SAR Interferogram formation and phase unwrapping

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Montpellier, July 2021

Learning Objectives

By the end of this presentation, you will be able to:

- Understand the basic physics of SAR interferometry
- Describe processing for making an interferogram
- Understand the phase unwrapping to reveal ground motion

Prerequisites

- Recommend basic knowledge of Radar Remote Sensing

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- Processing sequence
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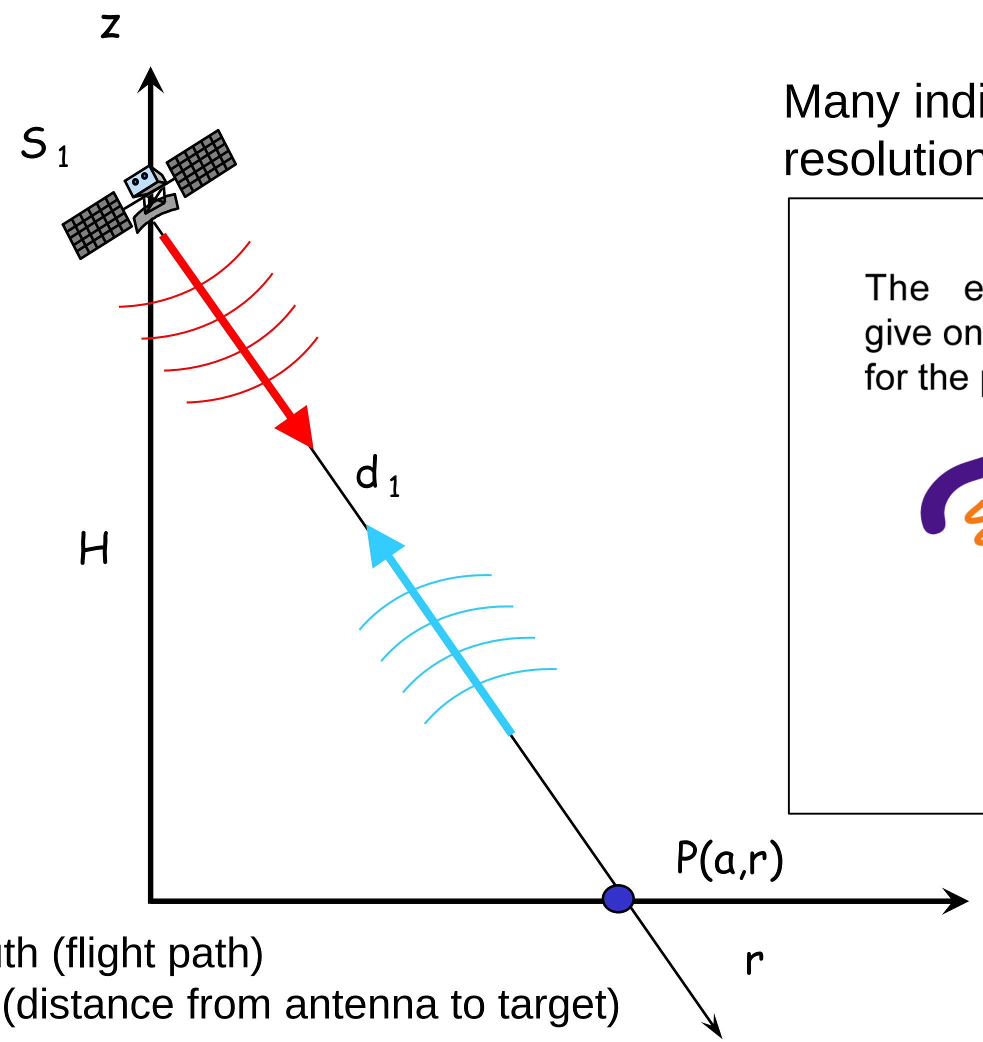
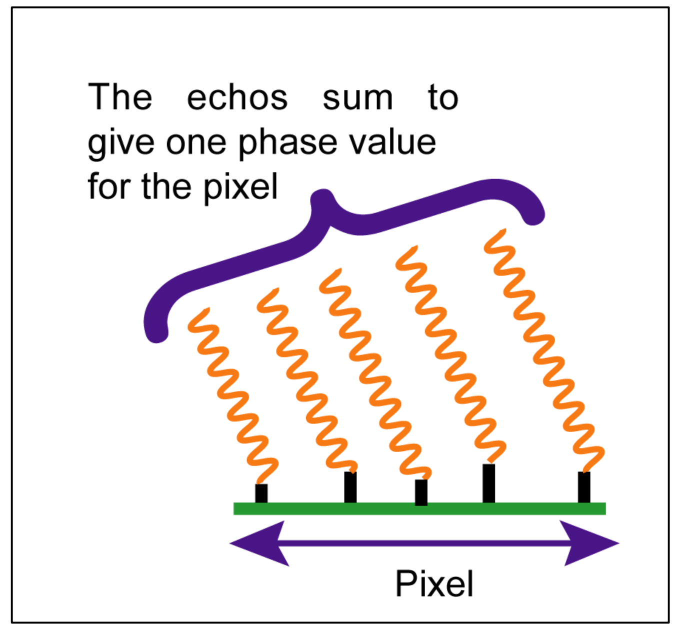
Synthetic aperture radar (SAR)

SAR is an active illumination system with wavelengths in the centimetre domain.

Each resolution cell has extent in the meter domain.



Many individual scatterers within one resolution cell

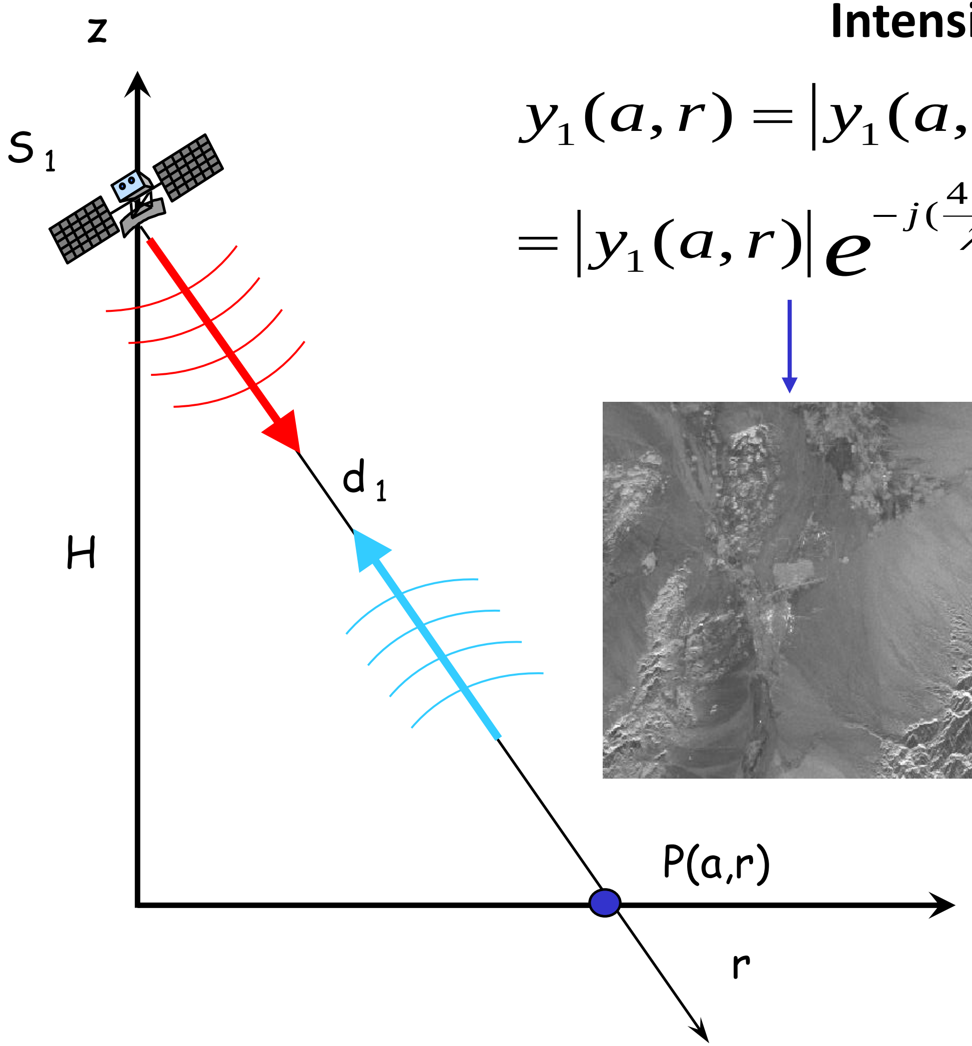


a : azimuth (flight path)
r : range (distance from antenna to target)

Synthetic aperture radar (SAR)

SAR data are getting attention due to the importance in real-world application context.

