Universität Stuttgart

# Remote Sensing
# Chapter 1: Basics

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## Contents

- Electric and magnetic fields
- Oscillations and waves
- Radiation budget
- Interaction of waves with matter

## Important quantities of fields and matter

- Fields
  - electric field
  - magnetic field
  - magnetic field strength
  - charge density
  - current density

$$[\vec{E}] = V/m$$
$$[\vec{H}] = A/m$$
$$[\vec{B}] = Vs/m^2 = Tesla$$
$$\rho = As/m^3$$
$$[\vec{J}] = A/m^2$$

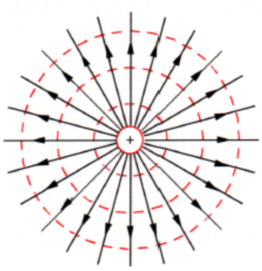
- Matter
  - Permittivity 介电常数 / 电容率
  - Permeability 磁导率
  - $\varepsilon_0, \mu_0$ electric und magnetic constants $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$
  - $\varepsilon_r, \mu_r$ depend on matter, dimensionless $\mu = \mu_0 \cdot \mu_r$

$$[\varepsilon] = As/Vm$$
$$[\mu] = Vs/Am$$

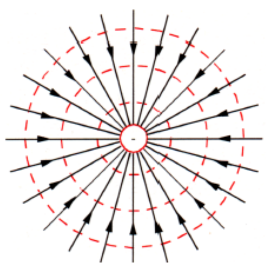


## The electric field

- The electric field *E* (here: static case)
  - surrounding an electric charge
  - exerts a force on other electrically charged objects
  - direction: from positive to negative charge



positive point charge („Monopole“)



negative point charge

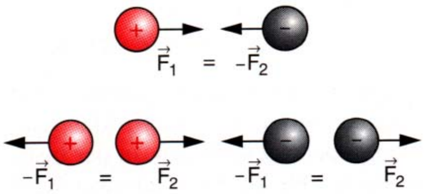
$$[E] = \frac{V}{m}$$

Voltage U [V]: causes current in conductors

$$U_{AB} = \int_A^B \vec{E} \cdot d\vec{s}$$

## Electrostatic force between electric charges

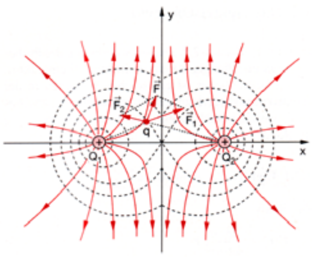
Attraction and repulsion of charges



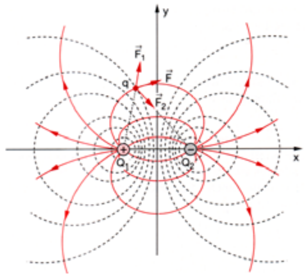

Coulomb's law

$$F = \frac{q_1 q_2}{4\pi\varepsilon r^2}$$

Permittivity



like charges repel each other



opposite charges attract each other (dipole)

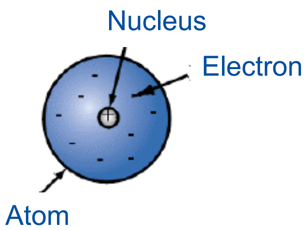
Permittivity:

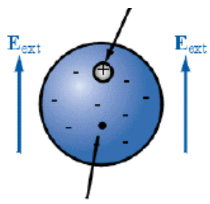
- $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$
- $\varepsilon_0$ is the electric constant
- $\varepsilon_r$ is *complex*: magnitude varies (e.g., f ($\lambda$) )
  → remote sensing
  – $\approx$ 1 for vacuum, air;
  – > 1 else (Water at MW $\approx$ 81)

→ Electrical effects play an important role in RS!

## Electric polarization (dielectric material) 介电材料

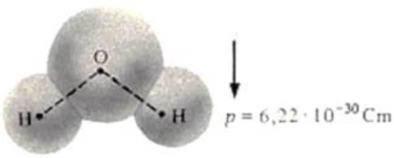
External E-fields cause electric dipole moments in dielectric material




Atom

Molecule




Water

The dipole behavior of liquid water is an important feature of microwave remote sensing:

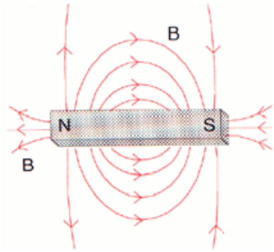
- Soil moisture
- Microwave oven

dipoles vibration

## The magnetic field

Static magnetic fields are caused by:

- permanent magnet
- direct current




permanent magnet

magn. field H: $[H] = \frac{A}{m}$

mag. field strength B: $[B] = \frac{Vs}{m^2} = Tesla$

$$\vec{B} = \mu_r \cdot \mu_0 \cdot \vec{H}$$

Permeability magn. constant

Permeability varies little for the most important types of matter

➔ Magnetic effects can be neglected in RS



## Oscillations and waves

## Oscillations

Periodical transform of energy inside the system into two forms

| Undamped harmonic oscillator | One possible solution |
|---|---|
| $$\frac{\partial^2 x}{\partial t^2} + \omega^2 x = 0$$ | $$x = x_0 \cdot \sin(\omega t)$$ |

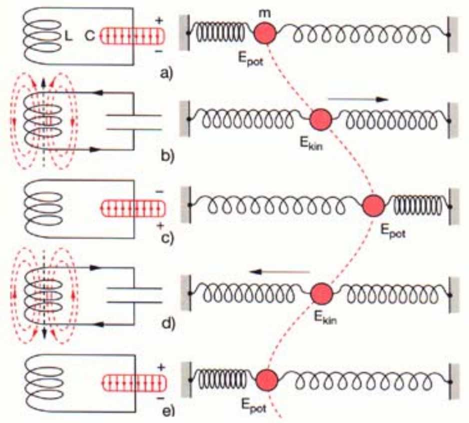
electrical circuit

$$\frac{\partial^2 q}{\partial t^2} + \frac{1}{LC} q = 0$$

q: charge of capacitor

感应器感应系数 L: inductance of inductor

电容 C: capacitance




spring pendulum

$$\frac{\partial^2 x}{\partial t^2} + \frac{k}{m} x = 0$$

k: spring constant

m: mass



## Notation as complex number: Phasor

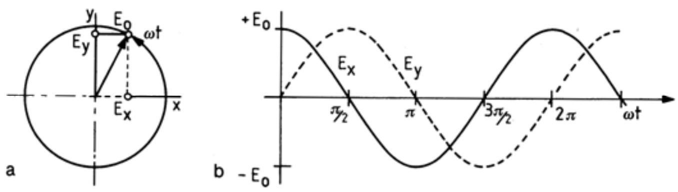
The differential equation of the undamped harmonic oscillator

$$\frac{\partial^2 E}{\partial t^2} + \omega^2 E = 0$$

has the solution: $$E = c_1 \cdot \cos(\omega t) + c_2 \cdot \sin(\omega t)$$

with coefficients $c_{1,2}$ depending on the start values. We can think of this two terms to be projections of a phasor rotating in complex plane onto the Cartesian axes (i.e., real and imaginary part)

Rotating phasor




Advantage of complex notation:

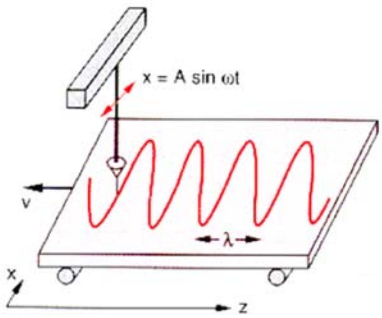
- Differential equations turn to simple algebraic operations
- Euler notation: more compact

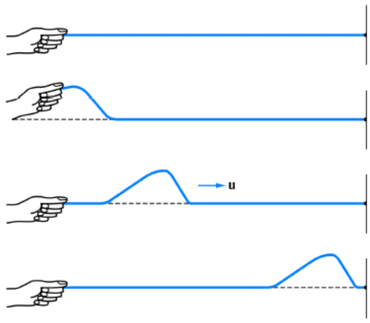
$$E(t) = E_0 \cdot \left(\cos(\omega t) + j\sin(\omega t)\right)$$
$$= \underline{\underline{E_0 \cdot e^{j(\omega t)}}}$$

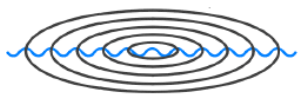
## Waves

Oscillations propagating through space are called waves.

