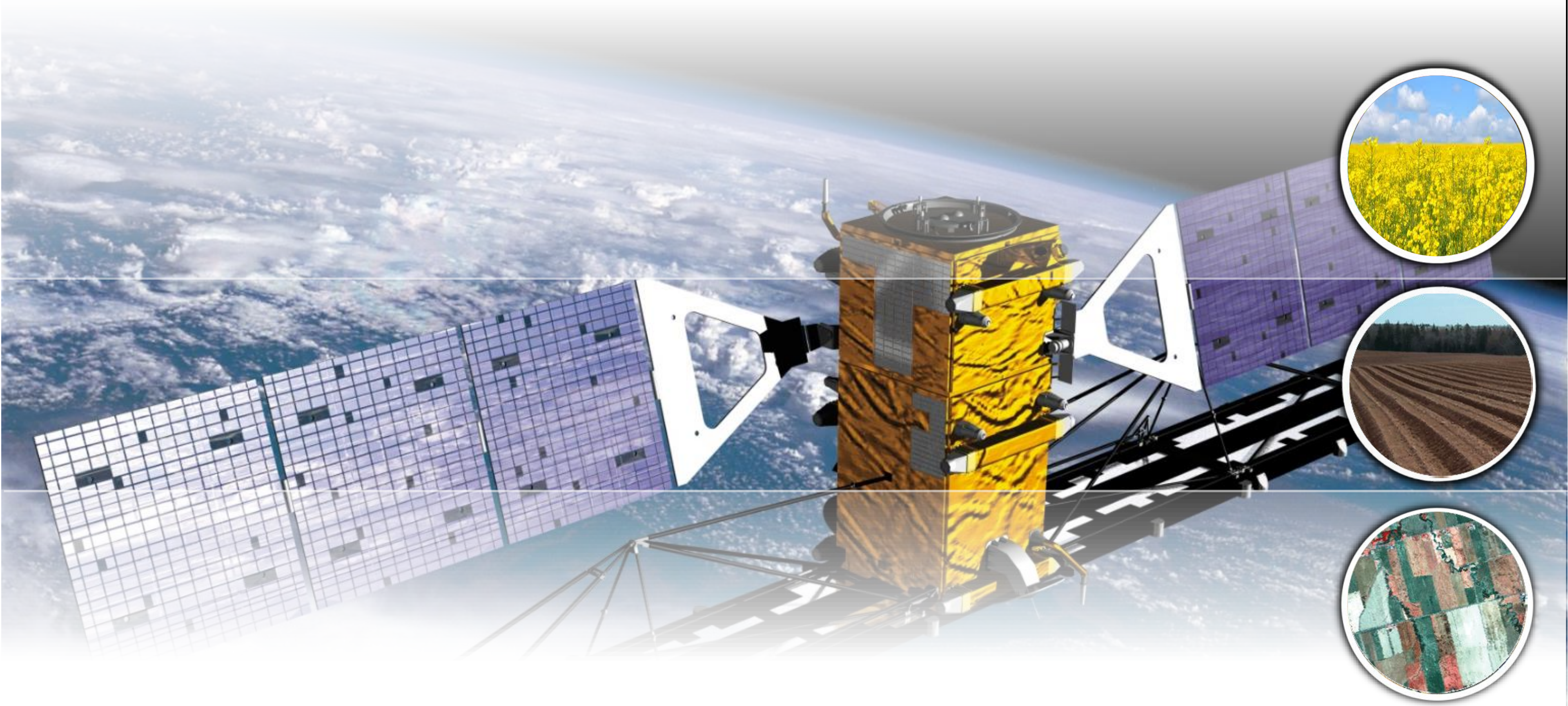
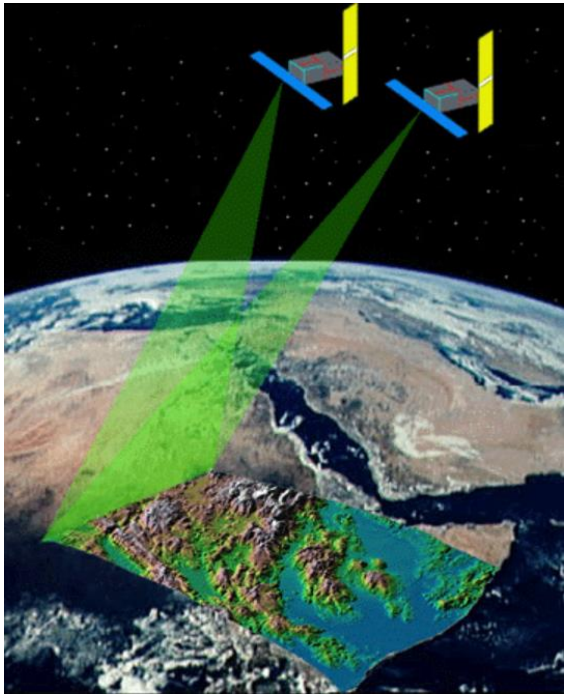
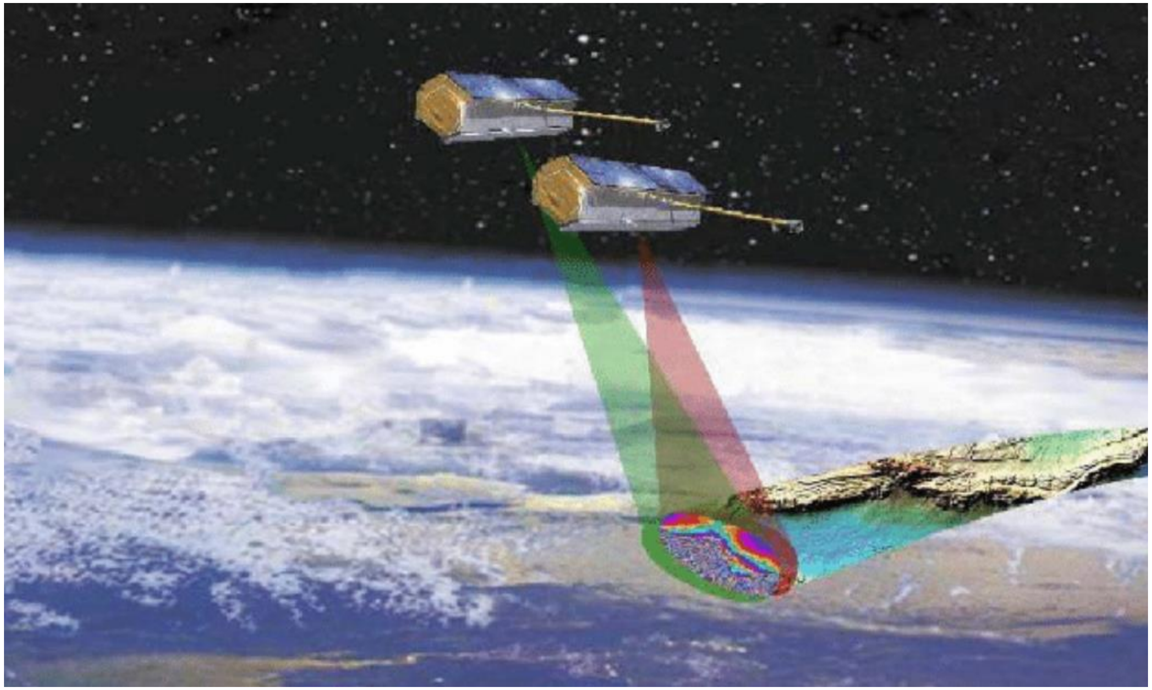