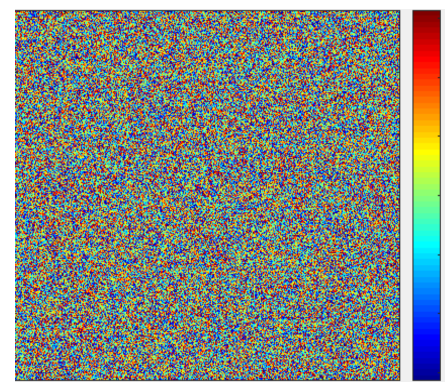
A Single Look Complex (SLC) SAR image can be decomposed into …



Intensity and **Phase**

$$y_1(a,r) = |y_1(a,r)| e^{-j(2\pi \frac{2 d_1(a,r)}{\lambda} + \phi_{scatt})} =$$

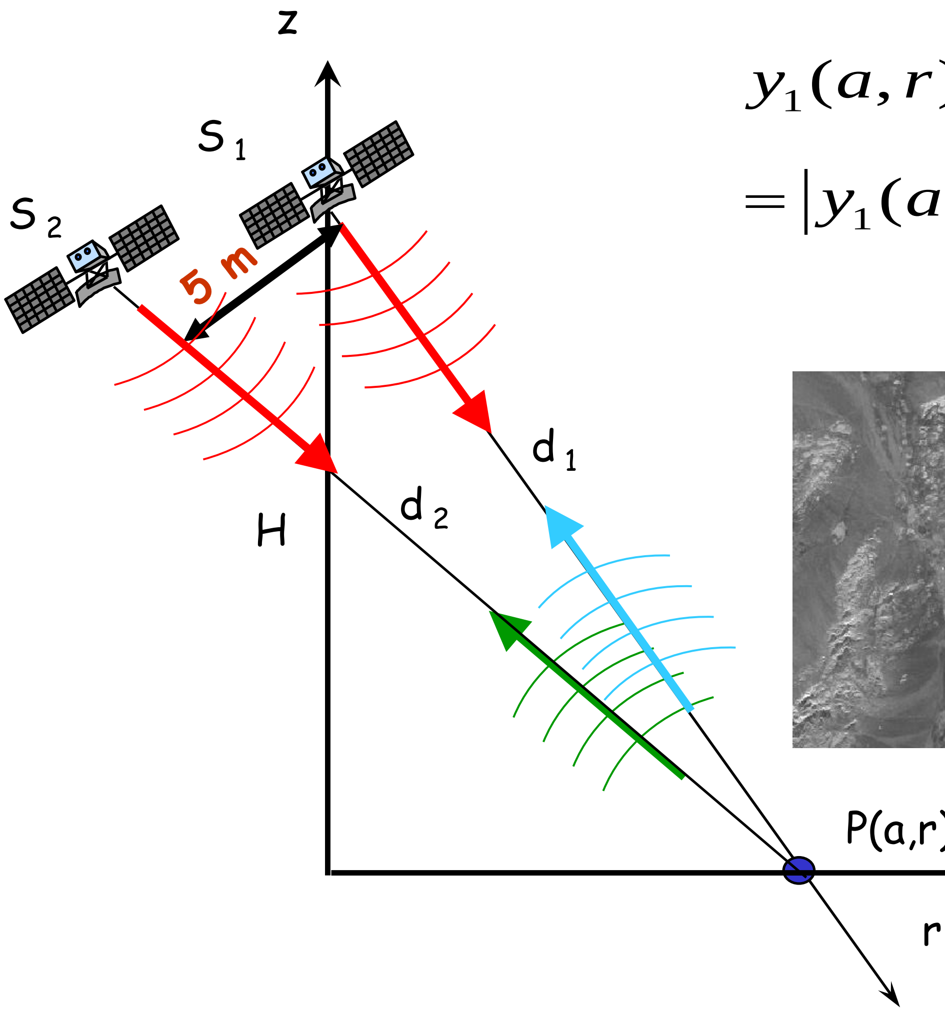
$$= |y_1(a,r)| e^{-j(\frac{4\pi}{\lambda} d_1(a,r) + \phi_{scatt})}$$



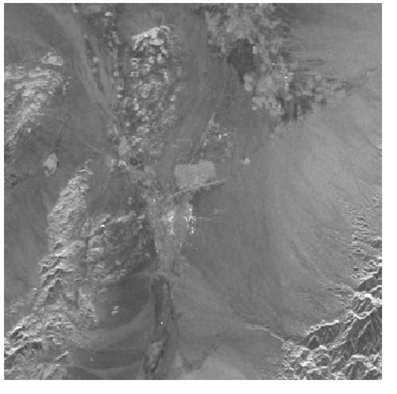
SAR: Interferometric phases

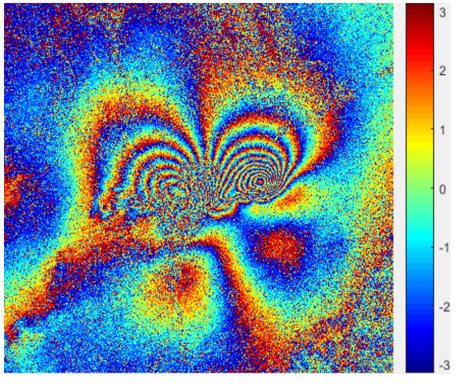
Interferometry SAR (InSAR) quantifies a phase shift of radar waves.

An example (BAM earthquake 2003)



$$y_1(a,r)\cdot y_2^*(a,r) =$$
$$= |y_1(a,r)||y_2(a,r)|e^{-j\frac{4\pi}{\lambda}(d_1(a,r)-d_2(a,r))}$$





SAR Interferogram Formation

phase of a complex SAR image pixel: $\phi_i = \underbrace{-\frac{4\pi}{\lambda} d_i}_{\text{range}} + \underbrace{\phi_{scatt,i}}_{\text{scattering}}$

complex SAR image #1: $u_1[i,k] = |u_1[i,k]| \cdot \exp(j\,\phi_1[i,k])$

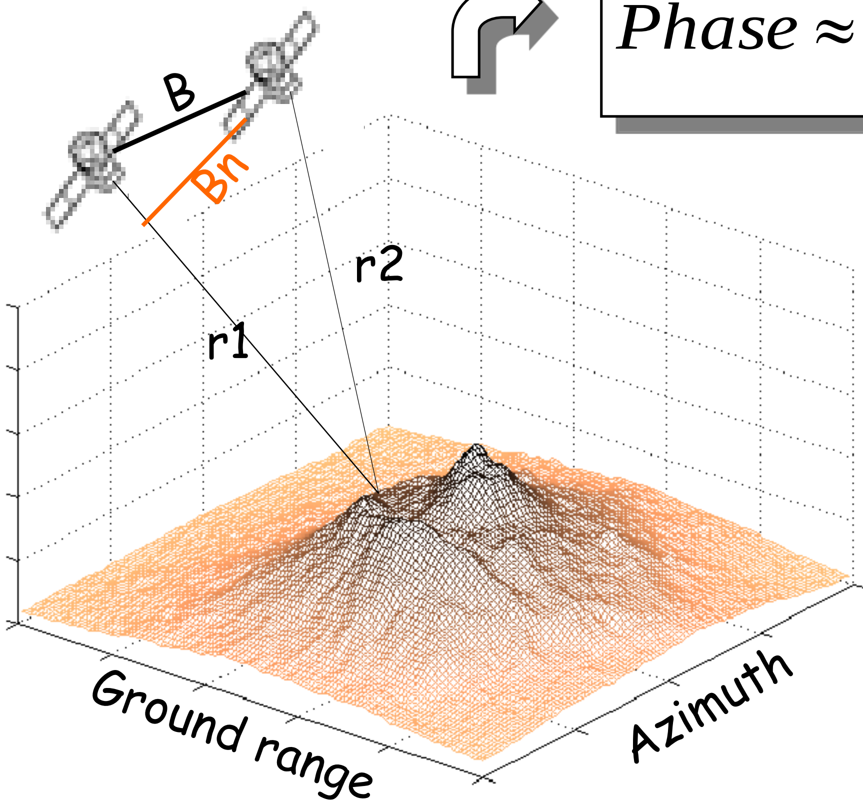
complex SAR image #2: $u_2[i,k] = |u_2[i,k]| \cdot \exp(j\,\phi_2[i,k])$

