Remote sensing

💡 Source: Prof. Dr.-Ing. Uwe Sörgel, [Lecture Remote Sensing]
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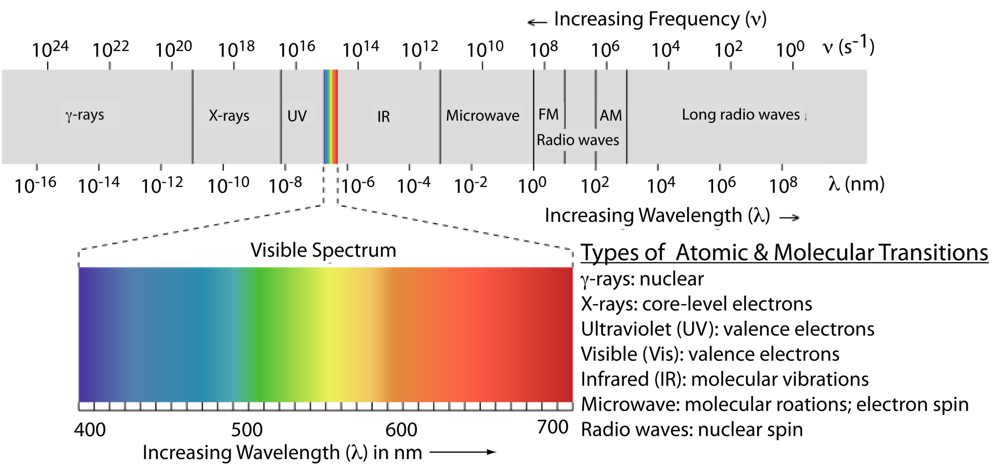
Introduction

Remote Sensing means the sensing of the Earth's surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resources management, land use and the protection of the environment.

Remote Sensing uses the radiant energy that is reflected, emitted or scattered from the earth and its atmosphere from various portions of the electromagnetic(EM) spectrum.

Basics

Electric and magnetic fields

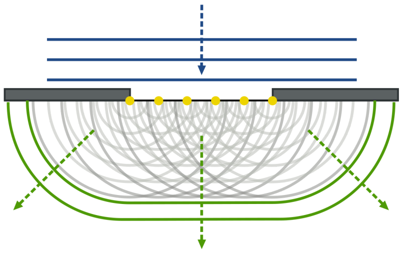


- **electrical effects play an important role in the remote sensing**
  - Coulomb's law $F = (q_1 q_2)/(4\pi\varepsilon r^2)$.
  - The permittivity $\varepsilon = \varepsilon_0 * \varepsilon_r$, with the electric constant, and is complex and the magnitude varies by the object. For example, in the mean water level is 81, which is rather large.
- **magnetic effects can be neglected in remote sensing**
  - In the static magnetic field, $\overrightarrow{B} = \mu_r \cdot \mu_0 \cdot \overrightarrow{H}$, With μ_r the permeability and μ_0 the magnetic constant, and the permeability varies little for the most important types of matter.
  - permanent magnet

Oscillations and waves

- the difference between oscillation and wave
  1. Oscillation is the **periodical transfer** of energy inside the system, two forms: **potential energy and kinetic energy**.
  2. Waves are oscillation **propagating through space**, which means **without oscillation there will be no wave**.
  3. Waves depend on **location**, **time** and **transport energy**. In another word, waves are classified into **transverse** and **longitudinal** while no such classification exists for oscillations.
- **wave equation for EM-wave in vacuum**
  - the complex natation is advantageous, only real part is of physically of interest
  - angular frequency $\omega = 2\pi/T$
  - wave number $k = 2\pi/\lambda$

- properties of periodic and plane EM waves
  - E, B, r - right hand rule
  - velocity of light
  - **transport energy**
  - E-field and B-field are in phase
  - plane of E-field oscillation defines polarization plane
- **relationship between wavelength and frequency** $\lambda \cdot f = c$
  - velocity of light depends on refraction index at surfaces
- **Wave Propagation - Huygens's principle**



  - Each point on wave front is a source of new elementary wave (**diffraction**)
  - Wave fronts are interacted by coherent superposition (**interference**)

Radiation budget

- Radiometry
  - **measurement of electromagnetic radiance**
  - emits radiance depending on its temperature - idealized object model: Black body(black body radiation)
    - **Wien's displacement law: The frequency of maximal radiance is proportional to temperature**
    - **Stephan-Boltzmann law: The total amount of thermal radiation emitted is directly proportional to the fourth power of its absolute temperature**
- radiation Budget equation $\Phi_i\lambda = \Phi_r\lambda + \Phi_a\lambda + \Phi_t\lambda$

$$\begin{aligned}
\rho_\lambda &= \frac{\Phi_{r\lambda}}{\Phi_{i\lambda}} \quad \text{reflectivity (also reflectance)} \\
\alpha_\lambda &= \frac{\Phi_{a\lambda}}{\Phi_{i\lambda}} \quad \text{absorptance} \\
\tau_\lambda &= \frac{\Phi_{t\lambda}}{\Phi_{i\lambda}} \quad \text{transmittance}
\end{aligned}$$

1. $\Phi_{i\lambda}$is the **incident** (incoming) radiant flux, defined as the amount of energy per unit time (i.e., power). $\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1$
2. $\Phi_{r\lambda}$ is the amount of power **reflected** from the object.
3. $\Phi_{a\lambda}$is the amount of power **absorbed** by the object.
4. $\Phi_{t\lambda}$is the amount of power **transmitted** from through the object.

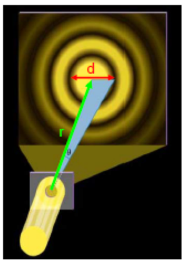
Interaction of waves with matter

General remarks

- the energy of the EM wave is proportional to frequency: $E = h * f$, long wave MW have far less energy than visible light
- interaction of EM wave with molecules
  - optical domain/ infrared (VIS, NIR-FIR): **in particular sensitive to chemical object structure**
  - thermal radiance TIR: **localize natural and anthropogenic heat sources**
  - microwave domain MW: sensitive to conductivity, roughness, morphology

Diffraction

- fan out of wave behind obstacles
- huygens principle
  - every point on the wave front is source of new elementary wave
  - wave front propagates by coherent superposition/ interference
- Which physical effect determines angular resolution of an imaging sensor? How can we improve such resolution without changing signal wavelength?



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

$d = 2{,}44 \cdot r \cdot \frac{\lambda}{D}$ ← Optical aperture/ Antenna size

1. Diffraction effect determines the angular resolution of an imaging sensor, because **the narrower the slit, the more wave will fan out**.
2. **angular resolution:** $\Delta\theta = 1,22 * \lambda/D$, with λ the wave length of signal, and D the antenna size (the optical aperture).
3. If we want to improve such resolution without changing signal wavelength, we can increase the size of **optical aperture**

Absorption/emission

- energy transfer from wave to matter
- subtractive color by absorption: CMYK
- penetration of EM waves into Matter
  1. **penetration proportional to wavelength**
  2. microwaves: dependence on moisture

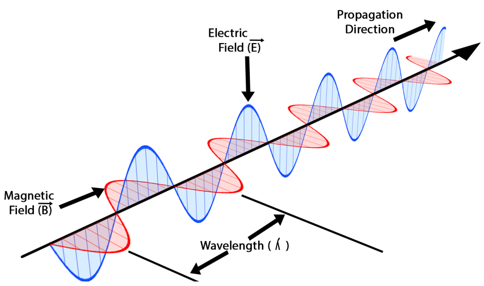
Scattering

- change of EM direction at particles in the atmosphere(Molecules, water droplets)
- the radiance becomes absorbed and is immediately emitted again
- **Energy and wavelength remain the same, direction may change**
- **rayleigh-scattering**
  1. object size is small compared to wavelength

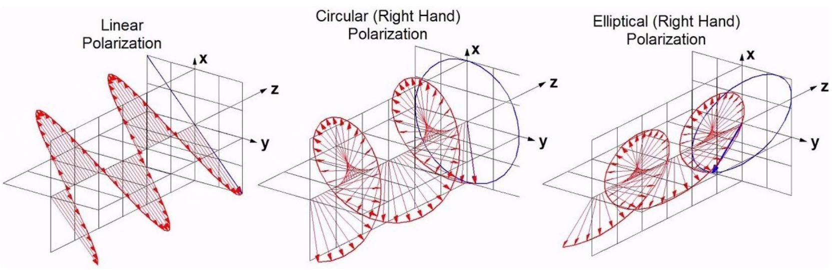
    - molecules in visible domain
    - raindrops in microwave domain
  2. strongly dependent on wavelength
     blue sky - shorter blue wavelength scatters more
  3. **large wavelength signal can penetrate clouds**
- **Mie-scattering**
  - Mie scattering is elastic scattered light of particles that have a diameter similar to or larger than the wavelength of the incident light.
  - The Mie signal is proportional to the square of the particle diameter.
  - Mie scattering is much stronger than Rayleigh scattering and, therefore, a potential source of interference for this weaker light scattering process.