- Waves depend on location and time
- Waves transport energy



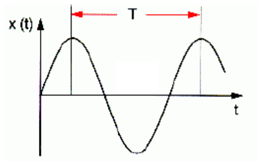
Examples for waves



## Wave equation for EM-wave in vacuum I

The equation of a harmonic oscillator and one solution:

$$\frac{\partial^2 x}{\partial t^2} + \omega^2 x = 0 \qquad x(t) = x_0 \cdot \sin(\omega t)$$




Wave shall propagate → we need a spatial component:

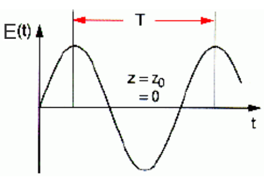
$$\frac{\partial^2 \vec{E}}{\partial x^2} + \frac{\partial^2 \vec{E}}{\partial y^2} + \frac{\partial^2 \vec{E}}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

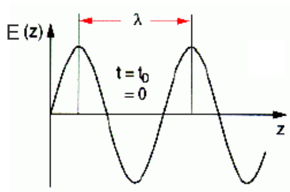
One solution for wave moving in z-direction:

$$\vec{E}(t,z) = E_0 \cdot \sin(\omega t - kz)$$

$$\omega = \frac{2\pi}{T} \qquad k = \frac{2\pi}{\lambda}$$

Angular frequency    Wave number



## Wave equation for EM-wave in vacuum II

The solution is valid

- for periodic
- and plane waves (propagation in one direction only)

➔ Are usually met in remote sensing (far field condition)

$$\vec{E}(t,z) = E_0 \cdot \sin(\omega t - kz)$$

Again the complex notation is advantageous (note: only real part is of physically of interest):

$$\vec{E}(t,z) = E_0 \cdot \left(\cos(\omega t - kz) + j\sin(\omega t - kz)\right)$$

$$= E_0 \cdot e^{j(\omega t - kz)}$$

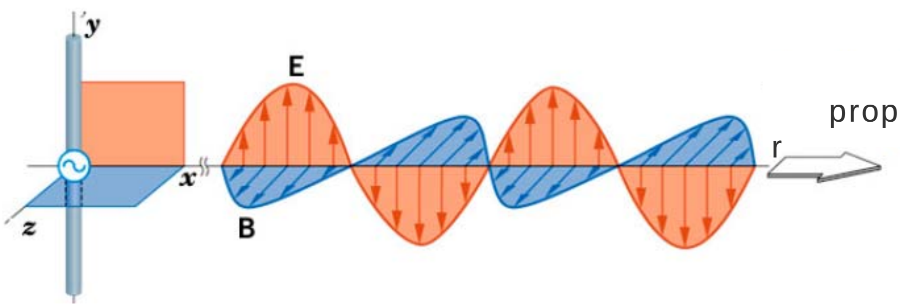
angular frequency $\omega = \frac{2\pi}{T}$

wave number $k = \frac{2\pi}{\lambda}$



## Properties of periodic and plane EM waves

- $\vec{E}$, $\vec{B}$ and propagation direction $\vec{r}$ follow right-hand rule
- Wave moves with velocity of light (material dependent)
- Wave transports energy (*radiation:* e.g., sunlight)
- E-field and B-field are in phase 协调
- Plane of E-field oscillation defines polarization plane
  - For example, given by transmitting dipole orientation
    set TV antenna in parallel to the radio wave



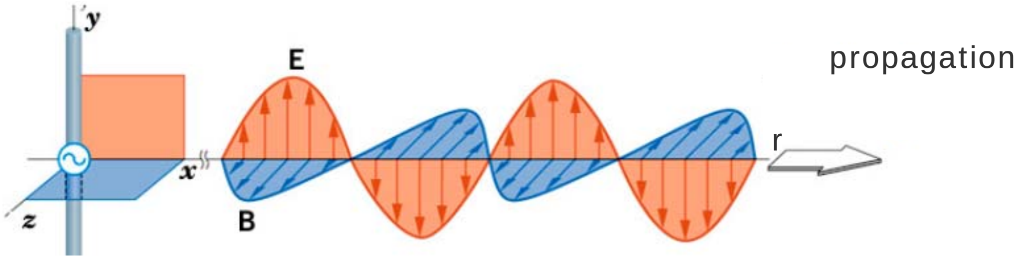
## Relation between wavelength and frequency

- Wavelength $\lambda$
- Frequency $\nu$ or $f$
- Velocity of light $c$

$$\lambda * f = c$$

Velocity of light depends on refraction index
➔ cause of refraction at surfaces

For visible and IR spectra *wavelength* is usually used to describe a system, whereas in MW *frequency* is preferred






# Radiation budget

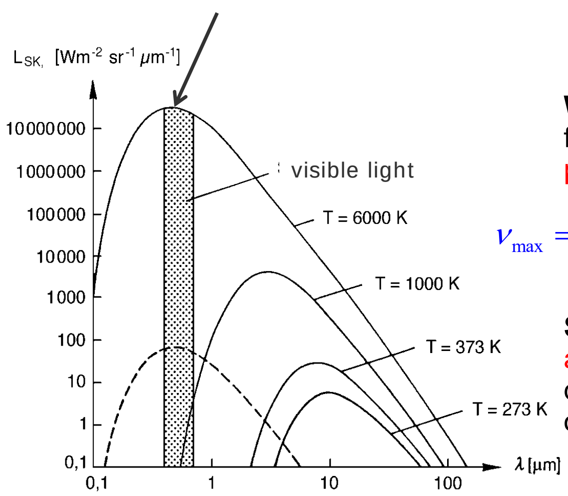
## Radiometry

- Radiometry is the science dealing with the measurement of electromagnetic radiance
- Every kind of matter emits radiance depending on its temperature
  - An idealized object model is the so-called Black Body
- Additionally, any matter reflects, absorbs, or transmits radiation of external sources



## Black-body radiation

Most important: Sun
($\lambda_{max}$ = 500 nm,
looks yellow-white
in visible domain)




**Planck's law** describes the spectral radiance from a black body as a function of temperature *T* and frequency ν:

$$\rho(\nu, T)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT}}d\nu$$

**Wien's displacement law:** The frequency of maximal radiance is proportional to temperature

$$\nu_{\max} = 5{,}88 \cdot 10^{10}\,\mathrm{Hz\,K^{-1}} \cdot T \text{ bzw. } \lambda_{\max} = \frac{2897{,}8\,\mu\mathrm{m}}{T/\mathrm{K}}$$

**Stephan-Boltzmann law:** The total amount of thermal radiation emitted is directly proportional to the fourth power of its absolute temperature

$$R_{tot} = 5.67 \cdot 10^{10}\ T^4$$

## Wien's displacement law: examples

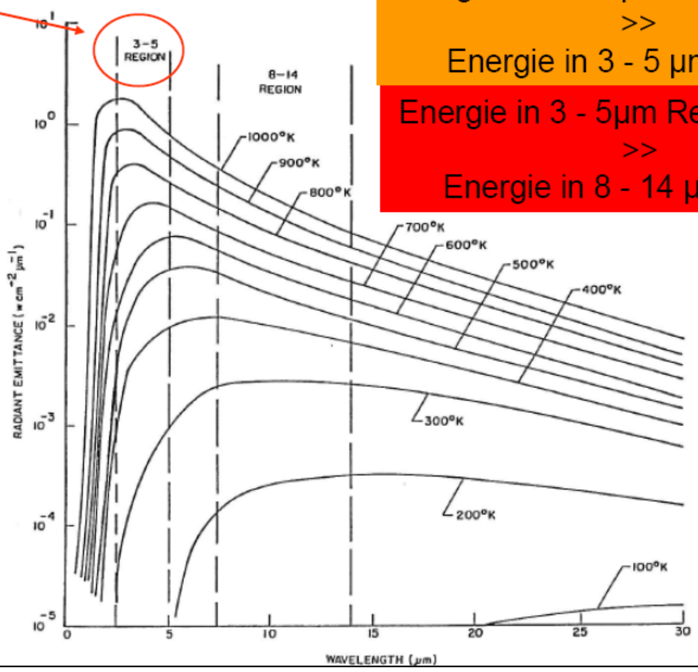
$$\lambda_{max} = \frac{2897,8\,\mu m}{T/K}$$

| Temp °C | Represents | $W/cm^{-2}$ | $\lambda_m$ ($\mu m$) | $W\lambda m$ ($Wcm^{-2}m^{-1}$) |
|---|---|---|---|---|
| -50 | Earth | 0.014 | 12.8 | 0.0007 |
| -25 | Earth | 0.023 | 11.7 | 0.0012 |
| 0 | Earth | 0.032 | 10.5 | 0.0020 |
| +25 | Earth | 0.045 | 9.6 | 0.0031 |
| +50 | Earth | 0.062 | 8.9 | 0.0045 |
| 600 | Flame | 3.2 | 3.3 | 0.66 |
| 5500 | Sun | 5900 | 0.5 | 8000 |

Table 6.1 Radiant Emittance at Various Temperatures

## Wien's displacement law: examples in infrared

Optimal for forest fire

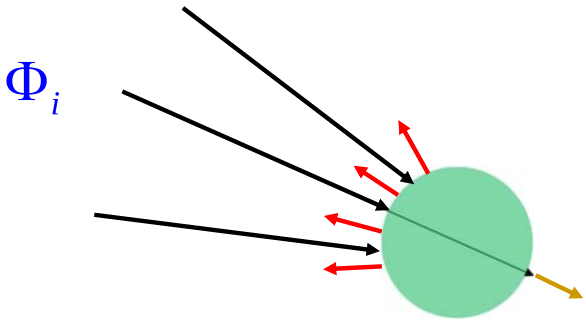



Energie in 8 - 14µm Region (300°K)
>>
Energie in 3 - 5 µm Region

Energie in 3 - 5µm Region (900°K)
>>
Energie in 8 - 14 µm Region

## Radiant flux Φ

- The fundamental unit to measure electromagnetic radiation is radiant flux Φ, measured in Watts.
- Φ is defined as the amount of energy per unit time (i.e., power).
- The incident (incoming) flux arriving an object is either reflected, absorbed, or transmitted.