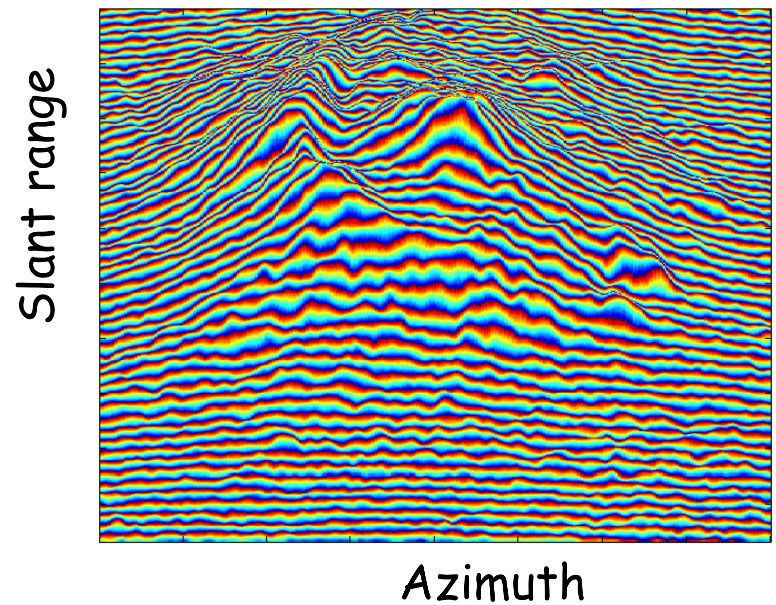
interferogram: $v[i,k] = u_1[\cdot]\,u_2^*[\cdot] = |u_1[\cdot]|\,|u_2[\cdot]|\,\exp(j\,\phi[\cdot])$

interferometric phase: $\phi[\cdot] = \phi_1[\cdot] - \phi_2[\cdot]$

SAR interferometric phase: geometric contribution

$$Phase \approx \frac{4\pi}{\lambda}\Delta r$$





Summary of the SAR interferometric phase contributions

$$\Delta\varphi = \Delta\varphi_{flat} + \Delta\varphi_{elevation} + \Delta\varphi_{displacement} + \Delta\varphi_{atmosphere} + \Delta\varphi_{noise}$$

$$-\frac{4\pi}{\lambda}\frac{B_n s}{R\tan\theta}$$

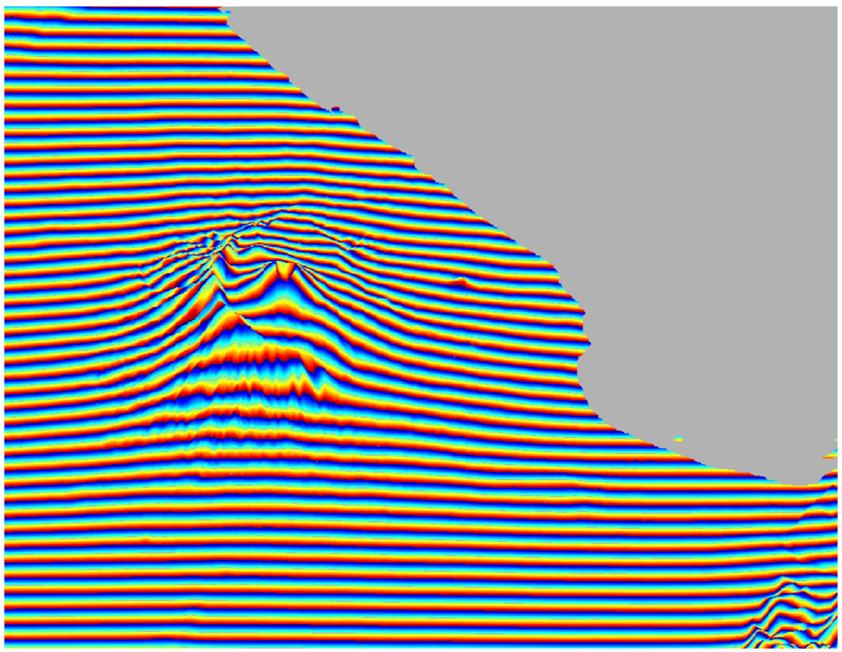
$$-\frac{\Delta q}{\sin\theta}\cdot\frac{B_n}{R_0}\cdot\frac{4\pi}{\lambda}$$

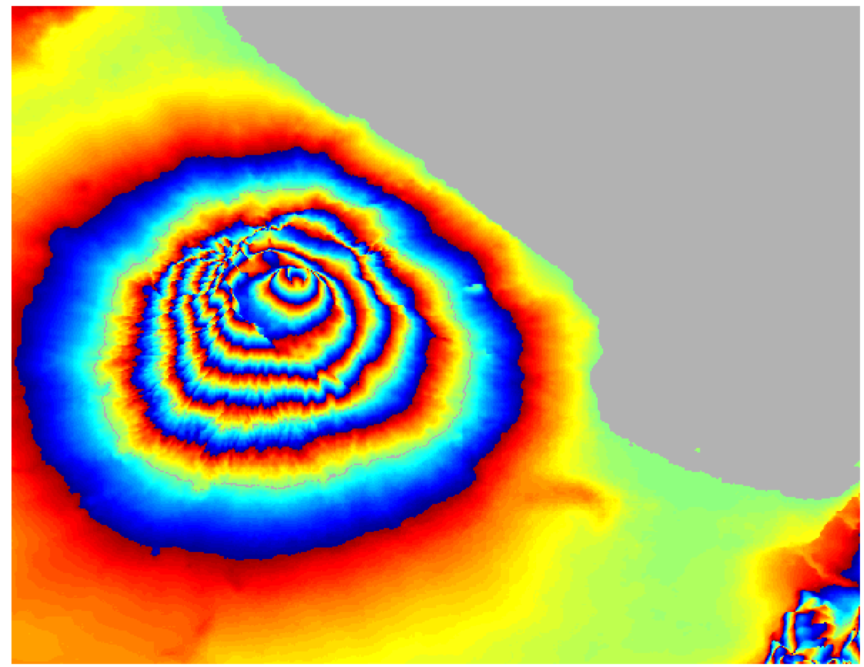
$$+\frac{4\pi}{\lambda}d$$

Interferogram flattening

Flattening is achieved by subtracting the phase contribute of flat earth.

