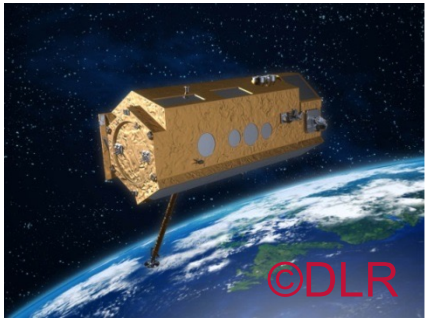
How to recover 3D information with SAR sensors ?

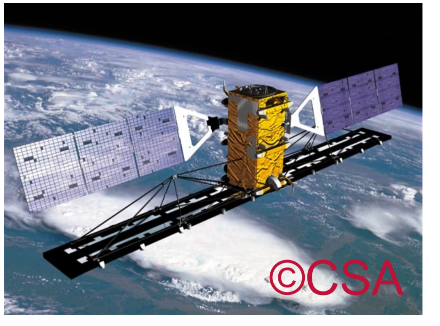
Florence Tupin, Jean Marie Nicolas

SAR systems

- **Why using SAR ?**
  - All time / all weather acquisition system
  - Phase information !....
  - Polarimetric information !...

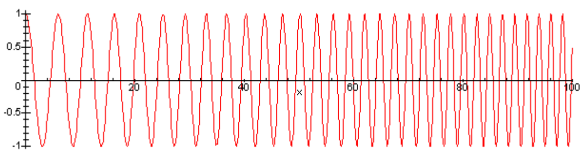


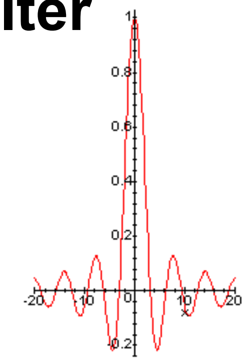
- **Applications**
  - Continental applications :
    - Agriculture / vegetation (forest) monitoring
    - Urban mapping, urban growth monitoring
    - Rapid mapping (disaster management, flood)
    - Digital surface model and movement monitoring
  - Maritime applications :
    - Ice monitoring, ship monitoring
    - Oil spill detection

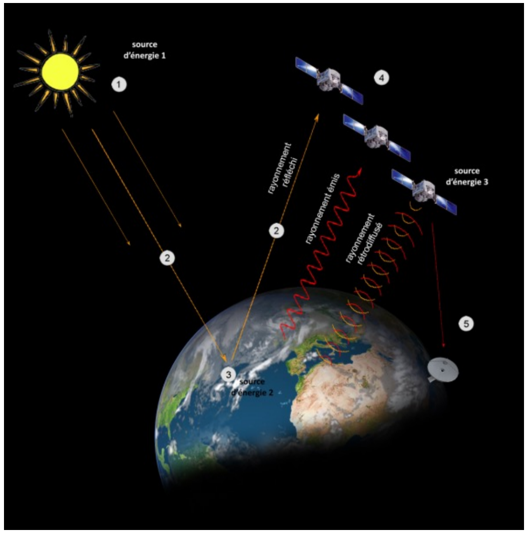


SAR acquisition

- **Range: chirp and matched filter**

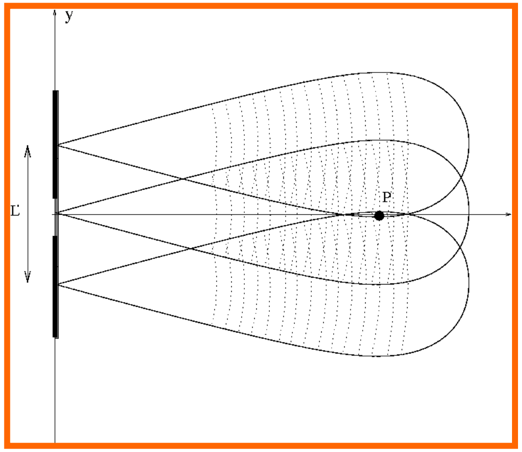


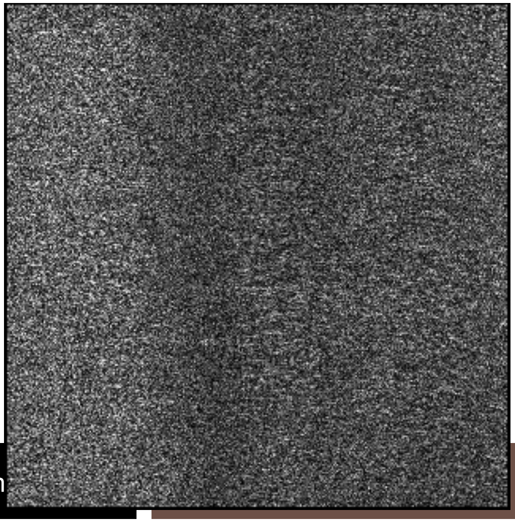




- **Azimuth: synthetic aperture**

« geometric chirp » and matched filter

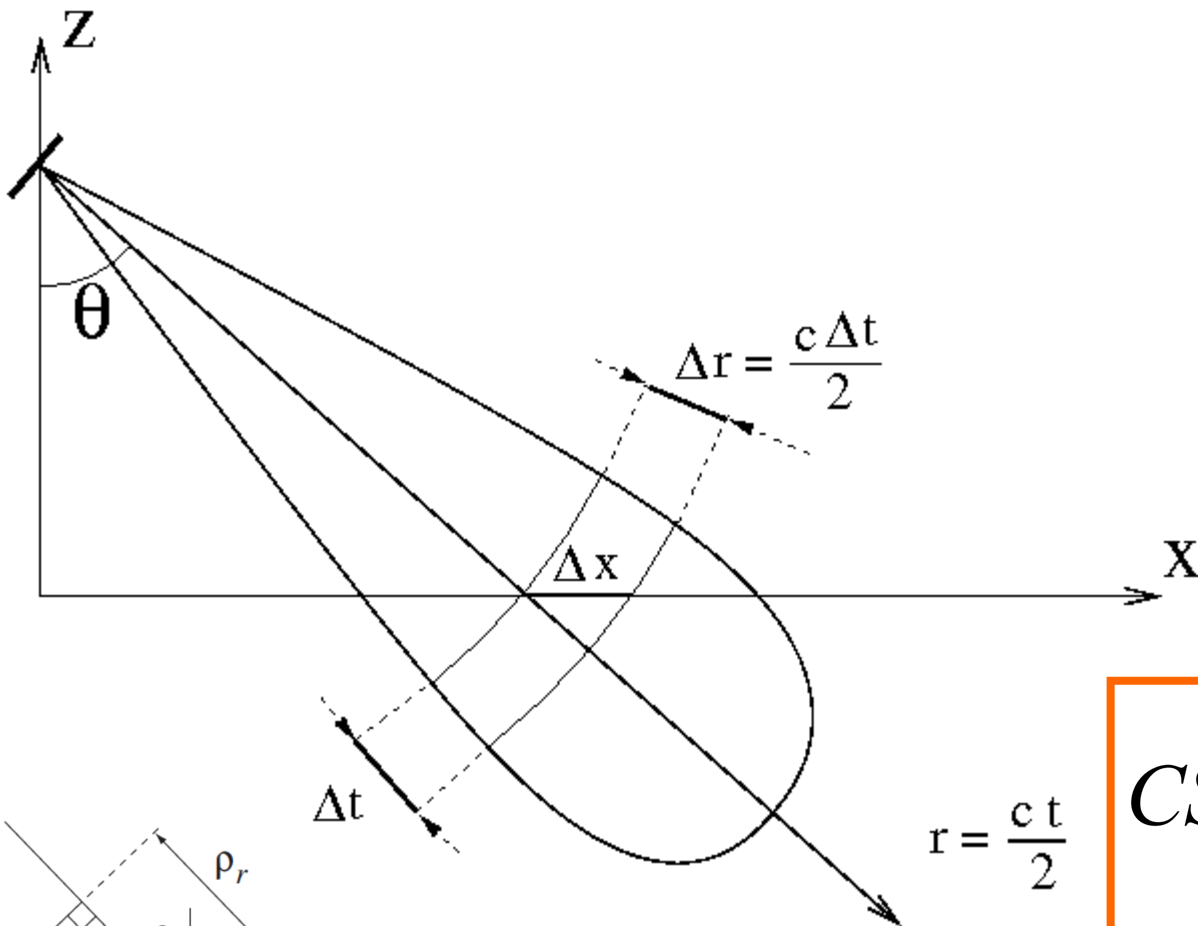


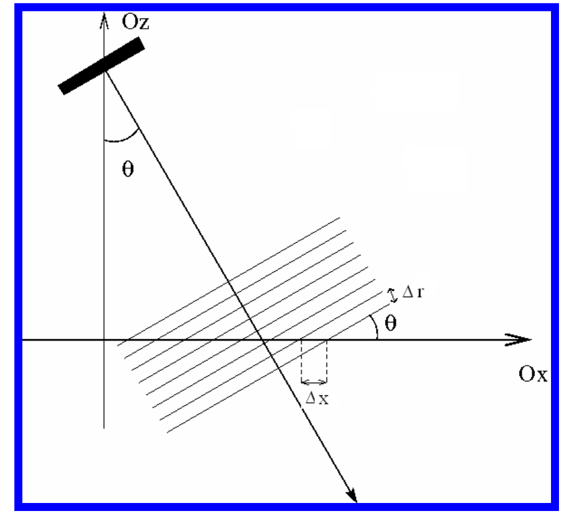


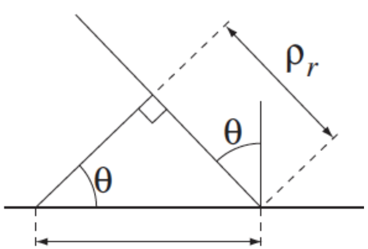
Overview of the session

- **Distance sampling and geometric distorsions**
- **Mono-image elevation**
- **Radargrammetry**
- **Interferometry**

Lateral viewing and distance sampling

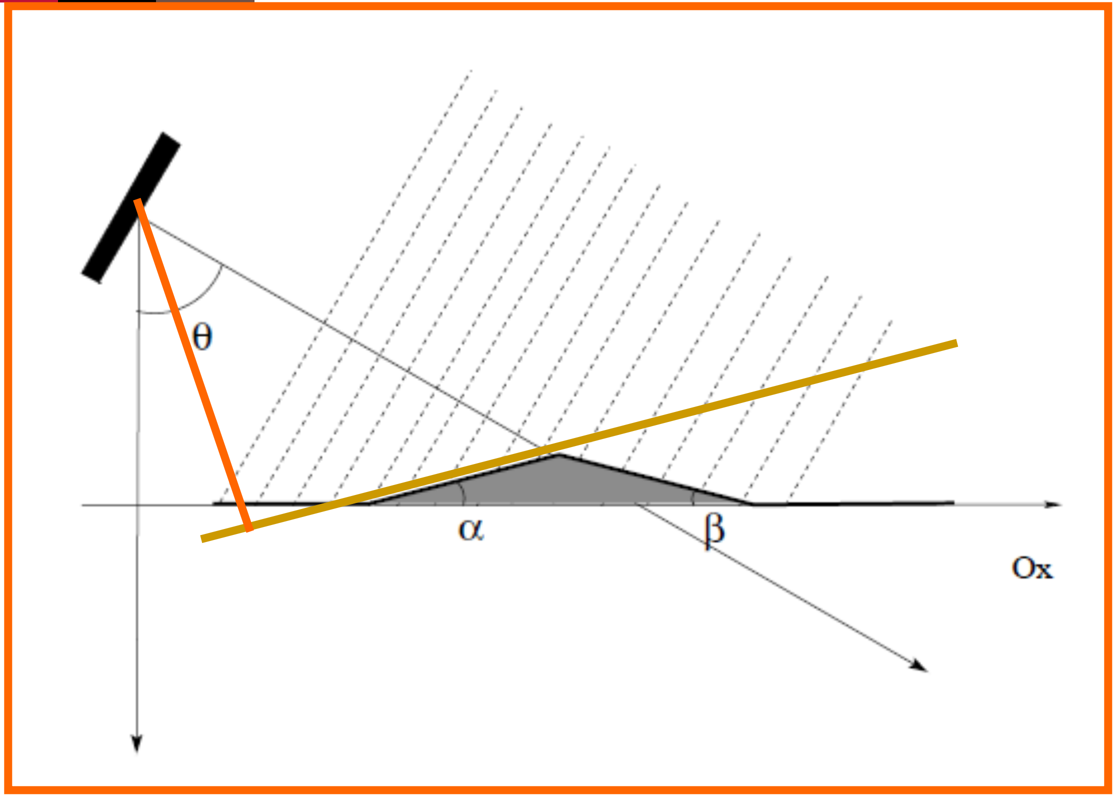


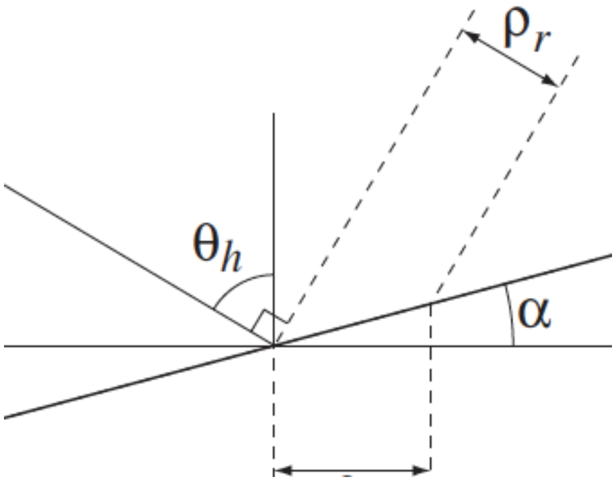




$$CS = \Delta x = \frac{\Delta r}{\sin(\theta)}$$

Influence of relief on the cell size

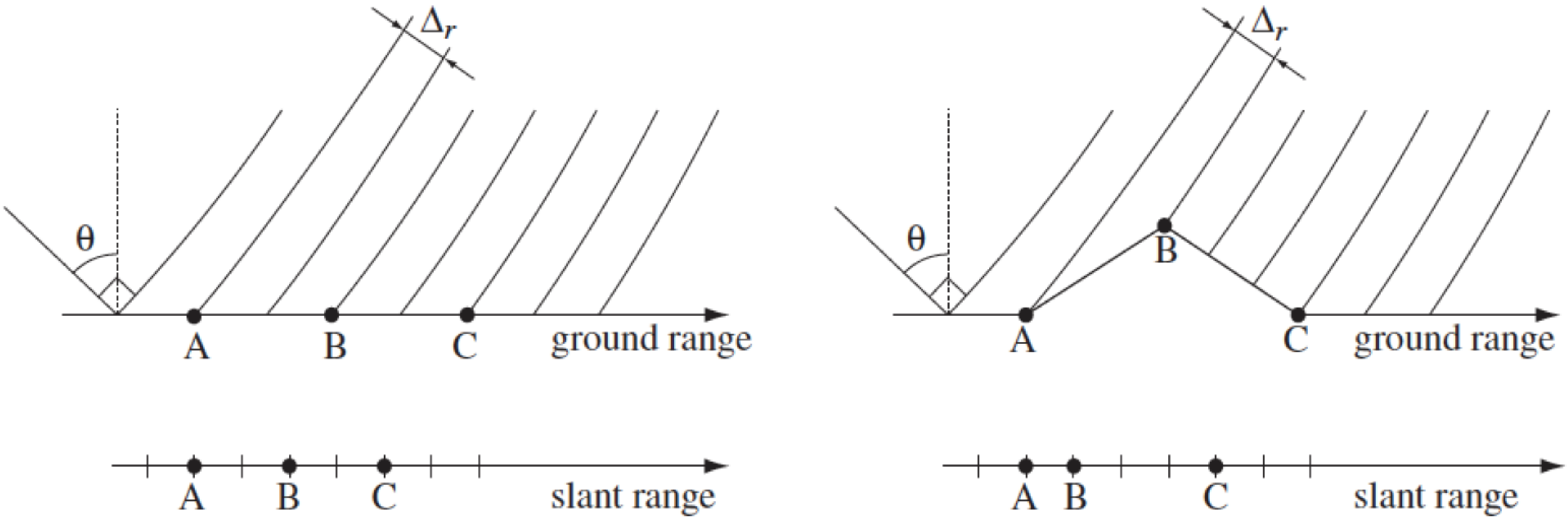




$$CS(\alpha) = \frac{\Delta r}{\sin(\theta - \alpha)}$$

- **Slope facing the sensor :**
  - Forshortening in the image (a wider area of the ground is seen in the pixel)
- **Opposite side of the sensor:**
  - Dilation on the image (a smaller ground area in 1 pixel)

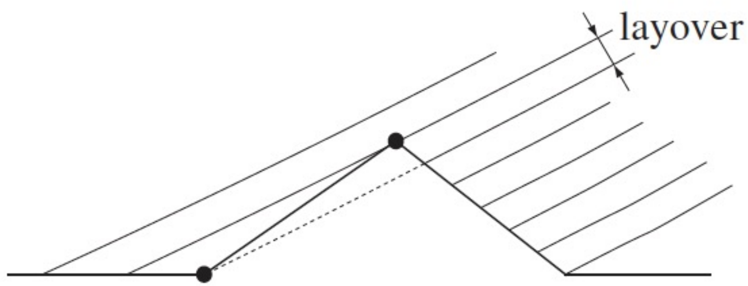
Geometric distorsions

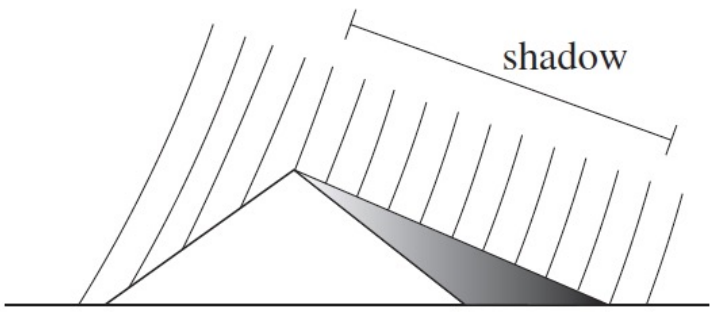


Foreshortening / dilation

TELECOM ParisTech

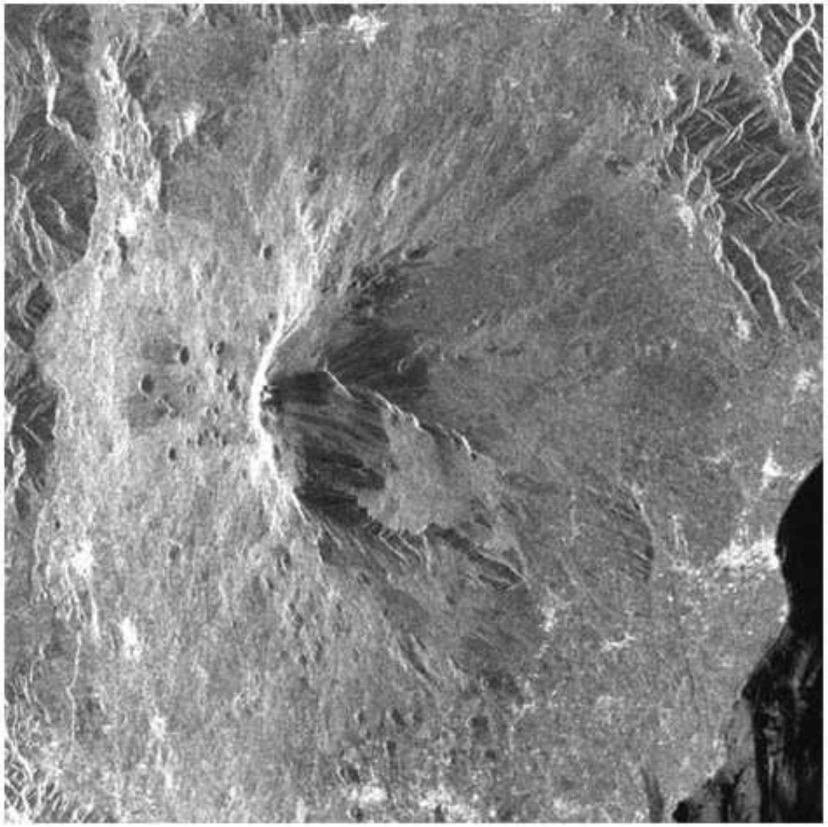
Geometric distorsions



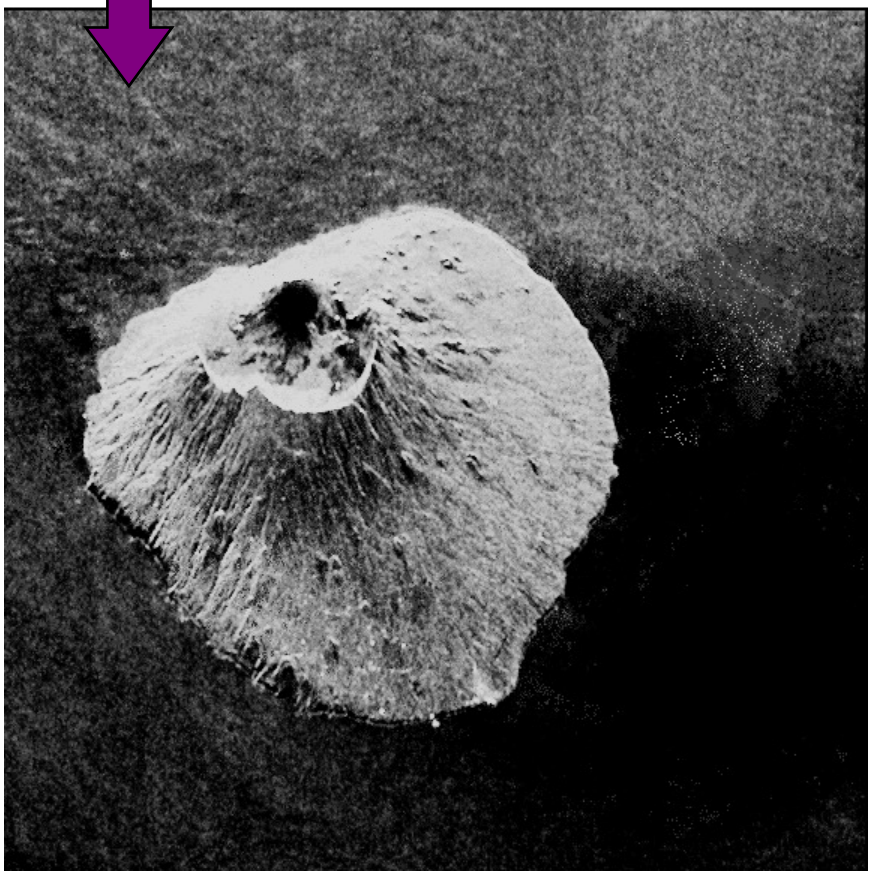


- **Overlay:**
  - If $\alpha > \vartheta$: inversion of the points and mixing of the target responses
- **Shadow phenomenon:**
  - No illumination of the back-slope (obstacle) $\alpha' >$ pi/2- ϑ
- **Influence of the incidence angle (increase in the swath) :**
  - Near range : lay-over ; far range : shadow