Lecture 7:
Interferometric SAR - Theory

What is InSAR?

- Radar interferometry can be broadly defined by use of phase measurements to precisely measure the relative distance to an object when imaged by synthetic aperture radar from two or more observations separated either in time or space.

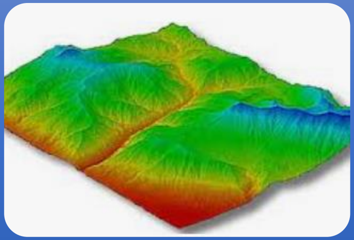




https://web.stanford.edu/group/radar/group.html

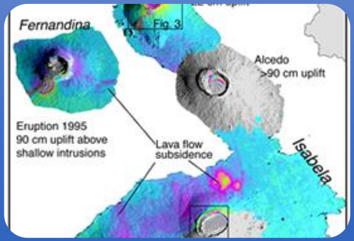
Rosen, 2014

Applications of InSAR: Examples (I)



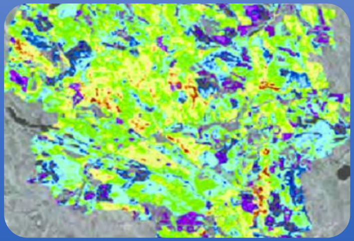
DEM generation

- SRTM
- TanDEM-X



Crustal deformation

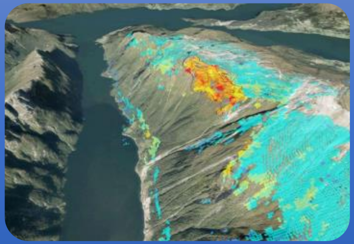
- earthquakes
- volcanoes



Forest monitoring

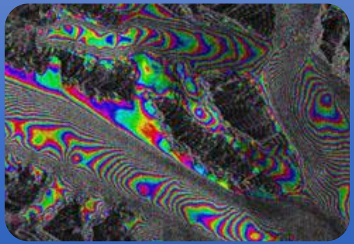
- Tree Height
- Tree species (PolInSAR)

Applications of InSAR: Examples (II)