## Radiation Budget Equation

$$\Phi_{i\lambda} = \Phi_{r\lambda} + \Phi_{a\lambda} + \Phi_{t\lambda}$$

$\Phi_{r\lambda}$ amount of power reflected from the object

$\Phi_{a\lambda}$ amount of power absorbed by the object

$\Phi_{t\lambda}$ amount of power transmitted through the object

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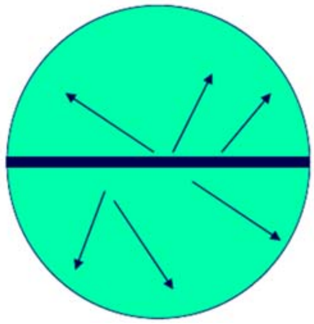
## Hemispherical reflectivity, absorptance, transmittance

• The signal can be reflected or transmitted in any direction of a hemisphere

$$\rho_\lambda = \frac{\Phi_{r\lambda}}{\Phi_{i\lambda}}$$ reflectivity (also reflectance)

$$\alpha_\lambda = \frac{\Phi_{a\lambda}}{\Phi_{i\lambda}}$$ absorptance

$$\tau_\lambda = \frac{\Phi_{t\lambda}}{\Phi_{i\lambda}}$$ transmittance





## Emission

• Emission: Self-radiation $\Phi_e$ of an object compared to black body $\Phi_{bb}$ at the same temperature:

$$\varepsilon_\lambda = \frac{\Phi_{e\lambda}}{\Phi_{bb\lambda}}$$

Kirchhoff's law: $\varepsilon = \alpha$

=> temperature doesn't change

$$\rho_\lambda = \frac{\Phi_{r\lambda}}{\Phi_{i\lambda}}$$ reflectivity (also reflectance)

$$\alpha_\lambda = \frac{\Phi_{a\lambda}}{\Phi_{i\lambda}}$$ absorptance

$$\tau_\lambda = \frac{\Phi_{t\lambda}}{\Phi_{i\lambda}}$$ transmittance

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1$$

# Interaction of waves with matter

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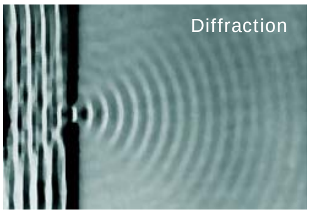
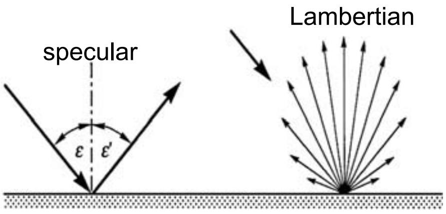
## Overview of important processes

- General remarks
- Diffraction
  - Fan out of wave behind obstacles
- Absorption
  - Energy transfer from wave to matter
- Scattering
  - Change of EM direction at particles in atmosphere (Molecules, water droplets)
- Reflection
  - at surface boundaries




Reflection

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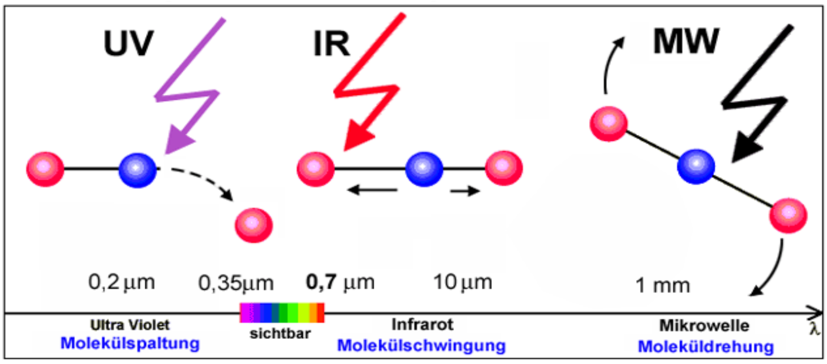
## Interaction of EM wave with molecules

The energy of the EM wave is proportional to frequency ($E = h \cdot f$)
→ long wave MW have far less energy than visible light

Interaction of EM wave with molecules




Decomposition Resonance Rotation

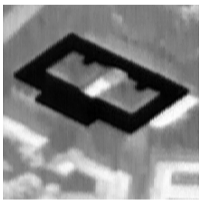


## Interaction of EM wave with molecules

Optical domain/ infrared (VIS, NIR- FIR)

- Certain wavelengths cause resonance of molecule structure, which leads to absorption of energy of this wavelength
  → In particular sensitive to chemical object structure

Thermal radiance (TIR)



- Measure of surface temperature
  → Localize natural and anthropogenic heat sources

Microwave Domain (MW)

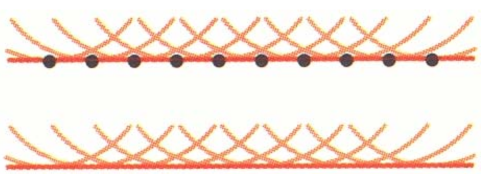
- Absorption und reflection mainly governed by physical object features.
  → Sensitive to conductivity, roughness, morphology
  导电性 形态学

# Diffraction



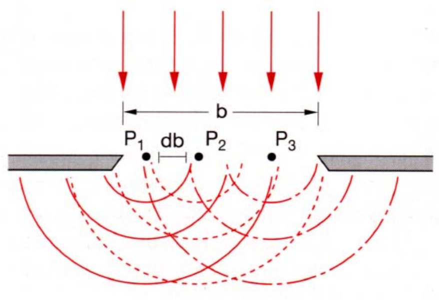
## Diffraction

Fan out of wave behind obstacles into shadow region



Huygens's principle:

- Every point on the wave front is source of new elementary wave
- Wave front propagates by coherent superposition (interference)

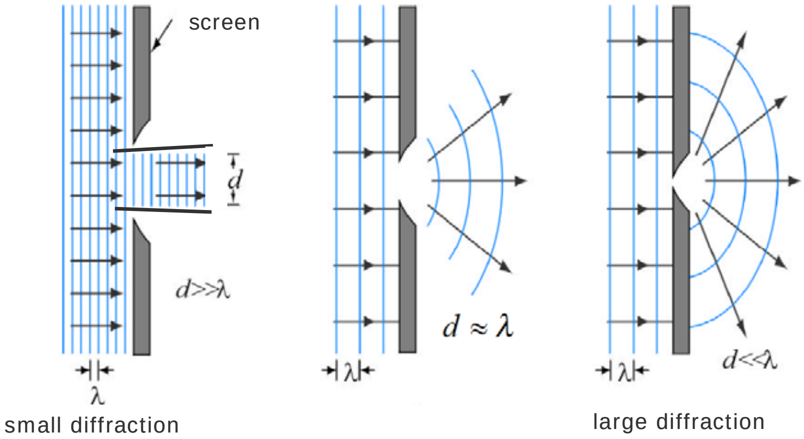



Diffraction at small slit:

- Elementary waves are generated inside slit only

➔ fan out of wave

## Diffraction

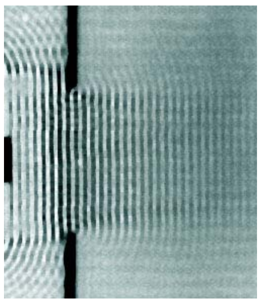



- The narrower the slit, the more the wave will fan out
- Ratio of wavelength $\lambda$ to slit width $d$ important:
  - Long wave signal fills space behind obstacle (MW RS, mobile phone)
  - Small obstacles (e.g. leafs) cause no shadows for $\lambda$ in the order of some centimeters



