GAMMA REMOTE SENSING

Basics of SAR imaging and SAR interferometry

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Scope of presentation

• Present principles and basic concepts of radar imaging and synthetic aperture radar (SAR). Focus is on terminology.

• Give a brief overview on how SAR images (raw level, SLC level, intensity level) are obtained. This will then be the focus of the SAR processing part (2nd day of course).

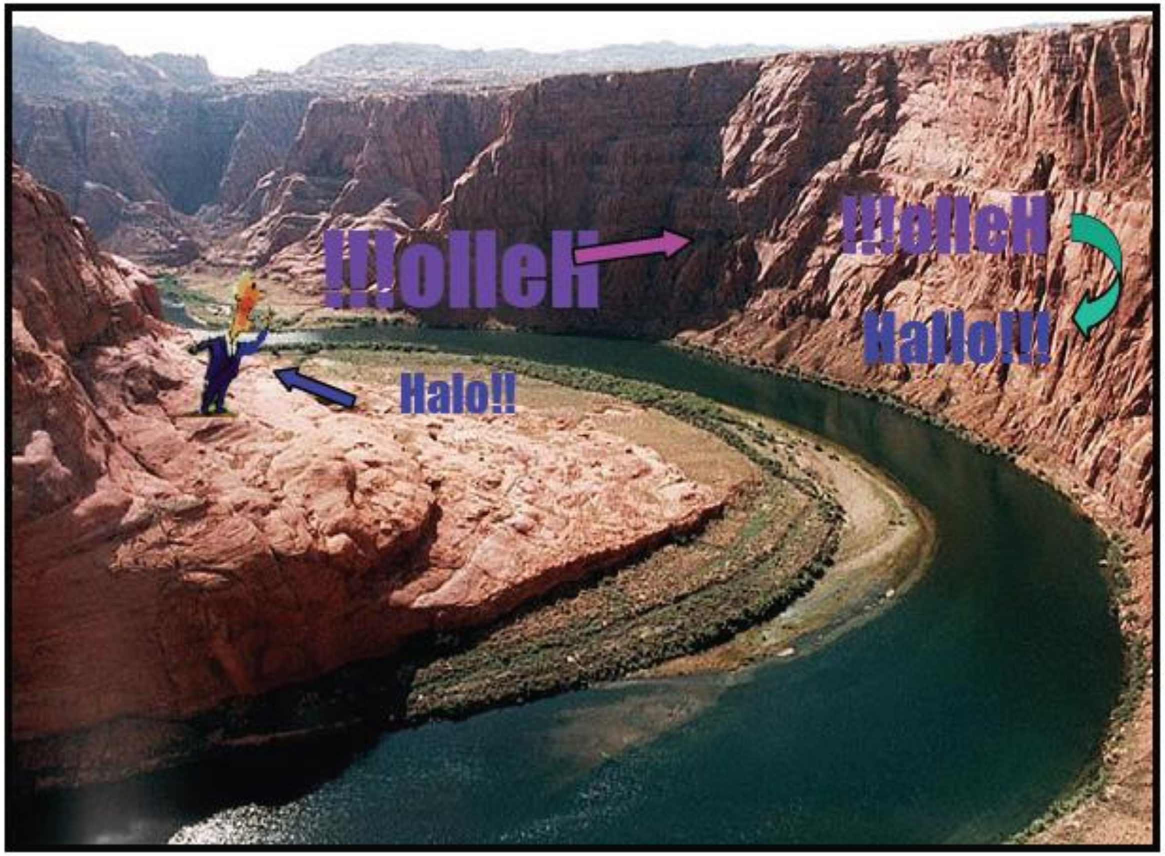
• Introduce to SAR interferometry and differential SAR interferometry (principles). Interferometric processing will be the focus of the 3rd day of the course.

Overview

- SAR basics
- SAR images: formats, properties
- SAR interferometry
- Differential SAR interferometry

Radar concept: the intuitive approach

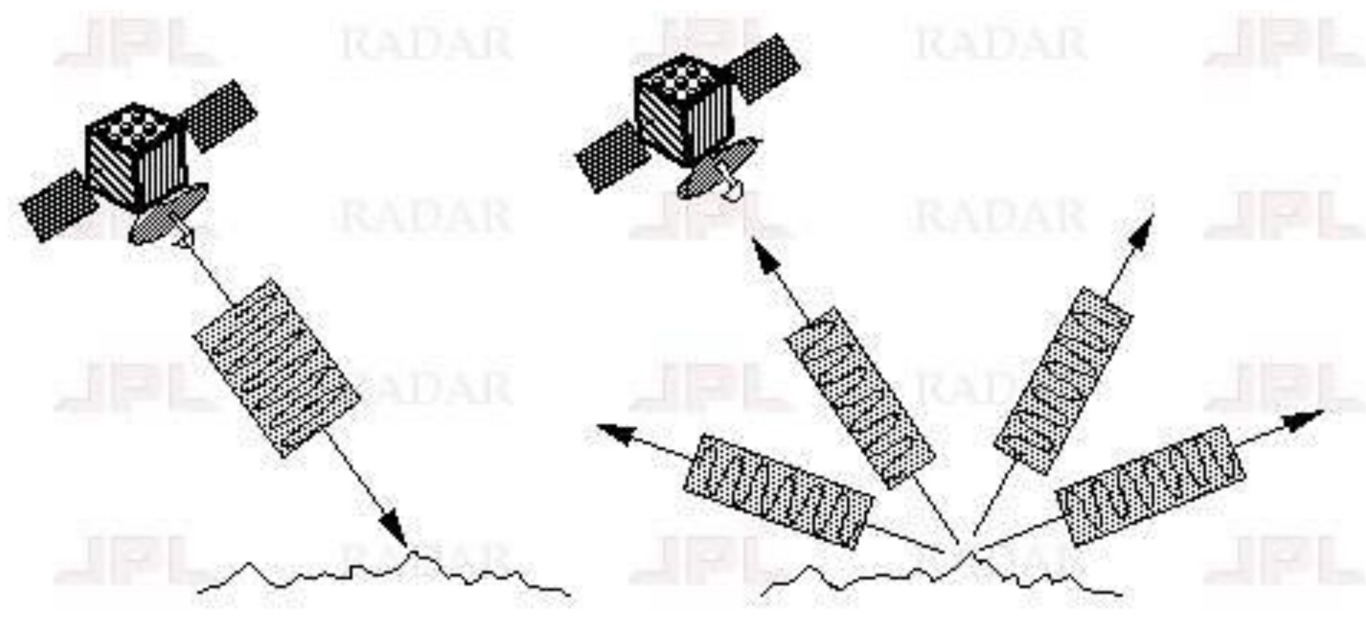
Imagine you are in the Grand Canyon and you shout. The cliffs will reflect the sound wave. After some time you will hear an echo, which is not exactly the same compared to what you shouted. This is the "principle" of a radar!



From Principles and Theory of Radar Interferometry, Paul Rosen, IGARSS 04

Concept of radar

- A radar transmits electromagnetic waves in form of pulses and records the echoes scattered back by objects encountered by the waves along their path.
- The echoes are a modified version of the transmitted pulse. Depending on the object scattering back the pulses, the echoes recorded by the radar are different (more or less energy, particular phase value etc.).

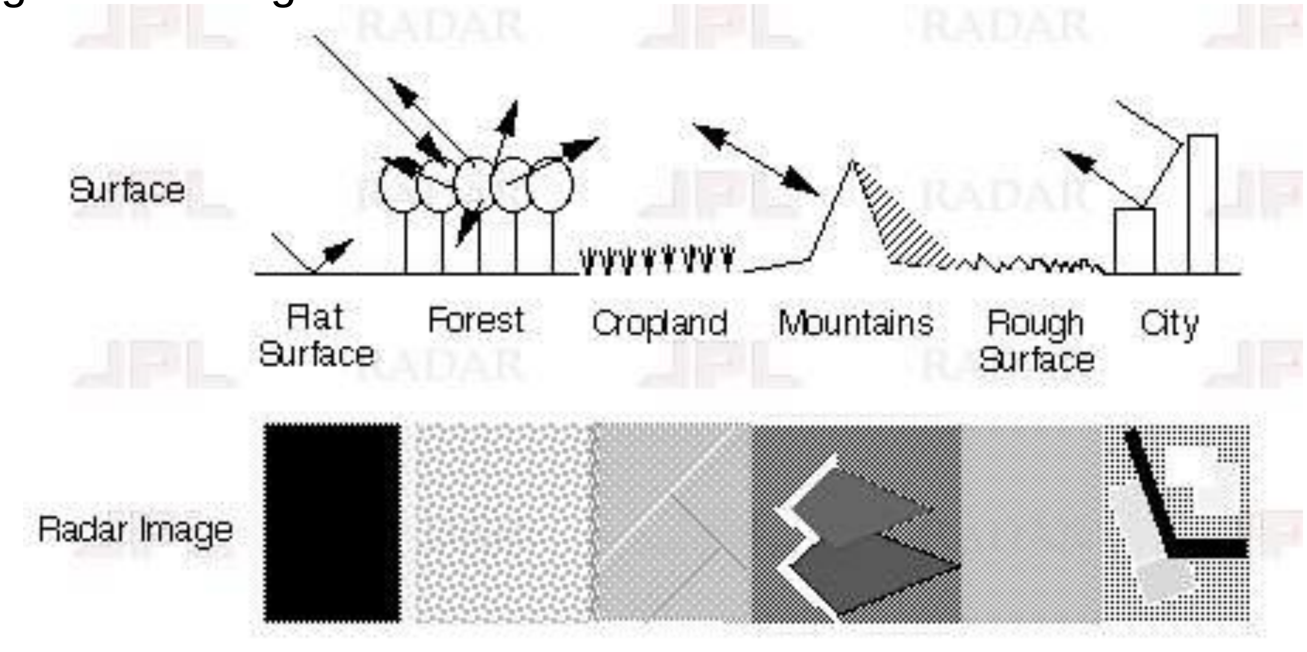


Radar transmits a pulse Measures reflected echo (backscatter)

http://southport.jpl.nasa.gov/

Concept of radar

- The scattering objects are also commonly referred to as targets or scatterers.
- The set of echoes scattered back by targets viewed by a radar can be used to form an image. This is why we speak of imaging radar.
- The information content of a radar image is related to the scattering strength of the targets and their distance from the radar



Imaging different types of surface with radar

http://southport.jpl.nasa.gov/

Electromagnetic wave

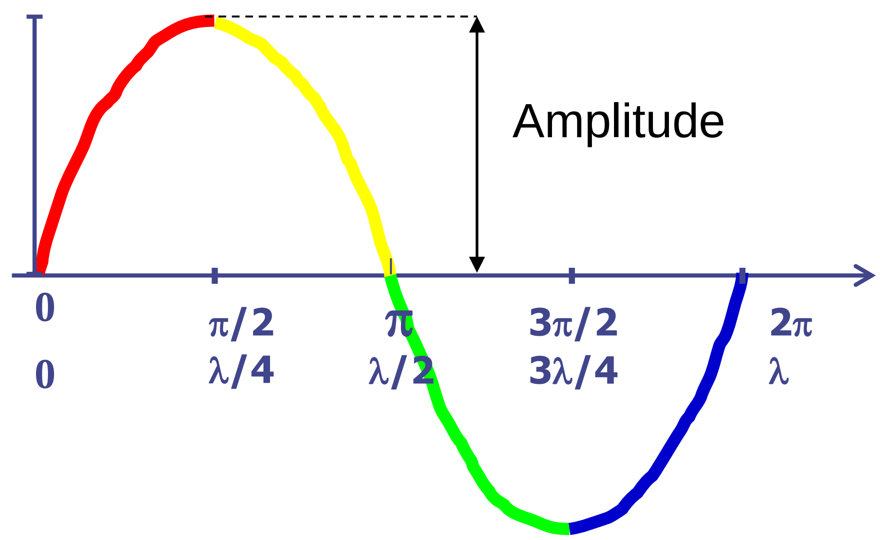
An electromagnetic wave represents the temporal and spatial variations of an electric and a magnetic field in space

Electromagnetic waves are characterized by

- Amplitude
- Wavelength or frequency, i.e. phase

Microwave wavelength λ

Phase
Distance



Electromagnetic wave

An electromagnetic wave can be mathematically represented by a complex number in the form

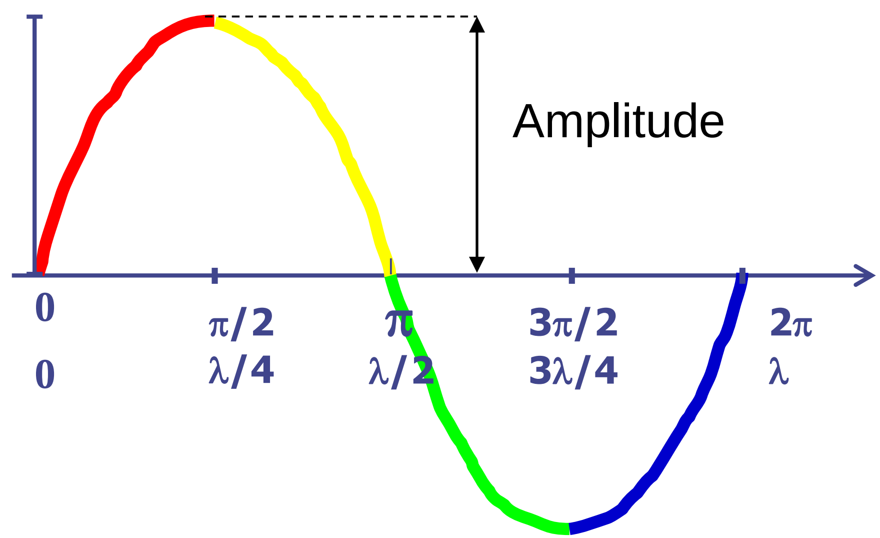
$$A \cdot e^{j\varphi}$$

where

- A is the amplitude of the wave, expressing the energy of the wave
- φ is the phase, i.e. a term related to the wavelength, giving the path traveled by the wave (in the $0, 2\pi$ interval)

Microwave wavelength λ

Phase
Distance



Complex number

A complex number is a number formed by two real numbers, of the form

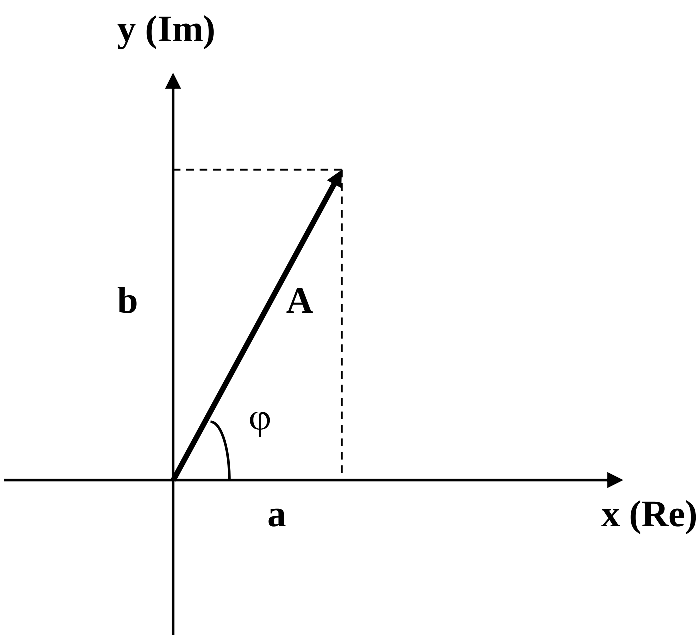
$$z = a + j \cdot b$$

$$a = \mathrm{Re}(z)$$

$$b = \mathrm{Im}(z)$$

where the real numbers a and b are called the real and the imaginary part of the complex number z. The simbol “j” is the imaginary unit, with the property $j^2 = -1$

A complex number can also be represented in terms of amplitude A and phase φ



$$z = A \cdot e^{j\varphi}$$

$$A = \sqrt{a^2 + b^2}$$

$$\tan\varphi = \frac{b}{a}$$

Some properties of complex numbers

The product of two complex numbers returns a complex number where

- the magnitude corresponds to the product of the magnitudes
- the phase corresponds to the sum of the phases

$$z_1 = A_1 \cdot e^{j\varphi_1} \qquad z_2 = A_2 \cdot e^{j\varphi_2}$$

$$s = z_1 \cdot z_2 = A_1 \cdot e^{j\varphi_1} \cdot A_2 \cdot e^{j\varphi_2} = \left(A_1 \cdot A_2\right) \cdot e^{j\left(\varphi_1 + \varphi_2\right)}$$

The conjugate of a complex number is a complex number with same magnitude and reversed phase

$$z_2 = A_2 \cdot e^{j\varphi_2} \longrightarrow z_2^* = A_2 \cdot e^{-j\varphi_2}$$

The product of a complex numbers with the conjugate of another number (called hermitian product) returns a complex number where

- the magnitude corresponds to the product of the magnitudes
- the phase corresponds to the difference of the phases

$$s = z_1 \cdot z_2^* = \left(A_1 \cdot A_2\right) \cdot e^{j\left(\varphi_1 - \varphi_2\right)}$$

Imaging radar: configuration

- Radar can always acquire, i.e. it does not suffer from cloud cover, fog and day-night cycle
- Radar systems used in remote sensing are typically mounted on airplanes or orbiting satellites and point to the ground in an either fixed or variable viewing geometry.
- Imaging radars are commonly arranged in a side-looking configuration. In this way the resolution in the viewing direction is increased

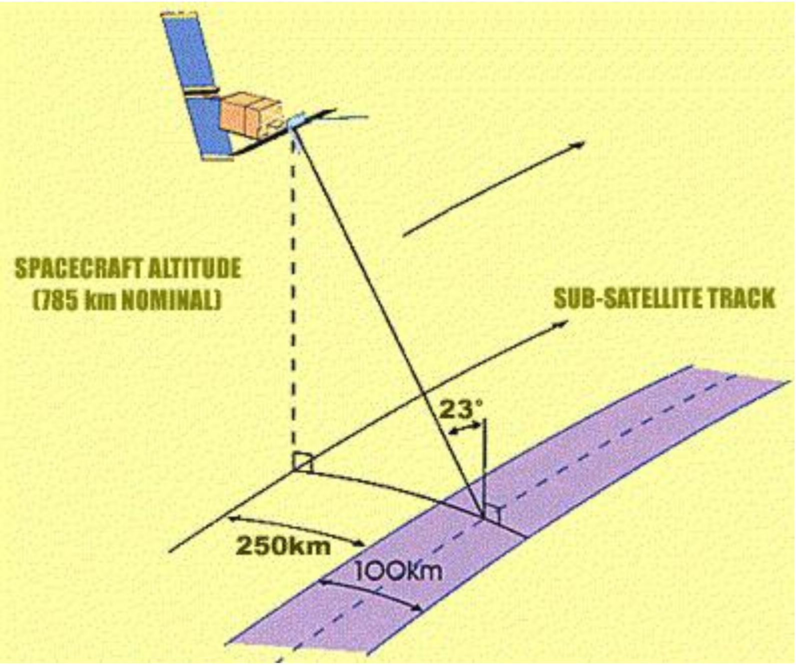
Radar systems – airborne v. spaceborne

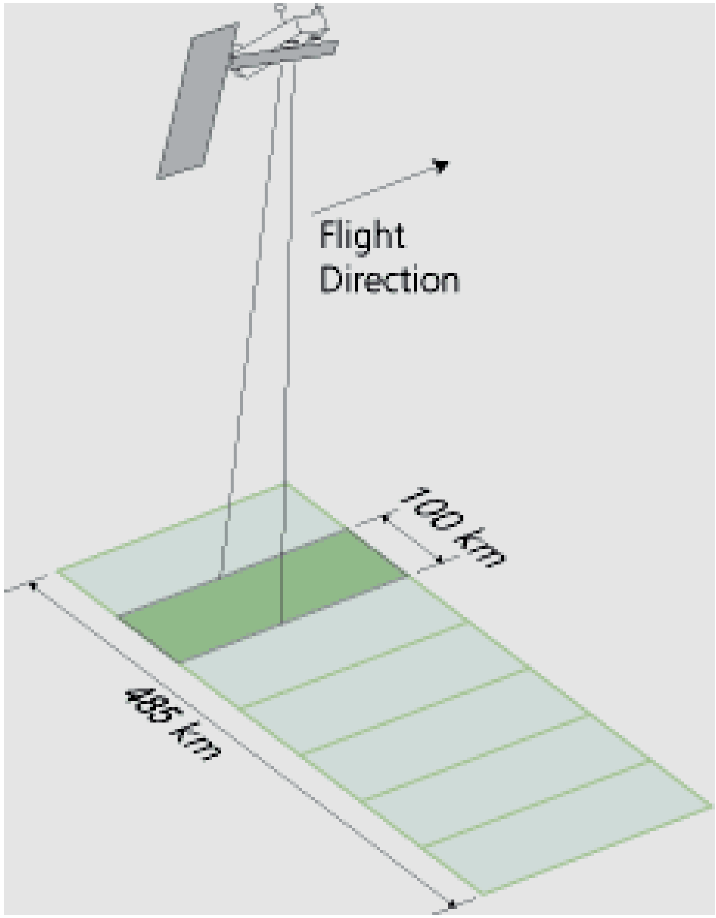
- Spaceborne radar have the advantage of global access, large swath (i.e. area seen on the ground), regular repeat imaging, large data archive, low data cost, reasonable resolution.
- Airborne radar have the advantage of high resolution and focused acquisition, multi-configuration mode (2 or more frequencies, incidence angles etc.) moreover easily changeable on ground.

