Universität Hamburg
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MIN-Fakultät
Fachbereich Informatik
Arbeitsbereich SAV/BV (KOGS)

IP2: Image Processing in Remote Sensing

4. Electromagnetic Radiation II: Radiation and Matter

Summer Semester 2014

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Agenda

- Measurement of Radiation
- Creation of Radiation
- Radiation Spectra
- Radiation and Surfaces
  - Reflection
  - Absorption
  - Spectral signatures

Measurement of EM Radiation

Three systems are commonly used, each with different units:

- The **radiometric system** measures integrated over all frequencies of the EM spectrum (→ Image Processing)
- The **spectrometric system** measures singe frequency phenomena (→ Remote Sensing, Astronomy)
- The **photometric system** is defined to measure the spectral range of “visible light” (Photography, Computer graphics)

Note: All systems use (unfortunately) scalar descriptors and no vectors, although radiation is a directed phenomena!

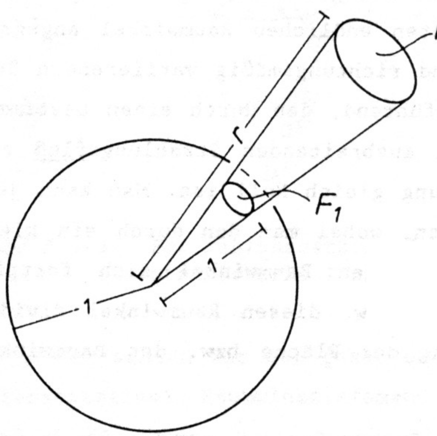
The Radiometric System

The radiometric systems measures the radiation energy with respect to the:

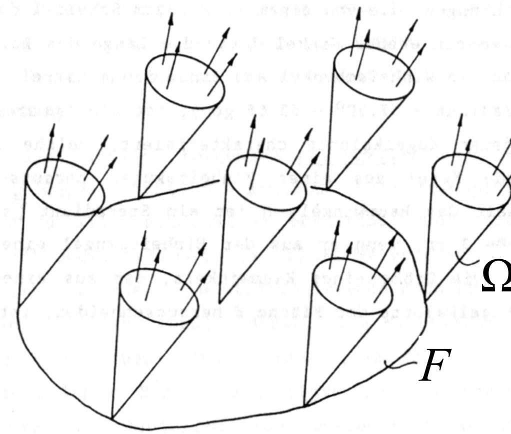
- Dihedral angle
  Raumwinkel
- Size of the emitting or irradiated area
- Duration of radiation

The Radiometric System

Dihedral angle and Radiant Flux



$$\Omega = F_1 = F\, r^{-2}$$

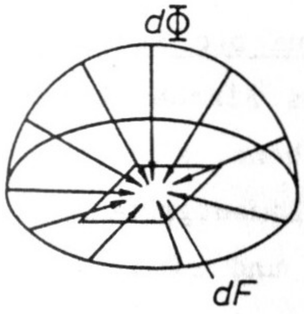


- Ratio Ω of the surface of the unit sphere, which is cut off by the given angle.
- Unit: Steradian [sr]
- Complete angle (all directions): 4π
- Half space: 2π

- Symbol: Φ
- Fundamental radiometric size: Time propagating radiation energy
  - Trough an area F
  - In a direction interval Ω
- Unit: Energy per time [Watt]

The Radiometric System

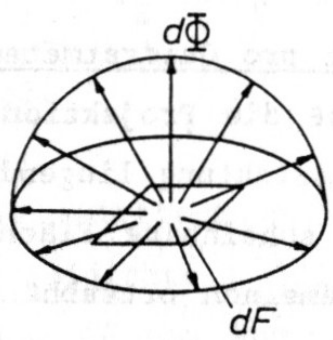
Irradiance and Radiant Exitance



$$E = \frac{d\Phi}{dF}$$

Irradiance E

- Measures the variation of the complete radiant flow per area
- Dihedral angle is the complete half space of F
- Unit: Watt per square meters: W/m^2



$$M = \frac{d\Phi}{dF}$$

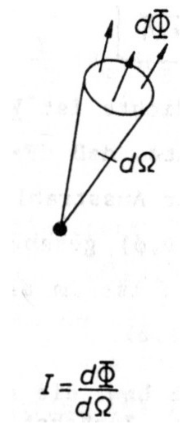
Radiant exitance M:

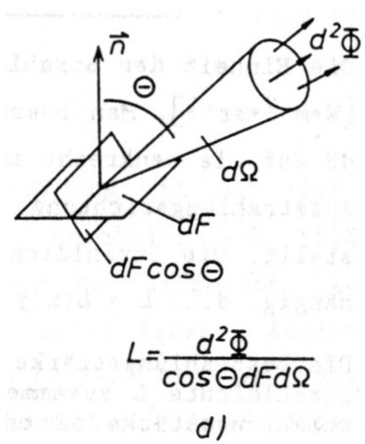
- Like irradiance, but for emitting radiation

Note: M and E are usually varying locally!

The Radiometric System

Radiant Intensity and Radiance





Radiant Intensity I:

- The variation of radiant flux Φ into the dihedral angle Ω
- Unit: Watt per steradian [W/sr]
- Independent of direction
- Important characteristic for point light sources

Radiance L

- Adds the orientation of the emitting area F to the definition of L
- Sources with constant L: Lambertian:
  $$M = L\int \cos(\Theta)\, d\Omega = \pi L$$
- Otherwise (normally): L depends on/varies with Θ

Example: Aerial Image of an acre (1)

Given:

- Light source: Sun:
  $I_s = 1.24\ 10^{25}$ W/sr,
  $r_s = 149.6 \cdot 10^6$ km,
  $\Theta = 30°$
- Altitude: 2000 m
- Camera: focus $f = 21$ cm,
  Aperture 3.75 cm
- Diffuse reflectivity of the acre:
  $\rho = M_g / E_g = 0.1$

To be determined:

- Irradiance E_B in the image center

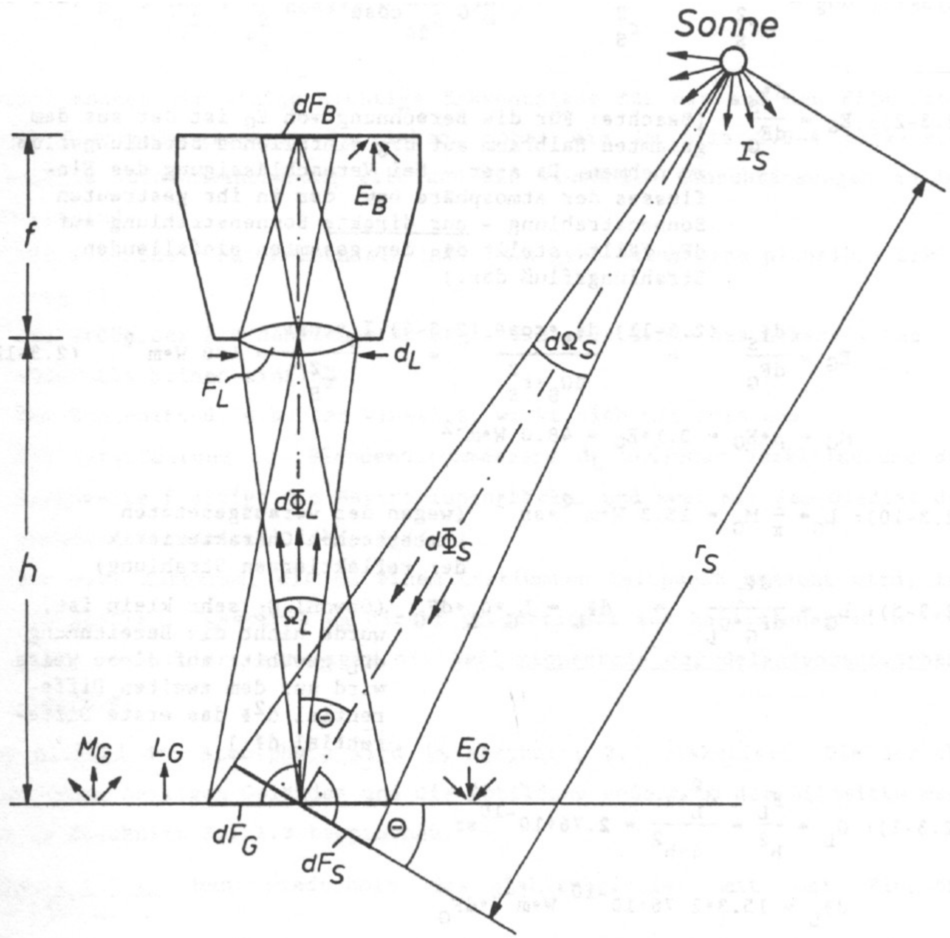


Bild 2.3-6: Aufnahme eines photographischen Bildes

Example: Aerial Image of an acre (2)

- Dihedral Angle:

$$d\Omega_S = \frac{dF_S}{r_s^2} = \frac{dF_G}{r_s^2} \Rightarrow dF_G = \frac{d\Omega_S \, r_s^2}{\cos(\Theta)}$$

- Radial intensity:

$$E_G = \frac{d\Phi_S}{dF_G}$$

Note: Only valid if all incoming radiation is supposed to be emitted directly from the given source (for the complete half space).

- For the example:

$$E_G = \frac{d\Phi_S}{dF_G} = \frac{d\Phi_S \cos(\Theta)}{d\Omega_S \, r_S} = \frac{I_S \cos(\Theta)}{r_S} = 480 W \, m^{-2}$$

$$M_G = E_G \, \rho = 480 \cdot 0.01 = 48.0 \, W \, m^{-2}$$

Example: Aerial Image of an acre (3)

- Radiance:

$$L_G = \frac{d\Phi_L}{dF_G\ \Omega_L} \Rightarrow d\Phi_L = L_G\ \Omega_L\ dF_G$$

- For the example (assuming Lambertian surfaces):

$$L_G = \frac{1}{\pi} M_G = 15.3\,W\ m^{-2} sr^{-1}$$

$$\Omega_L = \frac{F_L}{h^2} = \frac{d_L^2 \pi}{4h^2} = 2.76\,10^{-10}\,sr$$

$$d\Phi_L = 15.3 \cdot 2.76\,10^{-10}\,W\ m^{-2} dF_G$$

$$\frac{dF_B}{dF_G} = \frac{f^2}{h^2} = 1.10\,10^{-8} \Rightarrow dF_B = 1.10\,10^{-8}\,dF_G$$

- For a lossless, sharp objective: $E_B = \frac{d\Phi_L}{dF_B} = \frac{dF_G \cdot 42.2\,10^{-10}}{dF_G \cdot 1.10\,10^{-8}} = 0.384\,W\ m^{-2}$

Example: Aerial Image of an acre (4)

In general:

$$E_B = \underbrace{\frac{d^2 L}{4 f^2}}_{Camera} \cdot \underbrace{\frac{I_S}{r_s^2}\cos(\Theta)}_{Sun} \cdot \underbrace{\rho}_{Acre} = \frac{d^2 L}{4 f^2} \cdot E_G \cdot \rho$$

Observations:

- The (flying) altitude has no contribution, but the distance to the sun has.
- The angle of the sun contributes with $\cos(\Theta)$
- The Irradiance E_B:
  - Increases with the square of the inverse aperture
  - Is directly proportional to the reflection index of the terrain.

Note:

- Influence of the atmosphere was neglected!
- Reflection indices are material characteristics. Thus many applications require a normalization of the measured Irradiances w.r.t. acquisition constraints.

  → This normalization is called **photometric registration**, the images are called **reflectance images**.

The Spectrometric System

- All former radiometric measures are defined on ranges of wavelengths, which have to be defined explicitly
- Spectral radiometric measures characterize wavelength dependent radiation:
  - All former measures will be restricted to a (differentially) small wavelength interval, and divided by it.
  - The Spectral radiometric measured are tagged be an index λ

- Examples:
  - Spectral radiant flow: $\Phi_\lambda = \frac{d\Phi}{d\lambda}$ in [W/m] or [W/nm]
  - Spectral Radiance: $L_\lambda = \frac{dL}{d\lambda} = \frac{d^3\Phi}{\cos(\Theta)\, dF\, d\Omega\, d\lambda}$ in [W/sr/m] or [W/sr/nm]