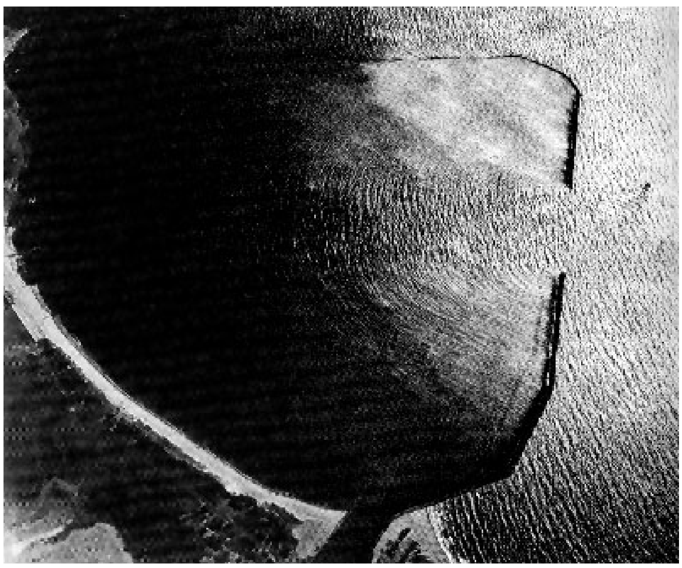
## Water waves

Small slit



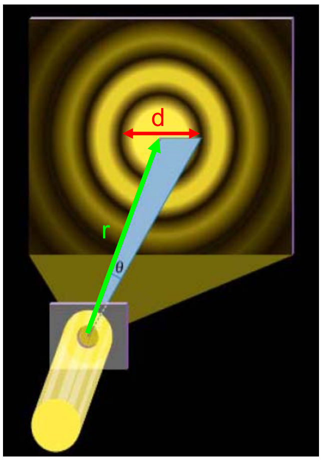
Large slit

Example for port



## Diffraction limits resolution of imaging sensors

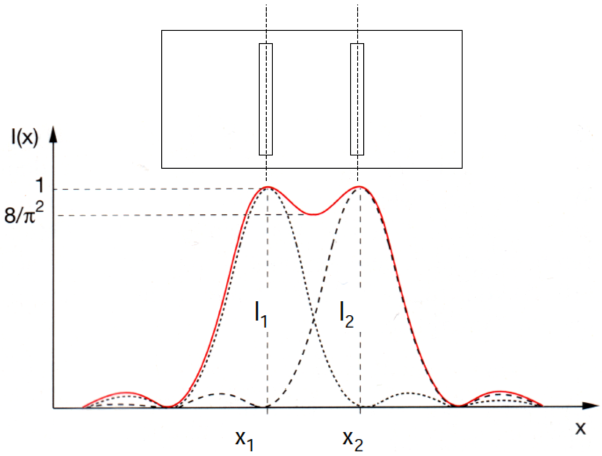
Point-like objects cause images of some extent




Diffraction at circular Aperture:
Distance *d* of 1. order minima

$$d = 2{,}44 \cdot r \cdot \frac{\lambda}{D}$$

← Optical aperture/ Antenna size




Rayleigh criterion for resolution limit:
maximum of first object coincides with minimum (due to interference) of second one

angular resolution → $\Delta\theta = 1.22\ \lambda/D$

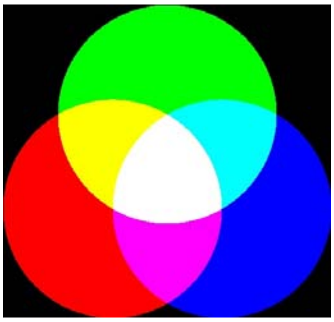


## Absorption (and Emission)

## Additive color

- Sun radiance contains all spectral colors, we observe white light.
- Displays: computer screen, beamer etc.
  - The red, green, and blue (primary colors) pixel can’t be resolved by human eye. Instead we observe the mixture of those three colors.

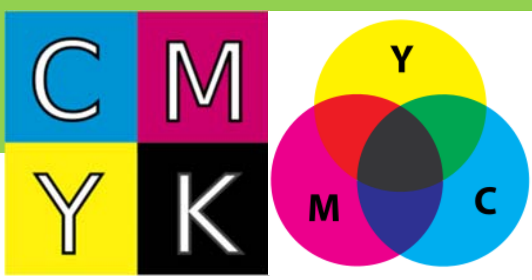
| Color | Byte binary (red, green blue) | Hexadecimal (red, green blue) |
|---|---|---|
| White | 255, 255, 255 | FF, FF, FF |
| Gray | 127, 127, 127 | 99, 99, 99 |
| Black | 0, 0, 0 | 0, 0, 0 |
| Red | 255, 0, 0, | FF, 0, 0 |
| Green | 0, 255, 0 | 0, FF, 0 |
| Blue | 0, 0, 255 | 0, 0, FF |
| Yellow | 255, 255, 0 | FF, FF, 0 |
| Cyan | 0, 255, 255 | 0, FF, FF |
| Magenta | 255, 0, 255 | FF, 0, FF |
| Orange | 255, 153, 0 | FF, 99, 0 |
| Pink | 255, 170, 170 | FF, AA, AA |
| Purple | 170, 0, 170 | AA, 0, AA |
| Teal | 0, 170, 153 | 0, AA, 99 |
| Brown | 153, 102, 51 | 99, 66, 33 |
| Tan | 255, 204, 102 | FF, CC, 66 |





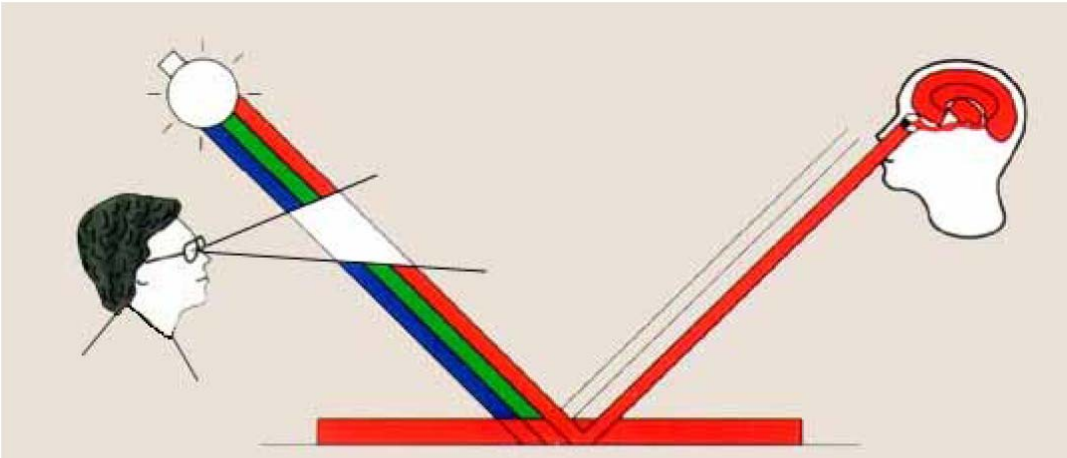
## Subtractive color by absorption

- Print: color pigments are filters due to absorption
  颜料
- No color pigment, no filtering → white paper
- Three primary colors: cyan, magenta and yellow in principle would fully absorb sunlight → black
- However, usually extra black ink cartridge
- Remote Sensing: the colors we observe are due to partial absorption of the almost white sunlight



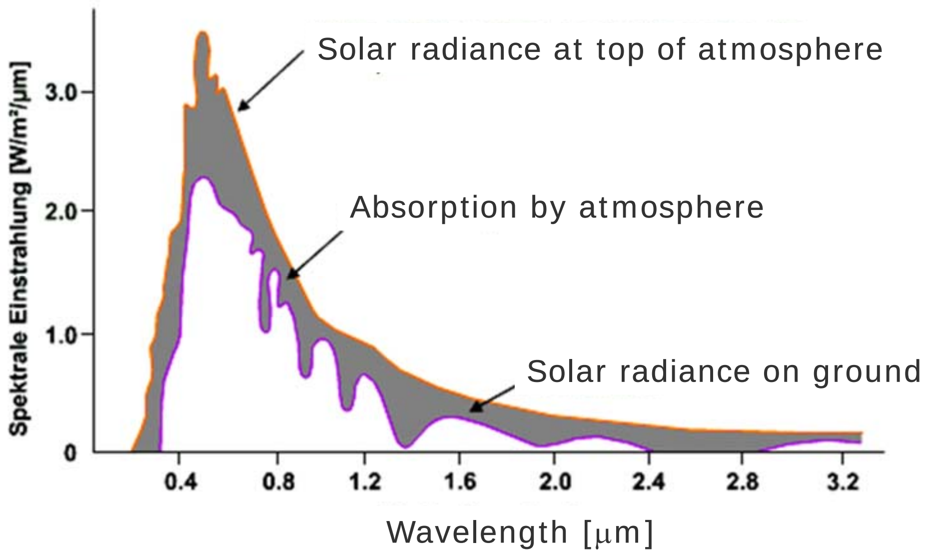
## Human observer: both systems relevant

1. Sun radiance contains *all spectral colors*, we observe *white* light
2. An object looks red if the blue and green become *absorbed*, while the red part is reflected