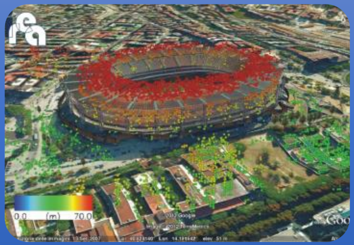
Land surface

- Landslide monitoring
- Subsidence related to mining



Cryosphere

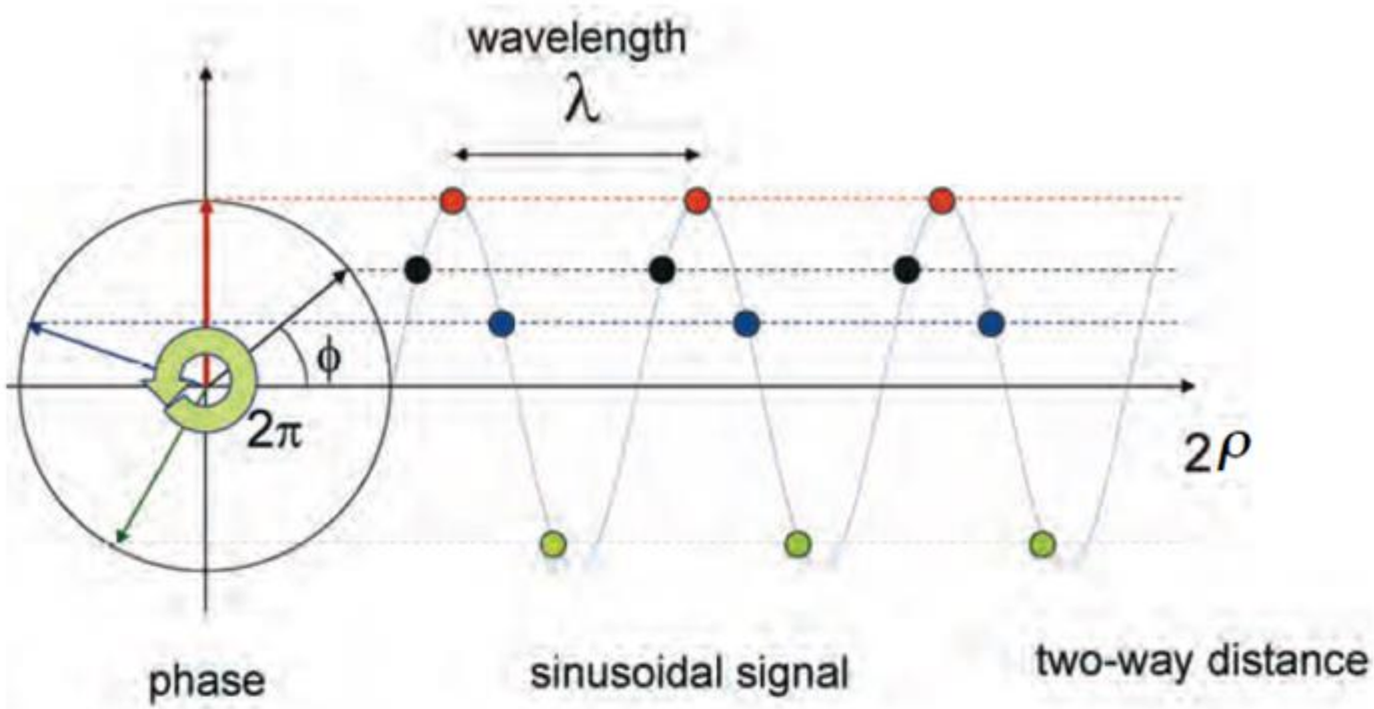
- Changes in glaciers and sea ice



SAR tomography

- 3D reconstruction

Phase in InSAR



$$\phi = \underbrace{2\pi}_{\text{Radians per wavelength}} \; \underbrace{\frac{2\rho}{\lambda}}_{\text{Number of wavelengths}}$$

Ferretti et al., 2007

Phase in InSAR

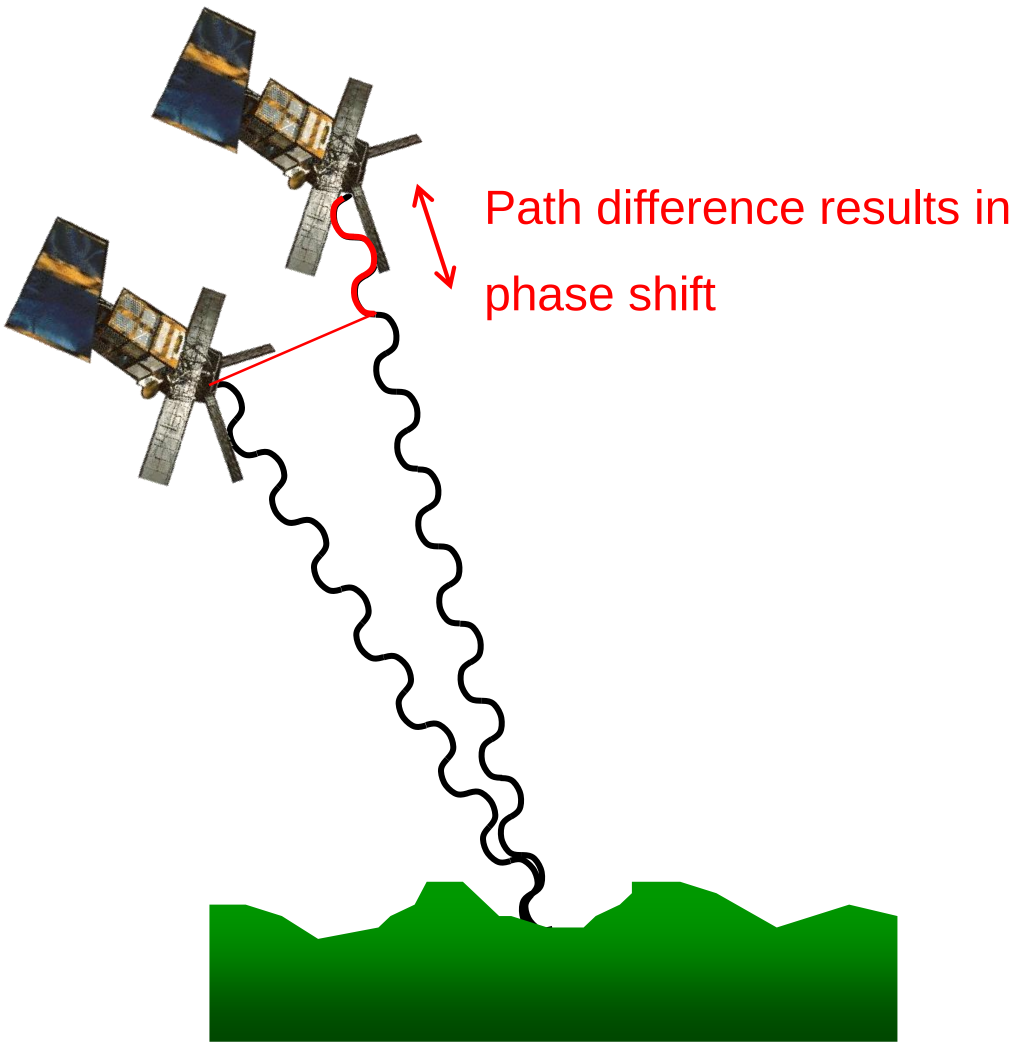
Phase of image 1 $\phi_1 = \frac{4\pi}{\lambda} \cdot \rho_1 + \text{ other constants } + n_1$

Phase of image 2 $\phi_2 = \frac{4\pi}{\lambda} \cdot \rho_2 + \text{ other constants } + n_2$

- The “other constants” cannot be directly determined.
- “Other constants” depends on scatterer distribution in the resolution cell, which is unknown and varies from cell to cell.
- Only way of observing the range change is through interferometry (cancellation of “other constants”).

InSAR for Topography

- Two measurements from different locations
- Difference between the two path lengths related to the difference in phase of the received electric fields.