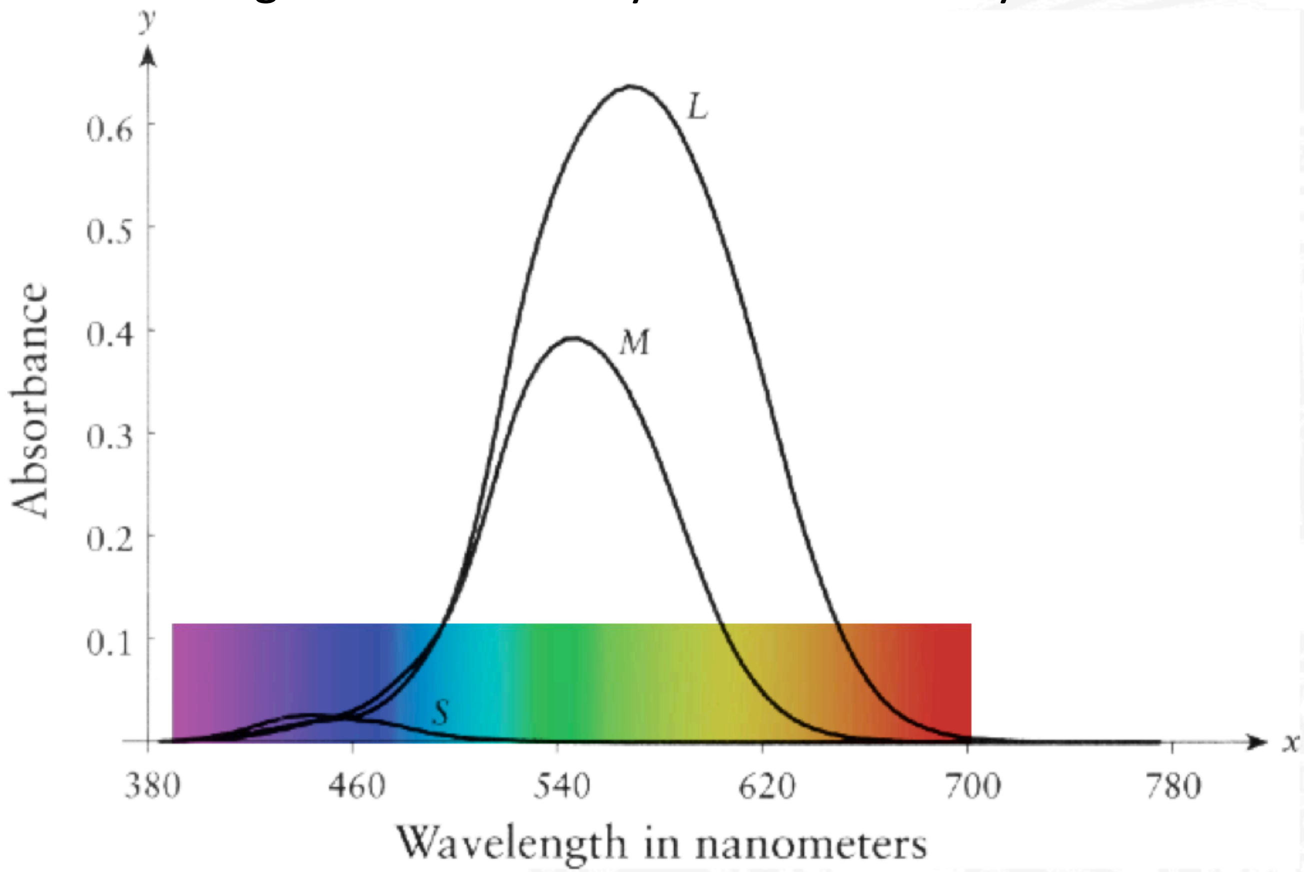
The Photometric System

- This system is defined for the visible light spectrum
- It normalizes the radiation measures w.r.t. the adaption of the (dark adapted) human eye
- Uses different units:
  - Luminous flux [Lumen, l]
    Lichtstrom
  - Quantity of luminance [Lumenhr., lmh]
    Lichtmenge
  - Luminous intensity [Candela, cd]
    Lichtstärke
  - Illuminance [Lux, lx]
    Beleuchtungsstärke
  - Light density [Stilb sb]
    Leuchtdichte
  - Spectral radiant exitance [Phot, ph]
    Spezifische Ausstrahlung

Sensitivity of the Eye's Cones

Zapfen

The radiometric measures are converted into a system by weighting the frequencies according to the sensitivity of the human eye:



Comparison of Photometric and Radiometric System

Radiometric Measures	Radiometric Units	Photometric Measures	Photometric Units
Radiant flux Φ	Watt (W)	Luminous flux Φ	Lumen (lm)
Irradiance E	($W\ m^{-2}$)	Illuminance E_P	Lux (lx) = ($lm\ m^{-2}$)
Radiant exitance M	($W\ m^{-2}$)	Spectral radiant exitance M_P	Phot (ph) = Lux (lx)
Radiant intensity I	($W\ sr^{-1}$)	Luminous intensity I_P	Candela (cd) = ($lm\ sr^{-1}$)
Radiance L	($W\ m^{-2}\ sr^{-1}$)	Luminance L_P	($cd\ m^{-2}$)

Sources and Creation of Radiation

- Thermic Radiation:
  - Black Bodies
    - Wien's displacement law
      Wiensches Verschiebungsgesetz
    - Stefan Boltzmann's Radiation law
  - Gray Bodies
    - Emissivity
- Energy levels:
  - Nuclear,
  - Atomic and
  - Molecular Effects

Black Bodies

Black Radiation: Idealized case of a body's radiation, where the energy distribution is given by Planck's Radiation Law.

Black Body: A body, which emits black radiation.

Planck's Radiation Law: The thermic emission of a black body is solely depending on the temperature and wavelength. The spectral radiance is given as:

$$L_{sk}(\lambda, T) = \frac{c_1}{\lambda^5}\left(-1 + e^{\frac{c_2}{\lambda T}}\right)^{-1}$$

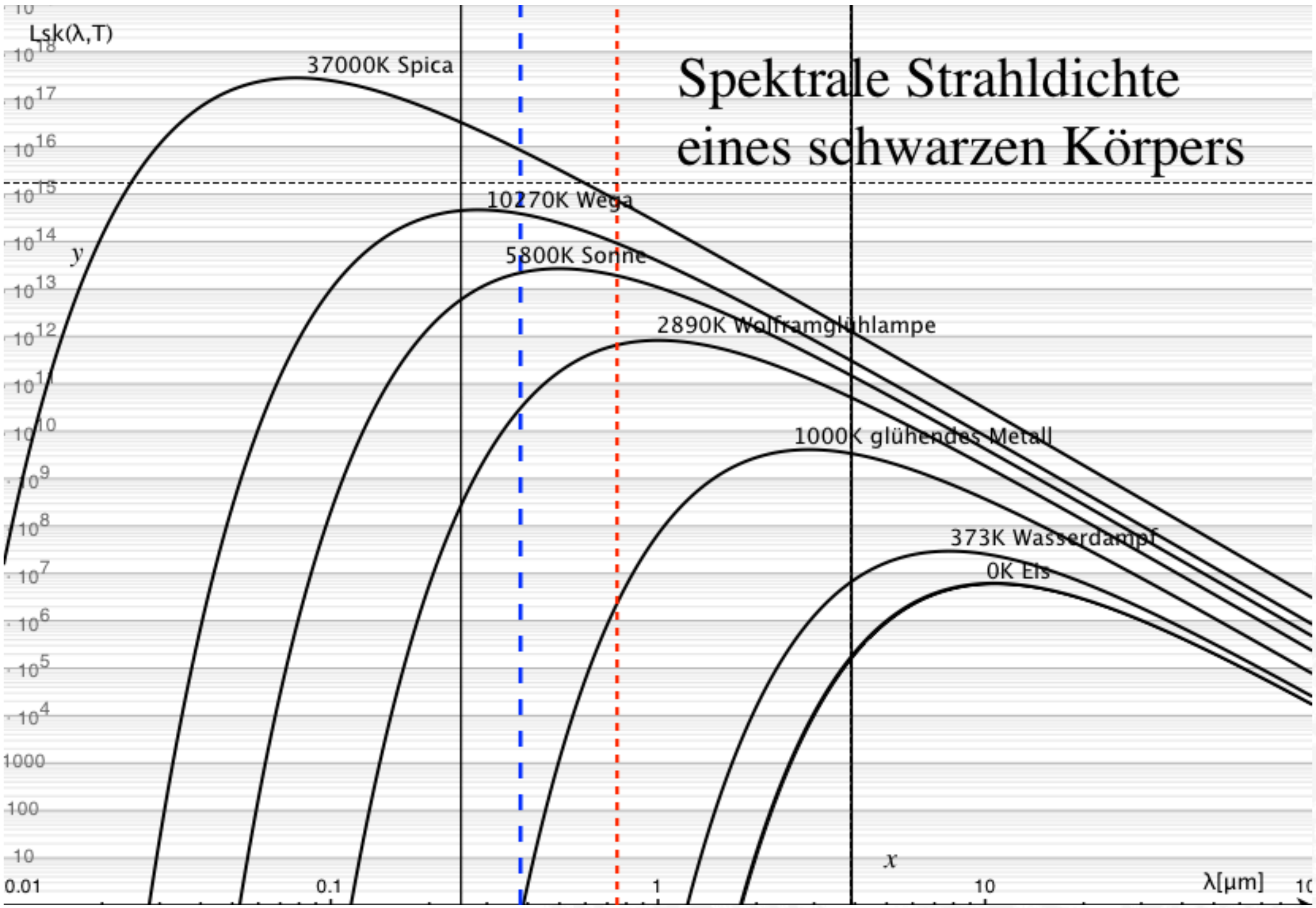
with: $c_1 = 2 \cdot h \cdot c^2 = 1.19 \;\; 10^{-16}$ W m^2 s/r

