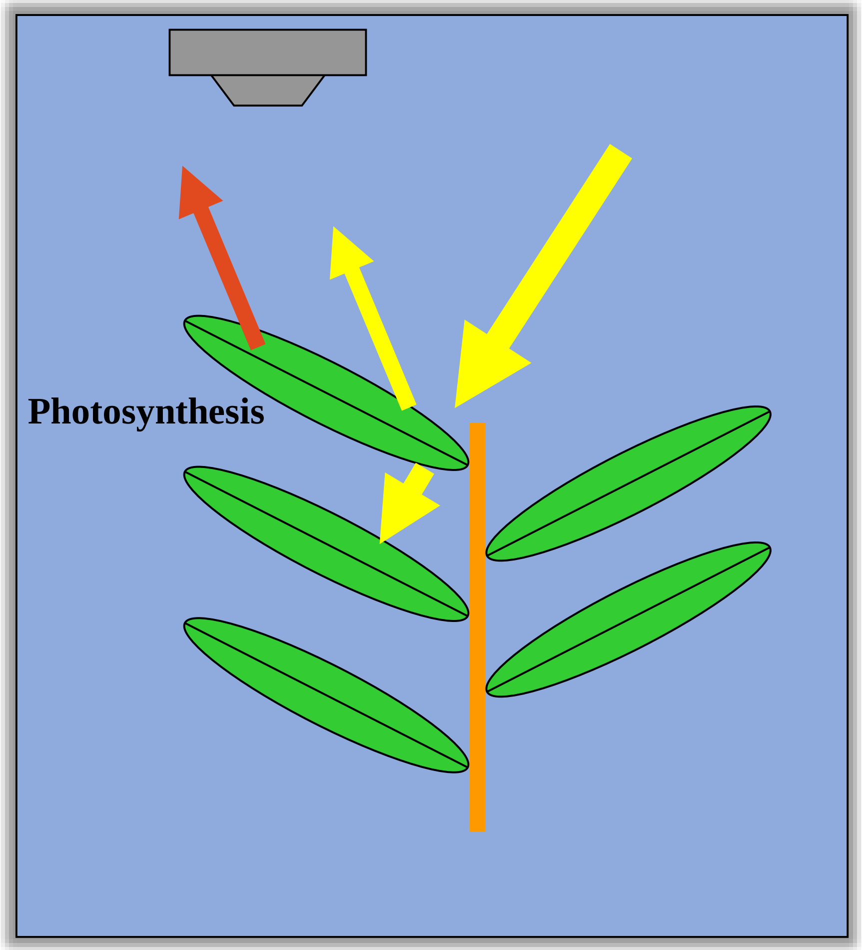


Original concept: http://hyperphysics.phy-astr.gsu.edu/ and https://kaiserscience.wordpress.com/physics/electromagnetism/physics-of-sunsets/

3rd: Interaction with Matter

EM interaction with media

- **Absorption** (uptake of energy)
  - Electron transfer, rotation, vibration
    - Heating, change in matter
- **Emission** („release“ of energy)
  - Electron transfer, rotation, vibration
- **Reflection**
  - Change of direction without energy uptake
- **Transmission**
  - Transfer without absorption or reflection



EM interaction with media

- Energy balance relationship:

$$E_{\text{emitted by sun}} = E_{\text{reflected}} + E_{\text{transmitted}} + E_{\text{absorbed}}$$

E… Incident Energy [W]

$$1 = E_r / E_i \quad + \quad E_t / E_i + E_a / E_i$$

$$1 = \quad R \quad + \quad T \quad + \quad A$$

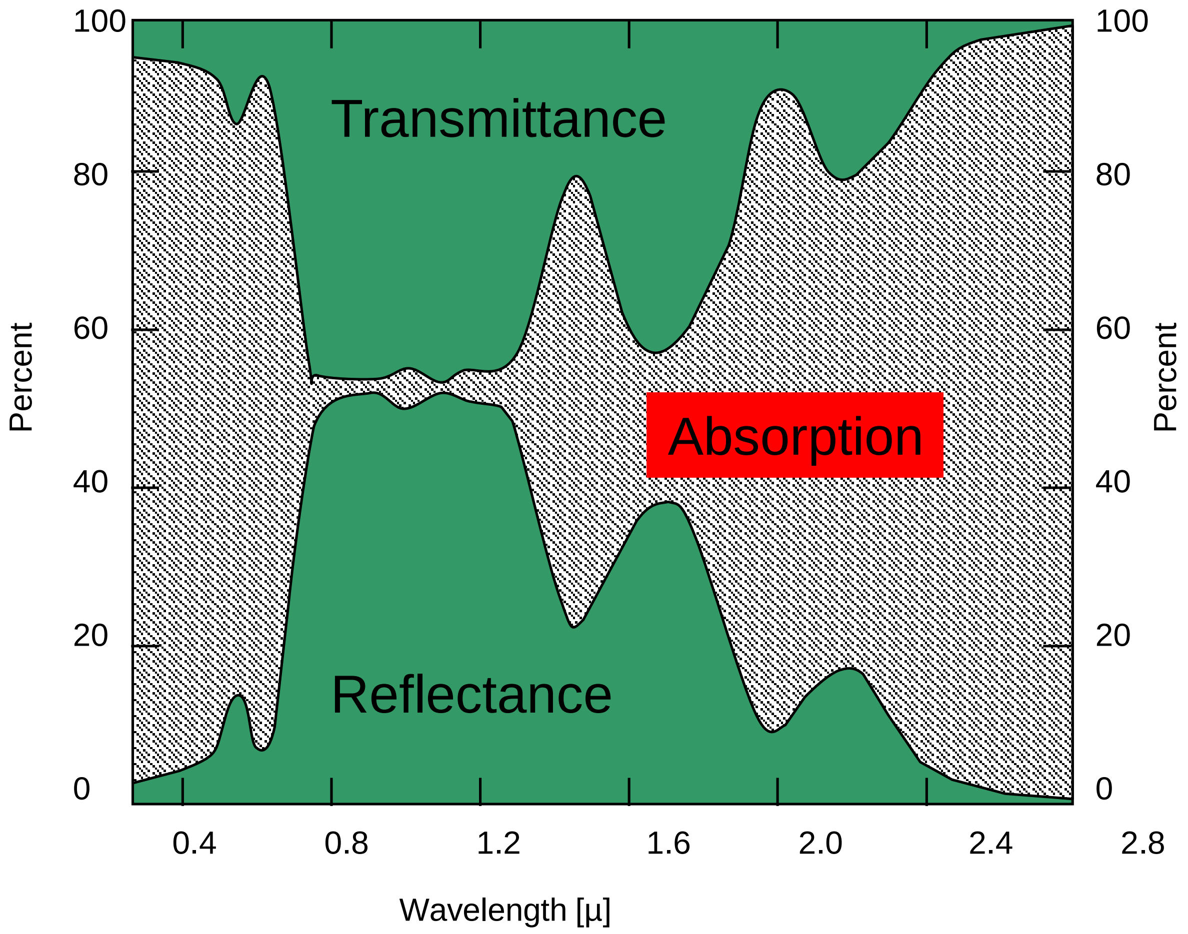
…Reflection-coefficient + Transmission-coefficient + Absorption-coefficient

- Opaque material: $T = 0 \quad \Rightarrow \quad 1 = R + A$

=> material property, independent of incoming radiant energy!