Slant range





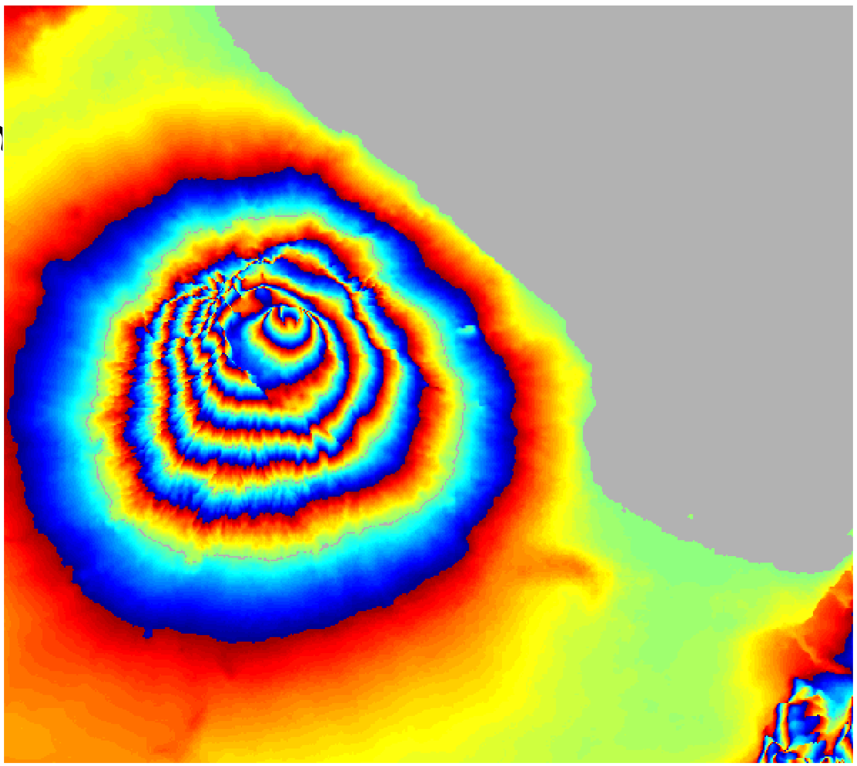
Azimuth

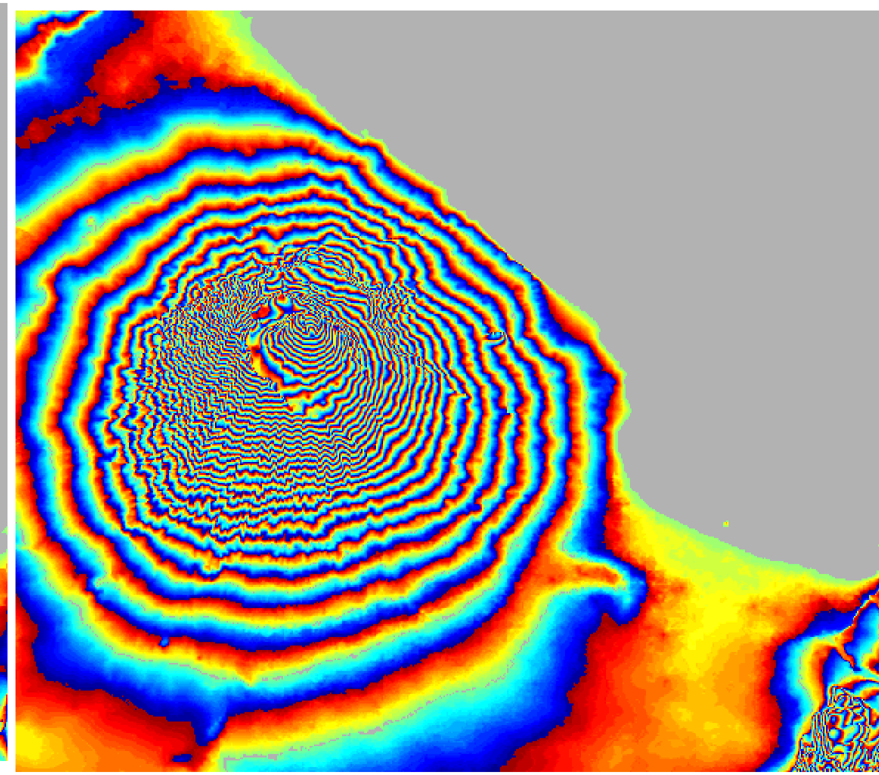
Mt. Vesuvius, baseline 50 m.

Bn=50

Bn=250

Slant range

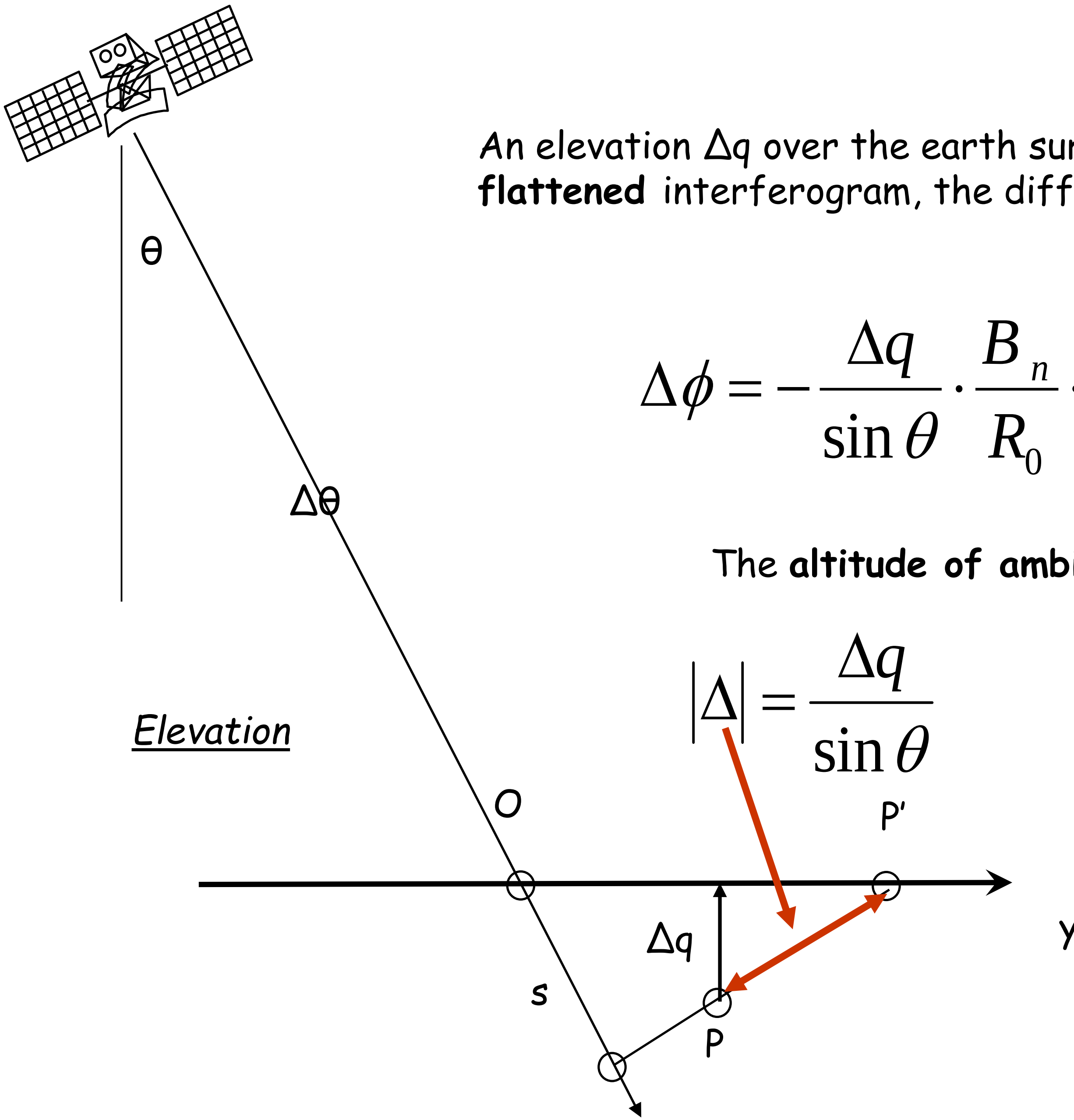




An elevation Δq over the earth surface, gives, to the **flattened** interferogram, the differential phase:

$$\Delta\phi = -\frac{\Delta q}{\sin\theta} \cdot \frac{B_n}{R_0} \cdot \frac{4\pi}{\lambda}$$