$c_2 = c \cdot h / k = 1.439 \; 10^{-2}$ m K

$h = 6.6262 \; 10^{-34}$W s^2 (Planck's quantum of action)

$k = 1.3807 \; 10^{-23}$ W s/K (Boltzmann's constant)

Black Bodies: Spectral Radiance



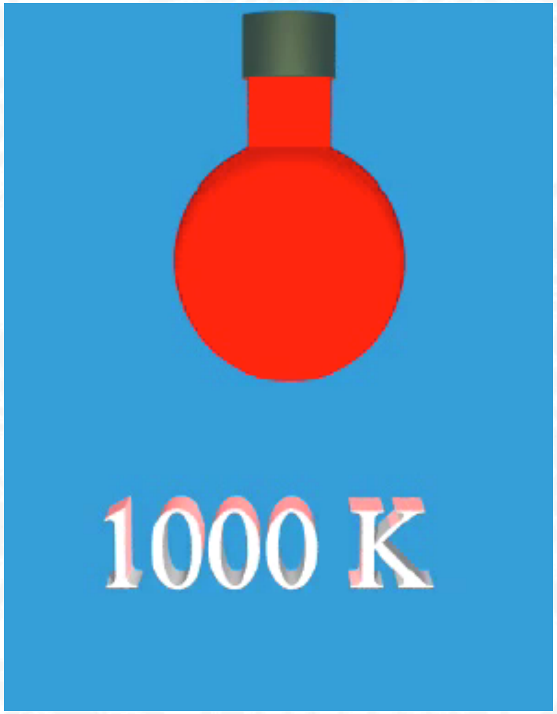
Stefan Blotzmann's Radiation Law

- The complete emission of a black body integrated over all wavelengths is proportional to the 4th power of the body's temperature.
- The Radiance is:

$$L_{sk}(T) = \sigma T^4$$

with:

$$\sigma = 2\pi^5 k^4/(15c^2h^3)$$
$$= 5.67\ 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$$



Wien's Displacement Law

The higher the temperature of a black body, the more the maximum wavelength λ_{max} is shifted to the shorter wavelengths:

$$\lambda_{max}\, T = \text{const.} = 0.2897 \text{ cm K}$$

- Examples:

Temperature [K]	λ_{max}	Color / Spectral Range	Radial Exitance (W m^{-2})
1000	29000	Infrared	5.8
4000	7200	Red	1500
7000	4120	Violet	14000
10000	2900	UV	58000
1000000	29	X-Ray	$5.8\ 10^{12}$

The Emissivity ε and ε_λ

- Black bodies are idealized models. Real bodies often emit less energy than expected
- Approximation by means of **gray bodies** with relative spectral radiance (w.r.t. the black body of same temperature)
- Spectral emissivity ε_λ is a material constant: $0 \leq \varepsilon_\lambda \leq 1$.
- To measure the temperature by observing the radiance, the spectral emissivity needs to be known.
- If the spectral emission ε_λ is unknown and the black body equations are used approximately, the temperatures may be overestimated at the order of degrees.

Material	Emissivity at 10µm (IR)
Metal	0.01 - 0.60
Compact snow	0.70 - 0.85
Loose snow	0.97 – 1.00
Wood	0.9
Dry sand	0.88 – 0.94
Sand	0.95 – 0.96
Wet soil	0.94 – 0.95

Sun Radiation Properties

The Sun can be modeled as a gray body:

- Emissivity: $\varepsilon = 0.99$
- Radiant flux: $\Phi = 3.9\ 10^{26}$ W
- Irradiance on the earth: $E = 1.37\ 10^{3}$ W m^{-2}
- Radiance of the sun disk as seen from earth: $L = 2\ 10^{7}$W m^{-2} sr^{-1}

Boundary wavelengths
(inside, 99% of the radiant flux is emitted):

- 3.90 µm (IR),
- 0.25 µm (UV)

Energy levels of Matter

- Matter (atoms, molecules, crystals) is meant to stay in **discrete energy levels** (kinetic, rotation, vibration).

> ⚠ **Light effects at this scale cannot be explained by Maxwell's Equations! Light has to be interpreted as a "stream of particles" (stream of photons)**

- At the transition between the energy levels, radiation will be
  - emitted (Emission lines at spectra)

  or

  - absorbed (Absorption lines at spectra).
- Energy e of the radiation depends on the frequency v:

  $$e = hv.$$

  with h Planck's Constant

Energy Level of an Atom

- The atom's electrons have a negative kinetic energy.
- The more distant they are from the (positive) nucleus, the higher is this energy
- Electrons can solely stay on finite discrete orbits around the nucleus.
- Level Transitions:
  - An electron, which descends to a lower level releases energy by means of a photon
  - An electron, which absorbs a photon of proper energy may ascend to a higher energy level.
- Level transfers of electrons are observable in visible and infrared light.

Energy Levels of Molecules

- In gases, molecules perform vibration and rotation movements.
- The movements levels are discrete here, to. But the number of levels is ordered:
  - Atomic orbits (fewest)
  - Vibration levels (more)
  - Rotation levels (most)
- The overall energy Q is the sum of:
  - The energy Q_E of the electrons in the atomic hull,
  - The vibration energy Q_V of the atoms of the molecule and
  - The rotation energy Q_R of the molecule.

Energy Levels of Fluids and Solids

In fluids and solids, the atoms are restricted in their rotation and vibration without interfering with each other.

→ Thus, the number of energy levels increases radically, which yields in continuous spectra!

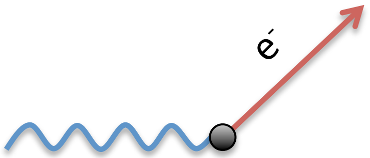
In complex organic molecules, there are free electrons, which cannot be assigned to a special atom. The energy level of theses electrons is about 2 eV.

→ This corresponds to photons in visible light. The absorption bands correspond to saturated colors:

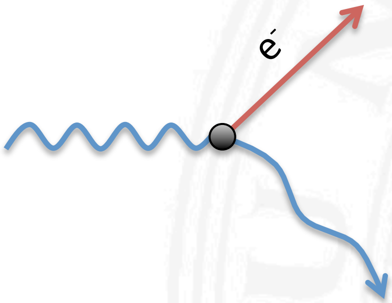
They are also called pigments!

