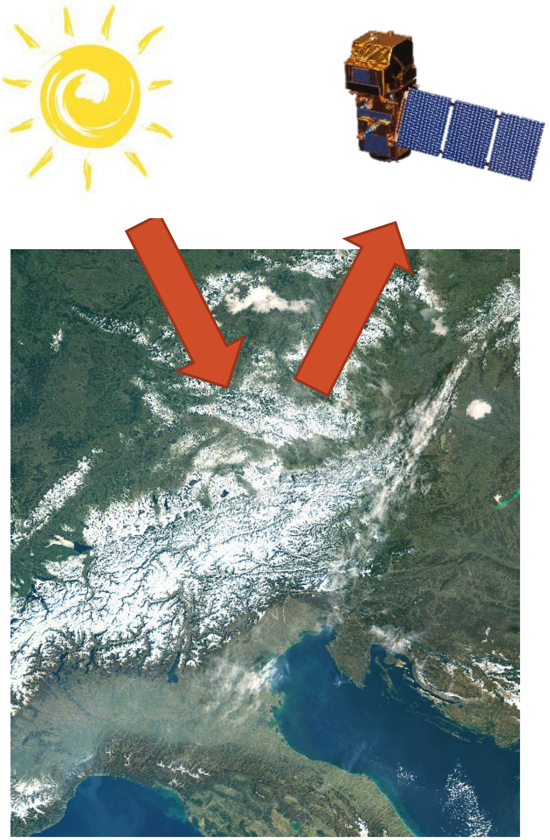
Introduction on Synthetic Aperture Radar

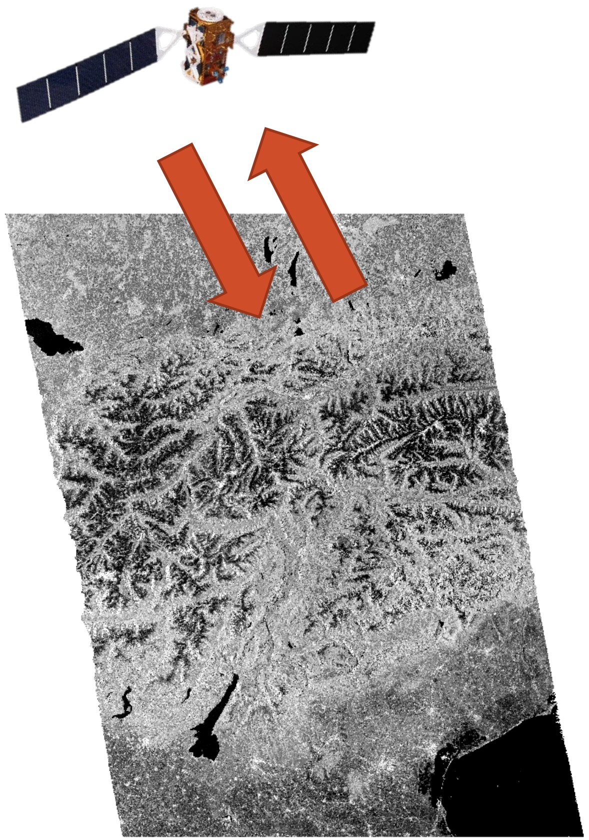
Alexander Jacob with huge credits to Mattia Callegari

SAR basic concepts

Passive and active sensors



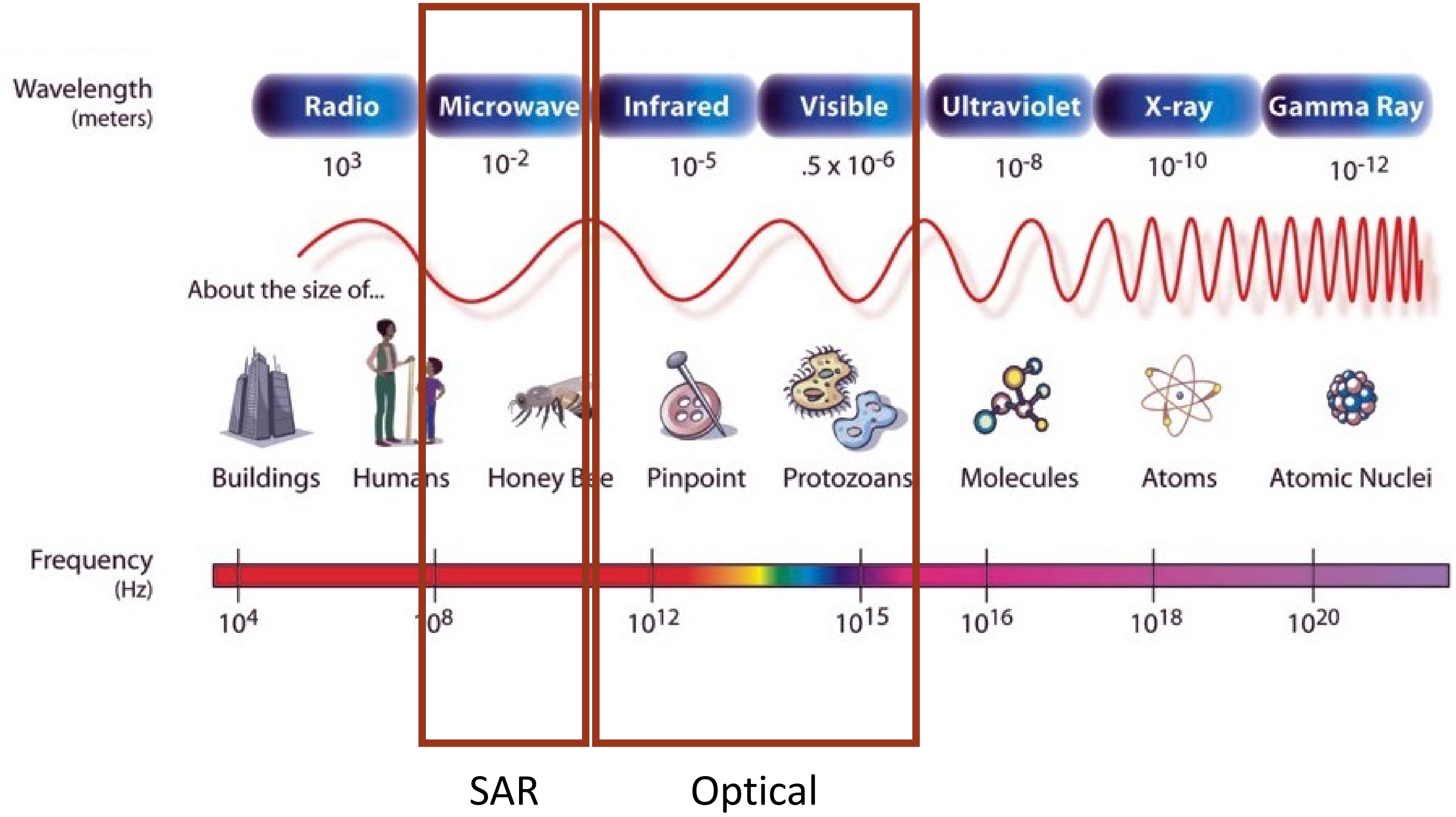
Optical passive sensor



SAR active sensor

- Optical sensors measure reflected solar light and only function in the **daytime**
- SAR sensors can operate in **day or night** conditions

Electromagnetic spectrum



- The surface of the Earth cannot be imaged with visible or infrared sensors when there are clouds
- Microwaves can penetrate through clouds, vegetation, ice, soil.

Why SAR?

- It provides **continuous monitoring**:
  - **Day and night** imaging capability
  - Nearly **weather independent** (not affected by clouds)
  - Key for hazards

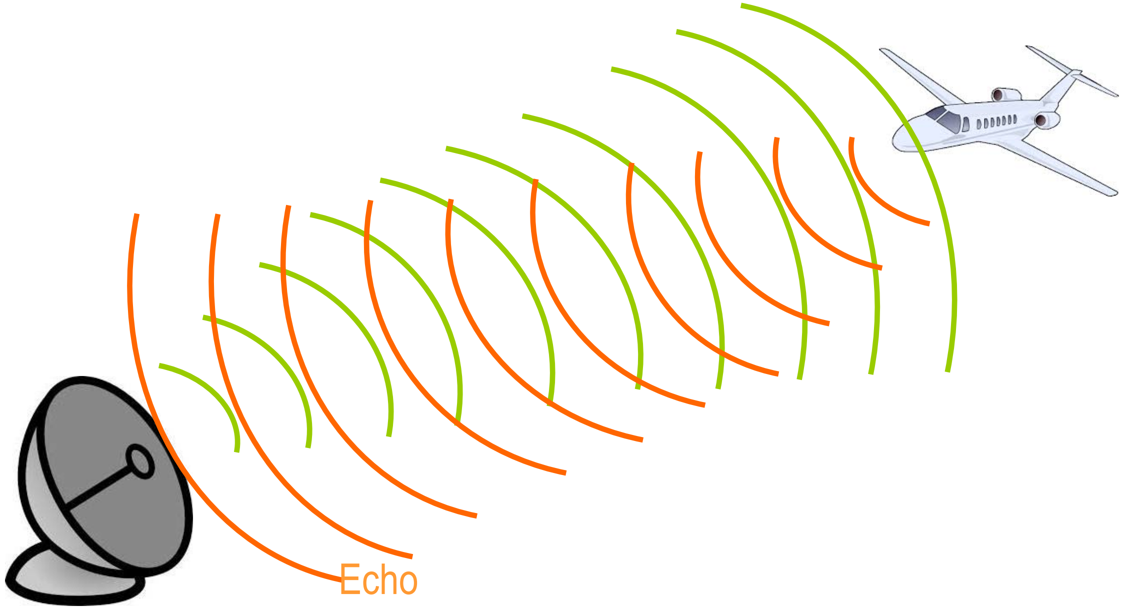
- Information content is **complementary to optical systems**:
  - Sensitive to different characteristic of the scene
  - **Penetration** of the signal through different kind of surfaces, e.g.:
    - Ice
    - Soil
    - Vegetation

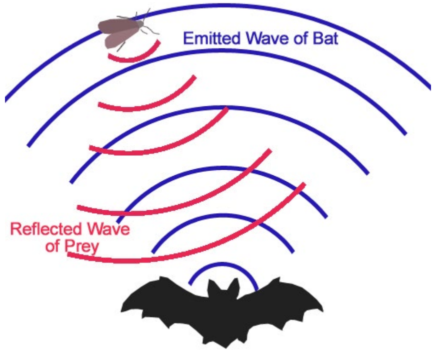
- Drawbacks:
  - More **challenging interpretation** of the image with respect to optical data
  - Higher geometrical distortion due to the **side looking geometry** (no nadir)

RADAR concept

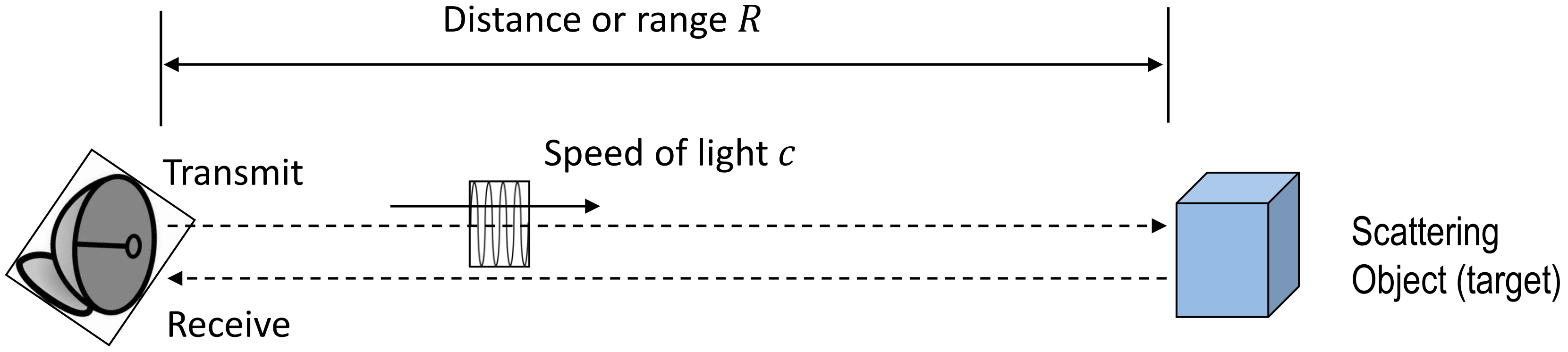
RADAR: Radio Detection And Ranging

- Radio waves (or Microwaves)
- Is there a target?
- At what distance?





Time and range

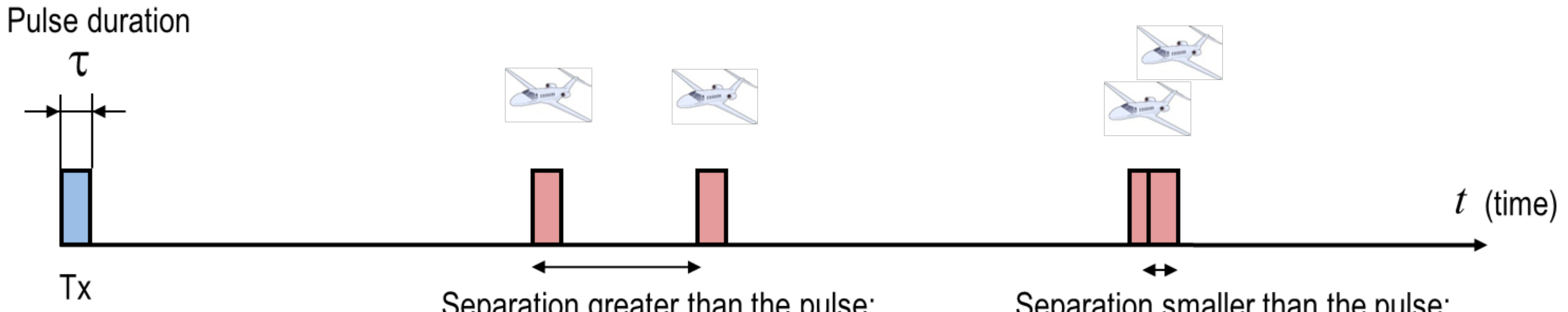


With T the total time delay between transmitting and receiving

$$R = \frac{T \cdot c}{2}$$

Radar resolution (range)

Radar can resolve two objects when they are separated more than the pulse duration



Separation greater than the pulse:
two separate responses

Separation smaller than the pulse:
they cannot be separated

Definition of resolution in range:

$$\rho_r = \frac{c\tau}{2}$$

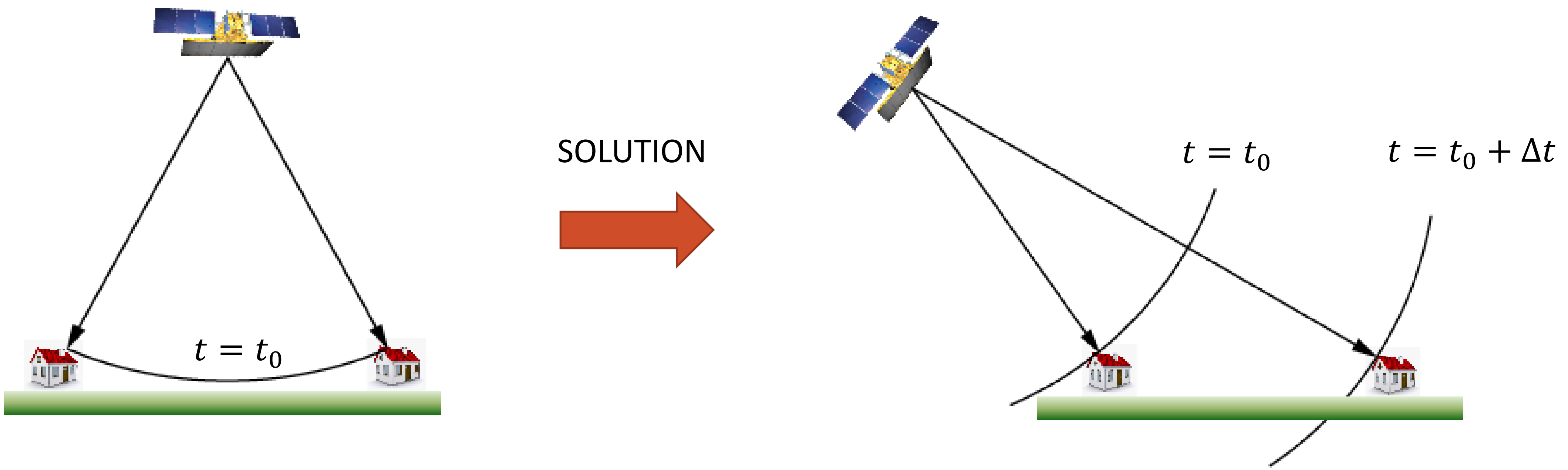
The smaller the pulse duration,
the better the resolution

(J.M. Lopez-Sanchez, 2014)