Geometric distorsion – Mount Etna



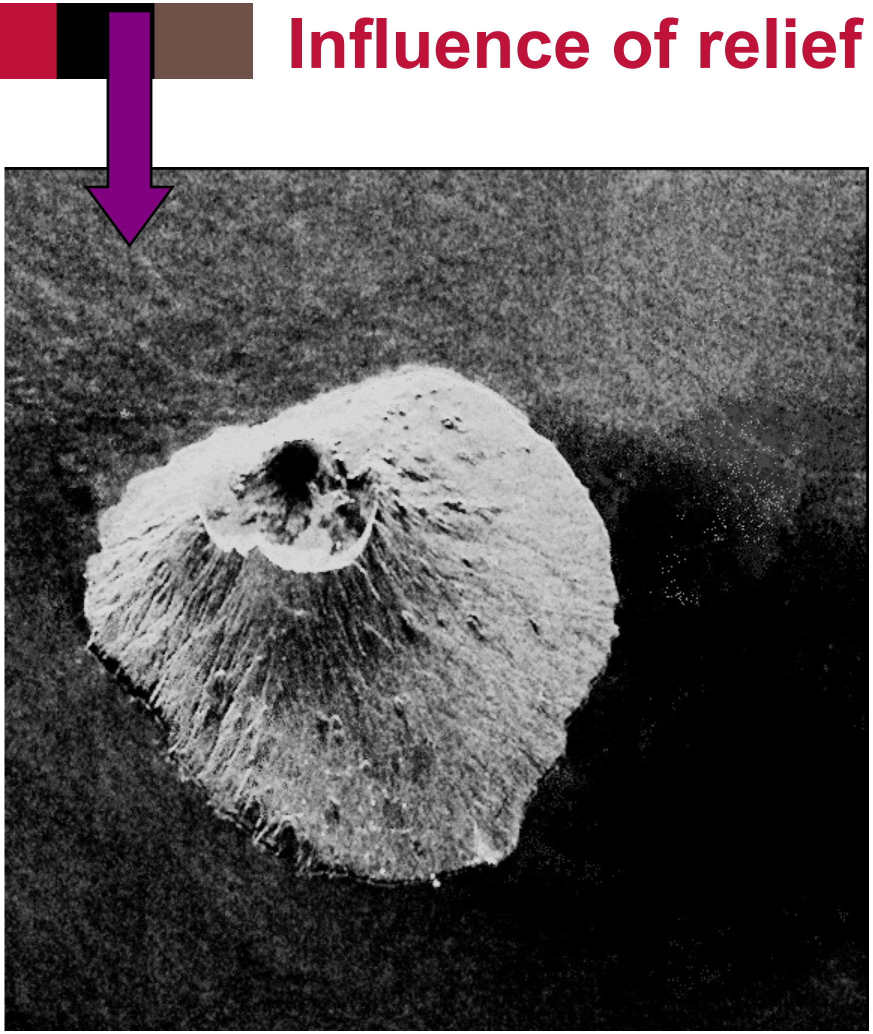
Influence of relief on the cell size



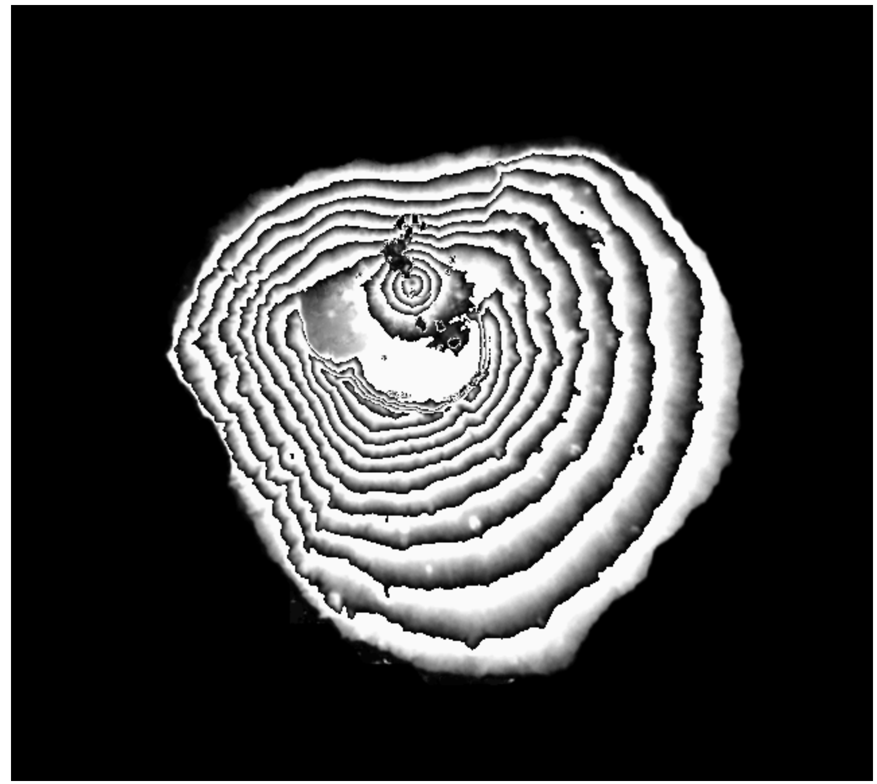
ERS image

Mosaïc on Google

Influence of relief on the cell size

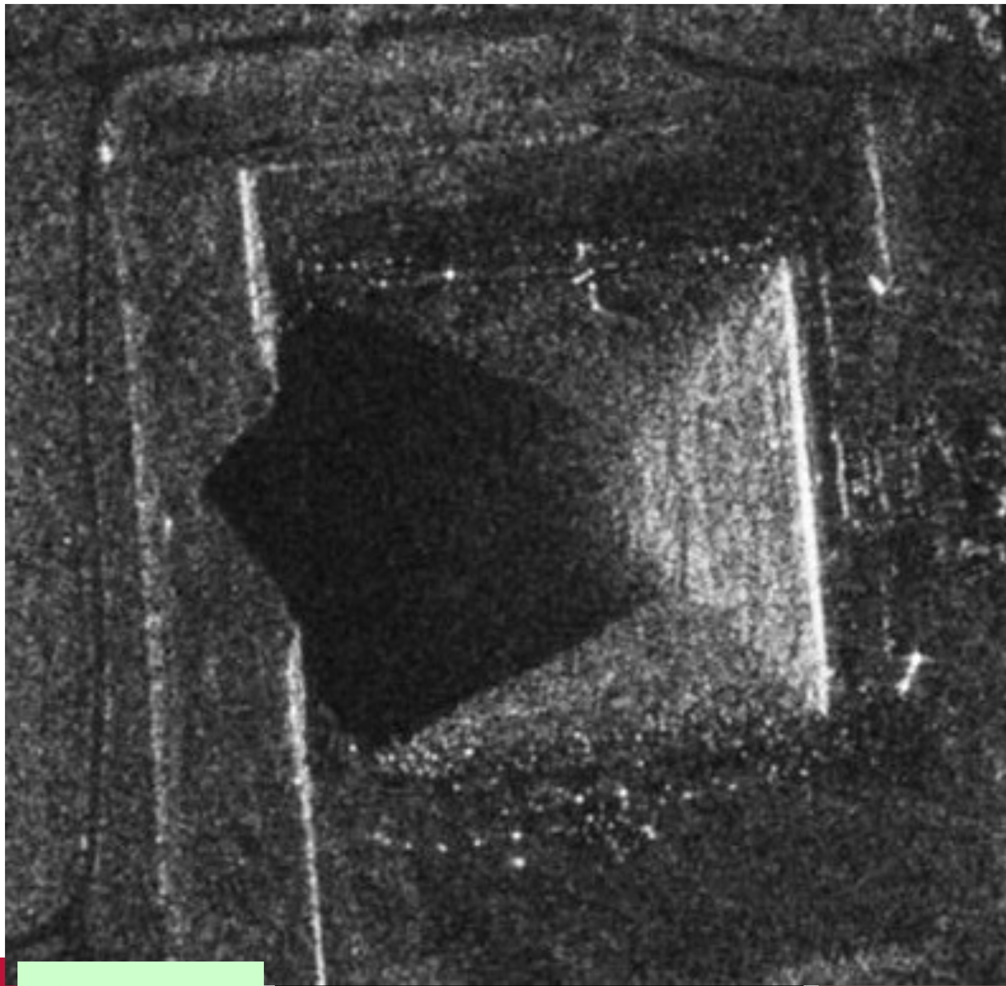


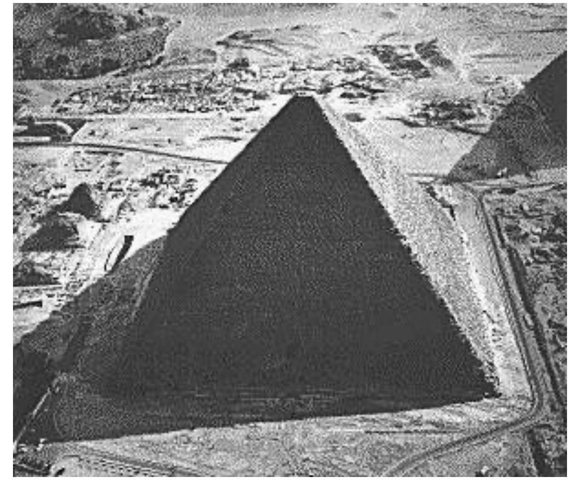
ERS image



Level lines: step of 256m

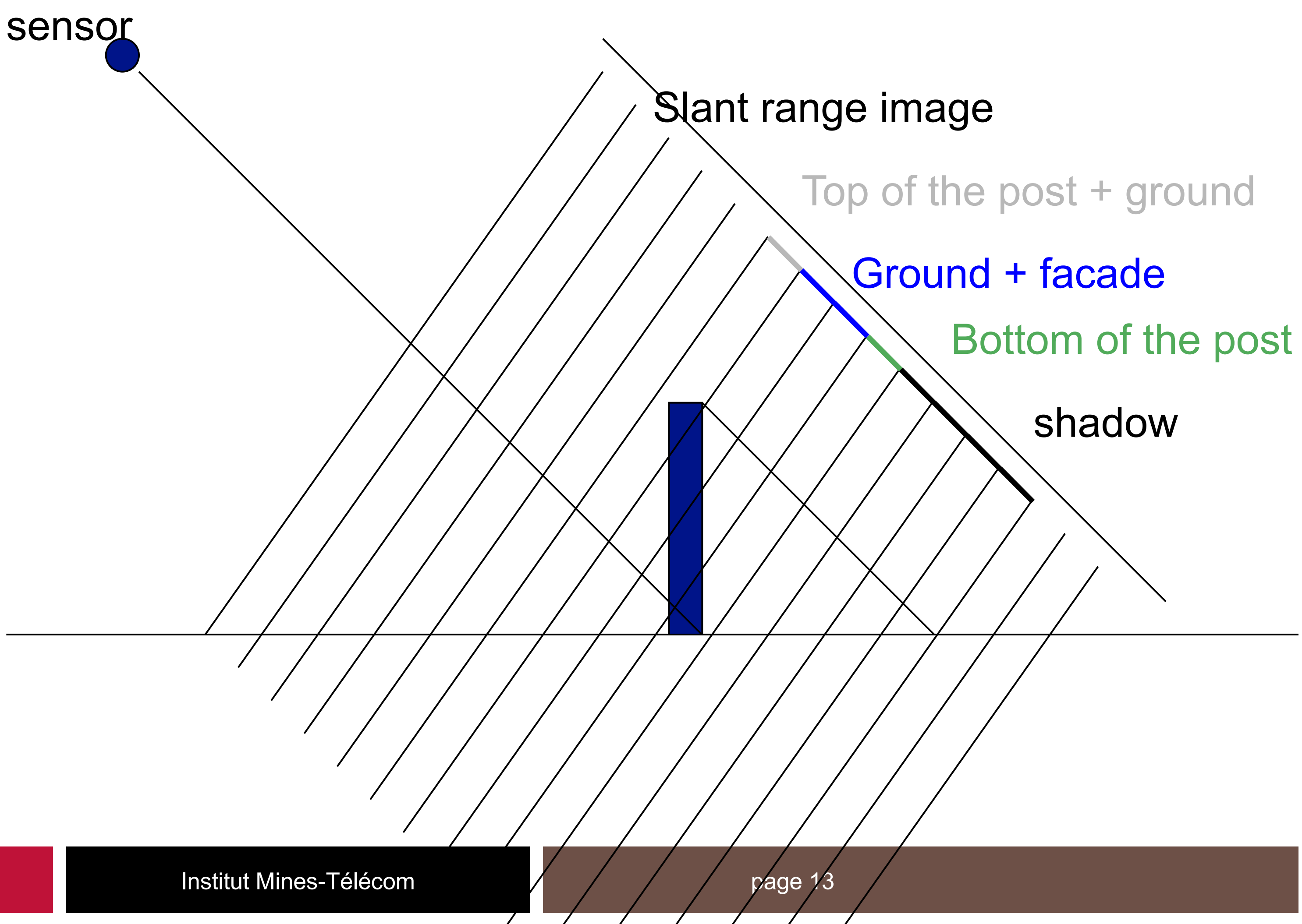
Example of shadow TERRASAR-X :Gizeh



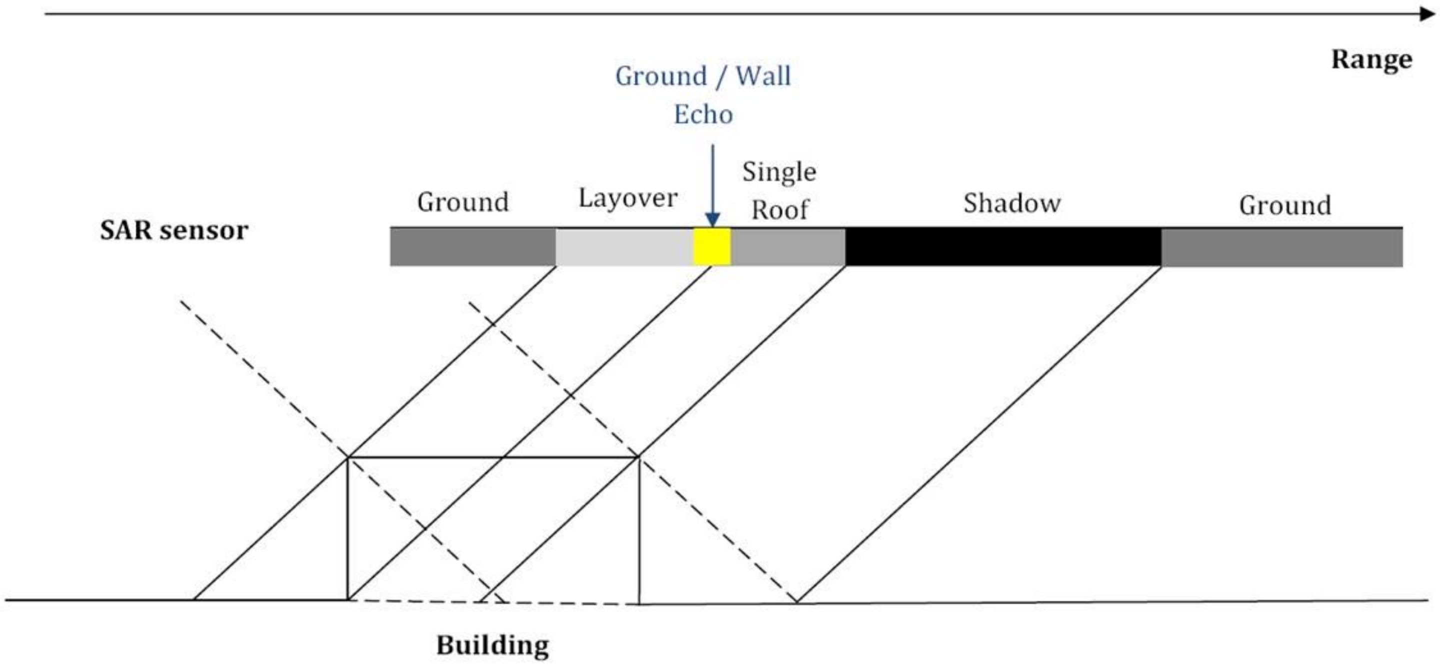


Geometric distorsions

- **Example of a vertical post**

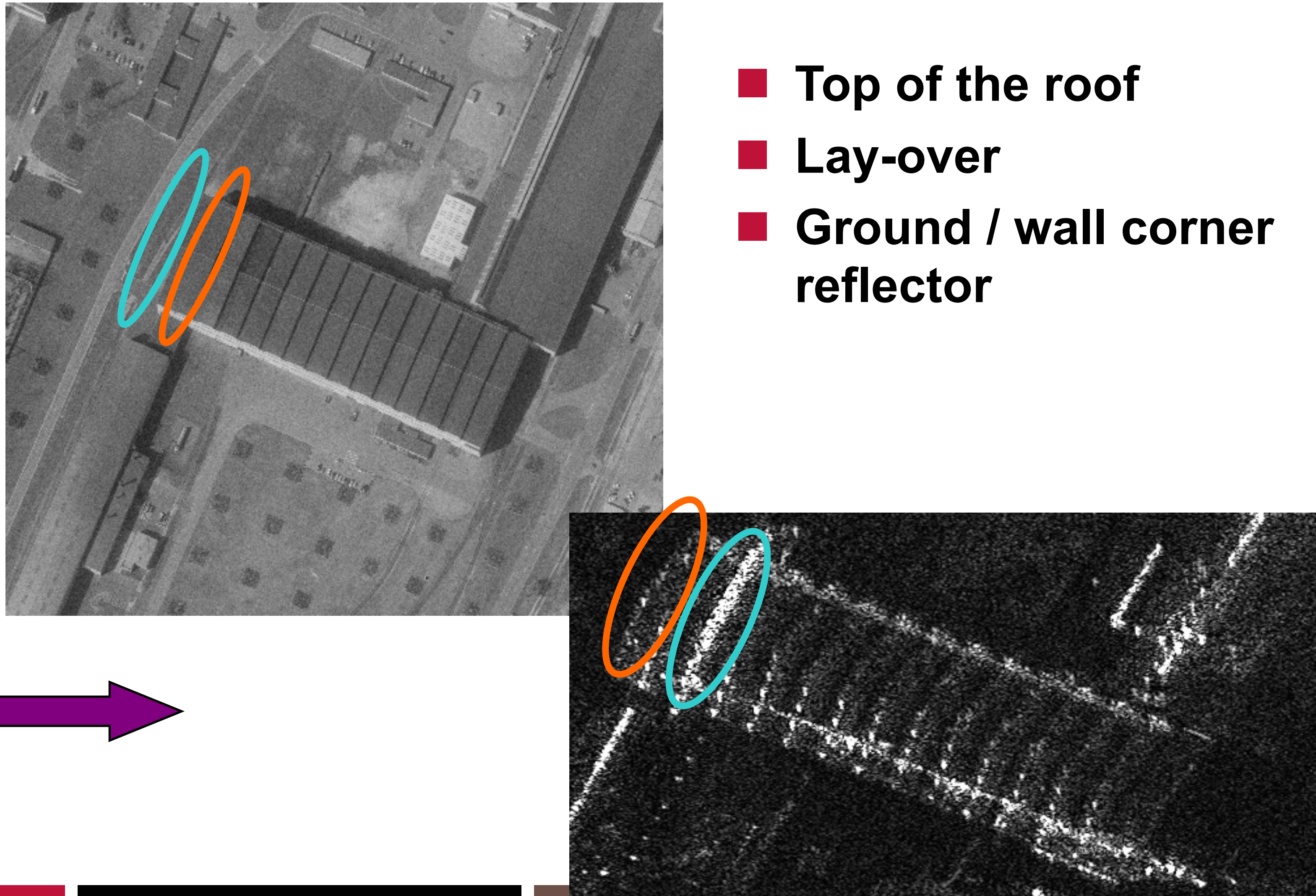


Geometric distorsions - building



Increased effects for buildings: vertical walls

Geometric distorsions - building



- Top of the roof
- Lay-over
- Ground / wall corner reflector

New-York and sky-scrapers – TerrSAR-X

Geometric distorsions - summary

- **Local slope :**
  - Foreshortning / dilation
- **Slope superior than the incidence angle**
  - Lay-over
- **Slope superior than the $\frac{\pi}{2} - $ incidence angle**
  - Shadow

How recovering 3D information with SAR data ?

SAR data and 3D

- **Backscattered electro-magnetic wave:** $z = Ae^{j\phi}$
  - Amplitude: backscattering coefficient of the scene
  - Phase: geometric information + cell scatterers contribution
- **Distance sampling:**
  - Geometric distorsions (lay-over, shadow)

- **3D information :**
  - Radarclinometry & shape from shading (amplitude)
  - Stereoscopy – radargrammetry (amplitude)
  - Interferometry (phase)
  - Tomography (n-D phase)

Overview of the session

- Distance sampling and geometric distorsions
- Mono-image elevation
- Radargrammetry
- Interferometry

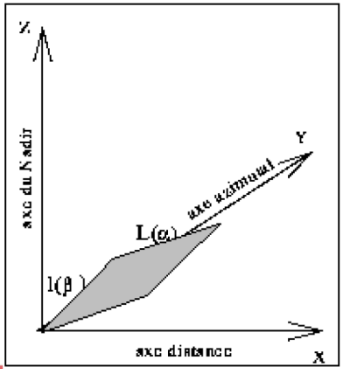
TELECOM ParisTech

Elevation from amplitude
« shape from shading »

$$CS = \Delta x = \frac{\Delta r}{\sin(\theta)}$$

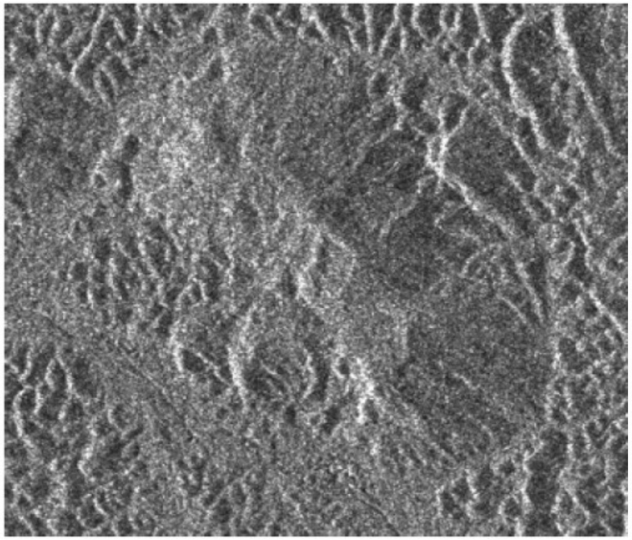
$$CS(\alpha) = \frac{\Delta r}{\sin(\theta - \alpha)}$$

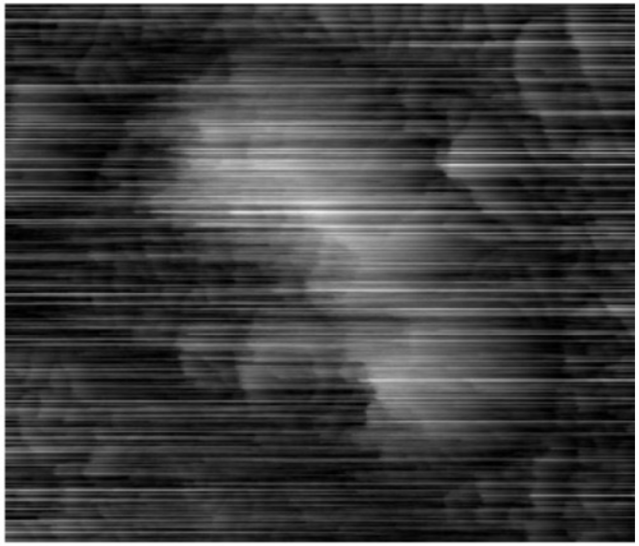
- **Data : 1 amplitude image**
- **Radarclinometry:**
  - For homogeneous areas :
    - Backscattered signal = f(local slope)

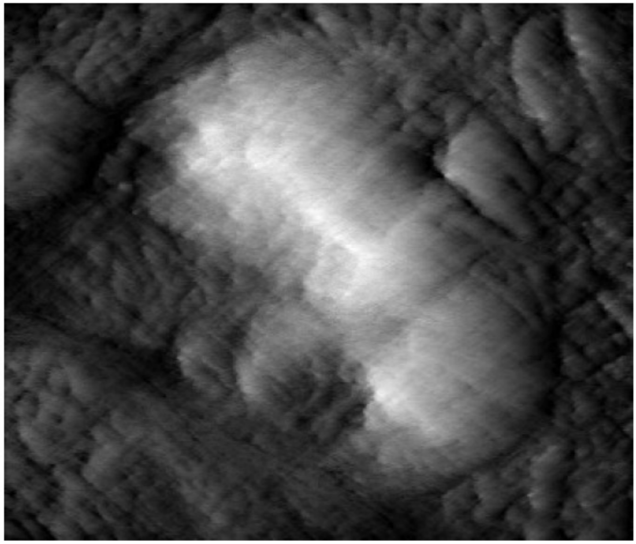


$$I(\alpha) = K\sigma_0 \Delta_x \Delta_y L(\alpha)$$

$$L(\alpha) = \frac{\sin(\theta)}{\sin(\theta - \alpha)}$$





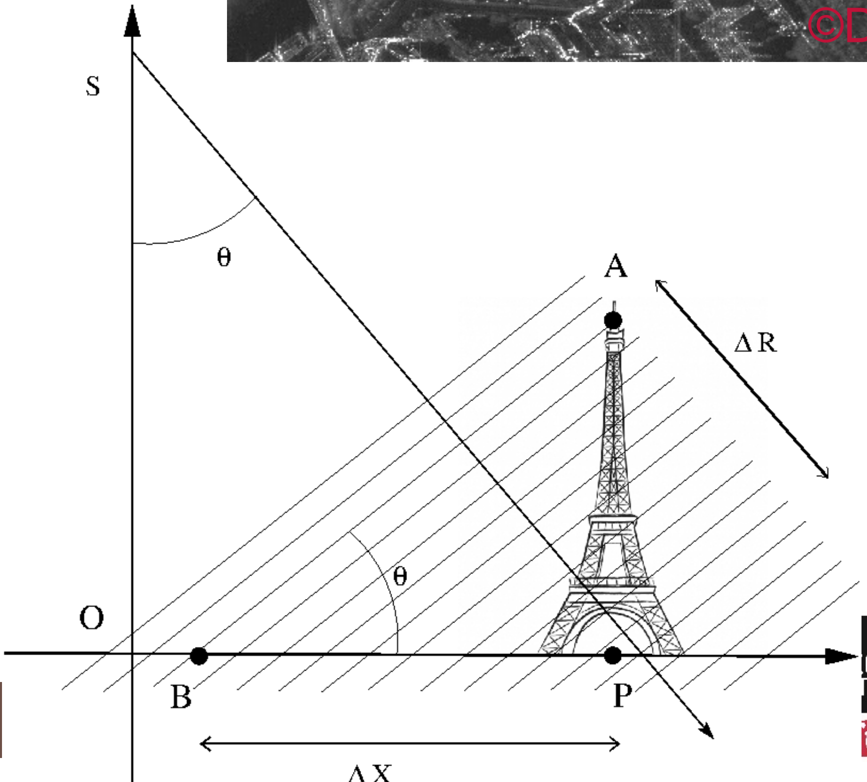


Elevation from amplitude
Lay-over / shadow

- **Terrasar-X, θ~34°**
- **Relation between H and BP**
- ΔX **ground range distance between the highest point and the ground**
- ΔR **slant range distance**

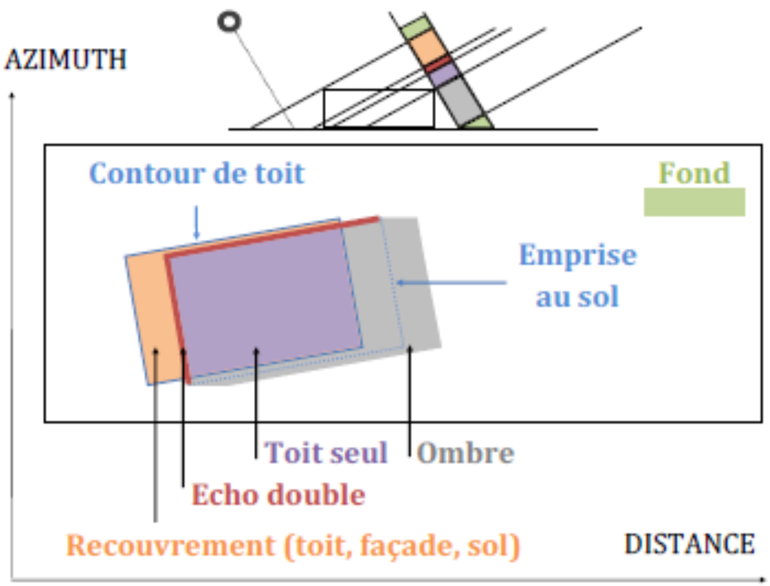
$$H = \Delta X \tan\theta$$

$$H = \frac{\Delta R}{\cos\theta}$$

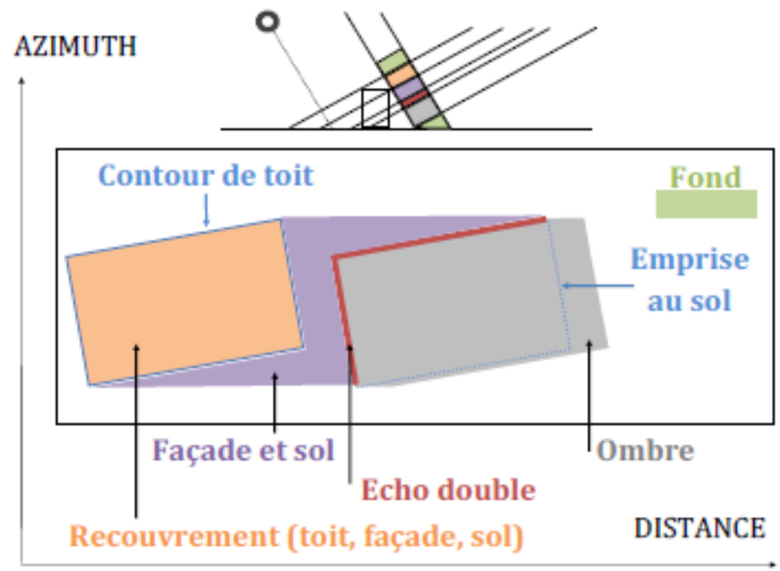


Elevation from amplitude
Lay-over / shadow

- **Data : 1 amplitude image**
- **Elevation from lay-over and shadow**
  - Layover area and shadow area measurement to recover elevation information

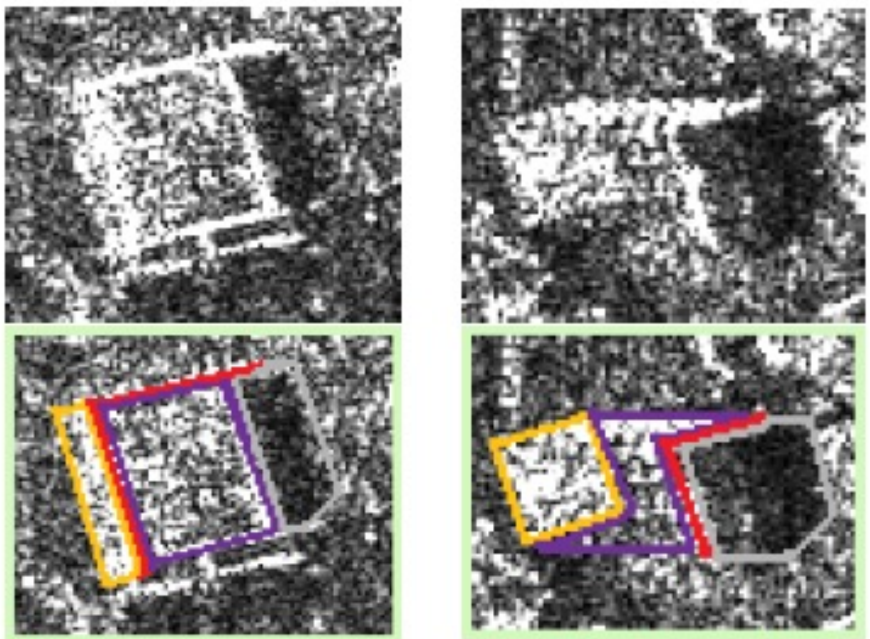


Cas 1 : $h_{bâti} < h_{limite}$



Cas 2 : $h_{bâti} > h_{limite}$

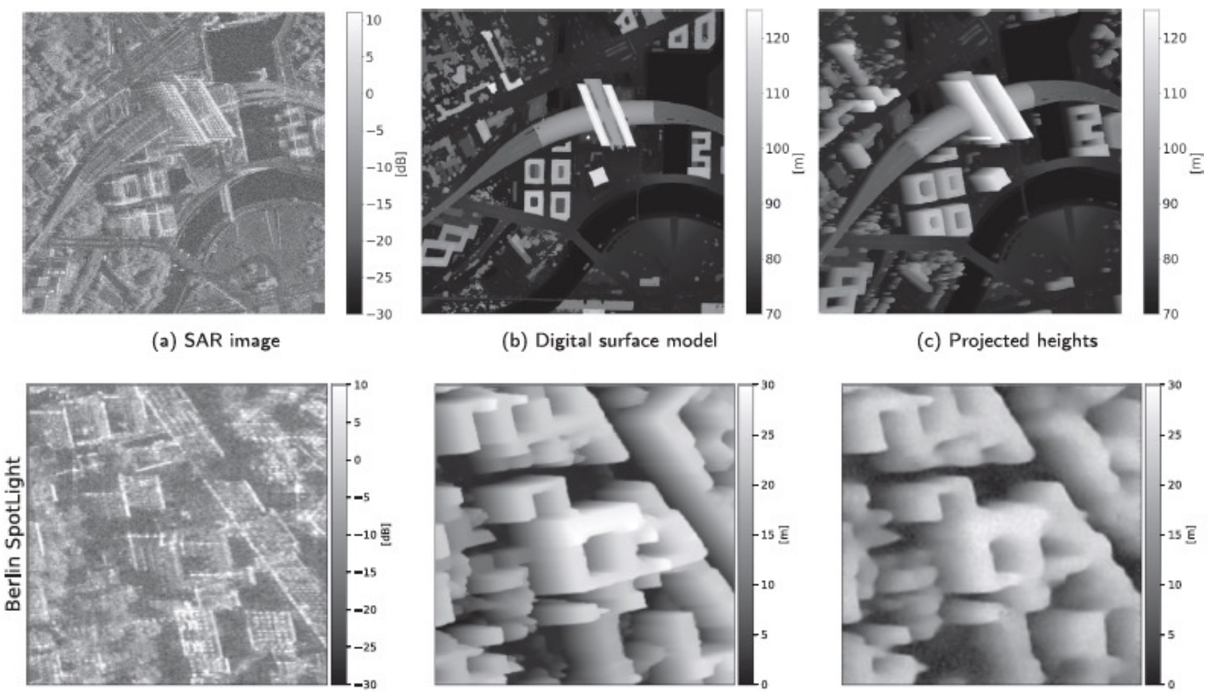
Man-made structures
Example of processing chain (1)



Cas 1 : $h_{bâti} < h_{limite}$ Cas 2 : $h_{bâti} > h_{limite}$

- **Processing chain**
  - Building footprint detection
  - h optimization
- **Elevation extraction:**
  - Hypothesis of elevation h
  - Computation of a radiometric signature using h, building shape and sensor parameters
  - Energy minimization depending on h
- **Limits**
  - Rectangular shape, flat roof

Man-made structures
Example of processing chain (2)



Figures extracted from :
Deep learning based single-image height reconstruction from very-high-resolution SAR intensity data, M. Recla and M. Schmitt, ISPRS 2022
© ISPR Int. Journal of Photogrammetry and Remote Sensing

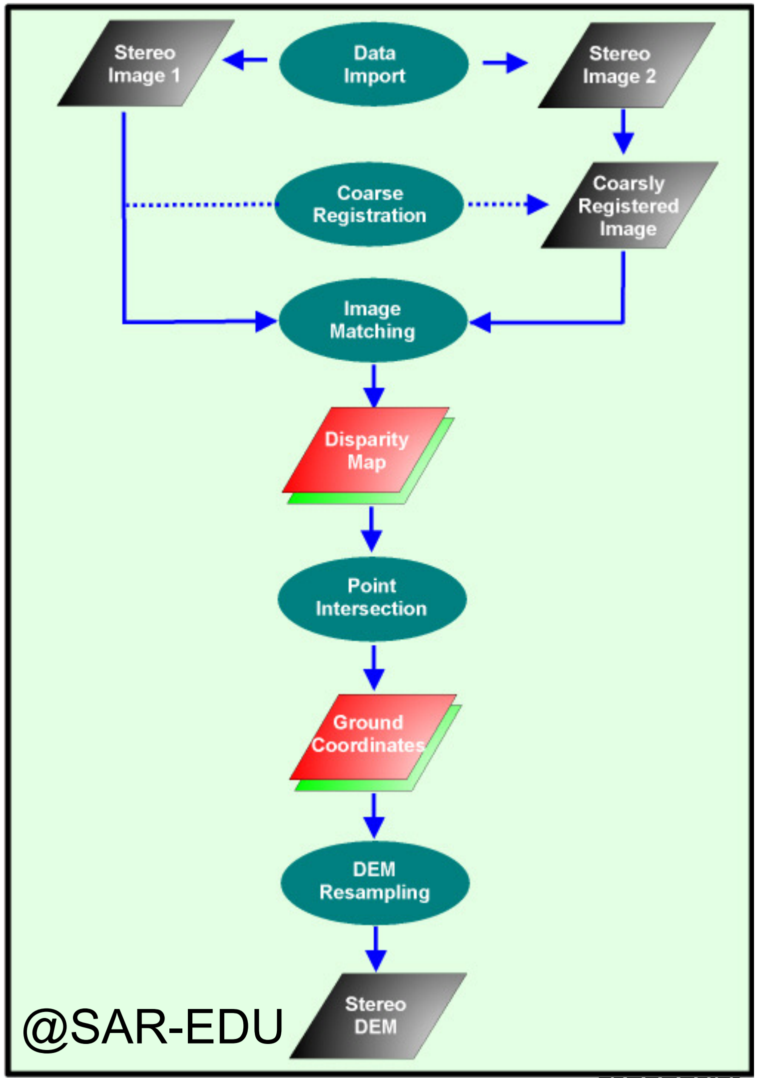
- **Processing chain**
  - Network trained to predict height from amplitude information
  - Supervised training : dataset obtained from airborne laser scanning and projected in SAR geometry
- **Test phase:**
  - Amplitude image
  - « Similar » acquisition angle