Parsons and Walker, 2011

InSAR for Topography

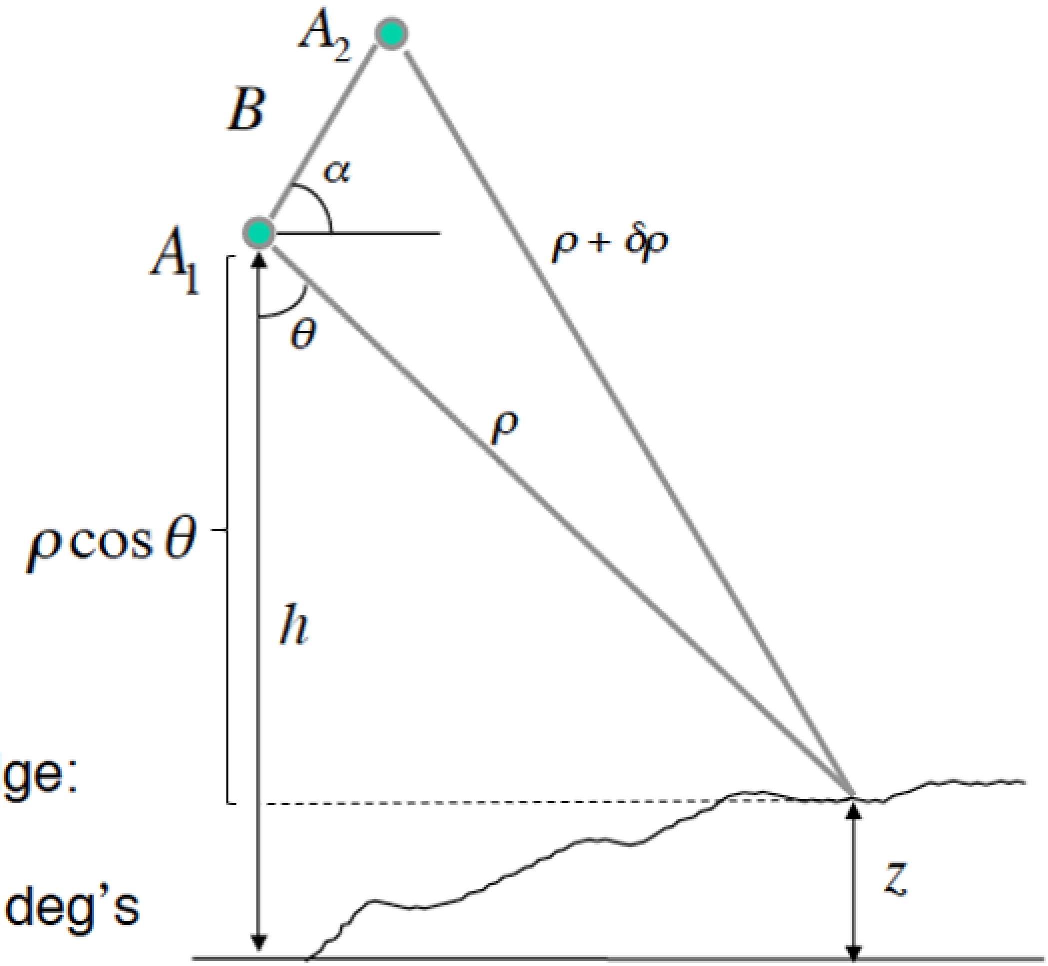
Measured phase difference:

$$\Delta\phi = -\frac{4\pi}{\lambda}\delta\rho$$

$$\delta\rho \xrightarrow{\text{Triangulation}} \theta$$

$$z = h - \rho\cos\theta$$

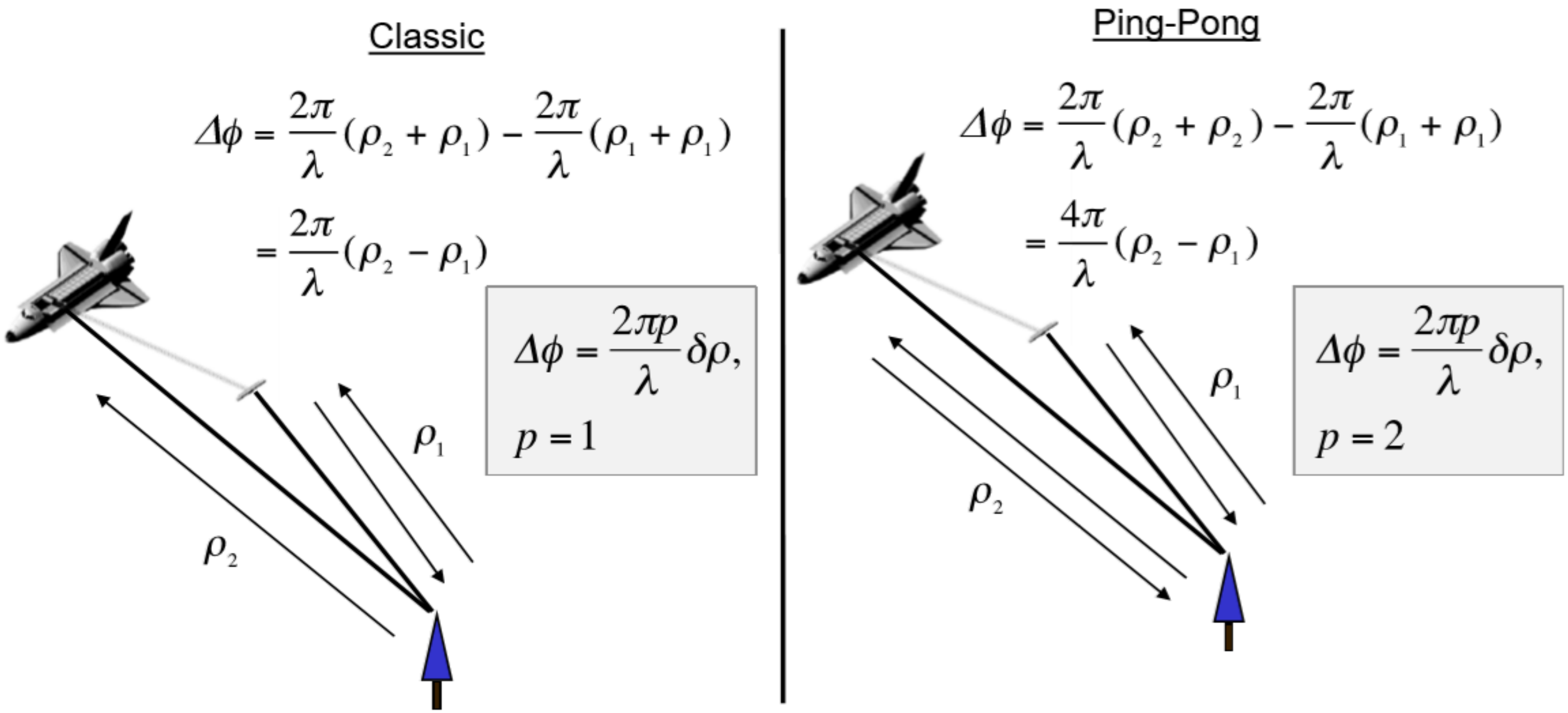
Critical Interferometer Knowledge:
- Baseline, (B,α), to mm's
- System phase differences, to deg's