RADAR for EO

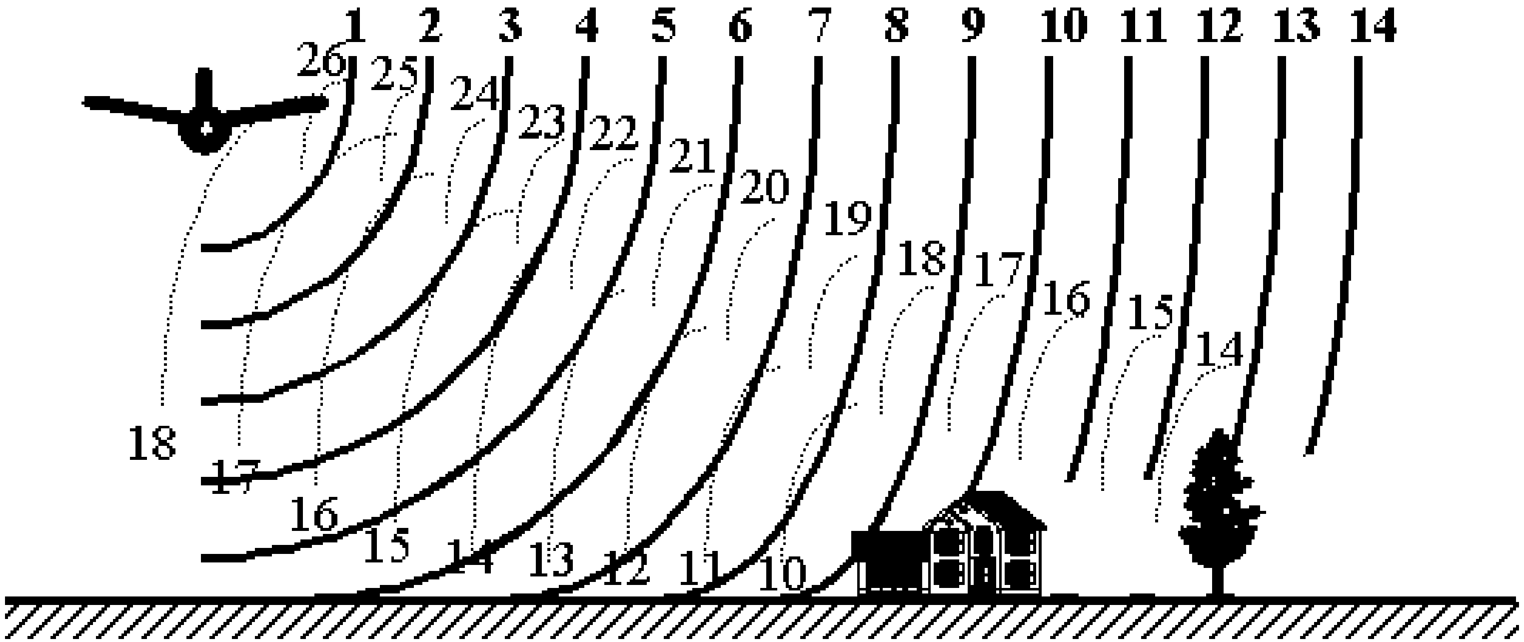
- A radar can distinguish objects by their range (distance)
- However if the radar is nadir looking ambiguities can occur

Nadir looking | **Side looking**



(J.M. Lopez-Sanchez, 2014)

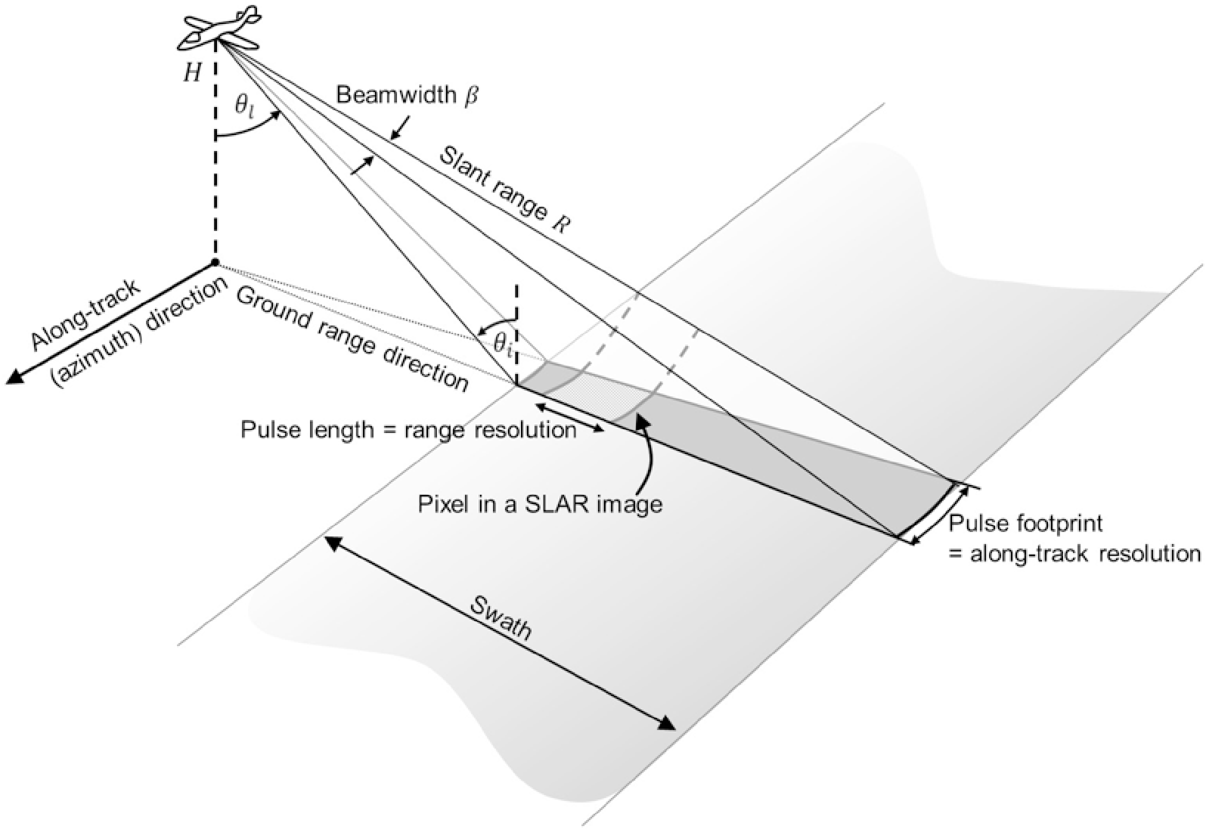
Side-Looking Airborne Radar (SLAR)



By emitting multipule pulses, the radar can measure the signal return of each target and locate them on the correct position on the Earth surface

Credit: Paul Messina, CUNY NY, after Drury 1990, Lillesand and Kiefer, 1994

SLAR ground-range resolution



- **Slant-range resolution**:

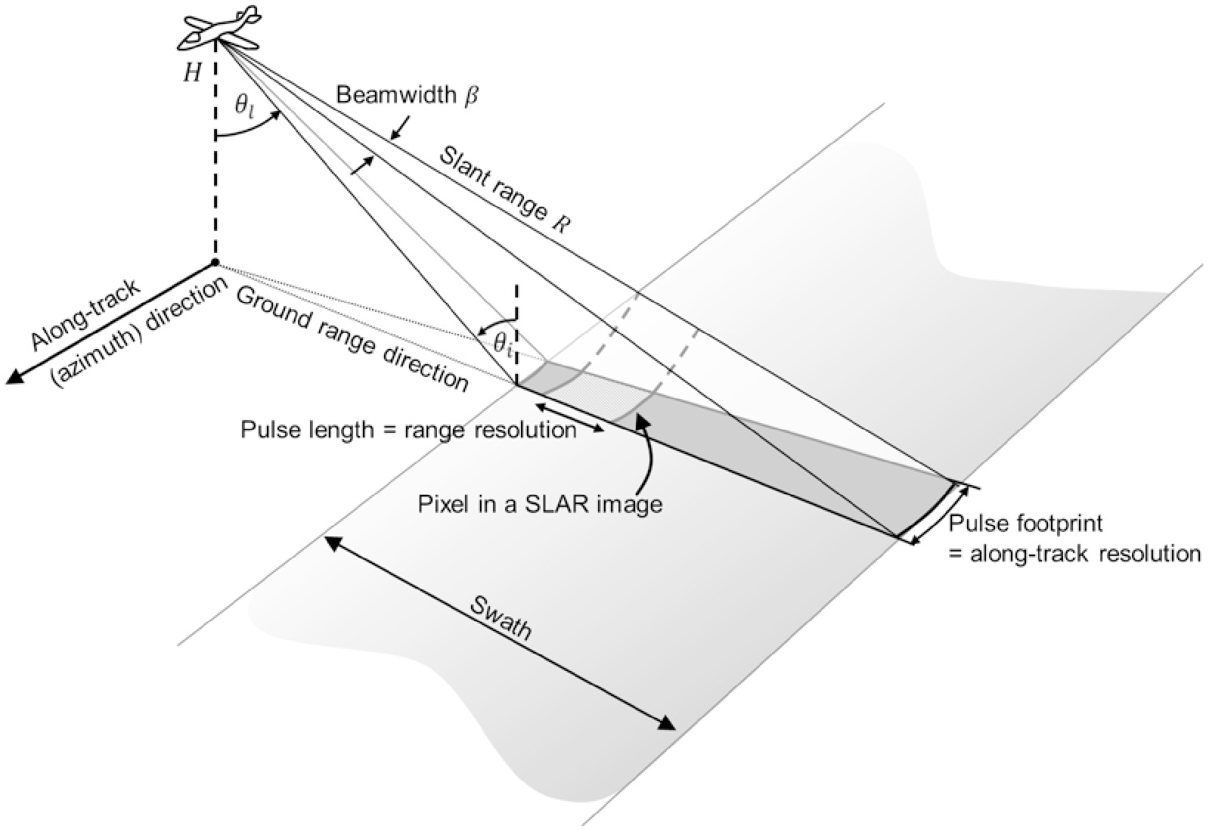
$$\rho_R = \frac{c\,\tau}{2}$$

- **Ground-range resolution**:

$$\rho_G = \frac{\rho_R}{\sin\theta_i}$$

- ρ_G is not constant across the swath: it improves with distance from nadir (due to the increase of θ_i)

SLAR azimuth resolution



- While flying along its track, the radar illuminates an instantaneous area on the ground, i.e. **antenna footprint**

- The size S of the footprint in along-track (**azimuth**) is largely defined by the relationship between system wavelength λ and the side length of the antenna L along this direction, as well as by the distance of the radar sensor from the ground R:

$$S \approx \frac{\lambda}{L} \cdot R$$

SLAR azimuth resolution

$$\rho_A = S \approx \frac{\lambda}{L} \cdot R$$

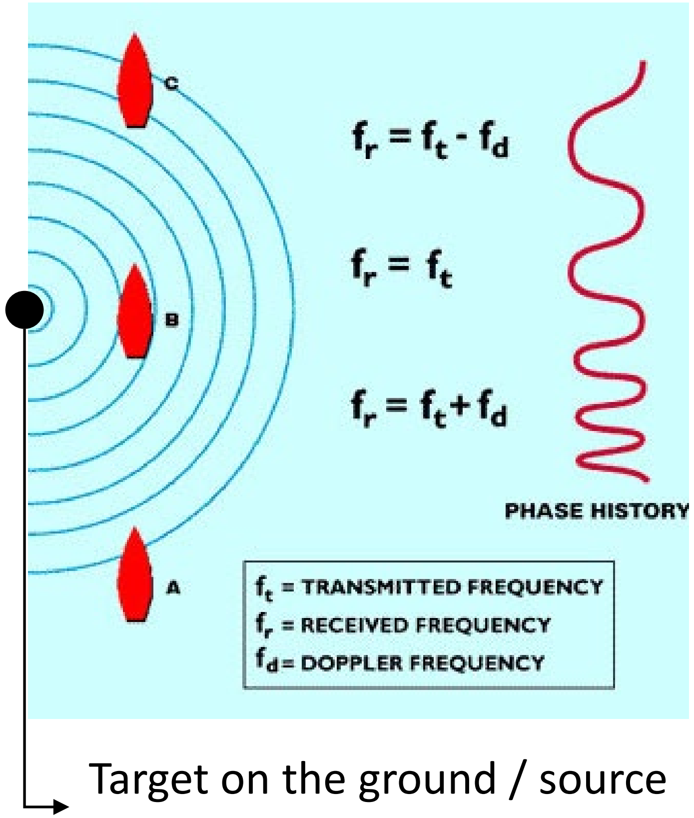
- The azimuth resolution ρ_A is linearly degrading with increasing distance between the sensor and the ground R

- E.g.: $\lambda = 0.03\ \mathrm{m}$ (C-band), $L = 3\ \mathrm{m}$.
  - If operated from an aircraft flying at 3 km of altitude and observing at a look angle of $\theta_l = 30°$, $\rho_A = \frac{0.03}{3} \cdot \frac{3000}{\sin 30°} = 60\ \mathrm{m}$
  - If operated from a spaceborne platform at $H = 800\ \mathrm{km}$, $\rho_A = 16\ \mathrm{km}$.
  - To keep the resolution at 60 m from this spaceborn platform, the antenna should be 800 m long

- Application of SLAR on spaceborn platform is impractical

Synthetic Aperture Radar (SAR)

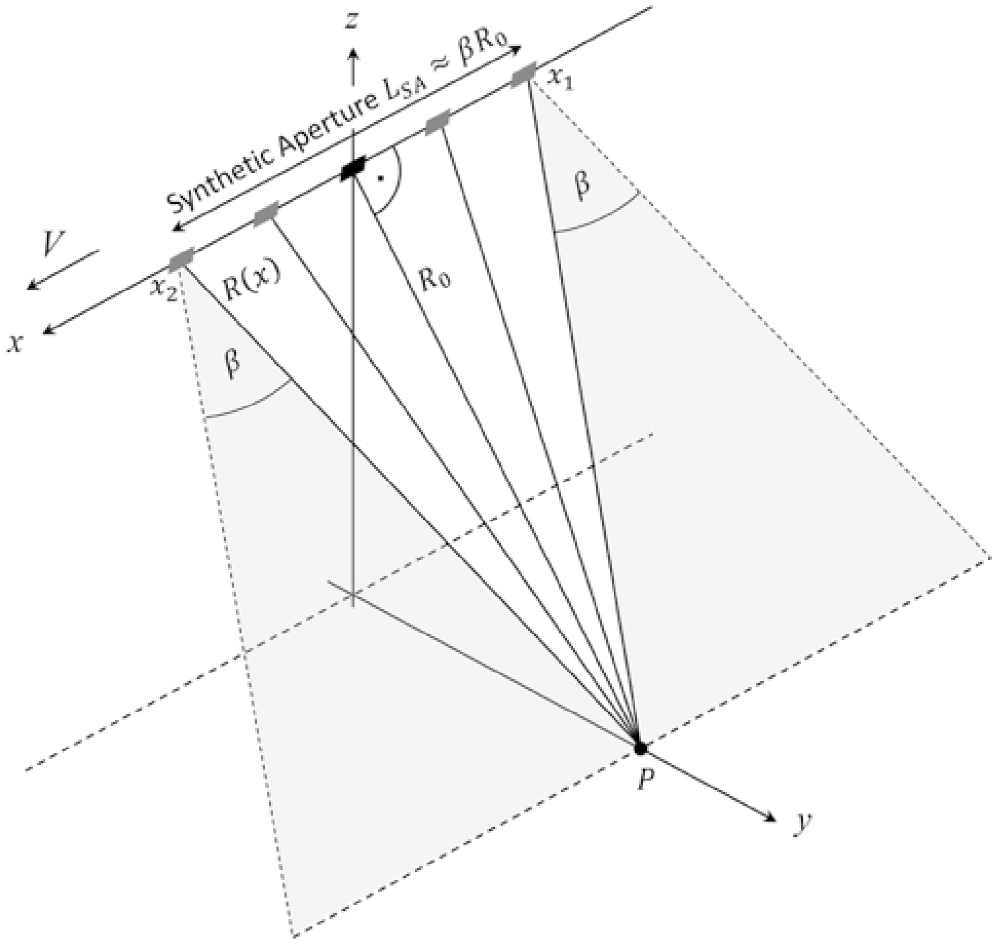
- In order to improve the azimuth resolution, SAR systems exploit the doppler effect.
- The same target can be observed and detected multiple times with different doppler shifts.
- For the same principle, targets under the same beam at the same time can be discriminated by analyzing the doppler frequency spectrum of the return signal



Target on the ground / source of the reflected signal

Synthetic Aperture Radar (SAR)

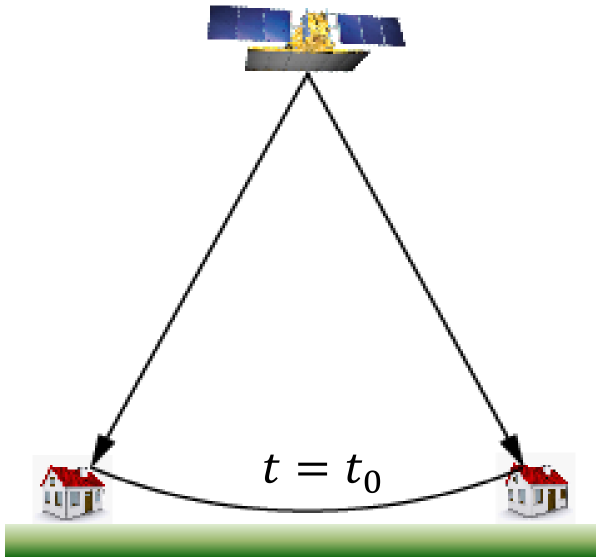
This allows to create (or “synthesize”) a much longer effective antenna (the so-called synthetic aperture) from a sequence of acquisitions made with a shorter antenna as it moves along its flight line. This principle allows high-resolution imaging even from spaceborne platforms using antenna hardware of a manageable size