Atomic Processes

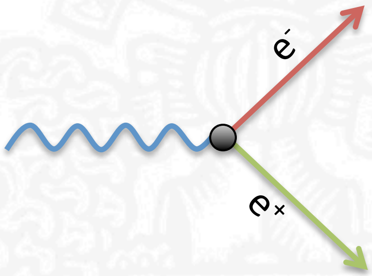
- High energetic radiation (Gamma-, X-Rays) can excavate electrons from their atoms. The freed atoms ionize the environment, which can be monitored by means of:
  - The emitted light or
  - The freed charges
- Three different effects:



Low energy:
Photoelectric effect

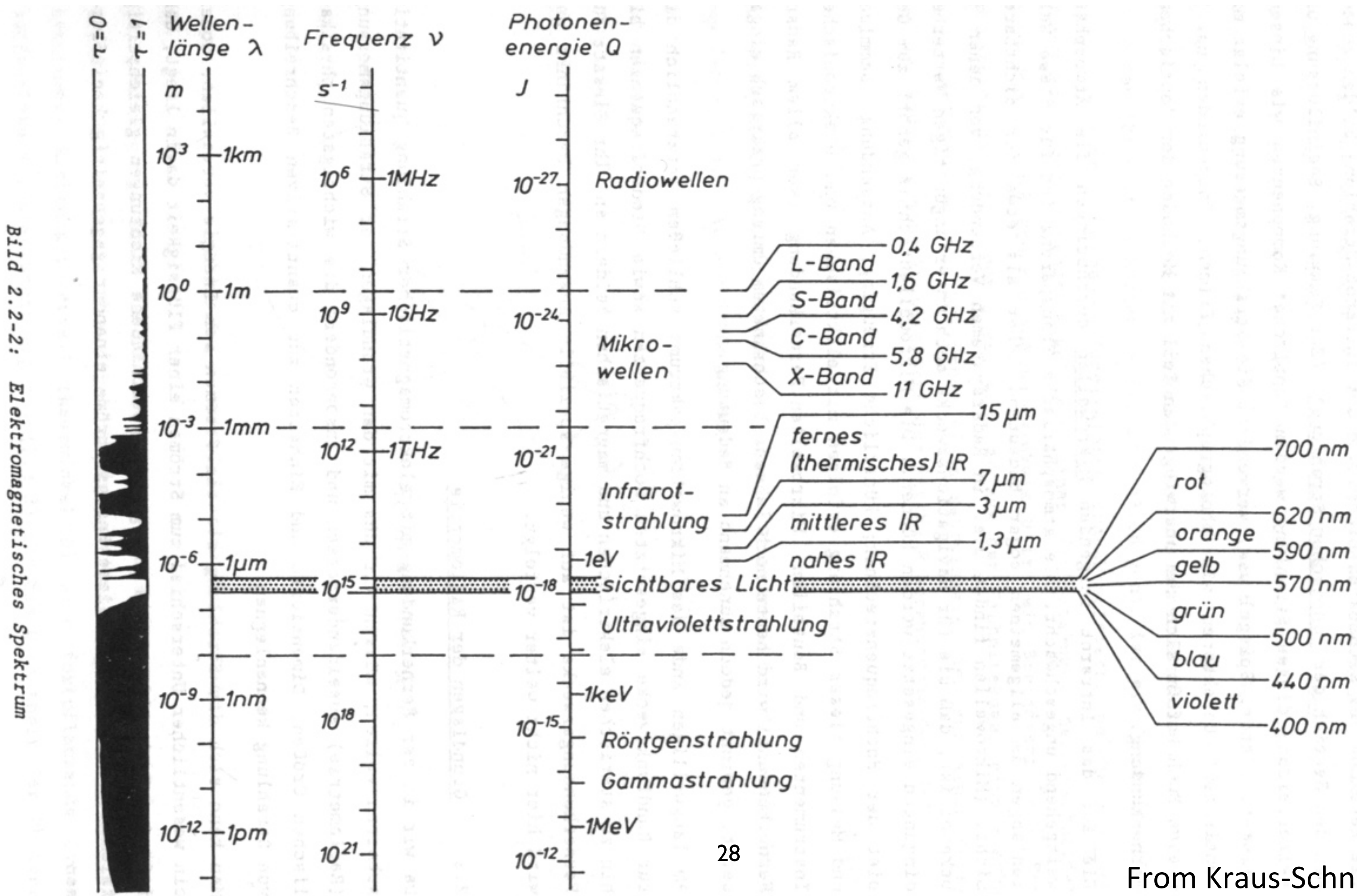


Moderate energy:
Compton effect



High energy:
Pair production

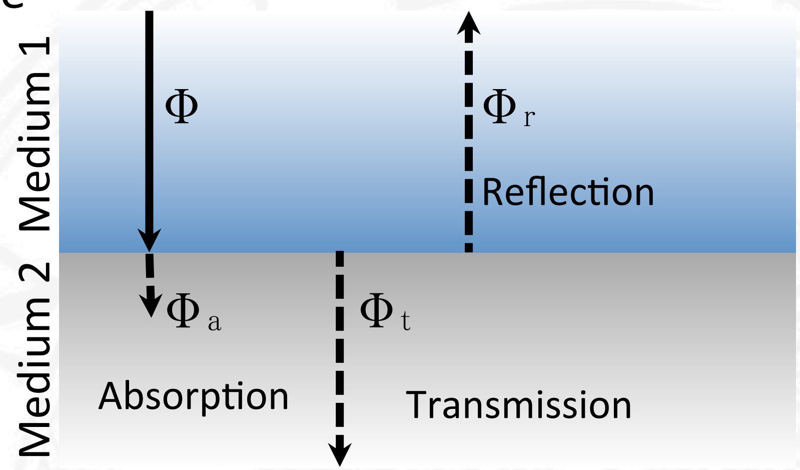
EM Spectrum: Notations, Energies and Atmospheric Windows



From Kraus-Schneider 1998

Energy and Matter Interaction

- At the boundary layer between two homogenous media, the dielectricity constant ε and the permeability μ may change
  Thus the impedance Z also changes.
- EM Radiation at boundary layers can be
  - Reflected or
  - Penetrate the medium and
    - Be refracted and transmitted or
    - Be absorbed.
- Energy is conserved:
  $\Phi = \Phi_r + \Phi_a + \Phi_t$
- Normalized names:
  - Reflection ratio $\rho = \Phi_r/\Phi$ (**Albedo**)
  - Absorption ratio $\alpha = \Phi_a/\Phi$
  - Transmission ratio $\tau = \Phi_t/\Phi$.



Spectral Radiation Coefficients

- Absorption, Reflection and Transmission are (usually)wavelength dependent. Thus, the radiation coefficients become functions of the wavelength:
  - Spectral absorption ratio $\alpha(\lambda)$.
  - Spectral transmission ratio $\tau(\lambda)$.
  - Spectral reflection ratio $\rho(\lambda)$.
- The sum of all three functions has to be equal to the incoming radiant flux:

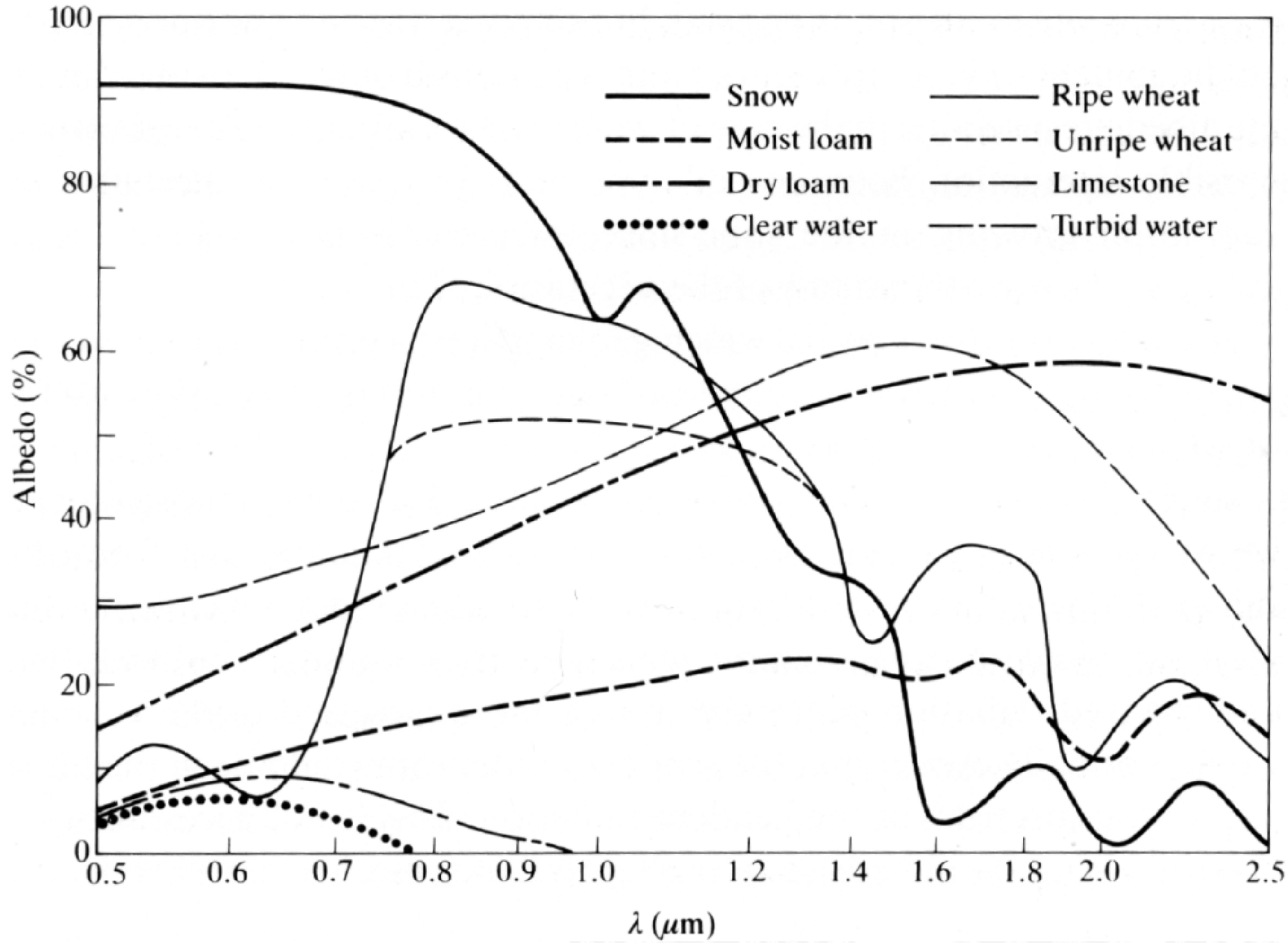
  $$\rho(\lambda) + \alpha(\lambda) + \tau(\lambda) = 1.$$
- If the material is solid (terrain, soil etc.):

  $$\rho(\lambda) + \alpha(\lambda) = 1.$$
- Kirchhoff's Law of thermic balance gives:

  $\alpha = \Phi_a/\Phi = \varepsilon = \Phi_e/\Phi$ and

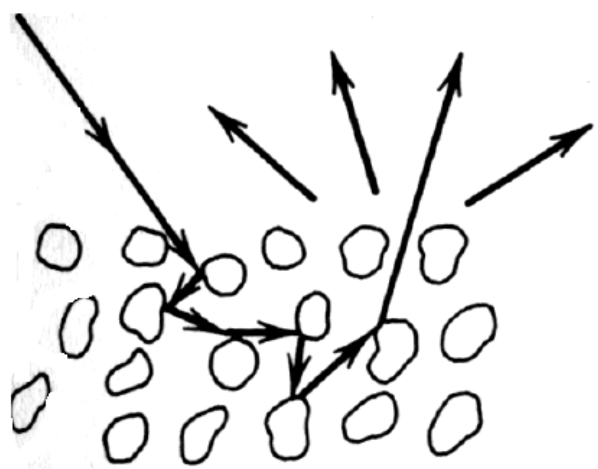
  $\alpha(\lambda) = \varepsilon(\lambda).$

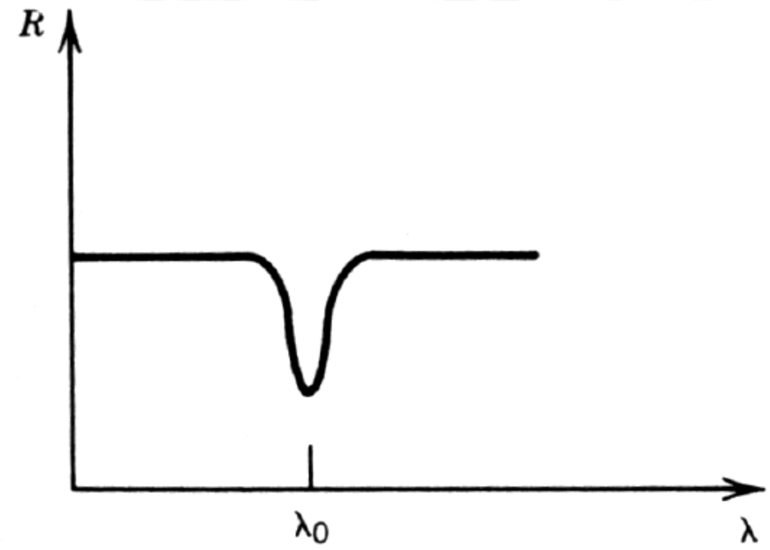
Typical Spectral Albedos



Reflection in Particle Layers

In the case of a particular layer in the volume scattering an resulting absorption leads to a decrease of the scattered energy near an absorption spectral line.





Reflectance Spectra

Reflectance spectra are an important basis for the classification of materials

Of high importance: **Critical Signatures:** Spectral ranges, where the reflectance differs from those of other materials

Example: Vegetation monitoring

- Chloroplasts absorb red (0.65 µm) and blue (0.45 µm) light, but reflect at the green spectral range.
  → The transmitted as well as the reflected light appears "green".
- At near infrared (NIR) the light will be multiply reflected at entrapped air between the cell boundaries:
  → Strong reflection at 0.7 - 1.3 µm.
- At far IR (1.3 - 2.7 µm) the water inside the cells absorbs.

Classification: Spectral Vegetation Indices

- Typical for leaves:
  - high reflectivity at near infrared (NIR)
  - high absorption at visible light (e.g. at red spectral ranges)
- This difference forms the base of different variants of the spectral vegetation index (VI,DVI, NDVI):
  - Difference: $I_{IR} - I_{red}$
  - Ratio: I_{IR} / I_{red}
  - Normalized ratio: $\frac{I_{IR} - I_{red}}{I_{IR} + I_{red}}$
- The use of ratios makes the coefficients independent of the incoming radiant flux.