Reflection and refraction

- Light = Elektro-magnetic Wave



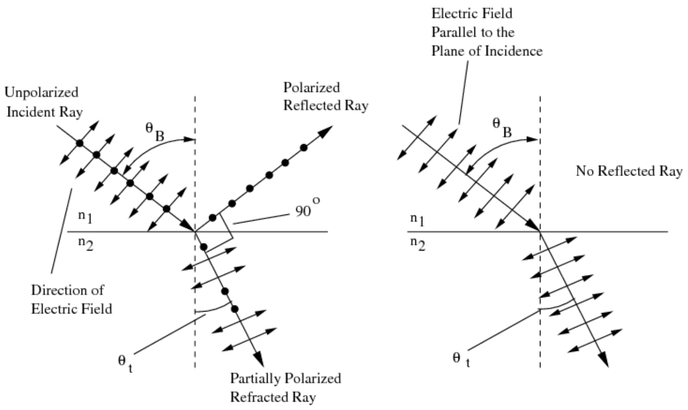
- at surface boundaries
- **polarization**



  - **polarization linear**
    - light maybe polarized
    - polarization filter
      - effect of filter depending upon rotation
      - 2 linear polarizing filter with 90 difference in direction - no lights go through
      - 2 linear polarizing filter with any other difference in rotation - intensity reduced
    - separation of stereo images
  - **circular (3D glasses):** electric and magnetic field are permanently changing
  - **elliptic**
- velocity of light depends on matter
  - **the frequency remains, the wavelength becomes smaller**

- **the refraction index is a function of wavelength**
- **dispersion, prism**

- snell's law of refration: $n1 * sin(\alpha) = n2 * sin(\beta)$
- cause of refraction
  - wave front hits surface oblique
  - dipoles inside matter are forced to oscillate
  - the change of velocity of light causes change of direction
  - brewster's angle



- BRDF (Bidirectional Reflectivity Distribution Function): $R(\Theta, \Phi, \theta, \varphi)$
- influence of surface roughness

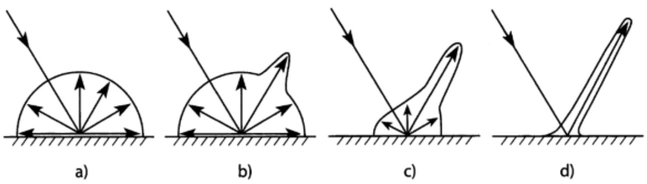


Fig. 2.28 Reflection indicatrices of different surfaces: (**a**) matt: purely diffuse reflection, (**b**) half-matt: dominant diffuse, minor directed reflection, (**c**) glossy: predominant directed and minor diffuse reflection, and (**d**) high glossy: exclusive specular reflection

  - rough surface - Diffuse reflection is the reflection of light or other waves or particles from a surface such that a ray incident on the surface is scattered at many angles rather than at just one angle as in the case of specular reflection.
  - smooth surface - specular reflection
  - **Roughness Criterion:** $\sigma_h > \frac{\lambda}{8 \cdot \cos(\theta)}$
    - the standard deviation of the roughness height regarding to a reference height
    - θ the local incident angle

Various kinds of resolution

- **digitalization = sampling and quantization**
- sampling
  - spatial resolution
  - spectral resolution

        - temporal resolution
- quantization: radiometric resolution
- **the difference between spectral and radiometric resolutions**
    - Spectral resolution is **the number and width of spectral bands**
    - Radiometric resolution tells **how many grey values (depends on the number of bits) can be coded**, this resolution against to the same spectral band

Image processing

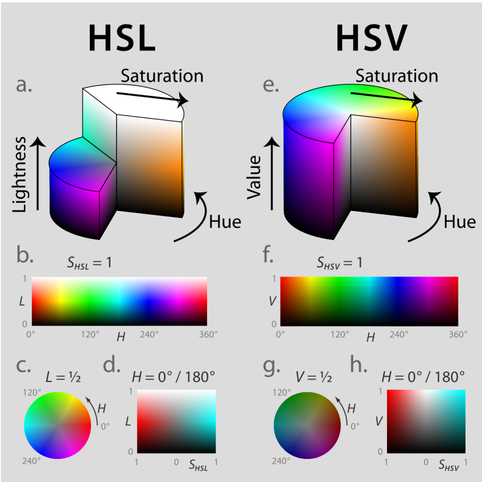
Introduction

- acquisition of object features in image
    - **information carrier** - electromagnetic radiation of specific wave length
        - reflected radiation: sunlight, laser, radar impuls
        - projected radiation: X-ray device, computer tomography
        - remitted radiation: thermal radiation
    - **recorded data** - EMR energy or a value proportional to EMR energy
    - **sensor**
        - photographic film
        - electric sensors
        - radar: antenna and high frequency electronics
    - **result**
        - film
        - CCD
        - brightness
        - prior to processing(and storage) analogue-digital(A/D)-conversion(digitisation) required
- image after digitization
    - sample: spatially discrete
    - quantized: discrete in energy values
    - image elements - pixel
- topics of digital image processing
    - **input image - processing - output image**
    - correct errors during acquisition by calibration
    - modify colour/grey values by scaling
    - transform to co-register images
    - eliminate errors by filtering
    - segment structures
    - code images and image sequences, storage

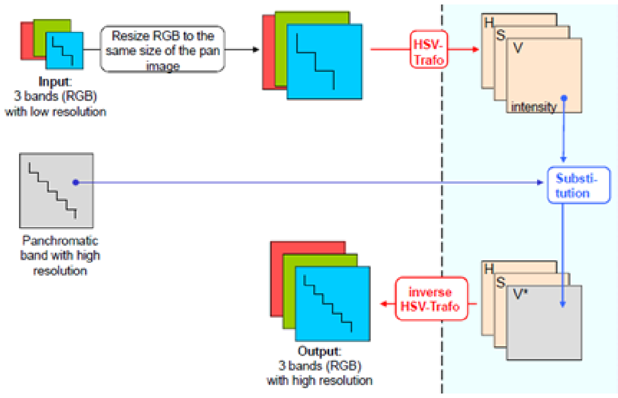
Image acquisition - CCD and CMOS technology

- inner photoelectric effect

- linear CCD sensor
  - sensor moves along track, image generated line by line
  - no shutter required
- CCD matrix sensor - interline transfer technique
- **spectral sensitivity, problem**
  - photo diodes are sensitive for **entire visible spectral domain**
  - in order to take color images mostly **filters are used**
    - remote sensing: multi and hyperspectral images
    - displays lick screen or beamer
      - only 3 colour: RGB
      - color perception by additive color mixing
- The spatial resolution of **hyperspectral bands** is often lower than the resolution of **panchromatic** band
  - hyperspectral bands have narrow bands so that they receive **less energy**. The percent of noise gets higher. To solve this problem we have to enhance the **Signal-to-noise ratio(SNR)**, for this purpose, we have to **enlarge the size of the chip (pixel size)**. The chip can receive more energy. And because the size of the chip gets larger, the resolution of hyperspectral bands gets lower.
  - For panchromatic bands, we **merge the visible bands(RGB)**. The energy is **enough** to get the high SNR. So we can use **smaller chips**. So that the resolution is better.
- **HSV color model - cylinder coordinates systems**



  - **Hue** is the **value index** of color, one hue represents one color
  - **Saturation** defines the level of color, describes how **colorful** one color is
  - **Value** equals the lightness of the color, defines how **light** or how **dark** the color is
- **pan sharpening** of optical satellite images take place in IHS space



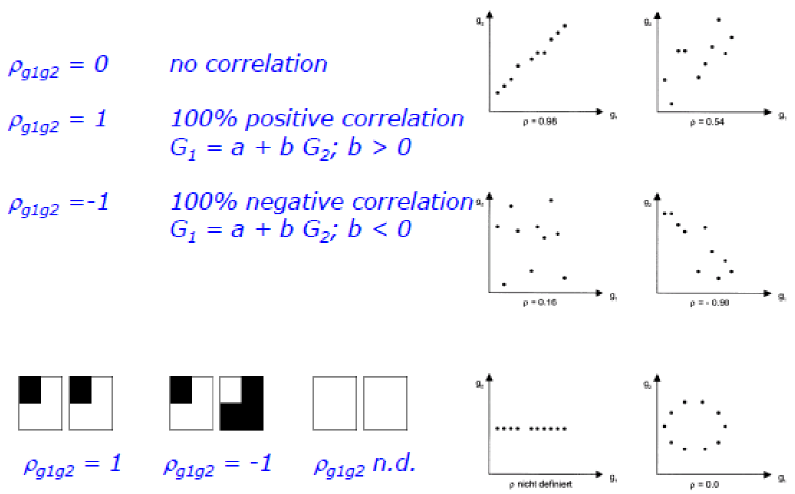
- Pan-sharpening is a process of **merging high-resolution panchromatic and lower resolution multispectral imagery** to create a **single high-resolution color image**.
- Pan-sharpening produces a high-resolution color image from three, four or more low-resolution multispectral satellite bands plus a corresponding high-resolution panchromatic band:
- Low-res colour bands + High-res grayscale band = Hi-res colour image
- steps
    1. oversample RGB channels to resolution of pan channel
    2. transform RGB to IHS(Intensity, Hue, Saturation)
    3. exchange I with pan channel(I')
    4. transform I'HS to R'G'B' image(pan sharpened image)
- fuse geometry and color data

- spectral sensiticity of CCD-sensor
    - **spectral response for CCD sensors in relation to photography and human eye(400-700nm, RGB)**
    - colour infromation only can be based on colour filters in front of CCD
- separation of spectral bands(color)
    - three layer ship: penetration depth depends on wavelength, 2 color sensitive layers vertically, expensive
    - color mosaic(Bayer Pattern)
        - single chip with color filters on pixels
        - later interpolation to full image size
            - lower real resolution
            - green domaintes(brightness)
            - cheap, mostly used for consumer grade cameras
            - 2 green: human vision more sensitive to green real resolution
    - color bands
        - panchromatic 400-900nm
        - blue 400-580nm
        - green 500-650nm
        - red 590-675nm
        - near infrared 675-900nm