Geometrical distortion

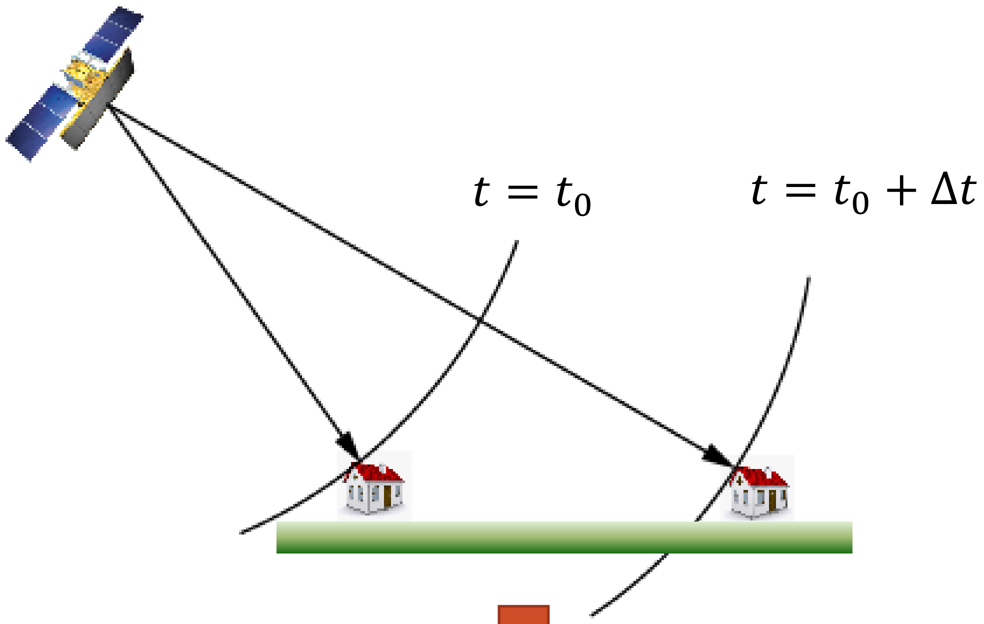
SAR looking geometry

Nadir looking



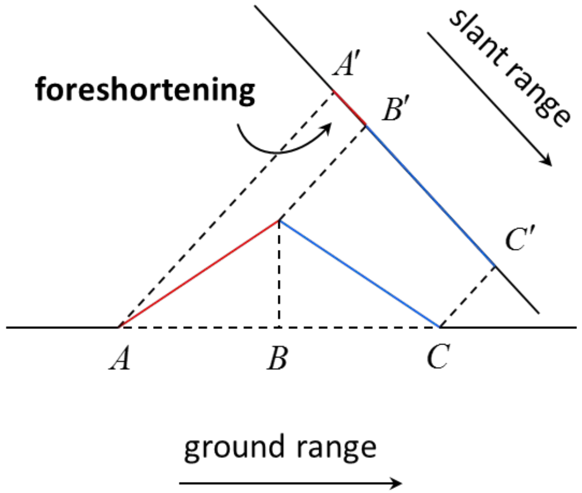
Nadir lookingeometry generates **ambiguities** on the position of the target

Side looking



Ambiguities solved, but large **geometric distortions** are generated

Geometric distortion: Foreshortening



→ Slopes oriented to the SAR appear compressed

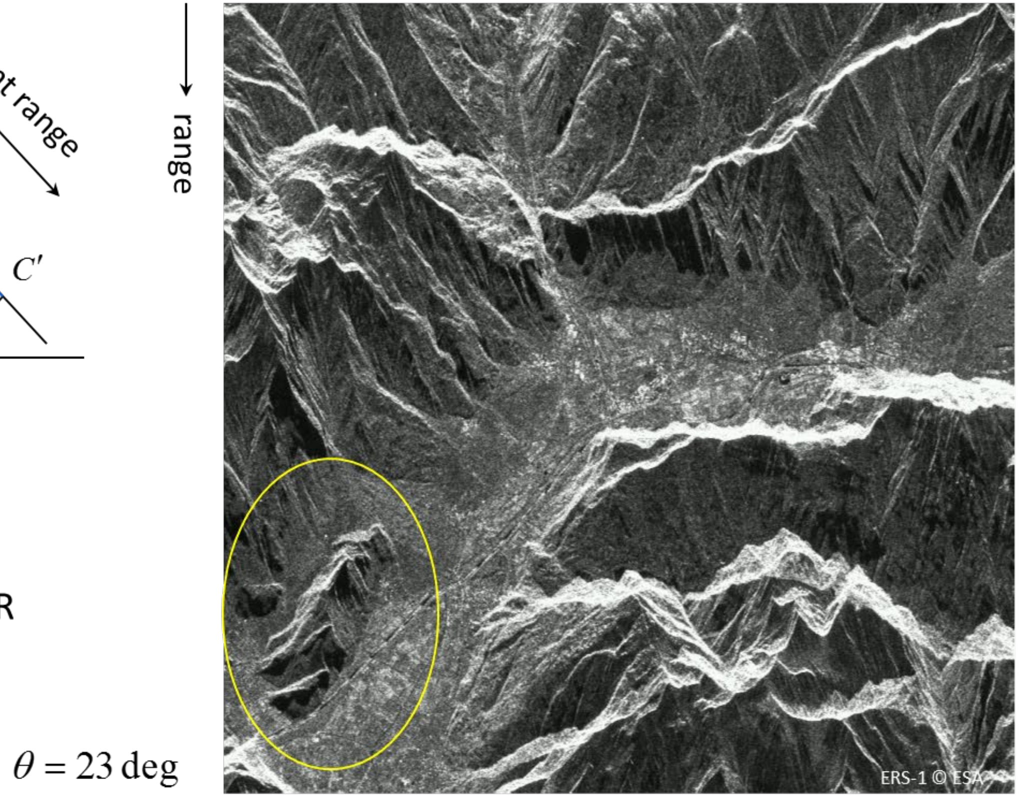
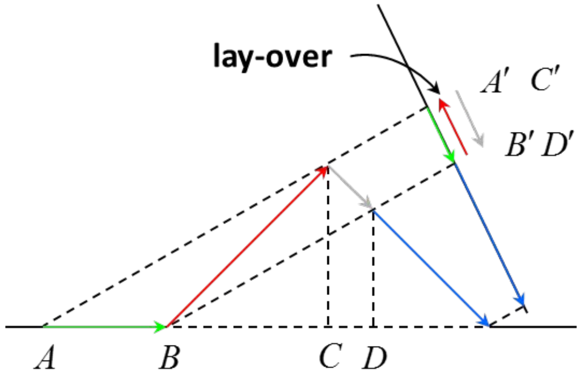
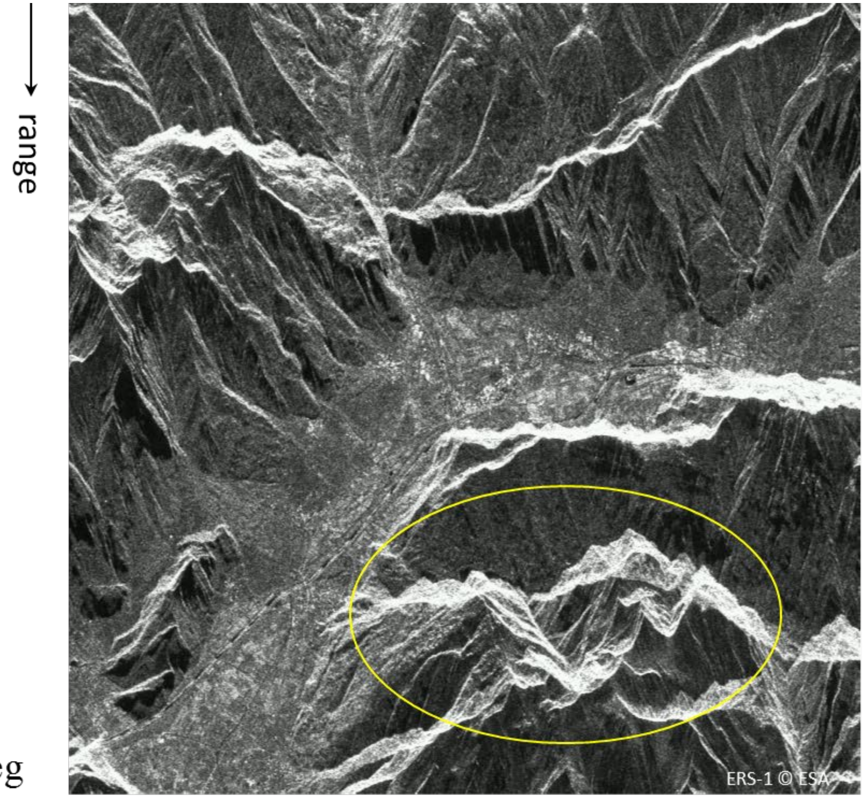


Fig.: © DLR

Geometric distortion: Layover



→ Steep slopes oriented to the SAR lead to ghost images



$\theta = 23$ deg

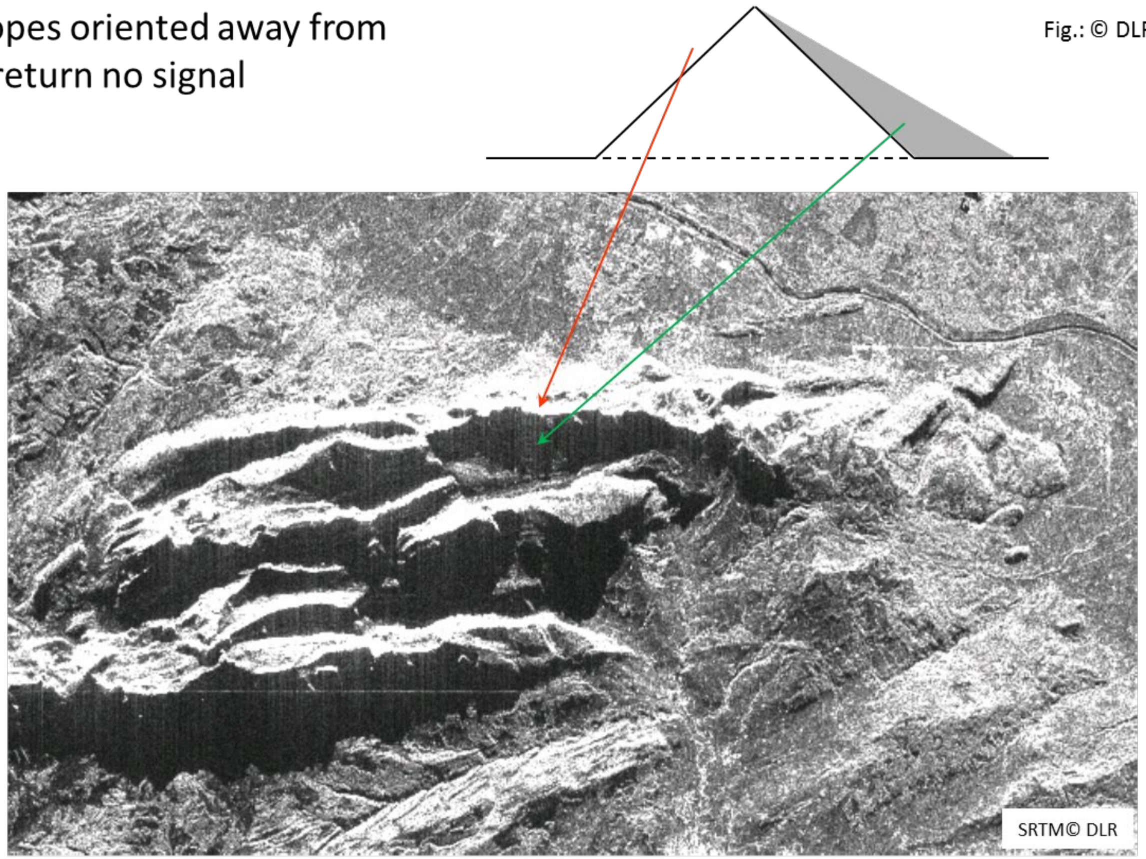
Fig.: © DLR

Geometric distortion: Shadow

→ Steep slopes oriented away from the SAR return no signal

radar shadow

Fig.: © DLR



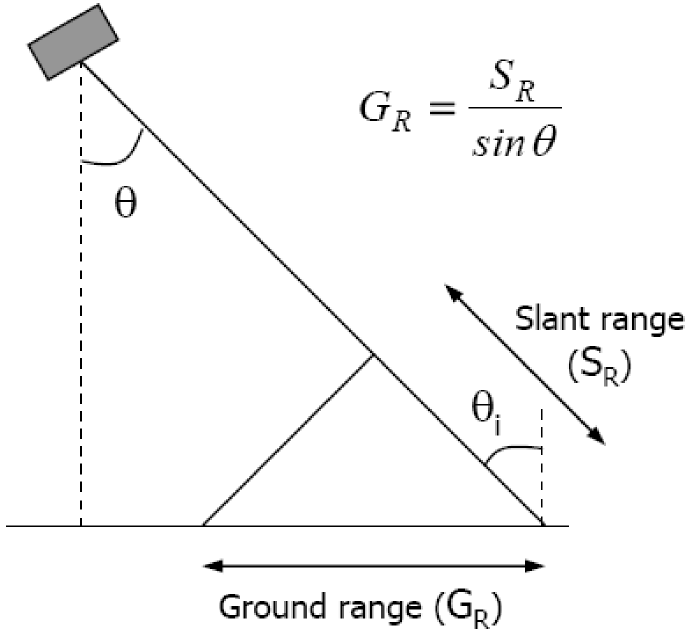
range

SRTM/X-SAR

$\theta = 54\,\mathrm{deg}$

Slant range – ground range

SAR data can be converted from the **slant range** projection (i.e. the original SAR geometry) into the **ground range** one.



Foreshortening effects can be corrected during the geometric calibration assuming the availability of high resolution Digital Elevation Model (DEM) data.

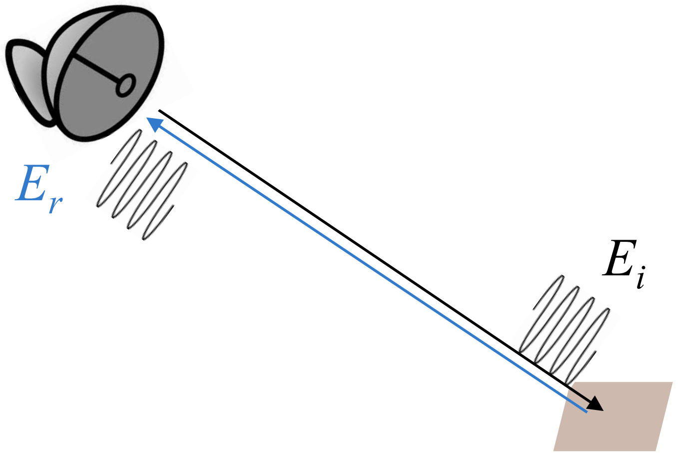
Layover and **Shadow** areas can be exactly calculated, but not corrected. These areas have no thematic information.

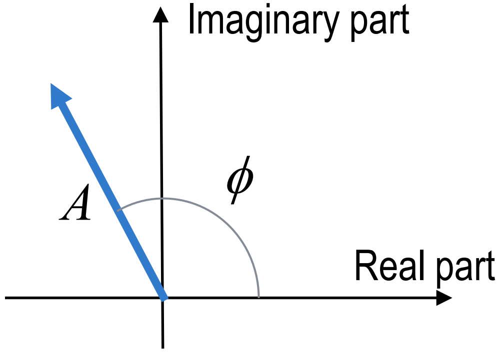
SARMap

Radar backscatter

Pixel values

- Each pixel of the SAR image is a **complex value**
  - It has real and imaginary parts
  - Or, equivalently, **amplitude** (modulus) and **phase**
- What is the meaning of such complex numbers?
  - They correspond to the ratio of the received electrical field (E_r) over the field incident to that location on Earth (E_i)

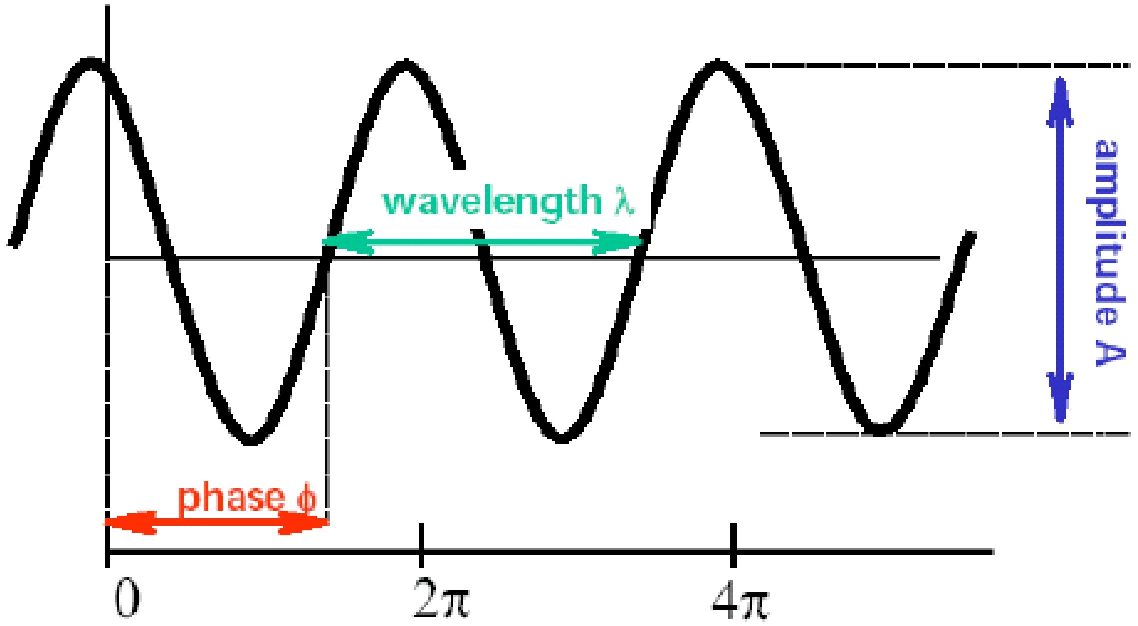


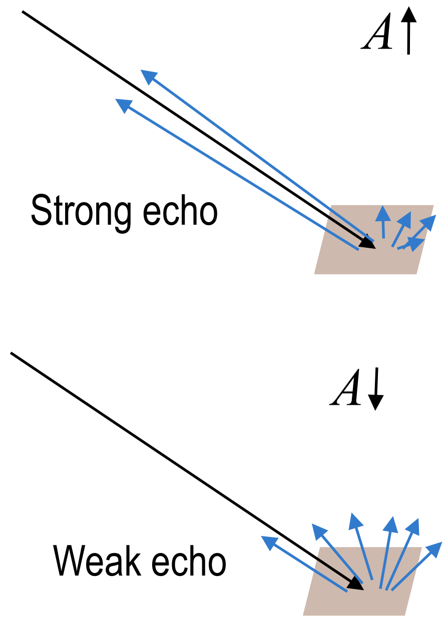


$$\frac{E_r}{E_i} = a + jb = Ae^{j\phi}$$

(J.M. Lopez-Sanchez, 2014)