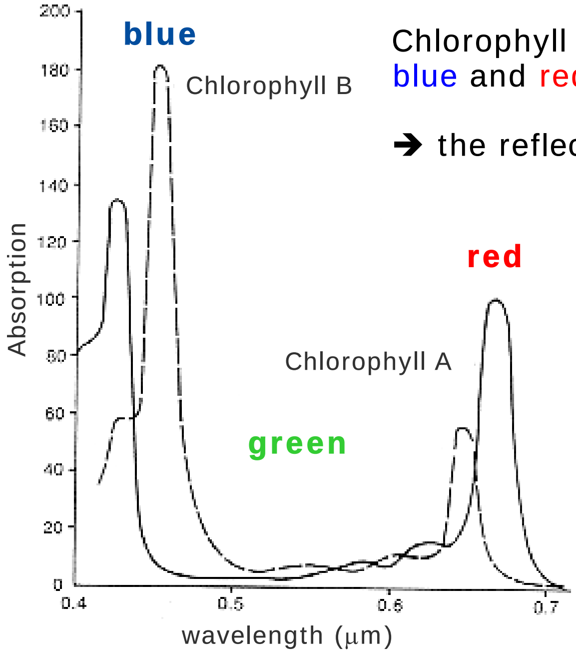




## Absorption inside Atmosphere



## Absorption of green leaves (visible spectrum)

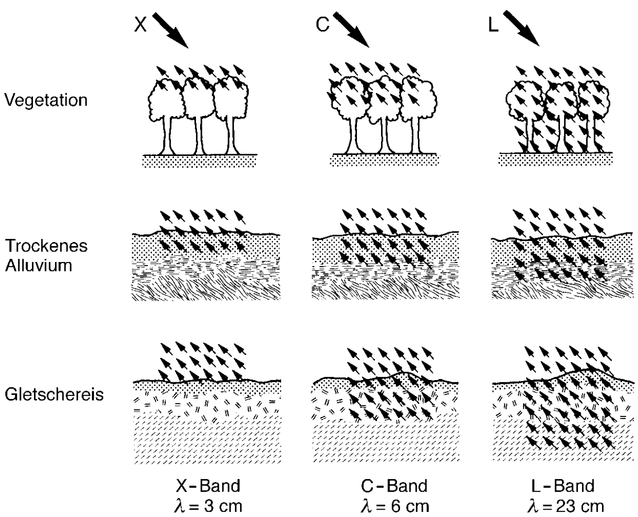


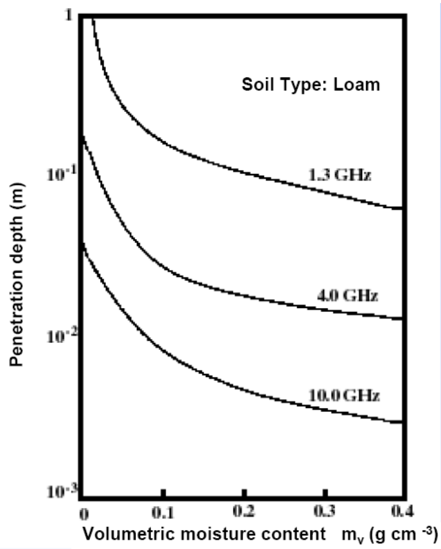

Chlorophyll has two absorption bands in the blue and red parts of the visible domain:

➔ the reflected green radiance gives colour



## Penetration of EM Waves into Matter



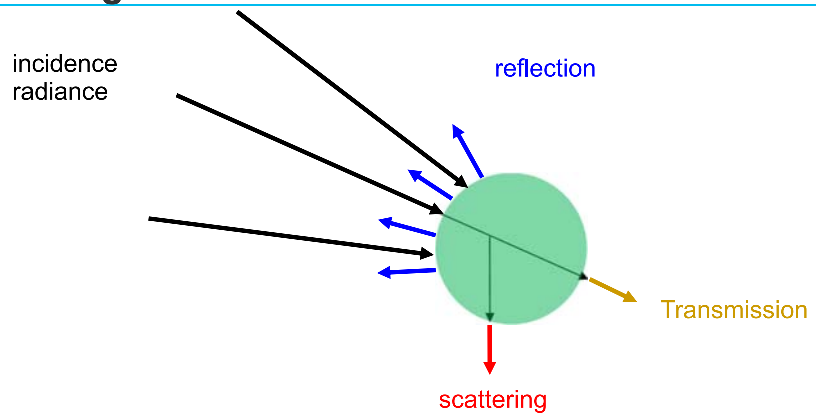

Penetration proportional to wave length

Microwaves:
Dependence on moisture

# Scattering



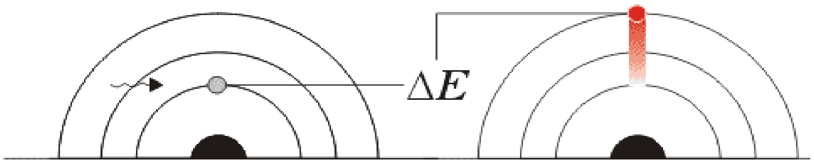
## Scattering of radiance



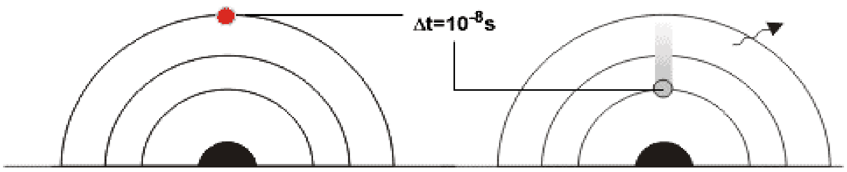

Scattering

- Change of EM direction at particles in atmosphere at molecules, water droplets etc.
- The radiance becomes absorbed and is immediately emitted again
- Energy and wavelength remain the same, direction may change

## Absorption and emission of a photon




Absorption occurs, if photon energy matches ΔE required to lift electron → depends on material (different ΔE)




spontaneous emission of photon in arbitrary direction
自发



## Rayleigh-Scattering

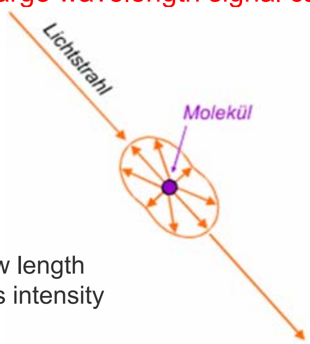
Scattering at objects, whose **size is small compared to wavelength**:

- Molecules in visible domain
- Raindrops in microwave domain

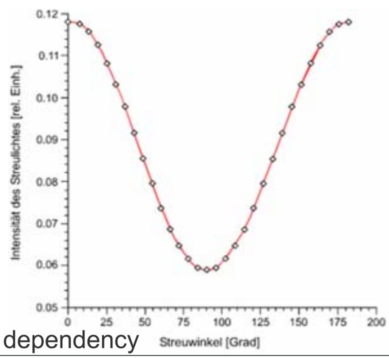
Strongly dependent on wavelength:

- The scattered intensity drops with the fourth power of λ: $I \sim \frac{1}{\lambda^4}$
  - Blue sky → shorter blue wavelength scatters more

→ large wavelength signal can penetrate clouds



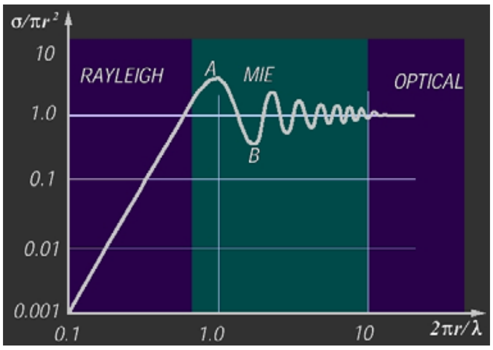

arrow length
gives intensity

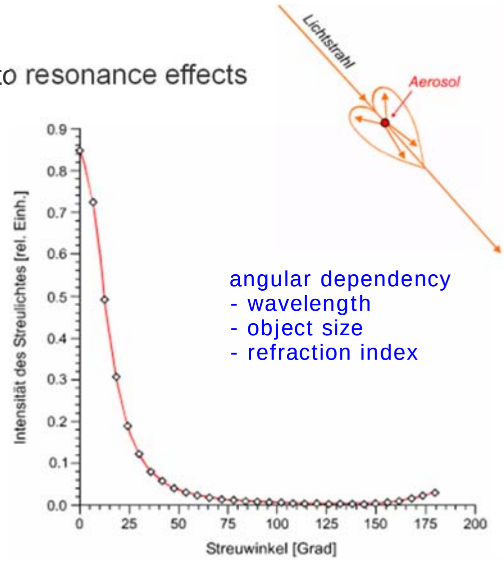



angular dependency

## Mie-Scattering

- Scattering at objects, whose size is in the order of wavelength:
  - Aerosols in visible domain (milky appearance of fog and clouds)
  - Birds in microwave domain
- Slight dependency on wavelength due to resonance effects