Rosen, 2014

Data Collection (Option I)

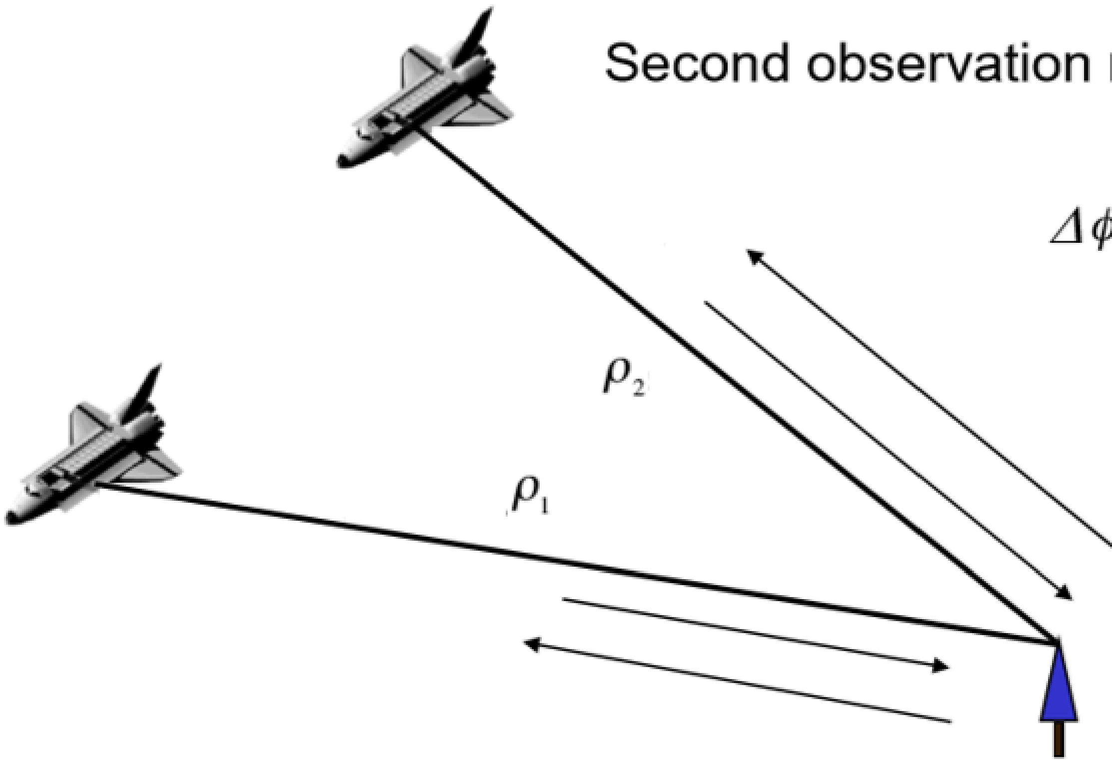
- For **single pass interferometry (SPI)** both antennas are located on the same platform, which is ideal for measuring topography. Two modes of data collection are common:
  - single transmitter mode - one antenna transmits and both receive
  - dual transmitter (ping-pong) mode - each antenna transmits and receives its own echoes effectively doubling the physical baseline. The measured phase differs by a factor of two.



Rosen, 2014

Data Collection (Option II)

- Interferometric data can also be collected in the **repeat pass mode (RPI)**. In this mode two spatially close radar observations of the same scene are made separated in time. The time interval may range from seconds to years. The two observations may be made with different sensors provided they have nearly identical radar system parameters. This kind of data can be used for topography or surface deformation measurements.



Second observation made at some later time.

$$\Delta\phi = \frac{2\pi}{\lambda}(\rho_2 + \rho_2) - \frac{2\pi}{\lambda}(\rho_1 + \rho_1)$$

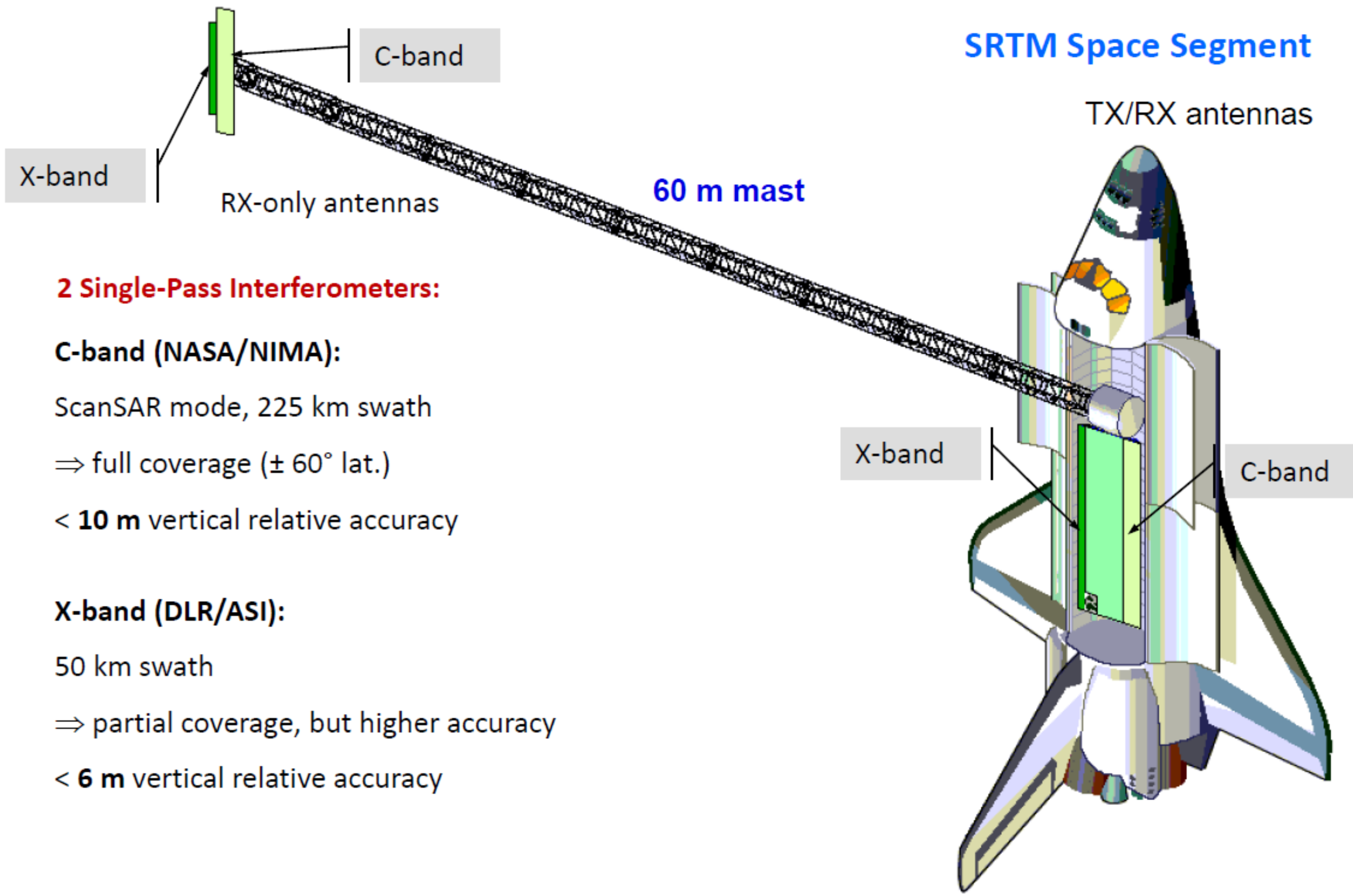
$$= \frac{4\pi}{\lambda}(\rho_2 - \rho_1)$$