- **how many combinations(TM)?**
  - combinatorics : draw k elements form set of n bands $\frac{n!}{(n-k)! \cdot k!}$, where TM: n= 7, k= 3
  - possible ways of visualization: $\frac{n!}{(n-k)! \cdot k!} \cdot k! = \frac{n!}{(n-k)!}$, $\text{here} : 35 \cdot 6 = 210$
  - remote sensing: 321/432
- ground sampling distance(GSD): distance of pixel centers on ground
- diffraction limits angular resolution
  - the real or effective resolution may be worse than GSD
  - on the other hand, there is no point in choosing GSD smaller than diffraction limit
  - diffraction at circular aperture: distance d of 1. order minima: $d = 2.44 * r * \lambda / D$
- resolution should match the desired application
- for recognition of a certain object, we need a handful pixel

Characterization of digital images

- average grey value μ - the average of all grey values of an image describes the general brightness of image: $\mu = \frac{1}{X \cdot Y} \cdot \sum_x \sum_y g(x,y)$
  - dark image <<127
  - bright image >>127
  - homogeneous image(average) 127
- variance $\sigma^2 = \frac{1}{X \cdot Y - 1} \cdot \sum_x \sum_y (g(x,y) - \mu)^2$
  - global measure for grey valure deviation from μ
  - related to the contrast *K* of an image: $K = (gmax - gmin)/(gmax + gmin)$
  - variance of a homogeneous grey value image of arbitrary brightness $\sigma^2 = 0$
- covariance(similarity)
- **correlation coefficients(similarity)**
  - qualitative measure of similarity, no quatitative result due to lack of normalization
  - correlation coefficient *ρ* of two images *G* and *G*: [-1,1]: the ratio between covariance and product of standard deviations of both images

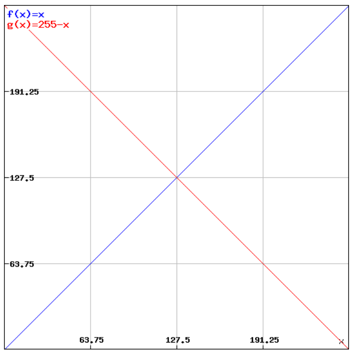


- histogram

- average μ and variance $\sigma 2$ only allow for rather general characterisation of an image
- histogtrams deliever more detailed information about the number of pixels with a certain gray value *gi*
- relative grey value occurrences $p(g) \;=\; a(g)/n,\, [0,\, 1]$
- histogram: visualisation
  - **a histogram does not contain information about the spatial distribution of grey values in the image**
  - lose the geomatic information
- histogram stretch

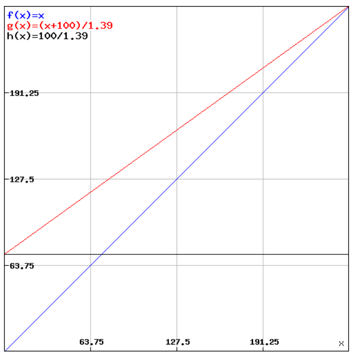
Point operations

- homogeneous
  - only original grey value influences results, position does not
  - transformation using charcteristic curve - the change of gray values from g1 to g2
    - inversion: $g_2(x,\, y) \;=\; -\, g_1(x,\, y) \;+\; 255$



    - lineal scaling: $g_2(x, y) = (g_1(x, y) + k_2) \cdot k_1$

$$
\begin{aligned}
k_1 &: \text{change of contrast} \\
k_2 &: \text{change of brightness} \\
k_2 > 0 &\quad \text{makes image brighter} \\
k_2 < 0 &\quad \text{makes image darker} \\
k_1 > 1 &\quad \text{enhances contras} \\
k_1 < 1 &\quad \text{reduces contrast}
\end{aligned}
$$

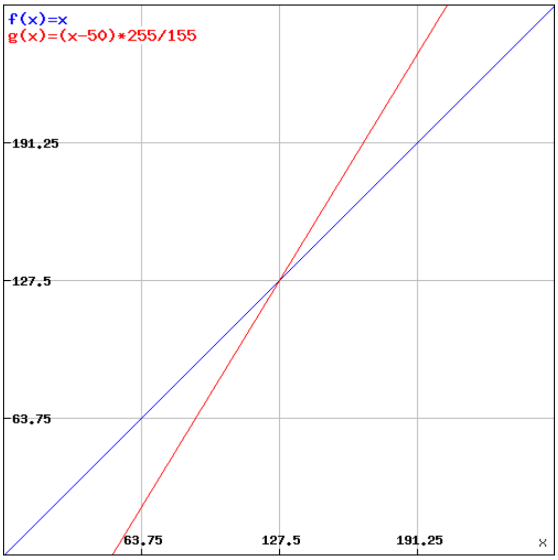


    - characteristic curves: piecewise linear scaling

$$g_2(x,y) = \begin{cases} 0 & \text{if} \quad (g_1(x,y)+k_2)\cdot k_1 \le 0 \\ (g_1(x,y)+k_2)\cdot k_1 & \\ 255 & \text{if} \quad (g_1(x,y)+k_2)\cdot k_1 \ge 0 \end{cases}$$

$$k_1 = \frac{255}{g_{\max} - g_{\min}}$$

$$k_2 = -g_{min}$$



- enhancement of interesting region only
- also non-linear function e.g. gamma correction
- often coded in LUT

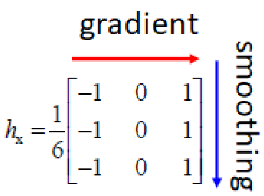
- histogram normalisation
- transformation using look-up tables
- algebraic transformations

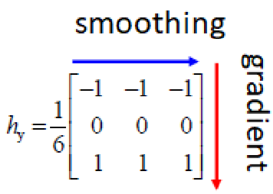
- **inhomogeneous**
  - local filter operations: a mixture of both
    - neighbourhood around current pixel is considered
    - neighbourhood is defined via a window(filter mask)
    - filter mask is continuously moved across the image
  - linear filtering
    - lineal digital filters h(x,y) carry out convolution operations on the image g(x,y) - convolution with 3 × 3 - filter

$$g'(x,y) = g(x,y) * h(x,y) = \sum_{i=-1}^{i=1} \sum_{j=-1}^{j=1} g(x+i, y+j) \cdot h(-i,-j)$$

    - use of local filters: smoothing, enhancement of specific features
  - **low pass filter - smoothing**
    - Different position - different operators
    - Homogeneouspoint operator - global calculation - take all the grey values intoconsideration

  - Inhomogeneous point operator - only consider the local part - depends on original grey value and position in image - low pass filter
  - reduce high frequency information
    - visiual imprression becomes softer
    - edges are smoothed
    - details and noise are reduced
    - no effect in homogeneous areas
    - overall brightness constant
  - box operator $\frac{1}{9}\begin{bmatrix}1 & 1 & 1\\1 & 1 & 1\\1 & 1 & 1\end{bmatrix}$
    - Disadvantage: not rotation invariant, does not suppress all high frequencies
    - Advantage: recursive implementation possible
  - gauss operator
    - stay same in both domains
    - Advantage: rotation invariant, suppresses all high frequencies
    - Disadvantage: only approx. recursive implementation - binomial filter
  - binomial filter $b_{2,2} = \frac{1}{16}\begin{bmatrix}1 & 2 & 1\\2 & 4 & 2\\1 & 2 & 1\end{bmatrix}$
    - discrete approximation of gauss filter, recursive implementation possible
    - 2D-Filter: separable in two 1D functions
- High pass filters - edge detection
  - prewitt-operator
    - simple realization $\begin{matrix} hx = 0.5{*}[-1 \quad 0 \quad 1] \\ hy = 0.5{*}[-1 \quad 0 \quad 1]' \end{matrix}$
    - differencing enhances noise - noise suppression by low pass filtering(smoothing) in across direction





    - filtering in both directions
    - amplitude and direction of gradient $g_{MAG} = sqrt(g_x^2 + g_y^2)$ $g_{DIR} = arctan(g_y/g_x)$
  - Laplacian operator - image sharpening
    - use superposition principle of linear filters
    - image sharpened by adding high-pass component from Laplacian

$$h_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \frac{1}{4}\begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 0 & -1 & 0 \\ -1 & 8 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$

$$h_2 = \frac{1}{8}\begin{bmatrix} -1 & -1 & -1 \\ -1 & 16 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

Geometric transformation

- spatial transformation using a mathematical function
  - simple geometric transformations
    1. translation: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} + \begin{pmatrix} dx \\ dy \end{pmatrix}$, 2 degrees of freedom (d_x, d_y)
    2. scaling: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} s_x & 0 \\ 0 & s_y \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$, 2 degrees of freedom (s_x, s_y)
    3. skew: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} 1 & b_x \\ b_y & 1 \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$, 2 degrees of freedom (b_x, b_y)
    4. rotation: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$, 1 dof. ($\alpha$)
  - further sptial transformations

    - similarity transform: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = s \cdot \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} + \begin{pmatrix} dx \\ dy \end{pmatrix}$ 4 dof.: (s, α, d_x, d_y)
    - affine transformation: $\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} + \begin{pmatrix} dx \\ dy \end{pmatrix}$ 6 dof.
    - higher order polynomials
    - projective transformation
      here: on a plane
      homogeneous coords.
      → linear transformation
      $\begin{pmatrix} \hat{x}_2 \\ \hat{y}_2 \\ h' \end{pmatrix} = \begin{pmatrix} h' \cdot x_2 \\ h' \cdot y_2 \\ h' \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \\ 1 \end{pmatrix}$ 8 dof.
    - locally varying transformations
      e. g. orthoprojection, rubber sheeting

- grey value determination
  - general spatial transformation results in the change from integer to non-integer positions
  - indirect method
    - compute inverse transformation T-1
    - determine grey valued for each position in target image - no holes
  - nearest neighbour interpolation
  - bilinear interpolation - two dimensions
  - Bicubic interpolation: The new grey value is interpolated from the neighbouring 16 values