Pixel values



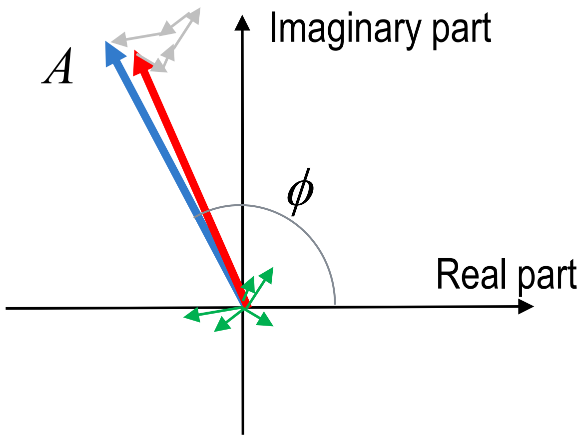


- Amplitude depends on target properties (structure and dielectric properties)
- Phase is a function of the distance between sensor and the target, as well as the target properties

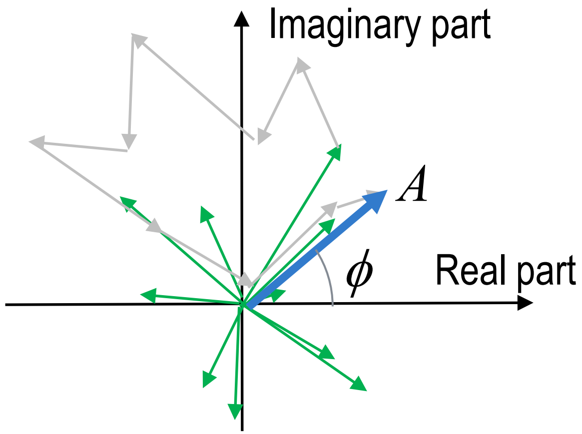
Pixel values

- Each pixel of the image (or resolution cell) is usually much larger than the wavelength and contains many scattering elements (scatterers)
- The received signal (pixel value) is the result of the coherent combination (sum) of all individual echoes
- Typical types of pixels:

Dominated by a single scatterer



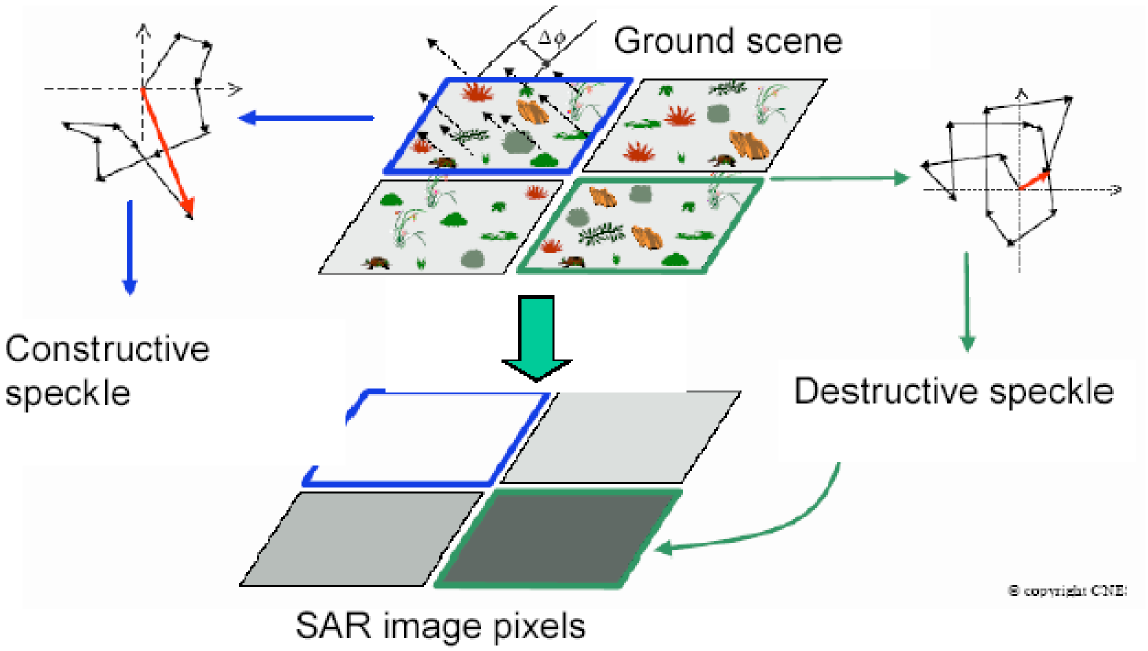
Distributed targets



(J.M. Lopez-Sanchez, 2014)

Speckle

- Most natural scenes correspond to **distributed targets**: composed of many scatterers
- The sum of all individual responses from elements inside the resolution cell changes from pixel to pixel, (even for a homogeneous portion of the scene): a **statistical characterisation** is required
- Fluctuations produced by these changes from pixel to pixel produce the granular appearance of the images: **speckle**



(J.M. Lopez-Sanchez, 2014)

Radar Backscatter

The radar echo contains information about the Earth's surface, which reflect the radar signal. This reflection is driven by:

- **Radar acquisition parameters**:
  - Frequency or wavelength
  - Polarization
  - Incidence angle
- **Surface parameters**:
  - Surface roughness
  - Structure of objects on the surface
  - Dielectric constant

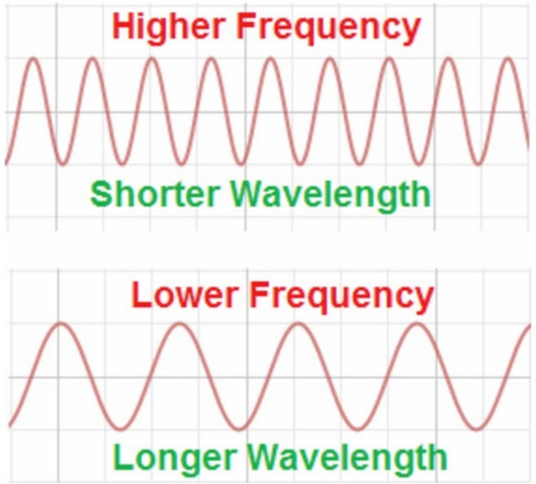
Frequency and wavelength

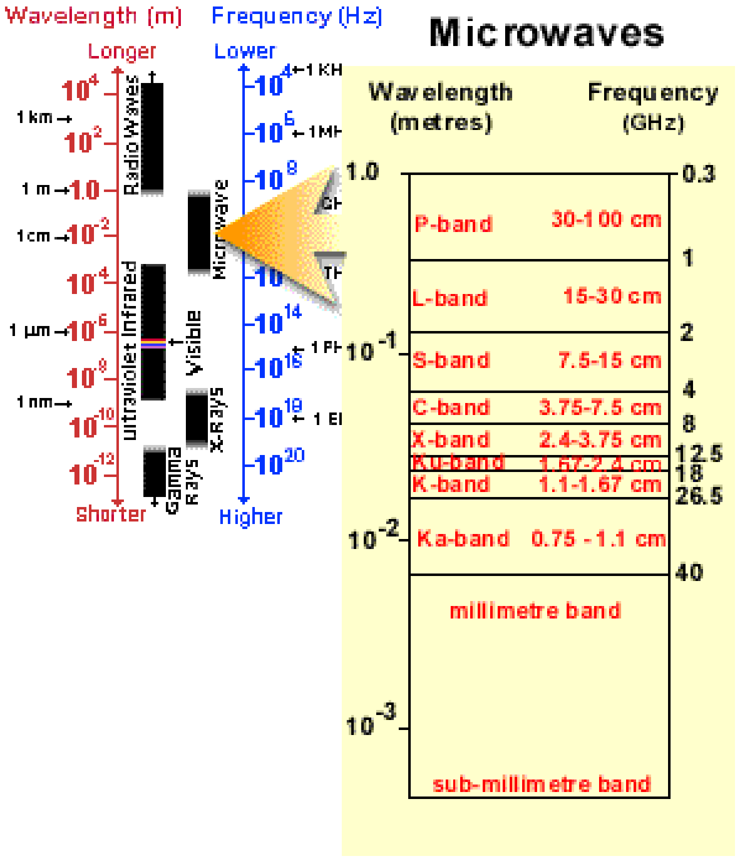
$$f = \frac{c}{\lambda}$$

Signal propagation velocity

frequency

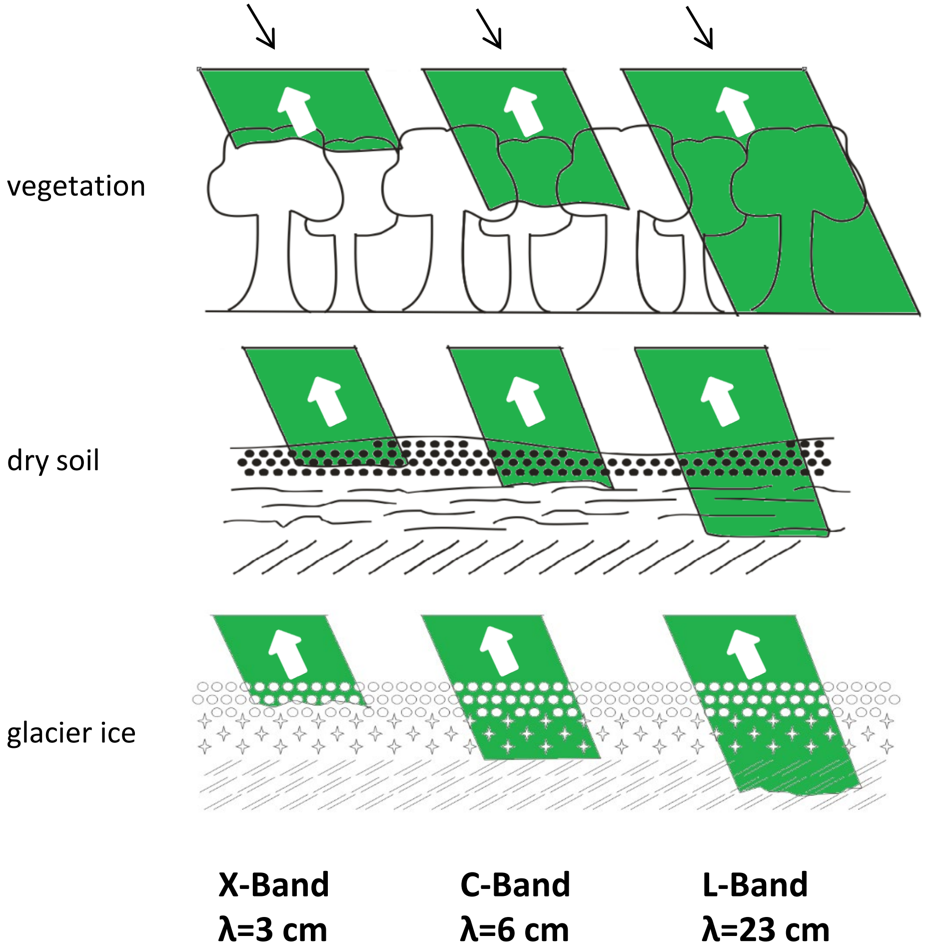
wavelength

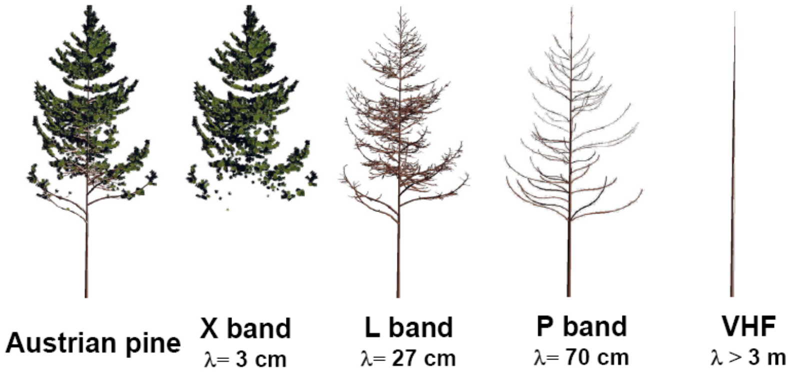




© CCRS / CCT

Frequency and wavelength

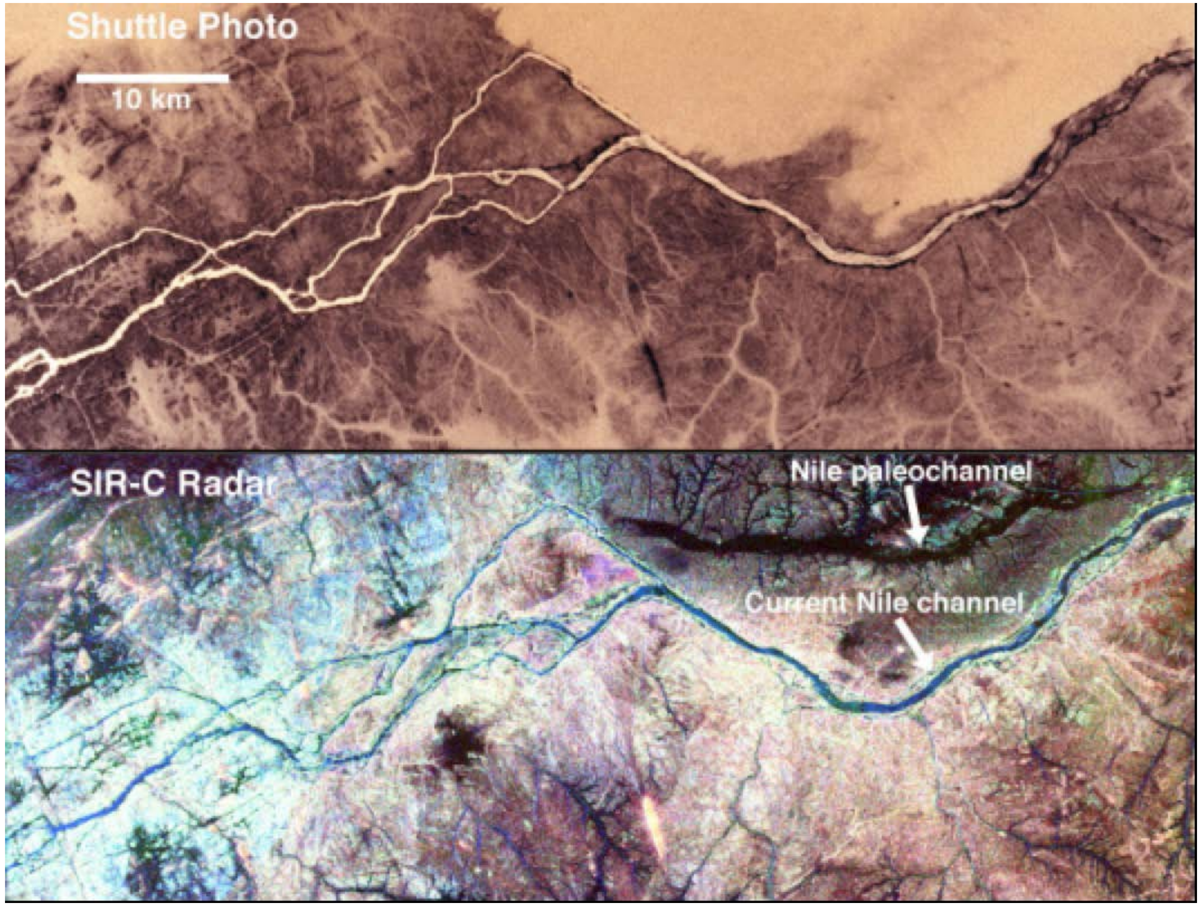




The main scatterers of the target surface are the elements having dimension of the order of the wavelength

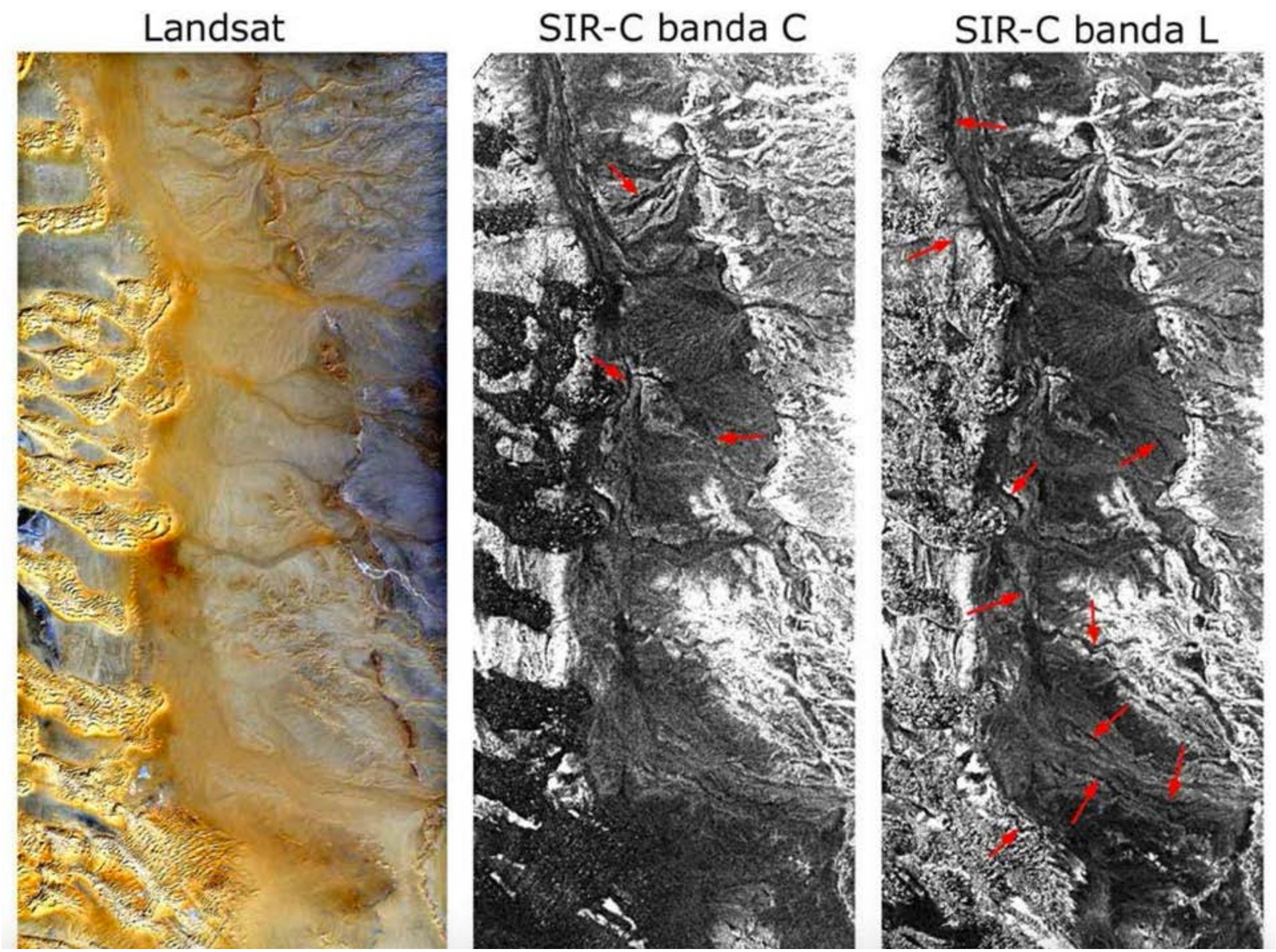
Fig.: © DLR

Radar penetration into dry soil



ARSET, Basics of SAR, Erika Podest

Radar penetration into dry soil



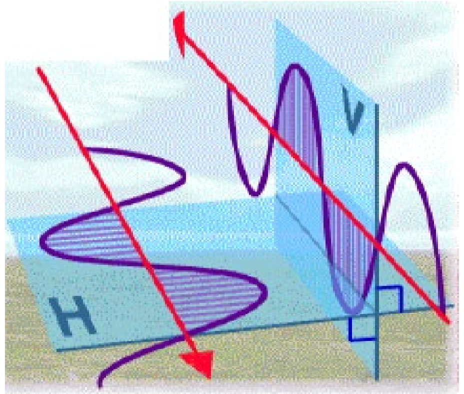
- Different satellite images over southwest Libya
- The red arrows indicate possible fluvial systems