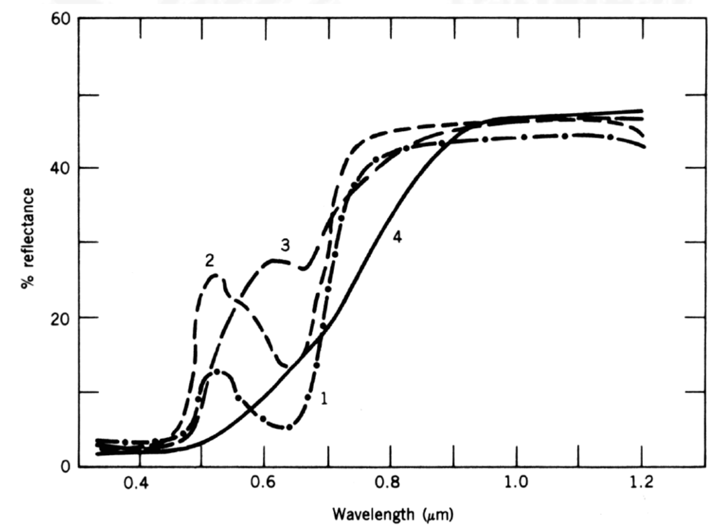
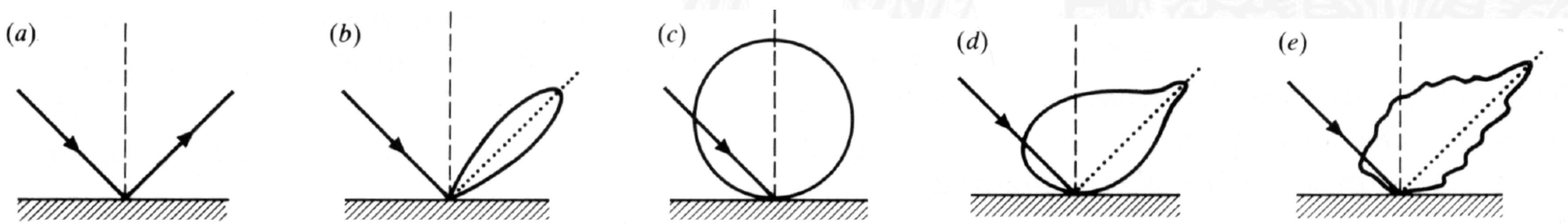


Figure 3-22. Reflectance spectra for a healthy beech leaf (1) and beech leaves in progressive phases of senescence (2–4). (From Knippling, 1969.)

Reflections at Surfaces

- Criteria for the roughness of a surface:
  - The Rayleigh-Criterion
  - Smoothness of natural surfaces
- Reflection and scattering at rough surfaces
  - Bidirectional reflection function
  - Spectra of natural surface
- Reflection and scattering at smooth surfaces:



specular *spiegelnd* | quasi-specular *quasi-spiegelnd* | lambertian *Lambertsch* | quasi-lambertian *quasi-Lambertsch* | complex *komplex*

The Rayleigh Criterion

- The difference in the distance to the surface depends on the incidence angle and the terrain height variation Δh. The phase difference is given by:

$$\Delta\Phi = \frac{4\pi\,\Delta h \cos(\Theta_0)}{\lambda}$$

- Δh can be estimated as the standard deviation from the mean terrain height.
- Using the Rayleigh criterion $\Delta\Phi < \pi/2$ we get:

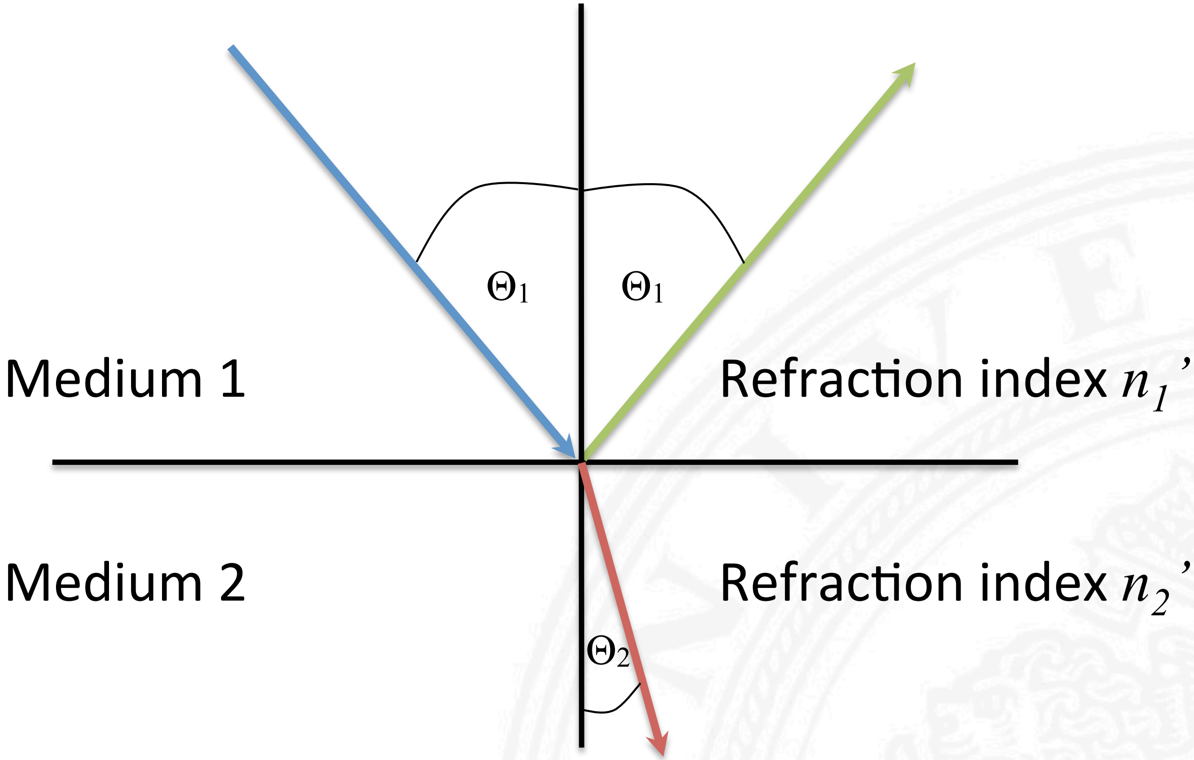
$$\frac{4\pi\,\Delta h \cos(\Theta_0)}{\lambda} < \frac{\pi}{2}$$

$$\Leftrightarrow \frac{\Delta h \cos(\Theta_0)}{\lambda} < \frac{1}{8}$$

Smoothness of Natural Surfaces

- At visible light:
  - Only few (and calm) water surfaces reflect mirror-like.
  - Terrain reflects diffuse.
- But: for Microwaves, even sand and gravel paths are "smooth" and thus reflect like a mirror!

Snell's Law



Snell's law for reflection on smooth surfaces ($\lambda \gg$ surface roughness):

$$n_1' \sin(\Theta_1) = n_2' \sin(\Theta_2)$$

Snell's law defines the direction of the refracted (and mirrored) rays.
The direction depends just on the real part of the refraction index n.

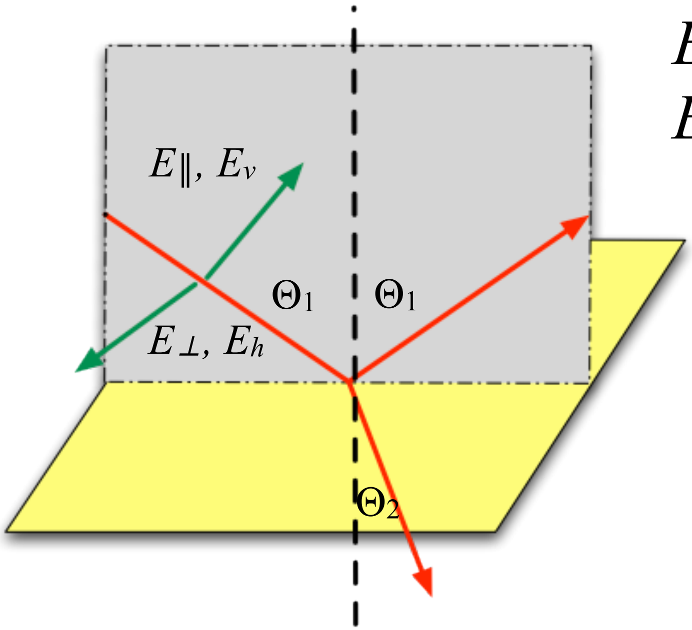
Transmission and Reflection Coefficients

The relative strength of the reflected and refracted radiation also depends on the polarization of the incoming radiation

- Let $E_{||}$ (or E_v) be vertical polarized radiation and
- Let $E_{\perp}$ (or E_h) be horizontally polarized radiation.
- Fresnel's (amplitude) coefficients r und t of the reflected and transmitted radiation are then defined as functions of the impedance of both media

Example on the next slide!