EM interaction with media

… and now as a function of wavelength:



Emission processes

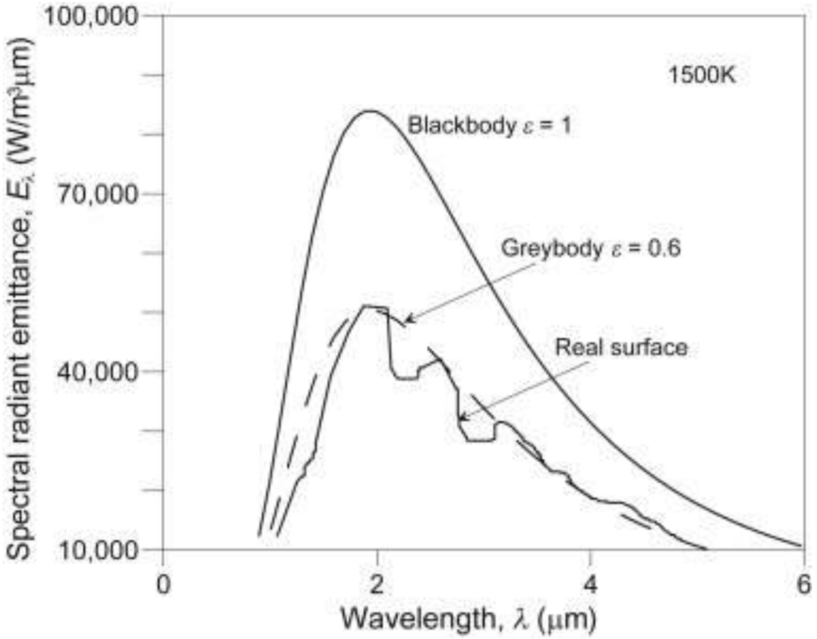
- Spectral emissivity:

$$\varepsilon_\lambda = M_\lambda / M_{\lambda,black}$$

- And thus:

$$M = \varepsilon\, \sigma\, T^4$$

- Only for Black Bodies (KIRCHHOFF):
  Blackbody Emission = Absorption = 100%
- Grey Body: $\varepsilon < 1$
- Selective Absorber & Emitter



https://www.sciencedirect.com/topics/engineering/emissivity

=> emissivity depends on temperature and material

Absorption processes

Electron transfer:

- Quantized: $\Delta Q = h * f$
- Occur normally < 1 µm
- Rarely detected due to mineral composition => complex overlay of absorption features

Vibration modes - bending & stretching:

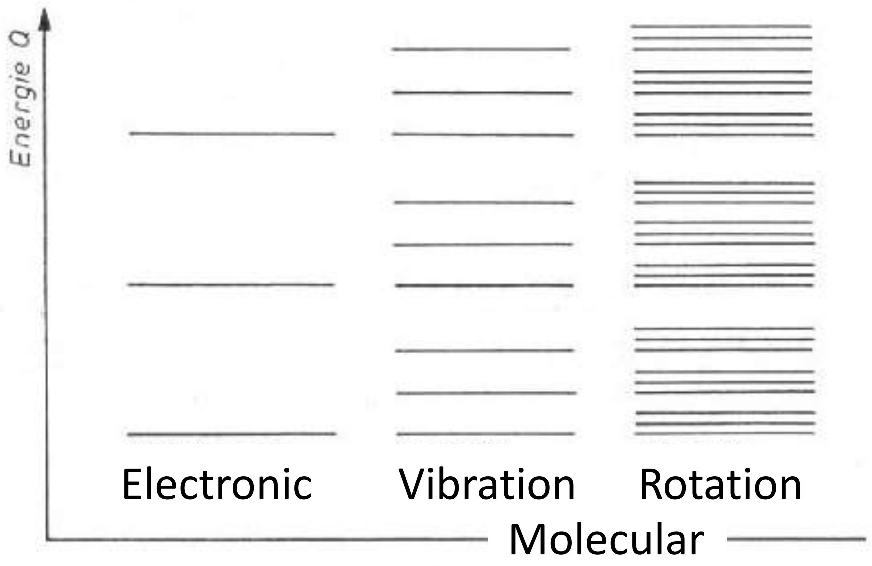
- „Sharper“ and frequent (3*N possible for molecules with N atoms)
- Occur normally >1 µm
- Many fundamentals per material, normally > 3 µm
- Resonance (combinations & harmonics)

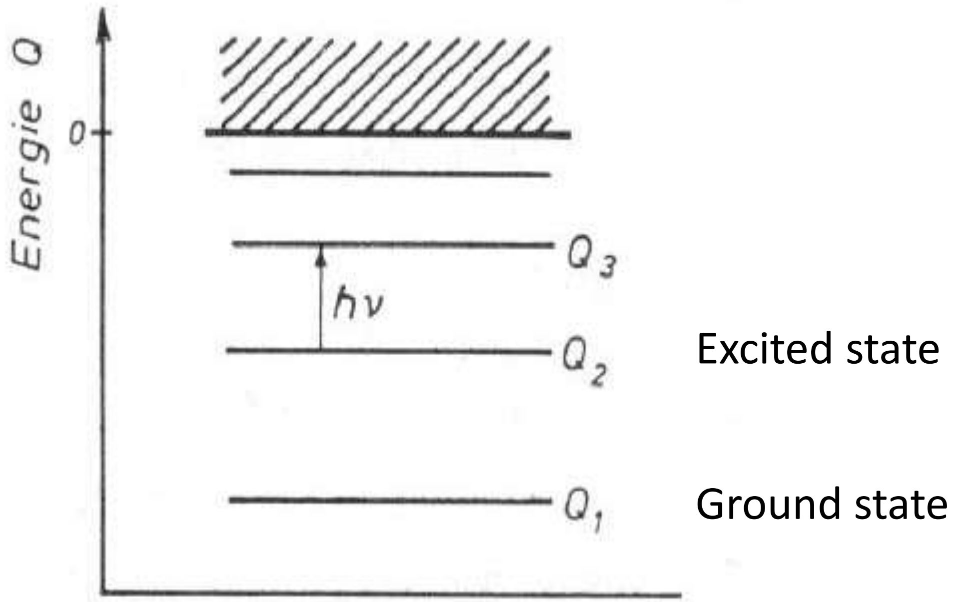
Fundamentals (Grundschwingung)

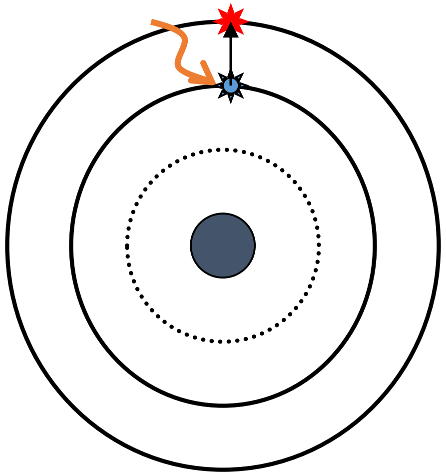
Harmonics (Obertöne): multiples of fundamentals, lower absorption depth
1st harmonic: 1/10 of fundamental absorption, 2nd harmonic: 1/100

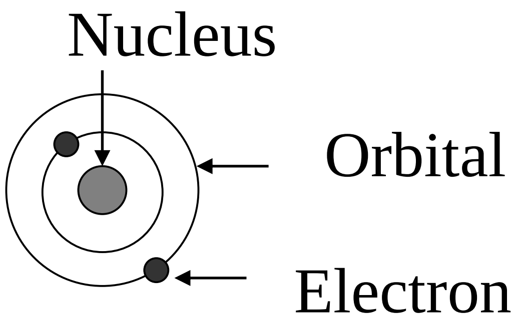
Combinations: Sum of fundamentals and/or harmonics