Optical Satellite sensors

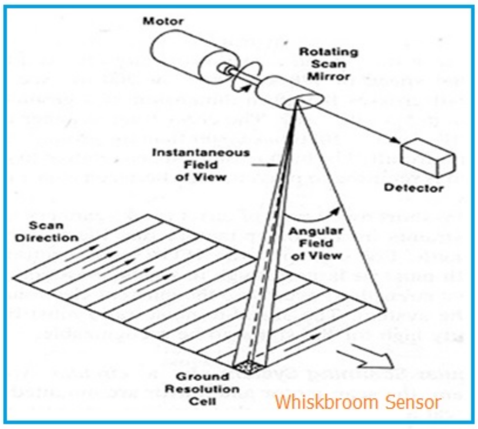
Motivation: mapping from space

- terrestrial and airborne mapping cannot deliver information necessary for sustainable development on global scale

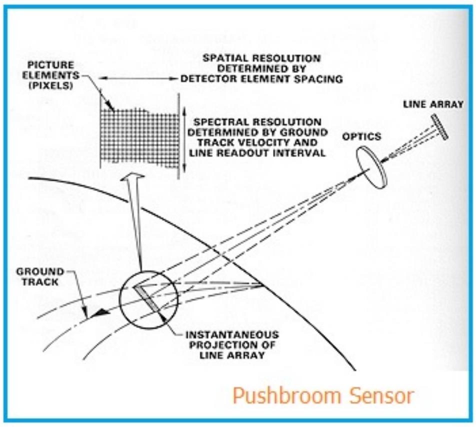
- monitoring of climate change
- rapid hazard response
- large scale mapping

Some technical issues

- geostationary satellites - orbit in 36000km altitude
- sun-synchronous orbit
    - revolution takes about 90-100 minutes in 500-900km altitude
    - inclination about 98° with respect to equator
    - Step by step the entire globe is mapped (except poles)
    - Pass over always at same local time (optical: acquire only images on dayside)
- **image acquisition in the morning**: data take approximately at half past 10 a.m.(equator)
    - earlier: shadows too large
    - later: too many clouds due to evaporation
- data broadcasted to ground stations
- direct sensor orientation: gyros (for determination of attitude change), star sensors and positioning system
- opto-mechanical sensor (Whiskbroom Scanner/Cross-track scanner, back and forth)

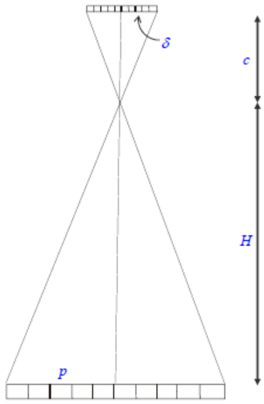


- Linear CCD Array (push broom scanner/along-track scanner)

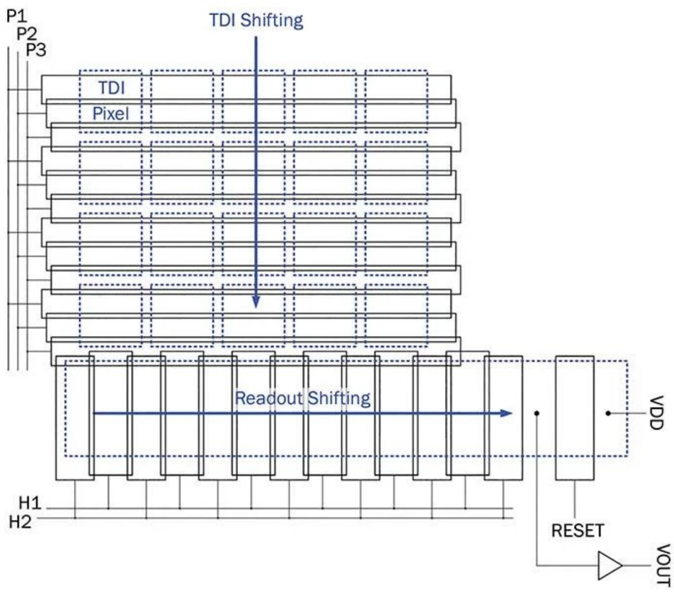


- pixel size on the ground $p = \delta * H/c$ = Ground sampling distance - usually nadir view

$$\frac{p}{H} = \frac{\delta}{c} \to p = \frac{\delta \cdot H}{c}$$



    - size of sensor elements δ
    - focal length of sensor c
    - altitude H
- TDI sensor: time delay and integration sensor



    - 1m pixel size corresponds to 0.14 ms (~7km/s)
    - longer integration time by shift of charge corresponding to speed of image movement on sensor
- sensor geometry: focal plane, merged image line
- correction of earth's rotation effects: fill in pixels are critical for classification, use only for visualization
- **orthophoto**: correction of perspective effects
    - Digital Terrain model: comon orthophoto
    - digital surface model: true orthophoto

Multispectral satellite sensors

- optical high resolution satellite sensors
  - use **linear CCDs** and are on sun-synchronous near-polar orbits
  - most multispectral systems have **4 channels (RGB, near IR)**
  - accuracy on the ground depends on available additional information(GCP, DTM) - **Geo-coding**
  - product specifications and availability varies, in particular: camera model, raw imagery, stereo imagery
  - **prices** quotas vary with **location, time to delivery and size**
  - value-added products(**orthoimages**)
- space imagery can be obtained only at regular intervals
- **cannot be obtained on demand in real-time**
  - celestial mechanics
  - ordering restrictions - one sensor for many users

Indices NDVI: $NDVI = \frac{NIR - Red}{NIR + Red}$

- **advantage** of index(Ratio): due to **different illumination**, the same land cover has different grey values in band A, same problem for band B. However, in the ratio image of the two bands, i.e. band A/band B, we have similar grey values for each class.
- normalized difference Vegetation **index(NDVI) = $(Band4 - band3)/(Band4 + band3), [-1, +1]$**
  - band 4 near infrared, band 3 red
  - NDVI=-1: black, NDVI= 1: white
  - a larger NDVI value indicates higher vitality

Hyperspectral sensors

Sensor	Satellite	Spatial grain (pixel size)	Spatial extent (swath width) (km)	Spectral grain (no. of bands)	Spectral grain (bandwidth)	Spectral resolution (nm)
Compact high-resolution imaging spectrometer (CHRIS)	Project for on-board autonomy (PROBA)	19–36 m	14	Up to 62, programmable	1–12 nm	Up to 410–1,050
Hyperion EO-1	Earth observing-1	10 m PAN, 30 m all other bands	7.7	220	10 nm	356–2,578
Global imager (GLI)	Advanced earth observing satellite-II (ADEOS-II)	250 m—6 bands corresponding to Landsat, 1 km—all other bands	1,600	36	12–2,985 nm	380–12,000
Medium-resolution imaging spectrometer (MERIS)	ENVISAT	250 m–1 km	1,150	15	2.5–12.5 nm, programmable	390–1,040
Moderate-resolution imaging spectrometer (MODIS)	TERRA	250 m VNIR, 500 m VNIR-SWIR, 1 km TIR	2,330	36	10–15 nm VNIR-SWIR	405–14,385

Depth from stereo

two images required of sufficient: overlap, baseline

Classification

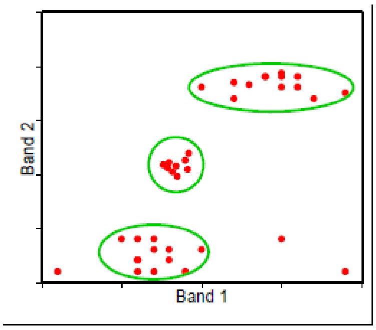
Introduction

- motivation: derive map from Remote sensing image
- **land cover and land use**
    - classification gives LAND cover
    - many users are more interested in how the terrain is being used: land use - high resolution image
    - example
        - grass is land cover
        - pasture and recreational parks are land use of grass
    - land use extraction requires e.g. context
- enlarging the dimension of feature space
    - dimension of feature space space must not get too large
    - a pixel of a multi-spectral image is one dimension of the feature
    - the choice of features is crucial for classification performance: usually model knowledge required!
- problem: too many features
    - price and pay
    - sometimes only a few of those dimensions important
    - irrelevant dimensions might be misleading
- **from images to features**
    - separate different materials by different spectral response
    - number n of bands gives feature space
- feature space: multi-dimensional coordinate system
- **land classification**

- aims to label each pixel in a scene to spectific land cover types
- pixels can then be either correctly classified, incorrectly classified, or unclassified
- two main types
    - unsupervised classificaion
    - supervised classification

Unsupervised classification

- not a prior knowledge assumed about data
- tries to spectrally separate the pixels
- users has control over: number of classes, number of iterations, convergence thresholds
- example spectral plot



    - two bands of data
    - each pixel marks a location in this 2d spectral space
    - our eyes can spite the data into clusters
    - some points do not fit to clusters
- k-means
    1. a set of number k of cluster centres are positioned randomly through the spectral space
    2. pixels are assigned to theire nearest cluster
    3. the mean location and variance(shape) are re-calculated for each cluster
    4. repeat 2 and 3 until movement of cluster centres is below threshold
    5. assigh class types to spectral clusters
- isodata: extends k-means but also consider shape(standard deviation) of clusters
    - steps
        1. a set of number k of cluster centres are positioned randomly through the spectral space
        2. pixels are assigned to theire nearest cluster
        3. the mean location and variance(shape) are re-calculated for each cluster
        4. combine clusters if centres are close
        5. split clusters with large standard deviation in any dimension
        6. delete clusters that are too small
        7. reclassify each pixel and repear
        8. stop after max iterations or at convergence limit