Overview of the session

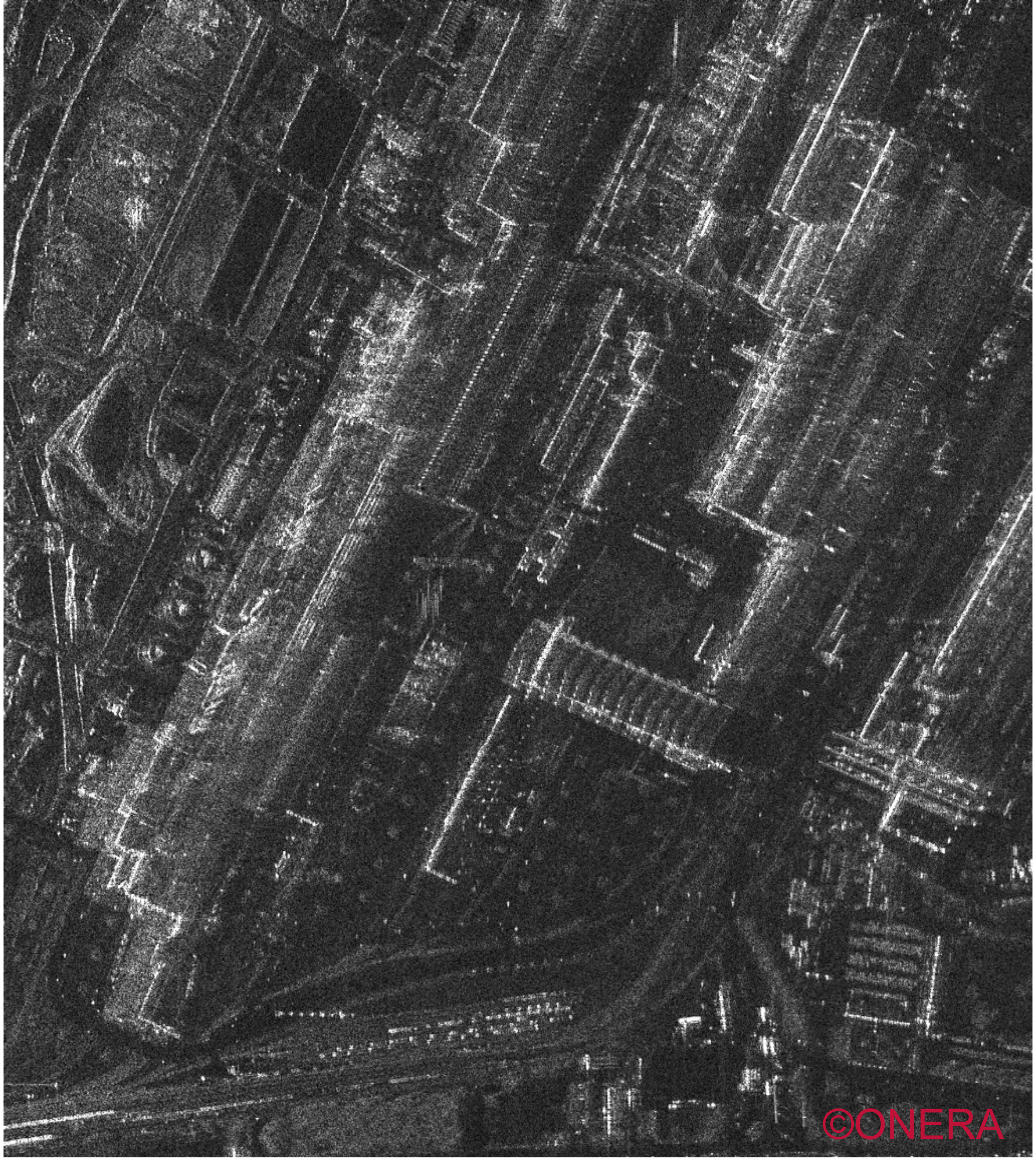
- Distance sampling and geometric distorsions
- Mono-image elevation
- Radargrammetry
- Interferometry

Radargrammetry / stereovision

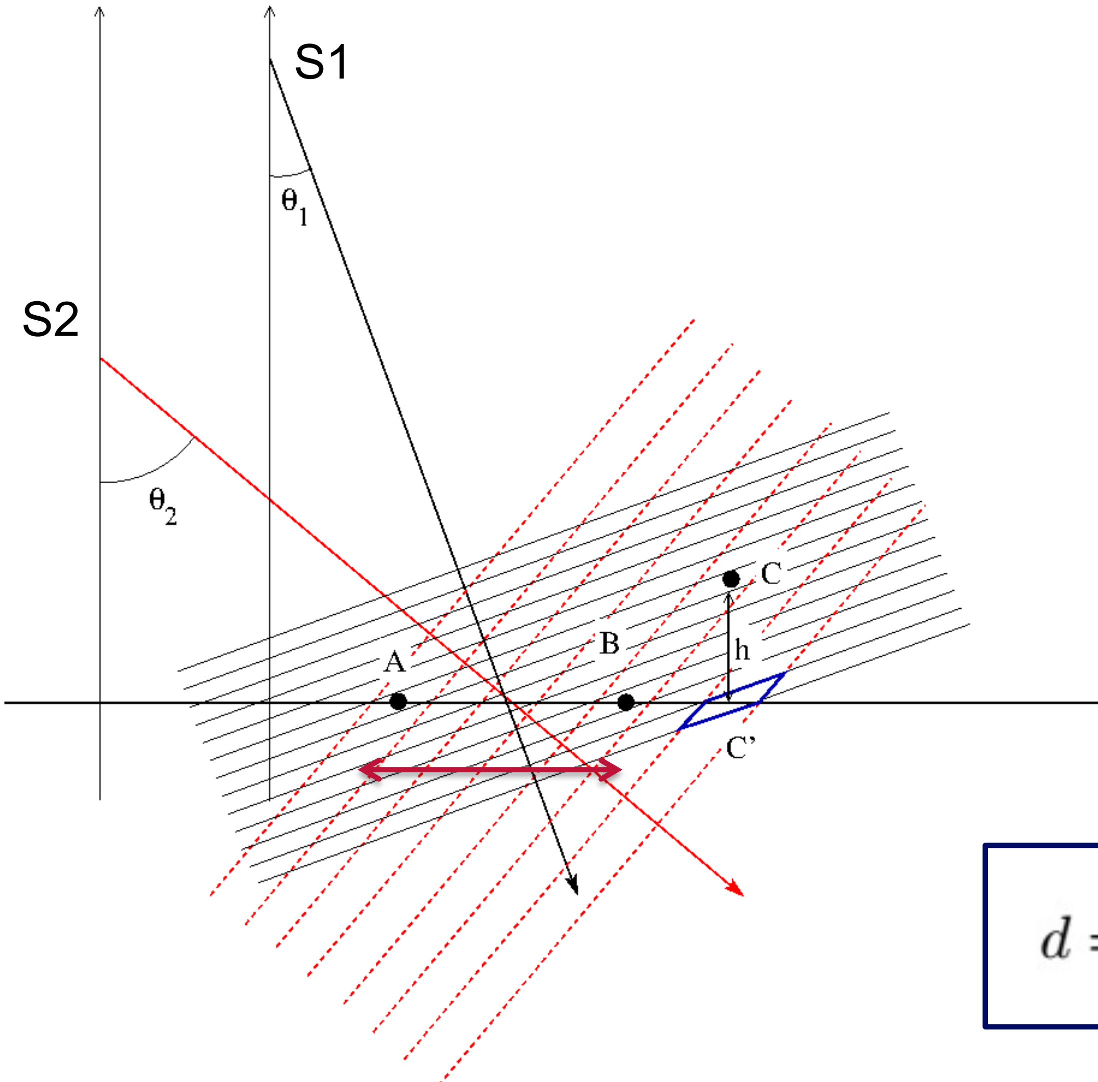
- **Data : 2 amplitude images**
- **Principle :**
  - Point matching in Im1 and Im2
  - Geometric equations to recover 3D information




©ONERA


©ONERA

Radargrammetry



- C': point on the ground
  In the same cell for both sensors

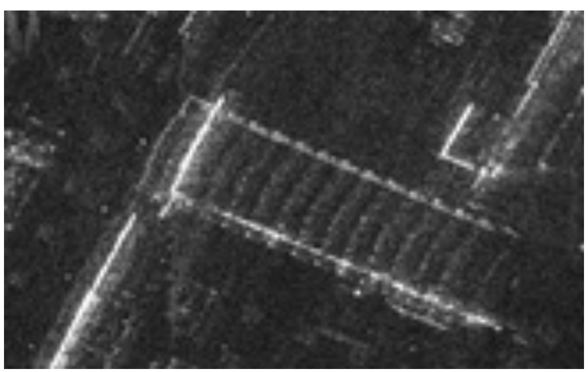
- C: point with elevation h
  - Seen in cell A for S1
  - Seen in cell B for S2
  - d=AB (point matching)
  - d=AC'-BC'

$$AC' = h/\tan\theta_1$$

$$BC' = h/\tan\theta_2$$

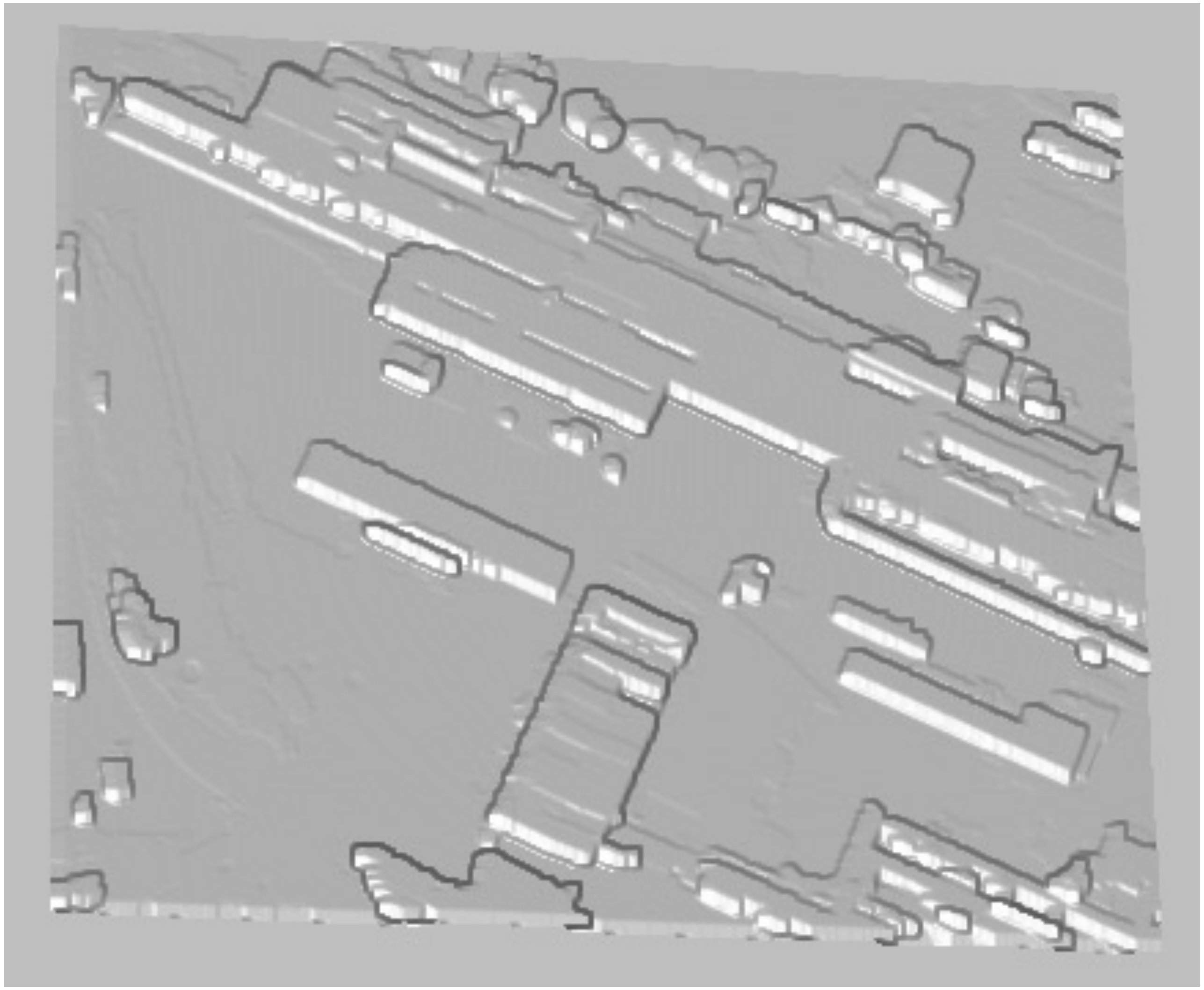
$$\boxed{d = h\left(\frac{1}{\tan\theta_1} - \frac{1}{\tan\theta_2}\right)}$$

Radargrammetry – processing chain



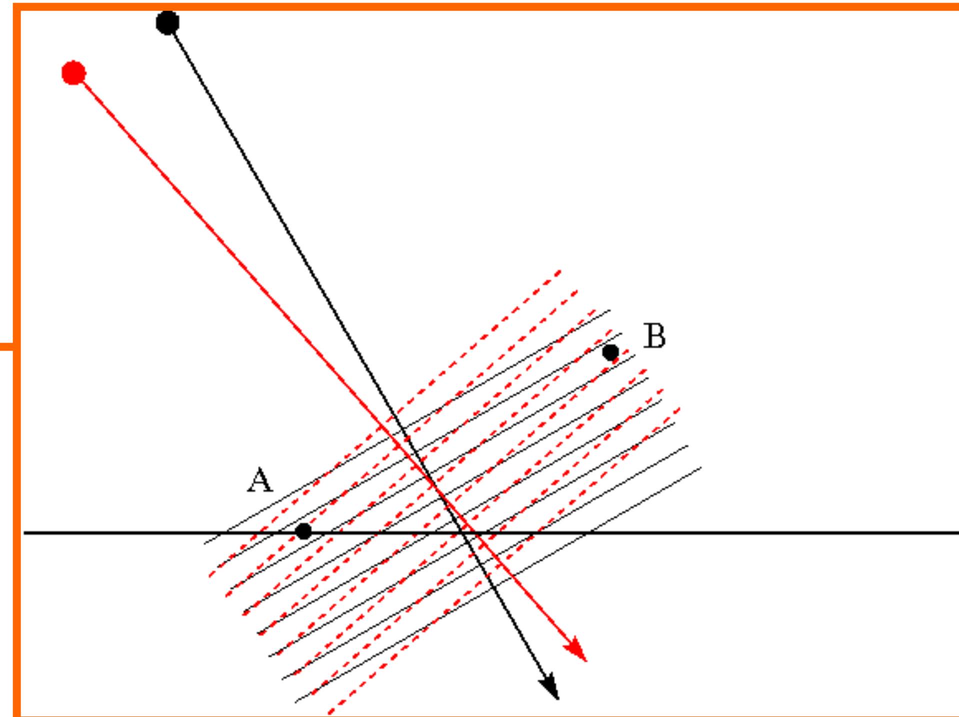
- **Steps:**
  - Pseudo-epipolar resampling (tie points and low-order polynomial)
  - Window based matching
  - Disparity map regularization
  - Conversion of disparities to 3D coordinates
  - Point cloud transformation into gridded DSM
- **Limits**
  - Sparse matching
  - Corner reflectors: mostly on the ground

3D reconstruction – Radarg./optic

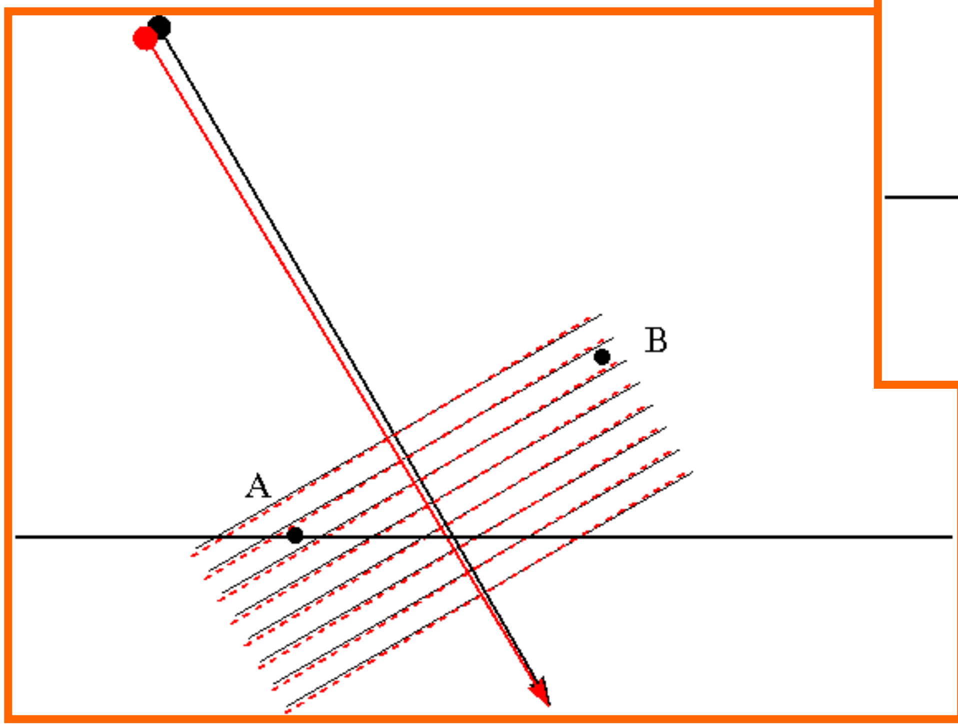


Overview of the session

- **Distance sampling and geometric distorsions**
- **Mono-image elevation**
- **Radargrammetry**
- **Interferometry**



Big baseline:
radargrammetry



Small baseline :
interferometry

Phase and geometry

- **Phase of a single image (backscattered)**

$$\phi(t) = 2\pi f_0 t + \phi_{pr}$$

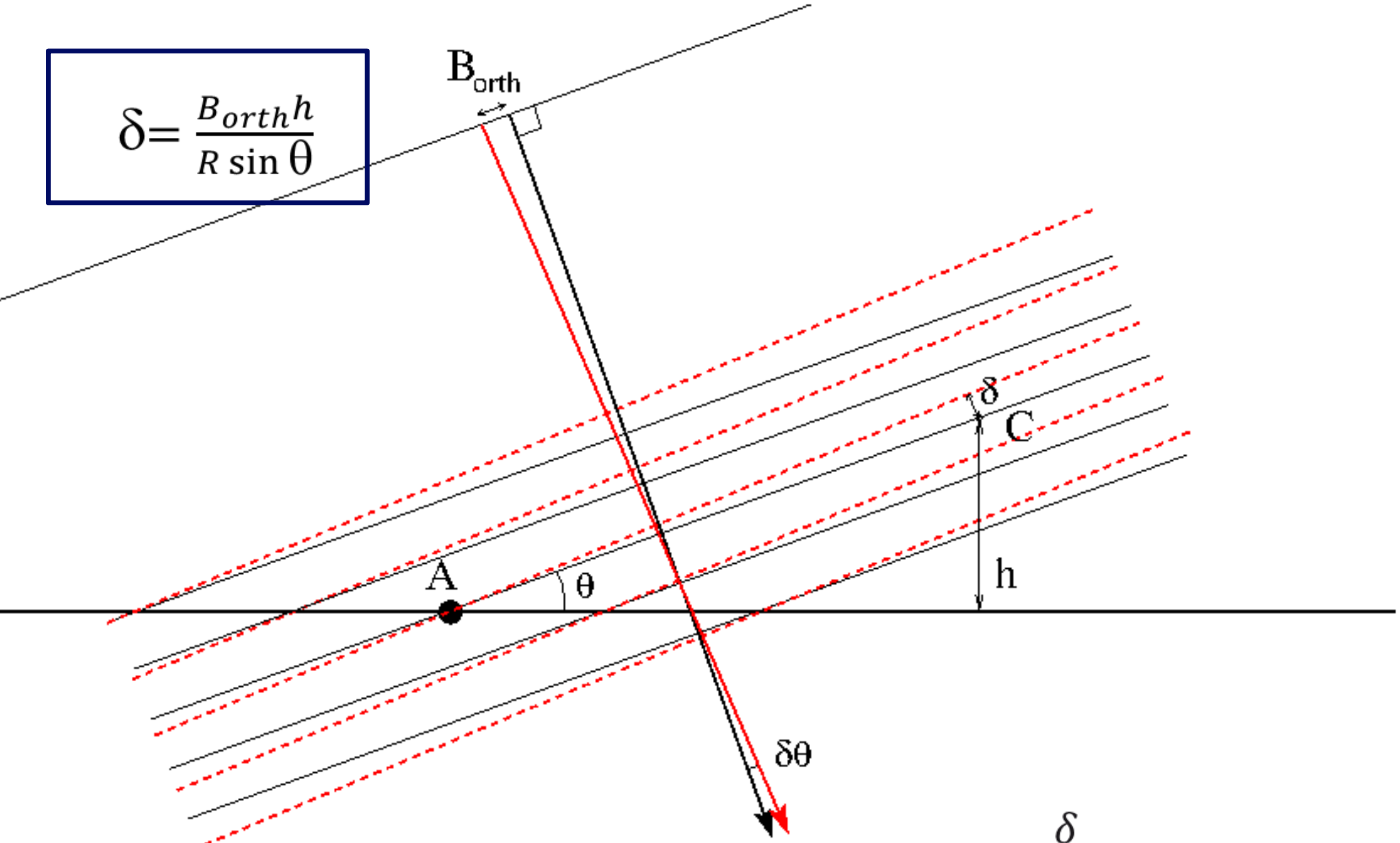
$$t = 2\frac{R}{c} = 2\frac{R}{\lambda f_0}$$

$$\boxed{\phi(t) = 4\pi\frac{R}{\lambda} + \phi_{pr}}$$

Combination of a geometric information (related to the range R) and the resolution cell contribution (phase shift due to cell scatterer organization)

Interferometry - principle

$$\delta = \frac{B_{orth} h}{R \sin \theta}$$



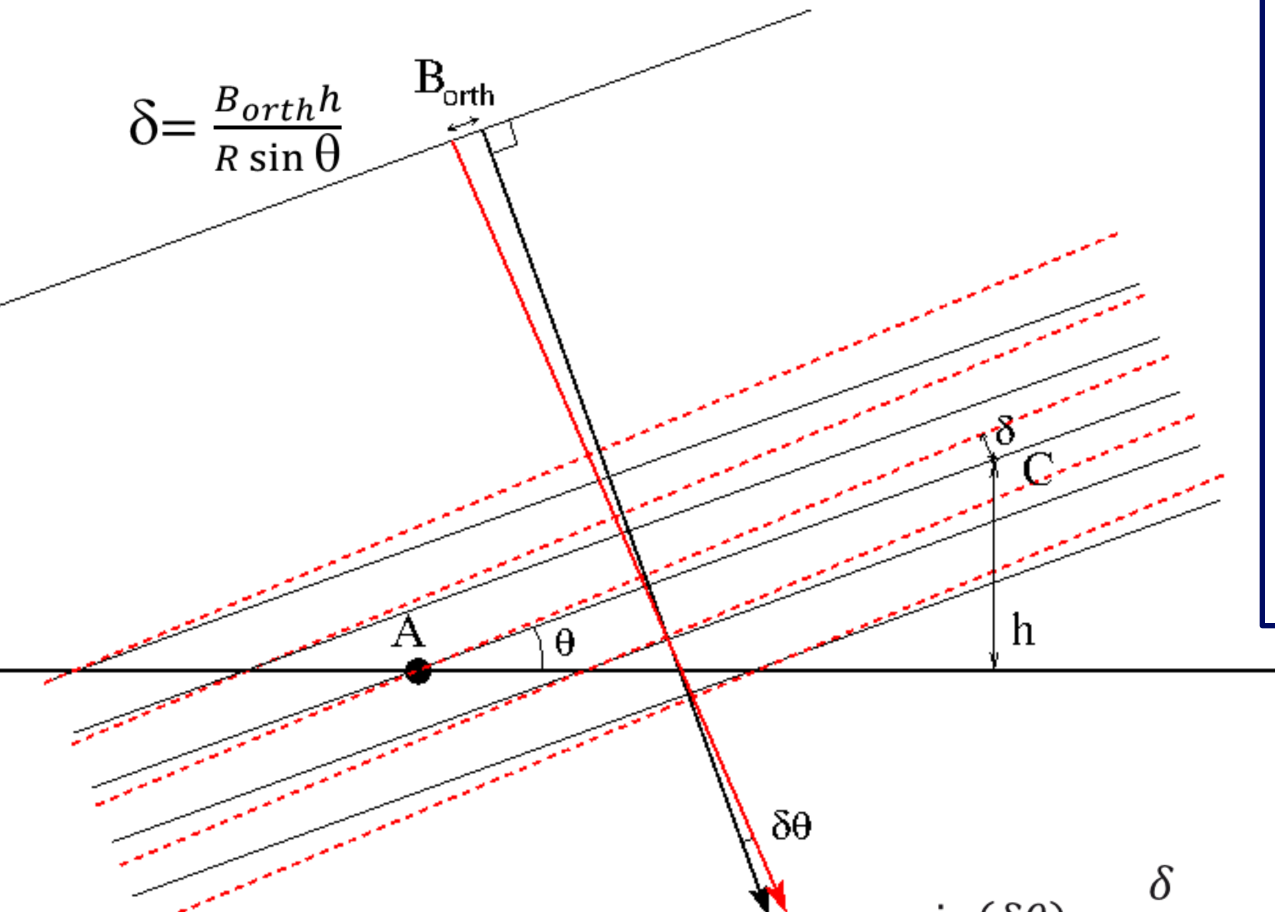
$$\sin \theta = \frac{h}{AC}$$

$$\sin(\delta\theta) = \frac{\delta}{AC}$$

$$\sin(\delta\theta) = \frac{Borth}{R}$$

Interferferometry - principle

$$\delta = \frac{B_{orth} h}{R \sin \theta}$$



$$\phi = \frac{4\pi R}{\lambda} + \phi_{pr}$$

$$\phi_2 - \phi_1 = \frac{4\pi(R_2 - R_1)}{\lambda} = \psi_{1,2}$$

$$R_2 - R_1 = \delta$$

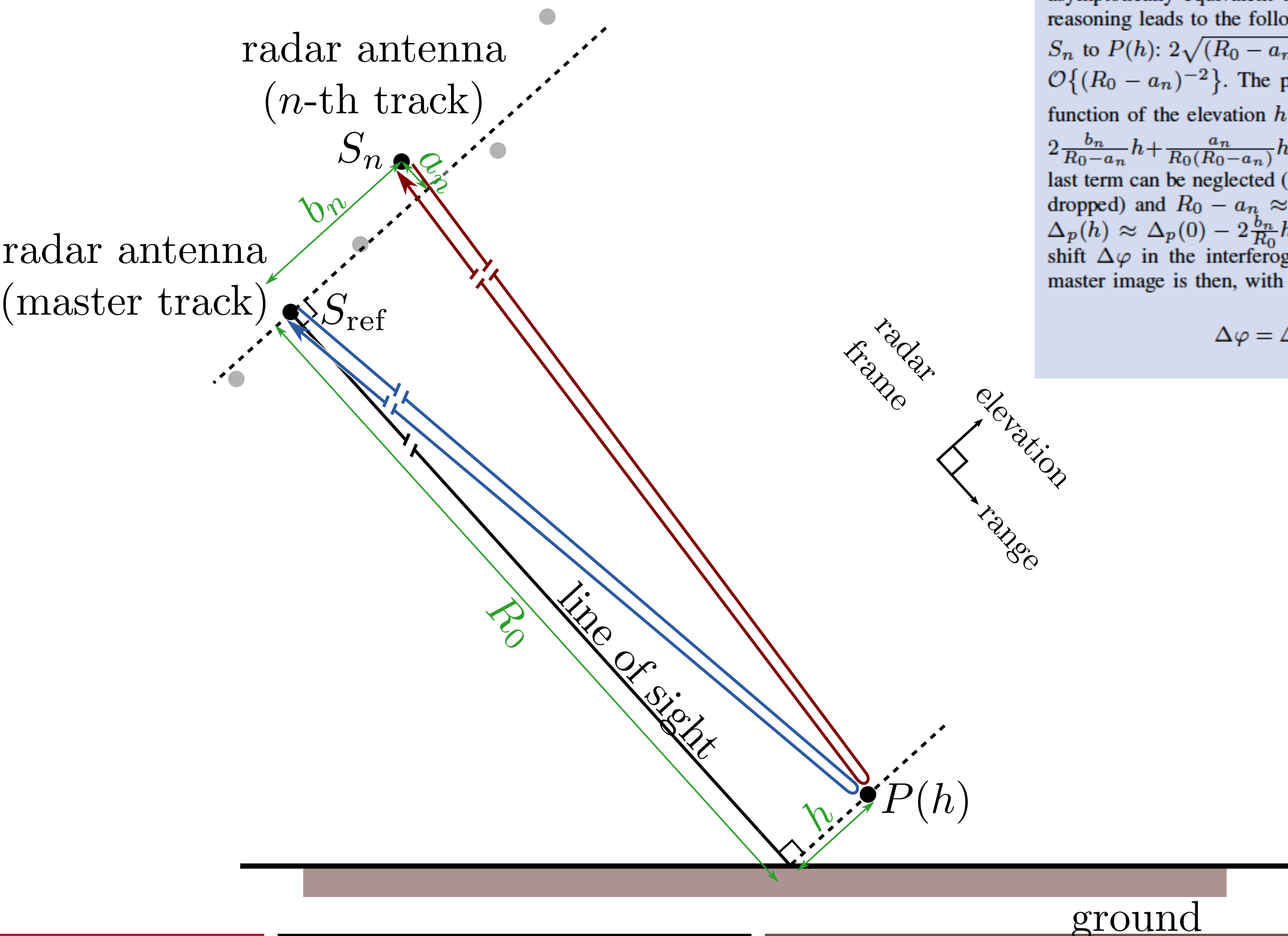
$$\psi_{1,2} = \frac{4\pi B_{\perp 1,2}}{R \sin(\theta) \lambda} h$$

$$\psi_{1,2} = \alpha_{geom_{1,2}} h$$

$$\sin(\delta\theta) = \frac{\delta}{AC}$$

$$\sin(\delta\theta) = \frac{Borth}{R}$$

Interferometry principles



The path length difference between the round-trip from the master antenna location S_{ref} to point $P(h)$ and the round-trip from the n-th antenna location S_n to point $P(h)$ determines the phase-shift. In the radar frame (orthogonal frame defined by the range and elevation directions, with origin S_{ref}), point $P(h)$ has coordinates $P(h) = [R_0, h]$, the master antenna $S_{\text{ref}} = [0, 0]$ and the antenna on the n-th track $S_n = [a_n, b_n]$. The round-trip distance from S_{ref} to point $P(h)$ is equal to $2\sqrt{R_0^2 + h^2}$. Given that $R_0 \gg h$, this distance can be expanded under the form $2R_0 + \frac{h^2}{R_0} + \mathcal{O}\{R_0^{-2}\}$ where $\mathcal{O}\{R_0^{-2}\}$ designates terms that are asymptotically equivalent to R_0^{-2} and may then be neglected. A similar reasoning leads to the following expansion of the round-trip distance from S_n to $P(h)$: $2\sqrt{(R_0 - a_n)^2 + (h - b_n)^2} = 2(R_0 - a_n) + \frac{(h-b_n)^2}{R_0 - a_n} + \mathcal{O}\{(R_0 - a_n)^{-2}\}$. The path difference Δ_p can then be expressed as a function of the elevation h of point $P(h)$: $\Delta_p(h) \approx -2a_n + \frac{b_n^2}{R_0 - a_n} - 2\frac{b_n}{R_0 - a_n}h + \frac{a_n}{R_0(R_0 - a_n)}h^2$. Given that both $a_n \ll R_0$ and $b_n \ll R_0$, the last term can be neglected (it is comparable to the terms in R_0^{-2} previously dropped) and $R_0 - a_n \approx R_0$, which leads to the linear approximation: $\Delta_p(h) \approx \Delta_p(0) - 2\frac{b_n}{R_0}h$, with $\Delta_p(0) = -2a_n + b_n^2/R_0$. The phase shift $\Delta\varphi$ in the interferogram formed between the n-th image and the master image is then, with $\Delta\varphi_0 = (2\pi/\lambda)\Delta_p(0)$:

$$\Delta\varphi = \Delta\varphi_0 - \frac{4\pi b_n}{\lambda R_0}h \pmod{2\pi}\,. \tag{1}$$

TELECOM ParisTech

Interferometry - principle

Measurement of path length differences :

- When finely registered (same cell sizes), it depends on the point elevation in the radar cell: topographic fringes
- Before fine resampling, ground range cells have different size, it implies a phase contribution along the swath (in range): orbital fringes

Conditions:

- The same scatterers organization should be measured by both sensors (no change of the ground)
- The atmospheric conditions should be the same
- The noise should be limited
- There should be no movement of the ground between the two acquisitions

Elevation and movement

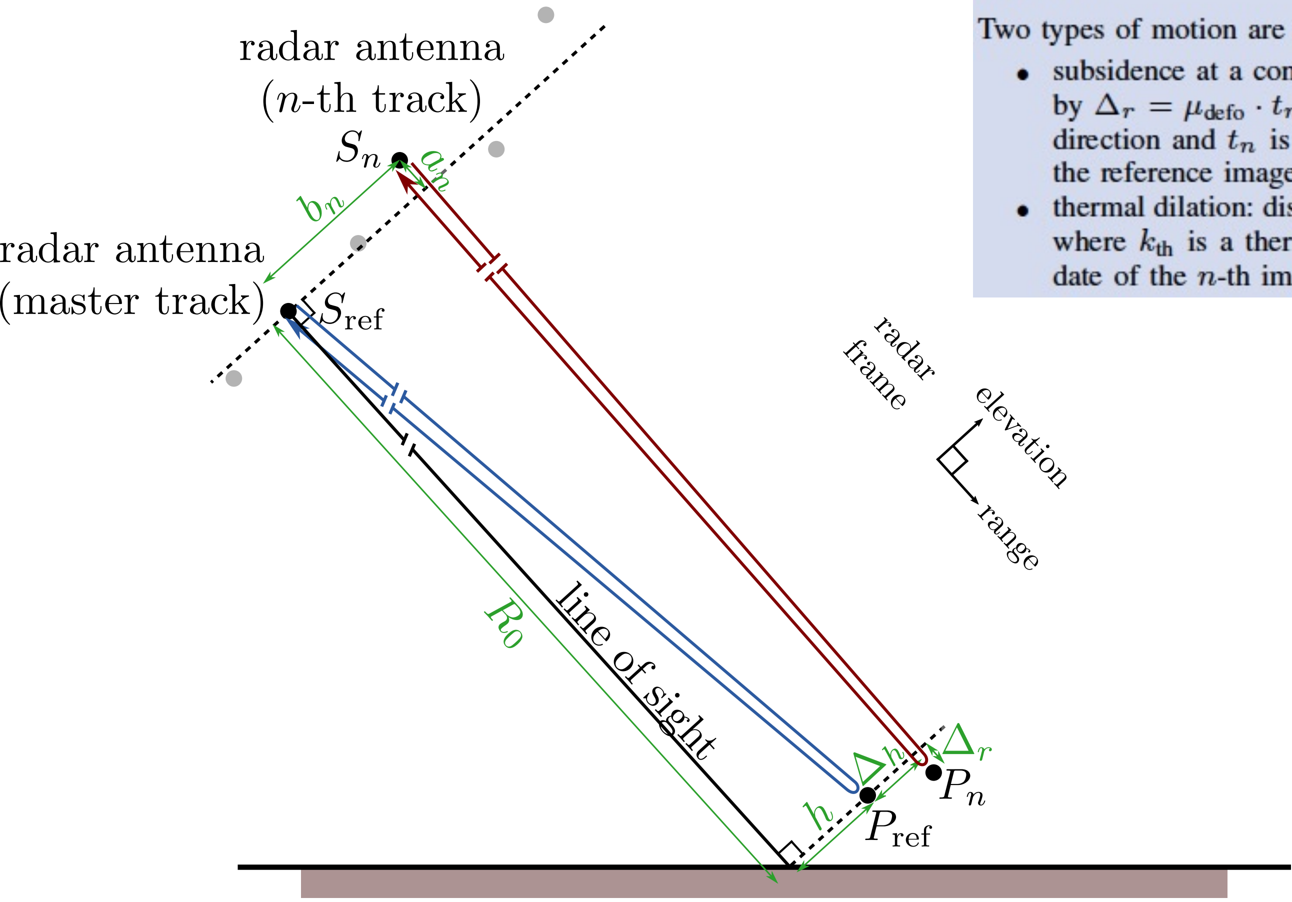
The scatterer, located at $P_{\text{ref}} = [R_0, h]$ in the master image, moved between the acquisitions and is located at $P_n = [R_0 + \Delta_r, h + \Delta_h]$ when the n-th image is acquired. The path length for the master image has not changed. For the n-th image, the new path length is equal to $2\sqrt{(R_0 + \Delta_r - a_n)^2 + (h + \Delta_h - b_n)^2}$. The same approximations as in the previous paragraph lead to:

$$\Delta\varphi = \Delta\varphi_0 - \frac{4\pi b_n}{\lambda R_0} h + \frac{4\pi}{\lambda} \Delta_r + \frac{4\pi(b_n + h)}{\lambda R_0} \Delta_h \pmod{2\pi}. \quad (2)$$

Since $R_0 \gg b_n + h$ and $h \gg \Delta_h$, the last term is negligible compared to the others: only the motion in the direction of the line-of-sight Δ_r can be recovered.