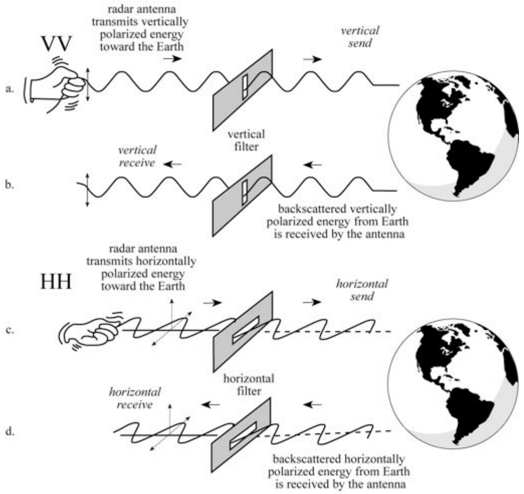
Image Credit: A Perego

ARSET, Basics of SAR, Erika Podest

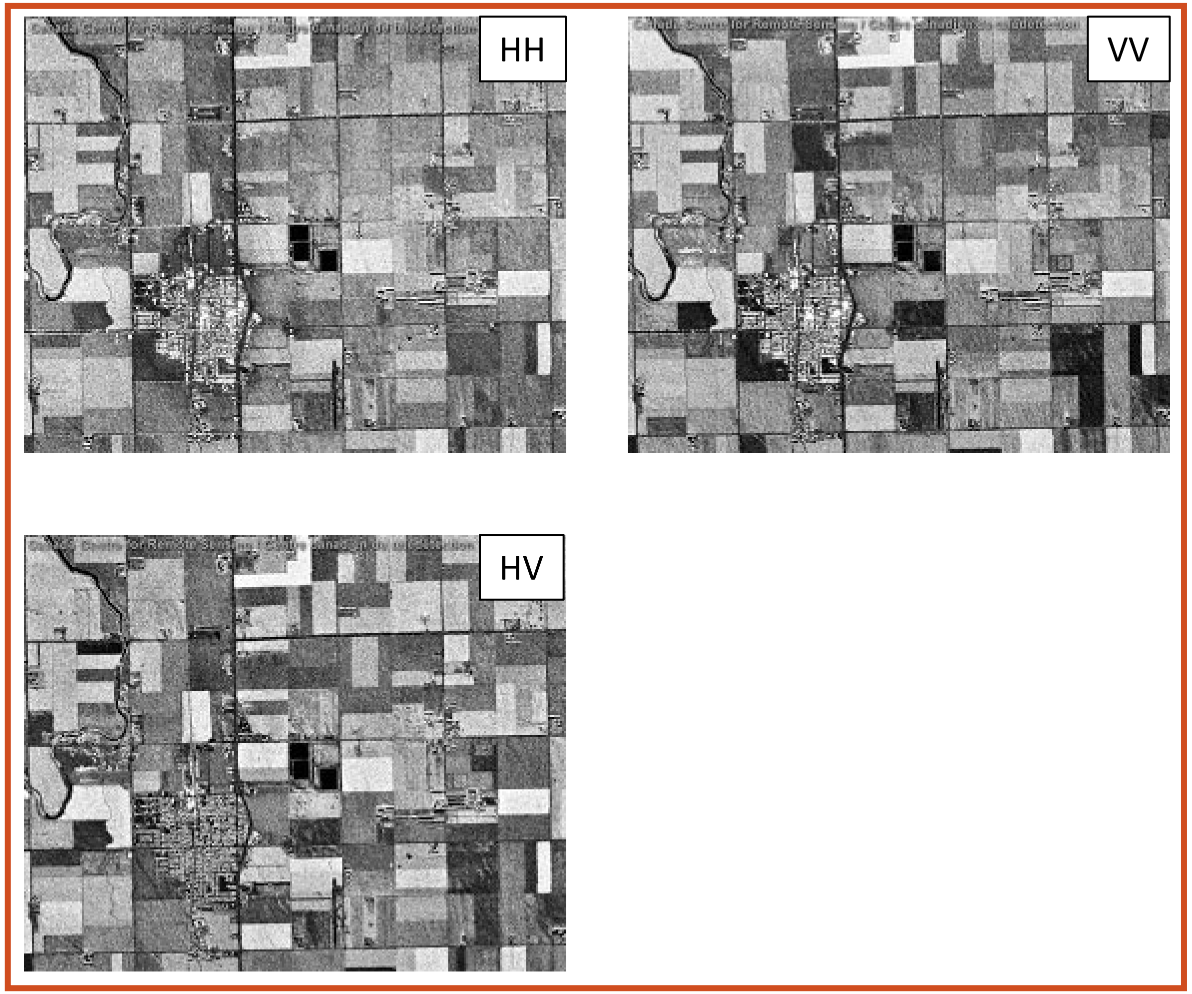
Polarization

- Radar signals can transmit horizontal (H) or vertical (V) electric-field vectors, and receive either horizontal (H) or vertical (V) return signals, or both.
- Quad-Pol Mode: when all four polarizations are measured
- HH: Horizontal Transmit, Horizontal Receive
- HV: Horizontal Transmit, Vertical Receive
- VH: Vertical Transmit, Horizontal Receive
- VV: Vertical Transmit, Vertical Receive
- Different polarizations can determine physical properties of the object observed



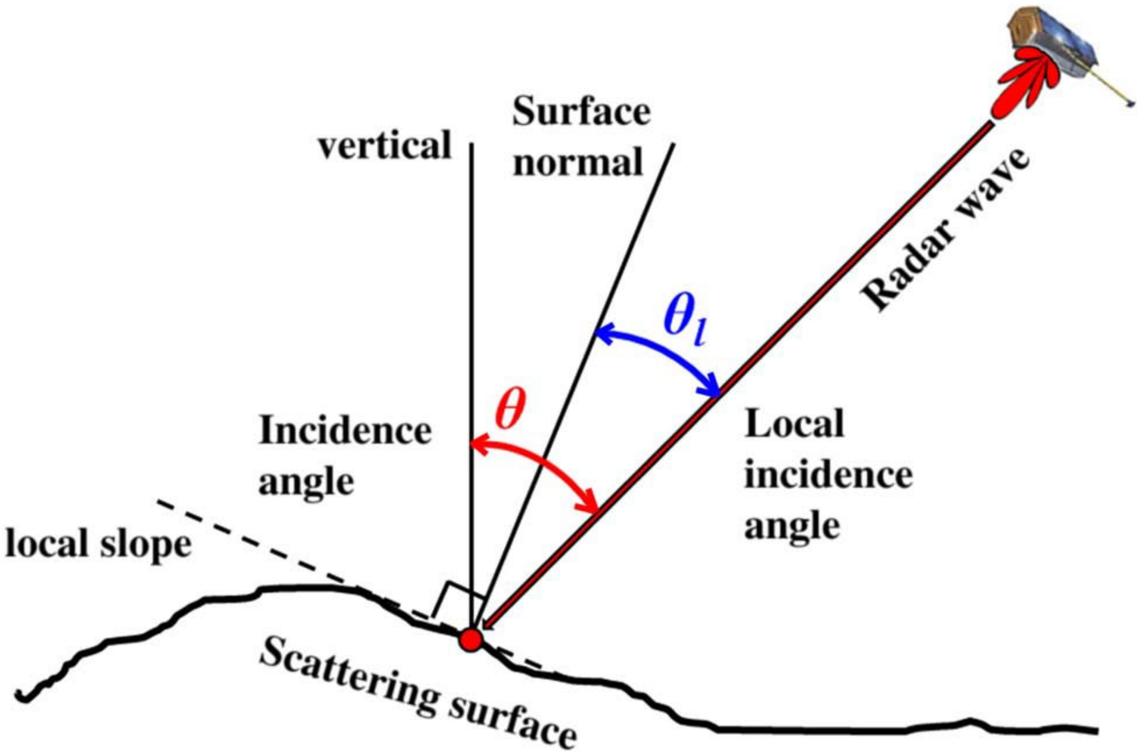


Polarization



R → HH, G → VV, B → HV

Incidence angle

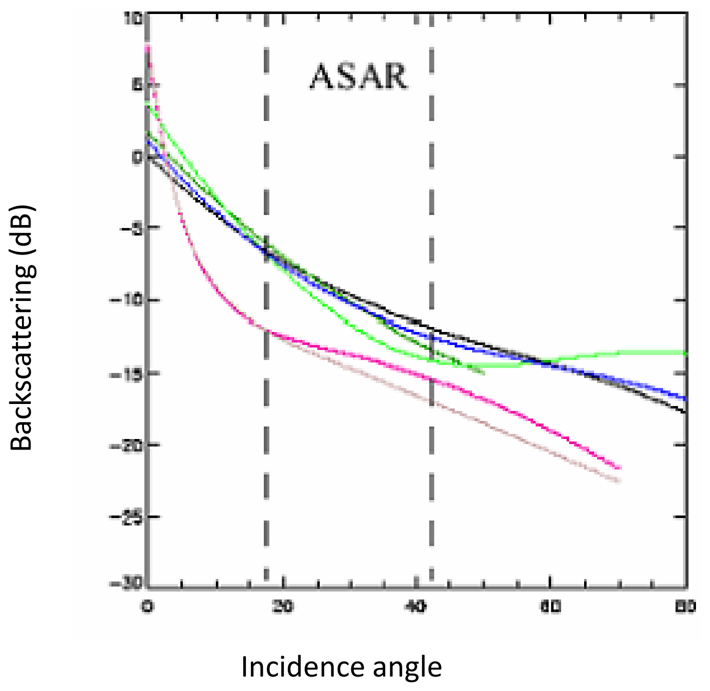


- The **incidence angle θ** describes the angle between the radar wave incident direction and the vertical direction to the ellipsoid.
- The **local incidence angle θ_i** describes the angle between the radar wave incident direction and the normal direction to the scattering surface.

Rizzoli and Bräutigam, 2014

Incidence angle

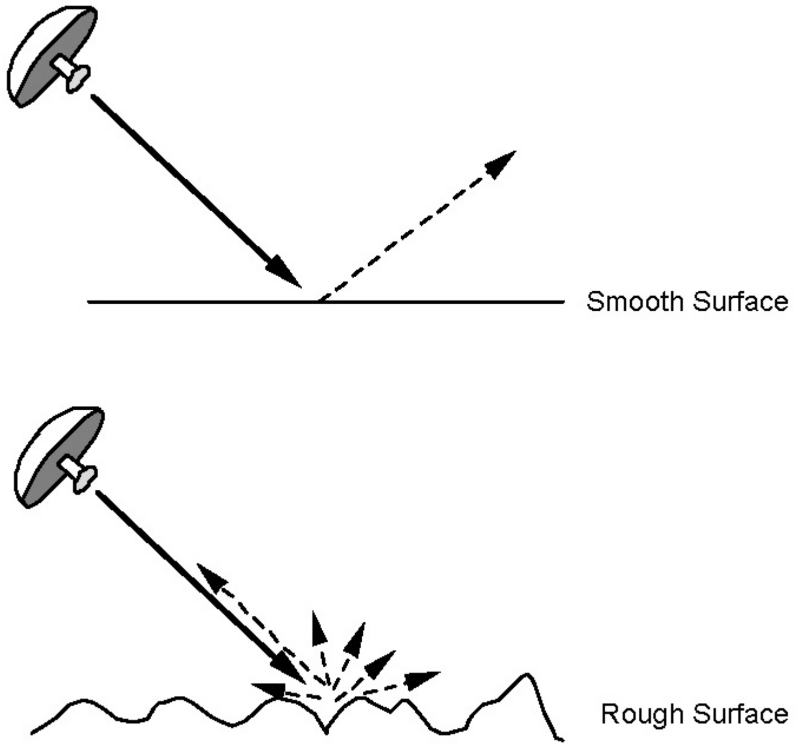
Different reflections may occur in different angular regions. Returns are normally strong at low incidence angles and decrease with increasing incidence angle.

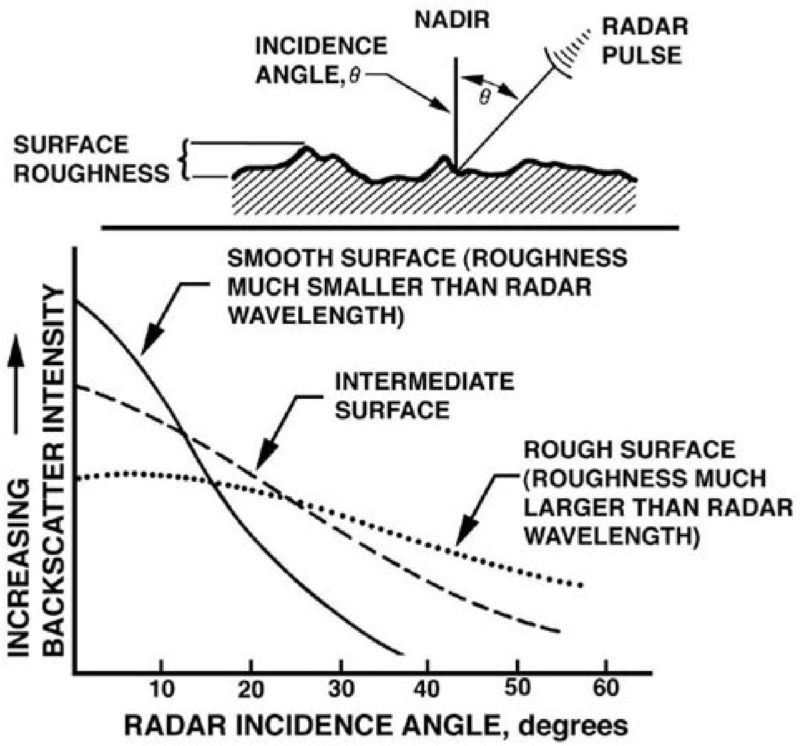


SAR backscattering variation for different land cover classes (different colors), while the dashed lines highlight the swath range for ENVISAT ASAR data.