ENVISAT, European Space Agency ESA

E-SAR, German Aerospace Agency, DLR

Radar systems – fixed v. variable viewing geometry





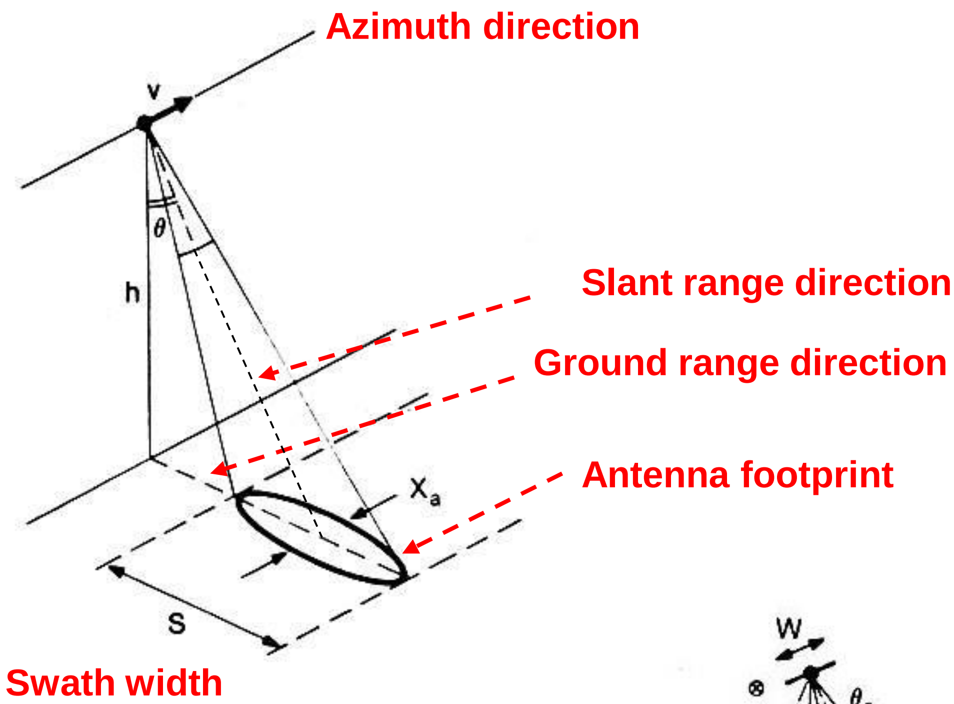
ERS-1, European Space Agency ESA

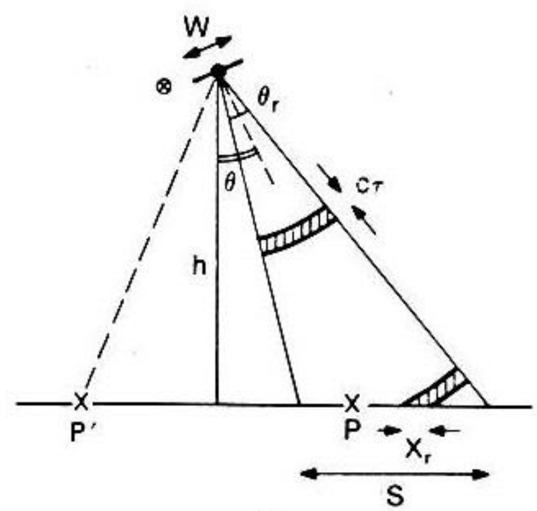
Fixed viewing geometry

ENVISAT, European Space Agency ESA

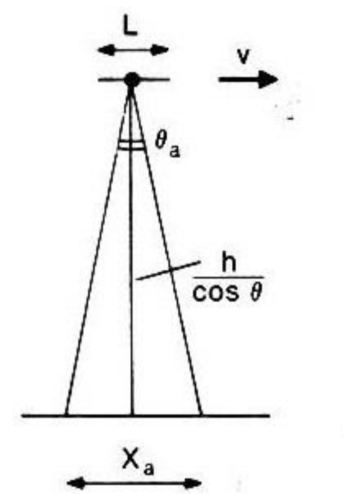
Can stir the radar antenna from steeper to shallower look directions

Radar systems – area viewed by a pulse





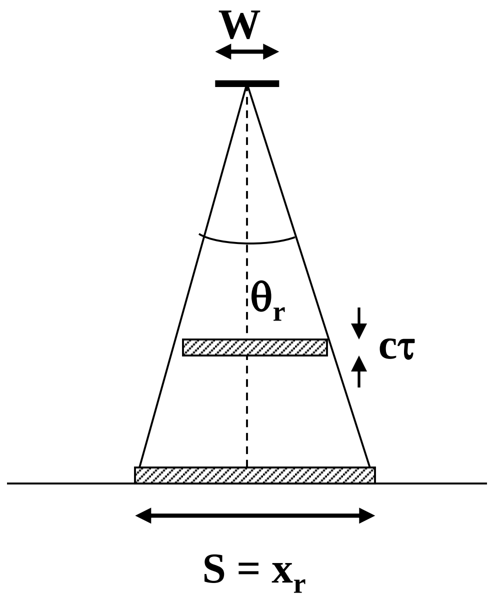
Range direction



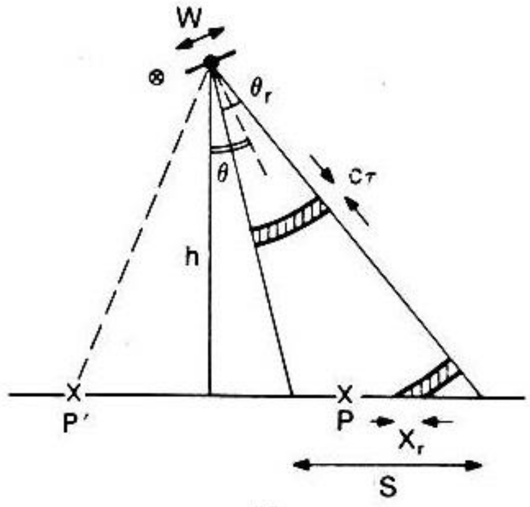
Azimuth direction

Range resolution

$\delta_r = \frac{c}{2B}$



Nadir-looking configuration



Side-looking configuration

- By looking sideways the range resolution increases because the returns from points at different range distances are separated in time, thus the radar sees them as separated
- The range resolution depends on the length of the pulse

$$x_r = \frac{c \cdot \tau}{2}$$

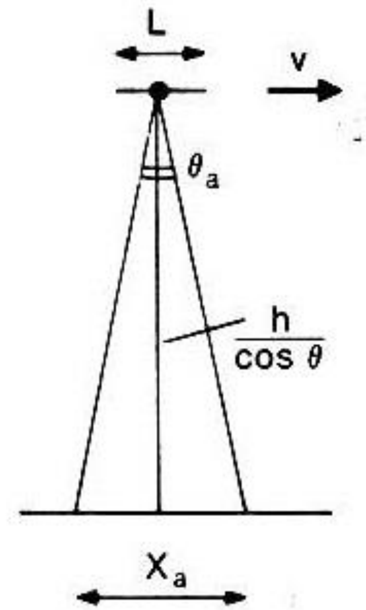
Azimuth resolution

The azimuth resolution of a radar is given by the size of the wave footprint in the azimuth direction.

The footprint is related to

- the antenna beamwidth in azimuth, θ_a, i.e.
  - the wavelength, λ
  - the size of the antenna in the azimuth direction, L
- the distance between the radar and the ground, R

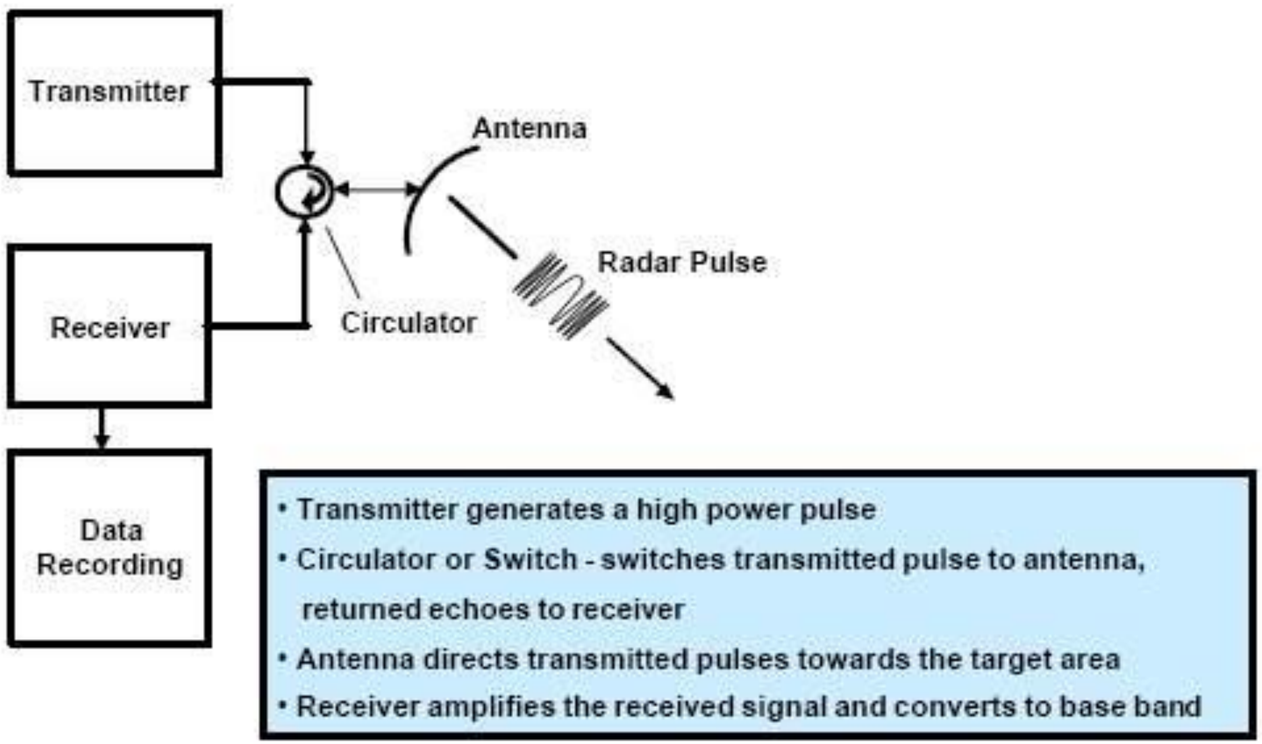
$$x_a = R\theta_a = R\frac{\lambda}{L}$$



- For a spaceborne radar with R=850 km, λ=5.6 cm and L=10 m, the azimuth resolution is about 5 km!
- Data from a spaceborne side-looking radar are therefore not used as such

Radar systems – the image acquisition process

- Transmission of pulses of e.m. waves
- Scattering
- Reception of echoes scattered back by the targets



Courtesy A. Moreira, MFFU Sommerschule 2004

Radar systems – wave transmission

- The radar signal is sent in form of short pulses. The pulses are transmitted at a fixed rate, the pulse repetition frequency (PRF)
- Typically the PRF is between 1000-2000 pulses per second
- Between transmissions, the radar goes in receiving mode
- A pulse is a short burst of limited energy, therefore to reach an object several thousands of km away and be received, it needs some sort of "help"
- The "help" is provided by the carrier wave, i.e. the pulses are "carried" by trailing waves, which are waves in the MHz-GHz frequency range
- The carrier frequency depends on the platform used for the radar (airborne or spaceborne) and on the range of applications the radar is designed for
- Carrier frequencies are typically referred to depending on the frequency band they belong to

Radar systems – carrier frequencies

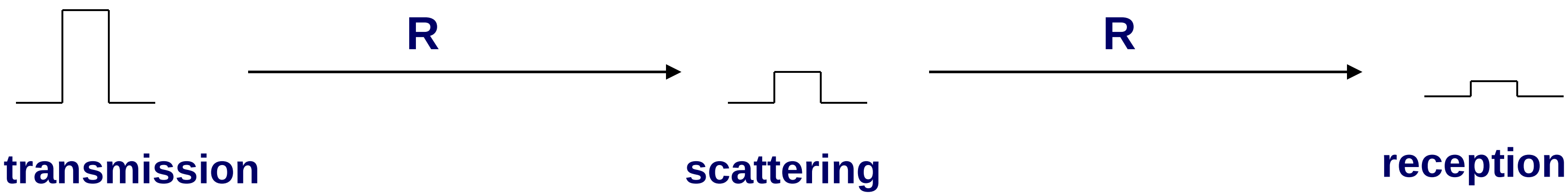
Band	Frequency	Wavelength
VHF	30-300 MHz	10-1 m
P-band	280-390 MHz	107-77 cm
UHF	300 MHz – 1GHz	100-30 cm
L-band	1-2 GHz	30-15 cm
S-band	2-4 GHz	15-7.5 cm
C-band	4-8 GHz	7.5-3.75 cm
X-band	8-12.5 GHz	3.75-2.40 cm

- Yellow background: airborne SAR
- Red background: airborne and spaceborne SAR
- Spaceborne SAR need high frequency to see through the ionosphere
- Higher frequency are also used but not often (e.g. Ka-band on DO-SAR)

Radar systems – the pulse

A pulse is a short burst of e.m. wave with a certain energy

The energy decreases with squared power of the distance R^2 to a target



- To obtain a high resolution, we want to send a pulse that is as short as possible
- To receive a signal with sufficient energy, a lot of energy has to be sent with the pulse → the shorter the pulse, the more powerful the transmitter
- For a spaceborne radar it is in practice impossible to send pulses that would allow achieving a decent resolution in range
- So, how to solve the problem?