Absorption processes

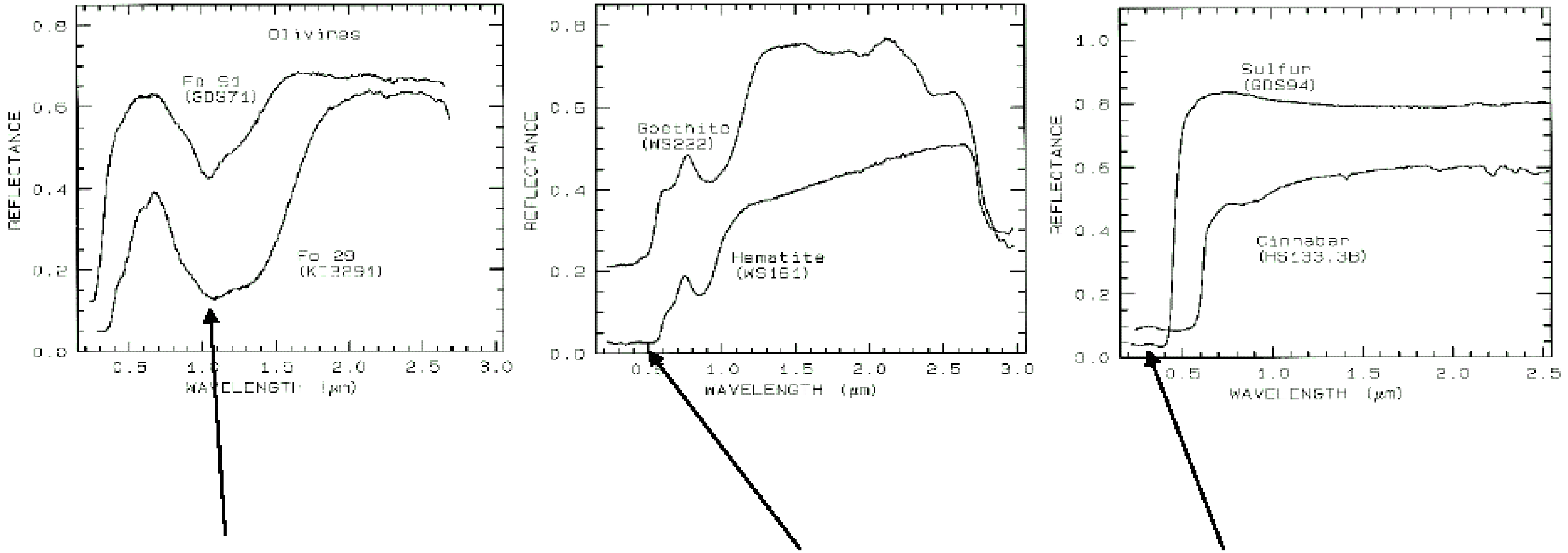








Absorption processes



Crystal field effect absorption caused by Fe^{2+}. Fe 29 has 53.65% FeO, Fe 91 has 7.93% FeO.

Charge transfer absorption caused by Fe^{2+}. Fe_2O_3 (hematite) and FeOOH (geothite).

Conduction bands caused by S and HgS.

Absorption processes

Example: Liquid Water H_2O

- Fundamentals
  - λ_1: 3.106 µm / 6.4 * 10^{-20} J symmetric OH - stretch
  - λ_2: 6.080 µm / 3.3 * 10^{-20} J HOH - bend
  - λ_3: 2.903 µm / 6.9 * 10^{-20} J asymmetric OH - stretch

- Harmonics
  (2* f resp. ½ * λ)
  - 1.553 µm / 1.3 * 10^{-19} J
  - 3.040 µm / 6.6 * 10^{-20} J
  - 1.452 µm / 1.4 * 10^{-19} J

- Combinations
  - 1.87 µm (1/ λ_3 +1/ λ_2) / 1.1 * 10^{-19} J
  - 0.962 µm (1/2* λ_1 + 1/ λ_3) / 2.1 * 10^{-20} J