SARMap

Surface roughness

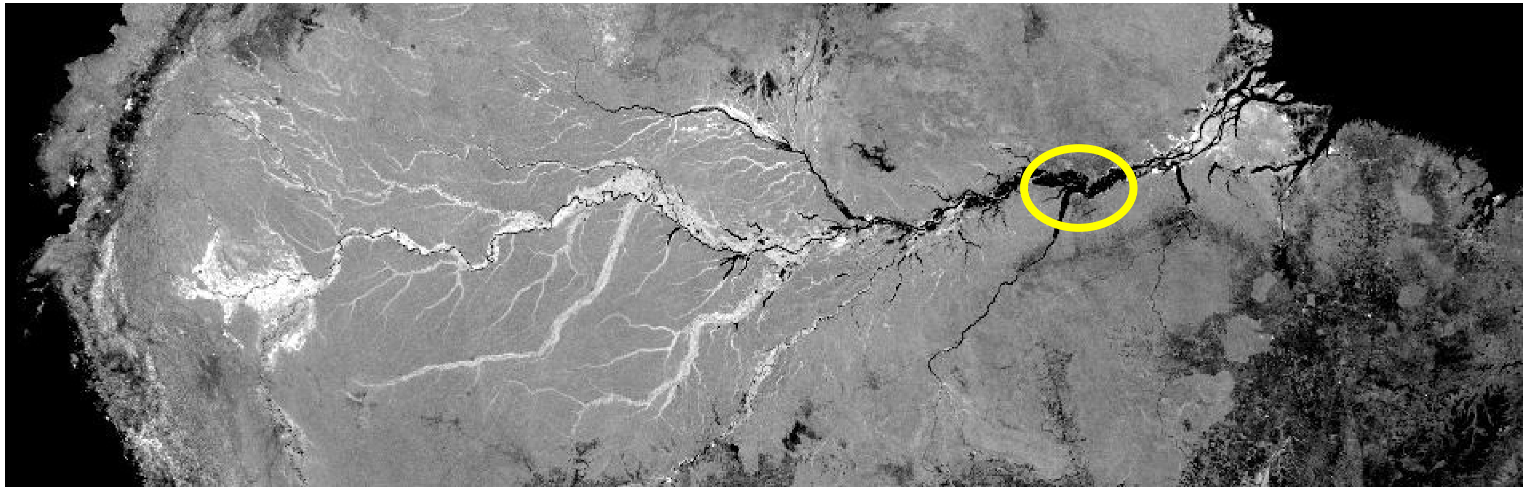




Introduction to Radar remote sensing, P. Mouginis-Mark

Target sufrace structure

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



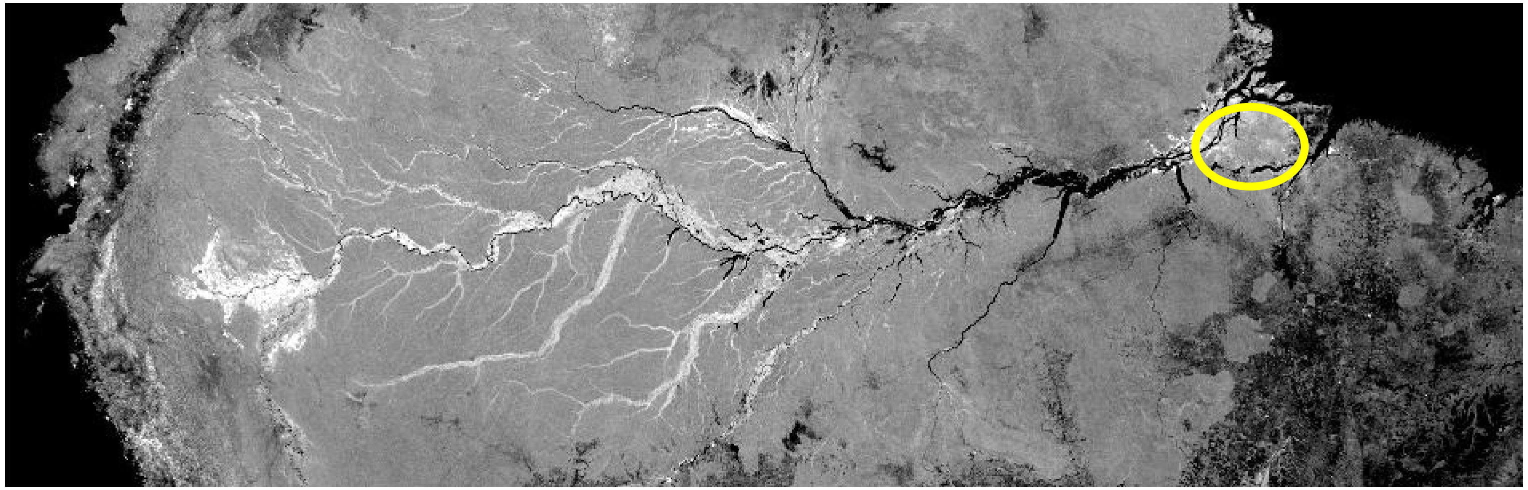
Smooth surface
(e.g. open water, road)

Pixel color

ARSET, Basics of SAR, Erika Podest

Target sufrace structure

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

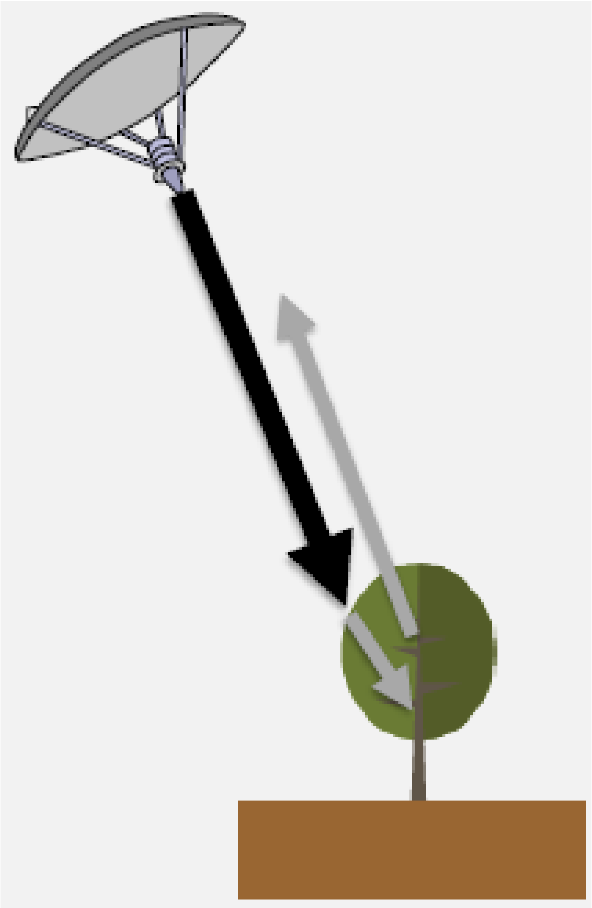


Rough surface
(e.g. deforested area,
tilled agricultural fields)

Pixel color

ARSET, Basics of SAR, Erika Podest

Target sufrace structure



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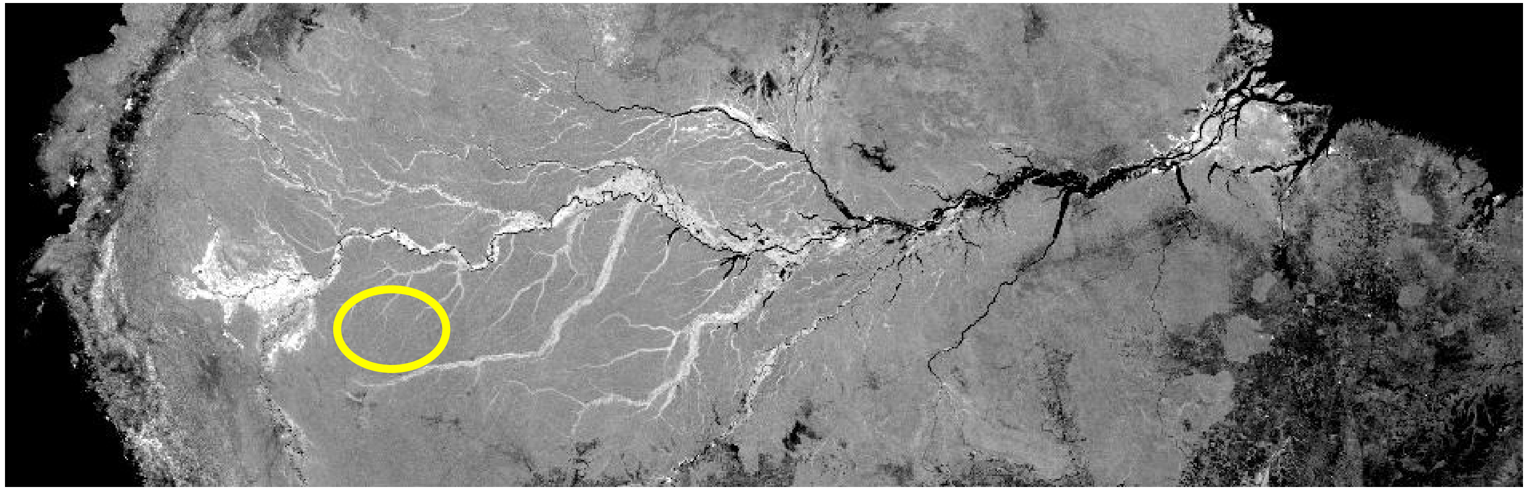
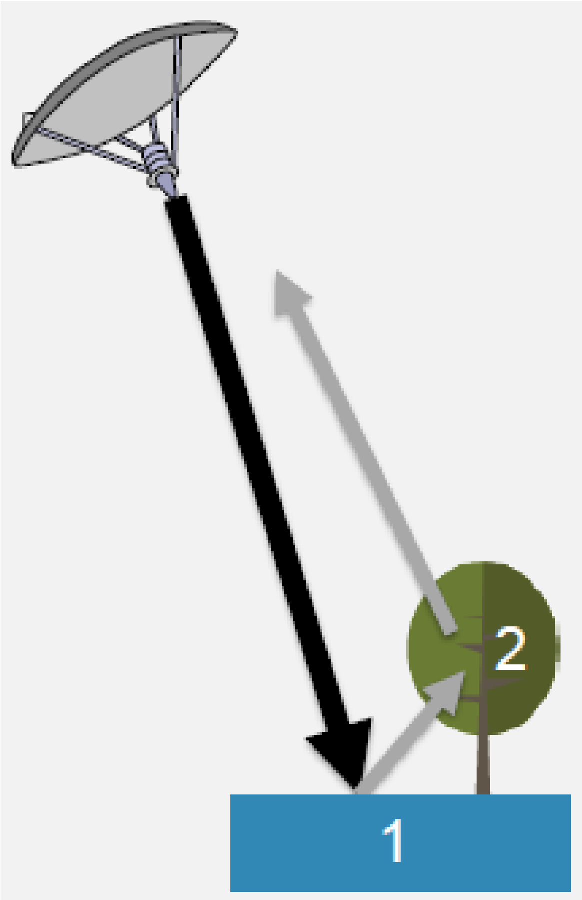


Volume scattering
(e.g. vegetation)

Pixel color

ARSET, Basics of SAR, Erika Podest

Target sufrace structure



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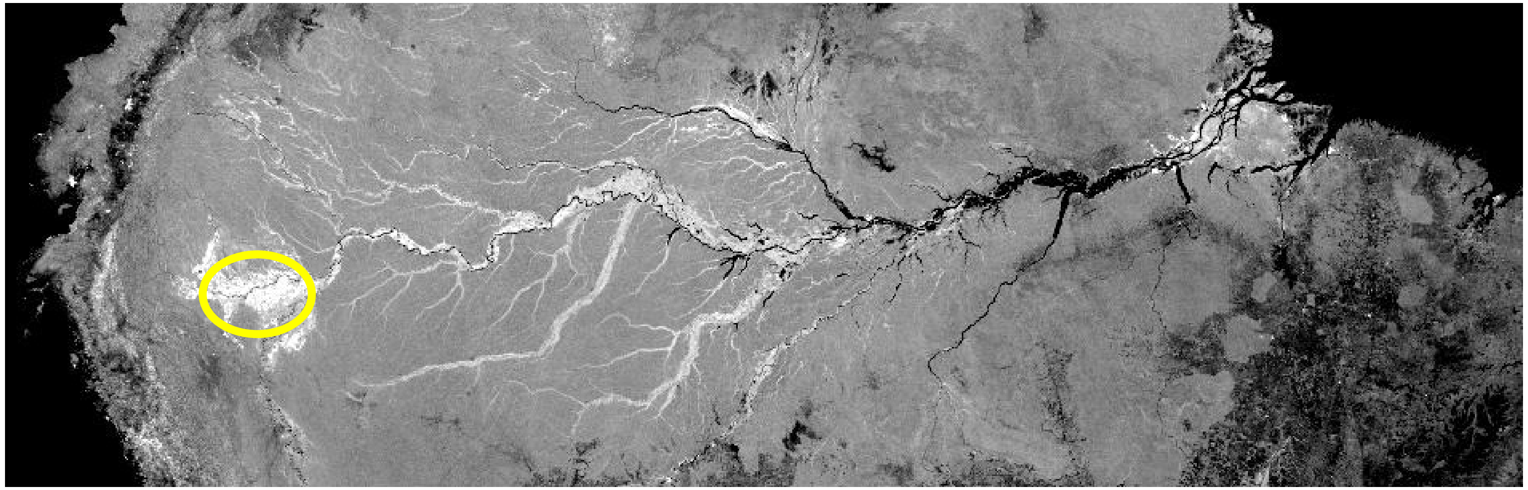
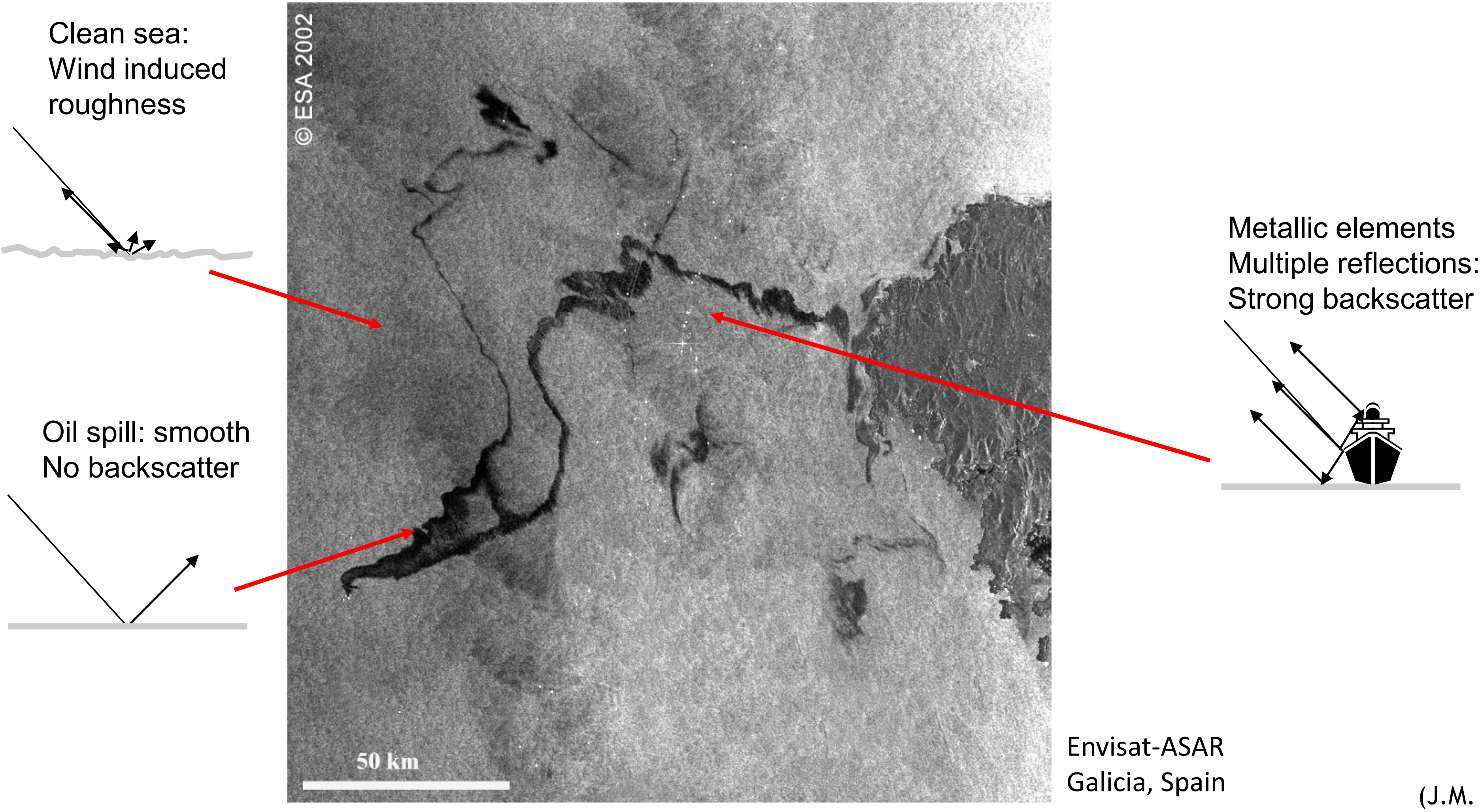


Double bounce
(e.g. inundated vegetation)

Pixel color

ARSET, Basics of SAR, Erika Podest

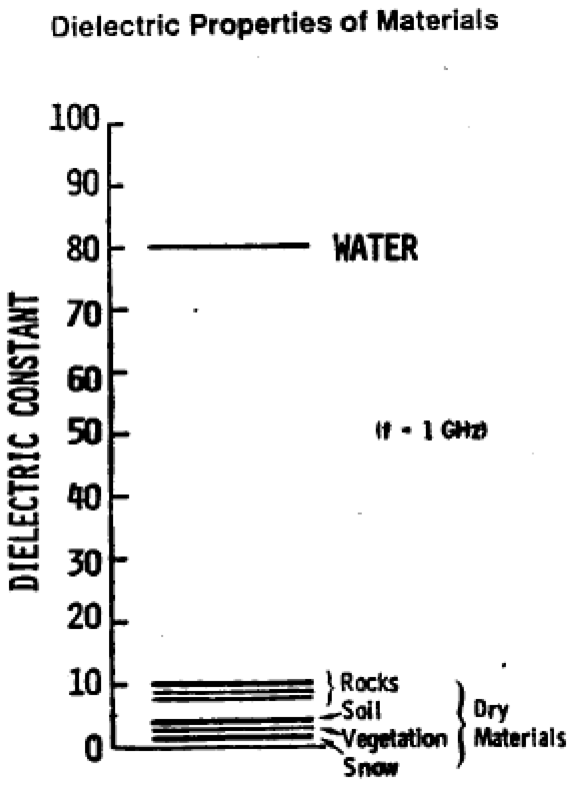
Target sufrace structure and roughness

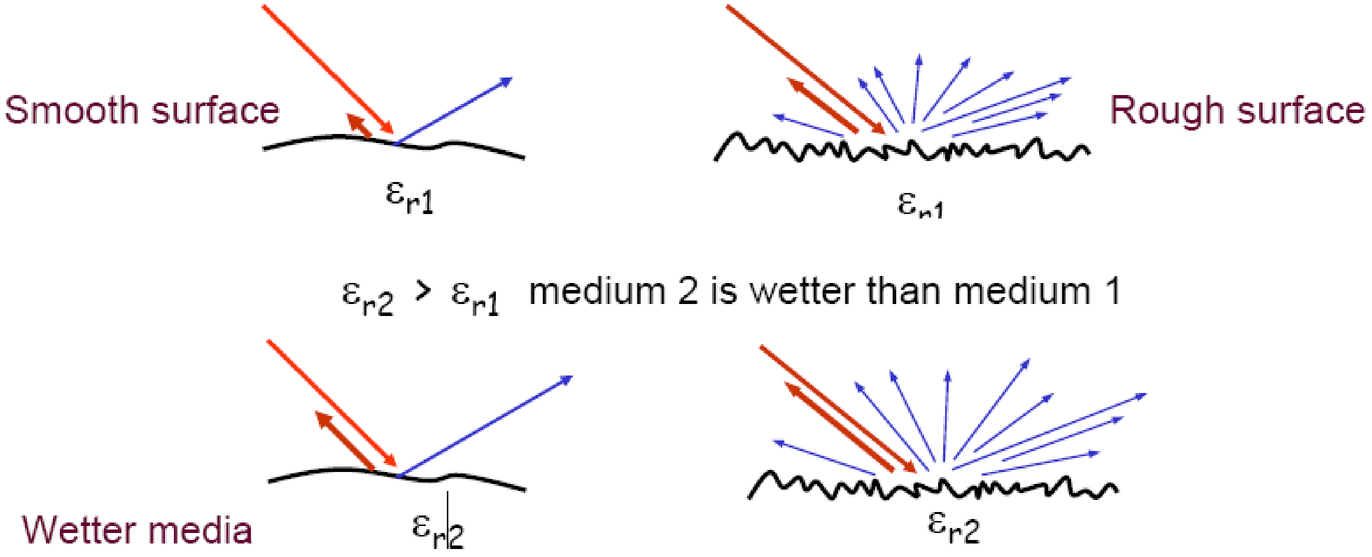


Envisat-ASAR
Galicia, Spain

(J.M. Lopez-Sanchez, 2014)