9. assign class types to spectral clusters

- application
  - unsupervised classification can often produce information that is not obvious to visual inspection
  - very useful where 'ground truth' data is difficult to obtain
  - results may not coincide with desired land cover classes
  - useful to trigger subsequent supervised classification

Supervised classification

- 2 ways to get the ground truth: **ground truth & empirical identification**
- principle of selecting training areas
  - homogeneous areas
  - several areas per class
  - areas well distributed across the scene
- minimum distance classifier
  - calculates mean of the specteral values for the training set for each class
  - measures the distance from a pixel of unknown class to the mean of each class
  - **assigns the pixel to the class with the shortest distance**
  - assigns a pixel as unknown if the pixel is bayond the distance defind by the analyst(optional)
- hierarchical decision tree
  - according to threshold the data are divided step by step
  - the thresholds are either set manually or derived by training
  - however, the same data can be separated in many ways
  - subjective, tendency to overfitting
  - problem: limited solution to too closed data

- **Bayesian classification**
  - generative approach
    - **the posterior probability $p(C|x)$ is maximized**
    - **posterior $p(C|x)$ is modelled indirectly according to the theorem of Bayes**
    - requires a model of the joint distribution $p(C,x)$ of the data x and the class label C
    - possible to generate synthetic data sets by sampling from the joint distribution
  - strong theoretical foundation: if the required distribution are known, Bayesian classification will deliver the result with the lowest proportion of classification errors!
  - recap: probabilities
    the joint probability: $\frac{|A,B|}{|\Omega|} = P(A,B)$
    the conditional probability: $P(B|A) = \frac{P(A,B)}{P(A)}$
  - **theory of Bayes** $P(A \mid B) = \frac{P(B|A)P(A)}{P(B)}$
    - P(A|B) – the probability of event A occurring, given event B has occurred
    - P(B|A) – the probability of event B occurring, given event A has occurred

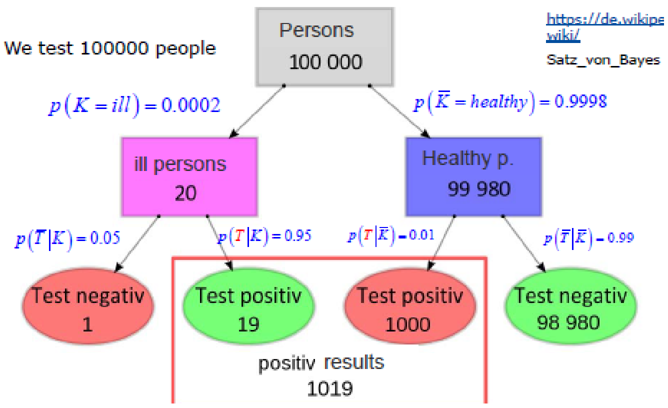
- P(A) – the probability of event A
- P(B) – the probability of event B

- **Derivation for our purpose**
  - joint distribution p(x, C) of data x(A) and classes C(B): $p(x, C) = p(C|x) * p(x)$
  - likewise: $p(C, x) = p(x|C) * p(C)$
  - due to $p(C|x) = p(x|C)$, $p(C|x) * p(x) = p(x|C) * p(C)$
  - therefore, $p(C \mid x) = \frac{p(x|C) \cdot p(C)}{p(x)}$
  - the theorem of Bayes allows inverse reasoning derive information about the cause(the object type) from the effect(the observed features)
  - $p(C)$**: prior probability** - corresponds to knowledge(bias) for the occurrence C
    - if no information is available: uniform distribution,
      - all classes have same probability,
      - maximum-likelihood
    - p(C) can be determined iteratively
      - classification under th eassumption of a uniform distribution of the occurrence of the indicidual classes
      - determination of $p(C)$ from the relative frequences of occurrence of the individual classes C
      - classicification according to the theroem of bayes
  - $p(x|C)$: likelihood
    - probability to observe x if it is known to belonging to class C
    - the likelihood is no probability density function of the classes C
    - **for each class** C^* **there is a model for** $p(x|C = C^*)$**, which describes the distribution of the feature for the classes**
    - detemination from data in training areas
    - non-parametric Models: direct determination of $p(x|C)$ from the training data
    - Parametric Models: based on the assumption of an analytical model for $p(x|C)$, whose parameters are estimated from the training data
  - $p(x)$: probability of the data(also called evidence)
    - equal for all values of C because it does not depend on C - MAP can also be applied without knowing $p(x)$: $max(p(C|x)) = max(p(x|C) * p(C))$
    - $p(x)$ ensure that $p(C|x)$ can be interpreted as a probability and can be used as such in further probabilistic process
    - $p(x)$ can be determined as the marginal distribution of $p(x, C)$
    - compute P(x) using the law of total probability

$$P(B) = \sum_j P(B|A_j) P(A_j)$$
$$\Rightarrow P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_j P(B|A_j)P(A_j)}$$
$$P(A|B) = \frac{P(B|A)P(A)}{P(B|A)P(A) + P(B|\neg A)P(\neg A)}$$

- Examples
  - It is known that from 100000 people 20 suffer from a certain severe illness: $p(K = ill) = 0.0002$, $p(\bar{K} = healthy) = 0.9998$
  - It exists a screening method for this disease:
    - Sensitivity of the tests: 95% of all ill persons are detected (T = 1) : $p(T|K) = 0.95$, $p(\bar{T}|K) = 0.05$
    - Unfortunately, the test delivers false positive result for 1% of healthy persons: $p(T|\bar{K}) = 0.01$, $p(\bar{T}|\bar{K}) = 0.99$
  - We may be interested in the portion of ill persons in the set of all persons with positive test results:

$$P(K|T) = \frac{P(T|K)P(K)}{P(T|K)P(K) + P\left(T|K^c\right)P\left(K^c\right)} = \frac{0,95 \cdot 0,0002}{0,95 \cdot 0,0002 + 0,01 \cdot 0,9998} \approx 0,0186$$



- workflow of Bayesian classification
  - Given:
    1. Models for the likelihoods $p(x|C^k)$ of all classes C^k
    2. Priori probabilities$p(x|C^k)$of all classes
    3. A feature vector x to be classified
  - Wanted: Class C_{map} of x according to the MAP criterion
  - Procedure:
    1. For all C^k. calculate $p(x, C^k) = p(x|C^k) \cdot p(C^k)$
    2. Calculate $p(x) = \sum_i p\left(x|c^t\right) \cdot p\left(c^t\right)$
       1. For all C^k: calculate $p(C^k|x) = p(x, C^k)/p(x)$
       2. C_{map} results as the label C^k for which $p(C^k|x)$ is a maximum.
- training: provision of examples
  - user marks image resion which correspond to a class *Ck*
  - assumption: all pixels in the selected region belong to *Ck*
  - training data must be provided for all classes
  - the training data must be representative for all classes
- modelling of the likelihood for the classes
  - based on training data

- different for parametric and non-parametric methods

- maximum likelihood method
  - Bayesian classification method **special case**: prior probability unknown - only likelihood
  - the classes *C* are often modelled to as multivariate normal distribution over feature space *x*
  - the corresponding probability density function for a sample of n independent identically distributed normal random variables (the likelihood) :
    where $\bar{x}$ is the sample mean.

$$f\left(x_1, \ldots, x_n \mid \mu, \sigma^2\right) = \left(\frac{1}{2\pi\sigma^2}\right)^{n/2} \exp\left(-\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 + n(\bar{x} - \mu)^2}{2\sigma^2}\right)$$

  - the pixel to be classified is labeled to belong to the class of the highest probability

Quantify classification performance

- Overall measure
  - Overall accuracy: Percentage of correctly classified pixels
  - Kappa coefficient: Agreement between classified pixels and ground truth $[-1, 1]$
- **user's accuracy**/Commission error: number correctly identified in a given map class/ number claimed to be in that map class
- **producer's accuracy**/Omission error: number correctly identified in reference plots of a given class/ number actually in that reference class
- **error matrix**
  reference source - y -user's accuracy
  classified map - x - producer's accuracy

	Class types determined from reference source					
Class types determined from classified map	# Plots	Conifer	Hardwood	Water	Totals	User's Accuracy
	Conifer	50	5	2	57	88%
	Hardwood	14	13	0	27	48%
	Water	3	5	8	16	50%
	Totals	67	23	10	100	
Producer's Accuracy		75%	57%	80%		Total: 71%

Airborne laser scanning

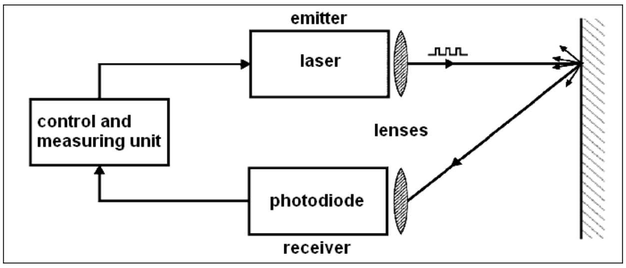
Overview

- measurement principle, 3D cloud
  - 3D position information
  - radiomatric information
- properties of airborne laser scanning
  - multi sensor system