Two types of motion are generally modeled:

- subsidence at a constant velocity: displacement on image n is given by $\Delta_r = \mu_{\text{defo}} \cdot t_n$, where μ_{defo} is the velocity in the line-of-sight direction and t_n is the time difference between the n-th image and the reference image,
- thermal dilation: displacement on image n is given by $\Delta_r = k_{\text{th}} \cdot T_n$, where k_{th} is a thermal coefficient and T_n is the temperature at the date of the n-th image.



Interferometry – processing chain

- **Interferometric processing chain**
  - Acquisition of 2 SAR images in interferometric configuration
  - Fine registration of the 2 images
  - Computation of the phase difference
  - Phase unwrapping

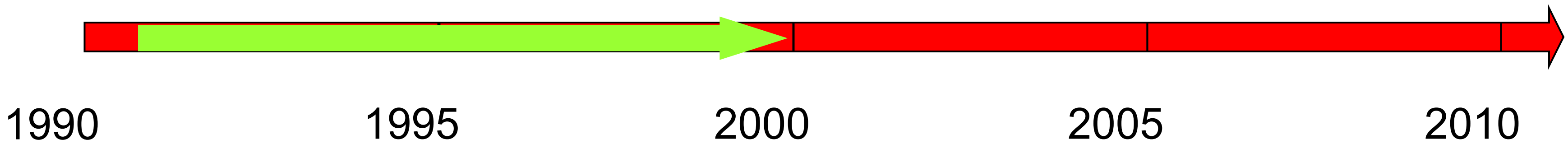
Interferometry – processing chain

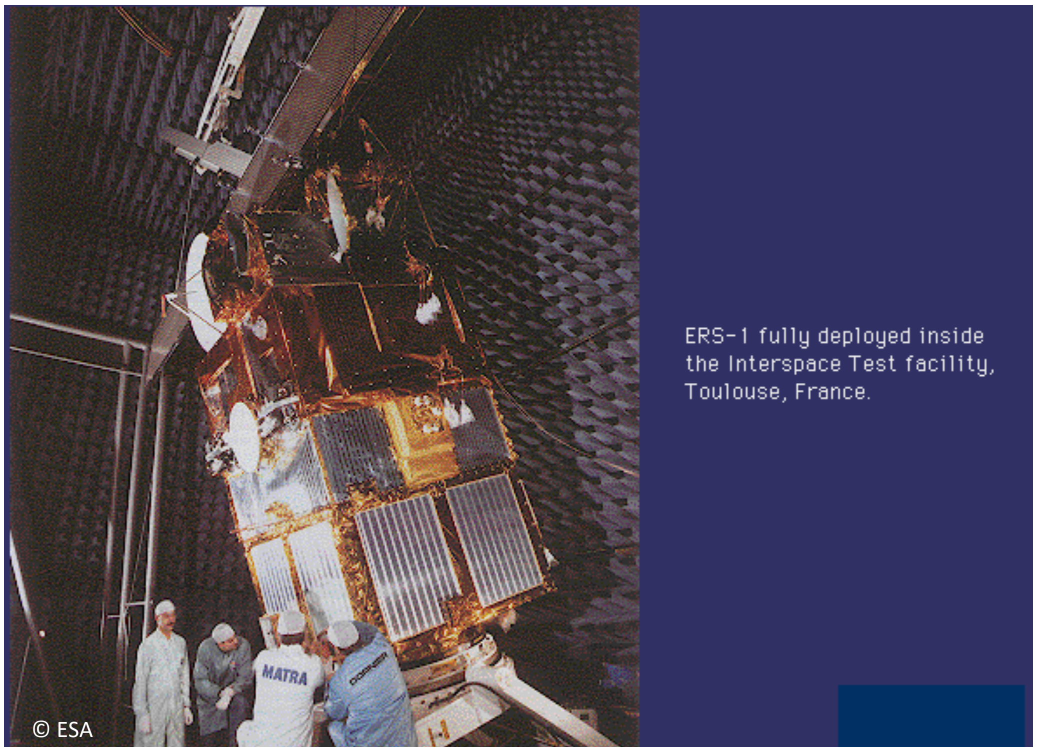
- **Interferometric processing chain**
  - Acquisition of 2 SAR images in interferometric configuration
  - Fine registration of the 2 images
  - Computation of the phase difference
  - Phase unwrapping

Interferometry – Main steps

- **Acquisition of 2 SAR images in interferometric configuration**
- **Conditions**
  - Slight difference of incidence angle
  - No change of scatterers
  - Same atmospheric conditions
- **Repeat pass interferometry**
  - Same orbit, same incidence angle
  - Revisit time
- **Single pass interferometry (simultaneous acquisitions)**
  - SRTM (Shuttle Radar Topographic Mission)
  - Airborne acquisitions
  - TanDEM-X / TerraSAR-X

Satellites for SAR Interferometry: ERS-1

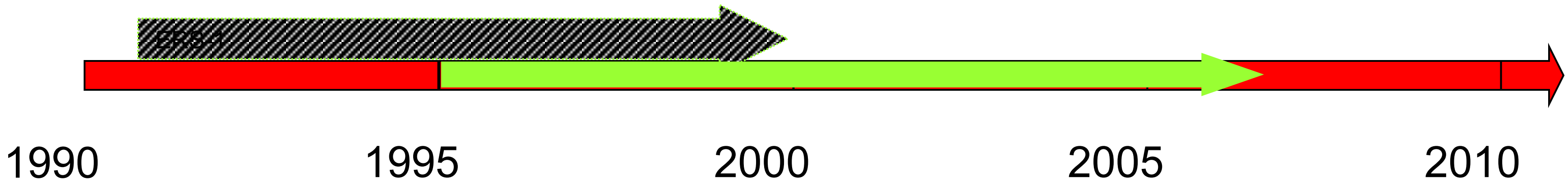




http://earth.esa.int/ers/satconc/satconc.html

- Operated by ESA
- Launched 1991 (†2000)
- C-Band (5.6 cm)
- 15.5 MHz bandwidth
- 35 day repeat polar orbit,
- Highly successful mission
- Initiated cross track and along track SAR interferometry

Satellites for SAR Interferometry: ERS-2



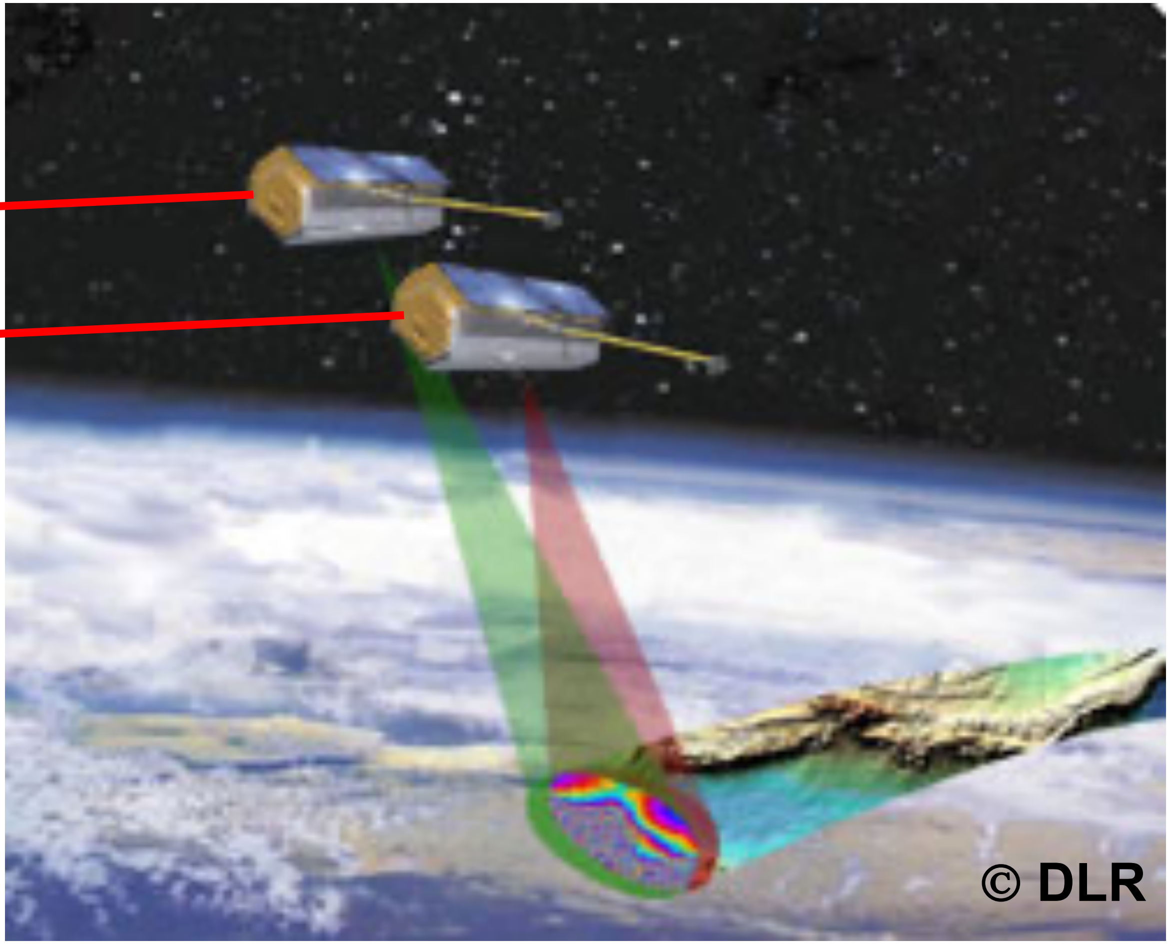
http://earth.esa.int/rootcollection/eeo/_foto21b.gif

- **Operated by ESA**
- **Launched 1995**
- **SAR instrument and orbit identical to ERS-1**
  - 1 day time delay
- **ERS-1/2 tandem operation 1995-1998**
  - controlled baseline
- **1 day time lag → low decorrelation → DEM generation**

Acquisition - SAR multi-pass (Terrasar-X)

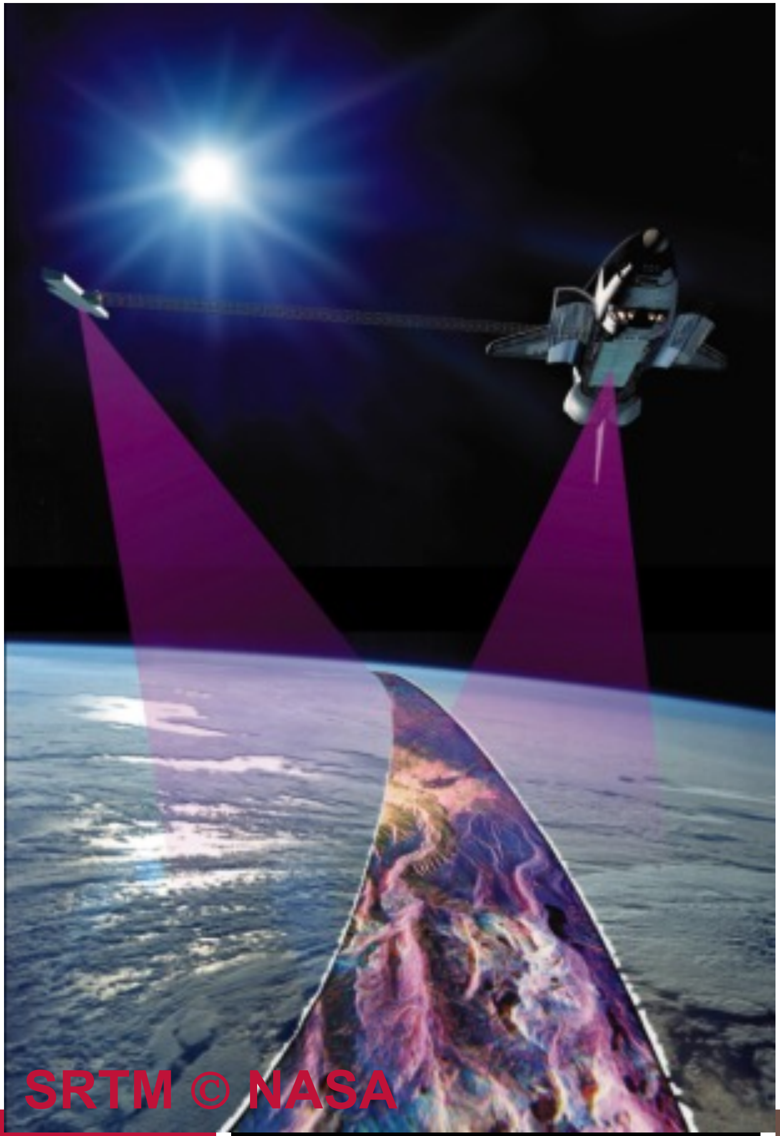
Day J

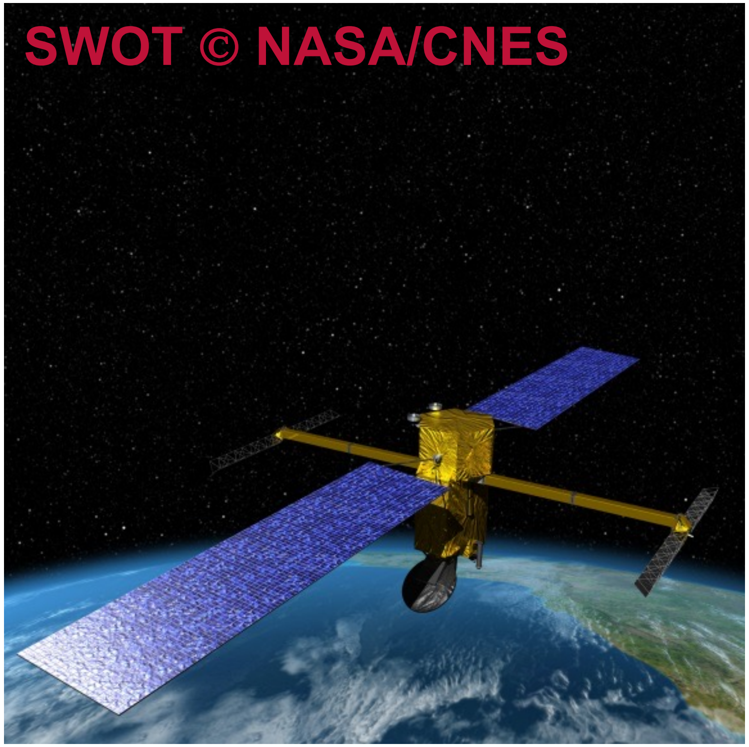
Day J + 11



Exploitation of the revisit of the sensor on the same orbit

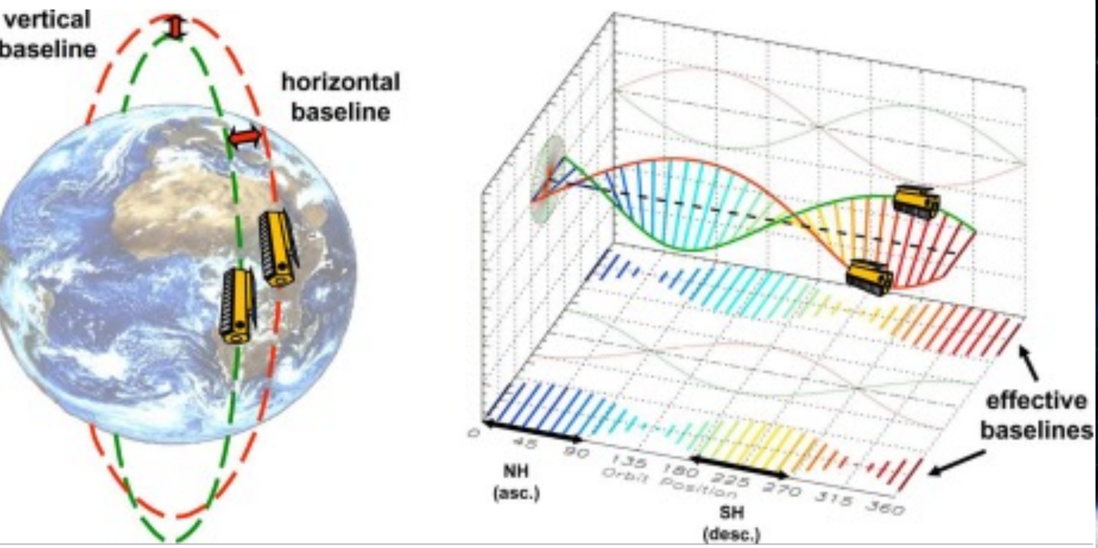
Acquisition - SAR mono-pass





Acquisition - SAR mono-pass

TerraSAR-X: 2007
TanDEM-X: 2011



HELIX satellite formation for TanDEM-X

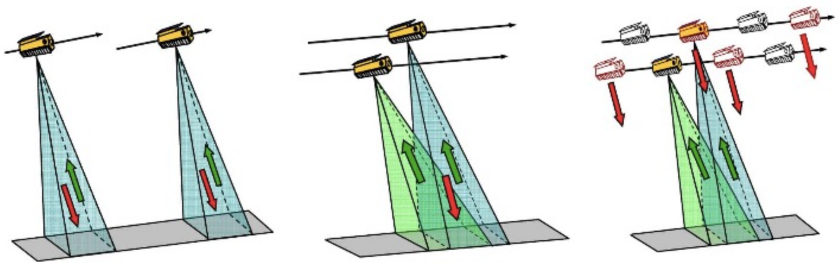


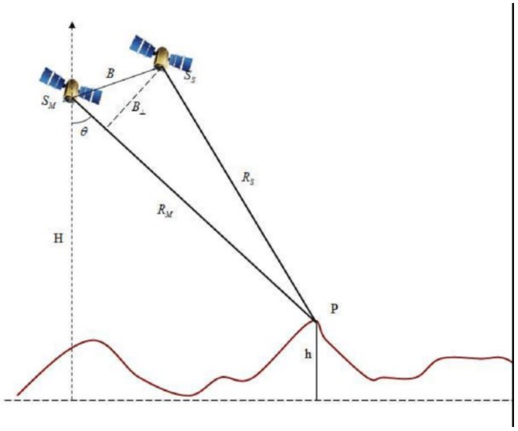
Fig. 1. Examples of data acquisition modes for TanDEM-X. (Left) Pursuit monostatic mode, (middle) bistatic mode, and (right) alternating bistatic mode.

Interferometry – Main steps

- **Processing chain**
  - Acquisition of 2 SAR images in interferometric configuration
  - Fine registration of the 2 images
  - Computation of the phase difference
  - Phase unwrapping

Registration

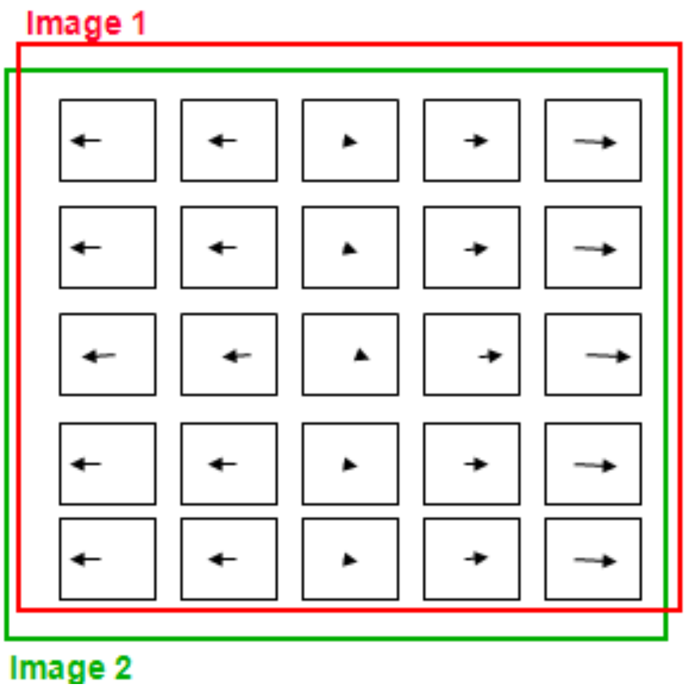
- **Repeat pass interferometry :**
  - Same orbital track, same incidence angle, same mode, same polarization
  - Different times, different positions (baseline)
  - Parallel baseline: relative image shift
  - Orthogonal baseline: range cell size variation along flat earth



TELECOM ParisTech

Registration in practice – different approaches

- **Accurate knowledge of sensor parameters: geometric registration**
  - Orbit, speed, clocks, times
  - Resampling of one image (« slave ») in the « master » image geometry
- **Image processing driven re-sampling**
  - Over-sampling with a factor of 100 (range)
  - Complex cross-correlation maximization
  - Computation of an affine transform



Registration in practice – coarse registration

Image processing registration

- Search for a global translation between the two amplitude images
- Minimization of the MSE between the master image and the translated slave image

$$MSE(k,l) = \sum_{(i,j)} (A_1(i,j) - A_2(i+k, j+l))^2$$

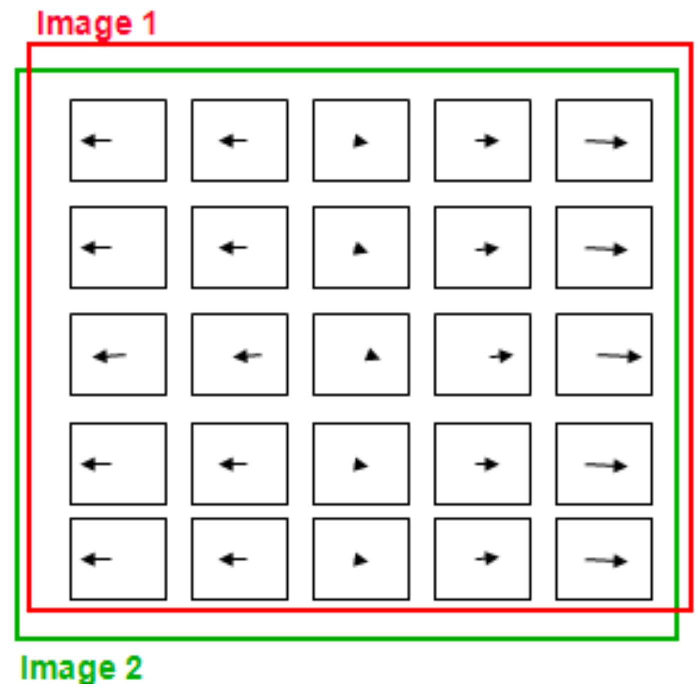
- Maximization of the correlation = convolution between the inverse of the translated master image and the slave image

$$Corr(k,l) = \sum_{(i,j)} A_1(i,j) A_2(i+k, j+l) = \tilde{A}_1 * A_2(k,l)$$

$$Corr(k,l) = TF^{-1}(TF(A_1)^{*}.TF(A_2))$$

$$z_1 = A_1 e^{j\phi_1}$$

$$z_2 = A_2 e^{j\phi_2}$$



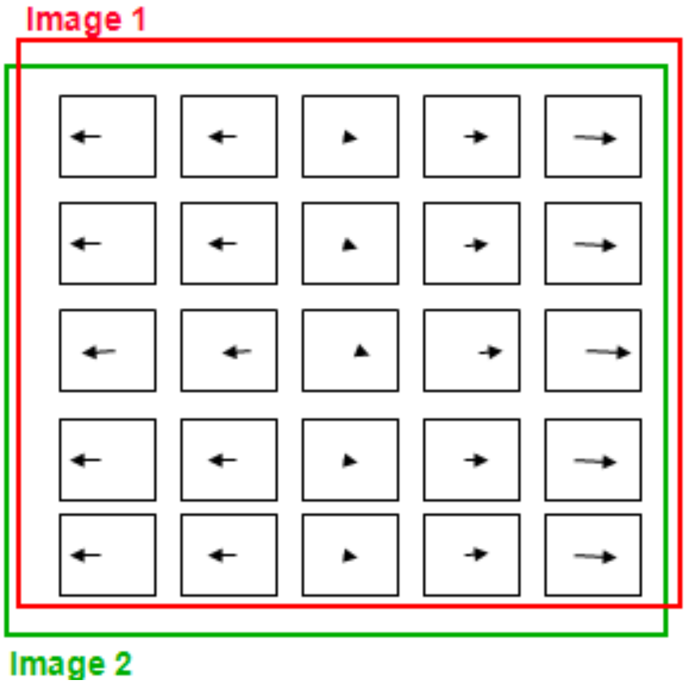
(See practical work session)

Registration in practice – coarse registration

Image processing registration

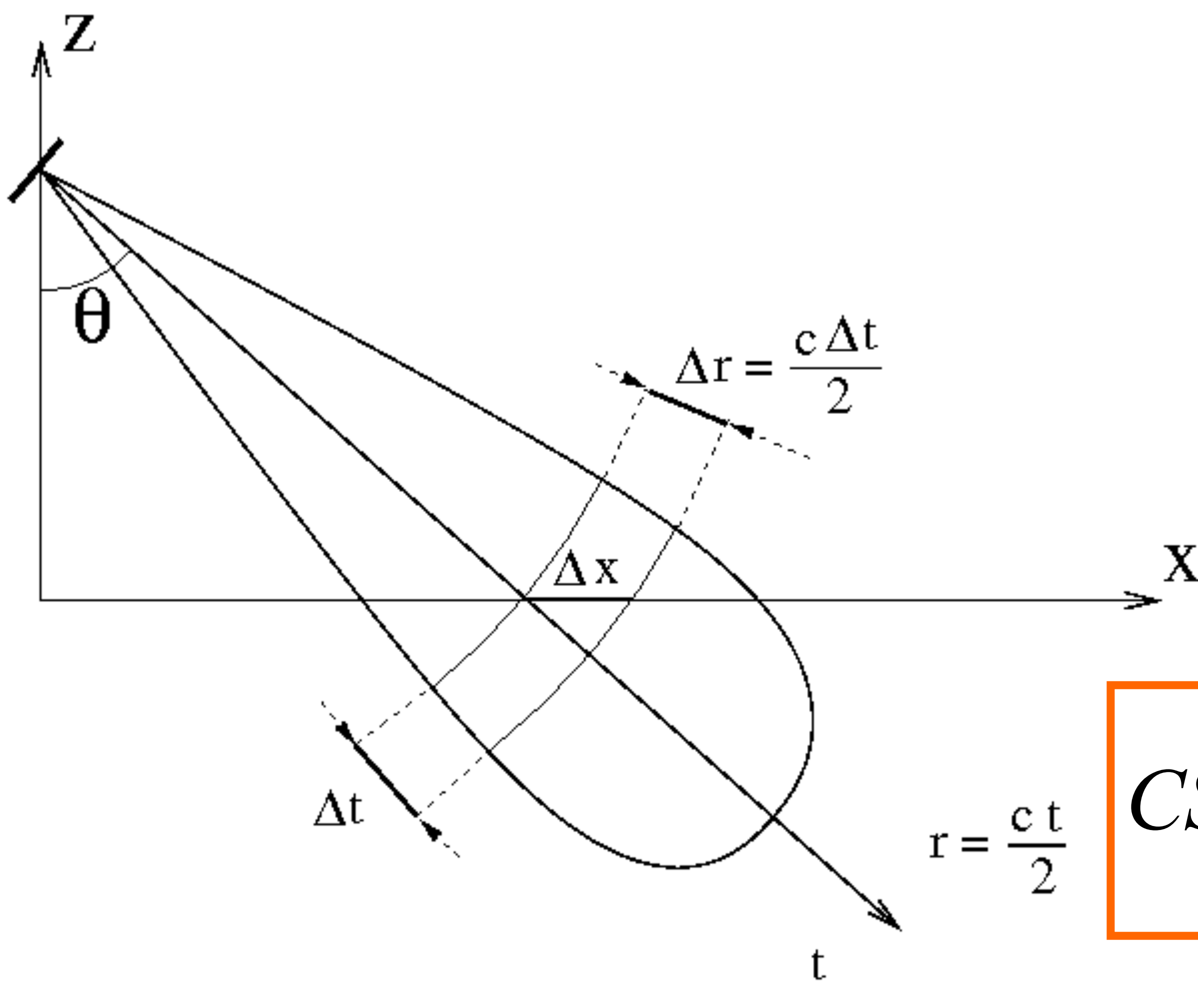
$$z_1 = A_1 e^{j\phi_1}$$
$$z_2 = A_2 e^{j\phi_2}$$