The **altitude of ambiguity** ($\Delta\varphi = 2\pi$) is then:



$$|\Delta| = \frac{\Delta q}{\sin\theta}$$

$$\boxed{\Delta q \times B_n = \frac{\lambda}{2}\sin\theta\, R_0 \approx 10000}$$

e.g.: B_n=100 → Δq =100 m

Calculation of the altitude of ambiguity

$$R_0 = 870\ \mathrm{km}$$
$$\lambda = 5.55 cm$$
$$\theta = 25°$$

$$\Delta\phi = -\frac{\Delta q}{\sin\theta}\cdot\frac{B_n}{R_0}\cdot\frac{4\pi}{\lambda}$$

$$If$$

$$\Delta\phi = 2\pi$$

$$then$$

$$\frac{\Delta q}{\sin\theta}\cdot\frac{B_n}{R_0}\cdot\frac{4\pi}{\lambda} = 2\pi$$

$$\Delta q \times B_n = \frac{\lambda}{2}\sin\theta\ R_0$$

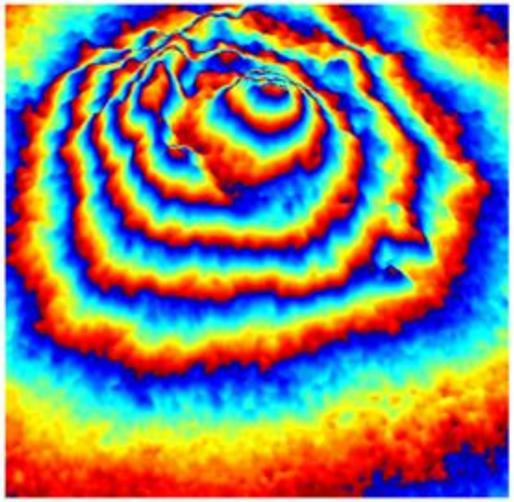
$$\approx 10000$$

The Interferometric phase has 2π periodicity

Altitude of ambiguity: height difference generating a 2π phase change

Bn =50 m

$$\Delta q_a \approx 188m$$

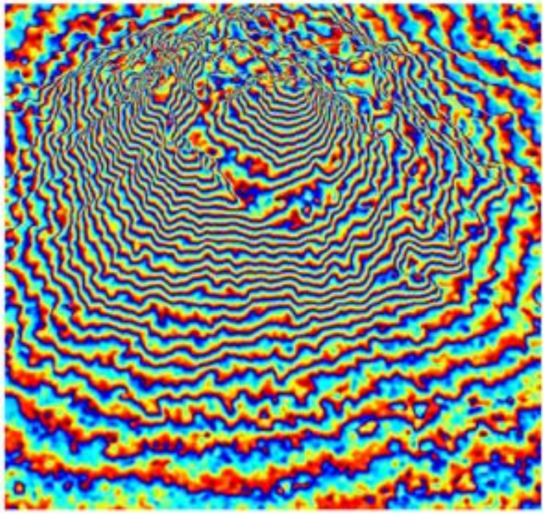


$$\Delta q_a = \frac{\lambda}{2B_n}\sin\theta\, R$$

$$\Delta q_a \times B_n = \frac{\lambda}{2}\sin\theta\, R$$

Bn =250 m

$$\Delta q_a \approx 37m$$



Topography: The greater the baseline, the greater the height accuracy

SAR interferometric phase: ground motion contribution

The sensitivity of the interferometric phase to the ground motion is much larger than that to the elevation difference.

In the Sentinel-1 case assuming a perpendicular baseline of 150m the following expression of the interferometric phase (after interferogram flattening) holds:

$$\Delta\varphi = \Delta\varphi_{elevation} + \Delta\varphi_{displacement} =$$

$$= -\frac{q}{10} + 225\, d$$

2π phase change will correspond to 63 m topography

or 28 mm motion

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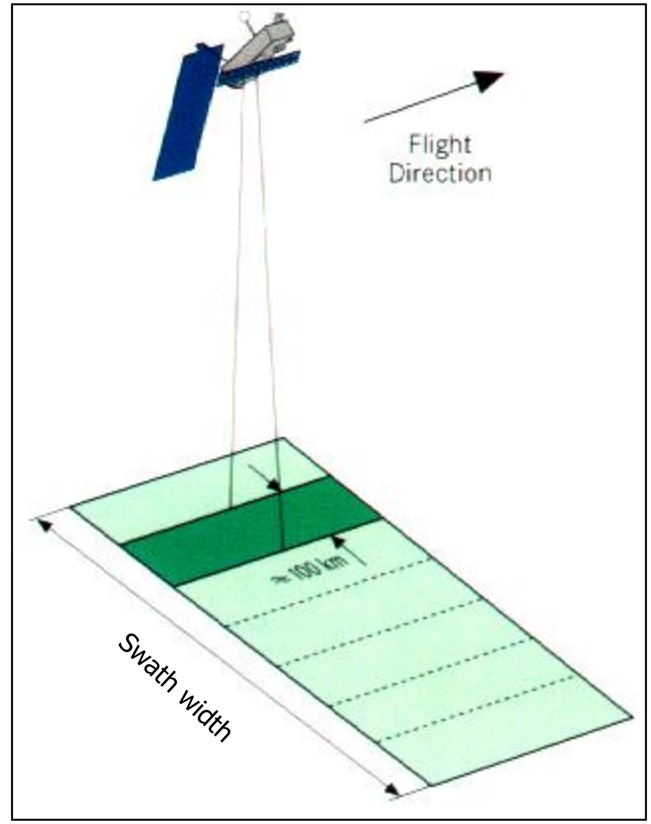
Stripmap Mode - Principle

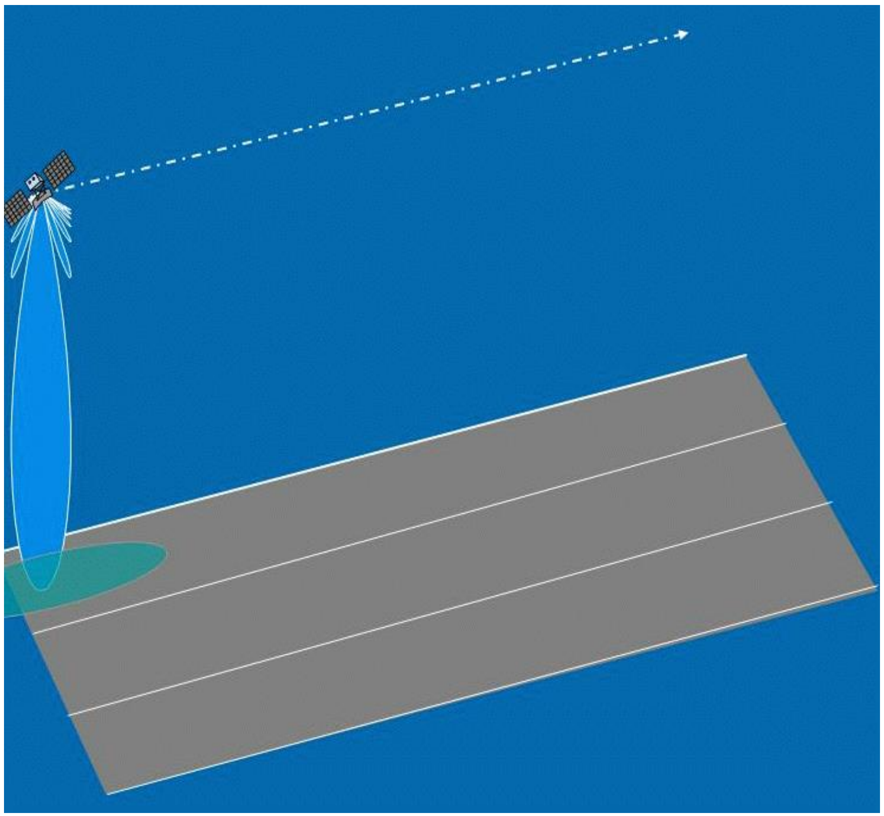
When operating as a Stripmap SAR, the antenna usually gives the system the flexibility to select an imaging swath by changing the incidence angle.

Note that the Stripmap Mode is the most commonly used mode. In the case of ERS-1/2 SAR and JERS-1 SAR the antenna was fixed, hence disabling selection of an imaging swath. The latest generation of SAR systems - like ALOS, TerraSAR-X, and COSMO-SkyMed, Sentinel-1 - provides for the selection of different swath modes.