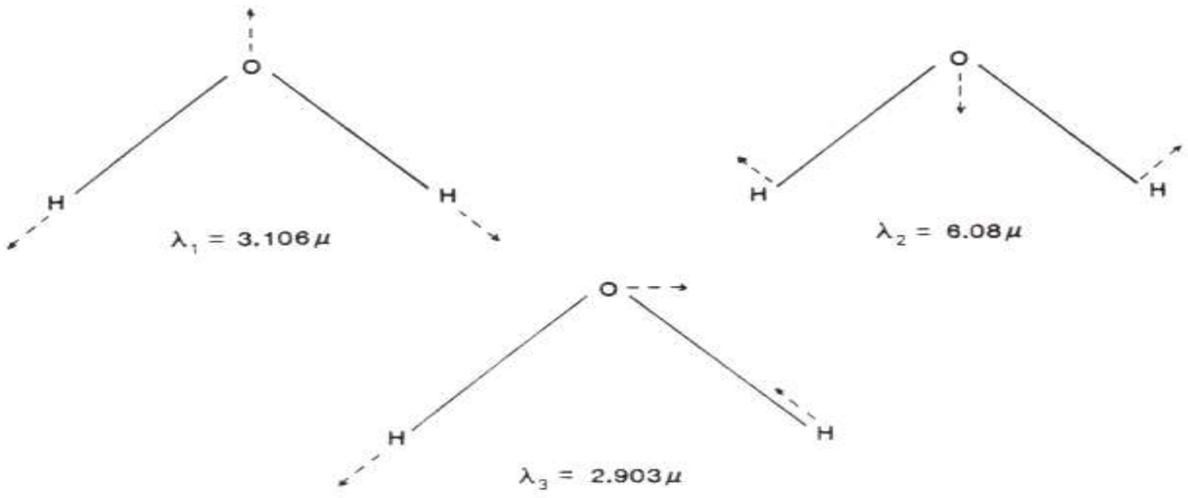


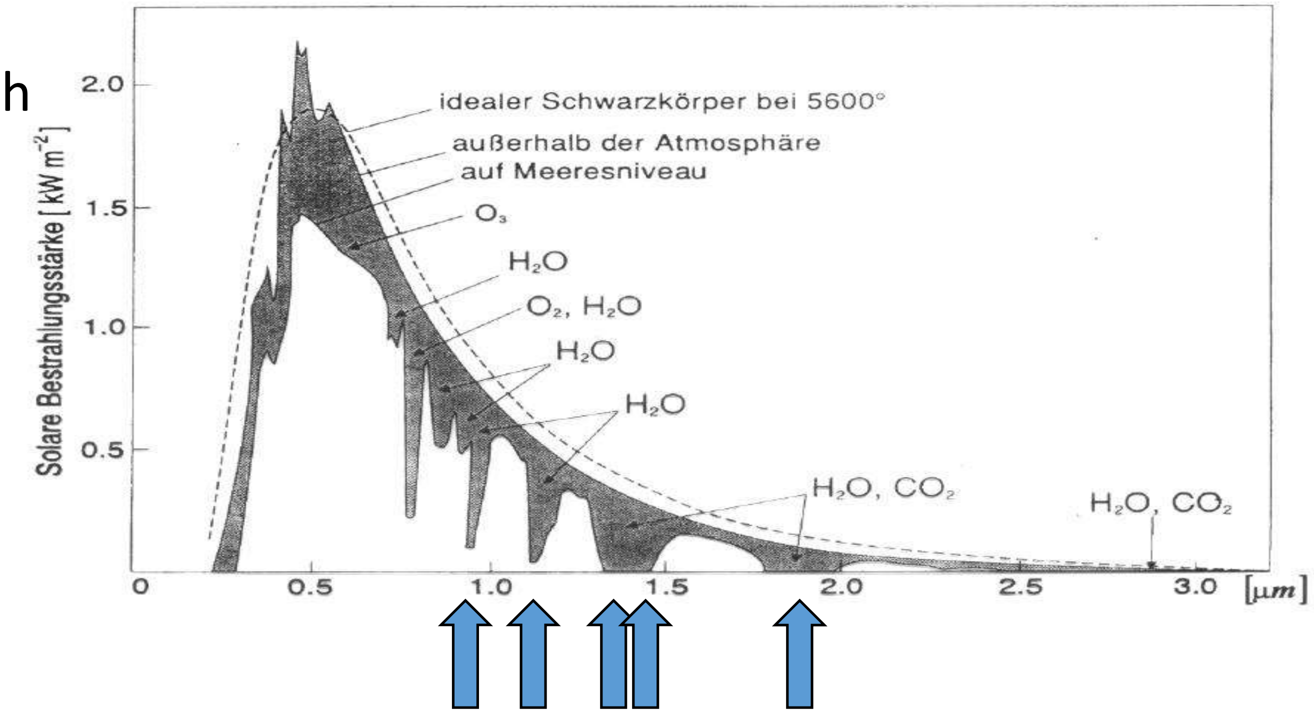
Fig.: ELACHI

Absorption processes

Example: Water Vapor

- Fundamentals
  - vi @ 2.74 µm symmetric stretch
  - v2 @ 6.27 µm HOH - bending
  - v3 @ 2.66 µm asymmetric stretch

- Harmonics and Combinations
  - 1.875 µm (v2 + v3)
  - 1.454 µm (2*v2 + v3)
  - 1.380 µm (v1 + v3)
  - 1.135 µm (v1 + v2 + v3)
  - 0.942 µm (2*v1 + v3)



Absorption & transmission processes

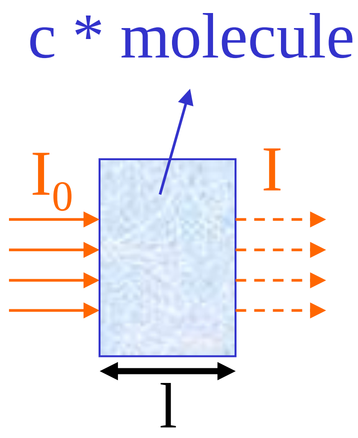
Beer-Lambert law (base for transmittance spectroscopy):

- Transmittance $t = I / I_0$

- $A = \log_{10}(I_0/I) = \varepsilon\, c\, l$

  A: absorbance
  ε: molecular absorption coefficient for molecule species [$mol^{-1}\ cm^{-1}$]
  c: concentration of absorbing molecules [mol]
  l: path length through sample [cm]

  => absorbance ~ molecule concentration



- Also valid for reflectances: $A = \mathrm{Log}_{10}\,(1/\rho)$

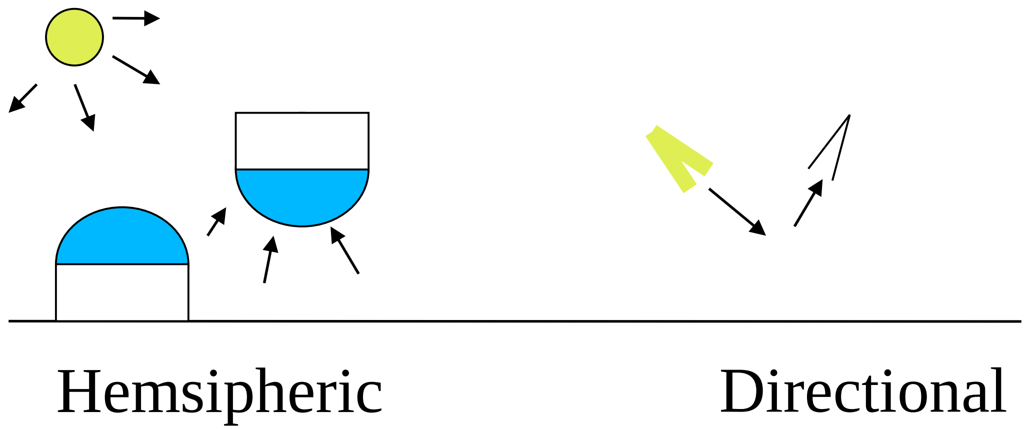
Absorption processes

- Sounds pretty simple, **<u>but</u>**:
  - Some features are related to many materials:
    e.g. OH bond is related to water, cellulose, starch, clays etc.
  - Overlapping features
  - Multiple scattering broadens features
  - No simple relationship between feature depth and component content (saturation effects)
  - In Vivo ≠ In Vitro
  - Noise, spectral bandwidth and position, …

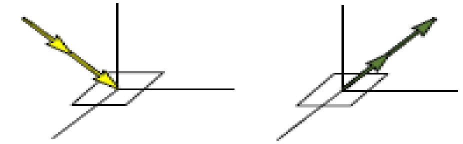
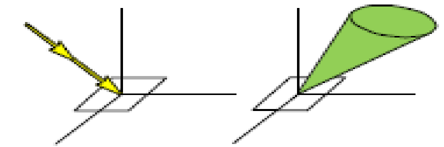
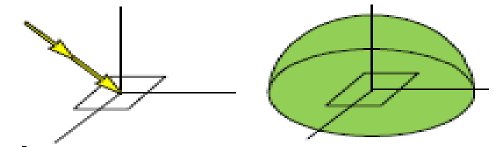
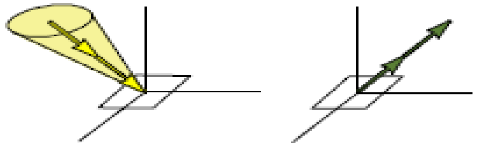
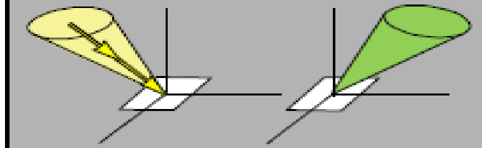
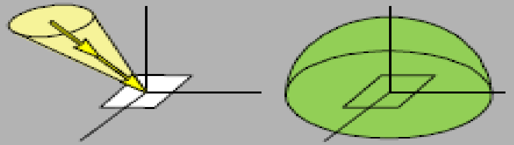
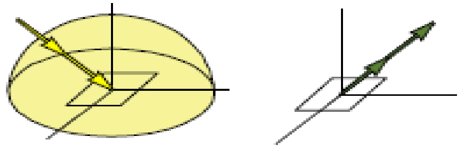
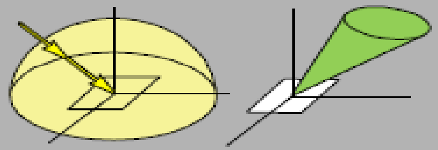
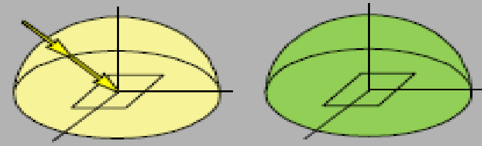
…more on reflectance behavior

Measurement principles

- Bidirectional
  pointed illumination, observation in one direction
- Directional - hemispheric
  pointed illumination, observation of hemisphere
- Hemispheric - directional
  hemispherical illumination, observation in one direction
- Hemispheric - hemispheric
  hemispherical illumination, observation of hemisphere