- The correlation peak gives the translation values between the master and the slave image
- Sub-pixelic registration: to be perfectly aligned the phase shift due to the difference of pixel size should be taken into account
- Two strategies:
  - Resampling of the slave image
  - Phase ramp correction= orbital fringe correction



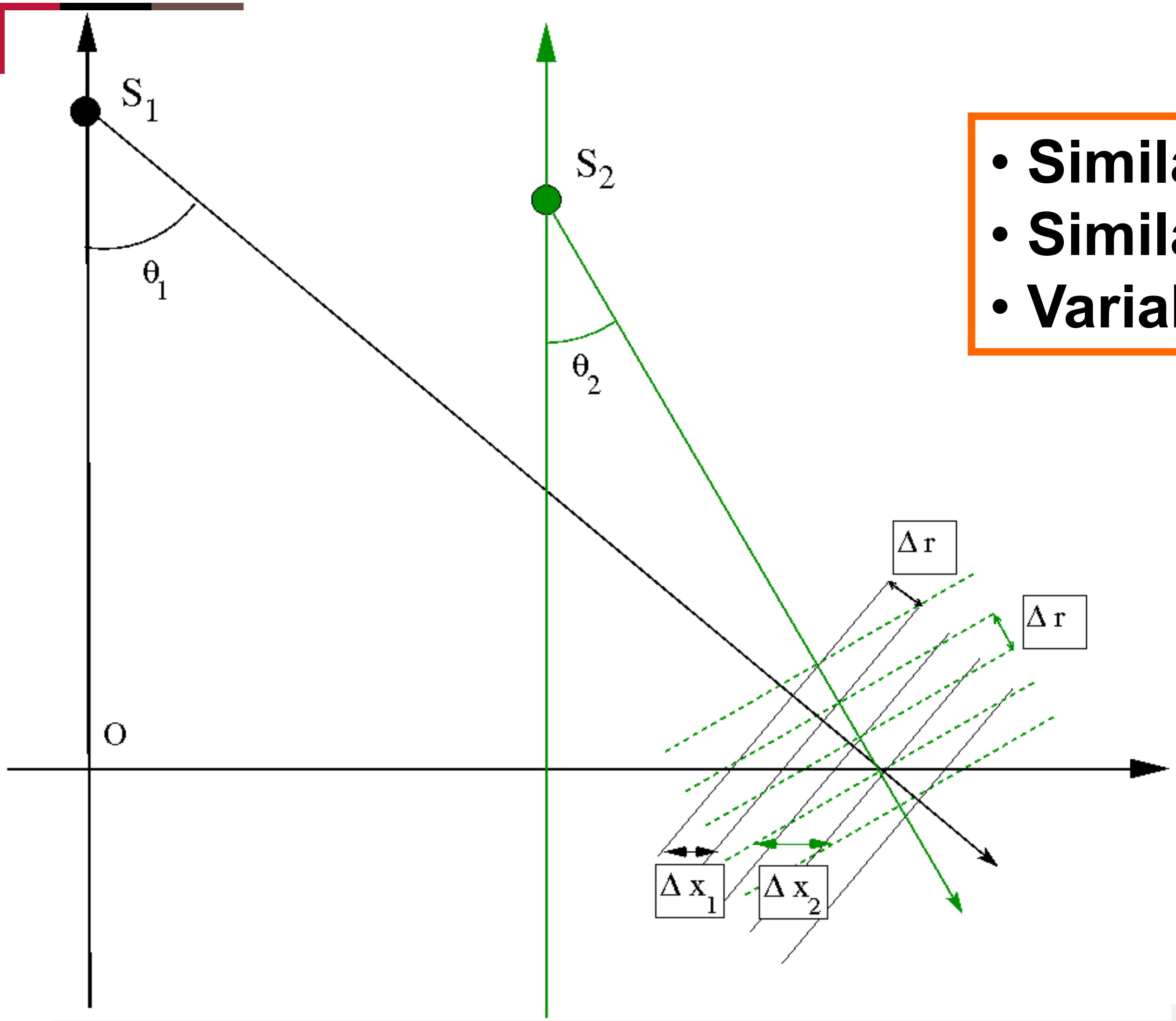
(See practical work session)

Registration in practice – fine registration



$$CS = \Delta x = \frac{\Delta r}{\sin(\theta)}$$

Flat earth: two incidence angles



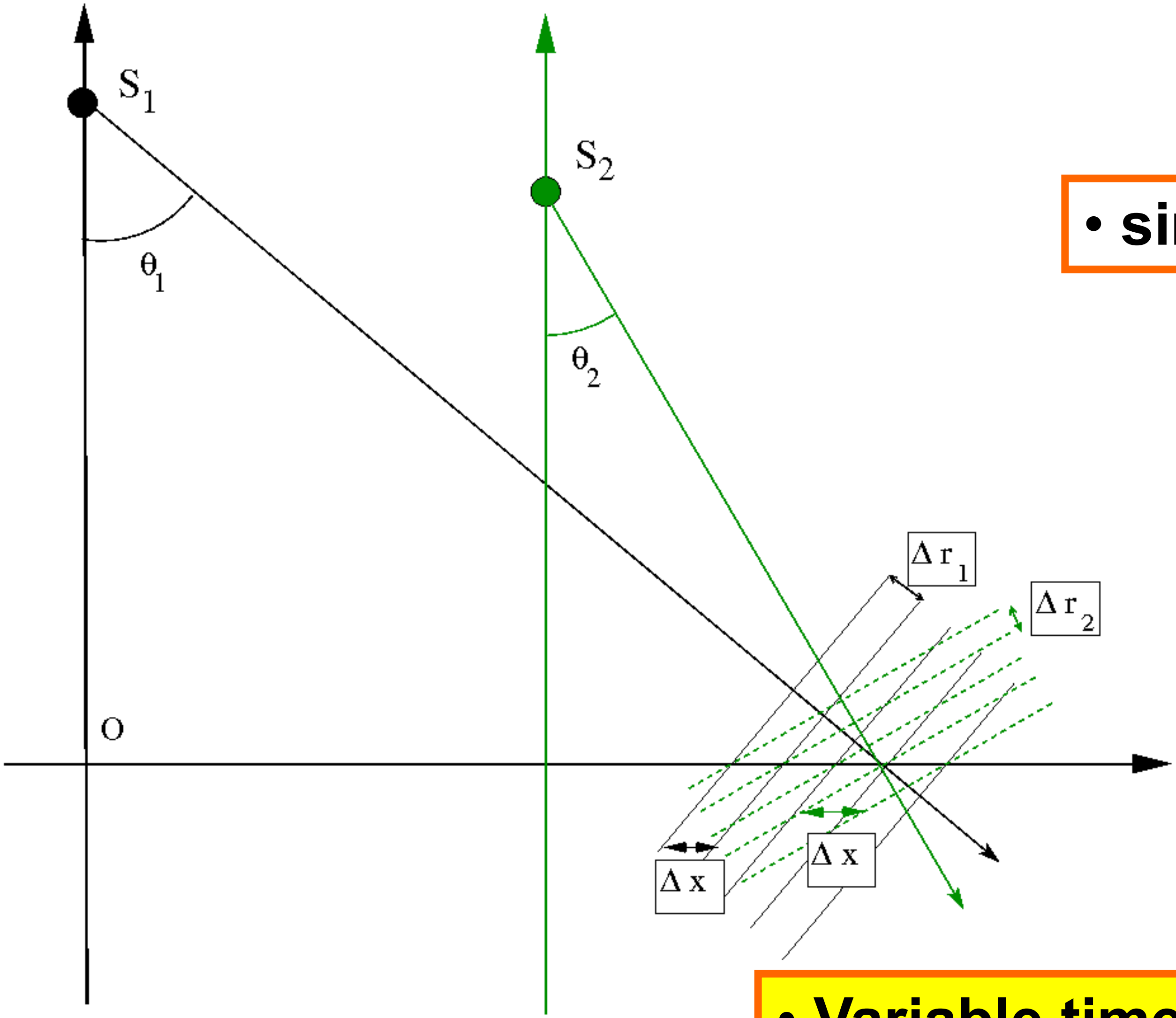
- Similar time cell
- Similar range cell
- Variable ground cells

$$\Delta x_1 = \frac{\Delta r}{\sin \theta_1}$$

$$\Delta x_2 = \frac{\Delta r}{\sin \theta_2}$$

- Re-sampling in time of one of the image to have similar ground cells

After re-sampling



• similar ground cells

$$\Delta r_1 = \Delta x \sin \theta_1$$
$$\Delta r_2 = \Delta x \sin \theta_2$$

• Variable time cells

Phase shift for one pixel

- **Phase contribution of flat earth**

$$\Delta r = \frac{c\Delta t}{2} \qquad \Delta x = \frac{\Delta r}{\sin\theta} = \frac{c}{2\,F_e\,\sin\theta}$$

- **Pixel size for master and slave images:**

$$\Delta x_M = \frac{c}{2\,F_e\,\sin\theta} \qquad \Delta x_S = \frac{c}{2\,F_e\,\sin(\theta+\delta\theta)}$$

- **Pixel size difference**

$$\Delta x_M - \Delta x_S = \frac{c}{2F_e}\left(\frac{1}{\sin\theta} - \frac{1}{\sin(\theta+\delta\theta)}\right)$$

Phase shift for one pixel

- **Pixel size difference and induced phase shift**

$$\Delta x_M - \Delta x_S = \frac{c}{2F_e}\left(\frac{1}{\sin\theta} - \frac{1}{\sin(\theta+\delta\theta)}\right)$$

$$\sin(\theta+\delta\theta) = \sin\theta\cos\delta\theta + \sin\delta\theta\cos\theta$$

$$\Delta x_M - \Delta x_S \approx \frac{c}{2F_e\sin\theta}\frac{\sin\delta\theta\cos\theta}{\sin\theta}$$

$$\sin\delta\theta = \frac{B_\perp}{R}$$

$$\Delta_{CS} = \Delta x_M - \Delta x_S \approx \Delta x \frac{B_\perp}{R}\frac{\cos\theta}{\sin\theta}$$

$$\Delta_R = \Delta_{CS}\sin\theta \approx \Delta x \frac{B_\perp}{R}\cos\theta$$

$$\boxed{\Delta\phi_{orb} = \frac{4\pi\Delta_R}{\lambda} = \frac{4\pi B_\perp}{\lambda R}\cos\theta\Delta x}$$

Phase shift for one pixel

- **Phase contribution due to uncorrected pixel size difference between the two sensors (flat earth)**

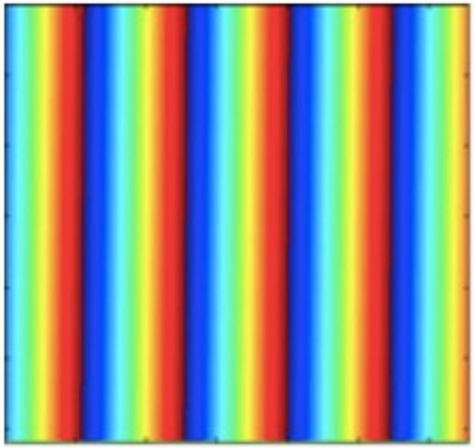
$$\Delta\phi_{orb} = \frac{4\pi\Delta_R}{\lambda} = \frac{4\pi B_\perp}{\lambda R}\cos\theta\Delta x$$

  - Can be computed using the sensor parameters
  - Create fringes in the range direction = orbital fringes are parallel to the track
  - To correct the orbital fringes:
    - compute the phase ramp

$$z_{orb}(n) = \mathrm{e}^{jn\Delta\phi_{orb}}$$

    - Correct the phase shift

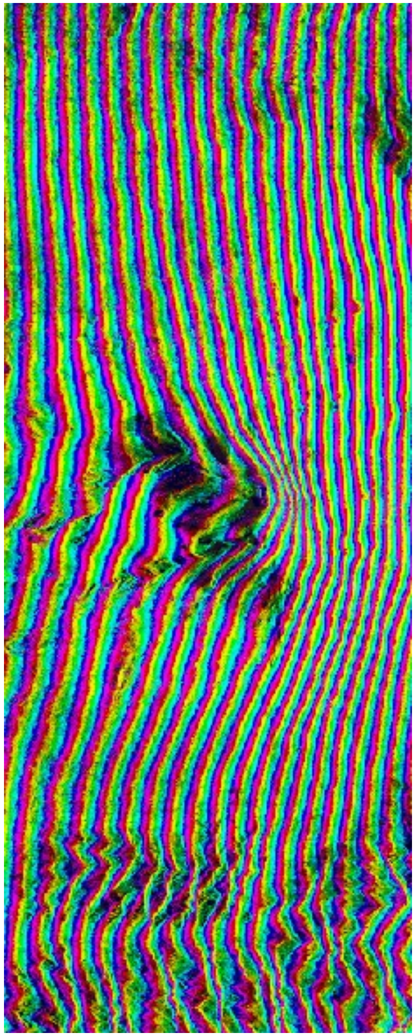
$$z_s^c(n) = z_s(n)\mathrm{e}^{jn\Delta\phi_{orb}}$$

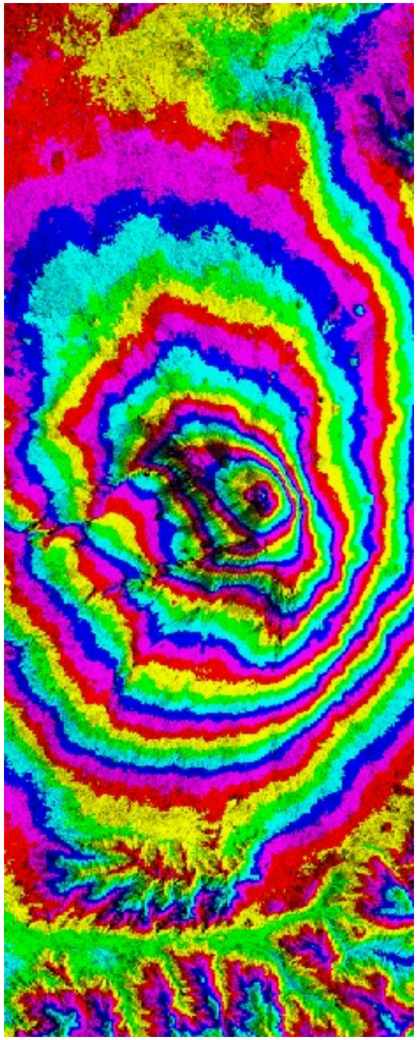


TELECOM ParisTech

Example of orbital fringes

$$z_m z_s^*$$



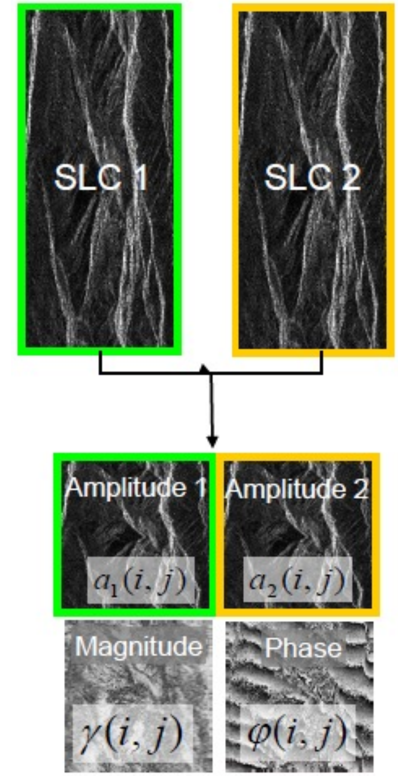


$$z_m z_s^{c*}$$

Interferometry – Main steps

- **Processing chain**
  - Acquisition of 2 SAR images in interferometric configuration
  - Fine registration of the 2 images
  - Computation of the phase difference
  - Phase unwrapping

Computation of phase difference



- **Two finely registered complex images:**

$$z_1(m,n) = A_1(m,n)e^{i\phi_1(m,n)}$$

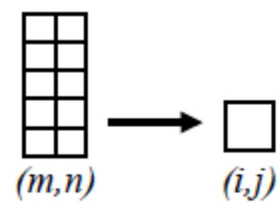
$$z_2(m,n) = A_2(m,n)e^{i\phi_2(m,n)}$$

- **Hermitian product**

$$z_1(m,n)z_2^*(m,n) = A_1(m,n)A_2(m,n)\exp(\phi_1(m,n)-\phi_2(m,n))$$

- **Interferometric product (multi-look)**

$$\boxed{\gamma(i,j)e^{i\phi(i,j)} = \frac{\sum\limits_{(m,n)} z_1(m,n)z_2^*(m,n)}{\sqrt{\sum\limits_{(m,n)} |z_1(m,n)|^2}\sqrt{\sum\limits_{(m,n)} |z_2(m,n)|^2}}}$$



  - Assume local stationarity

Interferometric product

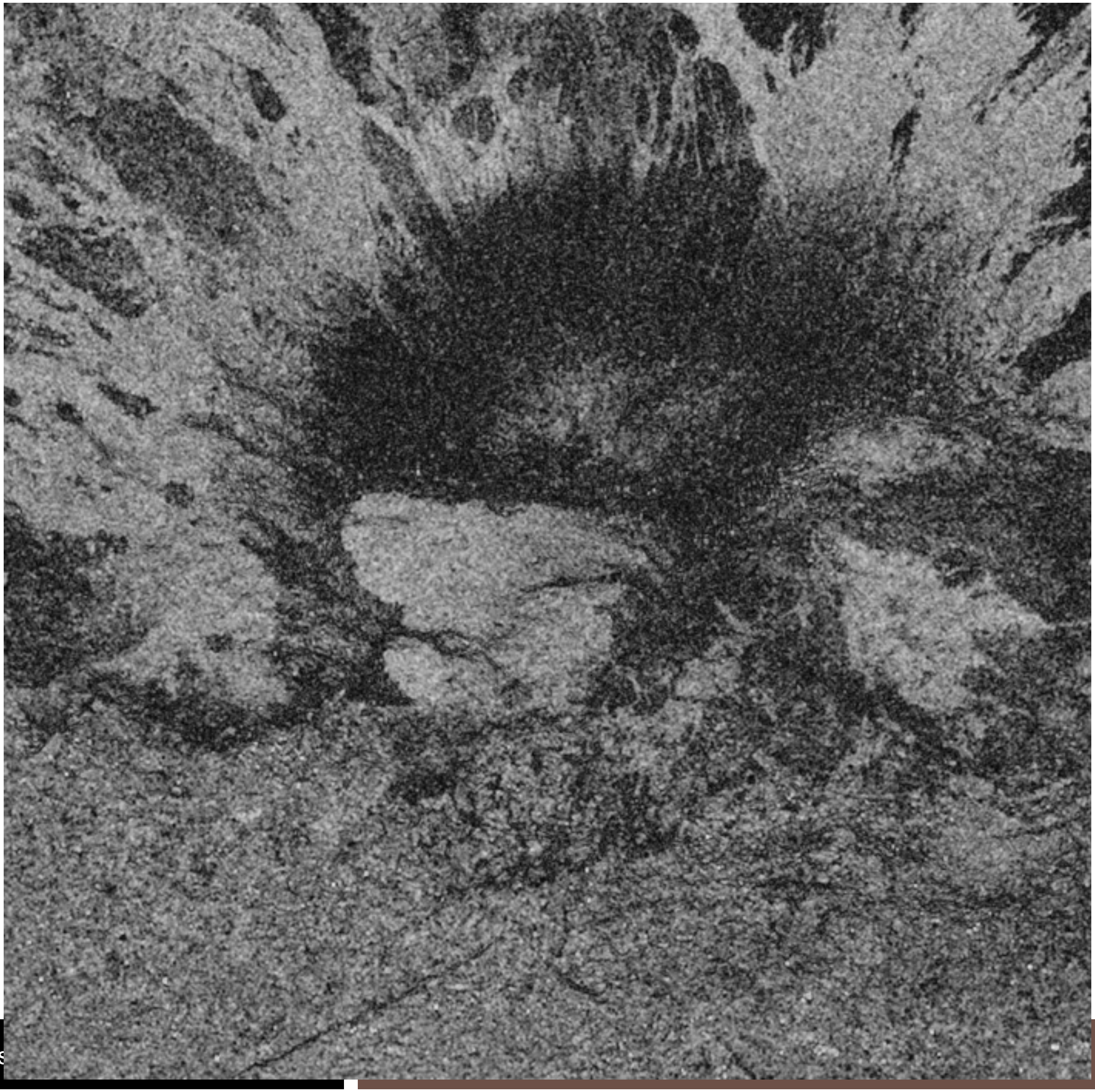
- **Interferometric phase**
  - Less noisy when large window but loss of resolution

- **Interferometric coherence**
  - In [0,1]
  - High coherence: similar complex values = reliable interferometric phase information
  - Low coherence: variable complex values (temporal changes, no signal – shadow / smooth areas, high difference of incidence angles, atmospheric conditions, …)

- **Interferometric filtering**
  - Replace the square window averaging by sample selection

Example of interferometric coherence

Mount ETNA
ERS1/2 Tandem
Mission



Some parameters

Altitude of ambiguity

- Wrapped phase :

$$\boxed{\psi_{1,2} = \frac{4\pi B_{\perp_{1,2}}}{R\sin(\theta)\lambda}h}$$

$$\psi_{1,2} = \alpha_{geom_{1,2}}h$$

- Elevation causing one topographic fringe

$$\psi_{1,2} = 2\pi$$

$$\boxed{h_{amb} = \frac{\lambda R\sin\theta}{2B_{\perp_{1,2}}}}$$

- Increase of the baseline : decrease of the altitude of ambiguity :
  - increase the topographic sensitivity
  - More difficult to unwrapp !

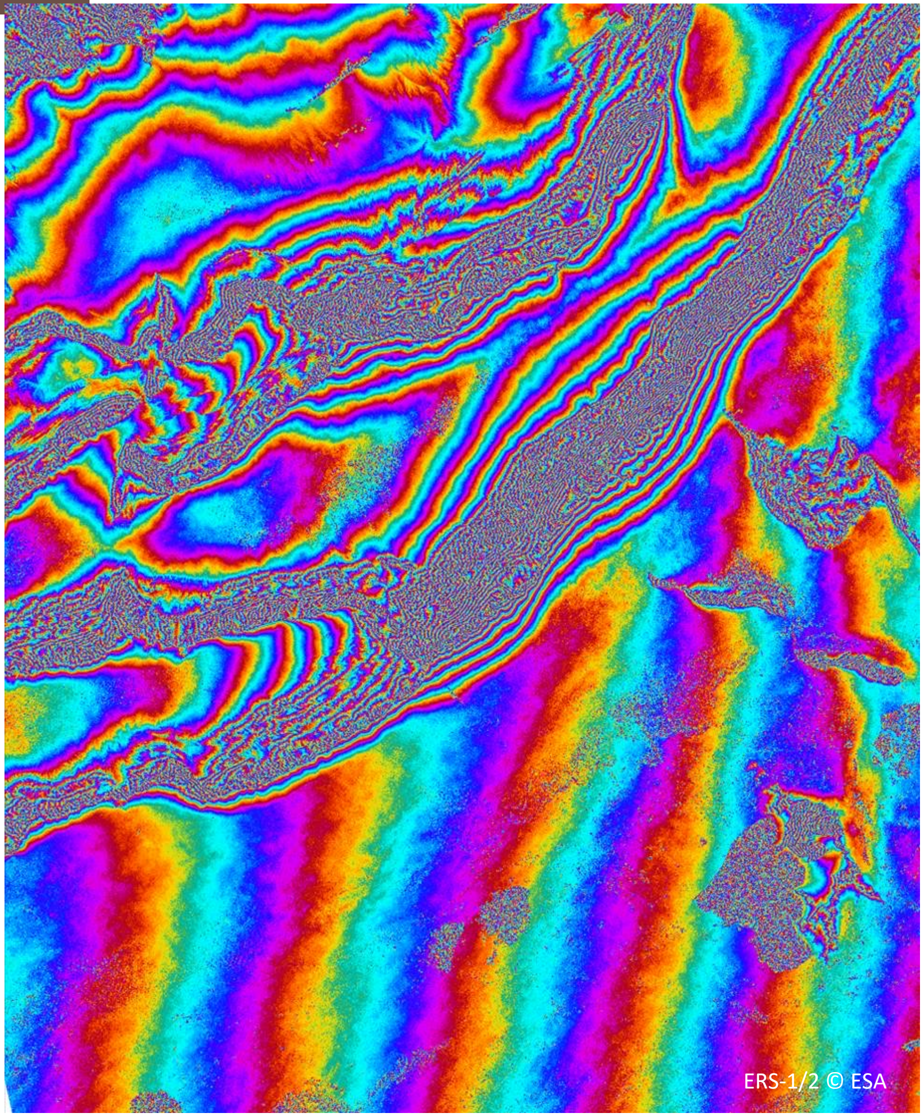
$$\sigma_h = \sigma_\psi \frac{h_{amb}}{2\pi}$$

ERS SAR Image

Bachu, China

approx. 100 km × 80 km

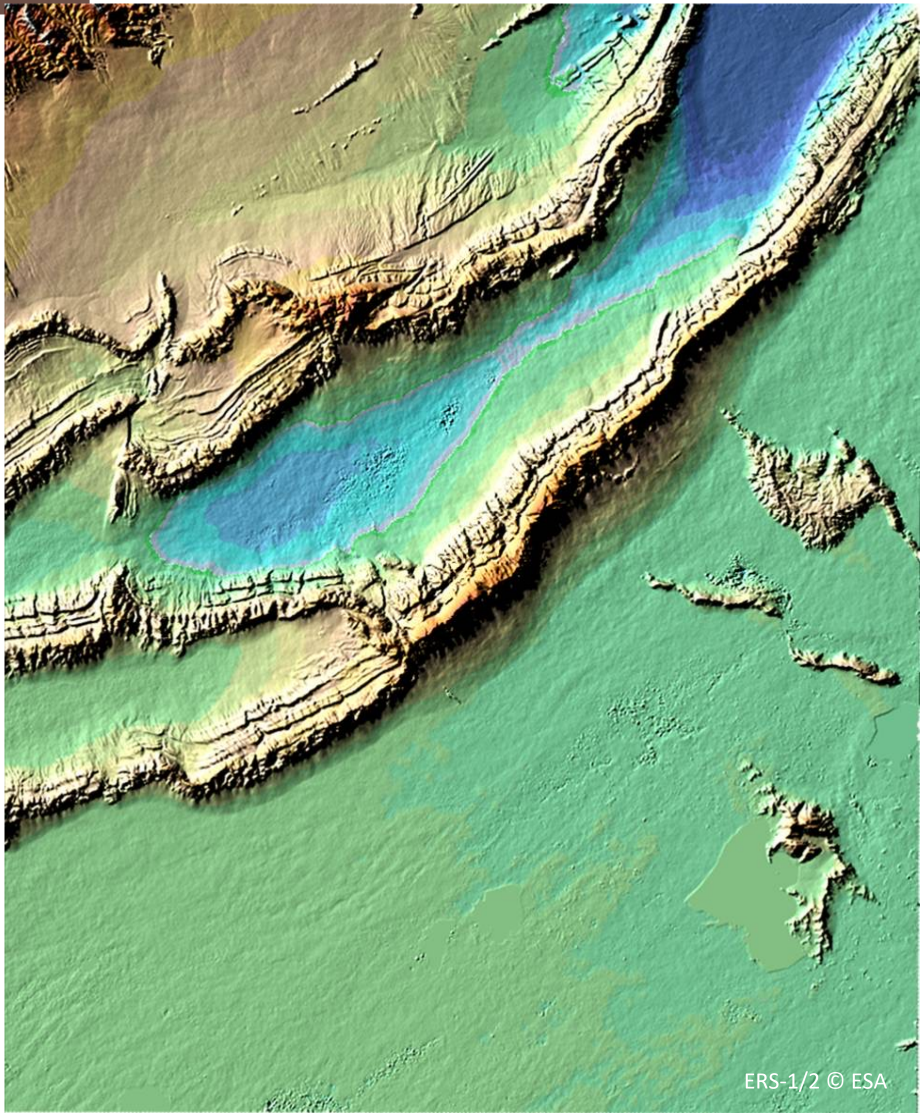
Interferometric Phase



Bachu, China

approx. 100 km × 80 km

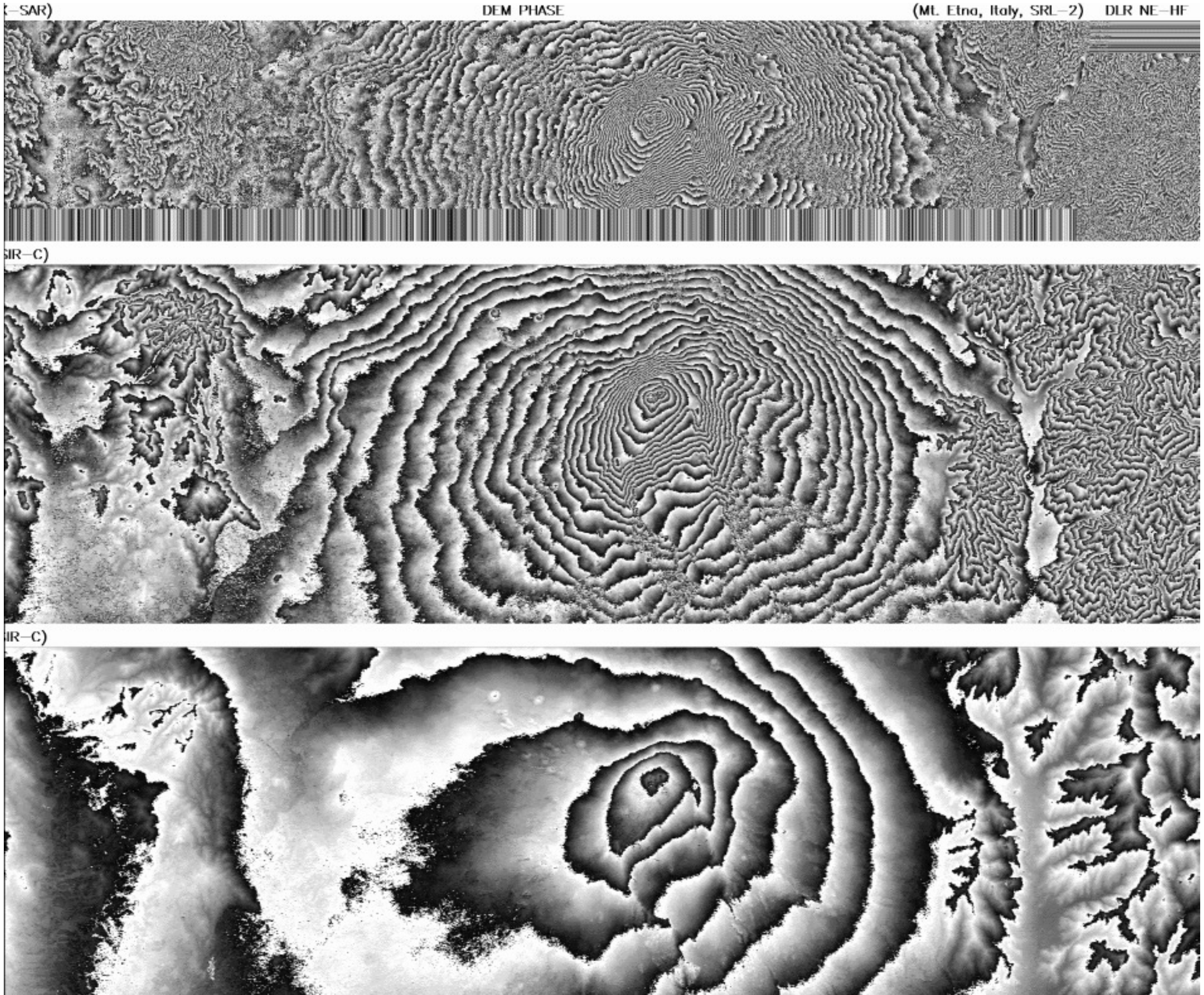
InSAR DEM (ERS-1/2)