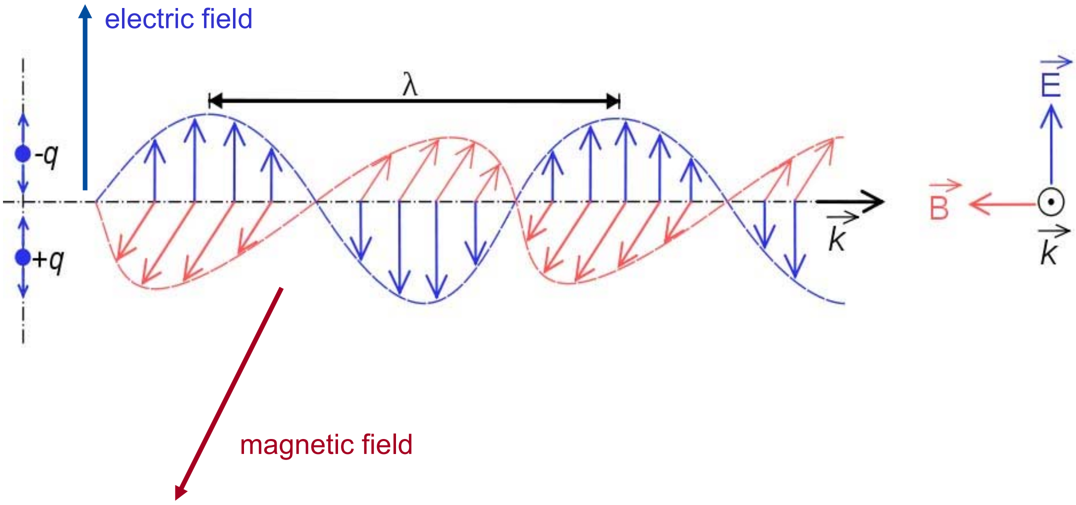

angular dependency
- wavelength
- object size
- refraction index

In visible domain $\sigma \sim r^2\pi$



# Reflection (and Refraction)

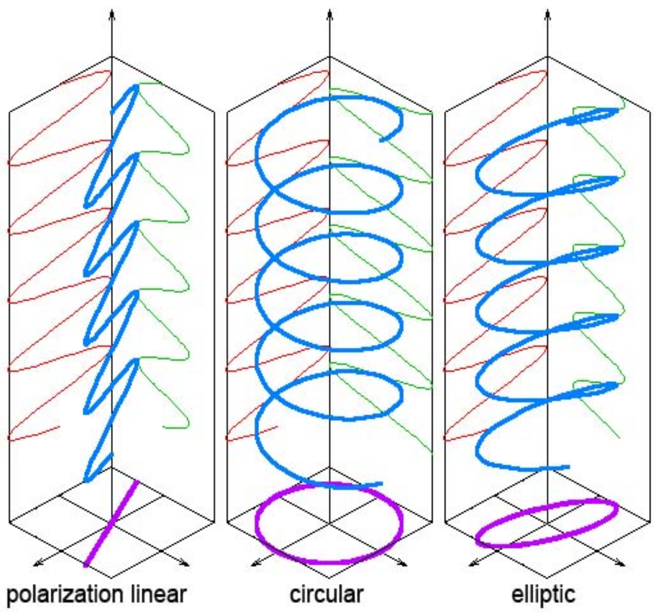
## Light = Elektro-magnetic Wave






## Polarization

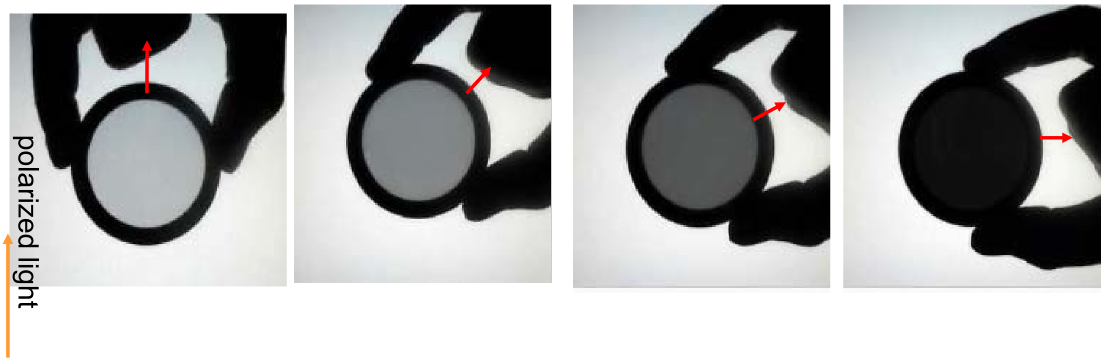
Light = electromagnetic wave




Light may be polarized –
Linear polarization = direction of electric and magnetic field are fixed
Circular polarized = electric and magnetic field are permanently changing the direction
Human cannot see it, but can be used for filtering of light by polarization filters

## Polarization filter

- Effect of filter depending upon rotation
- Polarizing filter have a rotation direction:
  - 2 linear polarizing filter with 90° difference in direction → no light goes through
  - 2 linear polarizing filters with any other difference in rotation → intensity reduced
- In photogrammetry used for separation of stereo images





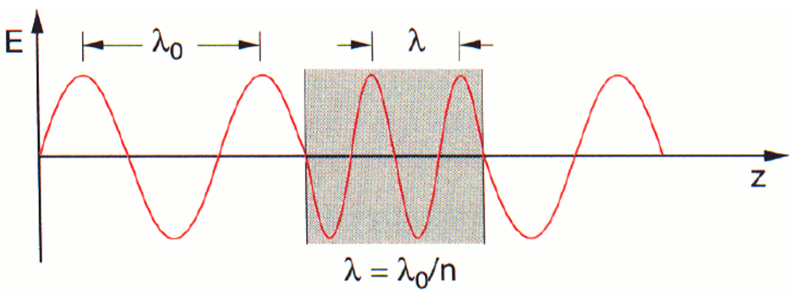

## Velocity of light depends on matter

The velocity of light (phase v.) $v_{ph}$ depends on $\varepsilon$ and $\mu$:

$$v_{ph\_mat} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c_0}{n_{mat}}$$

refraction index > 1

The *frequency* remains, the *wavelength* becomes smaller




The refraction index is a function of wavelength, too

Dispersion ➔ Prism

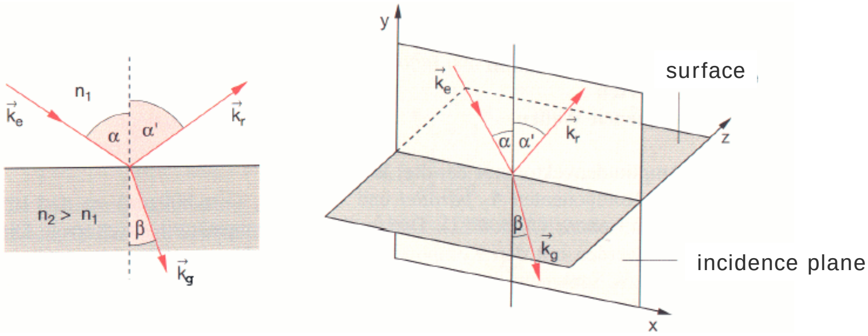
散布

## Reflection and refraction

Propagation direction changes at surfaces

- frequency is preserved
- Reflection: incidence angle $\alpha$ = reflected angle $\alpha'$
- Snell's law of refraction:

$$\boxed{n_1 \cdot \sin(\alpha) = n_2 \cdot \sin(\beta)}$$

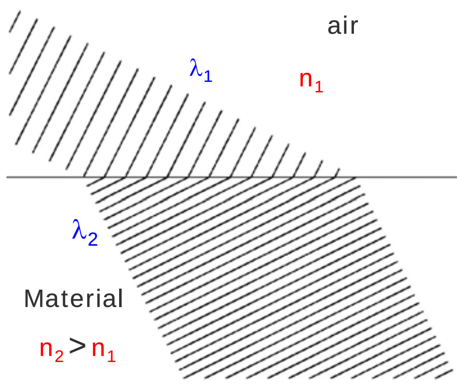


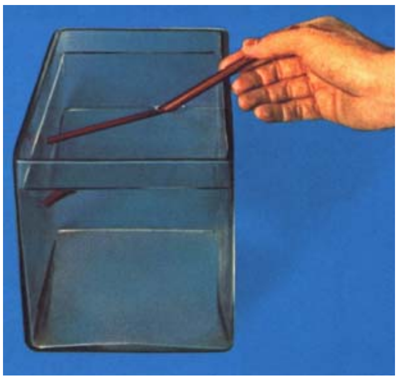



## Cause of refraction

1. Wave front hits surface oblique
2. Dipoles inside matter are forced to oscillate
3. The change of velocity of light causes change of direction

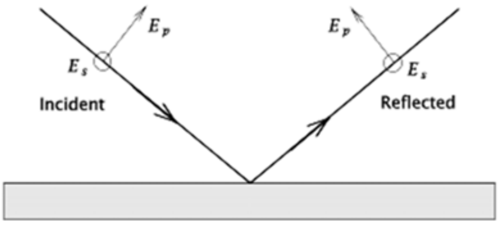
   ➔ refraction



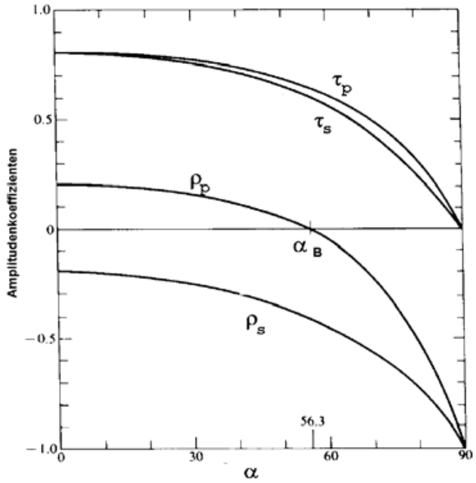



# Reflection: Fresnel's formulas

- The Fresnel formulas relate amplitudes of incident vs. reflected and transmitted waves, respectively (details not treated here)
- Curve of indices ($\rho$ → reflection, $\tau$ → transmission) depend on:
  - matter
  - wavelength




p-polarized: parallel to paper (screen)
s-polarized: normal to paper plane




air (n=1), glass (n=1,5)