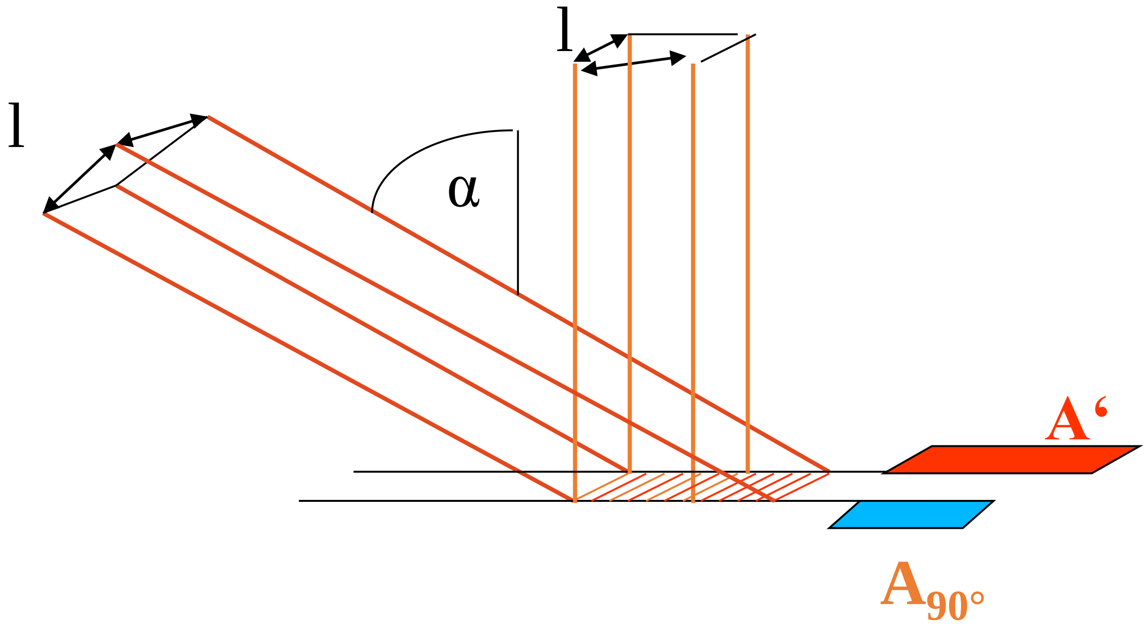
Measurement principles

Incoming/**Reflected**	**Directional**	**Conical**	**Hemispherical**
Directional	Bidirectional Case 1 	Directional-conical Case 2 	Directional-hemispherical Case 3 
Conical	Conical-directional Case 4 	Biconical Case 5 	Conical-hemispherical Case 6 
Hemispherical	Hemispherical-directional Case 7 	Hemispherical-conical Case 8 	Bihemispherical Case 9 

Schaepman-Strub, RSE 2006

Physical basics

Lambertian Cos.-Law



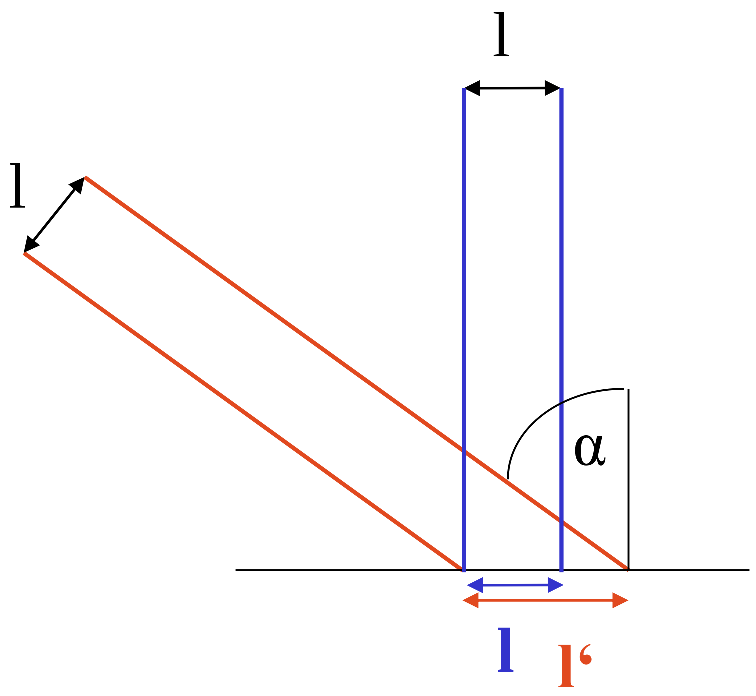
Area A‘ = $A_{90°}$ / cos α

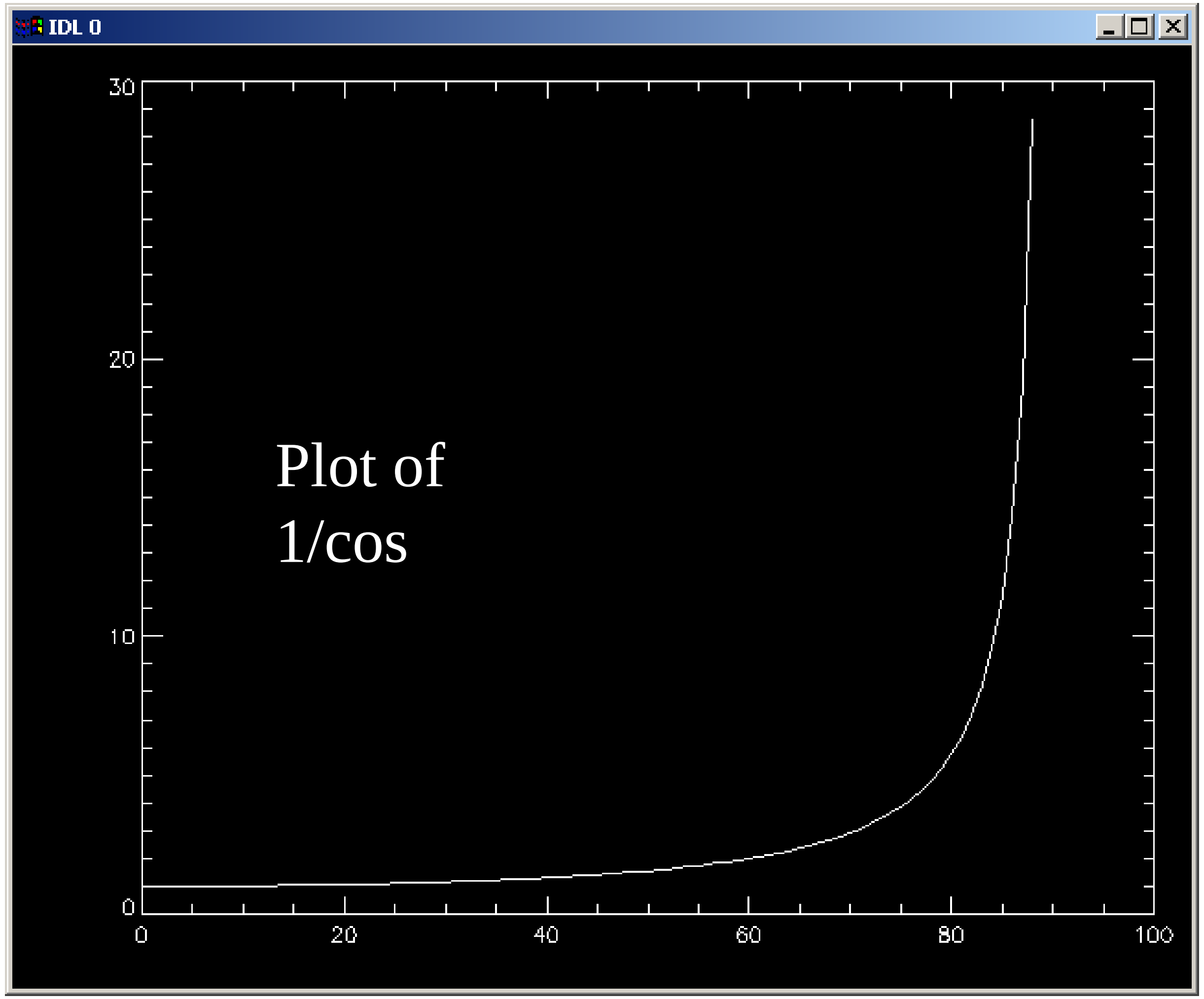
Radiant Flux [W m^{-2}]