Bachu, China

approx. 100 km × 80 km

Interferometric Sensitivity as a Function of Wavelength



$$h_{amb} = \frac{R \sin(\theta)\lambda}{2B_{\perp_{1,2}}}$$

X-band

C-band

L-band

Fig.: Mt. Etna
data: SRL-2 (© DLR)

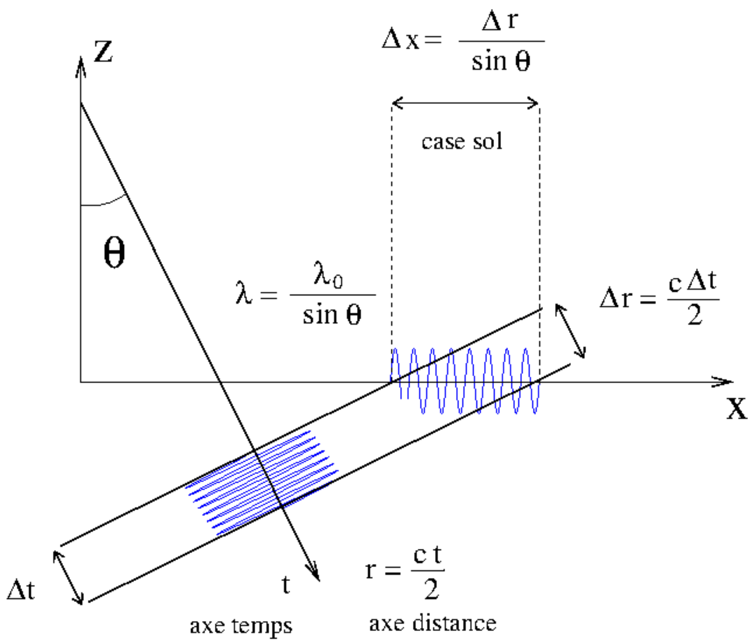
Some parameters

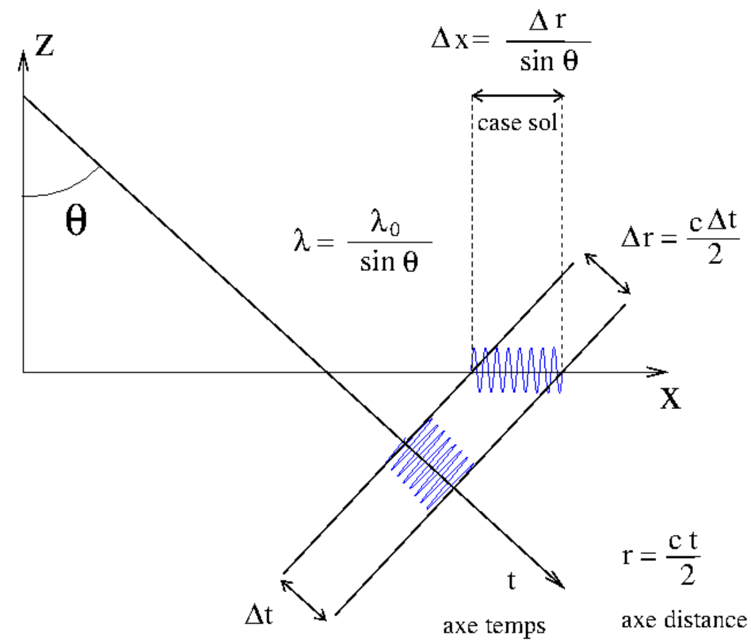
- **Altitude of ambiguity**
  - The largest the baseline : the best the sensitivity

$$\sigma_h = \sigma_\psi \frac{h_{amb}}{2\pi}$$

- **Critical orthogonal baseline**
  - The largest the baseline : the noisiest the phase
  - Difference of incidence angles: geometric decorrelation (the scatterers are seen with different viewing angles)

Critical baseline :





- **Same backscattering of the pixels**
- **⇒ angle difference should be limited**

$$B_\perp^{crit} = \frac{\lambda R}{2\cos\theta\Delta x} = \frac{\lambda R\tan\theta}{2\Delta r}$$

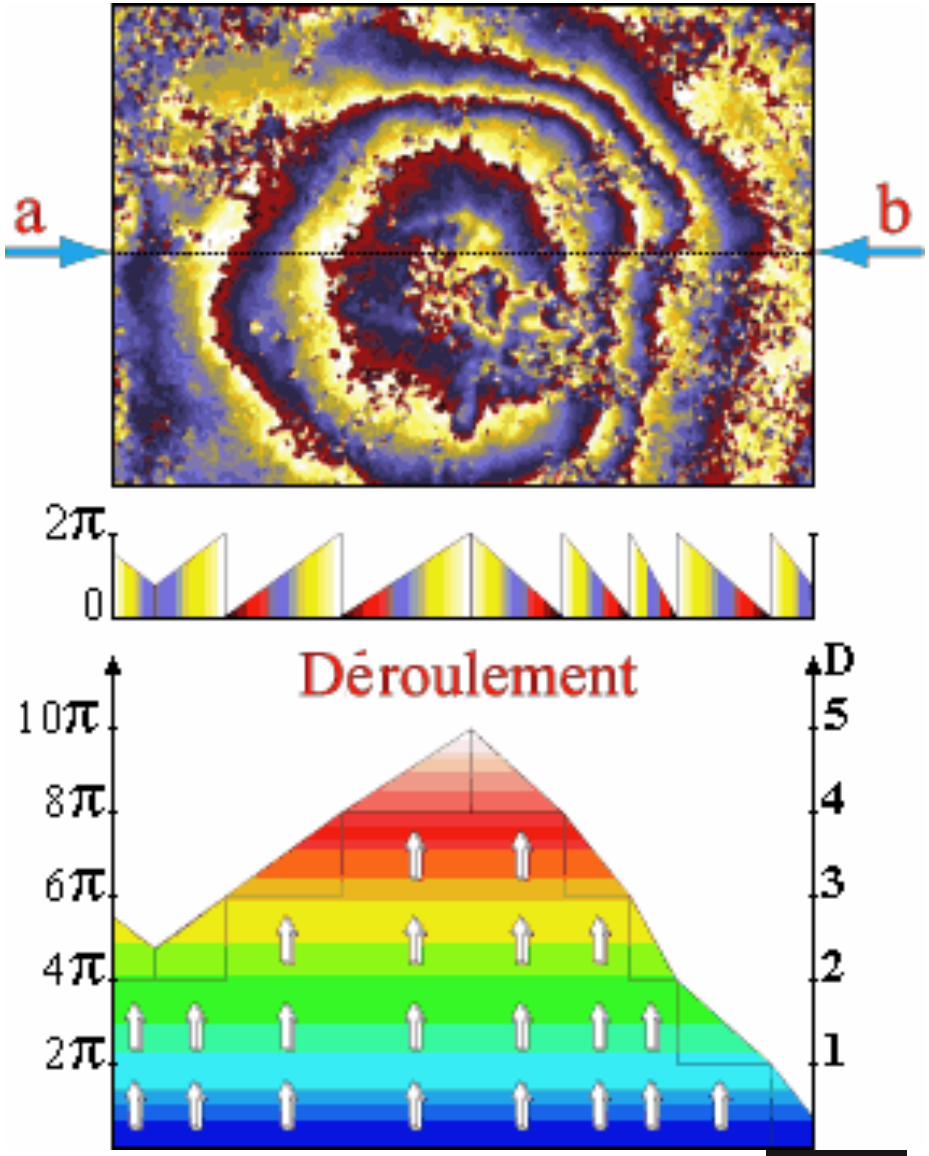
$$\Delta\phi_{orb} = 2\pi \iff \frac{4\pi B_\perp}{\lambda R}\cos\theta\Delta x = 2\pi$$

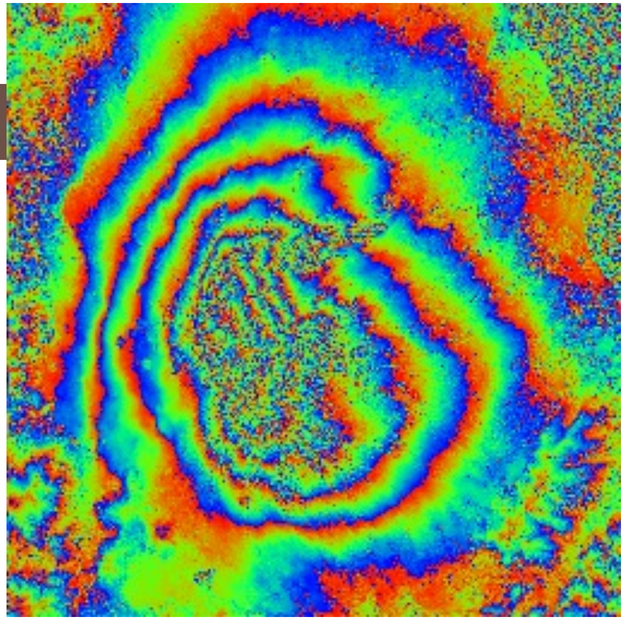
Interferometry – Main steps

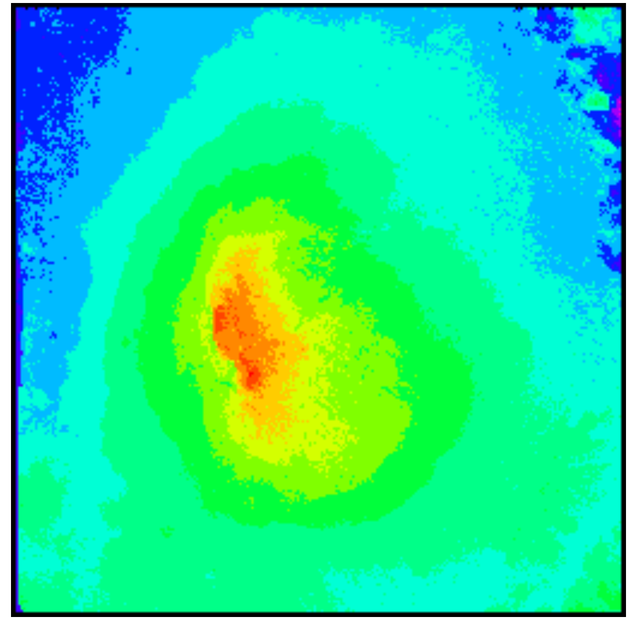
- **Processing chain**
  - Acquisition of 2 SAR images in interferometric configuration
  - Fine registration of the 2 images
  - Computation of the phase difference
  - Phase unwrapping

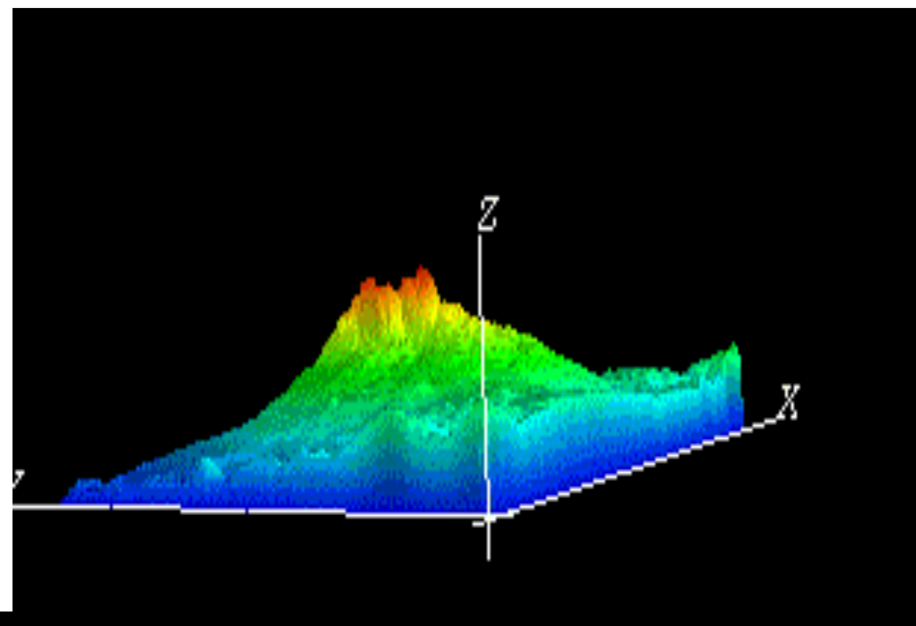
Phase unwrapping

$$\Phi(P) = \phi(P) + 2k\pi$$

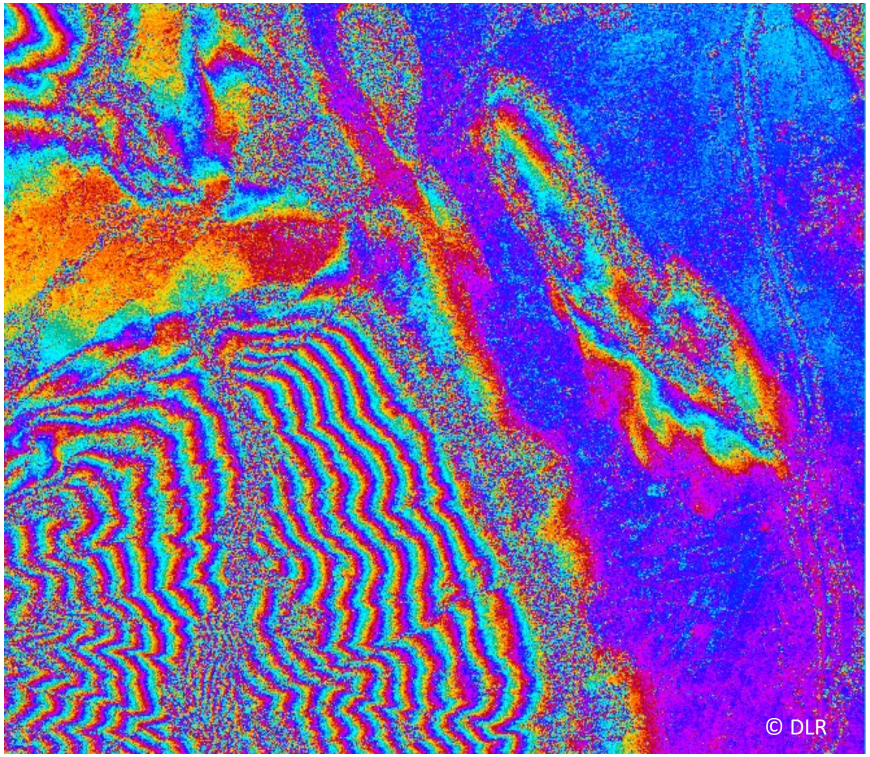


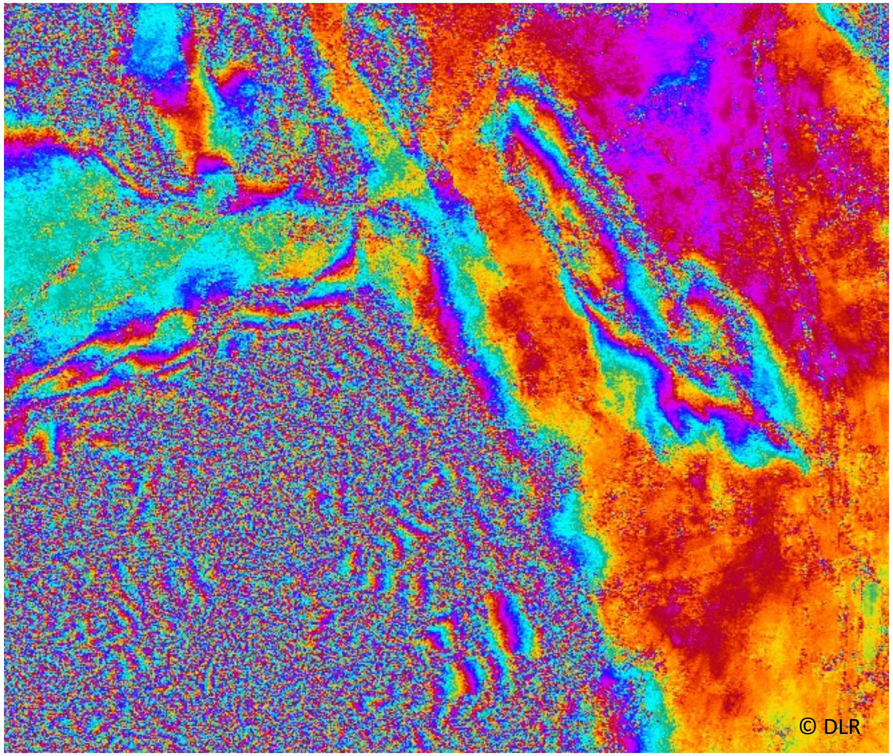





Z
X

Interferometric Phase is Ambiguous





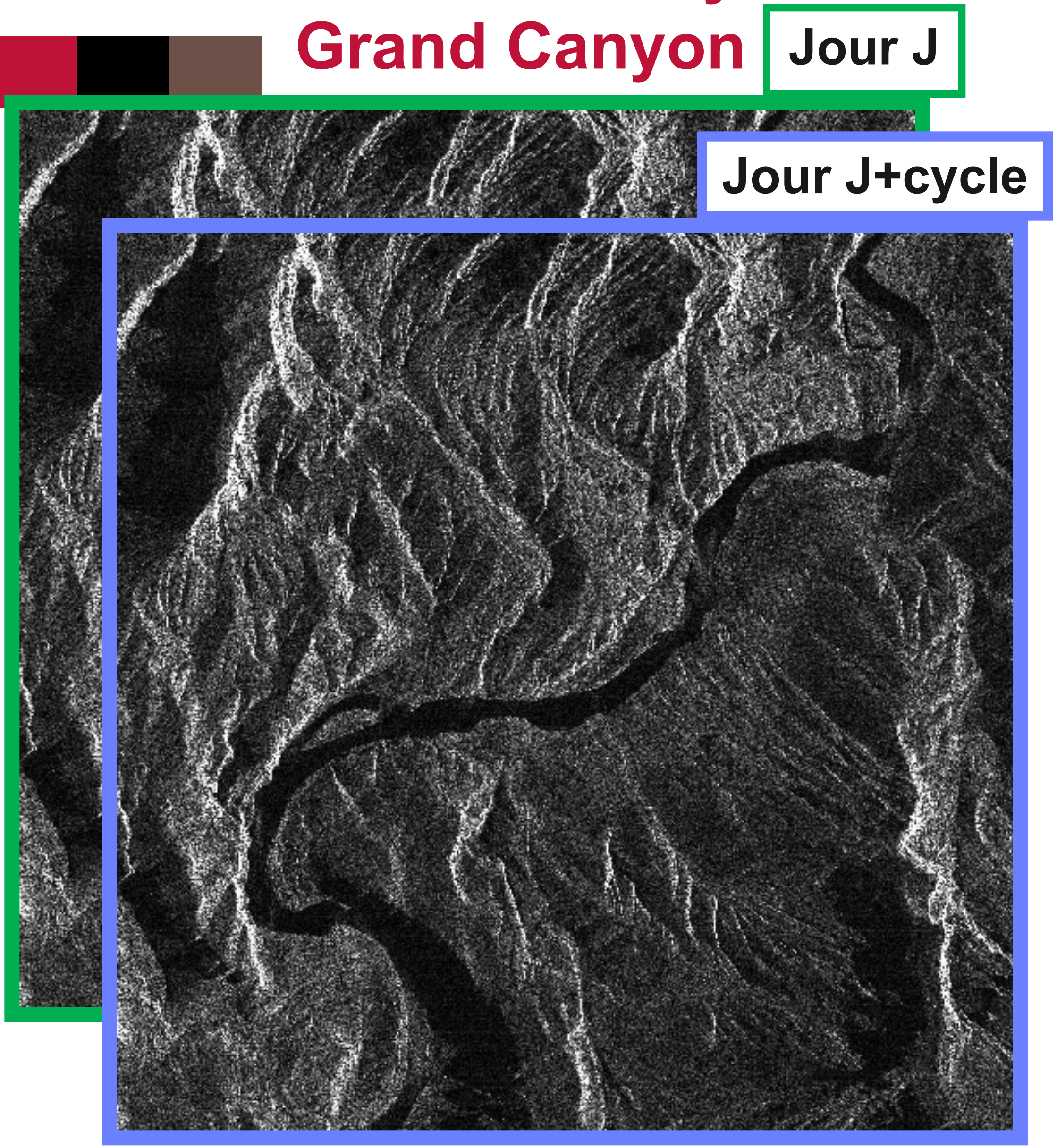
good fringe quality

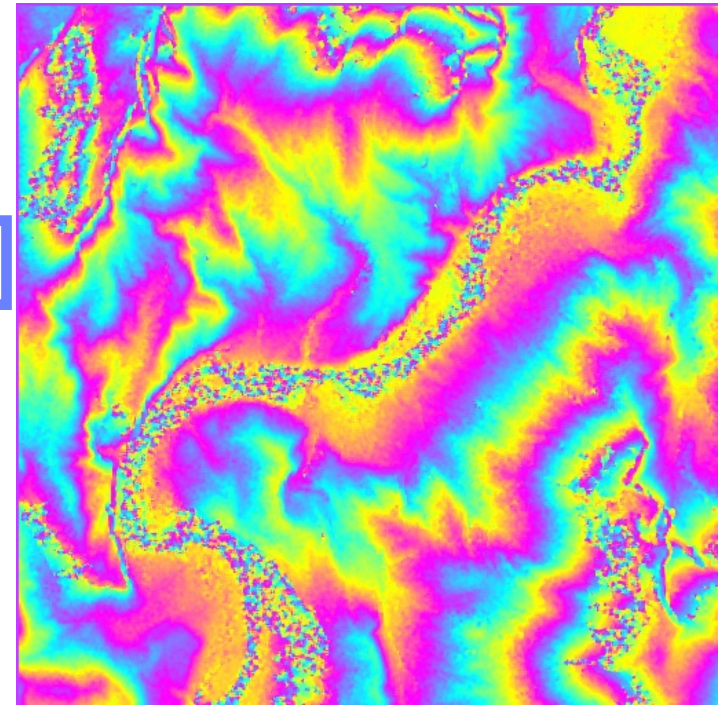
ERS-1/2, 13/14 Jan. 1996

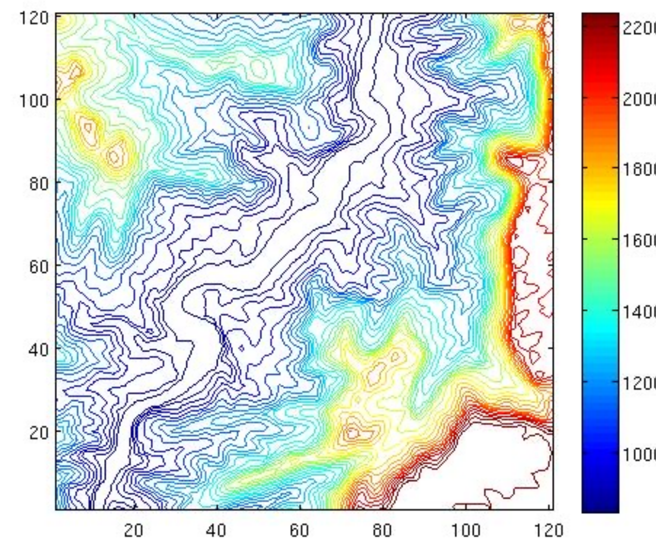
bad fringe quality

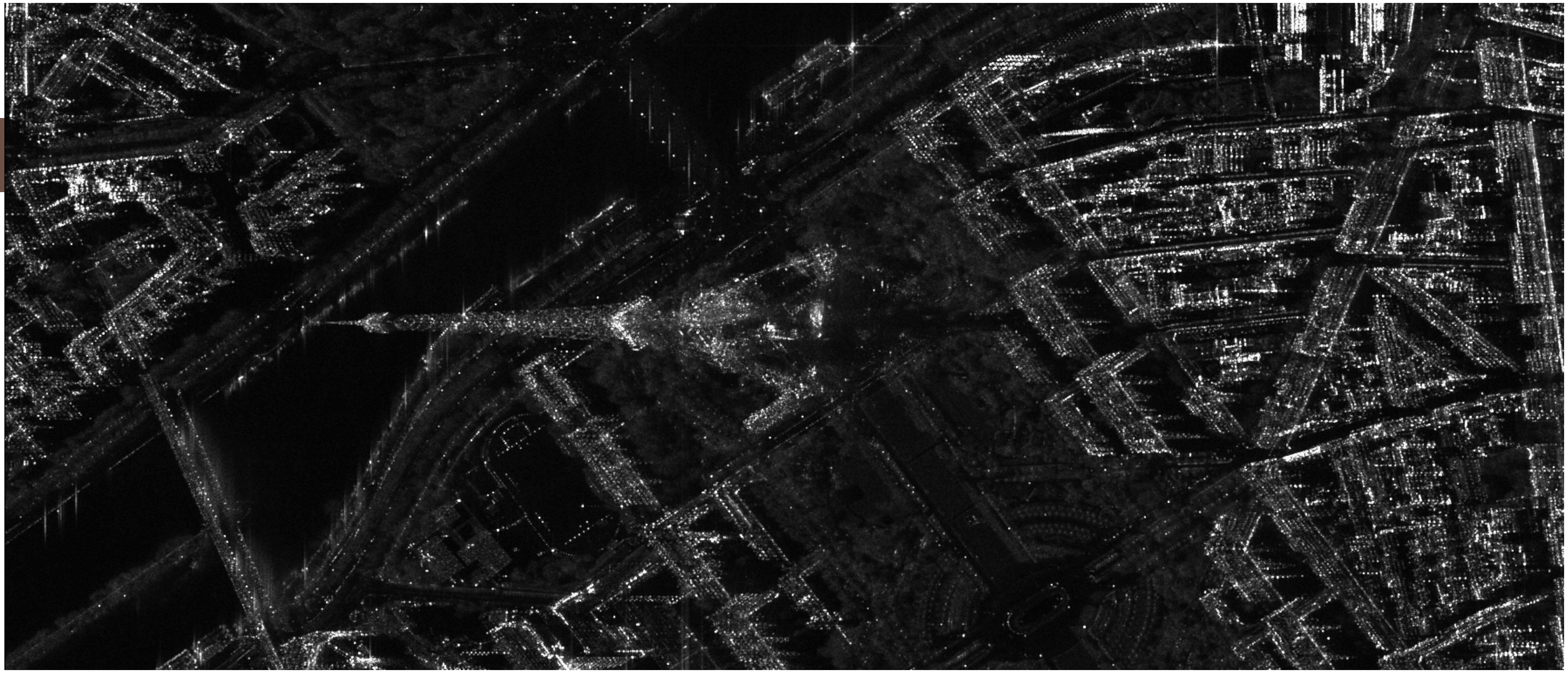
ERS-1/2, 23/24 March 1996

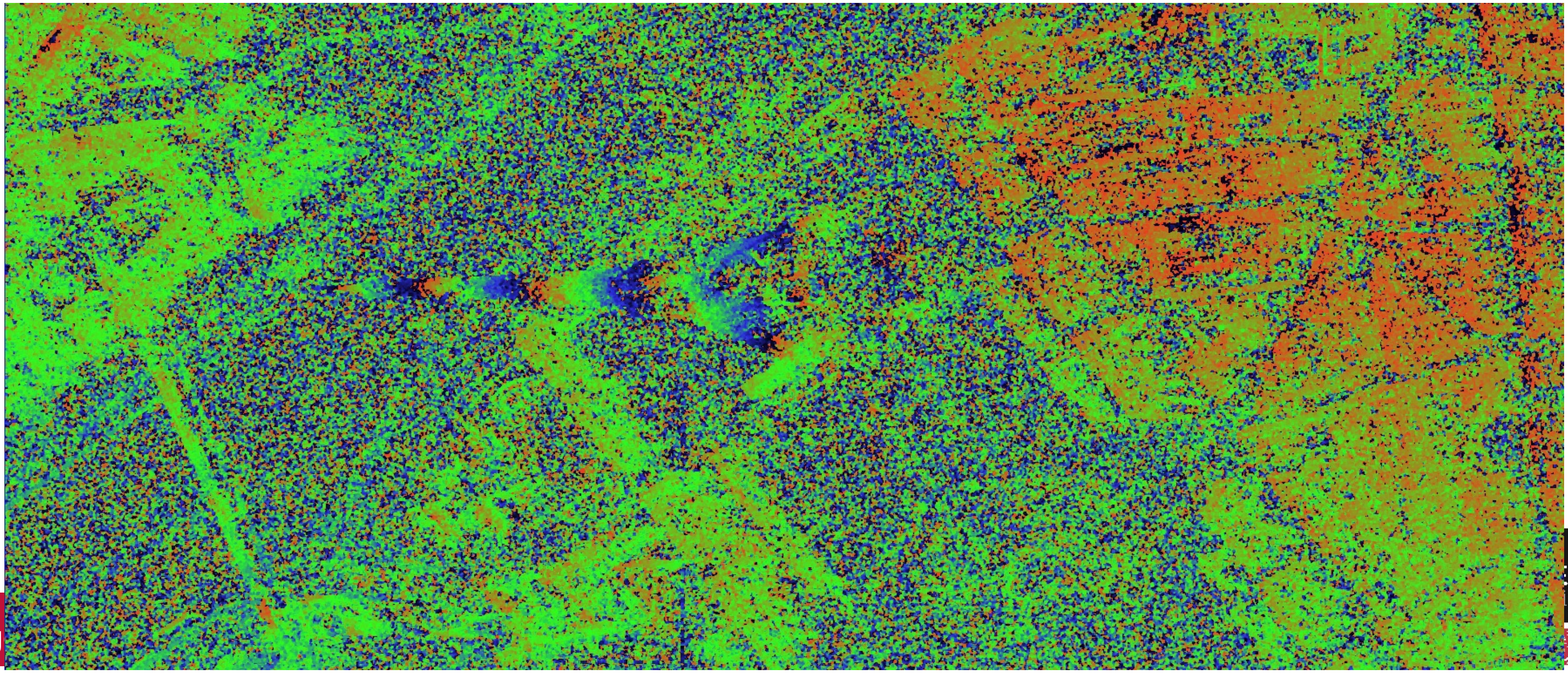
Interferometry
Grand Canyon





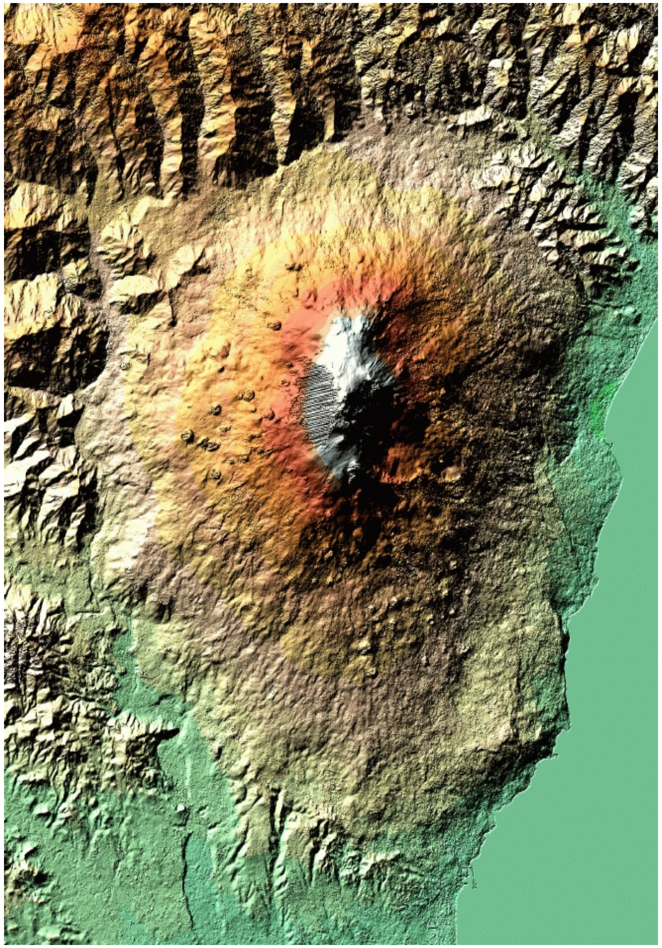






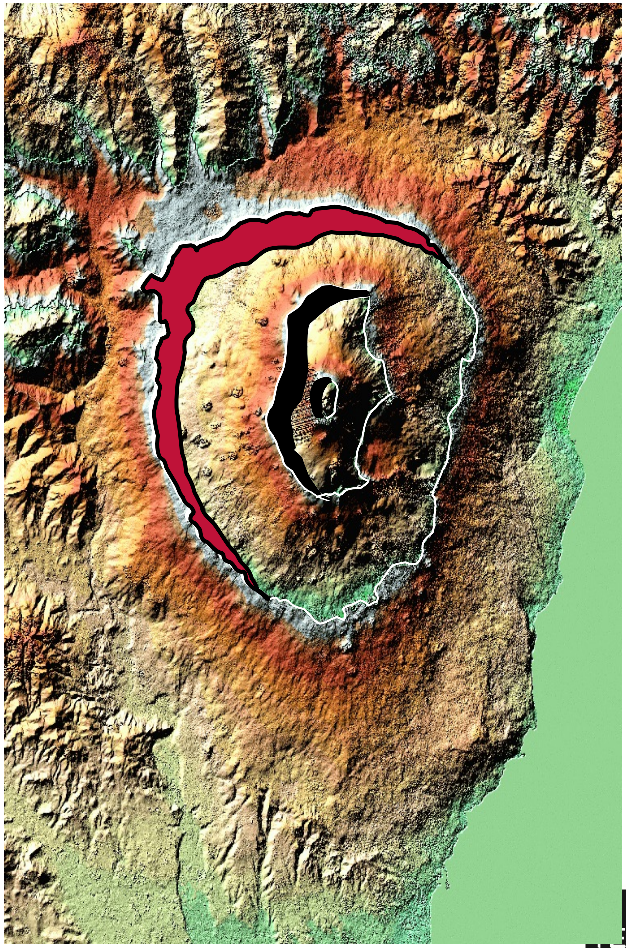
Find the "Most Likely" Solution

this is much more likely ...