$$\Delta\phi = \frac{2\pi p}{\lambda}\delta\rho,$$

$$p = 2$$

Rosen, 2014

InSAR Missions - SRTM (Shuttle Radar Topography Mission)



2 Single-Pass Interferometers:

C-band (NASA/NIMA):

ScanSAR mode, 225 km swath

⇒ full coverage (± 60° lat.)

< **10 m** vertical relative accuracy

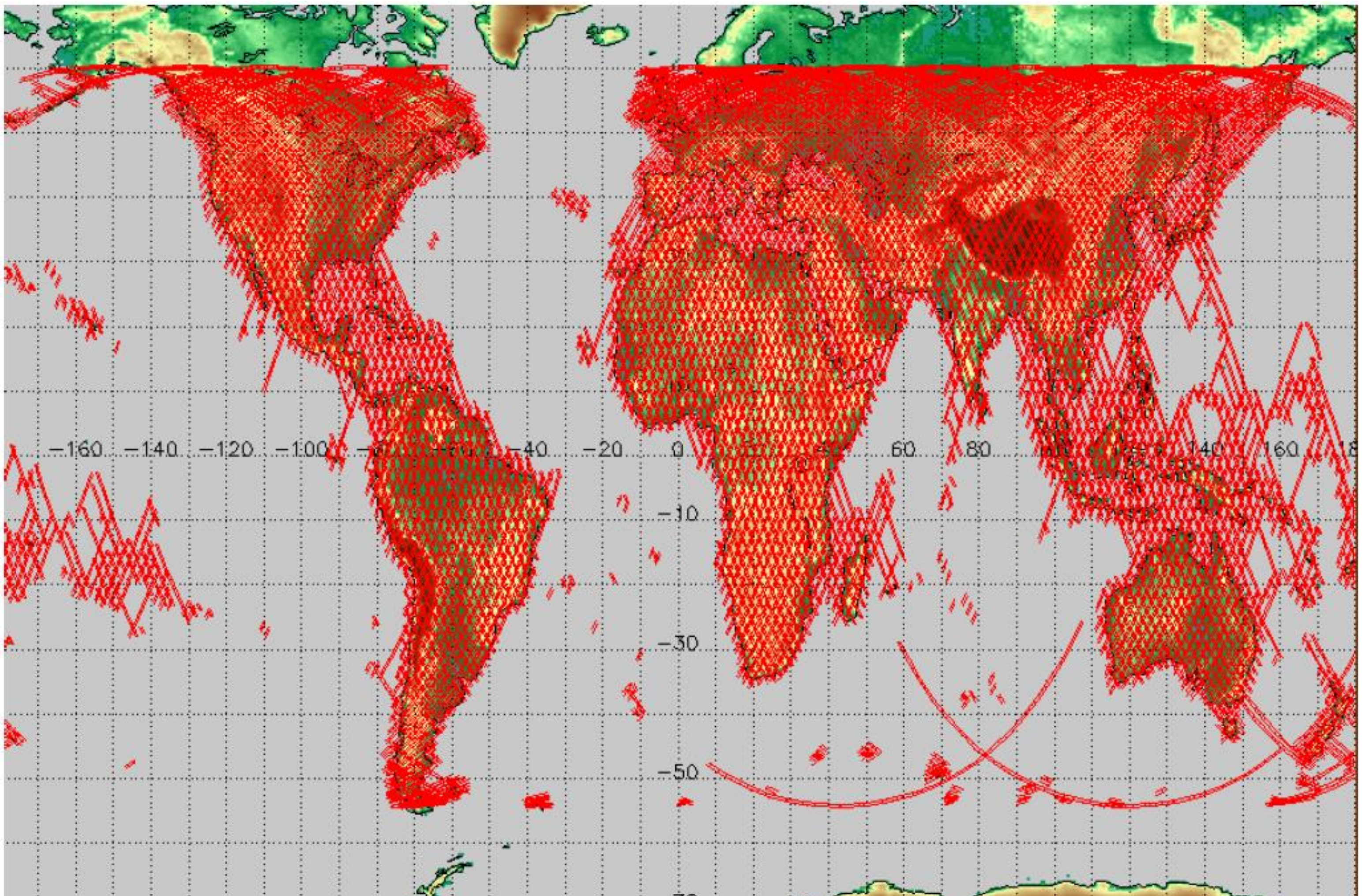
X-band (DLR/ASI):