$E_\alpha = E_0 \cos \alpha$

Physical basics

Lambertian Cos.-Law

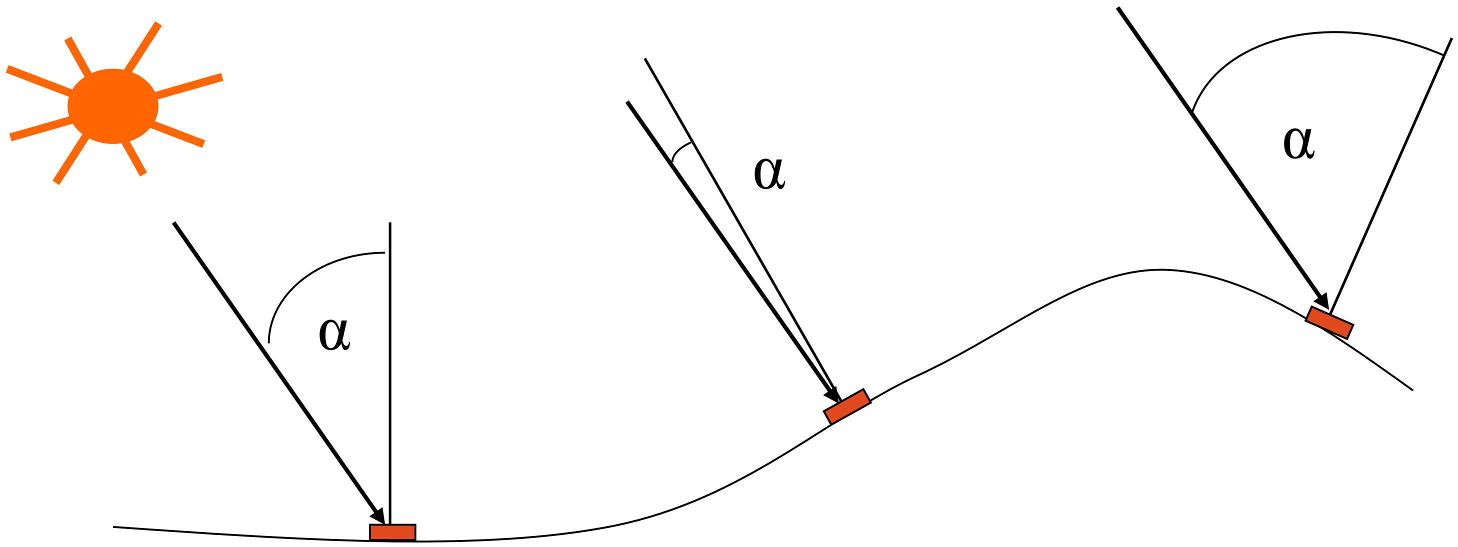




Physical basics

Radiant Flux [W m^{-2}] $E_\alpha = E_0 \cos \alpha$

=> Illumination condition cased by terrain & sun angle



Physical basics

Reflection behaviour of surfaces

Specular
angle of incidence = angle of reflection

Diffuse
same brightness in all viewing directions

if σ h < λ / (8 * cos Θ)
Θ…view angle
σ h: standard deviation of surface roughness