Data: SRTM © DLR

... than this



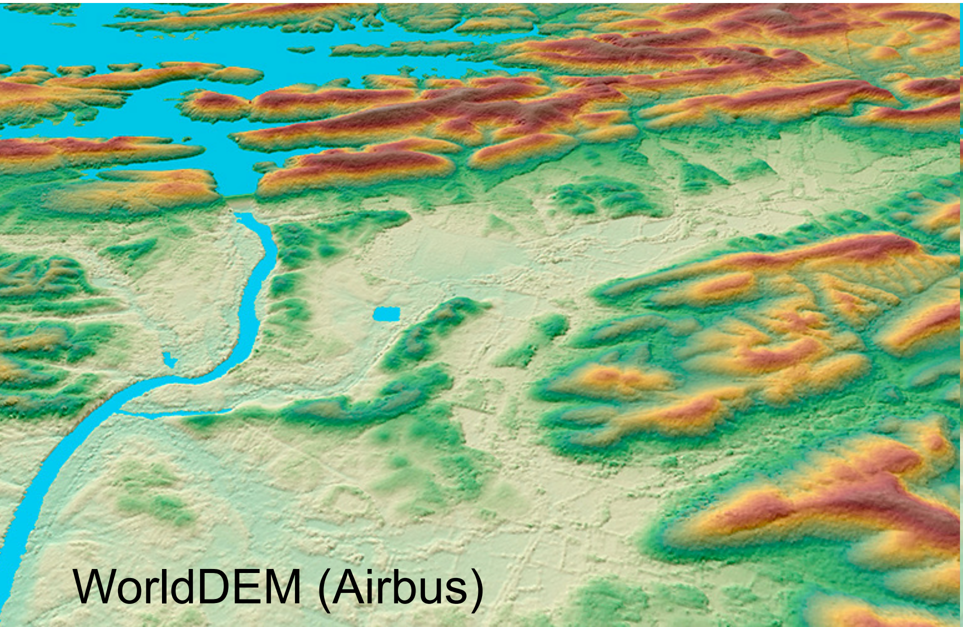
Data: SRTM © DLR

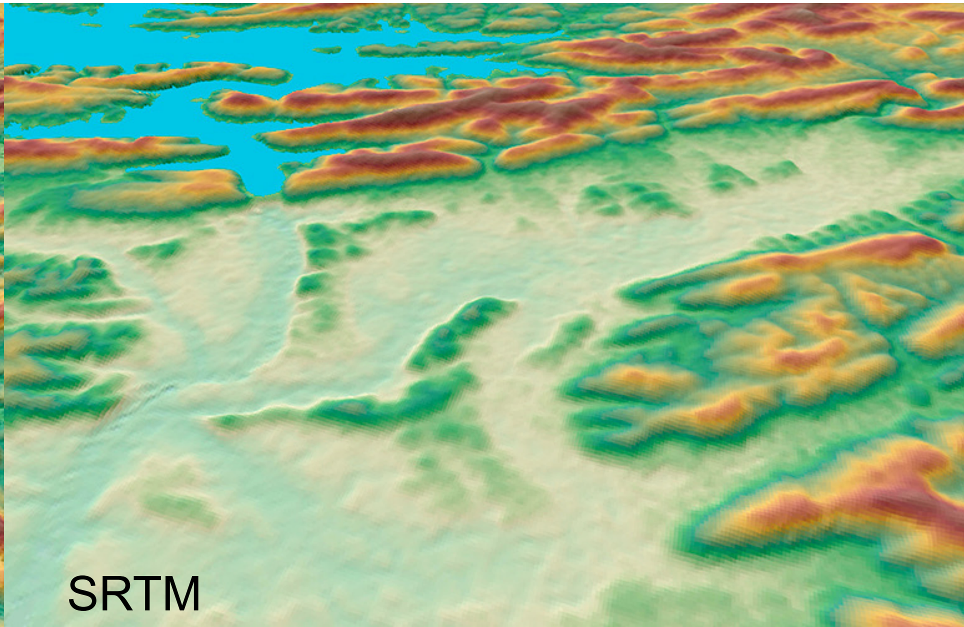
Unwrapping approaches

- **Local approaches**
  - Local unwrapping by adding the $2k\pi$ values
  - Problem : uncoherencies when unwrapping condition not fulfilled
- **Global approaches**
  - Global optimization of a functional (likelihood given by wrapped phase values + prior smoothness constraint)
- **Multi-channel / multi-frequency approaches**
  - Phase becomes non - ambiguous

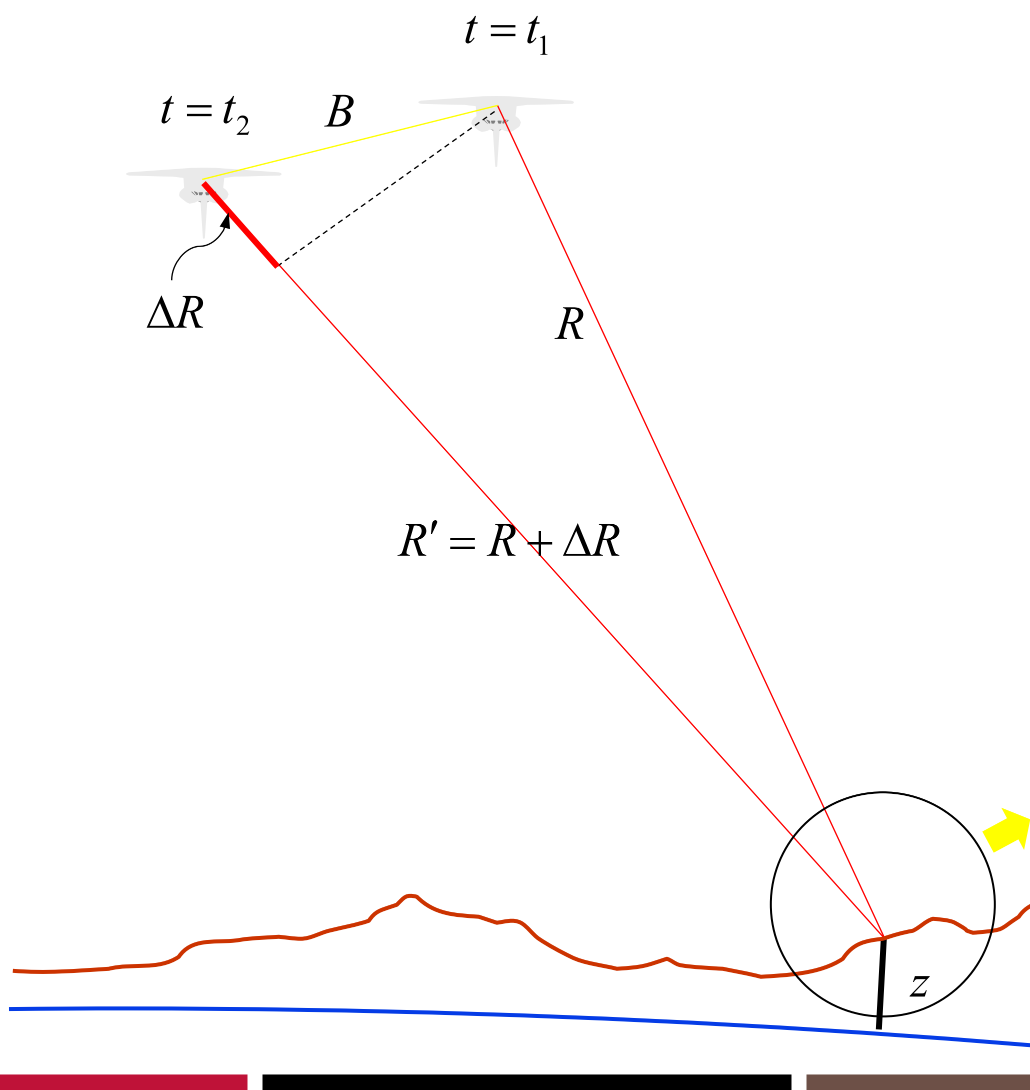
InSAR - DEM

Mission	mode	Planimetric accuracy	Altimetric accuracy
SRTM (2000)	Bande X Mono-pass interferometry	60m (30m)	16m abs. 10m rel.
TanDEM-X WorldDEM (2011)	Mono & multi pass interferometry	12m	4m abs. 2m rel.





Differential Interferometry



Interferometric phase:

$$\phi = \phi_{topo}(z; B) + \phi_{diff}$$

$$\phi_{diff} = \frac{4\pi}{\lambda} \Delta R_{diff}$$

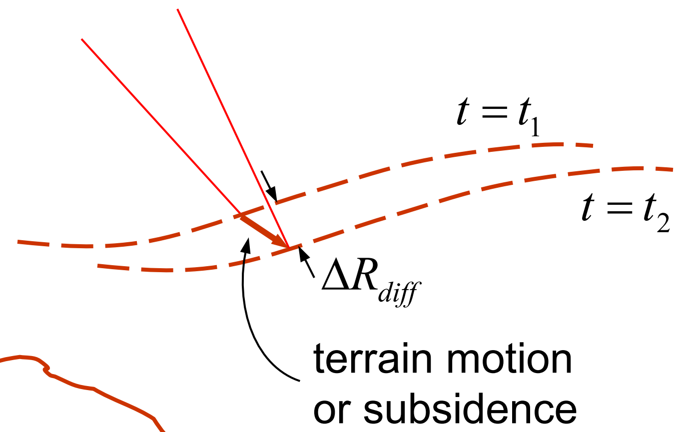
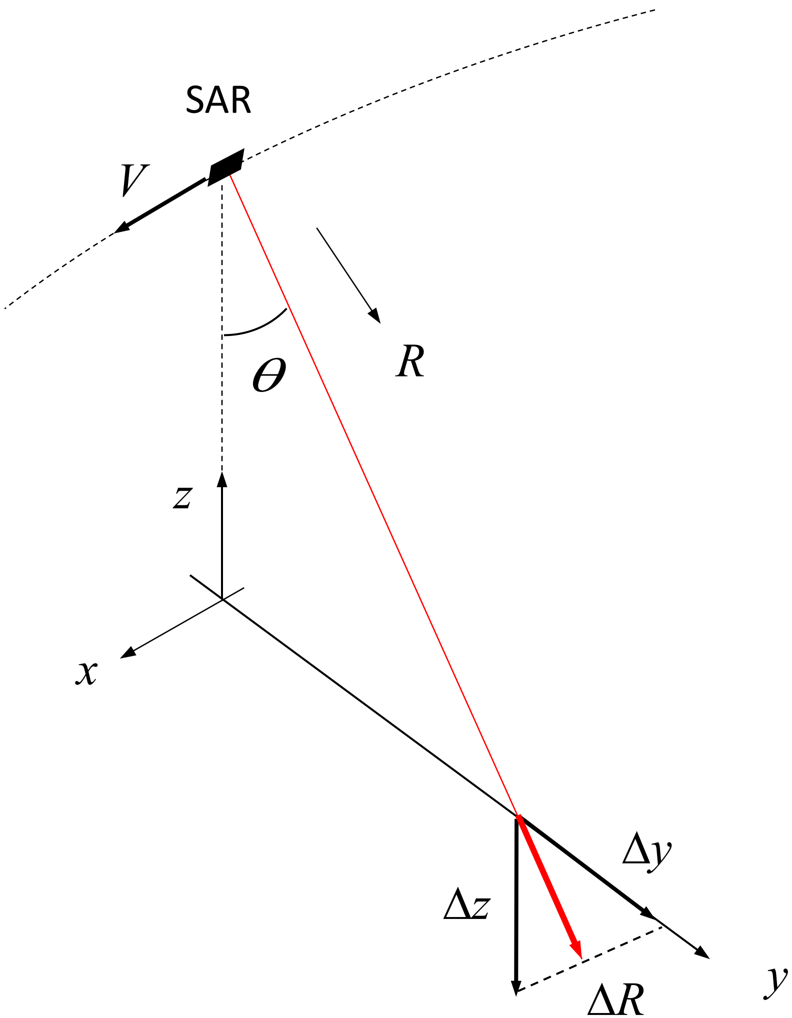


Fig.: © DLR

Sensitivity for Displacement



$$\psi_{t,t'} = \frac{4\pi\delta R}{\lambda}$$

$$\Delta R = \Delta y \sin\theta - \Delta z \cos\theta$$

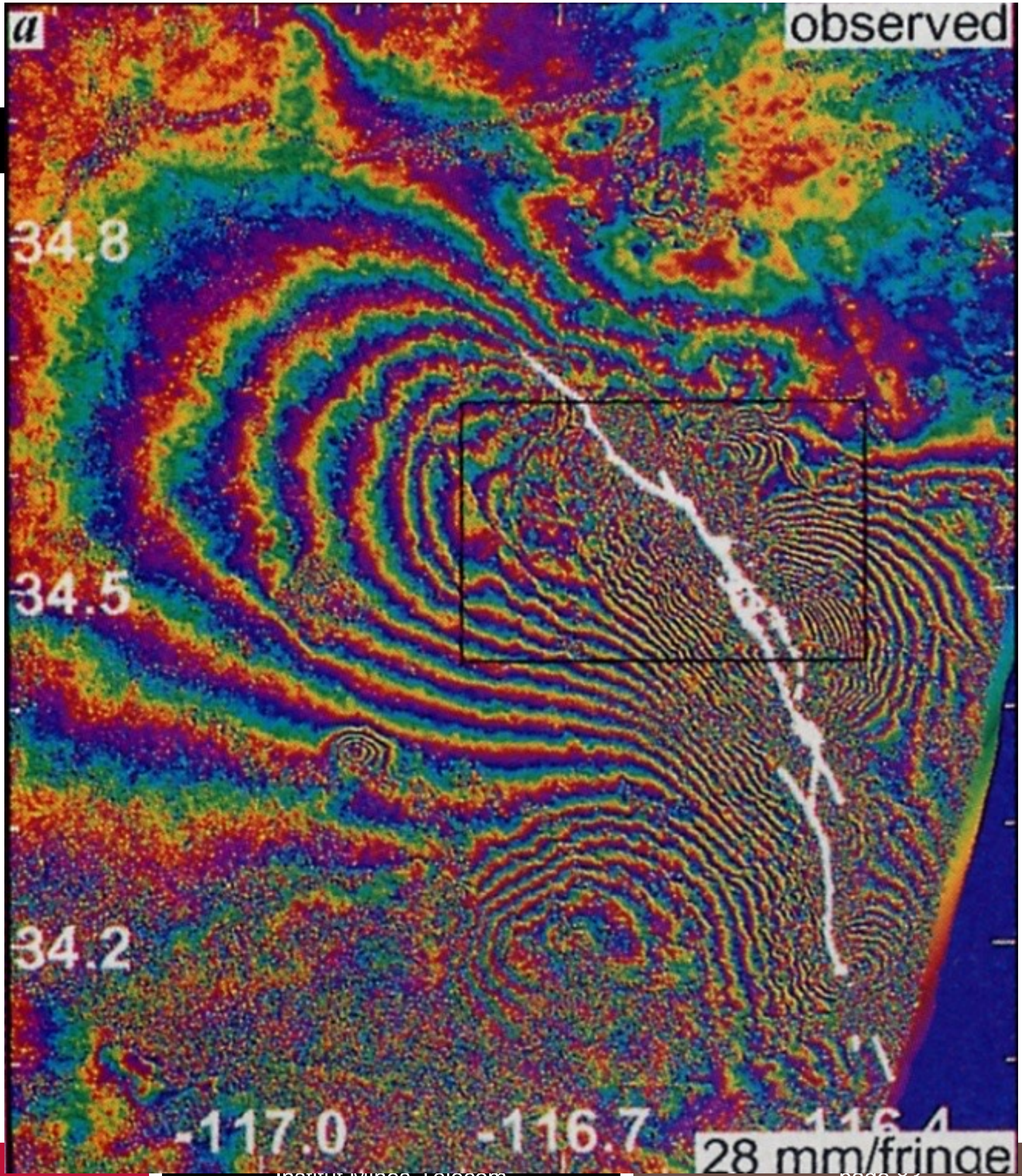
$$\psi_{t,t'} = 2\pi \iff \delta R = \frac{\lambda}{2}$$

for ERS:

1 fringe (2π) corresponds to

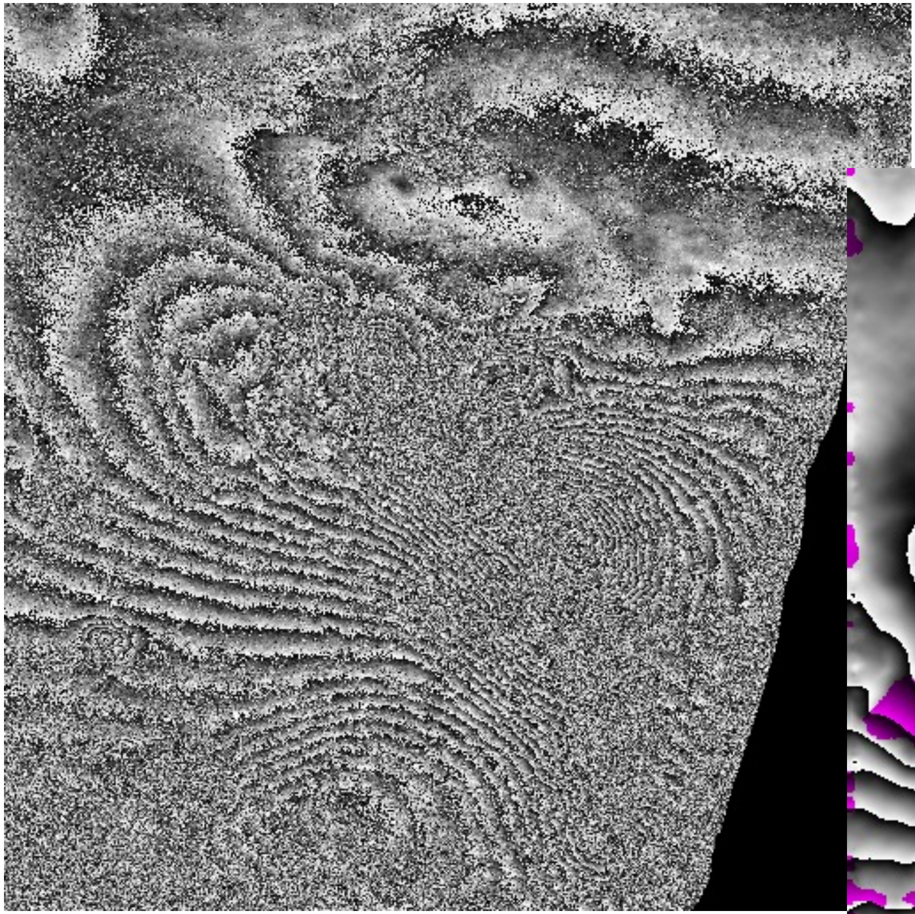
- **2.8 cm in R**
- **3.0 cm in z (e.g. subsidence)**
- **7.2 cm in y (motion)**

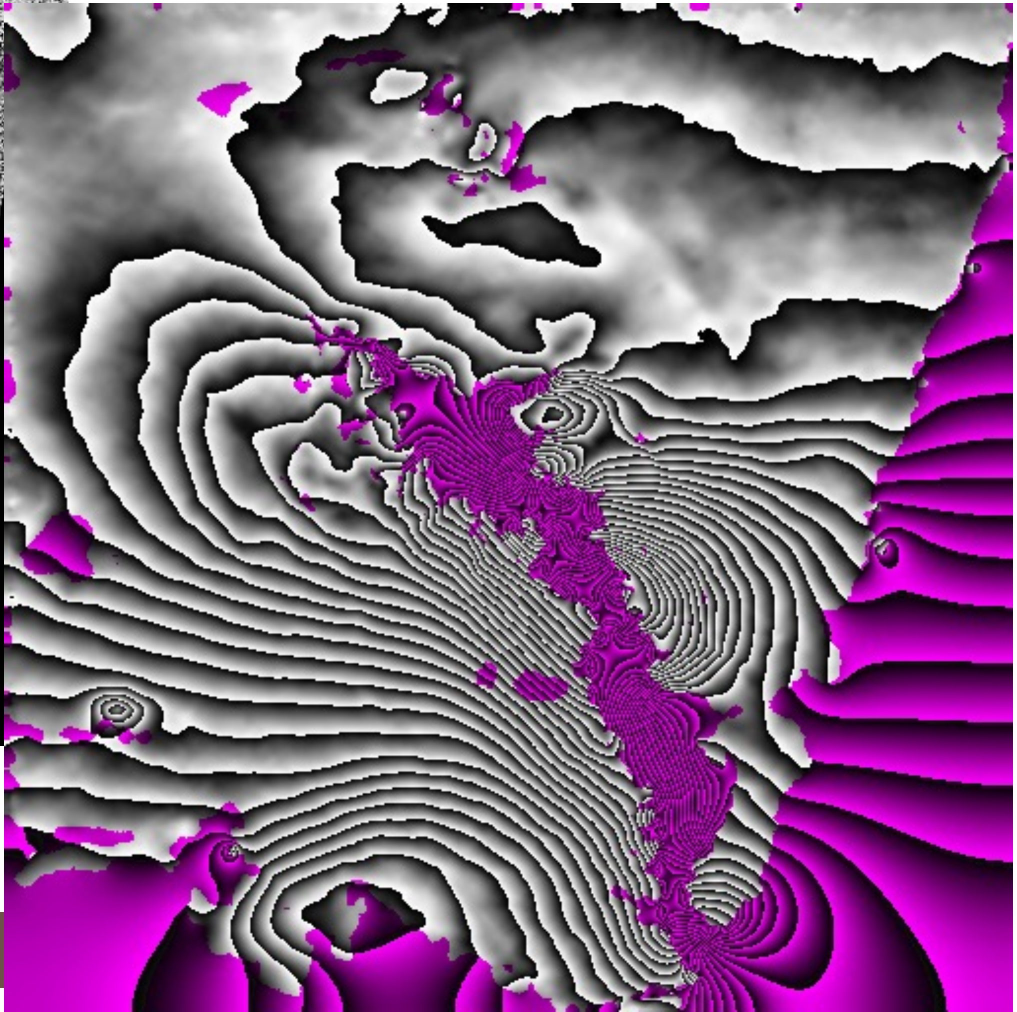
Fig.: © DLR



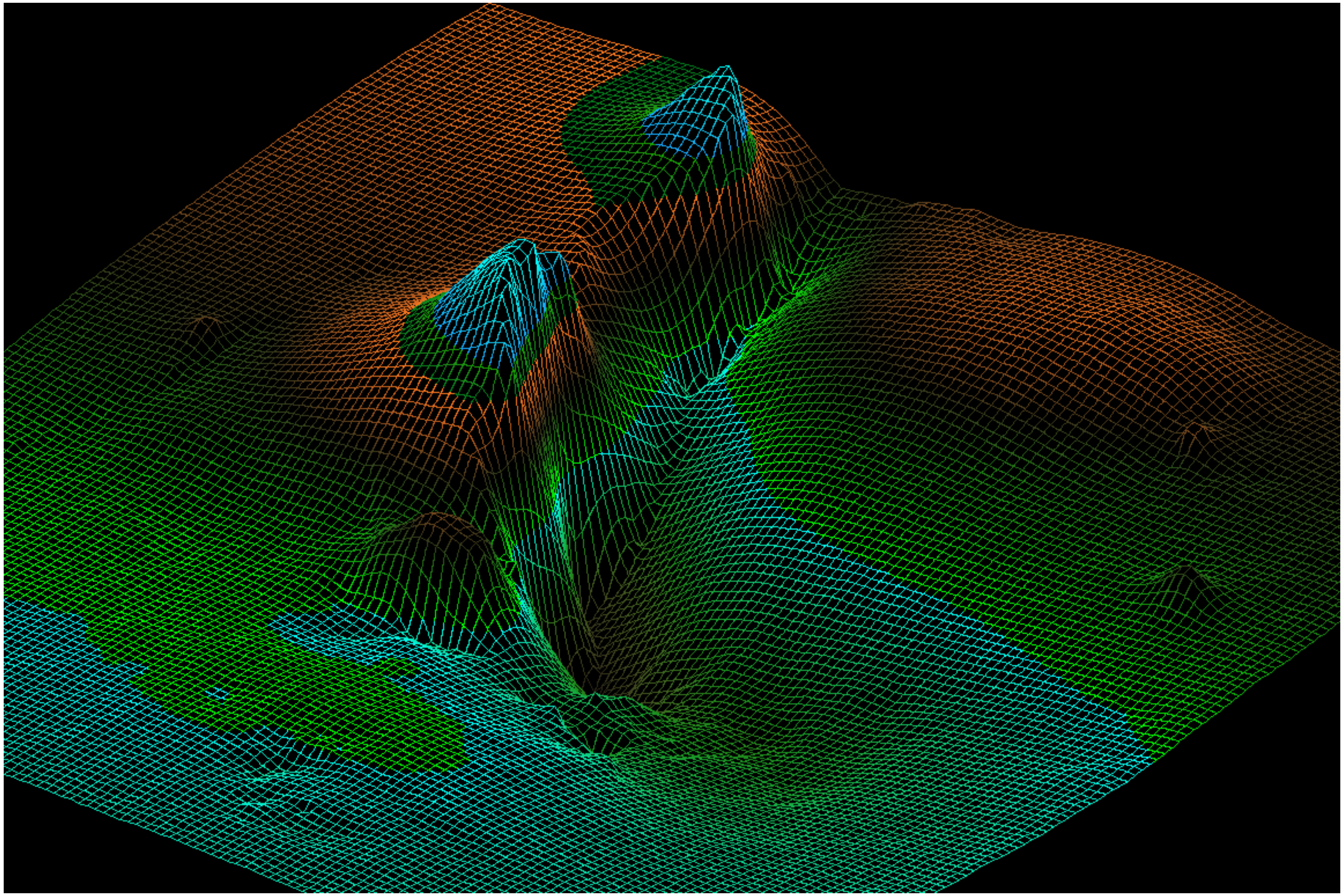
Massonnet et al., The displacement field of the Landers earthquake mapped by radar interferometry, Nature 364, 1993.