Time/space v. frequency domain

- Each signal can be represented in terms of its frequency components
- The form of the signal in the frequency domain is called spectrum
- The interval of frequencies is called the signal band
- The difference between the highest and the lower frequency is called the signal bandwidth
- With the Fourier Transformation it is possible to convert a signal from the time (or space) domain to its correspondent in the frequency domain

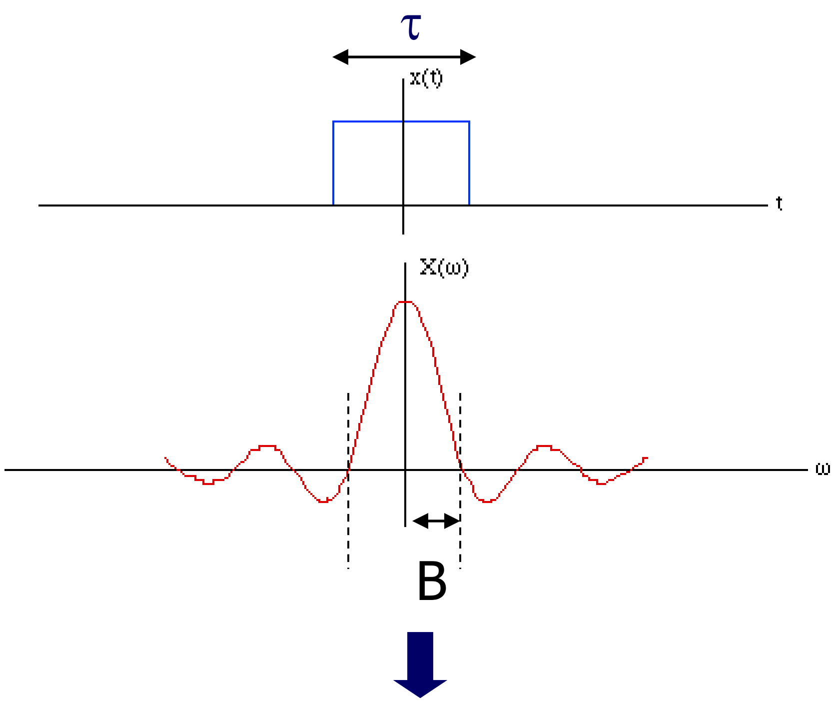
$$\underbrace{x(t)}_{\text{Signal in the time domain, } x(t)} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \underbrace{X(f)}_{\text{Signal in the frequency domain, } X(f)} \cdot e^{j2\pi ft}\,df$$

Each signal can be seen as the weighted sum of sinusoids of different frequencies

Frequency property of a pulse

- The Fourier transform of a pulse is a sinc function (sinc = sin(x) / x)
- The length of the pulse (τ) and the half width of the sinc (B) are related

$$B = \frac{1}{\tau}$$

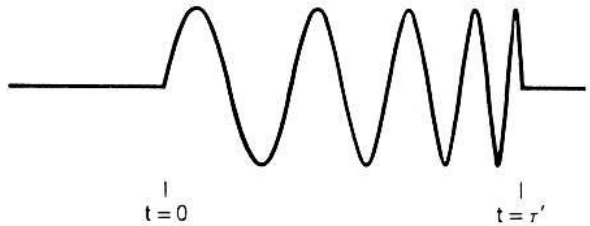


- The shorter the pulse, the larger the bandwidth of the signal
- Range resolution increases by increasing the bandwidth of the signal

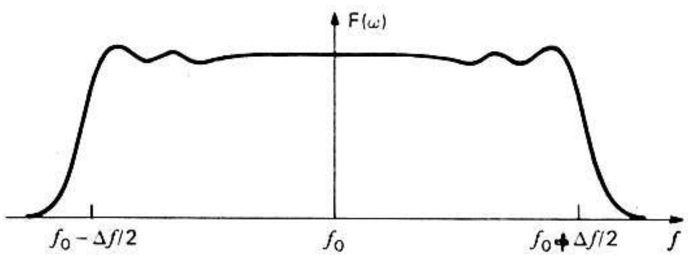
$$x_r = \frac{c \cdot \tau}{2} = \frac{c}{2B}$$

The chirp

The chirp is a pulse modulated in frequency, i.e. amplitude and frequency of the pulse change in time



Chirp in the time domain



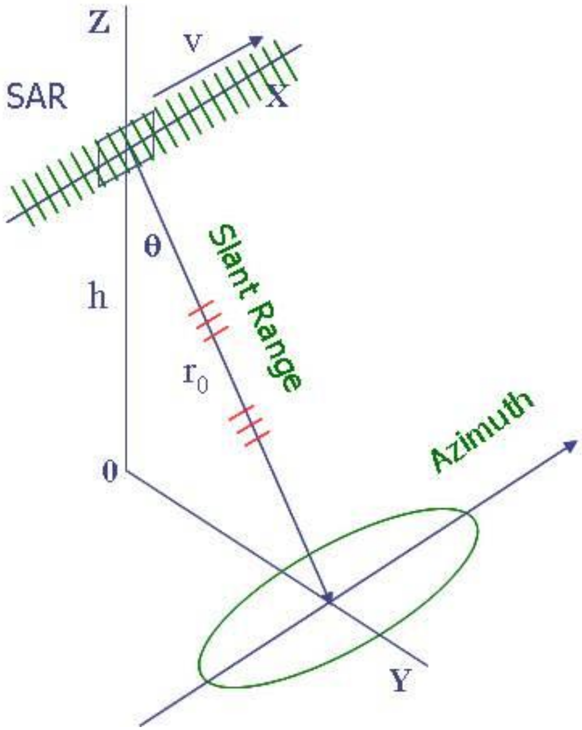
Chirp in the frequency domain

A chirp signal has a larger bandwidth, B, compared to a pulse with constant amplitude with the same length in time, hence …

… transmitting chirp pulses increases the range resolution of the radar (and we can relax on the length of the pulse)

$$x_r = \frac{c \cdot \tau}{2} = \frac{c}{2B}$$

Moving from radar to SAR



Radar looks sideways and sends out a frequency modulated pulse to obtain high range resolution. Azimuth resolution is instead bad.

As it is, a radar image is not useful but we can make a "trick" by considering two points

- Radars are mounted on a flying platform (airplane, satellite) so they "move"
- Radar typically sends out a LOT of pulses in one second (1000-2000)

so that ….

- Each object on the ground sends back to the radar a lot of echoes
- Each echo is characterized by a different distance to the radar

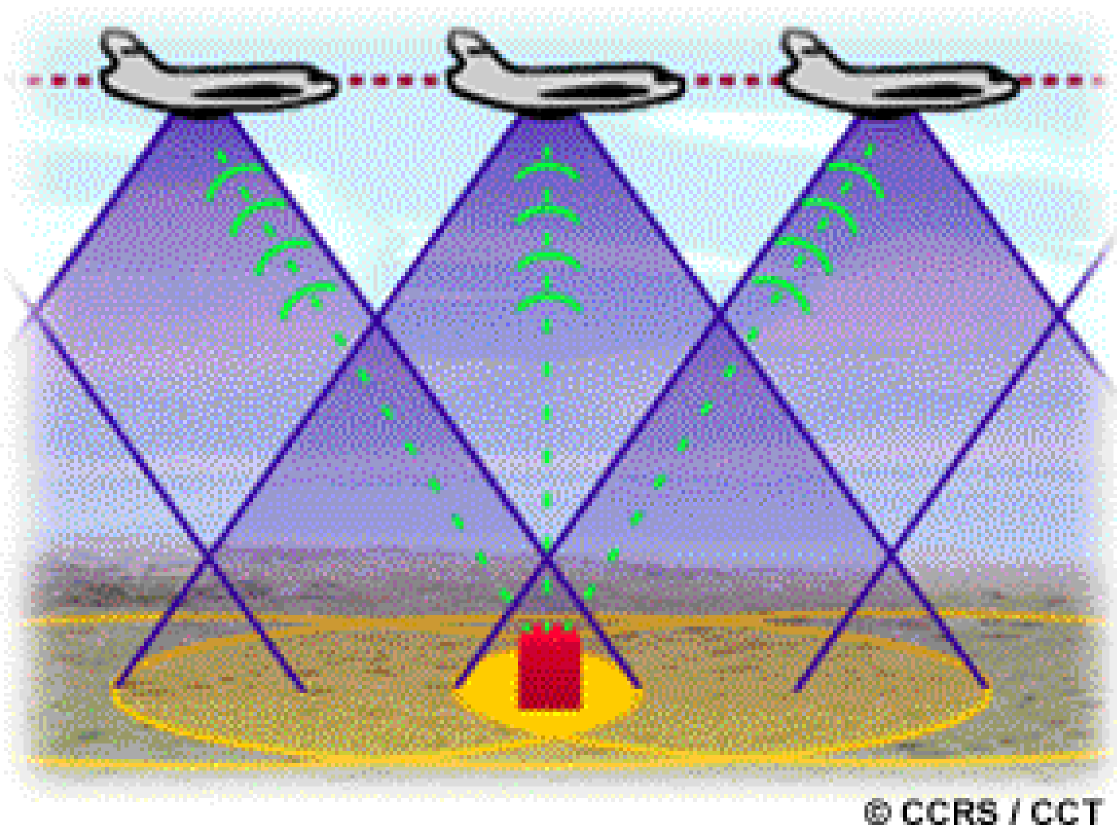
If we synthesize the echoes together, we can locate precisely and with high resolution a scatterer in the along-track direction

This is the concept of Synthetic Aperture Radar – SAR

SAR is not an object, it is a way to treat radar echoes

The concept of SAR

- The target is viewed by the radar from the moment it enters the antenna beam to the moment it leaves the antenna beam
- During this time, it sends back a very large number of echoes
- Each echo is characterized by the time required for the pulse to travel to the target and back to the radar, related to the range distance



Doppler history

Each echo is also characterized by a different Doppler frequency, f_d,

$$f_d = \frac{-2v_r}{\lambda} = \frac{-2v}{\lambda} \cdot \frac{x}{R}$$

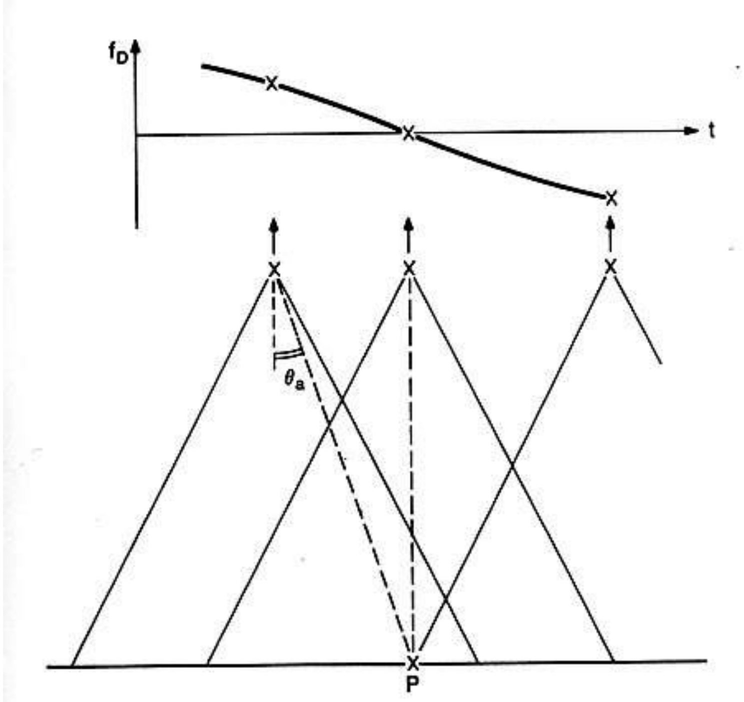
v_r = radial component of velocity of platform

x = position of target with respect to the radar along the azimuth direction

R = slant range distance

λ = wavelength

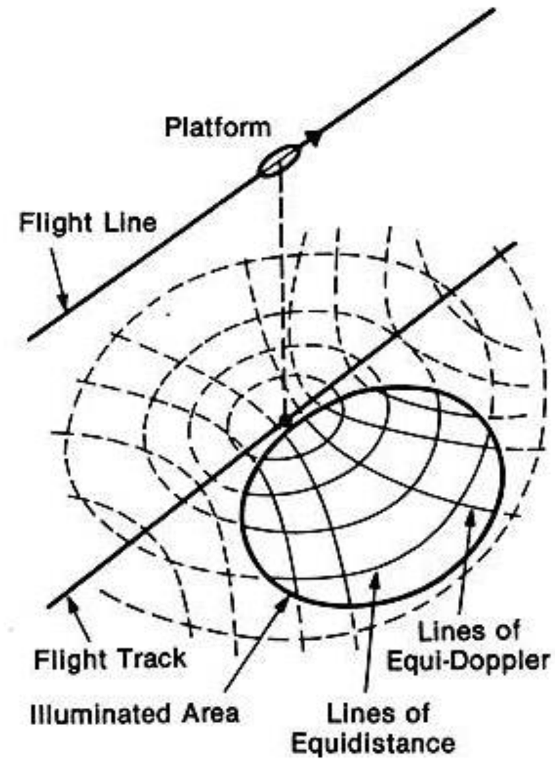
In other words each point on the ground has its own Doppler history

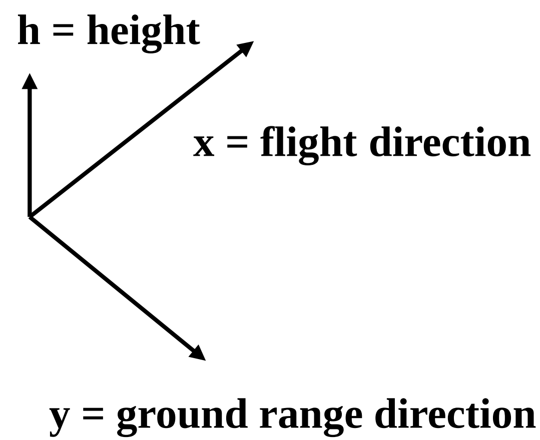


Location of a scatterer using range and Doppler data

Points with the same distance to the radar are connected by circular curves

Points with the same Doppler shift are connected with hyperbolas



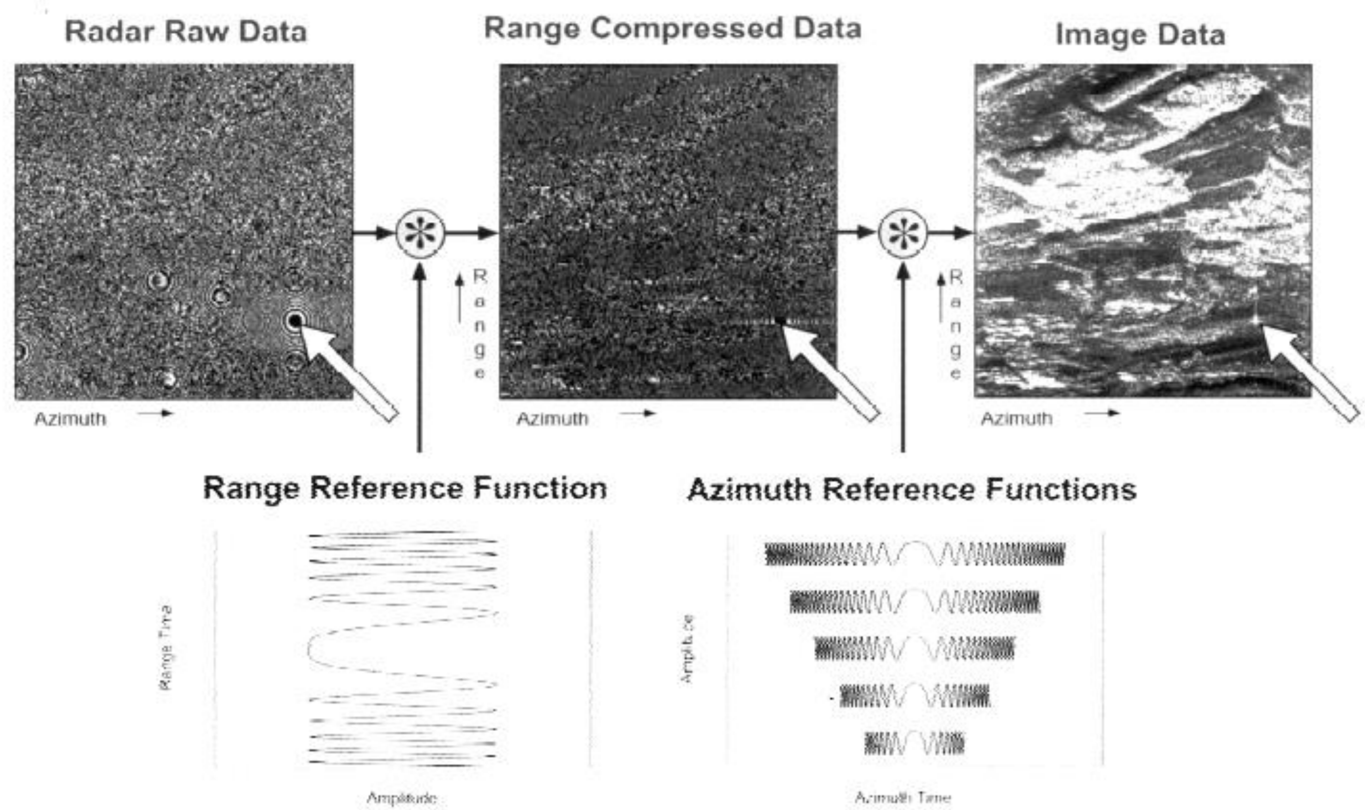


In this way scatterers can be located on the ground precisely

SAR image formation

The radar records echoes scattered by targets on the ground and transmits the data to a receiving station. Each echo contains time information.

SAR processing software uses the time information in the echoes and analyzes the Doppler frequency history of each point to obtain the SAR image



(DLR Nachrichten, Heft 86, Juni 1997, p. 42)

Overview

- SAR basics
- SAR images: formats, properties
- SAR interferometry
- Differential SAR interferometry

Outputs of SAR processing

After SAR processing we can obtain the following products

- Single Look Complex (SLC) image
    - Multi-look image
- Ground range images (e.g. ESA’s PRI or GRD data)

SLCs are complex images in the ***radar geometry*** (i.e. slant range/azimuth)

MLIs are real-valued images obtained from an SLC by multi-looking

Ground range images are real-valued images in the ***ground geometry*** (i.e. ground range / azimuth)

SLCs and Ground range images can be obtained

- with a SAR processor (e.g. GAMMA’s MSP module)
- by ordering as such from a distributing entity (e.g. ESA, JAXA, Spot Image etc.)

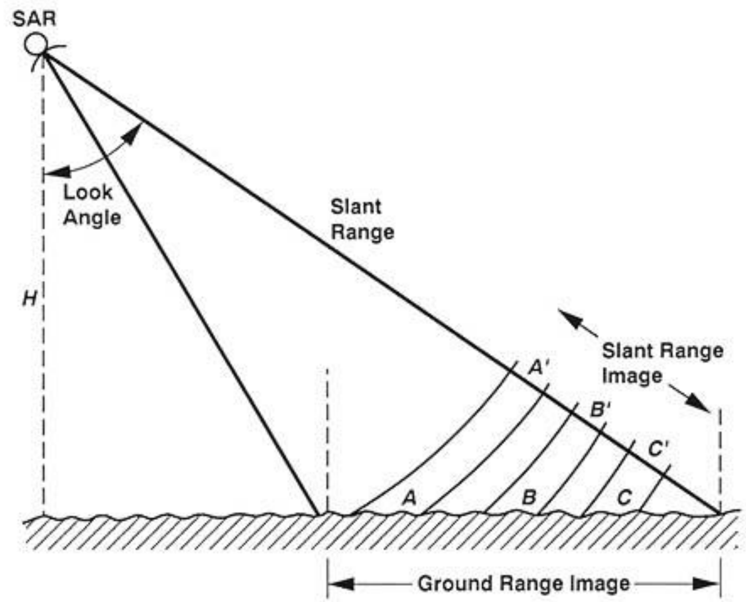
Slant v. ground range geometry

- Slant range

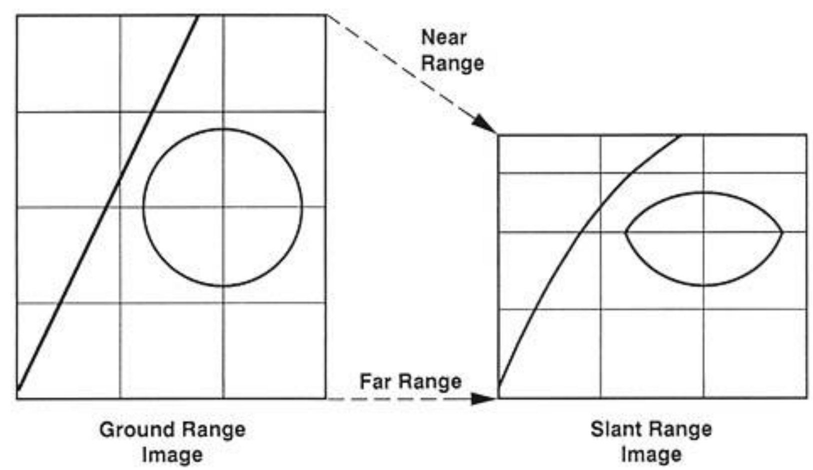
This is the natural radar geometry in which an image is acquired.