# Brewster's angle

- In remote sensing important at horizontal planes like water surface
  - Reflection of vertical polarization vanishes at Brewster's angle
  - Photography / sun glasses (Polaroid):
    - Polarization filter sorts out disturbing dominant horizontal signal
    - Diffuse signal remains

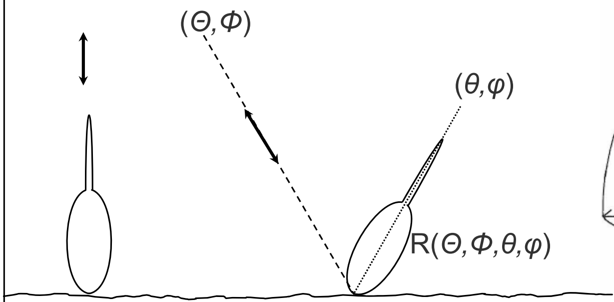
Polarization: horizontal, vertical parts of signal

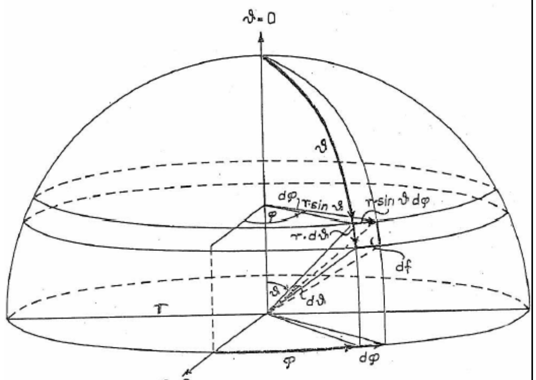
## Reflectance of objects: BRDF

- Radiation $L_{\lambda r}(\theta,\varphi)$ in direction $(\theta,\varphi)$ is defined by

$$L_{\lambda r}(\vartheta,\varphi)=\int R_{\lambda}(\Theta,\phi,\vartheta,\varphi)\cdot L_{\lambda i}(\Theta,\phi)\cdot\cos\Theta\cdot d\Omega_i$$

  - $L_{\lambda i}(\Theta,\Phi)$ incoming radiation from direction $(\Theta,\Phi)$
  - BRDF (Bidirectional Reflectivity Distribution Function): $R(\Theta,\Phi,\theta,\varphi)$
  - $d\Omega$ infinitesimal solid angle




$$d\Omega = \sin\vartheta\cdot d\vartheta\cdot d\varphi$$

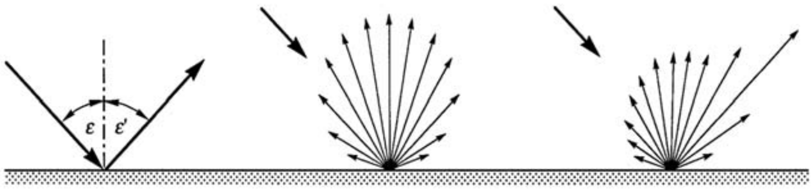


## Influence of surface roughness

- Smooth surface → specular reflection
- Rough surface (with respect to wavelength):
  - Diffuse Reflection (Lambertian)
  - Rayleigh criterion of roughness:
    - Standard deviation of height $\sigma_h$
    - Incidence angle $\theta$ (between radiance and plane normal)

$$\sigma_h > \frac{\lambda}{8\cdot\cos(\theta)}$$

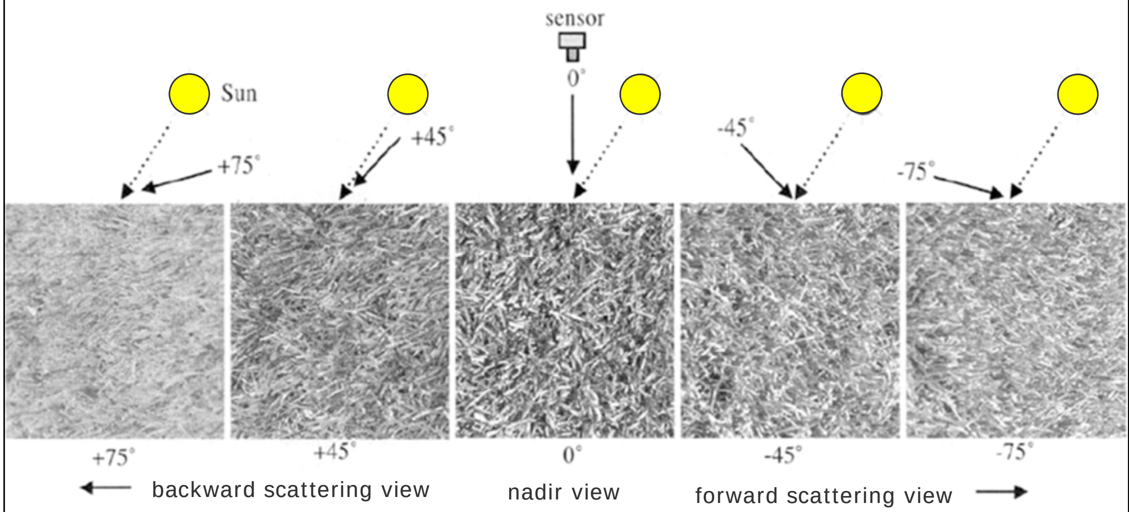
- Often we observe directed diffuse reflection.




specular reflection | Lambertian reflection at very rough surface | directed diffuse reflection

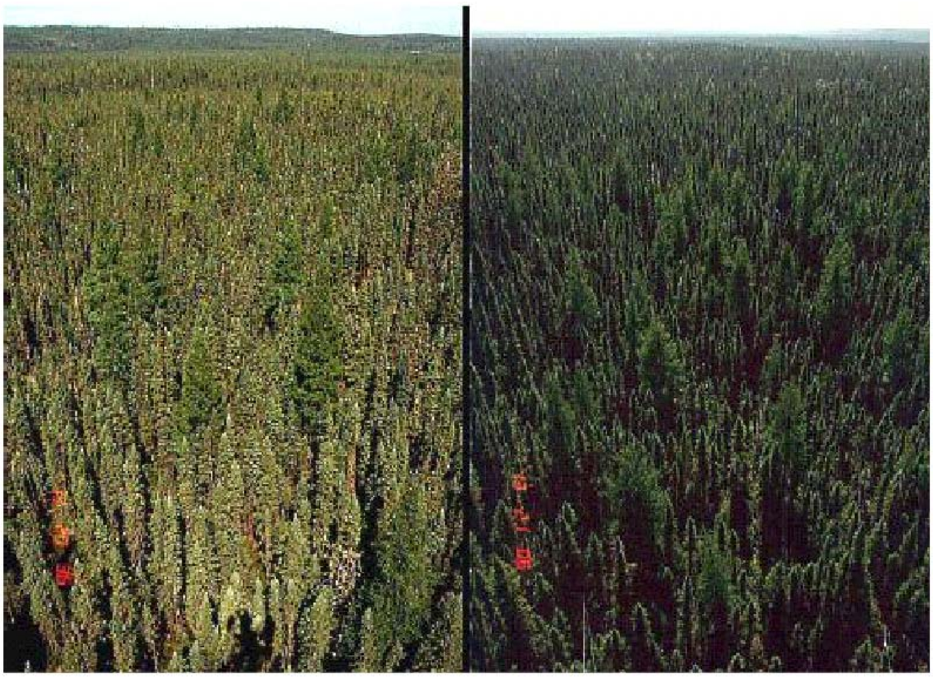
## Effects of differing viewing angles

Reflectance from a grass field






## Effects of differing viewing angles



# Various kinds of resolution



## Resolution in remote sensing

- Four kinds of resolution are relevant in remote sensing:
  - Spatial resolution
  - Spectral resolution
  - Temporal resolution
  - Radiometric resolution

Sampling

Quantization

- Since we deal with digital data, the two steps of digitization play a crucial role:
  - Sampling
  - Quantization