Fresnel Coefficients (1)



$E_\parallel, E_v$ vertically polarized radiation
$E_\perp, E_h$ horizontally polarized radiation

$$r_\perp = \frac{Z_2\cos(\Theta_1) - Z_1\cos(\Theta_2)}{Z_2\cos(\Theta_1) + Z_1\cos(\Theta_2)}$$

$$t_\perp = \frac{2Z_2\cos(\Theta_1)}{Z_2\cos(\Theta_1) + Z_1\cos(\Theta_2)}$$

$$r_\parallel = \frac{Z_2\cos(\Theta_2) - Z_1\cos(\Theta_1)}{Z_2\cos(\Theta_2) + Z_1\cos(\Theta_1)}$$

$$t_\parallel = \frac{2Z_2\cos(\Theta_1)}{Z_2\cos(\Theta_2) + Z_1\cos(\Theta_1)}$$

Note:
If $\Theta_1=0$ the difference between $r_\perp$ and $r_\parallel$ will be vanishing.

Fresnel Coefficients (2)

- The Fresnel coefficients of reflected vertical polarized radiations are smaller compared to horizontal polarized radiation.
- Starting at a certain angle (dependent on the refraction index) no vertical polarized radiation can be reflected anymore. This angle is called **Brewster angle Θ_B**:

$$\frac{n_2}{n_1} = \tan(\Theta_B)$$

- For randomly polarized radiation, the reflected radiation is more polarized than the incoming radiation
- Ratio of the Fresnel coefficients depends on the refractive indices and characterized the material.

  → Thus, for microwave Remote Sensing, different polarization modes are combined for the measurement.

The Absorption Index $\varkappa$

- Let N_r and N_i be the real and imaginary part of the refraction index n:

  $$n = N_r + i\,N_i$$

- The (negative inverse) ratio of both parts is called absorption index $\varkappa$:

  $$\varkappa = -\,N_i\,/\,N_r$$

- Metals have a high absorption index!
- Example for $\lambda = 589\ nm$:

Metal	$\varkappa$	n	r
Silver	3.67	0.180	95.3%
Gold	2.82	0.370	85.1%
Sodium	2.61	0.005	99.7%

Source: DTV-Lexikon der Physik

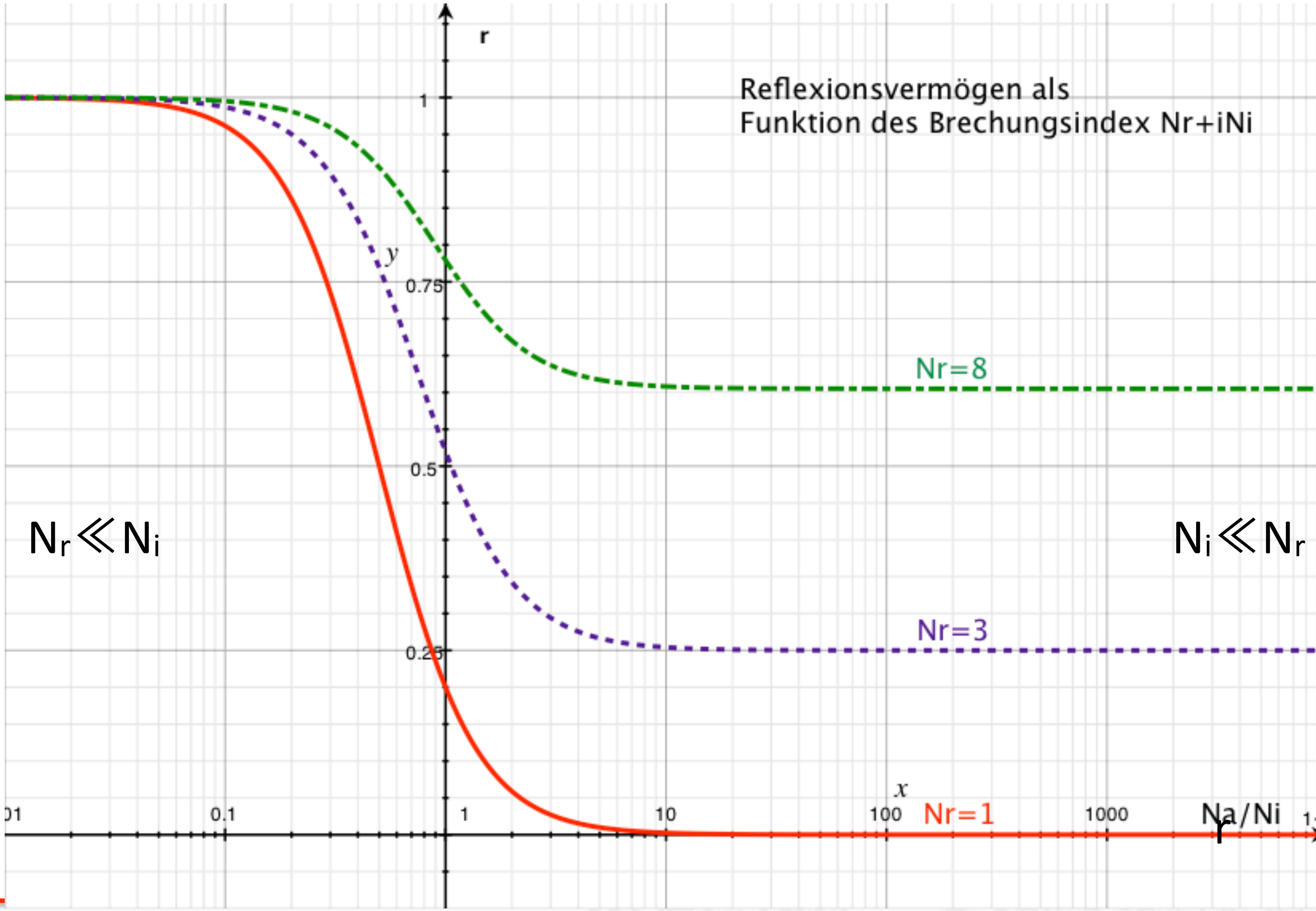
Reflectivity

Reflexionsvermögen

- The larger the real part N_r of the refraction index n the larger the reflectivity:
  - If $N_i \ll N_r$: $|r|^2 = (N_r - 1)^2 / (N_r+1)^2$
- If the imaginary part of the refraction index is large (strong absorption):
  - If $N_r \ll N_i$: $|r|^2 = 1$
- Close to strong absorption lines, the reflectivity is $r = 1$. The reflected radiation is dominated by the color of the emitting body

  → Restrahlen Effect.

The Restrahlen Effect



Reflectivity Next to Strong Absorption Lines