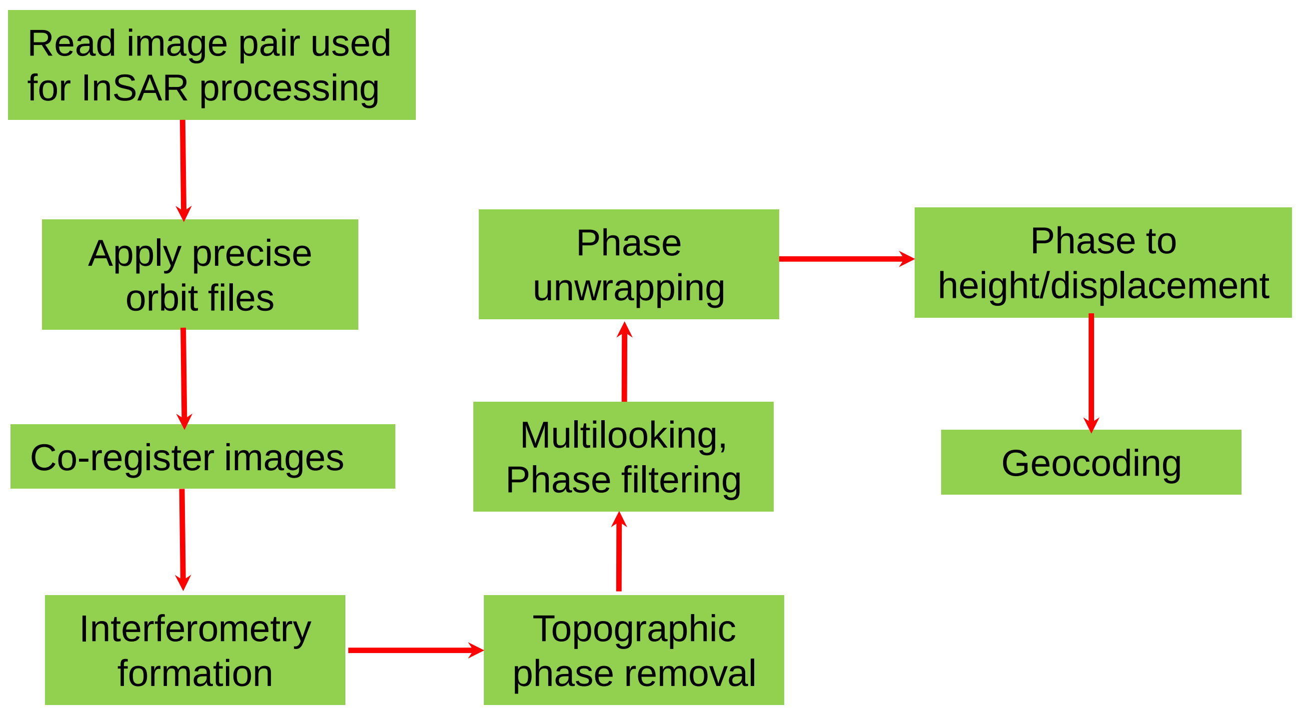
TOPS Mode - Principle

Terrain Observation by Progressive Scan SAR

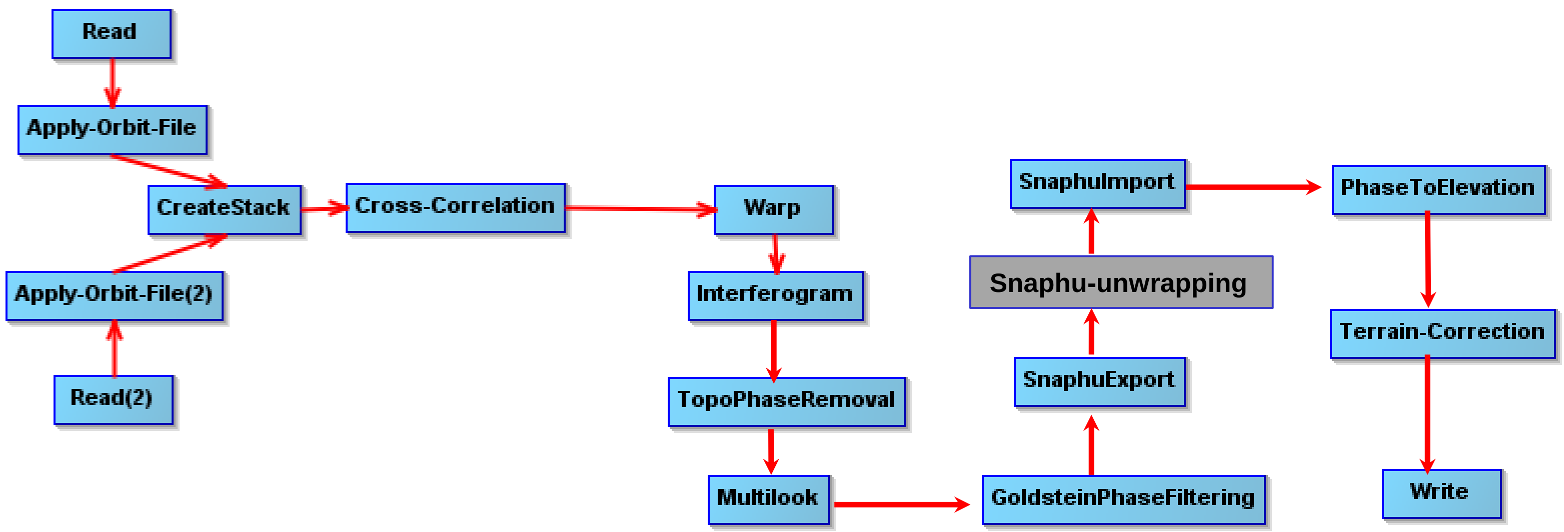


- Reduce aperture time by steering the antenna electronically **backward** - **forward** in azimuth
- More azimuth distance, less illumination time per target
- Saved time can be used to electronically steer the antenna to other elevation directions
- → **+** increased swath width (e.g. S1: 3x = 250 km)
- → **-** reduced resolution (e.g. S1: 17 m)