=> “optical” reflection is normally diffuse

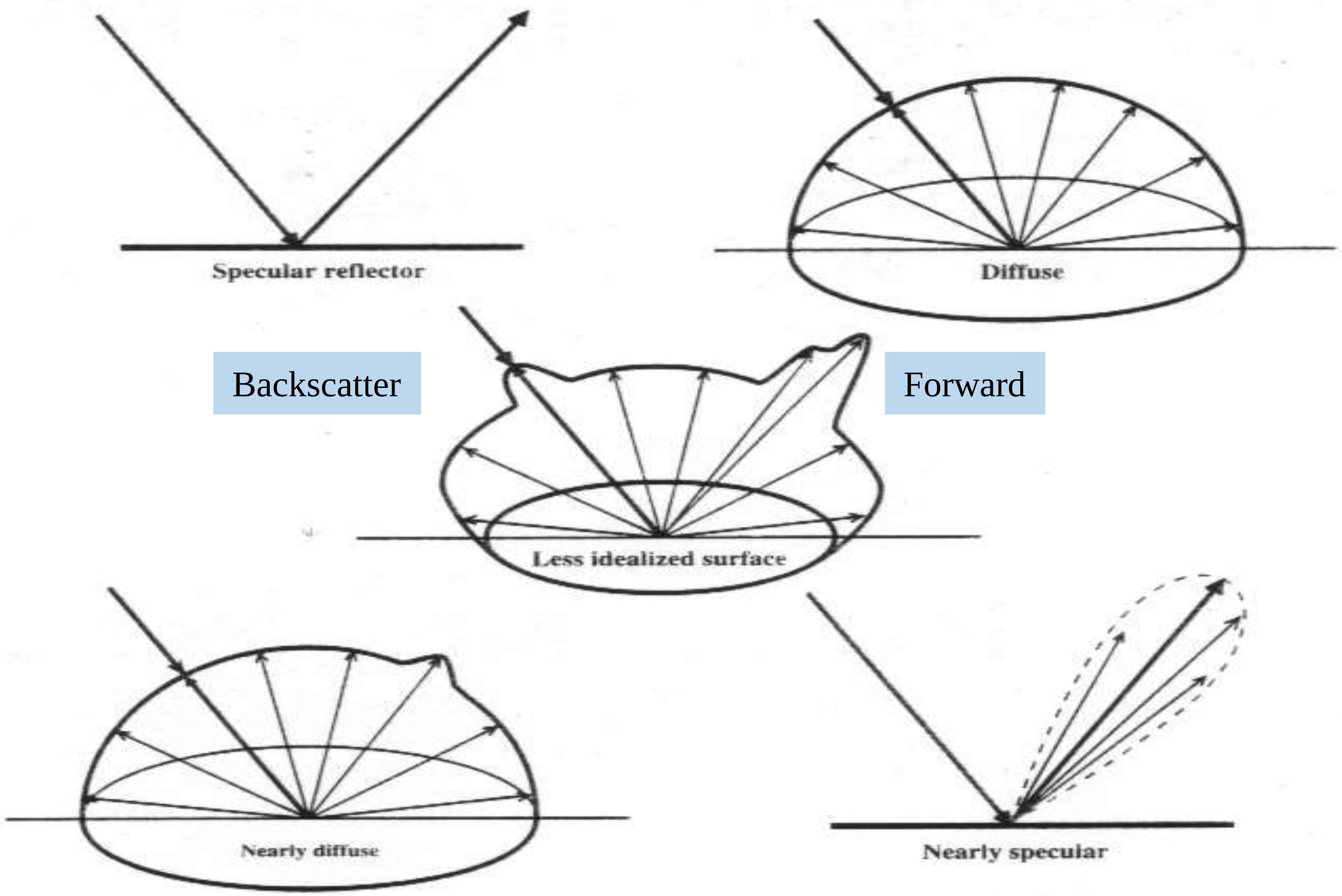
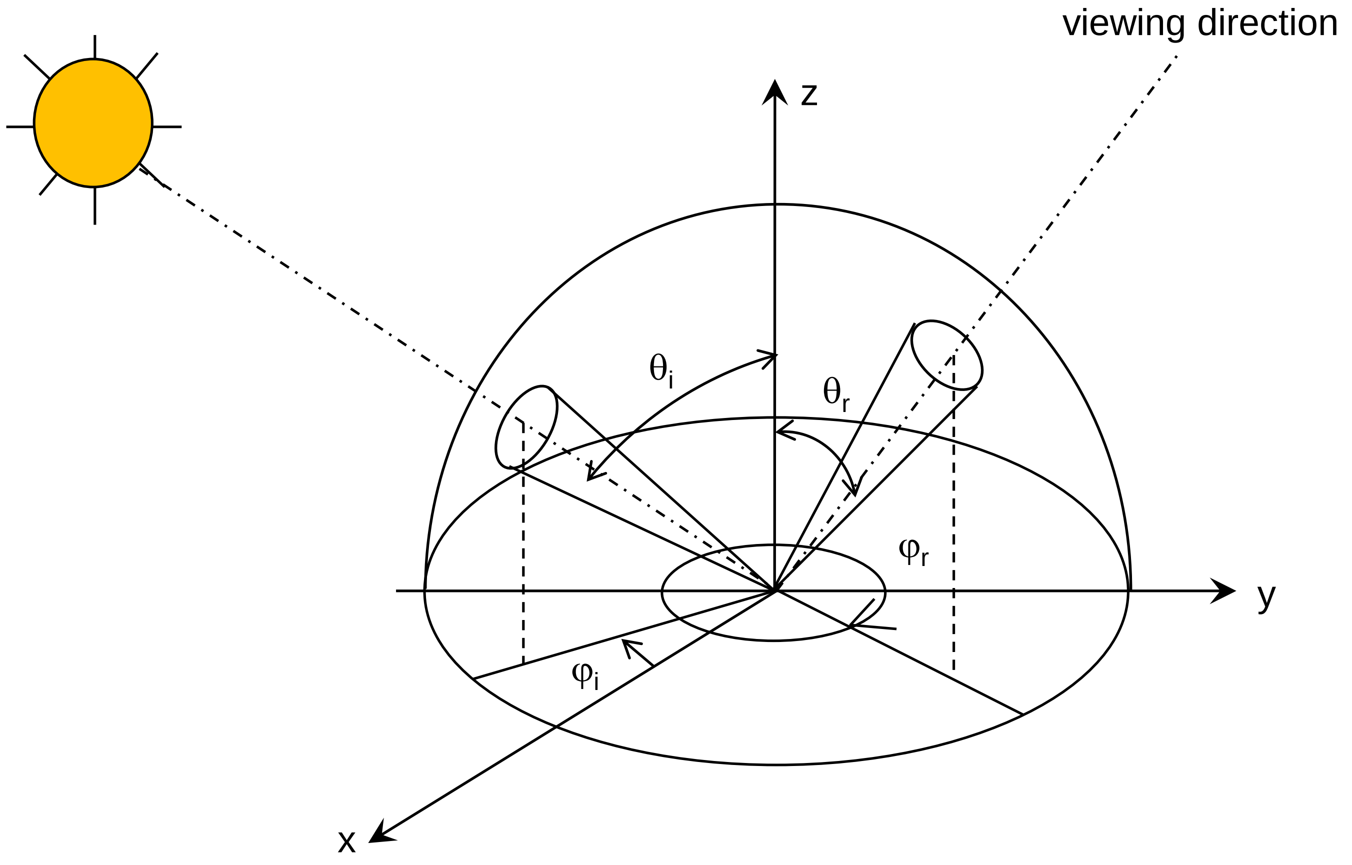


Figure 4.7 Reflectance characteristics of idealized surfaces.

Measurement principles

BRDF

Bi-Directional Reflectance Function



Measurement principles

- BRDF
  $L_\lambda = \rho_\lambda E_\lambda (\cos \Theta) f_r$ $\quad\quad$ f_r = bidirectional distribution function
  for Lambertian surfaces.: $\rho_\lambda = (L \lambda \pi) / (E \lambda \cos \Theta)$
- Shade due to surface roughness
- HotSpot-effect:
  If view direction = illumination direction => no shade visible
  => brighter & specular => no Lambertian

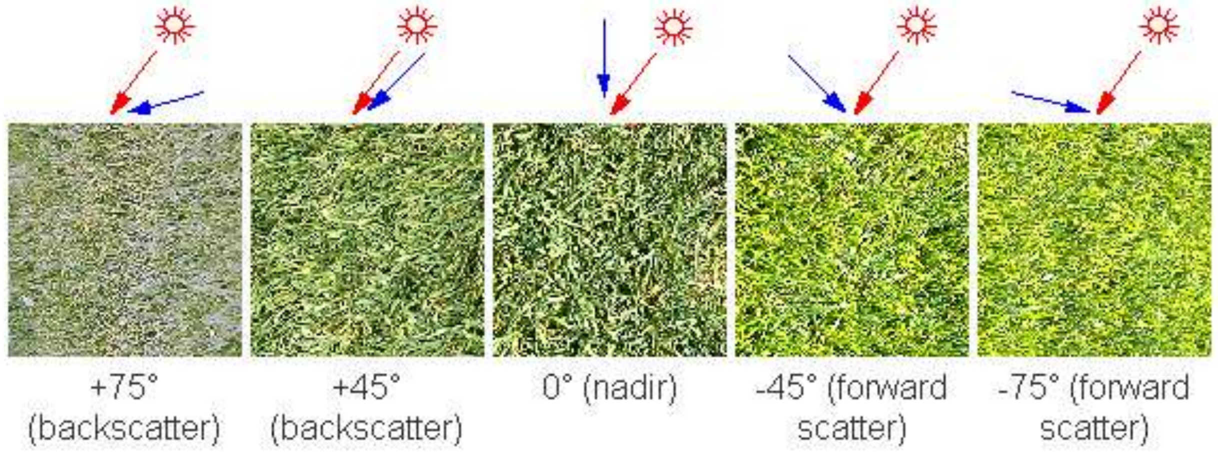
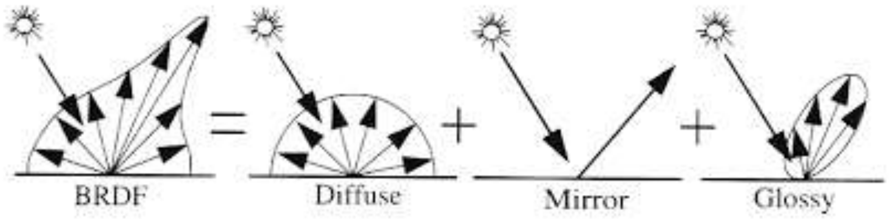


Fig. 2: Bidirectional reflectance effect on a grass lawn, observed under different viewing angles from a FIGOS mounted camera in the solar principal plane. Solar zenith angle is 35°, indicated with red arrows. The view directions are given in blue. The camera is operated in the manual modus keeping aperture, exposure time and focal length constant (k=16, t=1/15, f=135mm).