- Ground range

This is the true geometry of the image



Images in slant range will appear “compressed” in the range direction



SAR images – raw data

Raw

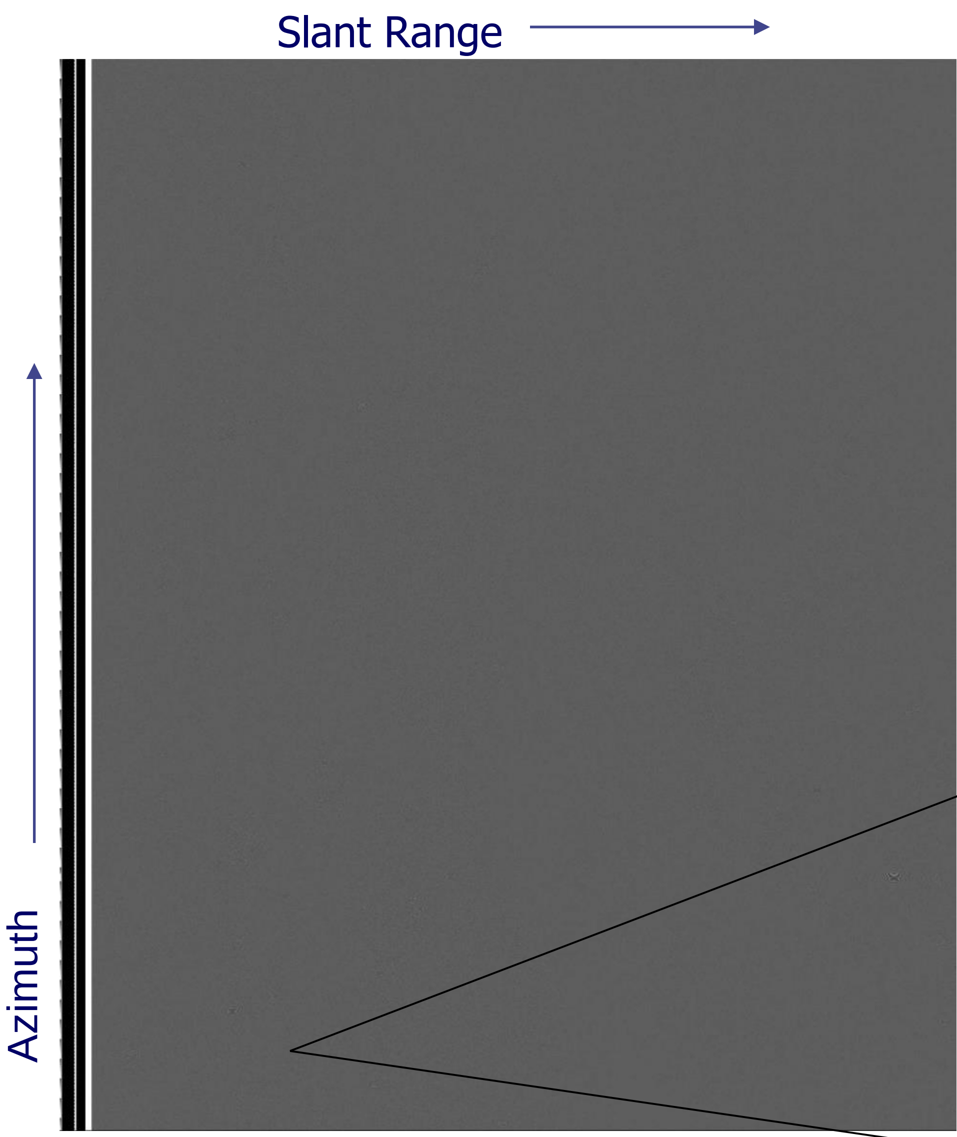
Raw data is data as it has been received by the radar, i.e. complex valued samples of the successive echoes received by the radar as it moves along the flight track.

Each line represents a particular echo scattered back to the radar by targets at a given along track position.

Each raw value typically consists of a byte for the real and a byte for the imaginary part.

From raw data SLCs and ground range images are obtained

Radar raw data (example for ERS-2)

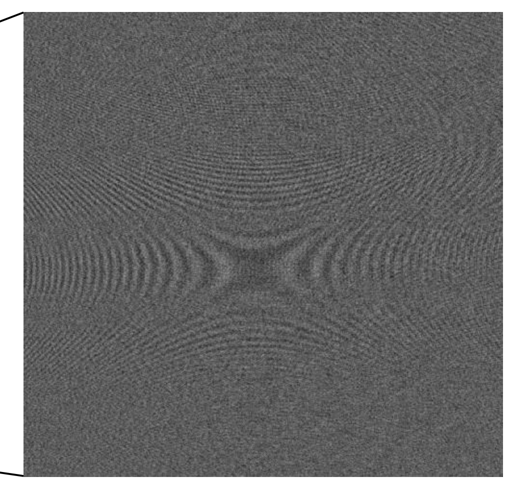


Believe it or not this is an area in the Netherlands!! ☺

Each line is an echo. In total we have ~ 11.000 echoes, corresponding to 50 km

Each pixel is a complex value reflecting the scattering properties of the objects on the ground

The zoom shows the response of a point target



SAR images – SLC data

SLC

Images in Single Look Complex SLC format represent the complex reflectivity of the targets seen by the radar.

SLC is the first level of radar imagery

Commonly the pixel of an SLC consists of either 4 or 8 bytes (2 or 4 bytes for the real resp. imaginary part).

SLCs are used for SAR interferometry and as basis to obtain MLIs

Radar amplitude and phase

The signal scattered back to the radar is a complex quantity consisting of

- Amplitude
- Phase

•The amplitude of the signal depends on the scattering strength of the target.

•The phase is primarily related to the two-way path distance (2R) between the radar and the target

•In addition a phase offset can be introduced by the scattering. This term depends on the specific target.

•The phase has values in the interval 0 – 2π

$$\varphi = -\frac{2\pi}{\lambda}\cdot 2R + \varphi_{scatter} = -\frac{4\pi}{\lambda}R + \varphi_{scatter}$$

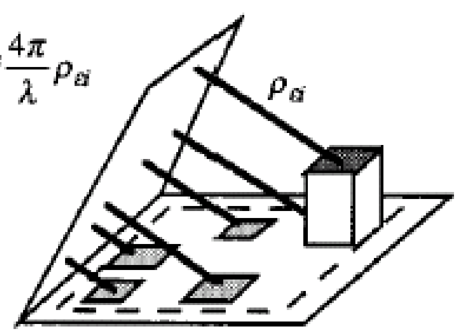
Radar amplitude and phase – distributed target

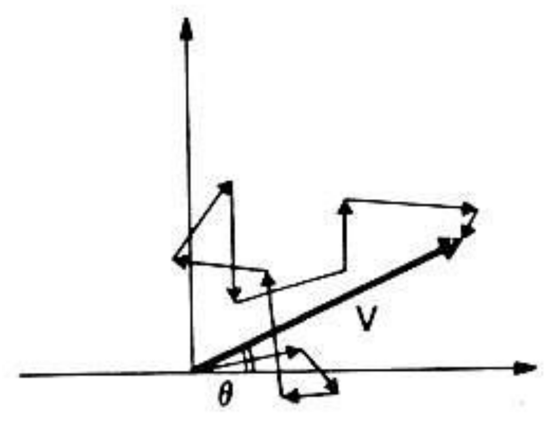
Let us now consider the case of several targets in a resolution cell (e.g. trees, buildings, poles etc.)

If a resolution cell contains few up to several hundredths targets, the signal received results from the coherence (=complex) sum of the contributions from the individual targets

Resolution Element

$$\sum_i A_{\varepsilon i} e^{j\phi_{\varepsilon i}} e^{-j\frac{4\pi}{\lambda}\rho_{\varepsilon i}}$$





The amplitude is related to scattering strength of the scatterers but also their mutual position. In this way signals tend to sum up or cancel out.

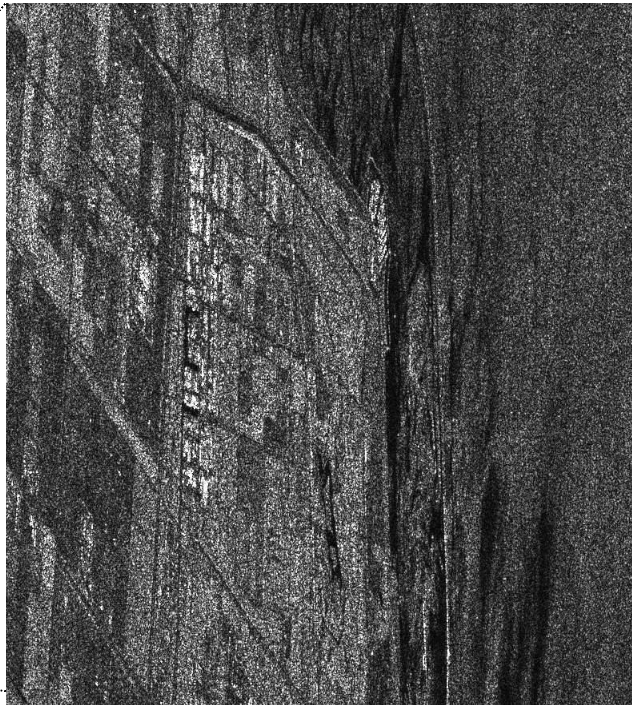
The phase of each target is deterministic (distance to the radar) but becomes random in the 2π interval because the coherent sum of the individual targets

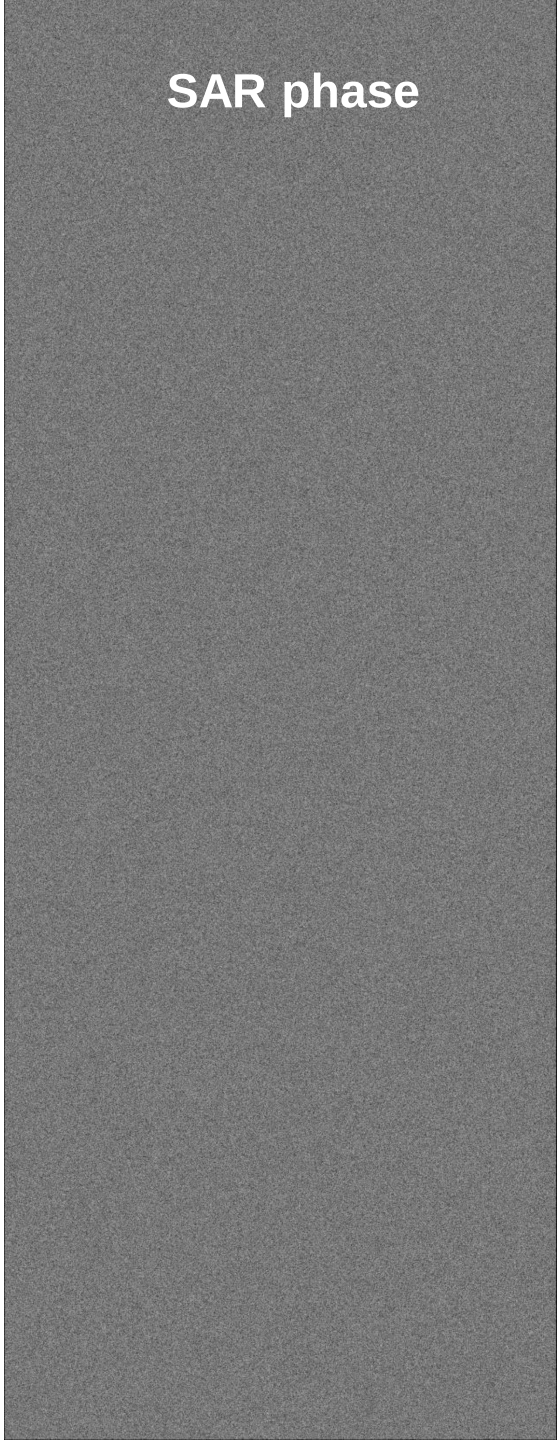
This effect is called speckle (= salt and pepper)

SLC imagery

Believe it or not this is the area in the Netherlands!! ☺

The images appear stretched because the pixel size in range (20 m) is 5 times bigger than in azimuth (4 m)





SAR images – MLI data

MLI

MLI means multi-looked intensity (intensity = squared amplitude)

MLIs are obtained from SLCs by spatial averaging.

The mean of several consecutive pixels of an SLC in range and/or in azimuth is computed. This is also called spatial multi-looking. The number of looks of an MLI image corresponds to the number of pixels being averaged together.

For example for the ERS case 1x5 multi-looking consists of averaging 5 pixels in azimuth and 1 in range to obtain one pixel. The resulting MLI is a 5-look image.

MLIs have less speckle but also less resolution compared to an SLC.

MLIs represent the scattering strength of a target

Typically, it is referred to such kind of images with the name of SAR backscatter image as well

Explanation of multi-looking (1/2)

We want to multi-look (ML) an image with factors 1 in range and 5 in azimuth

Magnitude of SLC image

(10 rows, 4 columns)

2	3	3	2
6	5	2	1
1	4	3	2
6	3	4	6
2	5	3	2
1	4	2	5
4	3	5	3
2	2	7	5
6	2	5	3
4	3	6	2

ML window on a block of 1x5 pixels

2	3	3	2
6	5	2	1
1	4	3	2
6	3	4	6
2	5	3	2
1	4	2	5
4	3	5	3
6	2	7	5
6	2	5	3
4	3	6	2

Average: 3.4

ML window on next block of 1x5 pixels

2	**3**	3	2
6	**5**	2	1
1	**4**	3	2
6	**3**	4	6
2	**5**	3	2
1	4	2	5
4	3	5	3
6	2	7	5
6	2	5	3
4	3	6	2

Average: 4.0

… and so on until end of SLC image

Explanation of multi-looking (2/2)

We want to multi-look (ML) an image with factors 1 in range and 5 in azimuth

Magnitude of SLC image

(10 rows, 4 columns)

2	3	3	2
6	5	2	1
1	4	3	2
6	3	4	6
2	5	3	2
1	4	2	5
4	3	5	3
2	2	7	5
6	2	5	3
4	3	6	2

Multi-looked intensity

(2 rows, 4 columns)

3.4	4.0	3.0	2.6
4.2	2.8	5.0	3.6

With multi-look we reduce the variability of the values of the original data (less noise), but also reduce resolution. MLI images are smaller compared to SLC images.

Radar backscatter - summary

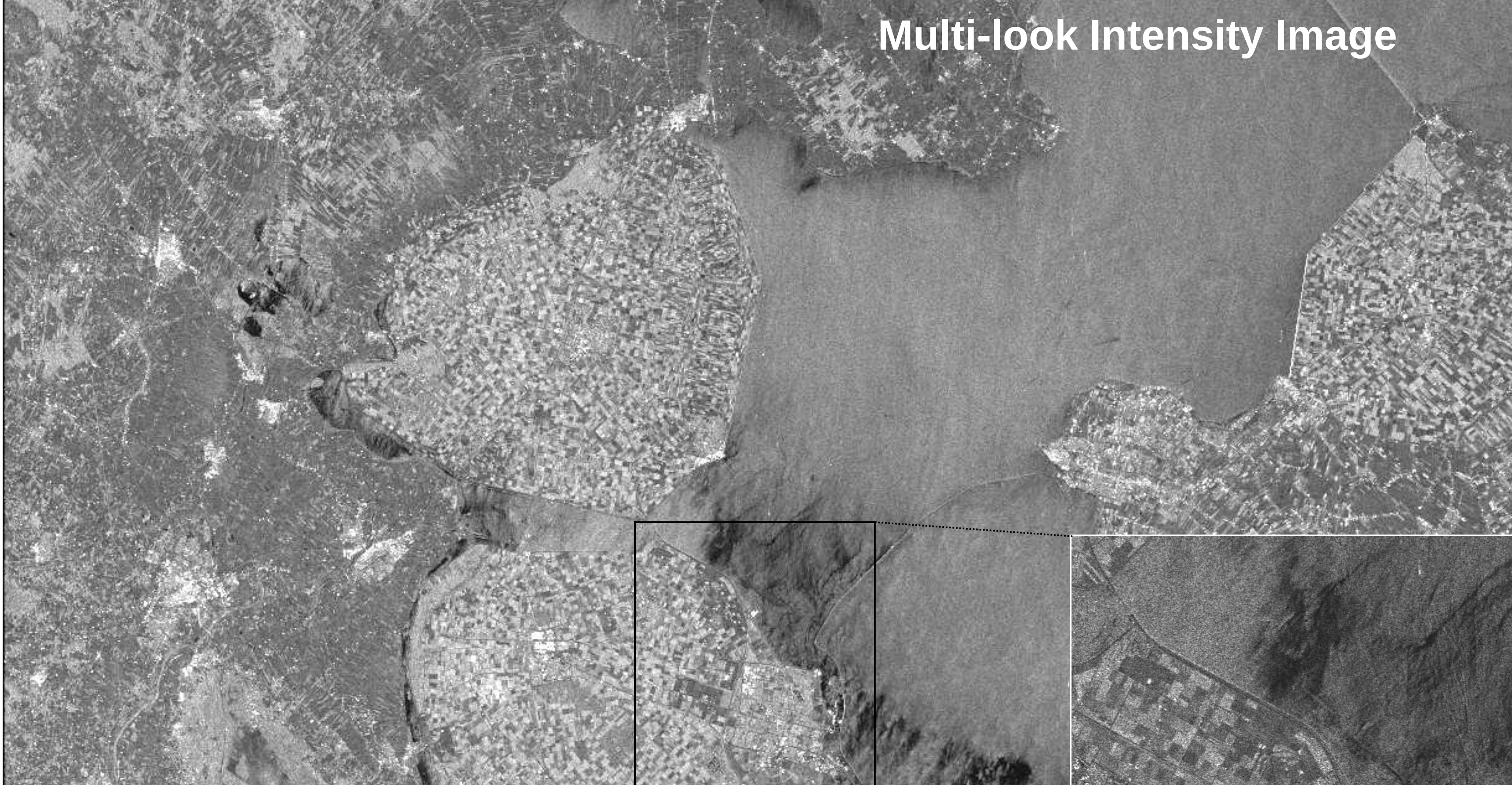
The radar backscatter is a function of

- •Surface roughness
- •Dielectric constant
- •Incidence angle
- •Frequency

Typically a resolution cell include more scatterers, in which case we speak of distributed target

Point scatterers are targets that dominate the scatter within a resolution element

- •Corner reflectors
- •Large structures - e.g. Oil tanks
- •Linear structures – e.g. pipes, gutters