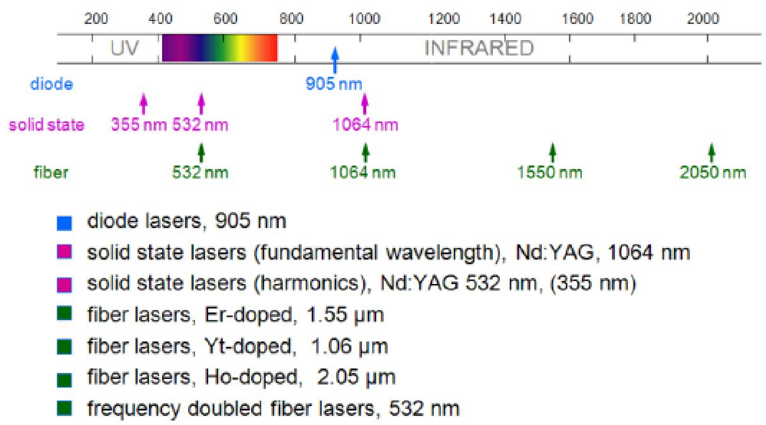
    - GNSS receiver for position of sensor
    - inertial measurement unit(IMU) fir measuring the orientation of the platform
    - laser scanner: scanning and ranging
  - active measurement system
    - light source
    - laser, independent from sunlight, no cast shadows
  - polar measurement system: point determined via measurement of a single direction and range(one position, good in vegetation)
  - penetration's capability: laser pulse can penetrate vegetation through small openings in the foliage
  - multi-target capability: for a single laser pulse, multiple echoes(i.e. returns) can be recorded
  - surface measurement system
    - random laser beam direction, no targeting of specific object points, capturing of surface via scanning
    - object reconstruction from 3D point cloud(in post processing)
  - radiometric infromation: laser = monochromatic light

Basics

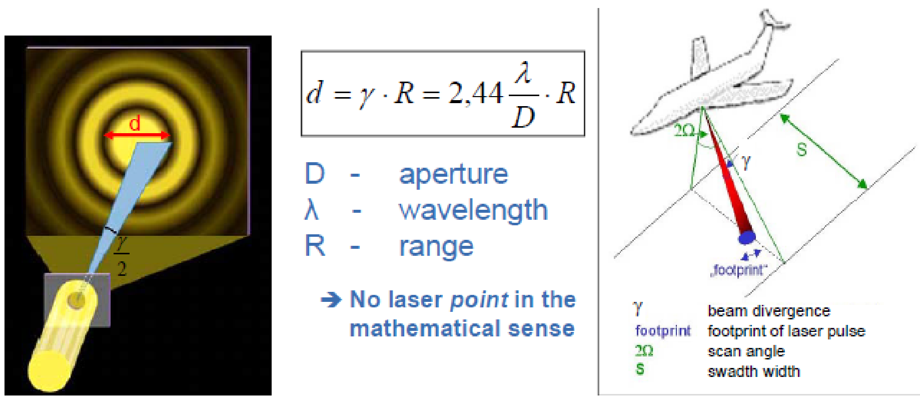
- conponents of an ALS systems
  - positioning: GNSS receiver
  - attitude: inertial measurement unit IMU
  - object detection: laser scanners



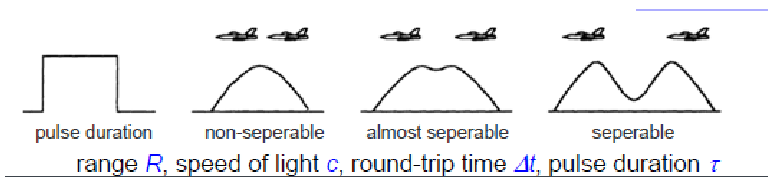
    - laser source
    - beam deflection - scanning
    - transmitter optics
    - receiver optics
    - photodiode; conversion of optical signal - electric signal
    - analog digital converter; electric signal - digital signal
    - target detection
    - range estimation unit(discrete echoes or full waveforem)
- available laser sources/ wavelength for ALS



- reflectance at different wavelengths for different application
  - 1550nm - soil, terrain model
  - 1064nm - vegetation, forestry - snow, glacier, snow heights
  - 532nm - snow, glacier, snow heights - penetrates water, bathymetry **!problem: eye safety!**
- properties of laser pulses
  d: diameter of main maximum(footprint - limit image resolution) d on the ground
  no laser point in the mathematical sense

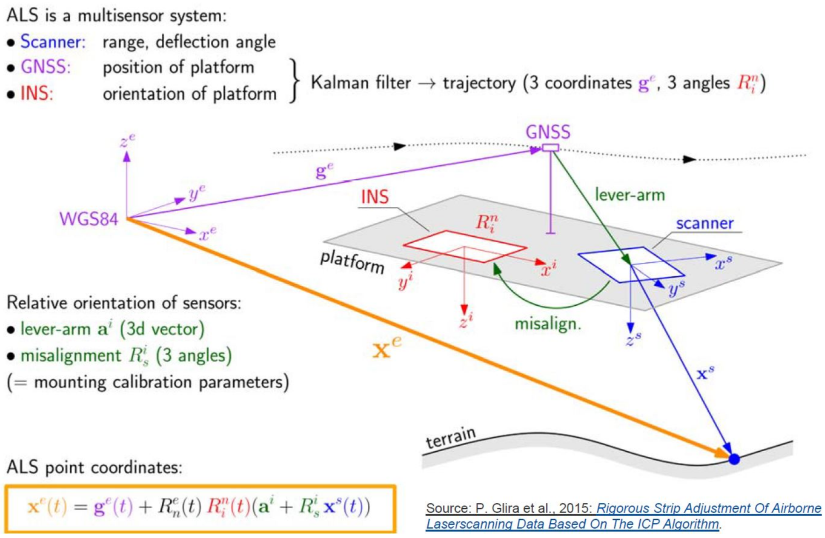


- time = distance:
  typical pulse length in ALS: $1ns - 10ns = 30cm - 3m$
- range estimation and range resolution
  - range estimation: round-trip travel time delta t of signal(sensor-target-sensor) $R = \frac{c \cdot \Delta t}{2}$
  - range solution: echoes representing targets(i.e. objects) maybe separable $\delta_R = \frac{c \cdot \tau}{2}$
  - overlay

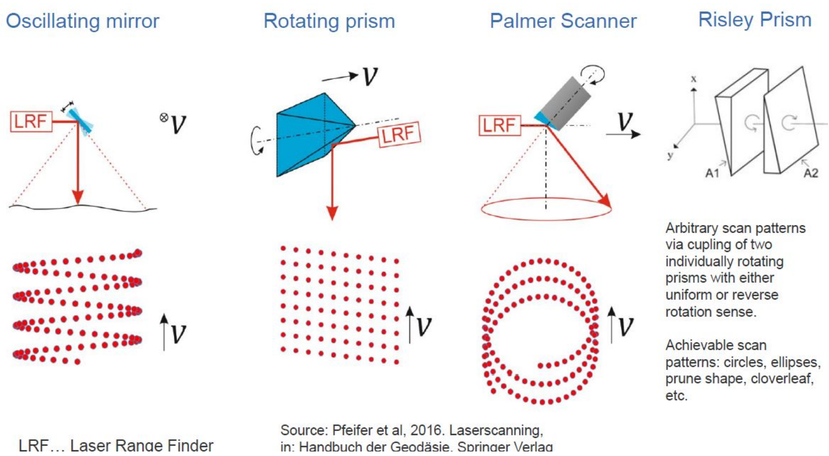


- signal recording: discrete echo vs. full waveform
- signal strength: laser-rader equation

- ALS sensor model: direct georeferencing



- Scanning mechanisms



- stripwise data acquisition
  - **overlap of adjacent strips required for**
    - seamless coverage of project area
    - redundant acquisition at strip boundary
    - **optional: increase of point density(overlap>50%)**
  - oscillating mirror
    - middle low density
    - side high density
- flight planning, quality assesment, strip adjustment

From 3D point clouds to digital terrain models

- 3d point cloud
- digital surface model, DSM: **open terrain with buildings and vegetation**
- digital terrain model, DTM: **terrain surface without buildings and vegetation**

Specific ALS systems

- laser bathymetry
- single photon LiDAR
- UAV laser scanning
- multispectral laser scanning: NDVI

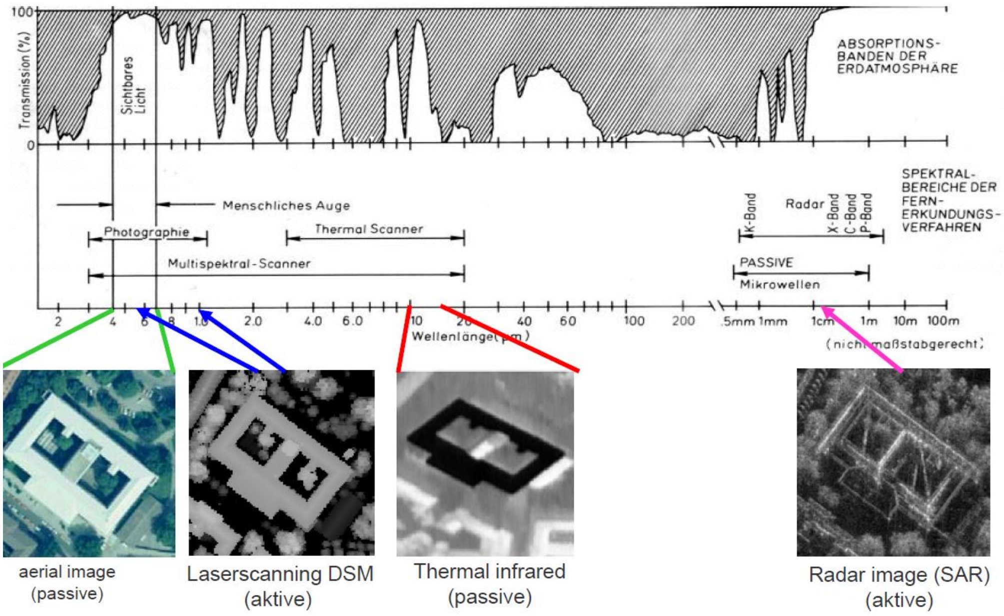
Selected applications

- building modeling
  - basis: 3D point cloud or 2.5D-DSM
  - mature solution available - commercial: semi-automatic approaches predominant
  - research
    - detection and modelling of detialed structures
    - inrease of lecel of automation
- power lines(ALS/ULS)
  - polar measurement system - one position
  - duties of poer supply companies
    - detectio of dameges on power lines and poles
    - monitoring of construciton work
    - monitoring of distance between power lines and vegetation
  - satandard techniques: expensive and laborious or not possible(photogrammetry)
- forest
- laser bathymetry
- the fusion of ALS+multi and hyperspectral images
  - full waveform laser: geometry
  - hyperspectral sensor: chemical composition
  - advantages:
    1. lawn and sealed surfaces hardly separable with (monochromatic) laser
    2. resolution of mixed pixels based on geometry feasible