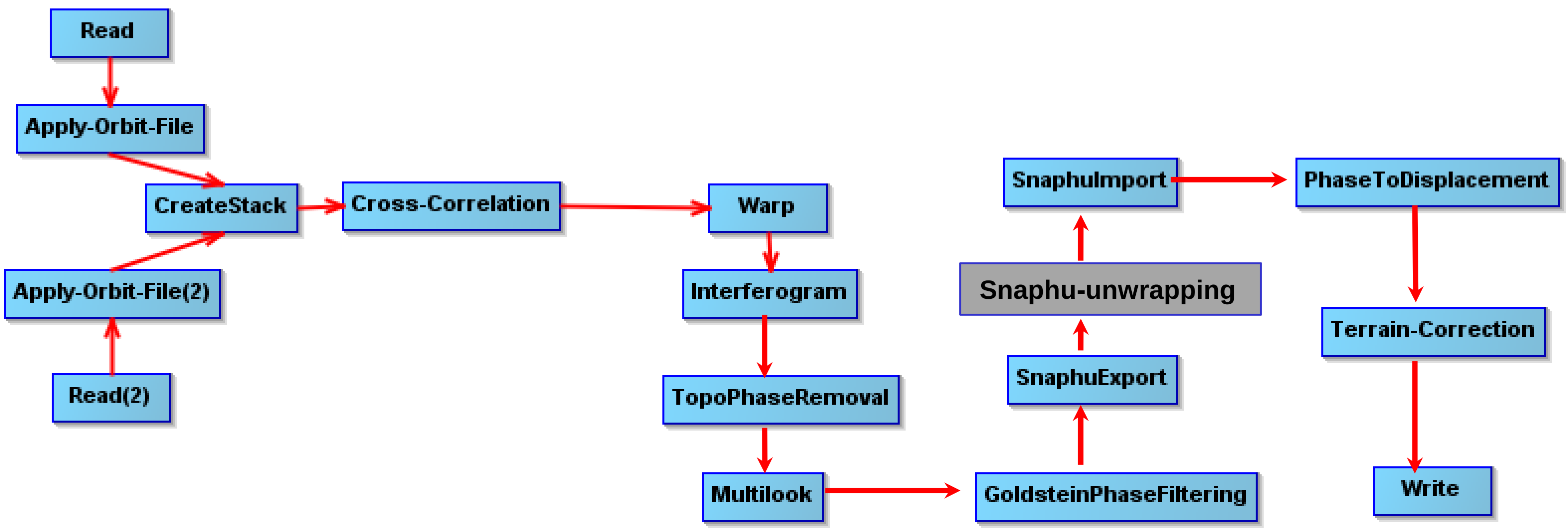
Processing chain



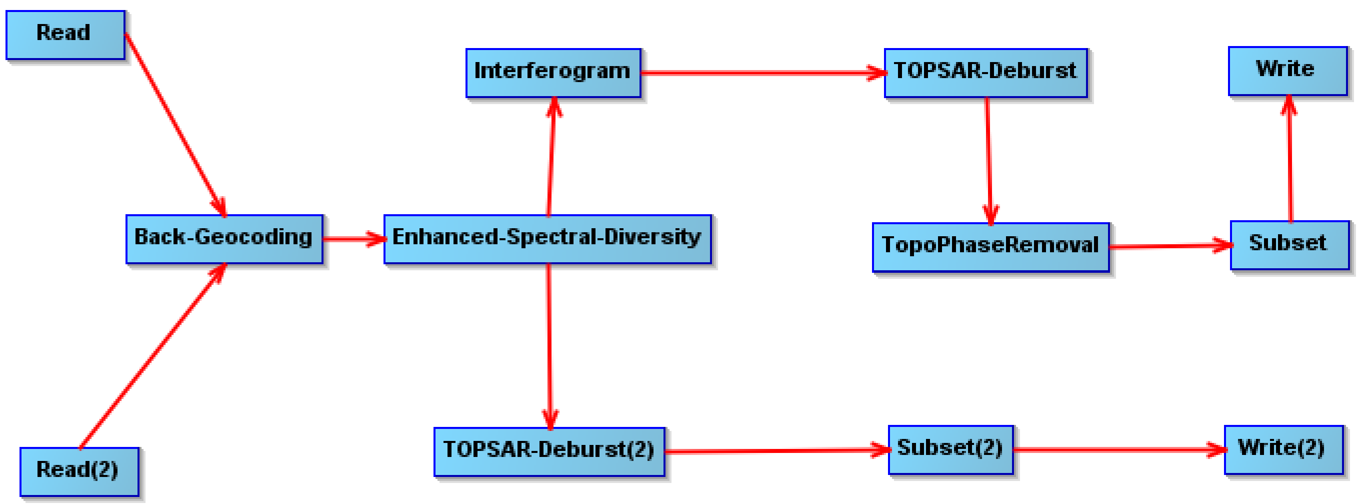
For stripmap to DEM generation (SNAP)



For stripmap to estimate displacement (SNAP)



For TOPS to estimate displacement (SNAP)



Coherence - A Measure of Interferogram Quality

Given two co-registered complex SAR images (v_1 and v_2), one calculates the interferometric coherence (g) as a ratio between coherent and incoherent summations:

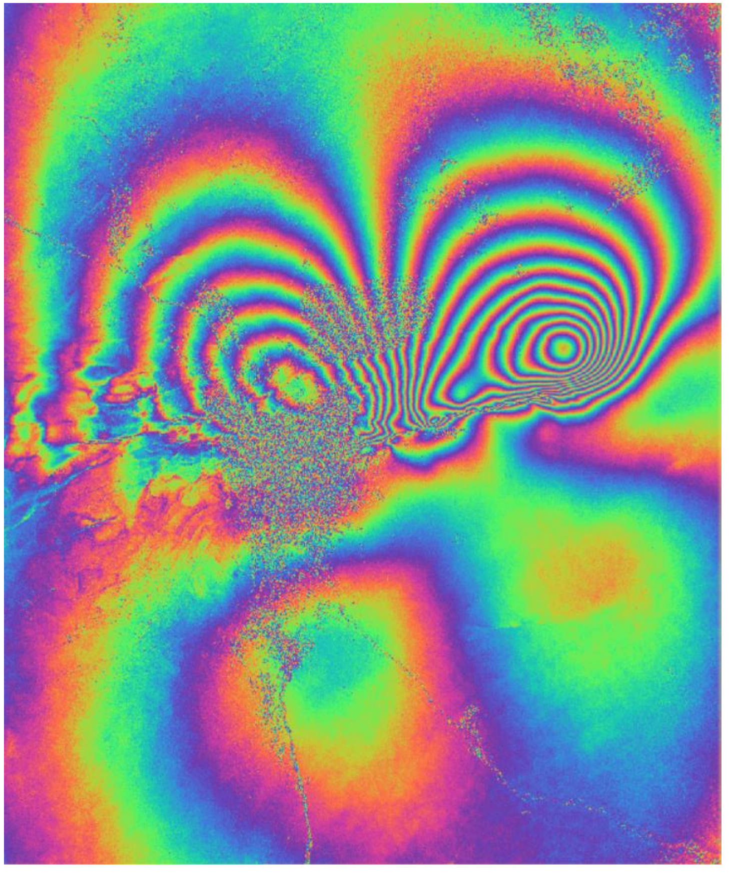
$$\gamma = \frac{E[v_1 v_2^*]}{\sqrt{E[v_1 v_1^*]}\sqrt{E[v_2 v_2^*]}}$$

Note that the observed coherence - which ranges between 0 (black) and 1 (white) - is, in primis, a function of systemic spatial decorrelation, the additive noise, and the scene decorrelation that takes place between the two acquisitions.

In essence coherence has a twofold purpose:

- To determine the quality of the measurement (i.e. interferometric phase). Usually, phases having coherence values lower than 0.2 should not be considered for the further processing.
- To extract thematic information about the object on the ground in combination with the backscattering coefficient.

Complex multilook



A “cleaned” interferogram is achieved by averaging in areas of uniform phase.

SNR improves $\propto$ the number of looks. Usually the averaging window is adaptive.