Now you know can see how this area
in the Netherlands looks like!! ☺

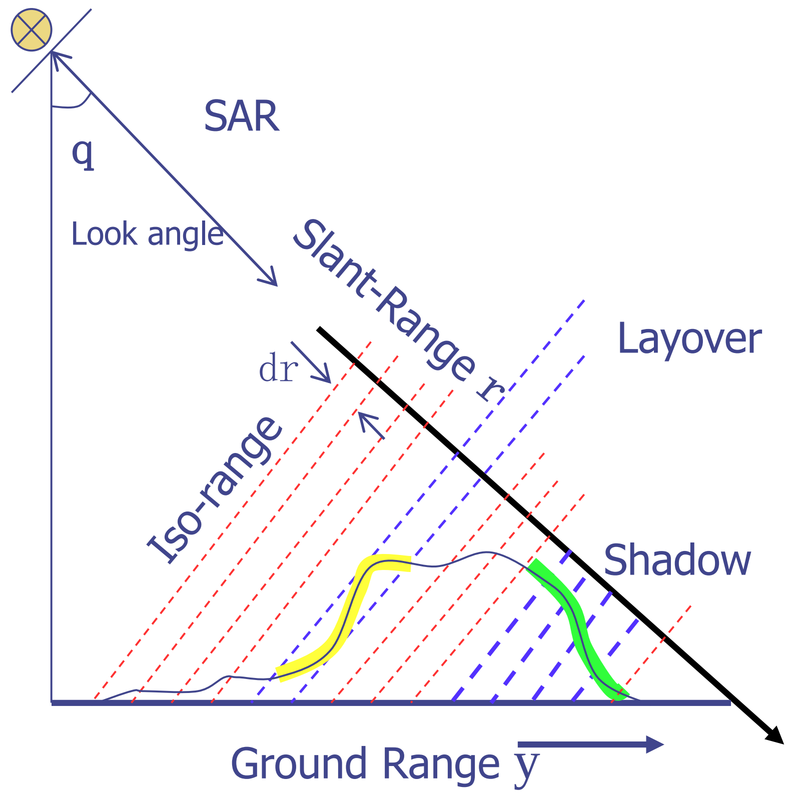
Because of the 1:5 ratio between pixel sizes, a multi-look factor of 1x5 has been applied. The result are squared pixels with 20m x 20m pixel size

Geometric distortions

Foreshortening alters the distance of two regions in areas with slopes

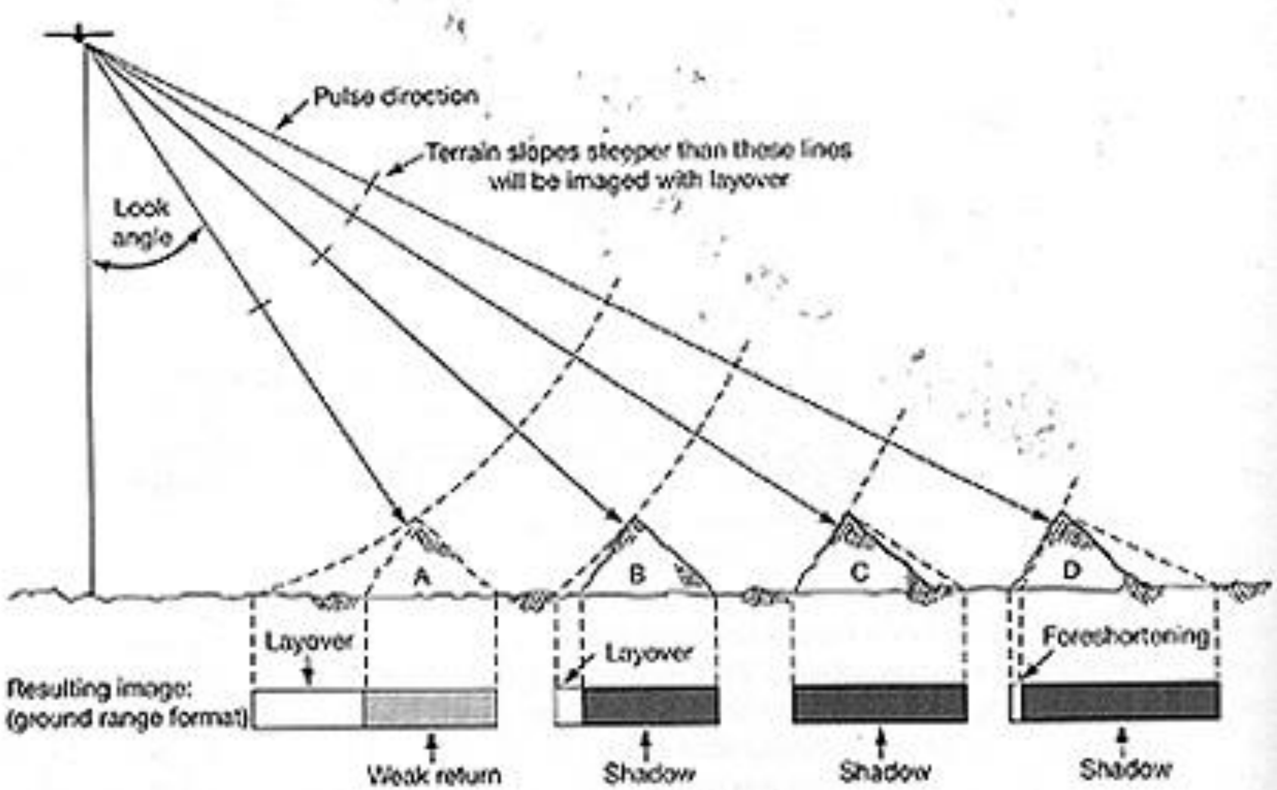
Layover occurs when multiple regions are at the same slant range

Shadow occurs because of occlusion by terrain



Layover and shadow lead to missing data in regions with steep sloped terrain.

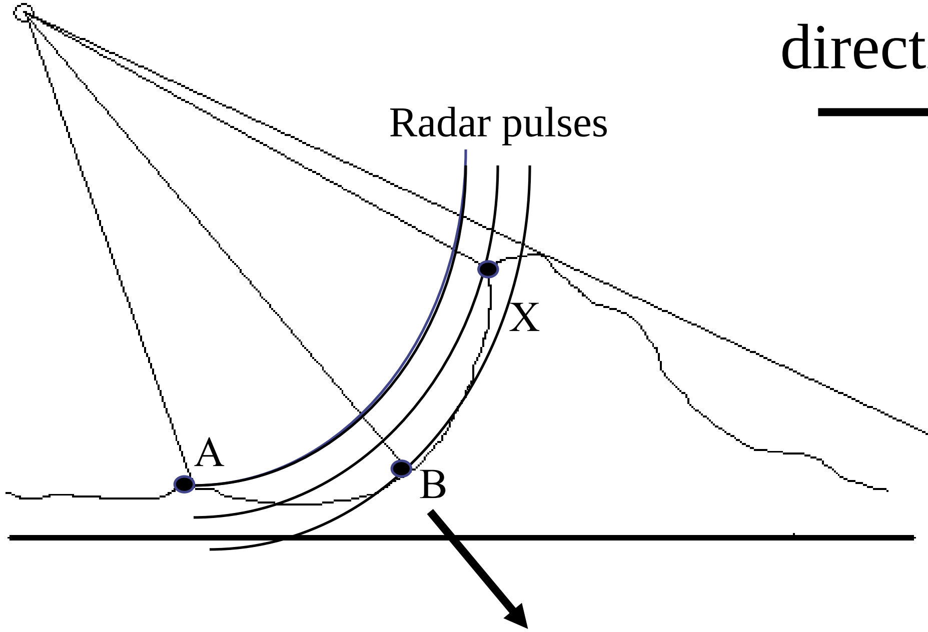
Geometric distortions (cont.)



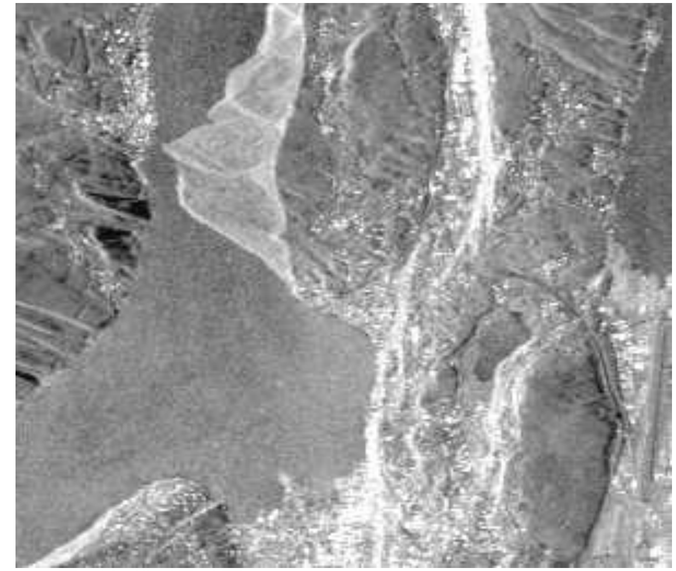
- Layover occurs for slopes facing the radar steeper than the look direction
- Shadow occurs for slopes tilted at least 90 degrees away from look direction

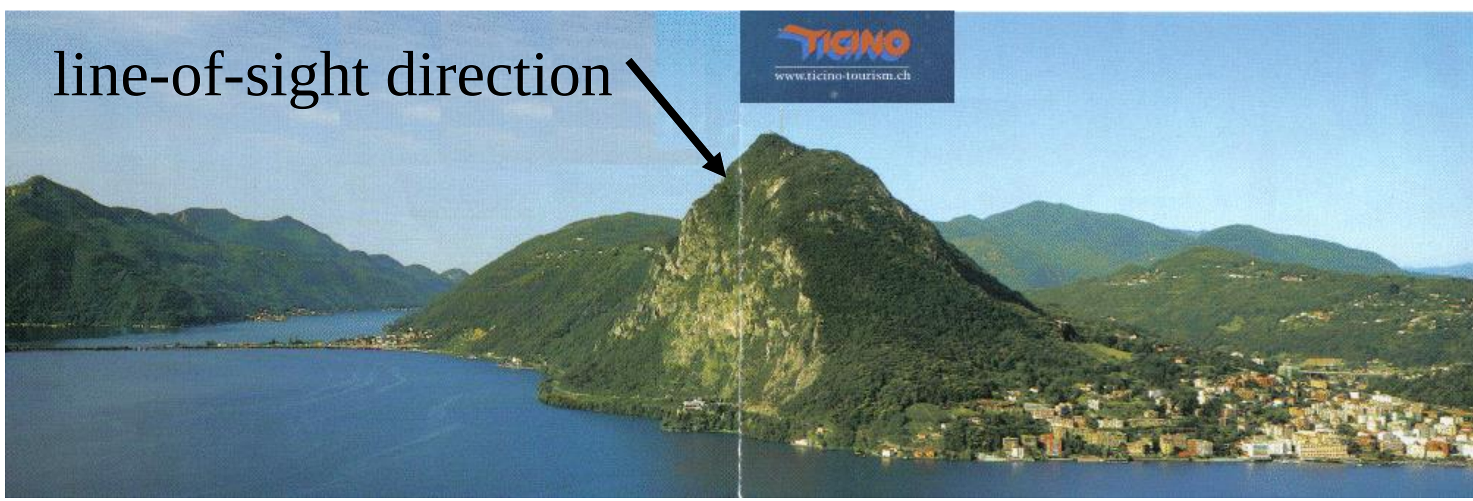
- Radar viewing with a steep look angle is proner to foreshortening and layover
- Radar viewing with a shallow look angle is more prone to shadow

Example of layover



line-of-sight direction





Lugano, Switzerland, and the Monte San Salvatore

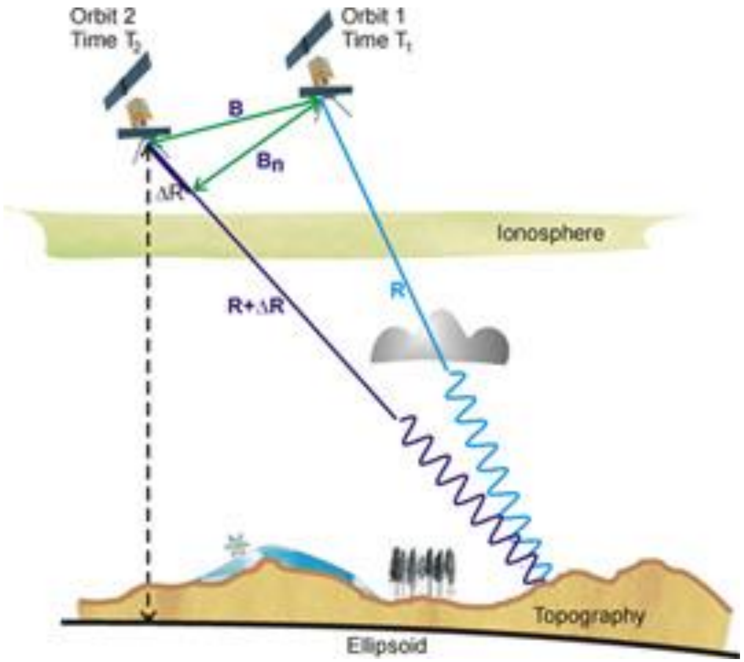
Overview

- SAR basics
- SAR images: formats, properties
- SAR interferometry
- Differential SAR interferometry

SAR interferometry (InSAR) : introduction

SAR interferometry (InSAR) consists of interfering two SAR images of an area, which have been acquired from two slightly different positions in space or time. When a target is viewed under two slightly different angles, the **elevation** can be precisely recovered using the **phase information** thus allowing a **3-dimensional reconstruction** of the viewed scene.

With SAR interferometry it is also possible to **retrieve bio- and geophysical** properties of land surfaces by exploiting the **degree of coherence** of the two images being interfered.



http://www.enveo.at/projects/2003esainsar/

Why can we retrieve elevation from the InSAR phase?

- Although SAR images contain both amplitude and phase, the information contained in the SAR phase is not exploitable for distributed targets because of speckle.
- Two images acquired with almost identical sensor positions have almost identical speckle.
- The interference of the signals contained in the two images cancels out the random contributions to the SAR phase.
- The interferometric phase represents the phase difference between the two images, therefore it contains information about the 3-dimensional position of a target.
- SAR interferometry is therefore an effective technique to map elevation (e.g. Digital Elevation Models) as well as to map elevation changes. Maps of geophysical displacement can be generated with differential SAR interferometry (DInSAR).
- The accuracy of the interferometric phase is related to the level of the degree of coherence.

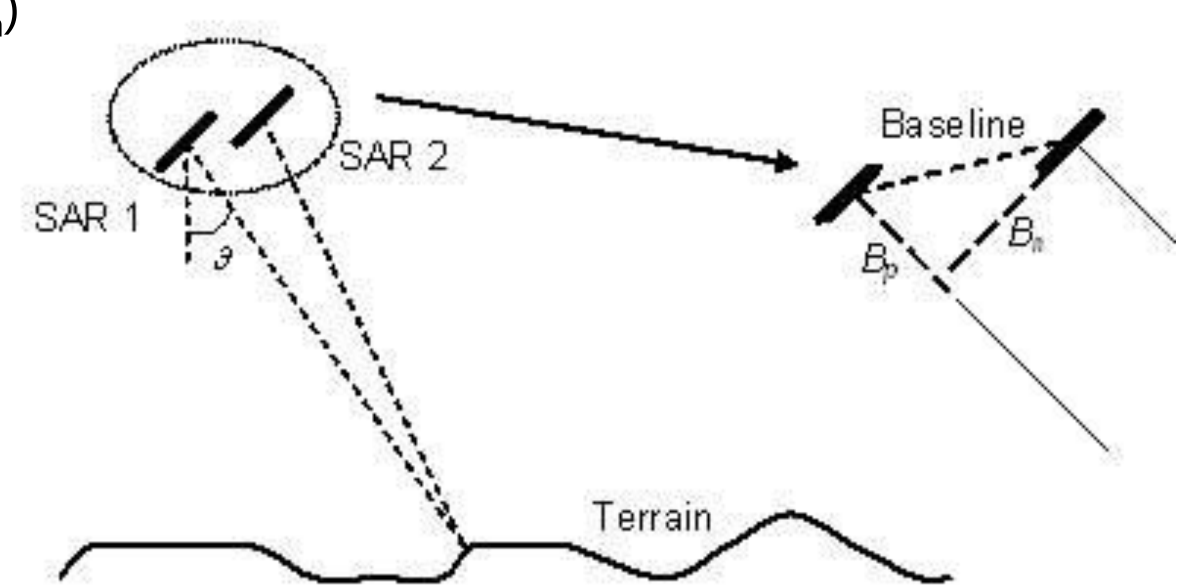
Why can we retrieve biophysical properties from coherence?

- The coherence measures the correlation between the signals scattered back to the radar by a target at two acquisitions.
- If the two images have been acquired simultaneously coherence is highest. Otherwise there are differences depending on the nature of the target.
- Coherence decreases for targets with larger volume scattering and affected by temporal changes between the acquisitions of the two images.
- Buildings and bare soils are surface scatterers and do not change between acquisitions. On the contrary forests can be seen as a volume including many elements (leaves, twigs, small branches, stem), many of them changing position in time → Forests have typically lower coherence than urban areas and bare soils
- Coherence contains thematic information with a good potential for land applications such as landuse classification, retrieval of biophysical properties and change monitoring.

The interferometric system

- Two radar antennas (SAR 1 and SAR 2) observe a target on the ground with a slight separation in space, the interferometric baseline.

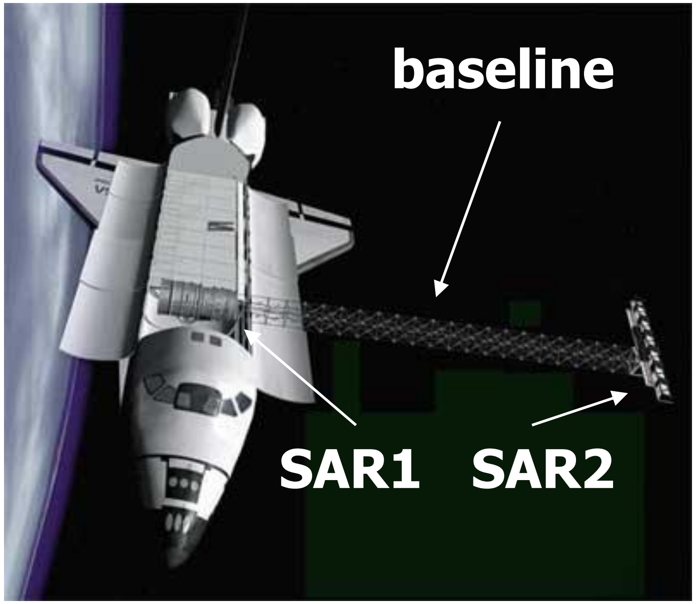
- The component of the baseline along the line of sight is called parallel baseline (B_p), the component orthogonal to the line of sight is called perpendicular baseline (B_n)



If the <u>two images</u> are acquired <u>simultaneously</u> → **single-pass interferometry**

If the <u>two images</u> are acquired <u>at different imes</u> → **repeat-pass interferometry**

Single-pass SAR Interferometry:
Shuttle Radar Topography Mission (SRTM)



SRTM STS-99 Mission, 22 days, February 2000

60m baseline between the inboard transmitter/receiver and outboard receiver.