Radar

Basics of radar

- Radar = radio frequency detection and ranging
- active illumination and sampling of echo signals
- no optic devices, but antennas and high frequency electronics
- interesting object feature - radar cross section, object geometry, object velocity
- signal feature: amplitude, phase and polariyation of the signal
- spectral domains used for remote sensing - Transmission of Atmosphere at good weather conditions:



- **radar(large wavelength) almost weather independent!**
- absorption
  - the energy of the EM wave is proportional to frequency: long wave EM have far less energy than visible light
  - absorption in the MW domain is mainly governed by the conductivity that depends on permittivity ε
    - introduction of currect in matter
    - rotation of dipole molecules(water) → thermal energy(microwave oven)
    - low conductivity leads to transmission
- object model: backscatter cross section σ
  - describes reflection of a single target
    - depends on
      1. directivity, geometric cross section area and reflectance
      2. signal frequency , signal polarization and moisture
    - backscatter **cross section**
      - The smaller λ (= the higher frequency), the larger σ!
      - high frequency returns more wavelength drops
  - strong aspect dependency of SAR: different aspects, different response

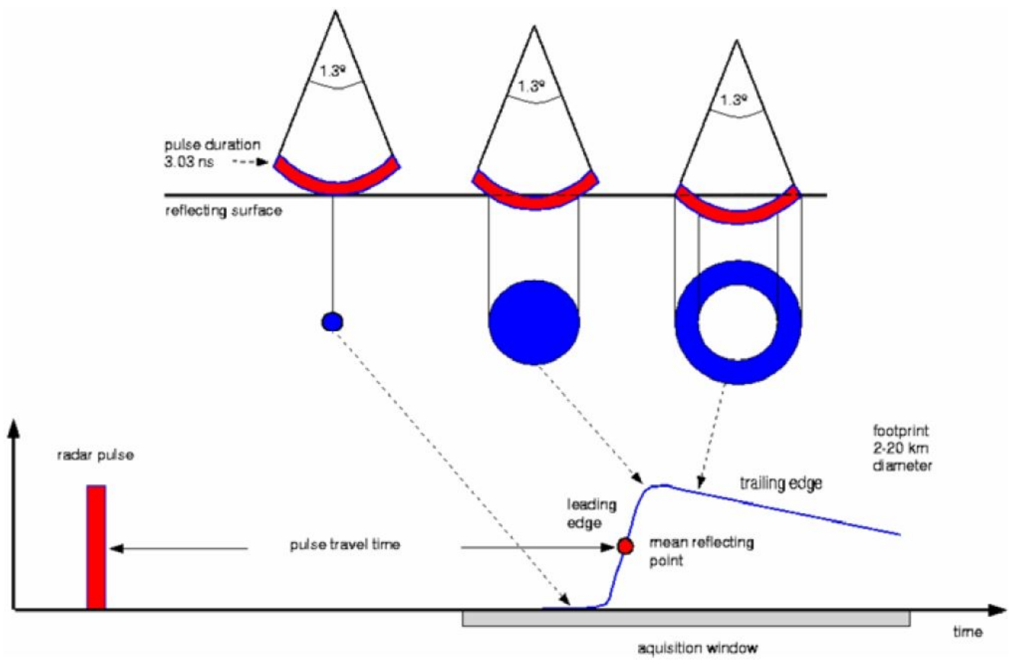
Passive sensors - microwave radiometer

- passive instruments for measurement of reflected or emitted radiance of earth surface and/or atmosphere
- measurement depends on: wavelength, observation position, polarization, material(particulary water content)
- major applications
  - determinatio of liquid and vapor water content of atmosphere
  - correction of altimeter data

- mapping of soil moisture, ice cover ocean salinity and sea ice cover

Active non-imaging sensors

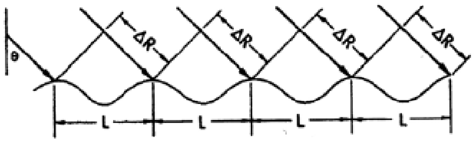
- Radar altimeter
  - active illumination in nadir direction with short pulse
  - distance to water surface from two-way signal runtime
  - product: global maps of sea level animalized caused by variations of the earth's gravity and ocean currents
  - **principle of radar altimetry**



- in remote sensing, resolution is usually governed by pulse length.
  - however, due to large distance and short pulses better then diffraction limit $R * \lambda / D$ we face here a exception
  - note: lasers usually work in diffraction limit domain
- **pulse-limited resolution**
  - **diffraction limit**: $\delta = \lambda * H/D$
    - sensor altitude *H*
    - pulse duration τ
    - wavelength λ
  - **pulse limit**: $\delta = 2 * rs$
    - **radius of resolution circle** $r_s = \sqrt{(c * H * \tau)}$
    - velocity of light *c*
- radar altimetry: error sources and accuracy
  - ionosphere: signal delay dependent on dispersive 'total electron content'(TOC)
    remedy: 2 frequencies

- troposphere: water vapor delays signal
  remedy: correction accoring to simultaneous radiometer measurements
- height accurancy over ocean: 3-10cm

- scatterometer

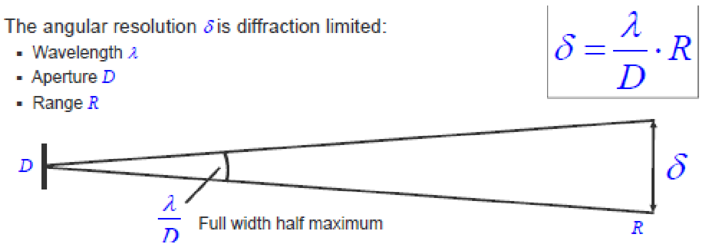


- main application: measurement of wind velocity oversea
- principle: precision measurement of backscatter
- in case of oblique signal, the backscatter of ocean is dominated by ripple waves induces by wind
- Bragg resonance: interference maxima in case of path difference of both signal components: $2dsin\theta \ = \ n\lambda$

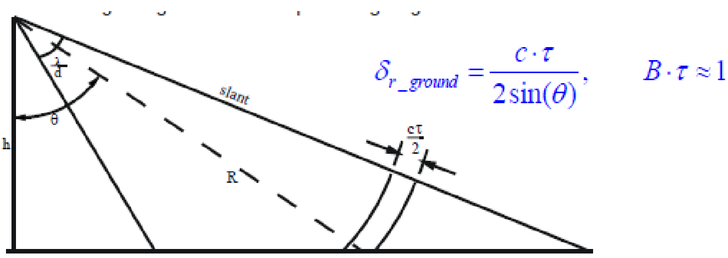
Active imaging sensors

1. **real aperture radar(RAR): poor angular resolution of radar**

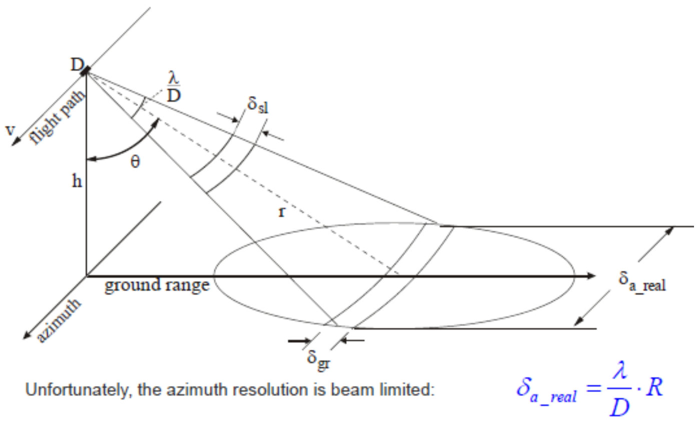
- **angular resolution of imaging sensors: poor angular resolution of radar**



- range resolution of imaging Radar
  - resolution in range direction requires oblique illumination
    - sampling of back scatter
    - object separation according signal runtime
  - resolution in slant range δ_r
    - **independent** from the sensor to scene distance
    - high range resolution requires large signal bandwidth *B*

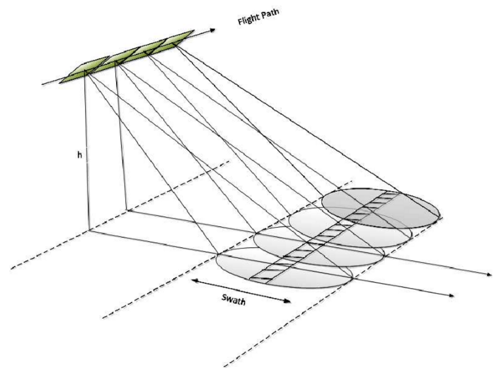


  - azimuth resolution

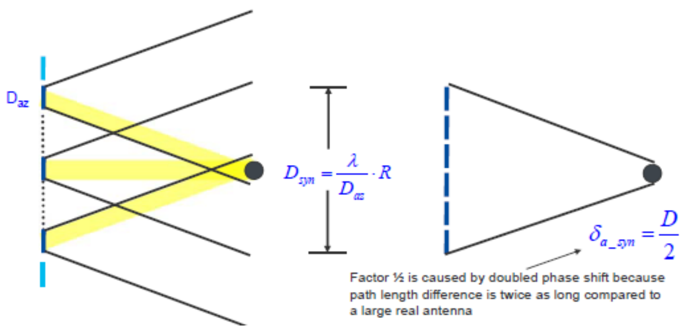


- applications
  - pro of real aperture radar: data can be interpreted at once without further processing
  - no high spatial resolution requried
  - real time requirements
  - e.g. coast guards: monitoring of oil pollution from ships