http://www.geo.unizh.ch/rsl/

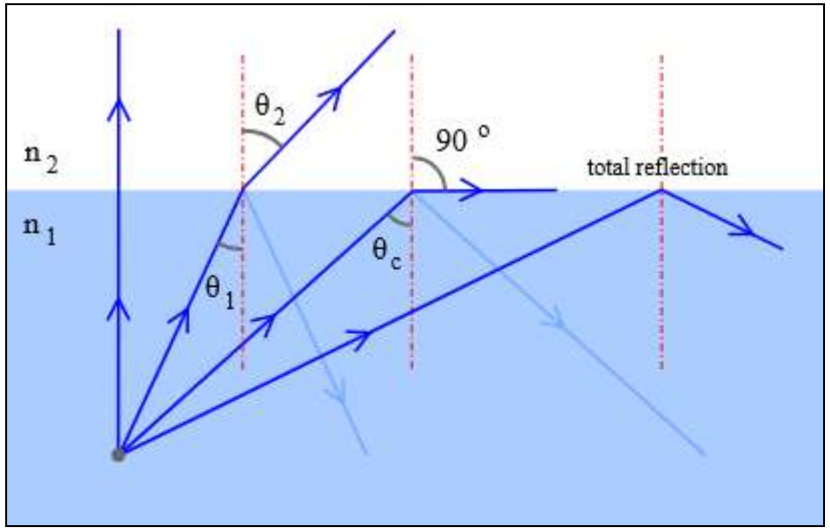


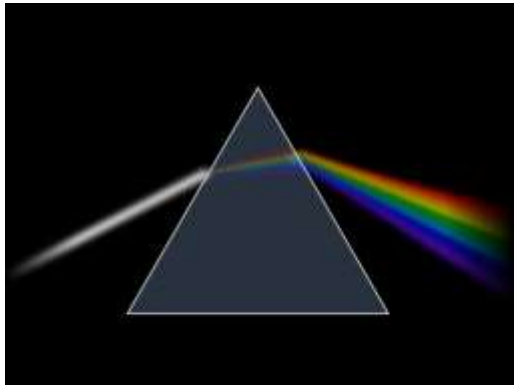
mpi-inf.mpg.de

Physical basics

Other relevant topics:

- Refraction: bending of light at transit from 2 materials with different optical thickness
- Special case: total reflection
  (from thicker to thinner, e.g. water -> air)
- Prism: bending index changes with wavelength
  (higher for smaller wavelength)
    - Spectrometer either use prism (e.g., EnMAP) or diffraction grating (e.g., DESIS)

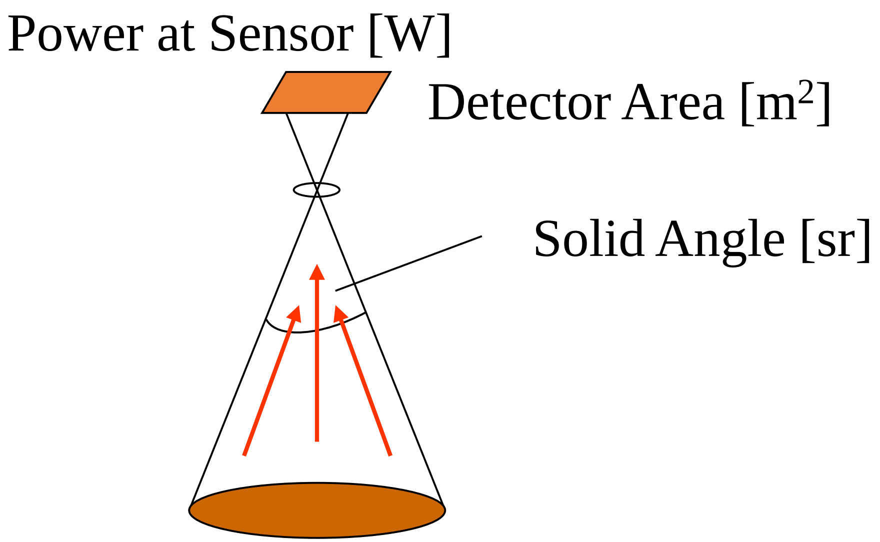




5th: Sensor

Sensor Model

- Input: At-sensor radiance („Amount of light“)
  - Sensor
- Output: DN (Digital Number)



10	23	0	…
56	23	23	…
22	43	5	…
11		17	…
…	…	…	

Sensor Model

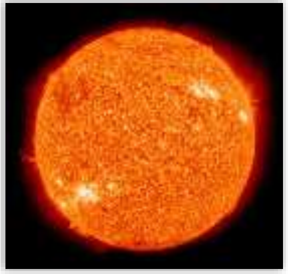
- Input: At-sensor radiance
  - (Scanner-Mechanics)
  - Optics inclusive Filter & Dispersion
  - Detectors
  - Electronics
  - A/D
  - Platform Motion & Attitude
- Output: DN

6th: Digital Image Processing

Image Chain

„Way of a **photon**

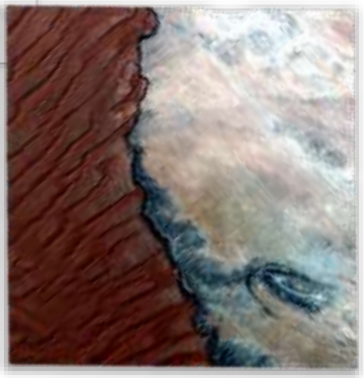
from the **sun**



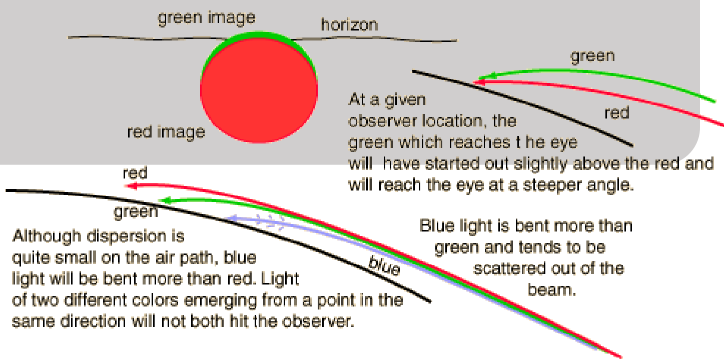
through **atmosphere**

to **earth**

to **EO sensor**

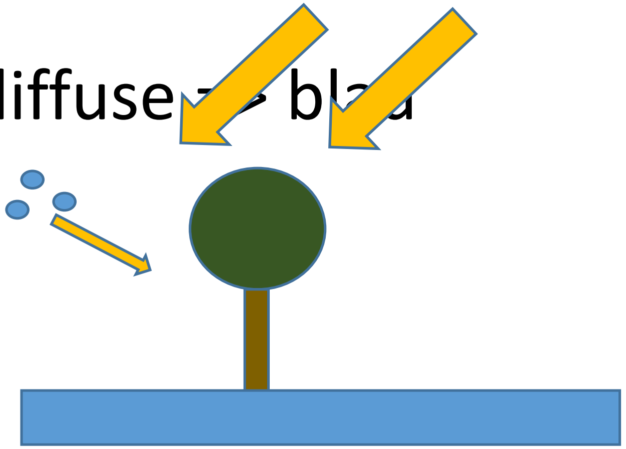


to **image**“



- Abbildung Schatten => diffuse => blau

Aerosols & Molecules
Rayleight



FUTURE

- „Red“ sunset & sunrise: path lengths, rayleigh scattering & refraction

$$\sigma_M = const\ \lambda^{-4}$$

$$\tau(\lambda, x) = \exp\left[-\gamma(\lambda)\ x\right]$$

$\gamma(\lambda)$ Extinction coefficient (km^{-1})

x Path length

Beer’s law