8.6 Tbytes (C-Band) 3.6 Tbytes (X-Band)

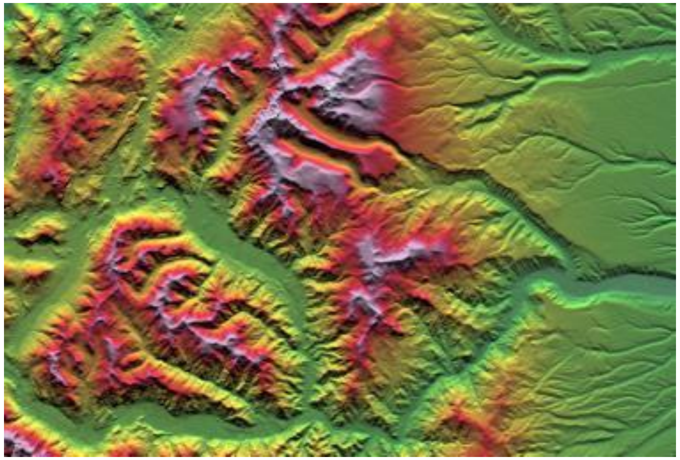
4 swaths operating in SCANSAR mode

Mapped 80% of the Earth land mass using C-Band between +60N and -56S

Produce 30m x 30m spatial sampling with 16 meter absolute height accuracy, 10 meter relative accuracy and < 20 meter circular accuracy (90% level).

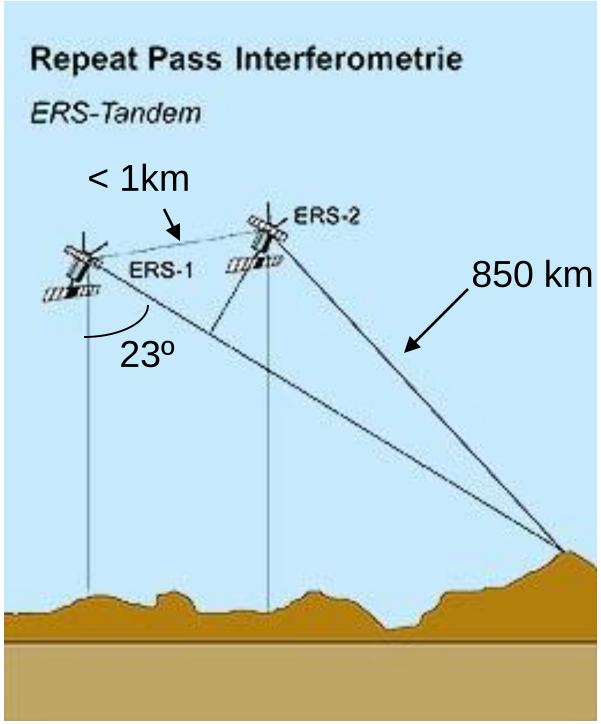
First fixed baseline single-pass spaceborne interferometric SAR

First Dual frequency (C-band and X-band) interferometric SAR



Laguna Mellquina, Andes Mountains, Argentina

Repeat-pass SAR Interferometry



- Almost identical sensor positions
- Acquisition time difference between passes can vary between some minutes, days, months or years
- Several applications of phase (DEM generation, subsidence, tectonics, sea ice movements etc.) and coherence (forestry, agriculture, urban mapping etc.)

Spaceborne SAR interferometric systems

Combination	Repeat-pass interval	Period
SEASAT	3 days	1978 (3 months)
ERS-1 and ERS-2	1, 3 and 35 days	1991-2011
JERS-1	44 days	1992 – 1998
ENVISAT ASAR	35 days	2002 - 2012
ERS-2 / ENVISAT ASAR	28 minutes	2002 - 2011
PALSAR	46 days	2006 - 2011
RADARSAT-1	24 days	1995 - 2013
RADARSAT-2	24 days	2007 -
COSMO-SkyMed 1/2/3/4	4 – 16 days (1 day)	2007 -
TerraSAR-X	11 days	2007 -
TerraSAR-X / TanDEM-X	Single pass	2011 -
RISAT-1	25 days	2012 -
KOMPSAT-5	28 days	2013 -
Sentinel-1	12 days	2014 -
ALOS-2 PALSAR-2	14 days	2014 -

L-band C-band X-band

SAR interferometry (InSAR) : principle (1/3)

The signal received by the radar from a target at distance R has an amplitude (A) related to the scattering strength of the target and a phase (φ) related to the two-way traveling path of the wave between the radar and the target

$$g = A \cdot e^{-j\varphi}$$

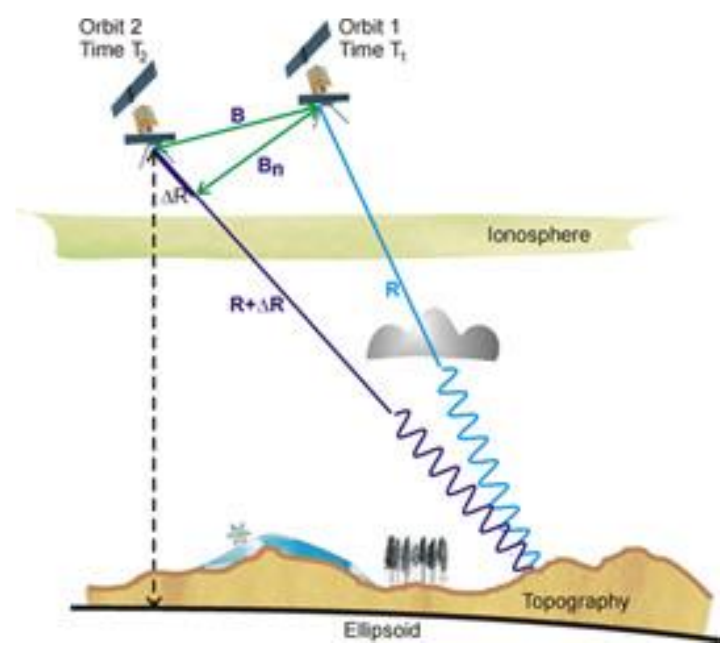
The traveling path is given by the distance between the radar and the target

In addition, there are phase effects arising in the resolution cell because of the different scatterers located at different positions within the cell ($\varphi_{scatter}$)

A further phase contribution arises if the wave travels through a medium with dielectric properties different than vacuum,

e.g. water vapor or wet snow layer (φ_{delay})

$$\varphi = -\frac{4\pi}{\lambda} R + \varphi_{scatter} + \varphi_{delay}$$



SAR interferometry (InSAR) : principle (2/3)

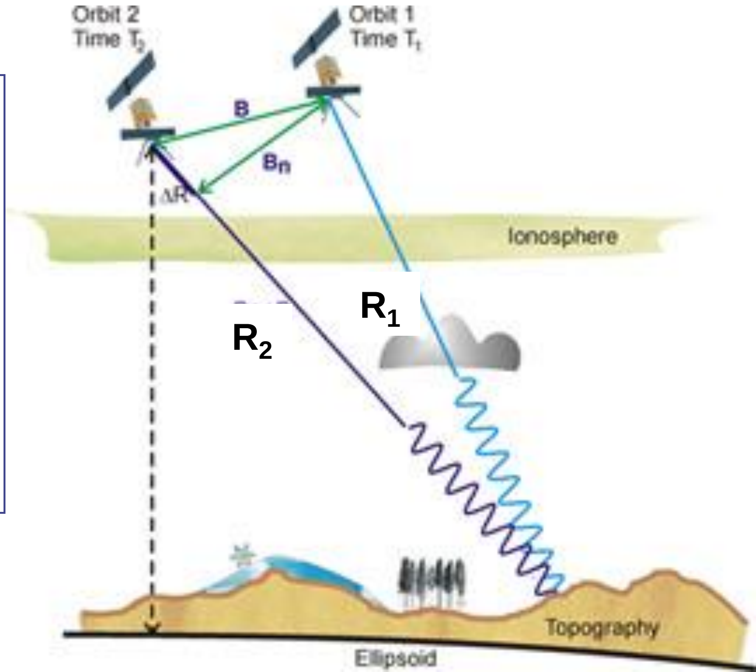
If we take the difference between the phases of a target viewed from two slightly different positions in space having slant range distance R_2 and R_1 we obtain

$$\phi = \Delta\varphi = \varphi_2 - \varphi_1 = \boxed{-\frac{4\pi}{\lambda}(R_2 - R_1)} + \boxed{\Delta\varphi_{scatter}} + \boxed{\Delta\varphi_{delay}}$$

The phase difference, ϕ, is related to the

- **path length difference**
- variations in the speckle pattern (repeat-pass case, unstable targets)
- variations of the medium properties (clear sky v. cloud or water vapor)

The path length difference ($\Delta R = R_2 - R_1$) corresponds to the parallel baseline which changes depending on which point we are looking at. Hence, it becomes clear why from the phase difference it is possible to obtain the 3-dimensional position of a point.



SAR interferometry (InSAR) : principle (3/3)

The phase difference can be obtained if we take the product of one SAR image, g_1, and the complex conjugate of the other SAR image, g_2

$$s_i = g_{1,i}\, g_{2,i}^{*} = \left(A_{1,i} A_{2,i}\right) \cdot e^{\,j\left[-\frac{4\pi}{\lambda}\left(R_2 - R_1\right) + \Delta\varphi_{scatter,i} + \Delta\varphi_{medium,i}\right]}$$

The result of the product is called the **<u>interferogram</u>**.

An interferogram is a complex image with

- magnitude given by the product of the SAR amplitudes
- phase (the InSAR phase) given by the path length difference, as well as variations of the scattering properties and the medium conditions

The main factors affecting the information content of an interferogram are

- spatial separation in space between the SAR systems
- temporal interval between image acquisitions (in the repeat-pass case only)

Limits of SAR interferometry – spatial decorrelation

The spatial baseline has an upper bound, above which the speckle patterns of the SAR images do not correlate with each other anymore.

The critical value of the baseline at which complete decorrelation occurs is given by (Goldstein et al., 1988):

$$B_n \leq \frac{R\lambda}{2L_c \cos\theta}$$

R: slant range distance
λ: wavelength
L_c : size of the resolution cell in slant range
θ: incidence angle.

- For ERS and ENVISAT the critical baseline is about 1100 m (R=850 km, θ=23º, L_c=25m, λ=5.6 cm).
- For JERS-1 and PALSAR the critical baseline is about 4 km (R=730 km, θ=35º, L_c=25m, λ=23 cm).

For most applications it is however recommended to combine images with B_n well below the critical value to avoid too strong decorrelation

Limits of SAR interferometry – temporal decorrelation

- In the repeat-pass configuration the scatterers may move (e.g. water surfaces and tree canopies) or their dielectric properties may change (e.g. snow, wet soils) between observations.
- The two SAR images are only partially correlated because of the temporal interval between the acquisitions.
- In general it is likely that the longer the time interval between acquisitions, the stronger the temporal decorrelation. However, this is not a rule!
- Taking into account that typically temporally unstable scatterers have dimensions of the order of a few centimeters or less (e.g. leaves, grass, snow grains etc.), temporal decorrelation is more pronounced at shorter wavelengths, e.g. at X- and C-band.

SAR interferometry: observables

The product of SAR interferometry is called the **interferogram**, a complex image obtained from the cross-correlation of two overlapping complex SAR images. In practise an interferogram is computed using an ensemble average

$$\gamma = \frac{E\left\{g_1 g_2^*\right\}}{\sqrt{E\left\{\left|g_1\right|^2\right\}\cdot E\left\{\left|g_2\right|^2\right\}}} = \boxed{\left|\gamma\right|}\cdot e^{-j\boxed{\phi}}$$

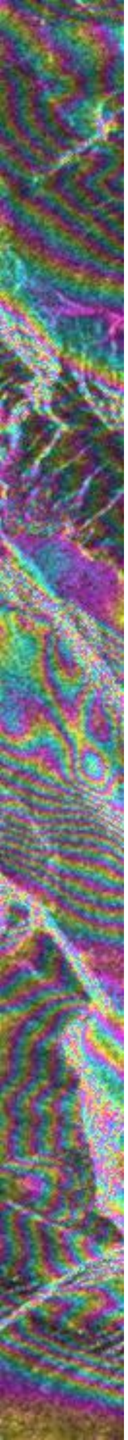
E: expectation value

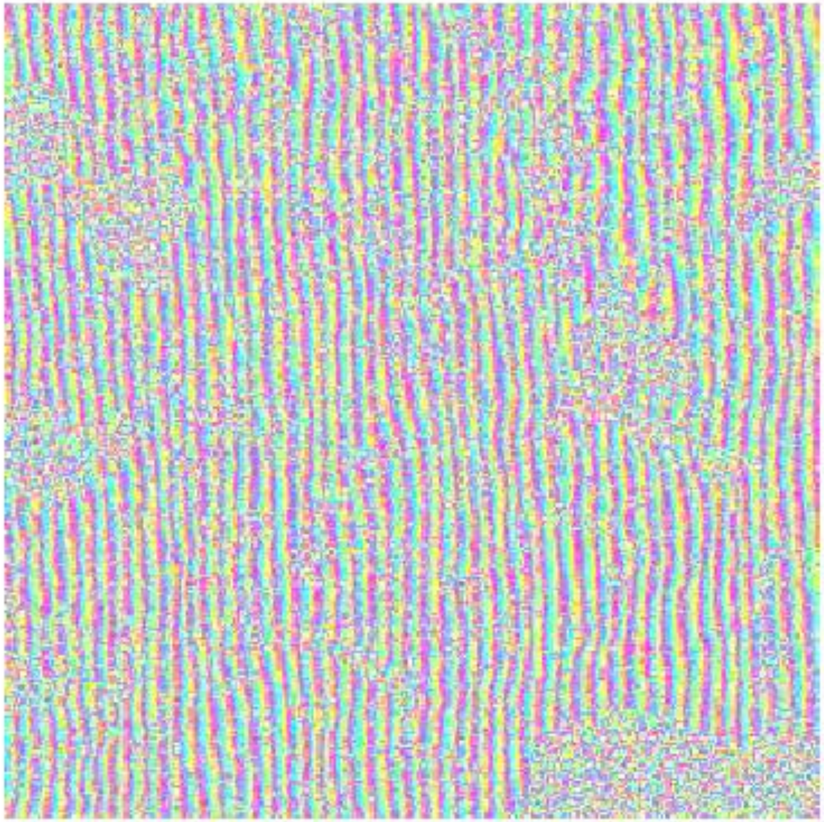
| |: magnitude of complex value

The **amplitude** is called degree of coherence, or simply **coherence**. The coherence measures the degree of correlation between the two SAR images. The coherence is a normalized quantity with values between 0 and 1.

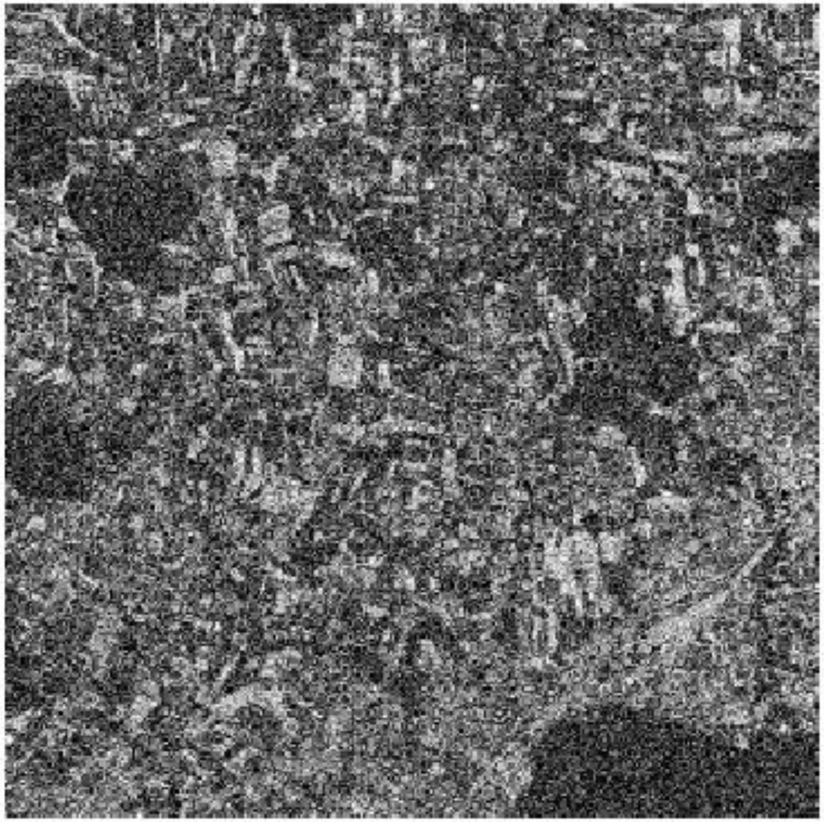
The **phase** is called the **interferometric phase**. The interferometric phase represents the difference in path length between radar and target. The interferometric phase image has values between 0 and 2π (or between $-\pi$ and $+\pi$ depending on the representation used) and therefore appears as a series of fringes.

InSAR Images – ERS case





Interferometric phase



Coherence

- Two consecutive fringes represent a phase difference of 2 π .
- When the coherence is close to zero, total decorrelation has occurred.
- Coherence close to 1 indicates a very stable and strong scattering object.
- Coherence is a measure of the phase noise or fringe visibility

Estimation of the interferometric quantities

- To compute the expected value the ensemble average has to be replaced by spatial averaging within a two-dimensional window.
- That is why we speak of estimation of the coherence and of the interferometric phase.
- According to the principle that an estimate becomes more accurate for increasing number of samples over which the estimate is computed, larger windows should be preferred.
- The true interferogram would be obtained in case of an infinite window size. In practice only an estimate of coherence and InSAR phase can be obtained. These are therefore affected by bias and uncertainty.

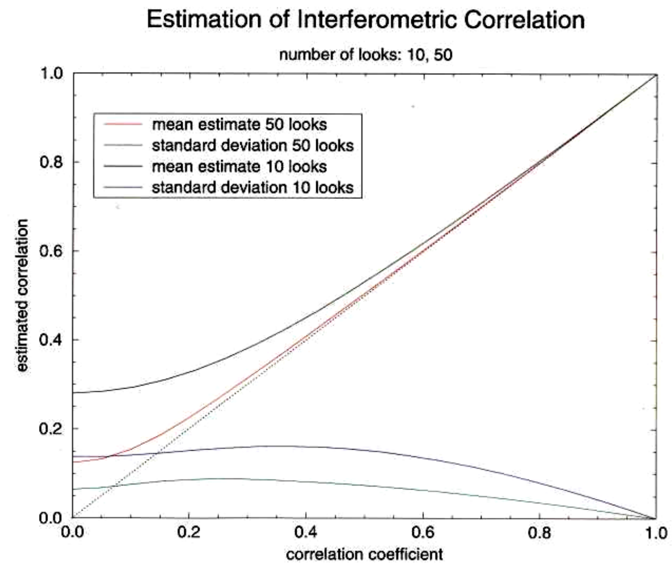
$$\hat{\gamma} = \frac{\sum_{i=1}^{N} g_{1,i} g_{2,i}^{*}}{\sqrt{\sum_{i=1}^{N} \left| g_{1,i} \right|^2 \sum_{i=1}^{N} \left| g_{2,i} \right|^2}}$$

N: number of pixels in the estimation window.