2. **synthetic aperture radar(SAR)**
   - principle of synthetic aperture radar

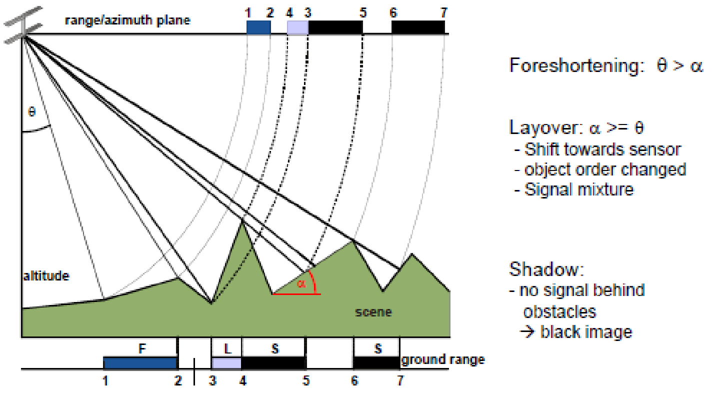


- measurement sequence along sensor flight pass - assembly of large antenna
- synthesis of SAR image using doppler signal shift
  - **side -looking illumination required!**
  - $\delta a_{syn} = \frac{D}{2(D - real\ size\ of\ antenna)}$
  - for image synthesis, all individual signal contributions are integrated into the correct image cell by compensation of their different runtimes (phase delays) - SAR processing



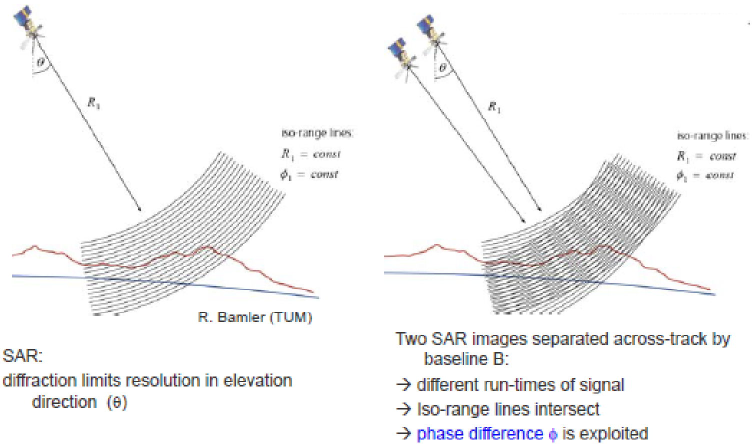
- radar backscatter coefficient
  - classical radar
    - detection of single/few targets, e.g. planes
    - non-targets(clutter) are not useful and disturb target detection
    - the feature of interest is in most cases the **Radar cross section** σ if the target(unit m^2)
  - radar remote sensing
    - there is no equivalent to clutter
    - besides point target(masts, cars etc,)
    - distributed targets(grass, fields, forests) often dominate the image content
      - their scatterer density determines mainly the appearance of the image
        - they are described by a dimensionless **radar backscatter coefficient** σ_0
        - different brightness caused by different density

- from cartesian to polar coordinates
  - the phase is evenly distributed(not further considered for single images)
  - however, the difference of the phase of two images carries valuable information - SAR interferometry
  - why is speckle a Nuisance
    - the speckle hides the quantity of interest, namely the typical radar backscatter coefficient $\sigma 0$ of the given land cover class
    - on average a grey value according to the radar backscatter coefficient σ0 of grass is exoected
    - speckle reduction: increases the radiometric resolution of the image; allows the usage of standard means of image processing(extraction of regions, edges, lines, contours)
- influence of topography on SAR mapping



  - foreshortening: smaller area in image - brighter
  - layover
    - shift towards sensor
    - object order changed
    - signal mixtual

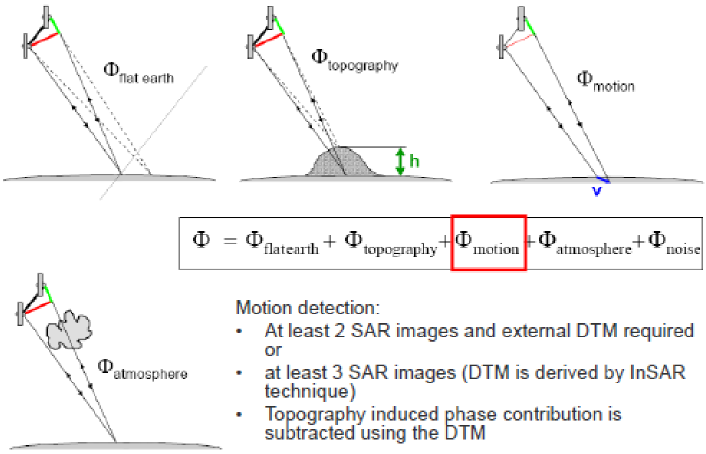
- top of mountain closer than the foot to the sensor
- shadow(occlusion)
  - no signal behind obstacles
  - black image - cannot be observed in the image
- SAR polarimetry - reflections may change wave's polarization direction
  - in remote sensing usually linear polarisation are used
    - E-Field vector either horizontal H or vertical V
    - 4 images $S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$
  - is used for
    - separation of surface or volume(vegetation) scattering process
    - object geometry
- SAR interferometry
  - amplitude & phase
  - InSAR: measurement of elevation angle



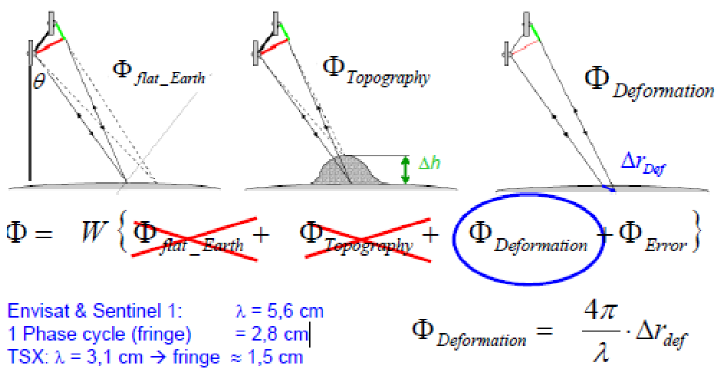
    - SAR
      - diffraction limits resolution in elevation direction θ
      - only know the distance
      - dont know the position
    - Two SAR image separated across-track by baseline B
      - different run-times of signal
      - iso range lines intersect
      - phase difference Φ is exploited
    - phase difference Φ depends on θ: Φ → θ → Height
    - ambiguity problem: for undulated terrain phase-unwrapping required
- modes for data acquisition
  - repeat-pass-interferometry
    - at least two passes

- mainly satellite sensors
- problem for multi-temporal data
  - **decorrelation of signals because we measure different things**
  - **atmospheric signal delay - phase delay**
- single-pass-interferometry
  - 1 satellite for 2 images
  - images are taken simultaneously
  - airborne sensors
  - same time, same atmosphere
  - distance cancel out
- Digital elevation models(DEM) from InSAR data
  - phase values *ΔΦ*: 0-2 pi
  - add 2 pi regularly
- after phase unwrapping and phase to elevation conversion →DEM

- differential SAR interferometry



  - terms of the differential phase

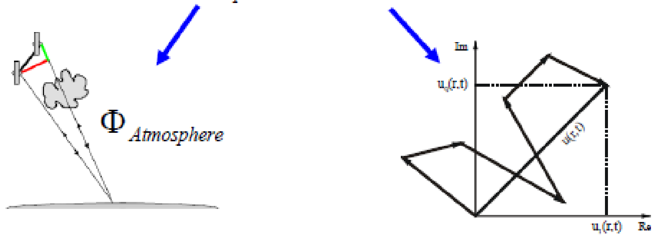


- possibility to measure the surface deformation of a few millimeters because 2 pi equals to a few centimeters only!
- **1 phase cycle(fringe) = λ/2**

- horizontal and vertical surface deformation
  - measured radial velocity can be split in horizontal and vertical components
  - those components can be distinguished using ascending and descending orbit
- problems

$$\Phi = W\left\{\Phi_{flat\_Earth} + \Phi_{Topography} + \Phi_{Deformation} + \Phi_{Error}\right\}$$

$$\Phi_{Error} = \Phi_{Orbit} + \Phi_{Topography\_sim} + \Phi_{Noise} + \Phi_{Atmosphere} + \Phi_{Decorrelation}$$



→ runtime changes

→ Objects change

  - **atmospheric signal delay**
    - **interferograms from only two images are problematic**
    - **atmospheric effects are spatially but not temporally correlated**
      - use as many images as possible and filter out this phase term(high-pass filter)
      - estimate atmospheric effects from GPS or imaging spectrometer
  - **temporal decorrelation**
    - large temporal gap: only noise in vegetation areas
    - good signal: dominant reflection at buildings , rocks etc.
- alternative method: **Persistent scatterer interferometry**
  - time-series of many SAR images
  - consider only pixel, which show stable reflection over time - sparse matrix of reliable motion vectors
  - dorts - buildings, urban
  - low density - agriculture area
  - persistent scatterer interferometry density rises with spatial resolution of SAR
    the smaller the resolution cell, the less clutter pro PS - we are able to detect weaker PS