Dielectric constant

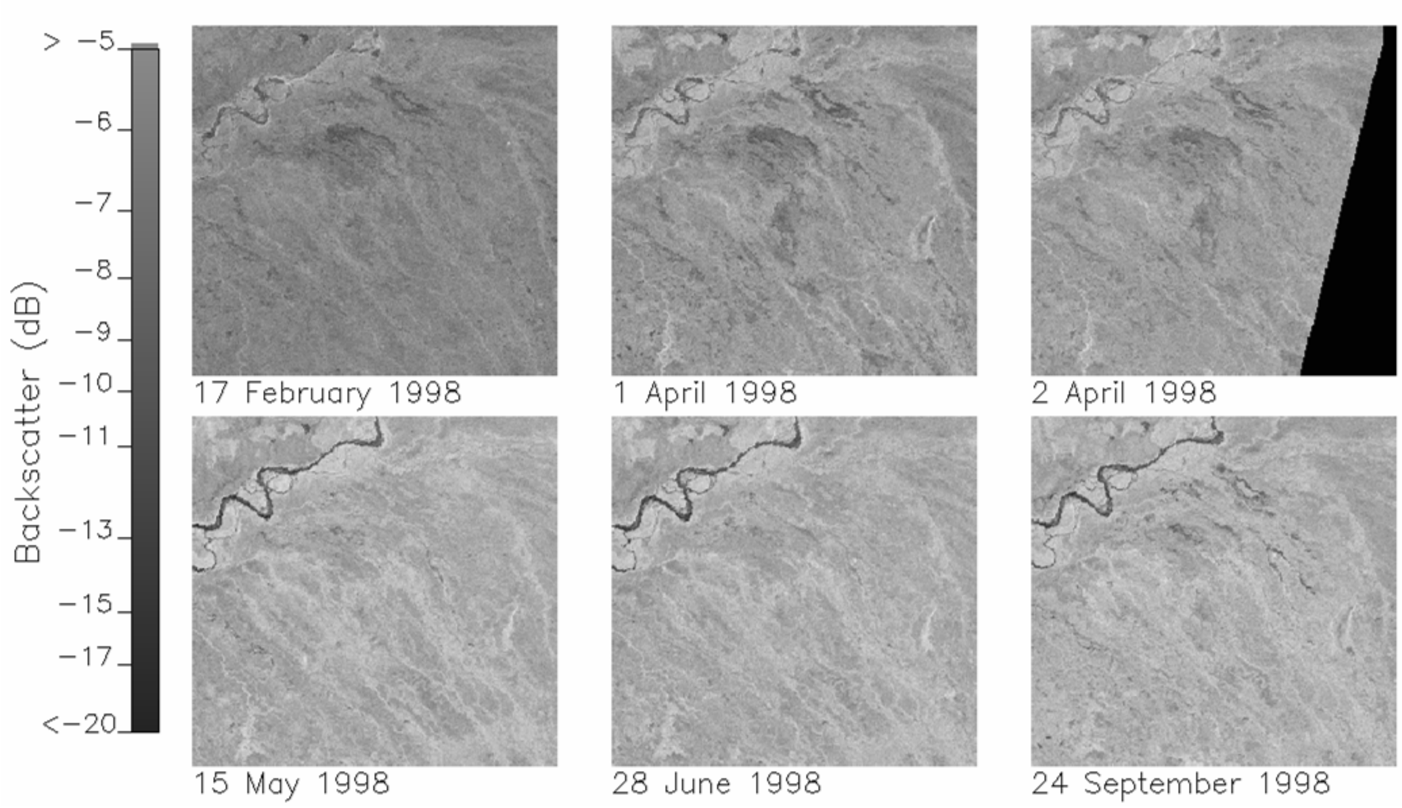




Radar backscatter also depends on the dielectric properties of the target: for metal and water the dielectric constant is high (80), while for most other materials it is relatively low: in dry conditions, the dielectric constant ranges from 3 to 8. This means that wetness of soils or vegetated surfaces can produce a notable increase in radar signal reflectivity.

Based on this phenomenon, SAR systems are also used to retrieve the soil moisture content - primarily - of bare soils. The measurement is based on the large contrast between the dielectric properties of dry and wet soils. As the soil is moistened, its dielectric constant varies from approximately 2.5 when dry to about 25 to 30 under saturated conditions. This translates to an increase in the reflected energy.

Dielectric constant



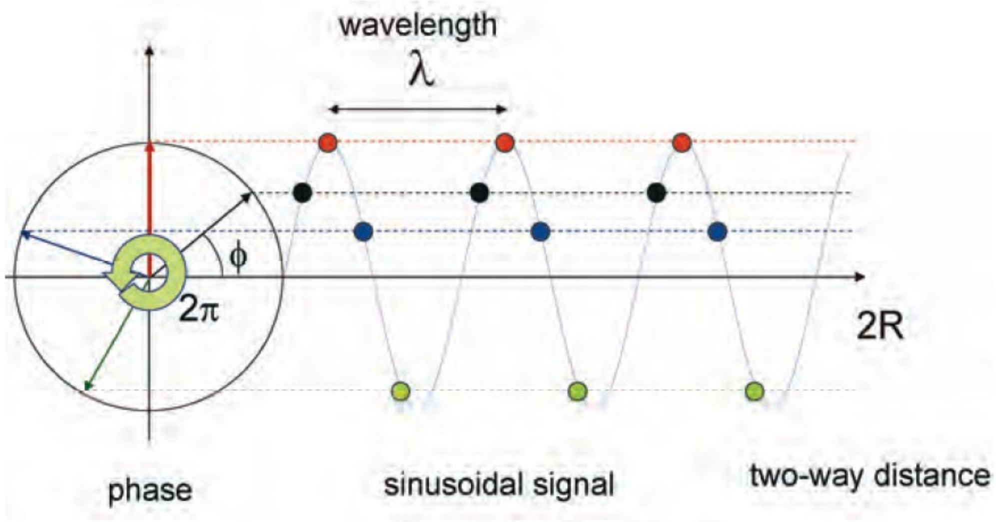
- During the land surface freeze/thaw transition there is a change in dielectric properties of the surface
- This causes a notable increase in backscatter

ARSET, Basics of SAR, Erika Podest

SAR interferometry

Phase

- Scatterers at different distances from the radar (different slant ranges) introduce different delays between transmission and reception of the radiation.
- Due to the almost purely sinusoidal nature of the transmitted signal, this delay τ is equivalent to a phase change ϕ between transmitted and received signals.
- The phase change is thus proportional to the two-way travel distance $2R$ of the radiation divided by the transmitted wavelength λ

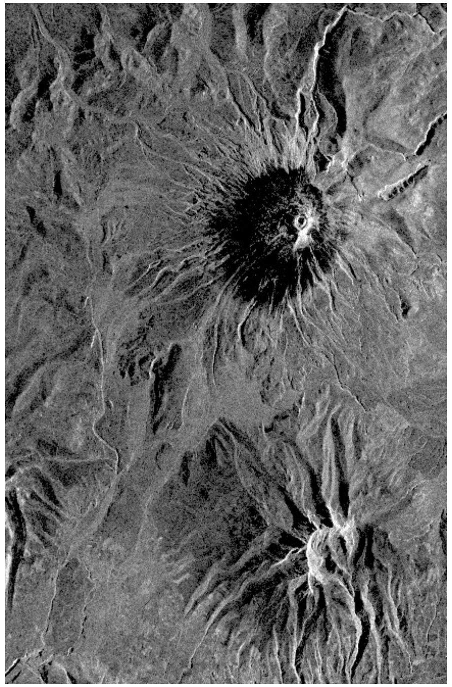


$$\phi = \frac{2\pi}{\lambda} 2R = \frac{4\pi}{\lambda} R$$

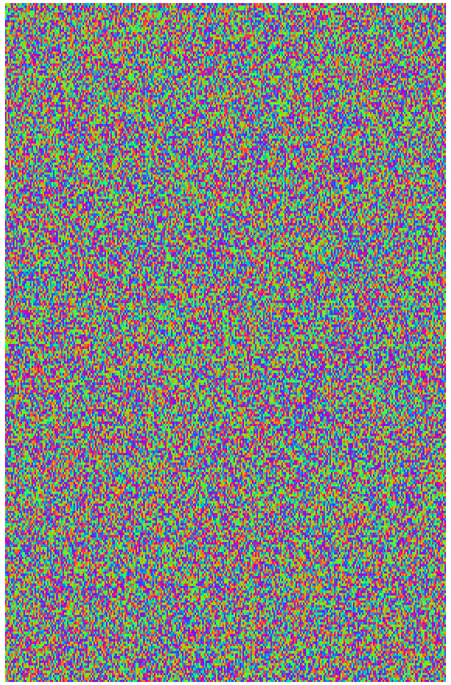
Phase

- Due to the periodic nature of the signal, travel distances that differ by an integer multiple of the wavelength introduce exactly the same phase change.
- The phase of the SAR signal is a measure of just the last fraction of the two-way travel distance that is smaller than the transmitted wavelength
- In practice, due to the huge ratio between the resolution cell dimension (of the order of a few metres) and wavelength (~5.6 cm for C-band SAR), the phase change passing from one pixel to another within a single SAR image looks random and is of no practical utility

Amplitude

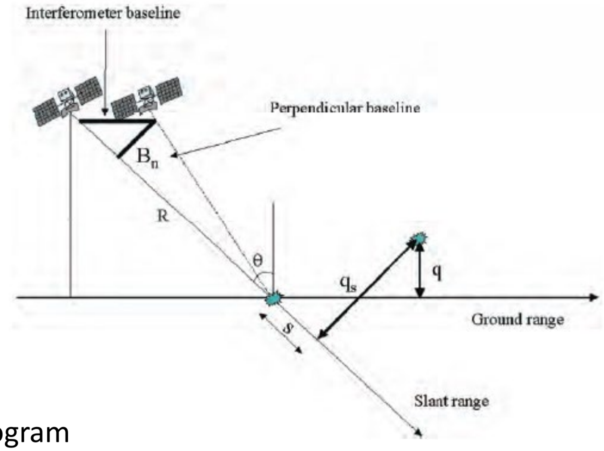


Phase

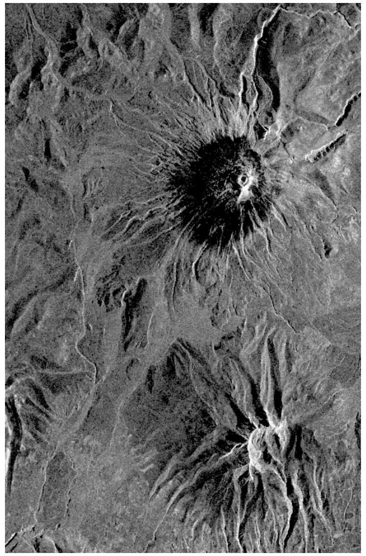


Interferometric phase

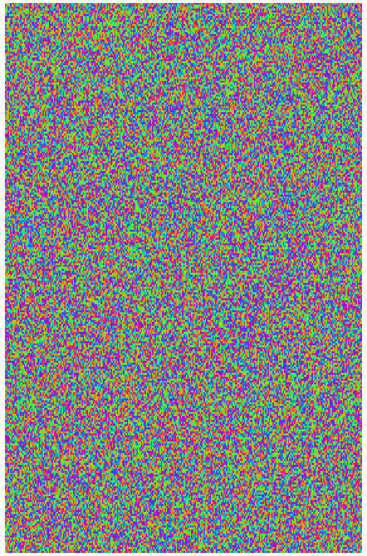
- Instead, if the same area is observed by two SARs from slightly different look angles, the variation of the travel path difference that results in passing from a reference resolution cell to another is much smaller
- The interferometric phase can thus be used to measure topography



amplitude



phase 1



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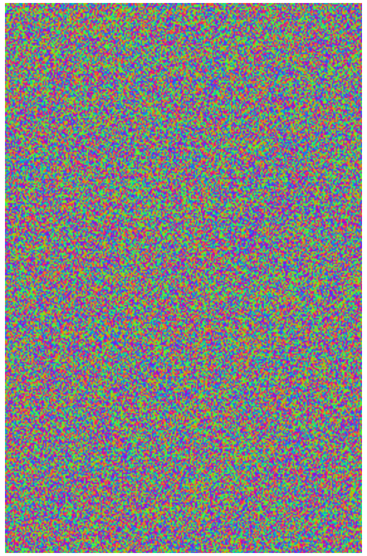
phase 2



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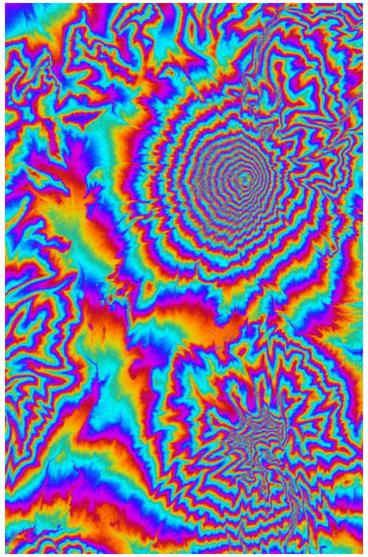
interferogram



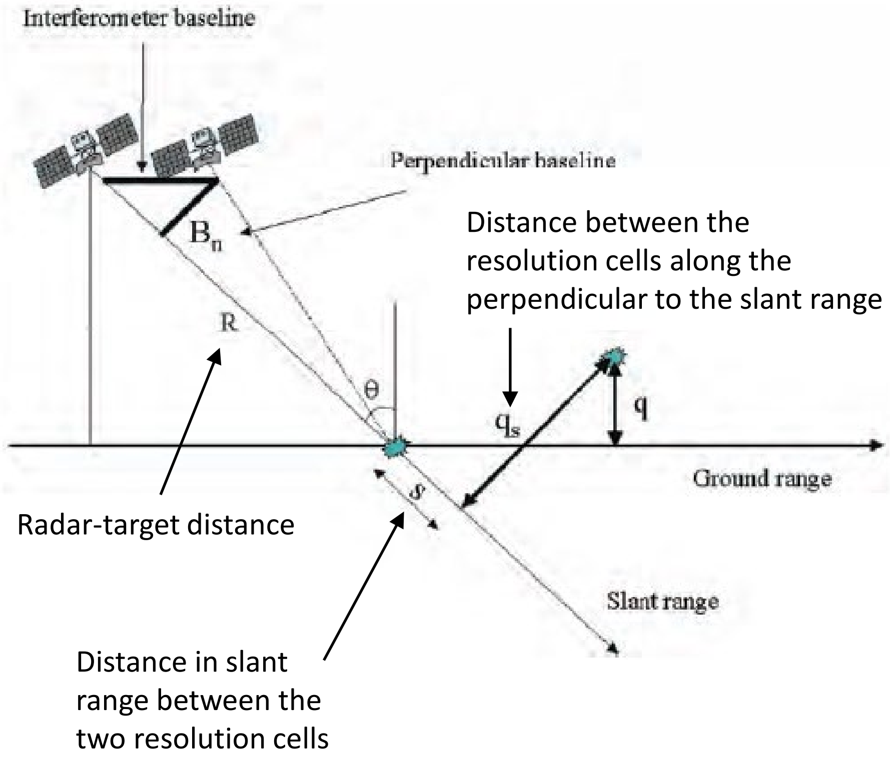
Interferometric phase

- More in detail, the variation of the travel path difference Δr that results in passing from a reference resolution cell to another can be approximated as:

$$\Delta r = -2\frac{B_n q_s}{R}$$

- The interferometric phase variation $\Delta\phi$ is then proportional to Δr divided by the transmitted wavelength λ:

$$\Delta\phi = \frac{2\pi\Delta r}{\lambda} = \frac{4\pi}{\lambda}\frac{B_n q_s}{R}$$