## Analog to digital conversion: overview (I)

**analogue image** (input): 2D continuous function g(x,y), x,y ∈ **R; **g(x,y) ∈ **R**

**digitalization**

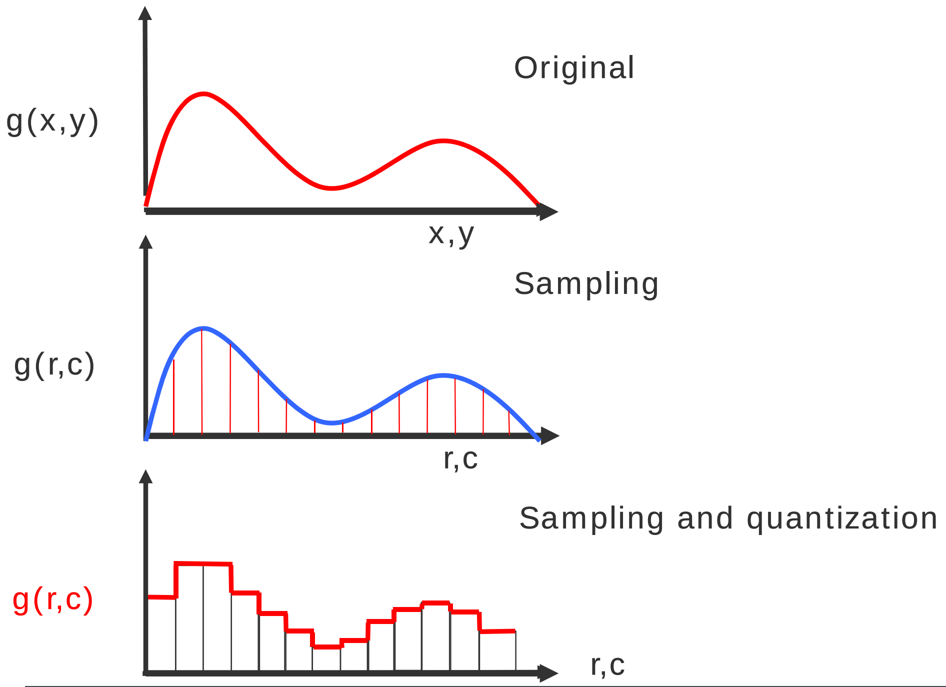
- sampling: r (row), c (column) ∈ **N**
  g is only defined at specific, in general equidistant, positions
- quantization: g(r,c) ∈ **N**
  g can only take on specific values from **N,** depending on number of bits

**digital image** (output)

$$\boxed{\text{Digitalization = sampling + quantization}}$$



## Analog to digital conversion: overview (II)



## Spatial or geometric resolution

- Spatial dimension
- Determines level of detail visible in the image
    - The minimal size of objects which can be recognized
    - Minimum distance to separate two objects

LANDSAT (30 m) IKONOS (1m)

© MicroImages, Inc., 2001–2012

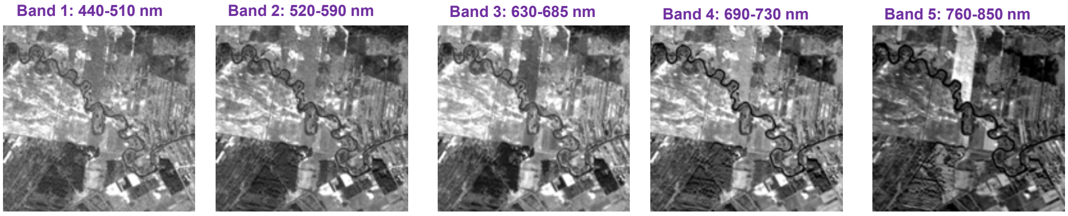


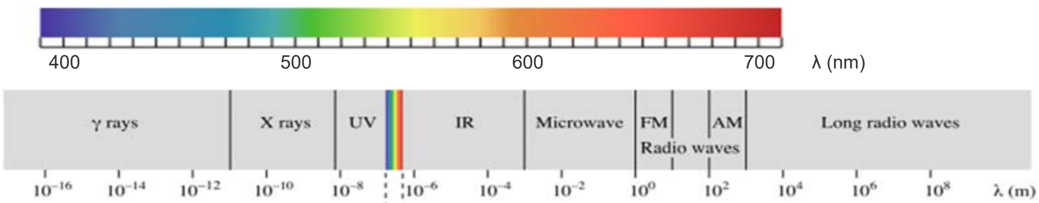
## Spectral coverage and resolution

- Coverage: portion of spectrum in which sensor operates
- Resolution: number and width of so-called spectral bands

RapidEye image taken in March 2014, southeast of Poland ()

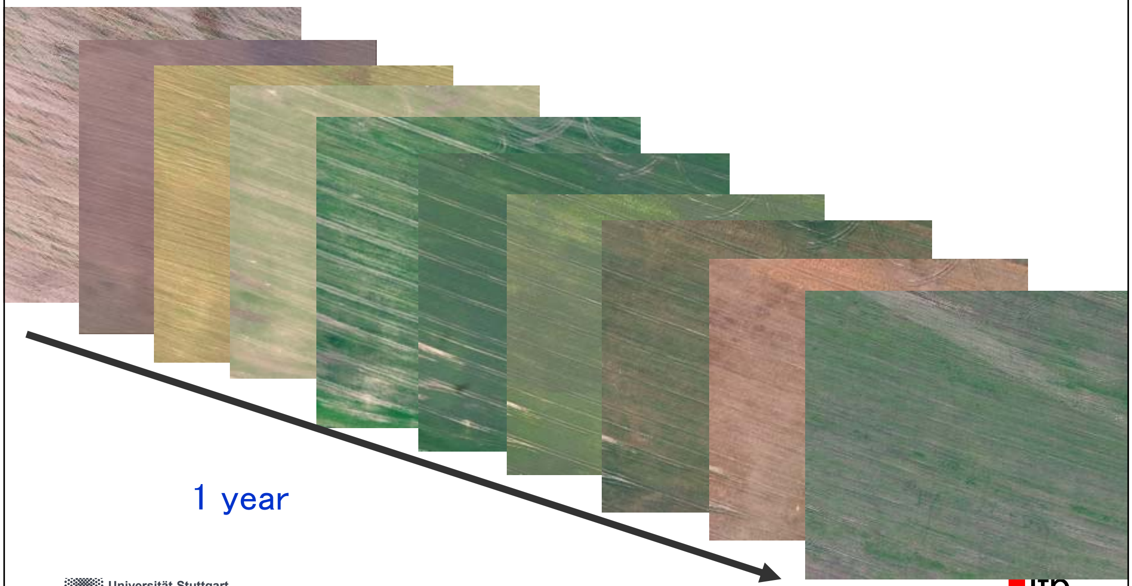
Band 1: 440-510 nm Band 2: 520-590 nm Band 3: 630-685 nm Band 4: 690-730 nm Band 5: 760-850 nm





## Temporal resolution

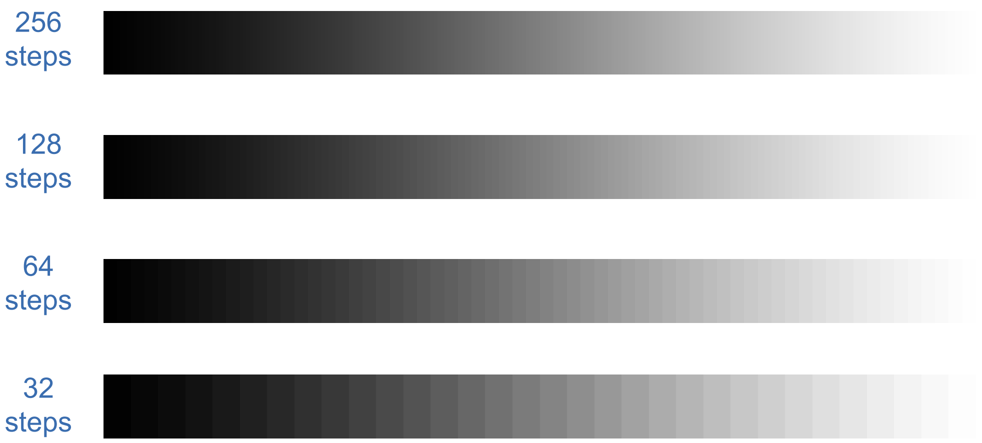
- Temporal dimension
- Repeat cycle of acquisitions for a certain scene






## Radiometric resolution

- How many states can be coded?
- In our case how many grey values (depends on number of bits)



## Stuff you should know:

- Which kind of signal do we exploit in RS?

  Electromagnetic Wave

- What are the characteristics of such radiation?

  electric, magnetic, polarization, oscillation propagation, constant velocity, Black-body radiation (sun), e=h*f, diffraction, absorption, reflection, scattering

- What is the difference between oscillation and wave?

  wave is oscillation that propagates in space

- Relevant terms of radiation budget?

  black body radiation; radiant flux
  absorptance, reflectivity, transmittance;
  emission



## Stuff you should know:

- Which physical effect determines the angular (spatial) resolution of imaging sensors?

  dTheta = 1.22*Lambda/D

- Difference between scattering and reflection?

  absorption==>emission  vs reflection

- How does reflection depend on surface roughness?

  specular VS diffuse VS Lambertian    Sigma < Lambda/(4*cos(theta))

- Different kinds of resolutions?

  spatial, spectral, temporal, radiometric