50 km swath

⇒ partial coverage, but higher accuracy

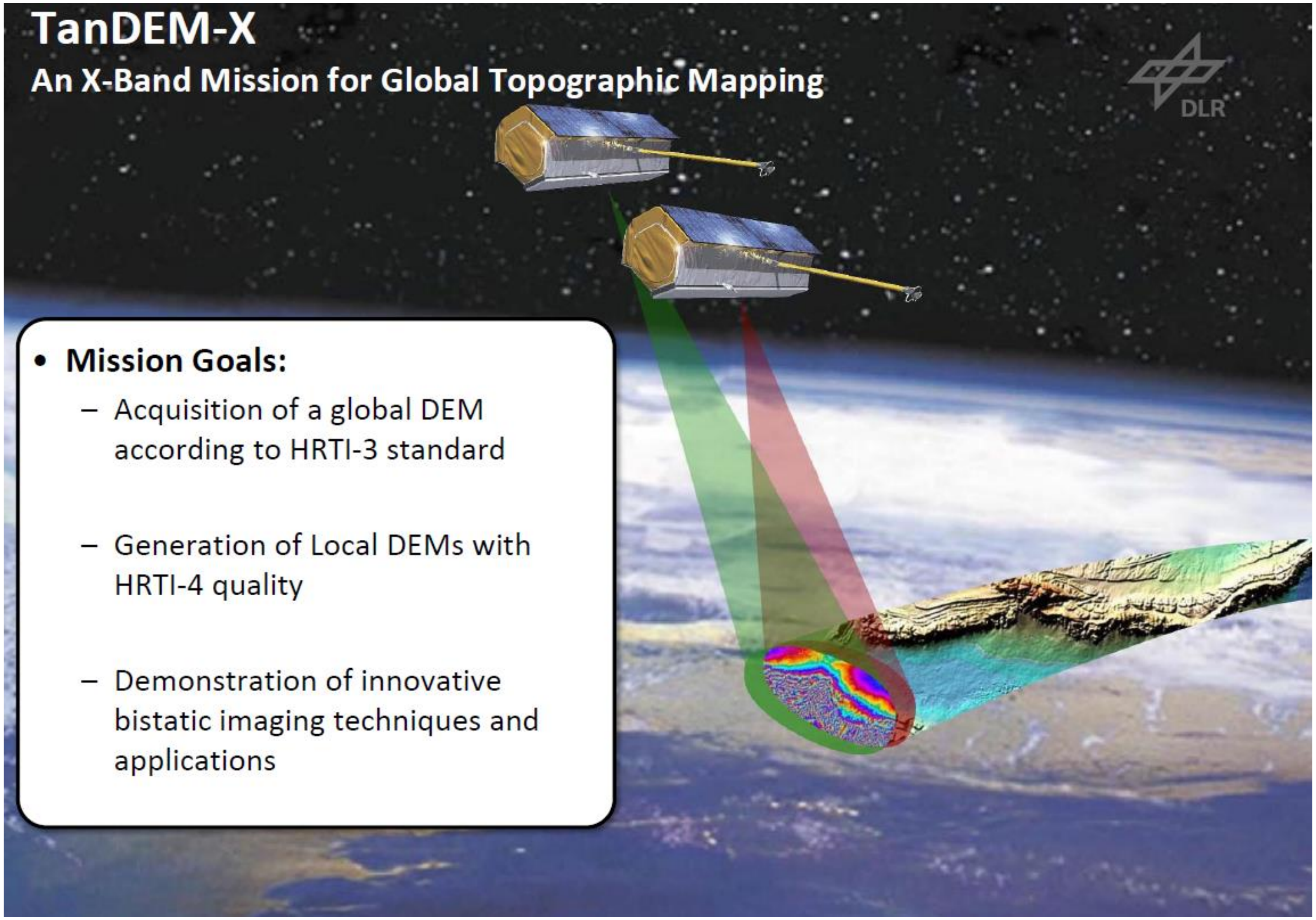
< **6 m** vertical relative accuracy

SRTM Coverage



Meyer, 2016

InSAR Missions – TanDEM-X

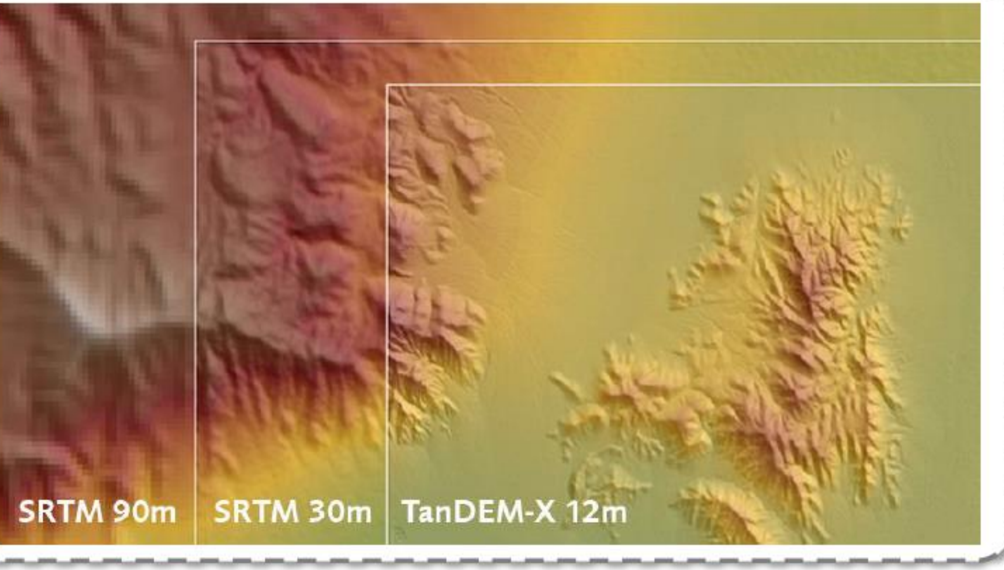


TanDEM-X
DEM Vertical Accuracy

	Spatial Resolution	Absolute Vertical Accuracy (90%)	Relative Vertical Accuracy (point-to-point in 1° cell, 90%)
DTED-1	90 m x 90 m	< 30 m	< 20 m
DTED-2	30 m x 30 m	< 18 m	< 12 m
TanDEM-X	12 m x 12 m	< 10 m	< 2 m
Level-4	6 m x 6 m	< 5 m	< 0.8 m