Interferogram flattening

- The distance q_s can be represented as the sum of two terms:
  1. One proportional to the altitude difference q between the point targets, referred to a horizontal reference plane

$$\frac{q}{\sin\theta}$$

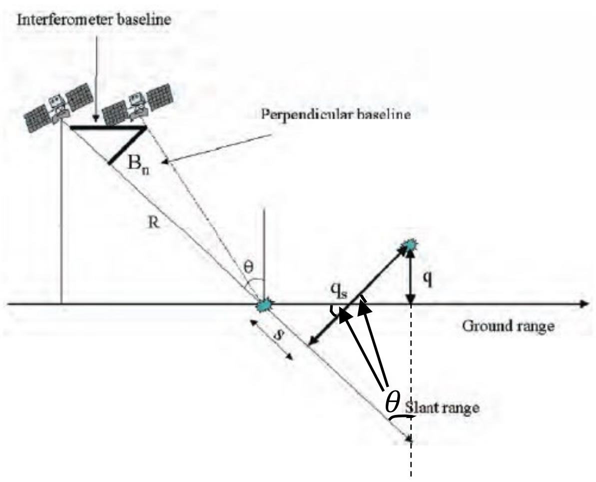
  2. One proportional to the slant range increment s of the point targets

$$\frac{s}{\tan\theta}$$

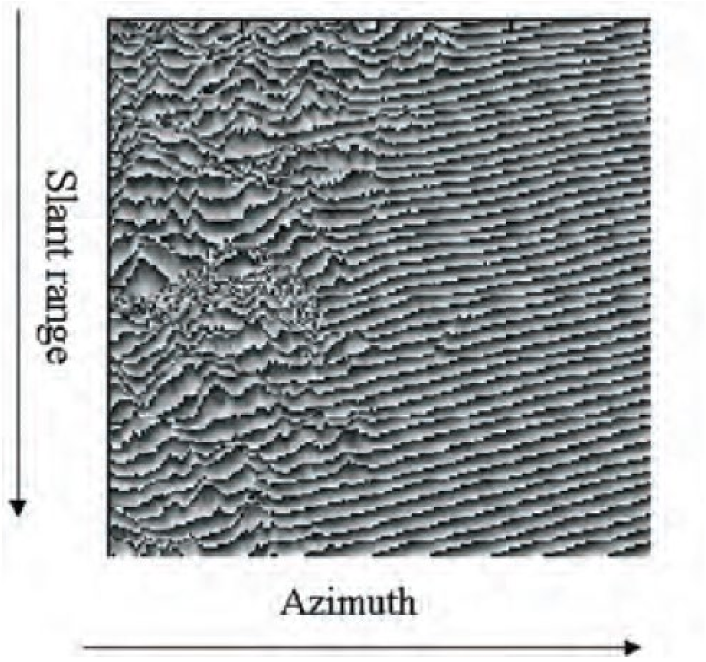
- Then, the interferometric phase variation can be written as

$$\Delta\phi = \frac{4\pi}{\lambda}\frac{B_n q_s}{R} = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} + \frac{4\pi}{\lambda}\frac{B_n s}{R\tan\theta}$$

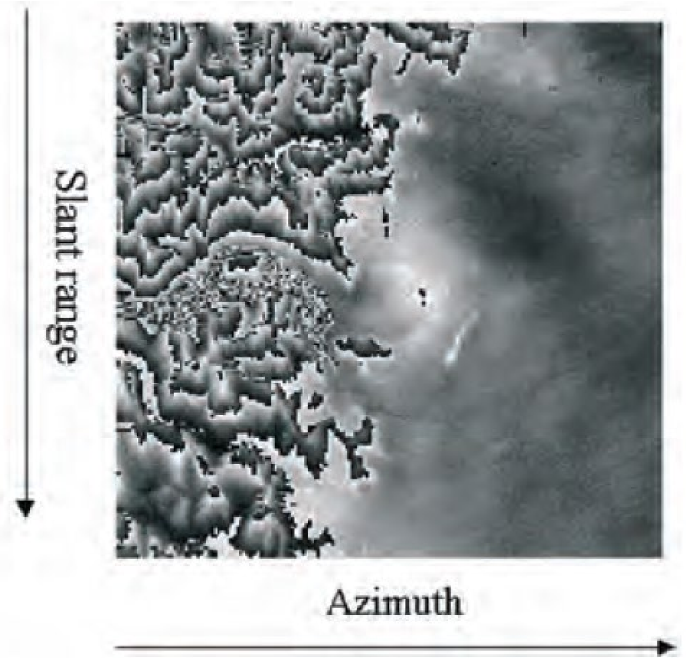
This term can be computed and subtracted from the interferometric phase. This procedure is called interferogram flattening



Interferogram flattening



Interferogram of a portion of the Italian Alps and the Pianura Padana that has been obtained from ERS data



Flattened interferogram

Altitude of ambiguity

- The altitude of ambiguity h_a is defined as the altitude difference that generates an interferometric phase change of 2π after interferogram flattening.

$$\Delta\phi_{flat} = \frac{4\pi}{\lambda}\frac{B_n q}{R \sin\theta}$$

$$h_a = \frac{\lambda R \sin\theta}{2B_n}$$

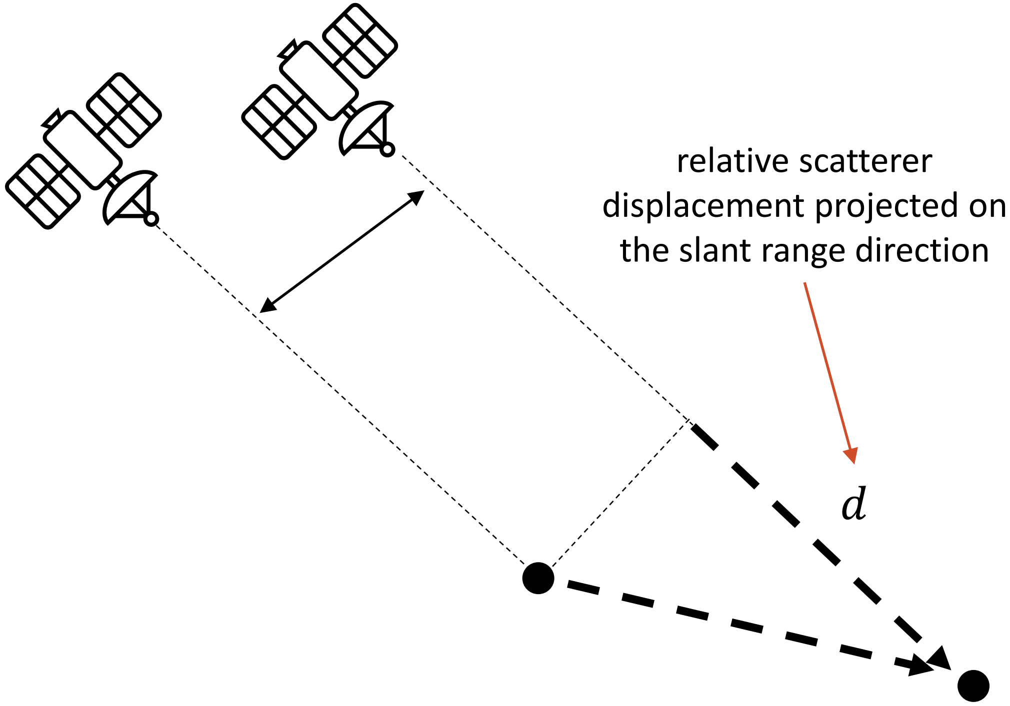
- For example, at C-band with $\lambda = 5.6\ \mathrm{cm}$, $\theta = 40°$, and $R = 850\ \mathrm{km}$, $B_n = 150\ \mathrm{m}$

$$h_a \approx 102\ \mathrm{m}$$

Terrain motion measurements with DInSAR

When the point scatterer on the ground slightly change its relative position in the time interval between two SAR observations (e.g. subsidence, landslide, earthquake, etc.), the following additive phase term appears in the interferometric phase:

$$\Delta\phi_d = \frac{4\pi}{\lambda} d$$



Terrain motion measurement with DInSAR

- After interferogram flattening, the interferometric phase contains both altitude and motion contributions:

$$\Delta\phi = \frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} + \frac{4\pi}{\lambda}d$$

- The sensitivity of SAR interferometry to terrain motion is much larger than that to the altitude difference. A displacement equal to $\lambda/2$ generate a phase variation of 2π

- E.g. $\lambda = 5.6\ \mathrm{cm}$, $\theta = 40°$, and $R = 850\ \mathrm{km}$, $B_n = 150\ \mathrm{m}$

$$\Delta\phi \approx \frac{q}{16} + 224\ d$$

With this example a phase variation of 2π is generated with an altitude difference equal to 102 m (altitude of ambiguity) or with a displacement equal to 2.8 cm

Phase noise sources

- **Phase noise due to temporal change of the scatterers.** Depending on the target characteristics scatterers can change very rapidly (e.g. water, snow) or slowly (e.g. rocks)
- **Phase noise due to different look angle.** Speckle will change due to the different combination of elementary echoes even if the scatterers do not change in time. The most important consequence of this effect is that there exists a critical baseline over which the interferometric phase is pure noise. The critical baseline depends on the dimension of the ground range resolution cell, on the radar frequency, and on the sensor-target distance. In the ERS case, the critical baseline for horizontal terrain is about 1150 metres.
- **Phase noise due to volume scattering.** The critical baseline reduces in the case of volume scattering when the elementary scatterers are not disposed on a plane surface but occupy a volume (e.g. the branches of a tree). In this case the speckle change depends also on the depth of the volume occupied by the elementary scatterers.
- **Atmospheric phase noise.** Different atmospheric humidity, temperature and pressure between the two SAR acquisitions can have visible consequence on the interferometric phase. This effect is usually confined within a 2π peak-to-peak interferometric phase change along the image with a smooth spatial variability (from a few hundred metres to a few kilometres)

InSAR coherence

- The InSAR coherence is the cross-correlation coefficient of the SAR image pair estimated over a small window (a few pixels in range and azimuth).
- Given two single look complex (SLC) SAR images s_1 and s_2 and defining with Ω an averaging moving window, the InSAR coherence γ at pixel k, l can be defined as:

$$\gamma(k,l) = \left| \frac{\sum_{(k,l)\in\Omega} s_1(k,l)\, s_2^*(k,l)}{\sqrt{\sum_{(k,l)\in\Omega} |s_1(k,l)|^2} \sqrt{\sum_{(k,l)\in\Omega} |s_2(k,l)|^2}} \right|$$

- InSAR coherence can be interpreted a measure of similarity between echoes received by the SAR sensor over the area Ω in two different time periods corresponding to the acquisition time of the SAR images s_1 and s_2.

InSAR coherence

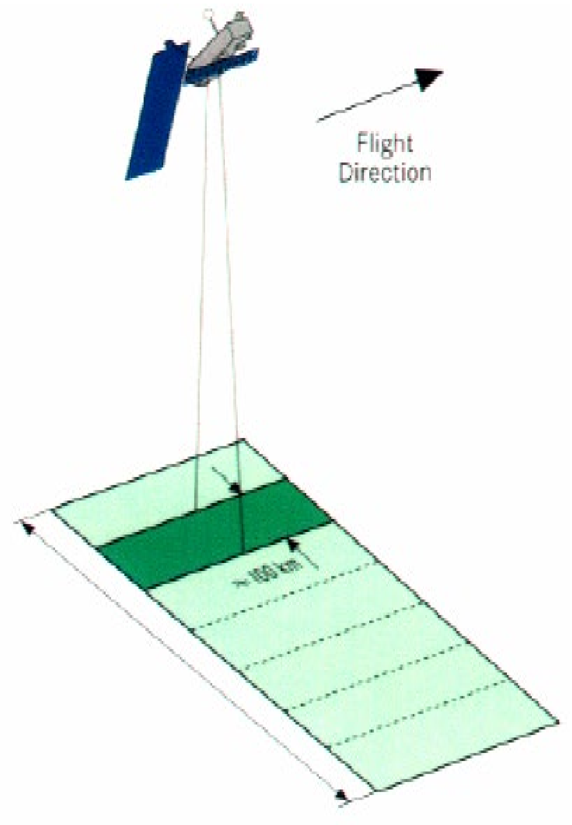
- The coherence value ranges from 0 to 1 and can and is related to the variability of the interferometric phase inside the coherence window.

- For this reason InSAR coherence is affected by:
  - Phase noise which may cause high spatial frequency changes on the phase, i.e. **temporal changes in the scatterer**, **different look angle**, **volume scattering** (no atmospheric phase noise)
  - **Large surface displacements** (bigger than half wavelength)
  - **Strong topographic effect**

SAR acquisition modes

Stripmap

Stripmap Mode is the most commonly used mode. When operating as a Stripmap SAR, the antenna usually gives the system the flexibility to select an imaging swath by changing the incidence angle.

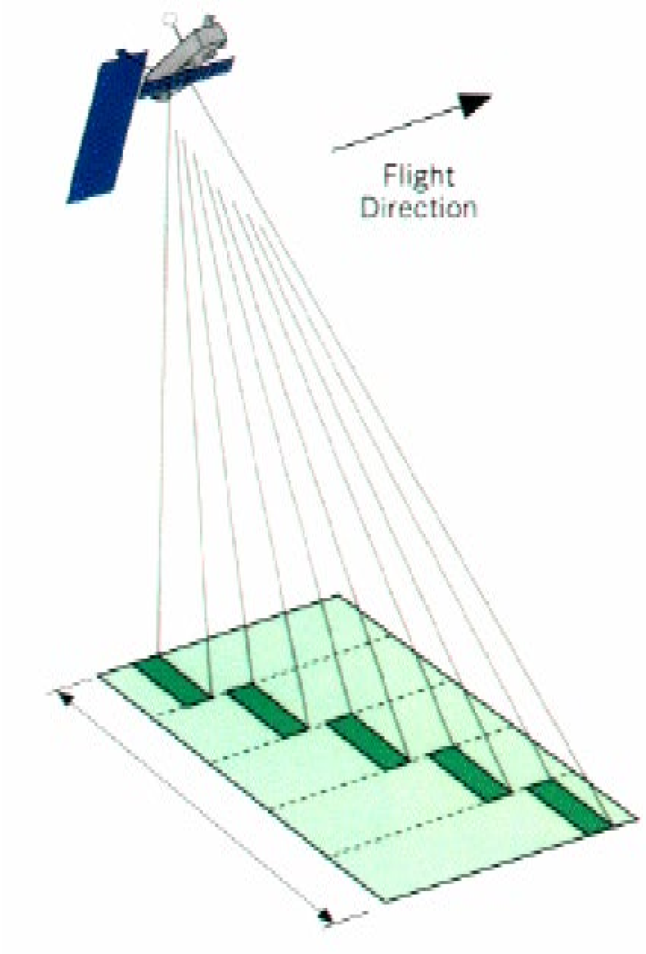


SARMap

ScanSAR

While operating as a Stripmap SAR, the system is limited to a narrow swath. This constraint can be overcome by utilising the ScanSAR principle, which achieves swath widening by the use of an antenna beam which is electronically steerable in elevation.

Radar images can then be synthesised by scanning the incidence angle and sequentially synthesising images for the different beam positions. The area imaged from each particular beam is said to form a sub-swath. The principle of the ScanSAR is to share the radar operation time between two or more separate sub-swaths in such a way as to obtain full image coverage of each.



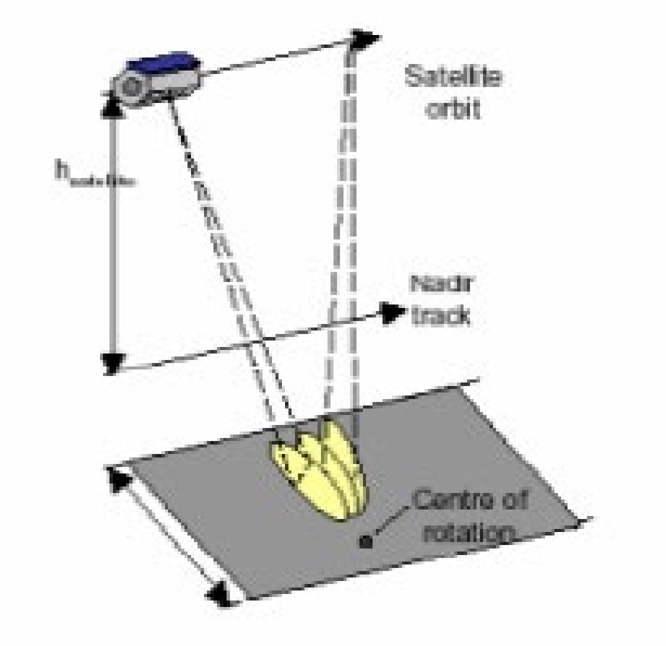
SARMap

Spotlight

During a Spotlight mode data collection, the sensor steers its antenna beam to continuously illuminate the terrain patch being imaged.

Three attributes distinguish Spotlight and Stripmap mode:

- Spotlight mode offers finer azimuth resolution than achievable in Stripmap mode using the same physical antenna.
- Spotlight imagery provides the possibility of imaging a scene at multiple viewing angles during a single pass.
- Spotlight mode allows efficient imaging of multiple smaller scenes whereas Stripmap mode naturally images a long strip of terrain.

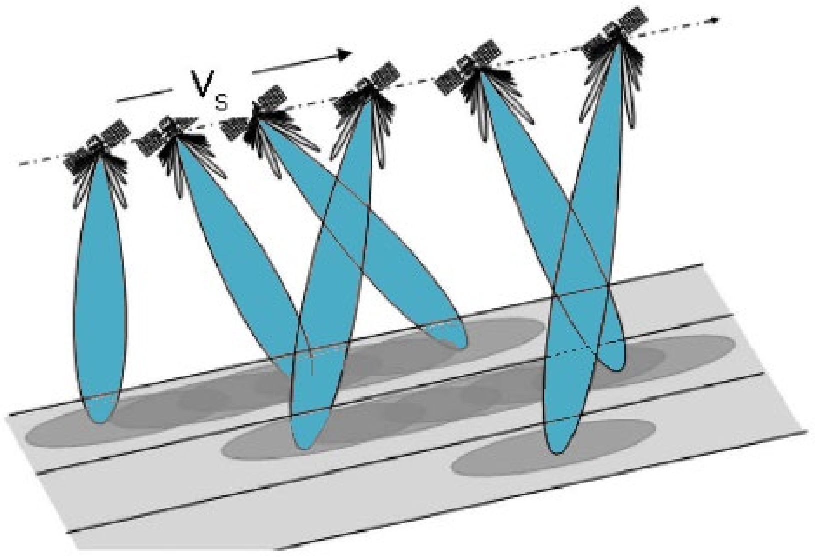


SARMap

TOPSAR

The Terrain Observation with Progressive Scans SAR (TOPSAR) technique is a form of ScanSAR imaging, where data is acquired in bursts by cyclically switching the antenna beam between multiple adjacent sub-swaths. TOPSAR acquisitions can provide large swath widths and enhanced radiometric performance by reducing the scalloping effect. TOPSAR is used in SENTINEL-1's Interferometric Wide swath and Extra Wide swath modes.

With the TOPSAR technique, in addition to steering the beam in range as in ScanSAR, the beam is also electronically steered from backward to forward in the azimuth direction for each burst, avoiding scalloping and resulting in homogeneous image quality throughout the swath



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