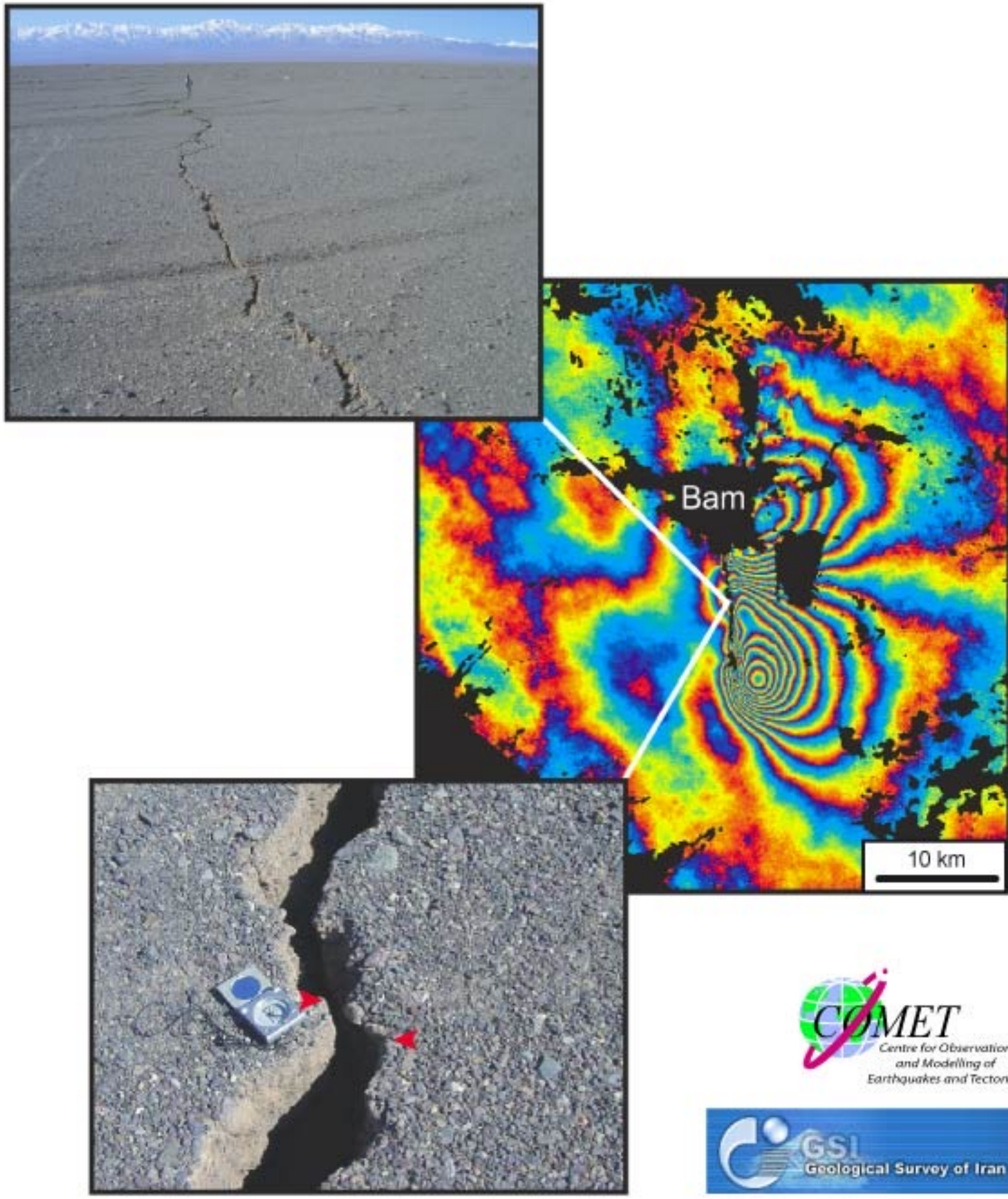
Differential interferometry





Differential interferometry





©http://www.comet.nerc.ac.uk

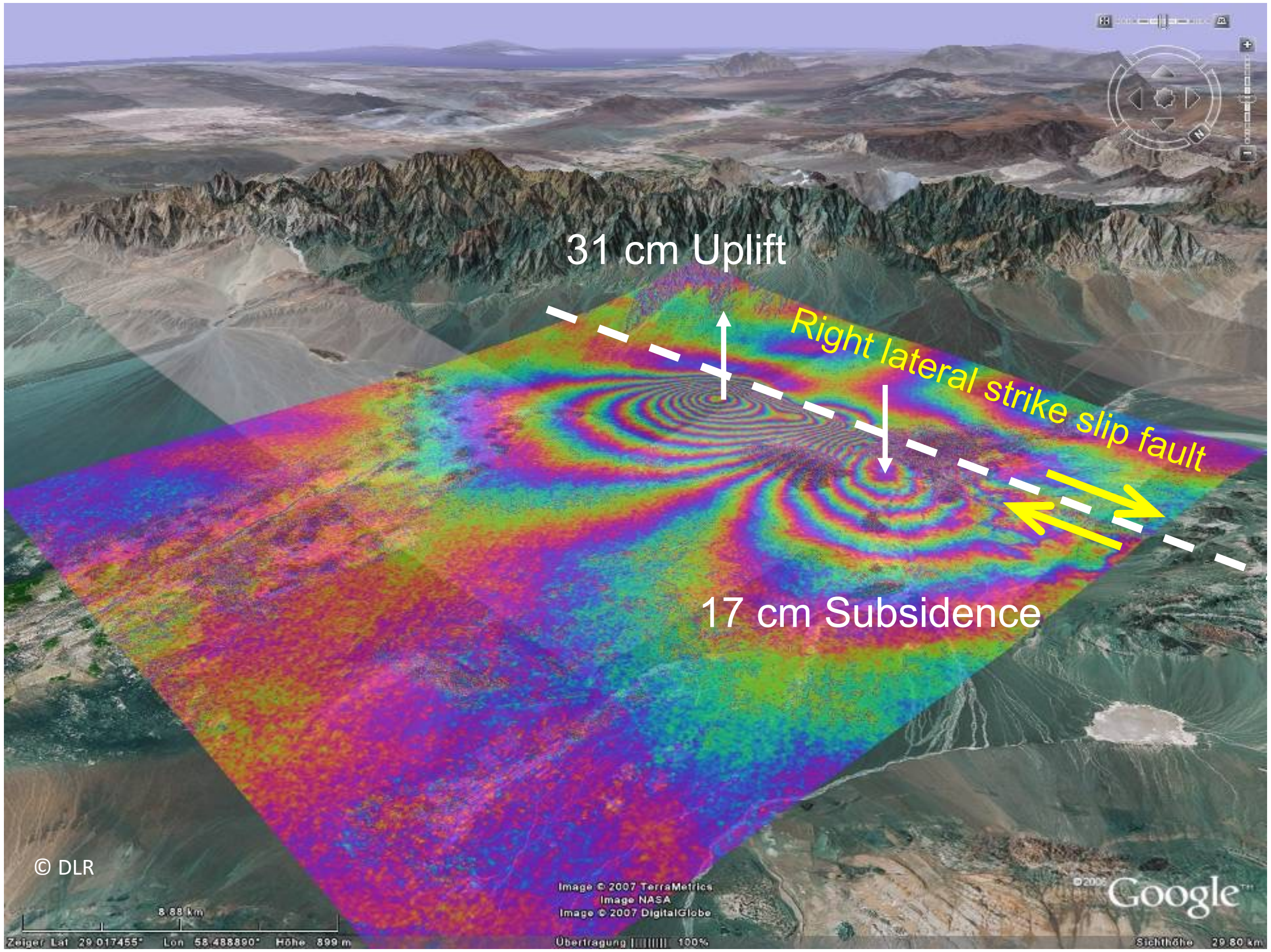
- **Baseline = 0.5 m !!**
- **1 frange ↔ 5 cm**

ENVISAT

COMET Centre for Observation and Modelling of Earthquakes and Tectonics

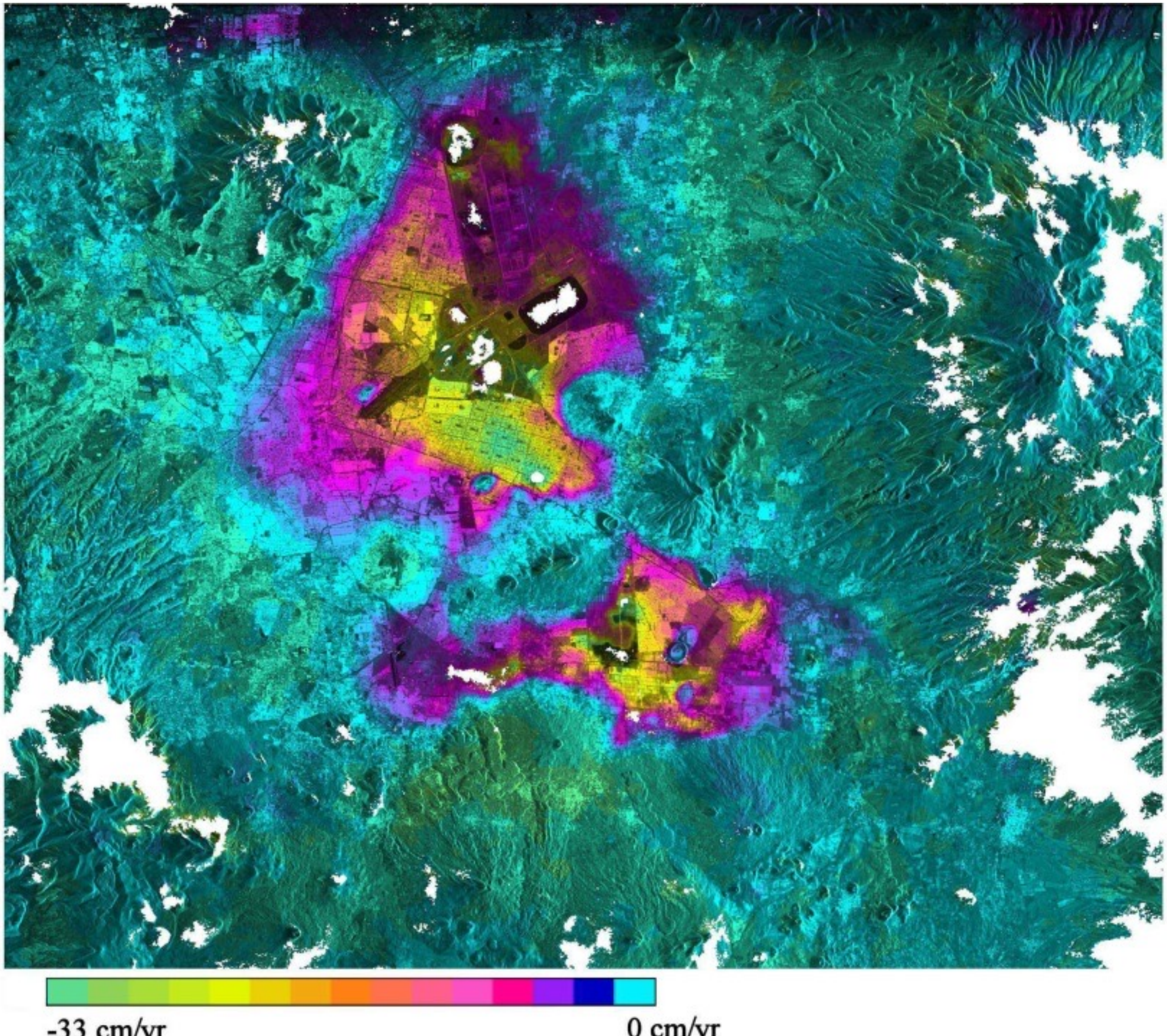
GSI Geological Survey of Iran

Coseismic Deformation of Bam Earthquake 26 Dec 2003

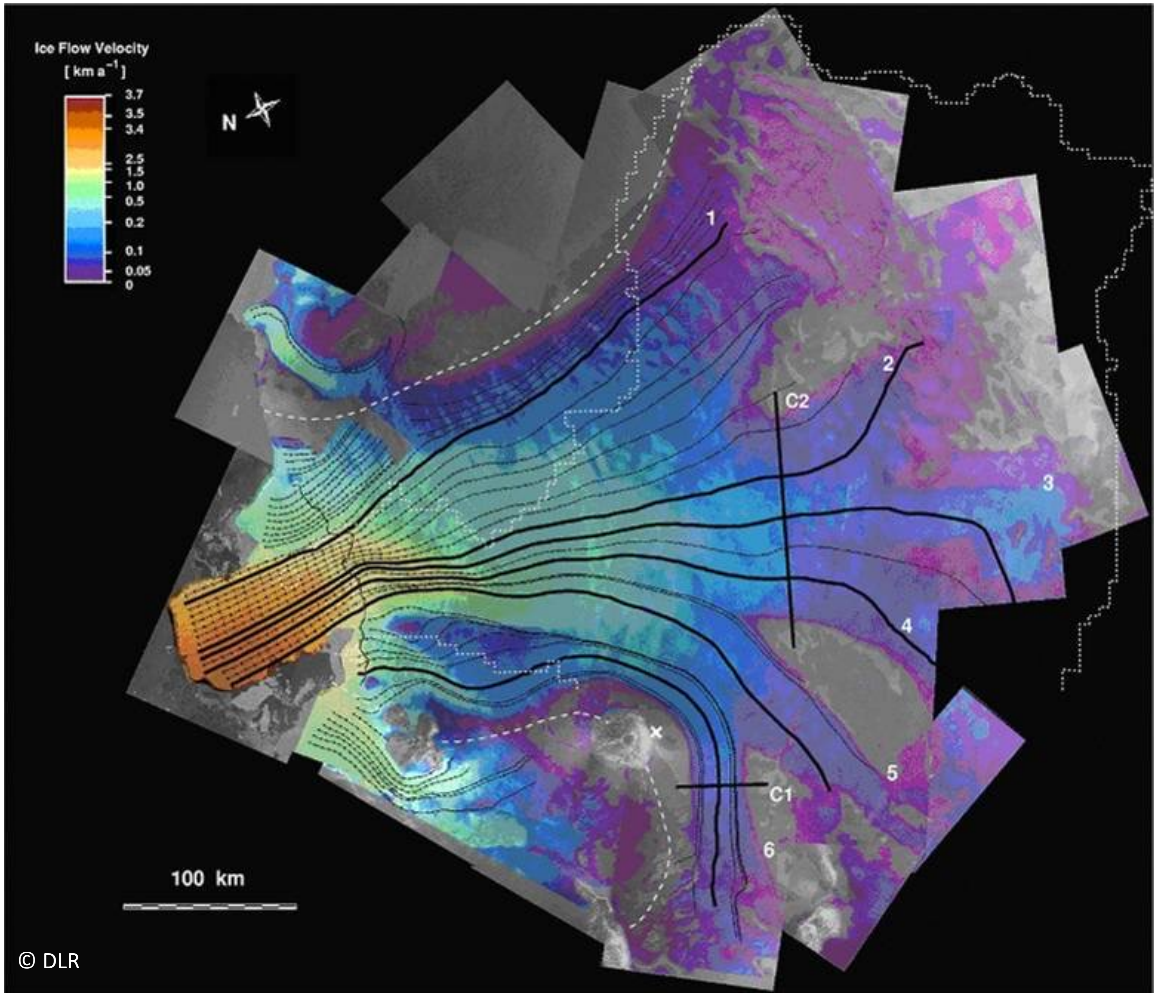


Data: ENVISAT/ASAR ©ESA, 2.12.2003/7.1.2004

Differential interferometry



Glacier Flow Field Derived from D-InSAR

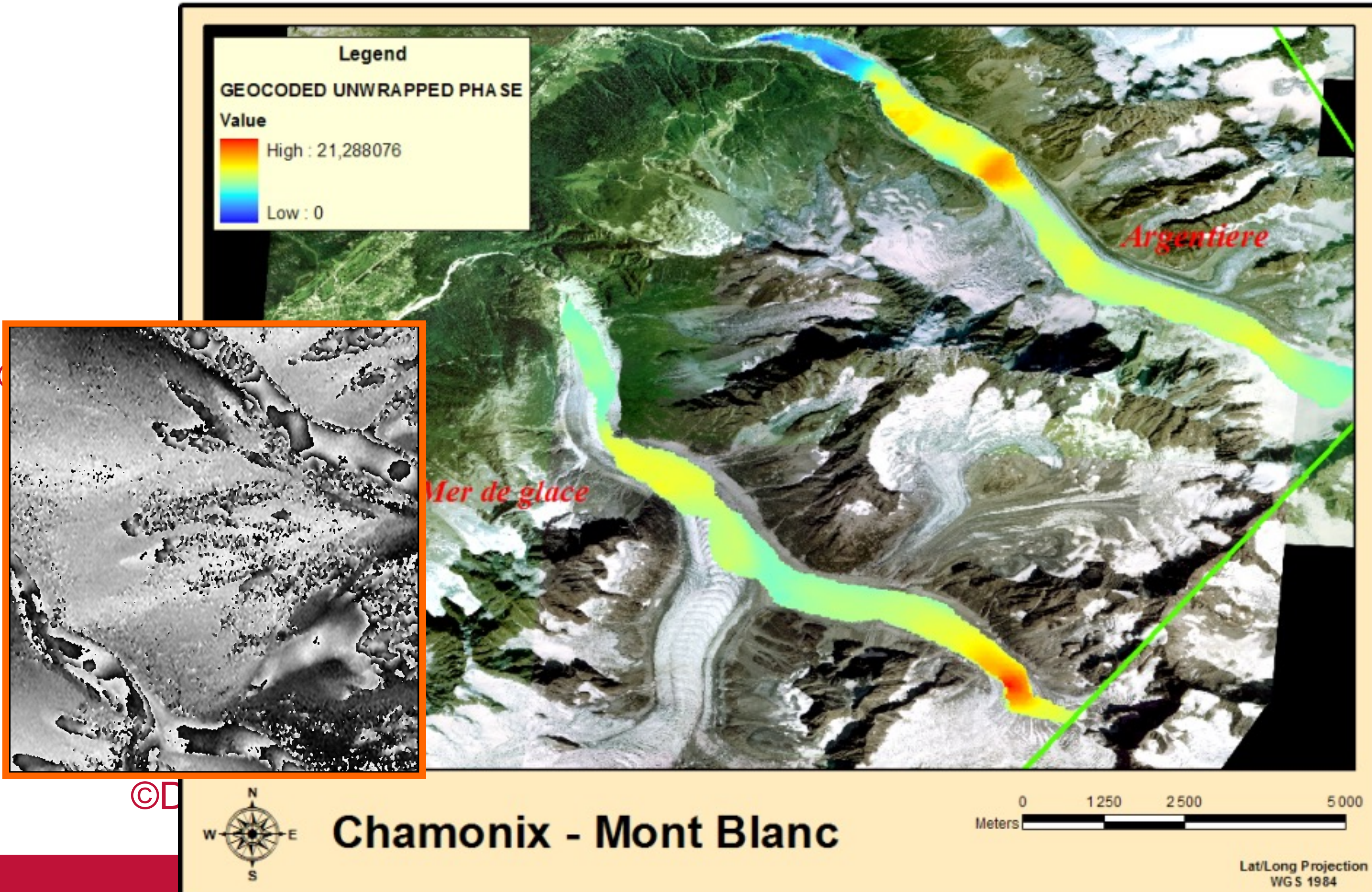


Antarctic Thwaites glacier
Data: ERS-1/2, ©ESA

approx.
500 km x 500 km

(Lang et al., 2004)

Differential interferometry + radargramm.



Multi-temporal SAR interferometric data

Point target analysis

- Exploitation of highly stable points

limited temporal and geometric decorrelation

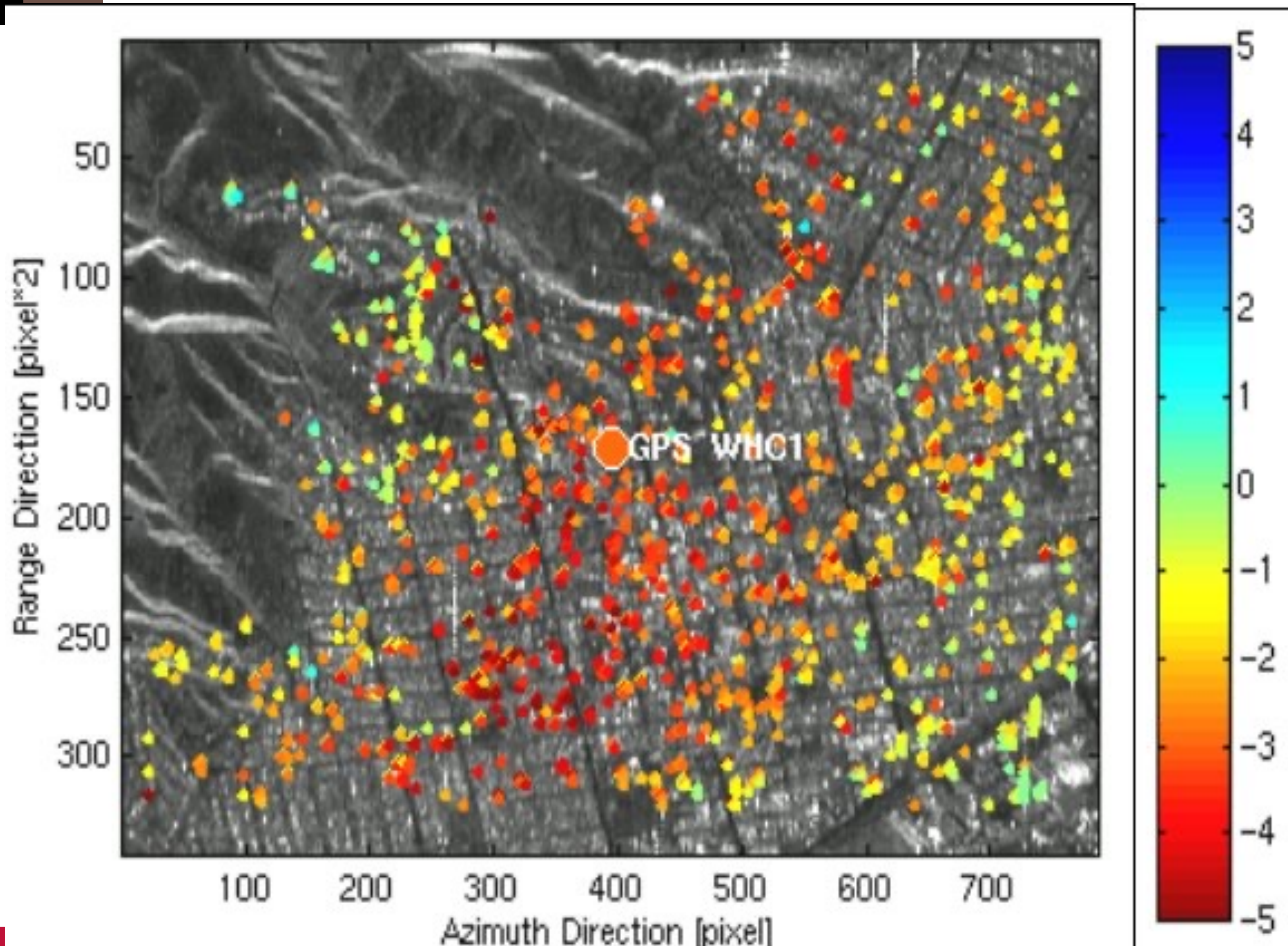
(corners –man-made structures-, rocks,…)

- Permanent scatterers (PS) approaches
  - Exploitation of the whole set of interferograms
  - Inversion constrained by a deformation model

Distributed targets

- Small Baseline (SBAS approaches)
  - Selection of interferograms with sufficient correlation (limited temporal and geometric decorrelation)
  - Temporal inversion

http://www.slamservice.info/img/TRE_PS.jpg



Permanent Scatterers for subsidence

Subsidence of Pomona: animation of Politechnico di Milano

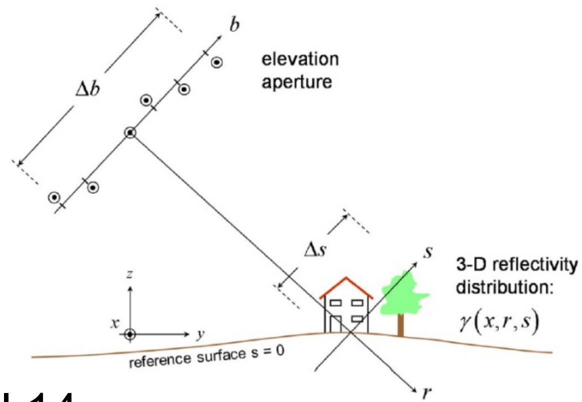
Summary: SAR Interferometry ...

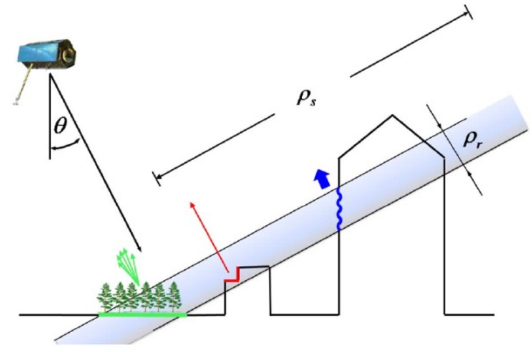
... combines two or more complex-valued SAR images to derive geometric information about the imaged objects (compared to using a single image) by exploiting phase differences.

$\Rightarrow$ Images must differ in at least one aspect (= “baseline”)

baseline type	known as ...	applications: measurement of ...
$\Delta\theta$	across-track	topography, DEMs
$\Delta t = \text{ms} \quad \text{to} \quad \text{s}$	along-track	ocean currents, moving object detection, MTI
$\Delta t = \text{days}$	differential	glacier/ice fields/lava flows, Snow Water Equivalent (SWE), hydrology
$\Delta t = \text{days} \quad \text{to} \quad \text{years}$	differential	subsidence, seismic events volcanic activities, crustal displacements
$\Delta t = \text{ms} \quad \text{to} \quad \text{years}$	coherence estimator	sea surface decorrelation times land cover classification

SAR tomography





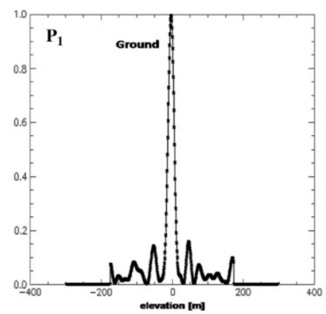
Zhu et al.14

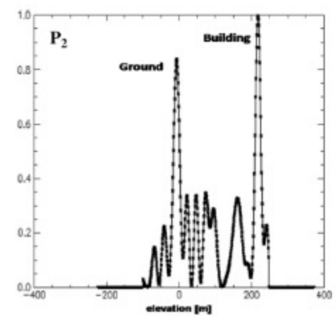
$$g_n = \int_{\Delta s} \gamma(s) \exp(-j2\pi\xi_n s)\, ds, \qquad n = 1, \ldots, N$$

$$\mathbf{g} = \mathbf{R}\gamma$$

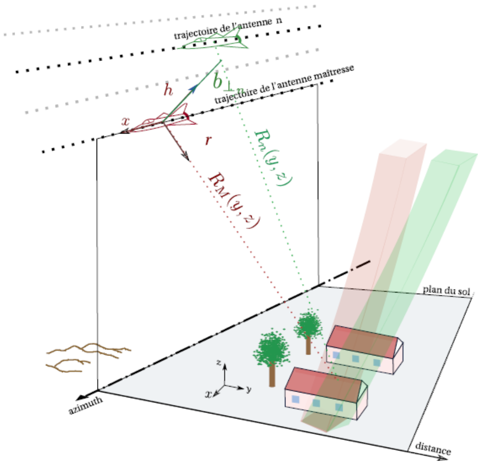
Inversion :

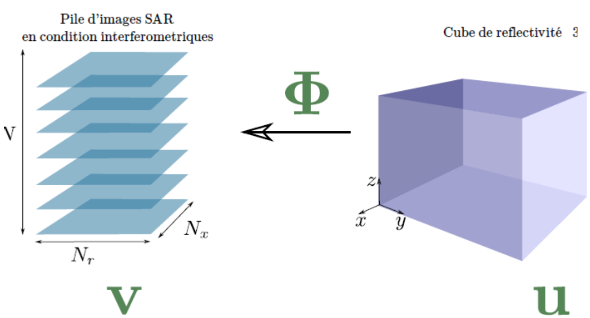
- Spectral analysis methods
- Parse methods





SAR tomography





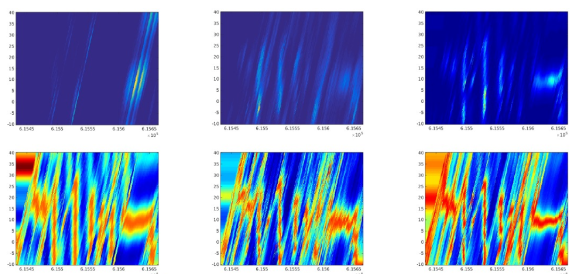
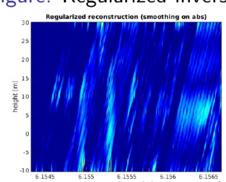
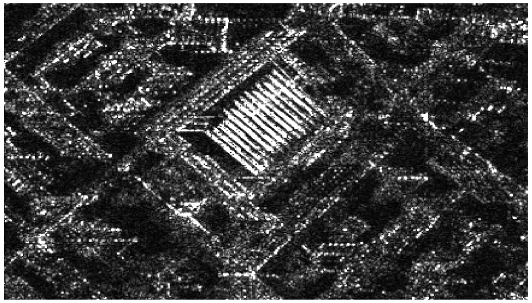
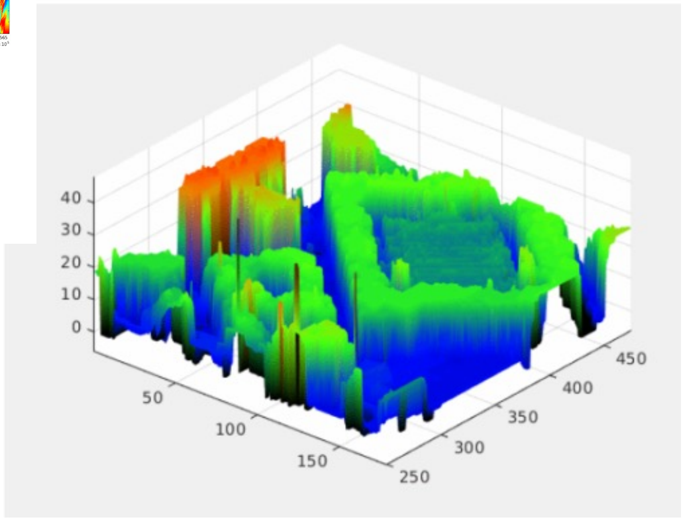


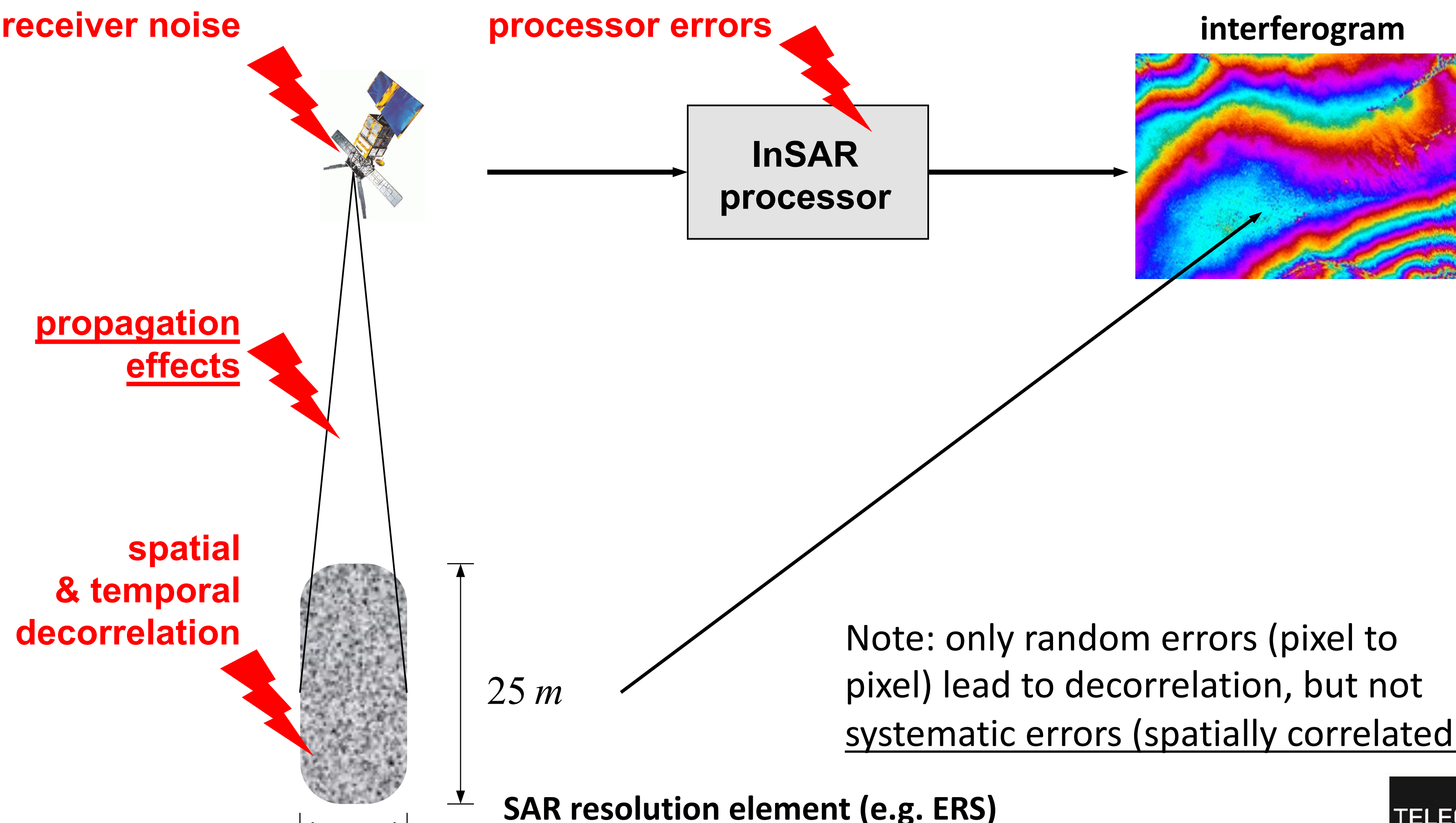
Figure: Regularized inversion







Interferometric Phase Error Sources



Note: only random errors (pixel to pixel) lead to decorrelation, but not systematic errors (spatially correlated)

Fig.: © DLR

InSAR limits

$$\phi = \phi_{orb} + \phi_{topo} + \phi_{mvt} + \phi_{atm} + \phi_{noise}$$

- **Many error sources:**
  - Atmospheric decorrelation
  - Temporal decorrelation
  - Baseline (geometric) decorrelation + lay-over and shadows
  - Phase noise
- **Corrections :**
  - Mono-pass systems
  - Atmospheric corrections
  - Phase filtering
  - Multi-sensors combination