Estimation of the coherence

The estimate of the coherence is the magnitude of the normalized interferogram

$$|\hat{\gamma}| = \frac{\left|\sum_{i=1}^{N} g_{1,i} g_{2,i}^{*} e^{-j\varphi_i}\right|}{\sqrt{\sum_{i=1}^{N} |g_{1,i}|^2 \sum_{i=1}^{N} |g_{2,i}|^2}}$$



- The estimate shows decreasing bias and uncertainty for increasing window size, i.e. number of independent looks; only for asymptotically large data sets the estimate is unbiased.
- The estimation is improved when topography is compensated for (term $e^{-j\varphi}$). Correction is best if a DEM is available. Otherwise the interferogram or an approximation can be used in which the phase is described by either a constant, linear, quadratic or higher order function over the estimation window.

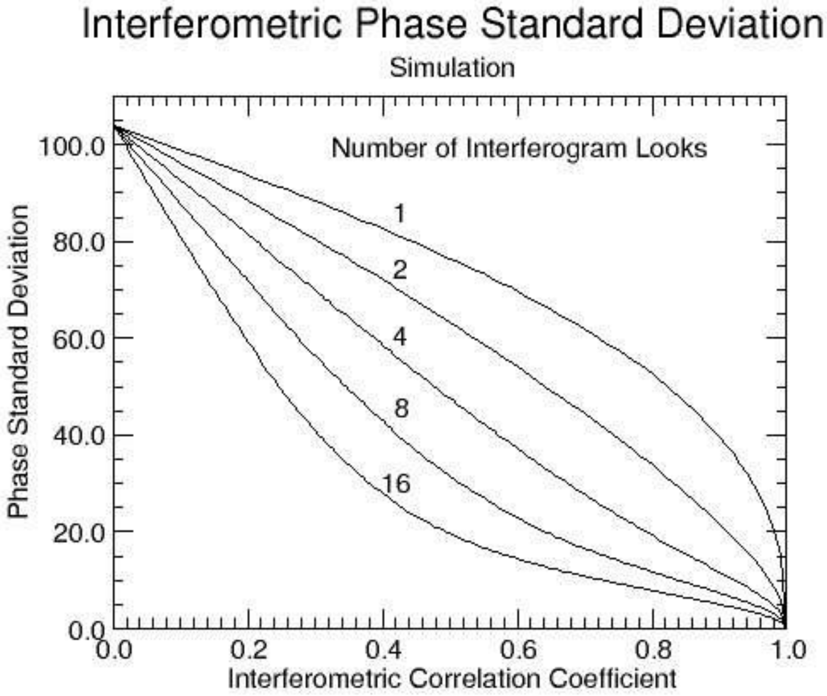
Estimation of the interferometric phase

The estimate of the phase is the argument of the complex interferogram

$$\hat{\phi} = \arg\left(\sum_{i=1}^{N} g_{1,i}\, g^{*}_{2,i} \right)$$

The uncertainty of the estimate is related to the degree of coherence and the number of samples (= number of looks) used for estimating the phase

$$\sigma_{\phi} = \frac{1}{\sqrt{2N}} \frac{\sqrt{1-|\gamma|^2}}{|\gamma|}$$



Coherence

Coherence measures the correlation between two images

$$|\gamma| = \cancel{|\gamma|_{processor}} \cdot \cancel{|\gamma|_{noise}} \cdot \cancel{|\gamma|_{azimuth}} \cdot |\gamma|_{spatial} \cdot |\gamma|_{temporal}$$

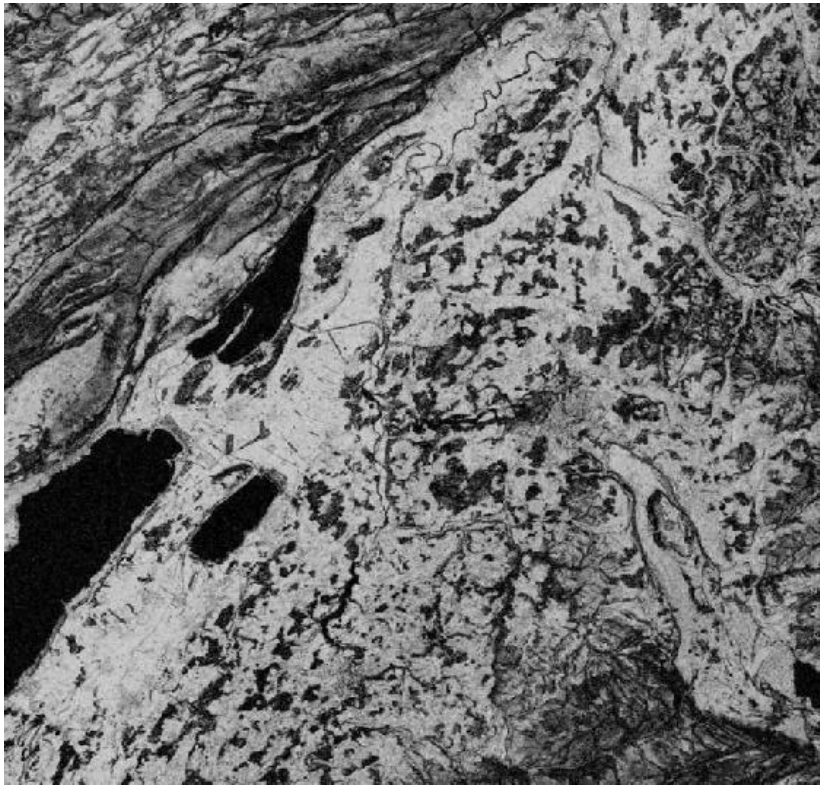
In the end the coherence is related to the

correlation in space $|\gamma|_{spatial}$

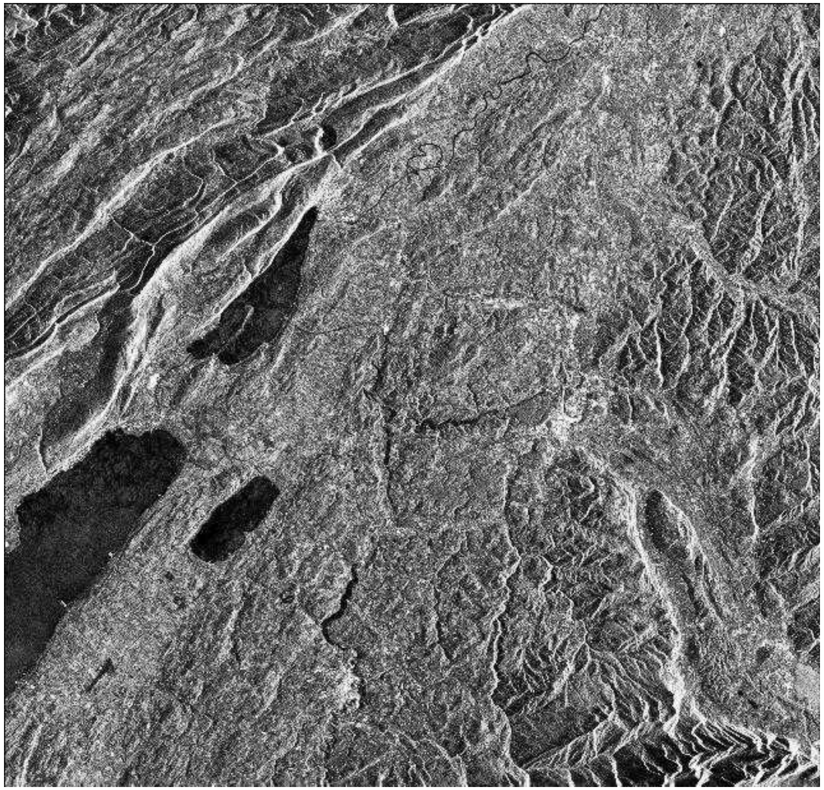
correlation in time $|\gamma|_{temporal}$

- The spatial coherence can be filtered out. A part remains if we have a volume (forest, snow, city). This is called volume decorrelation and increases with the spatial baseline.
- The temporal coherence can NOT be filtered out, it is a property of the image. This is also referred to as temporal decorrelation term and depends on the stability of the objects between the two acquisitions.
- Being a correlation in absolute values, the coherence has values between 0 (total decorrelation, no coherence) and 1 (full correlation)

Coherence – example from the ERS-1/2 tandem mission, Bern



Coherence of ERS-1/2 Tandem pair acquired on 26/27 November 1995 over Bern, Switzerland. A linear grey scale between 0.1 (black) and 1.0 (white) was used.



Backscatter intensity over Bern, Switzerland, observed on 26 November 1995 by ERS-1. Image brightness corresponds to backscatter intensity using a logarithmic scale

InSAR phase

InSAR phase measures the phase difference of a target with respect to the radar

$$\phi = \phi_{flat\_Earth} + \phi_{topo} + \phi_{disp} + \phi_{path} + \phi_{noise} + n \cdot 2\pi$$

$$\phi = \boxed{-\frac{4\pi}{\lambda} R} + \boxed{\frac{4\pi B_n}{\lambda R \sin\theta} z} + \boxed{\frac{4\pi}{\lambda} \eta} + \boxed{\frac{4\pi}{\lambda} \rho} + \boxed{\phi_{noise}} + \boxed{n \cdot 2\pi}$$

"Flat Earth"

Related to Earth curvature

Can easily be removed

"Topographic phase"

Related to surface height (z)

Used to determine elevation from phase

"Displacement phase"

Related to coherent movements of surface (η)

Used to determine surface movements from phase

"Atmospheric phase"

Related to path delays in atmosphere (ρ)

Must be removed to correctly interpret the InSAR phase

"Noise"

Due to decorrelation

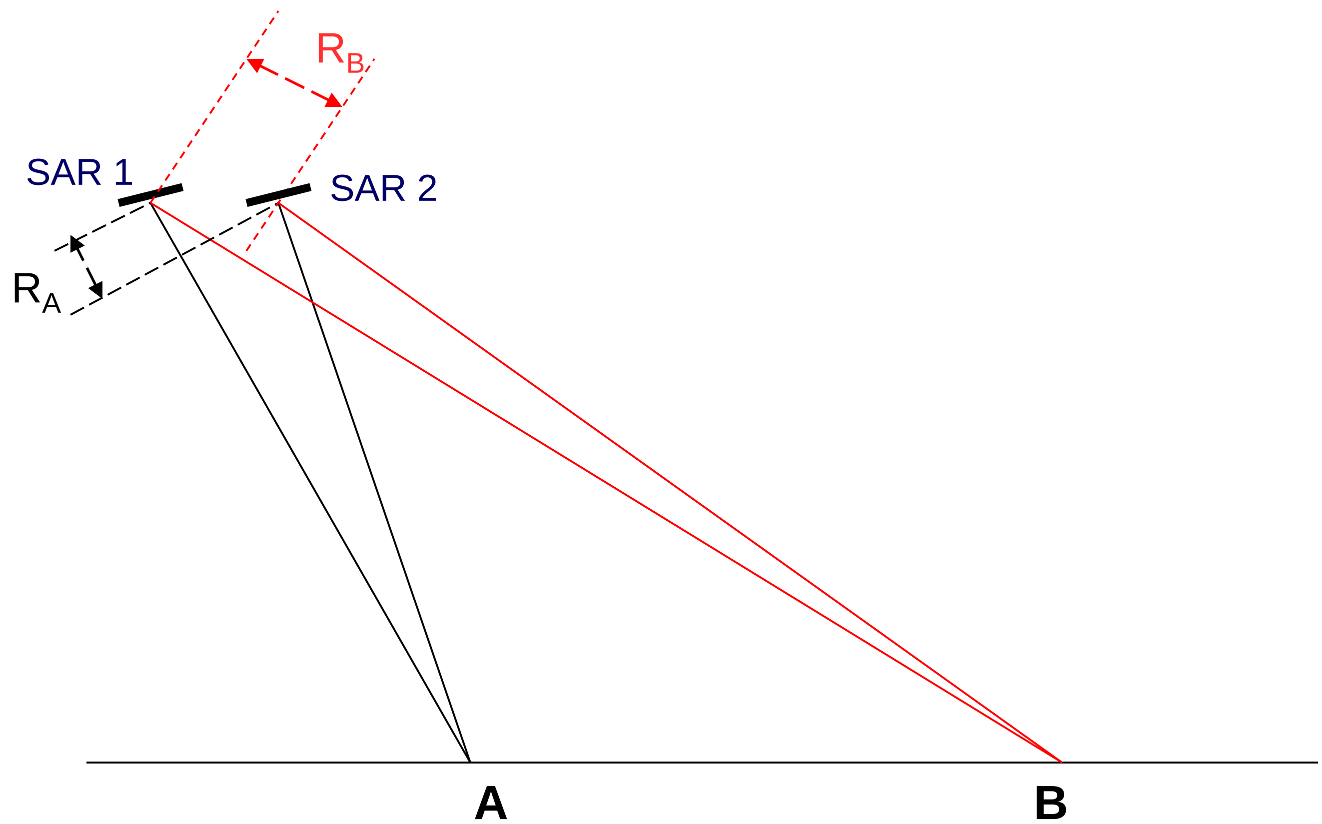
Must live with it!

"Phase unwrapping term"

Due to the fact that InSAR phase is between 0 and 2πp

Flat Earth phase

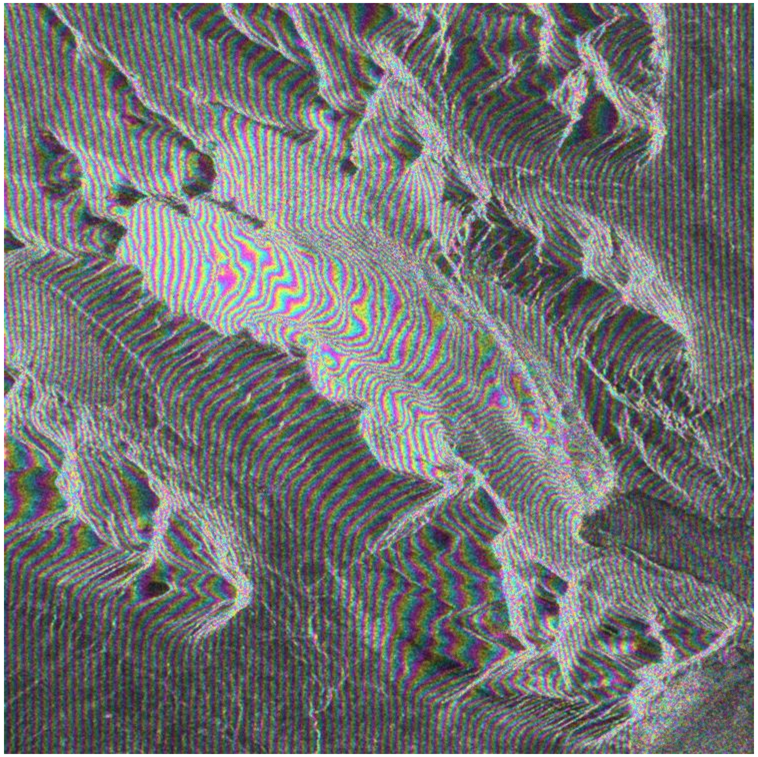
- The points A and B are at the same elevation but present different R values so that the interferometric phase at the two points is different.



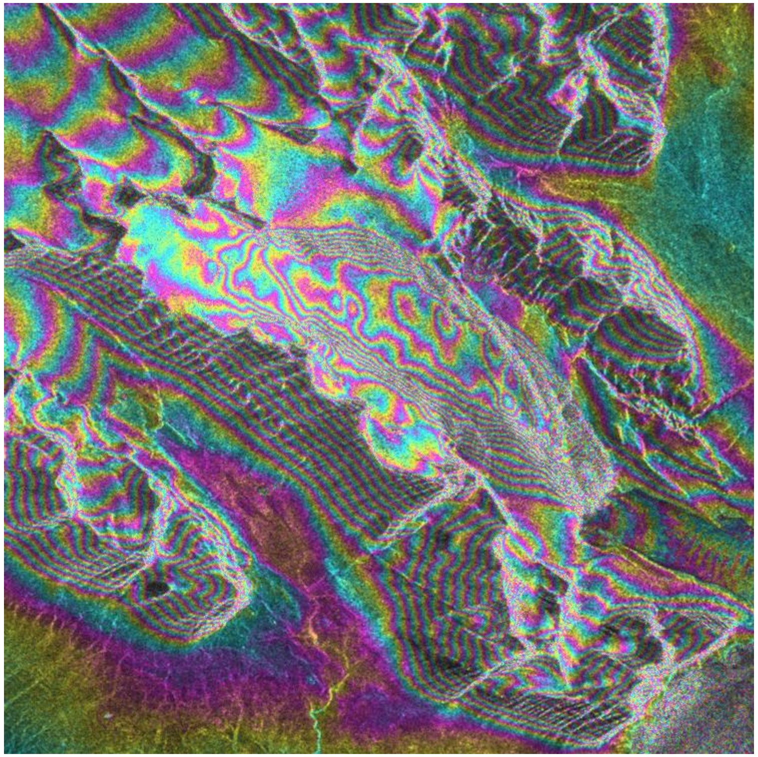
- The interferometric phase changes across range being repeatedly between 0 and 2π. The longer the baseline, the faster the change rate (i.e. the denser the interferometric fringes)

Interferogram - Phase Flattening

- Raw interferogram includes a quasi-linear phase trend caused by tilt of terrain surface relative to the baseline
- Flattening removes interferometric phase modeled using a sphere with radius of curvature derived from the ellipsoid



Raw interferogram



Flattened interferogram

Topographic phase

- Once the Flat Earth term has been removed, assuming there are no surface movements, no atmospheric distortion and no phase noise, the interferometric phase is only related to the elevation
- SAR interferometry allows a straightforward estimation of elevation

$$\phi = \frac{4\pi B_n}{\lambda R \sin\theta} z \quad \Longrightarrow \quad z = \frac{\lambda R \sin\theta}{4\pi B_n} \phi_{topo}$$

- Topographic fringes appear as contour lines
- The spacing between the fringes depends on the perpendicular baseline: the longer the perpendicular baseline, the narrower the fringes

Effects of longer perpendicular baseline

☺ higher sensitivity to elevation variations

☹ visibility of the fringes decreases because of spatial decorrelation

There has to be a trade off between sensitivity to elevation variations and decorrelation effects when considering applications of interferograms to estimate elevation.