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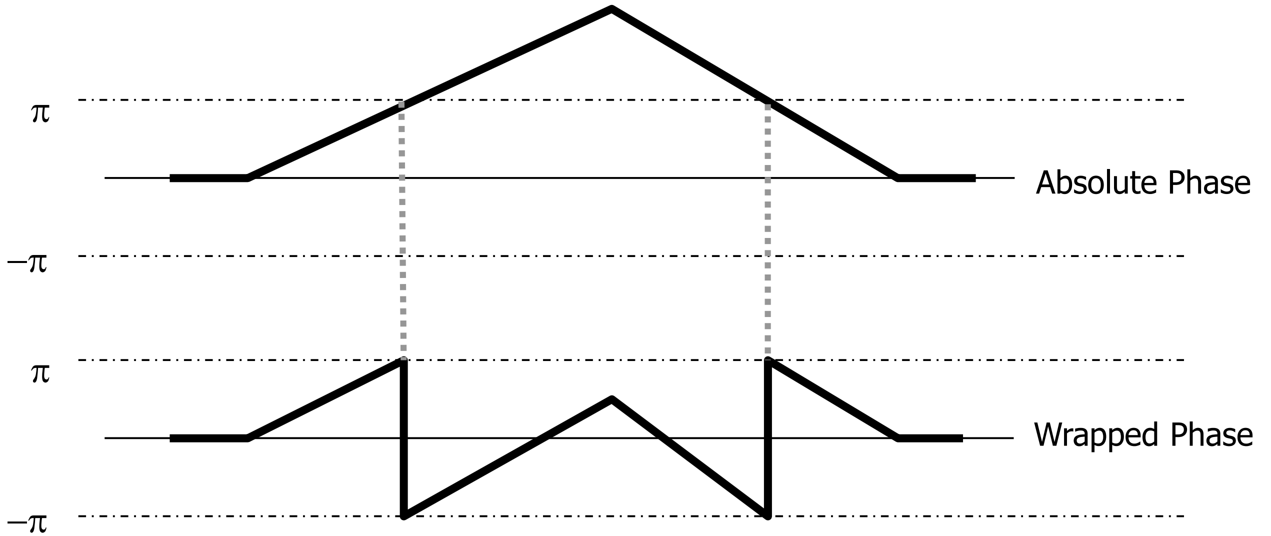
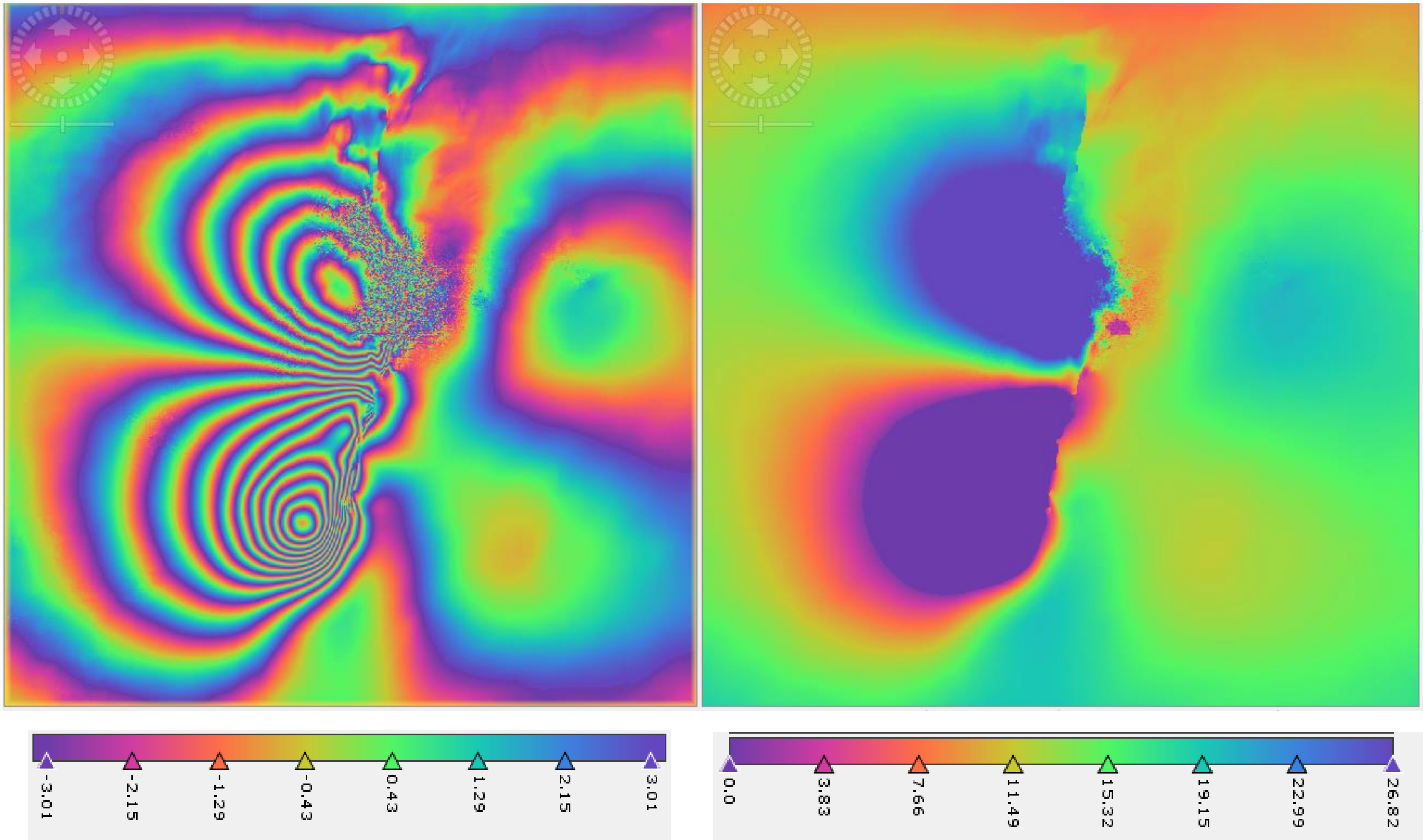
Interferometric Phase

The interferometric phase (ϕ) is expressed as ϕ = tan(Imaginary(*Int*) / Real(*Int*)), modulo 2π.

Phases are represented as angles within the range $-\pi \sim +\pi$.



In order to resolve this inherent ambiguity, phase unwrapping must be performed.

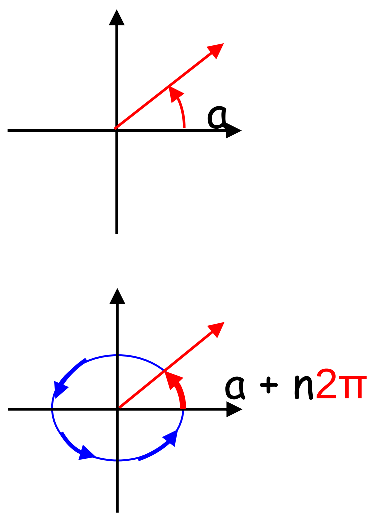

-3.01
-2.15
-1.29
-0.43
0.43
1.29
2.15
3.01
0.0
3.83
7.66
11.49
15.32
19.15
22.99
26.82

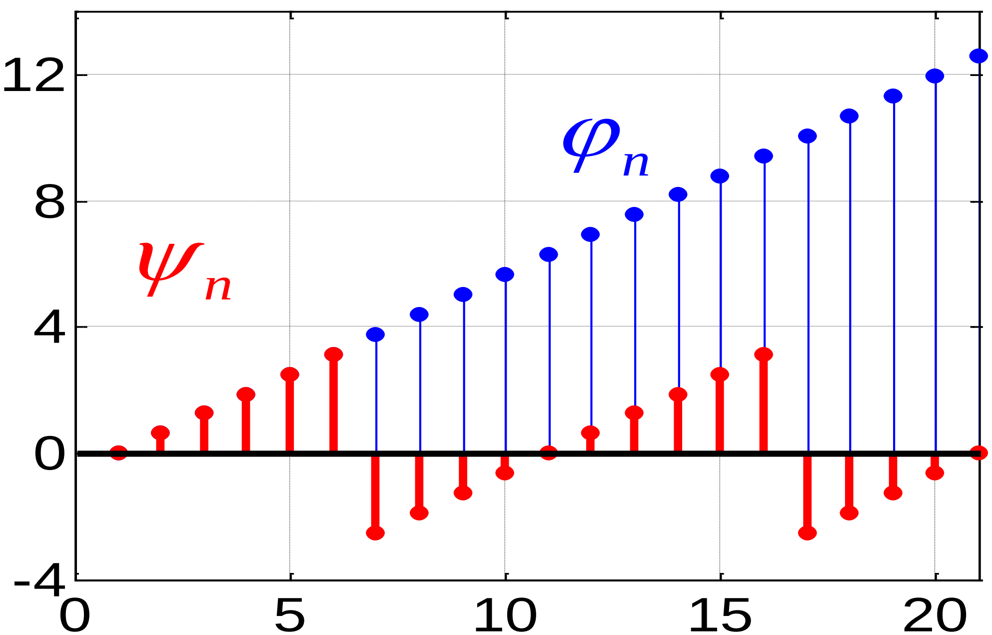
1D Phase unwrapping

Problem: Wrapped phase value of sample *n* are represented as angles within the range -pi ~ +pi.

$$\psi_n = W(\varphi_n) = angle\{\exp(j\varphi_n)\}$$

Given a sequence of wrapped phase values ψ_n we want to recover the unwrapped phase values φ_n





1D Phase unwrapping

Solution:

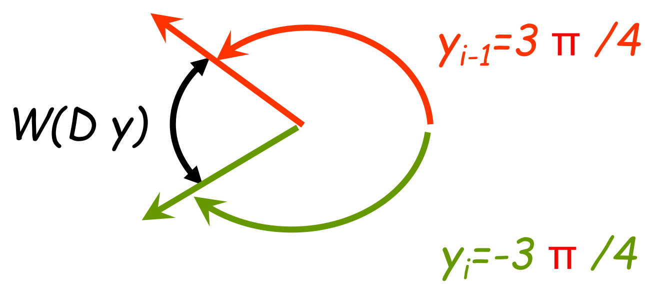
We assume that the phase difference between 2 samples (adjacent) is not aliased, hence the absolute value of discrete gradient $\Delta f= f_i- f_{i-1}$ should always be < π.

The discrete gradient Δf is estimated it by **wrapping the difference of the wrapped phase** $\Delta_e f= W(\Delta y)$.

For example $y_{i-1} = 3\pi/4; y_i =- 3\pi/4$ ⇨

$\Delta y= -6/4\pi$

$\Delta_e f= W(\Delta y)= -6/4\pi +2\pi = \pi/2$



The unwrapped phase f is then computed (but for a constant) by integrating the gradient $\Delta_e f$.

If the absolute value of the discrete gradient $\Delta f= f_i- f_{i-1}$ is > π , then unwrapping errors occur.

Recommend resources

InSAR Principles Guidelines for SAR Interferometry

https://www.esa.int/About_Us/ESA_Publications/InSAR_Principles_Guidelines_for_SAR_Interferometry_Processing_and_Interpretation_br_ESA_TM-19