Topographic phase – ambiguity height

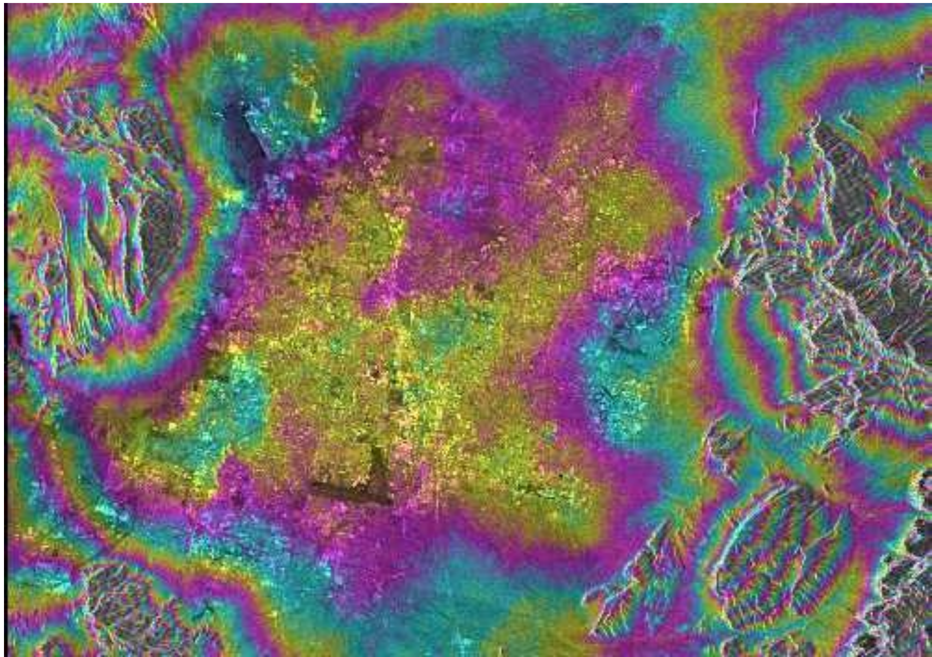
- The sensitivity of the interferometric phase to elevation can be quantified with the “ambiguity height”
- The ambiguity height is the elevation difference corresponding to a full phase cycle (2π):

$$\Delta z_{amb} = \frac{\lambda R \sin\theta}{2B_n}$$

- The ambiguity height depends on perpendicular baseline and interferometric system. It increases for shorter baselines and/or longer wavelength.

Example of ERS-1/2 topographic fringes from Las Vegas, Nevada, overlaid on the SAR intensity image.

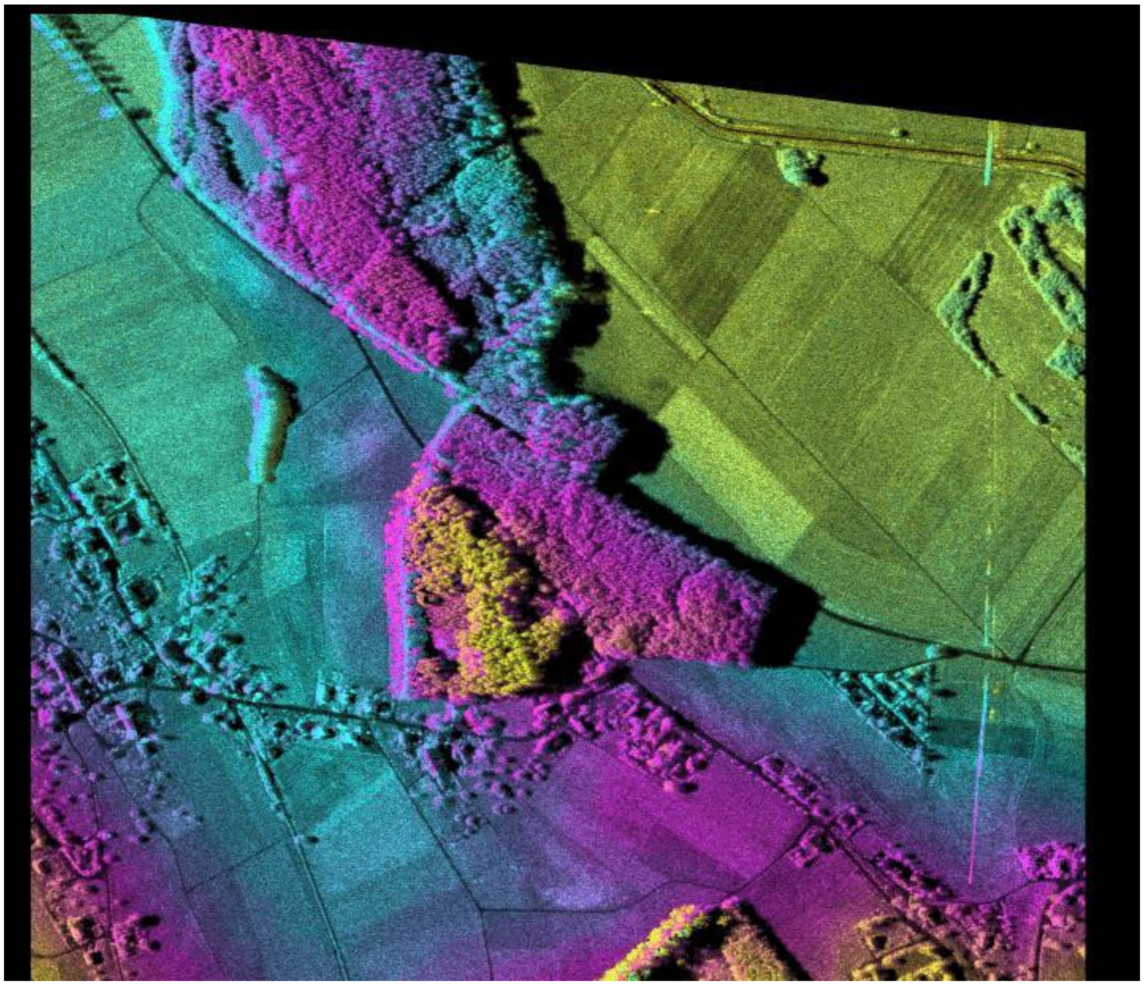
Ambiguity height, i.e. elevation difference between consecutive fringes of the same color, is 90 m.



InSAR elevation

What elevation does an interferometric system "measure"?

- For surfaces: elevation of the surface
- For volumes: elevation of the phase scattering centre (i.e. where the scattering of the volume can be considered to be originated from)



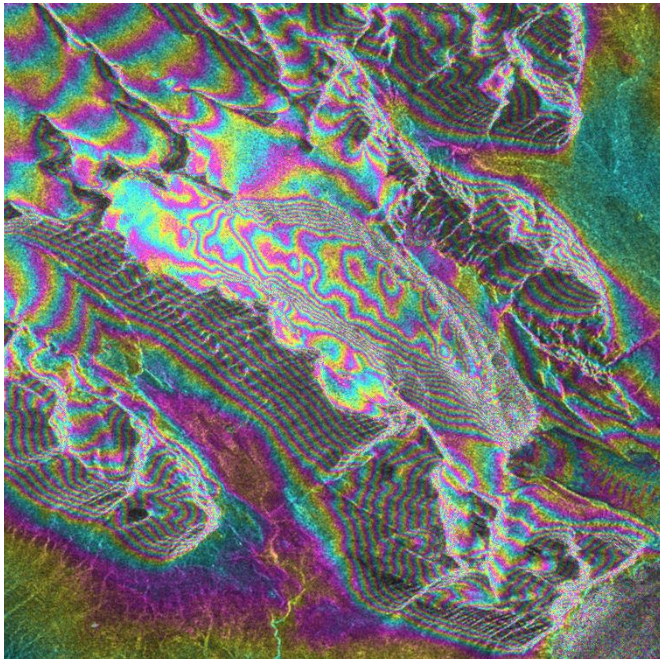
DOSAR C-band DEM,
forests and fields,
Solothurn, Switzerland

Overview

- SAR basics
- SAR images: formats, properties
- SAR interferometry
- Differential SAR interferometry

Differential SAR Interferometry - DInSAR

A flattened interferogram does not only have a topographic term



⇒ topography

⇒ displacement

⇒ atmosphere

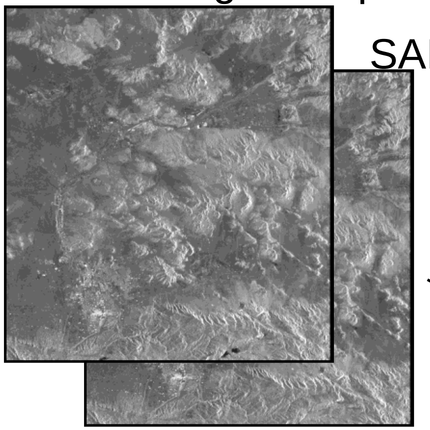
⇒ noise

- Objective of DInSAR: Separation of ϕ_{topo} from total phase to determine ϕ_{displ}
- 2-pass: Simulate ϕ_{topo} based on existing DEM. Phase unwrapping not required for the simulated interferogram. High accuracy of DEM required.
- 3- and 4-pass: Derive ϕ_{topo} from independent interferogram, no existing DEM is required but phase unwrapping required.

Example of Differential Interferometry to map seismic displacement

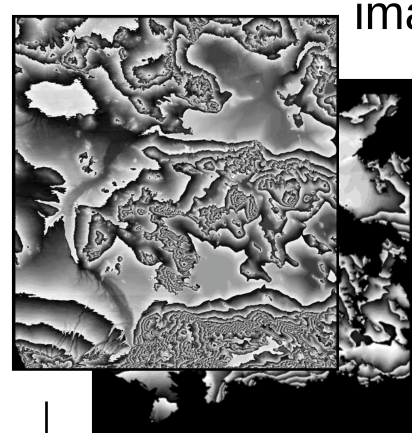
SAR image 24 April 1992

SAR image 7 August 1992

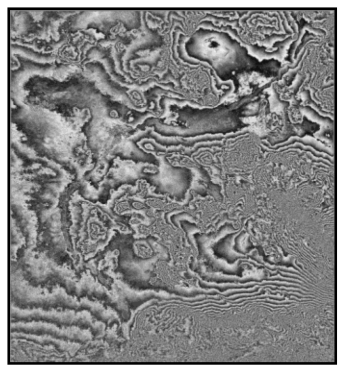


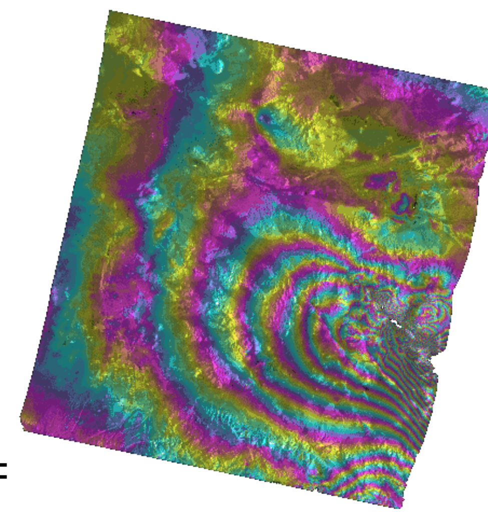
(a) DEM simulated unwrapped phase image

or (b) INSAR pair: 24-25 Sep 1995 unwrapped phase



24 Apr.1992 - 7 Aug. 1992 interferogram





Geocoded displacement map associated with the Landers earthquake of June 28, 1992. 1 color cycle = 2.8 cm displacement in the line-of-sight direction

Displacements phase

- If a target moves between acquisitions, the wave at the second acquisition has to travel a different path length compared to if no movement had occurred

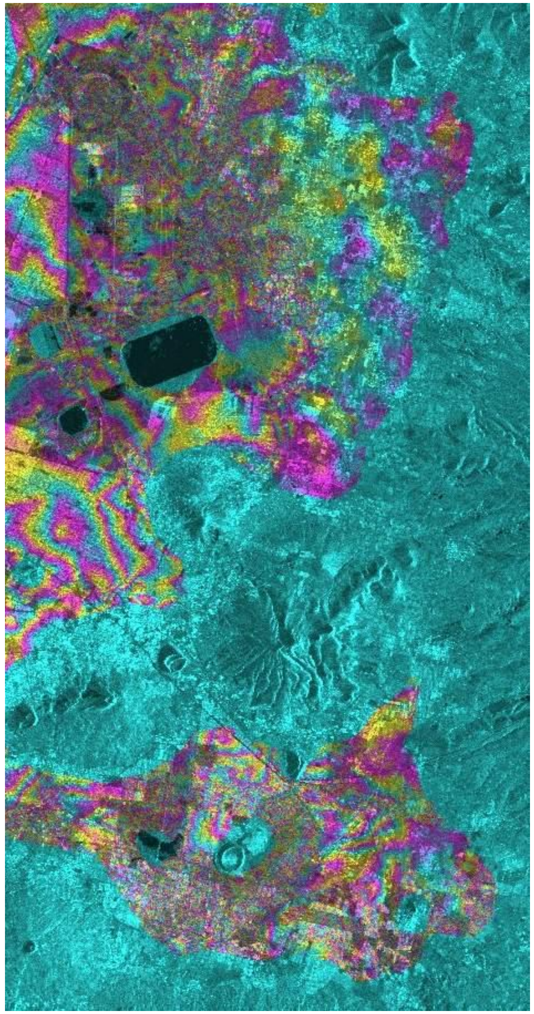
- From the interferometric phase, the displacement along the line of sight R_{disp} can be estimated

$$R_{disp} = \frac{\lambda}{4\pi}\phi_{disp}$$

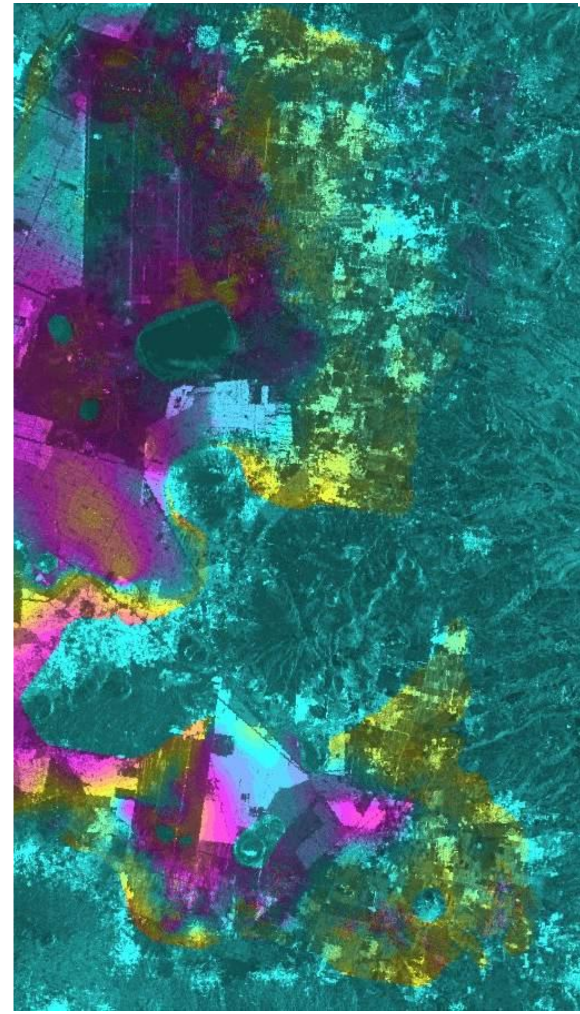
- The phase due to displacements does not depend on the baseline
- The sensitivity of the phase to the displacement is related to the wavelength
- Longer wavelength are less sensitive to displacements
- A phase difference of 2π between two points corresponds to a displacement of 2.8 cm at C-band and 12 cm at L-band

To estimate the displacement it is necessary to remove the flat Earth component and the topographic phase (with a DEM or an estimate of the elevation)

Displacement phase of Mexico City at C- and L-band



ERS C-band interferogram (29 Dec. 1995 - 16 May 1996 - 139 days difference). Bn = 26 m.



JERS-1 L-band interferogram (3 Apr. - 26 Sep. 1996 - 176 days difference). B_n *= 567 m.*

The ERS phase presents stronger sensitivity to displacement (more fringes) as well as stronger phase noise

Atmospheric phase

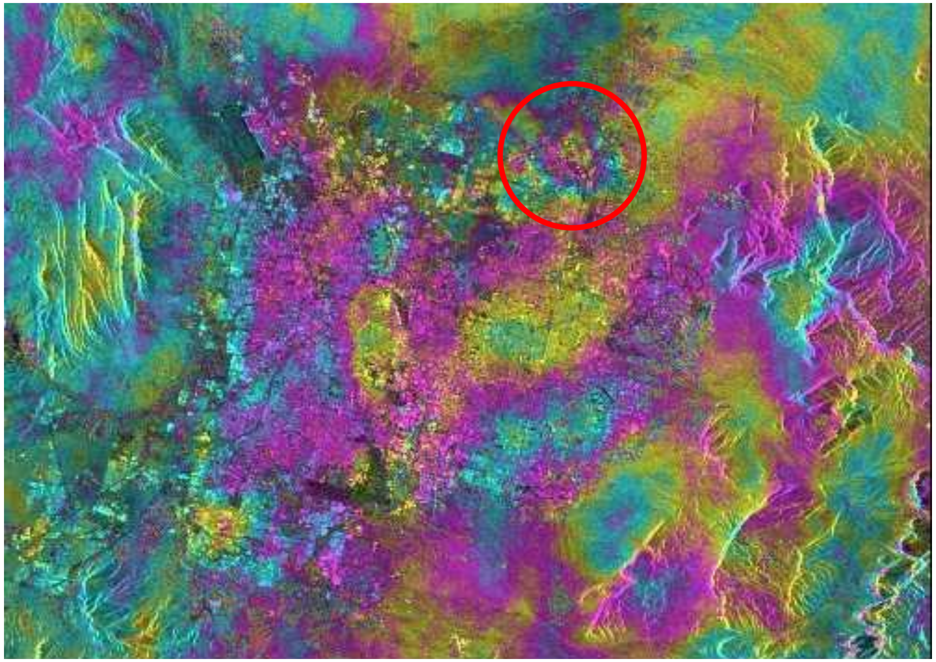
Changes in the atmospheric conditions (mainly water vapour but also electron density in the ionosphere) or dielectric (coherent) changes of a volume on the ground delay the propagation of the microwave → there is an additional path length between the SAR and the surface elements → an additional phase

$$\phi_{path} = \frac{4\pi}{\lambda} R_{path}$$

- The phase due to atmospheric artifacts does not depend on the baseline
- The sensitivity of the phase to the atmosphere is related to the wavelength
- Longer wavelengths are less sensitive to atmospheric distortions
- A propagation delay (R_{path}) of 2 cm would result in an additional phase of an almost full fringe at C-band but only of 1/6th of a fringe at L-band
- In case of stronger delays the variations of in space might be so large that at higher frequencies phase unwrapping could fail because of more cycles being wrapped

Effects of atmospheric phase on interferogram

Path delays can strongly alter the information content of the interferogram



The only area affected by displacements (subsidence) is indicated in the circle. All other fringes are due to path delays in the atmosphere (ERS interferogram, Las Vegas, Nevada)