Visualization of improved DEM quality:

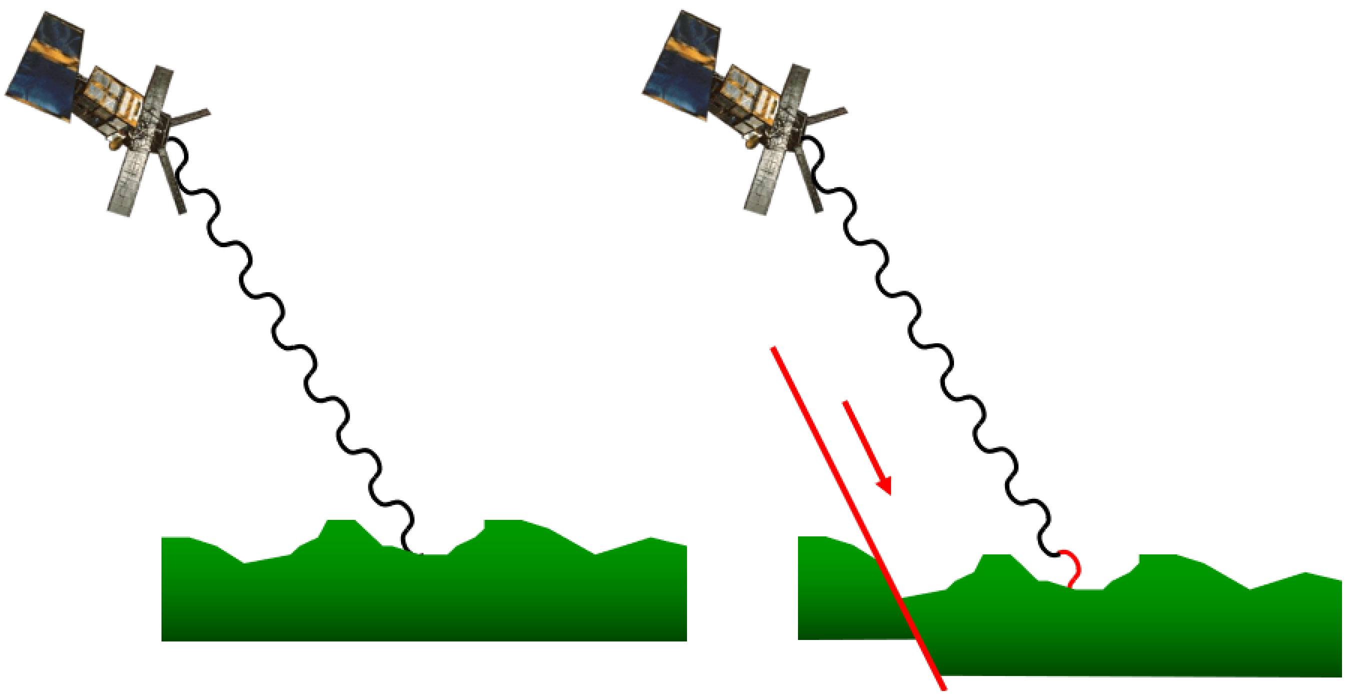
TanDEM-X vs. SRTM DEMs



DLR

InSAR for Deformation Monitoring

- Two measurements at different times.
- If the ground does not move, then residual phase will be zero apart from effects of environmental and instrumental noise.
- If the ground moves between SAR observations, then the residual phase will not be zero.

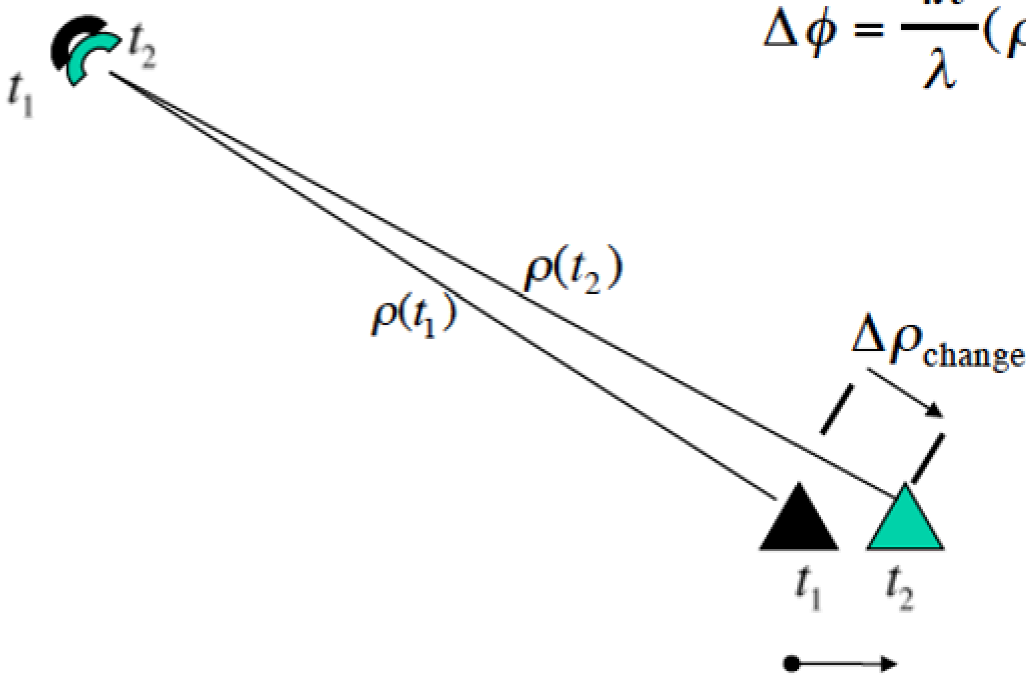


Parsons and Walker, 2011

Data Collection (Option I)

- When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

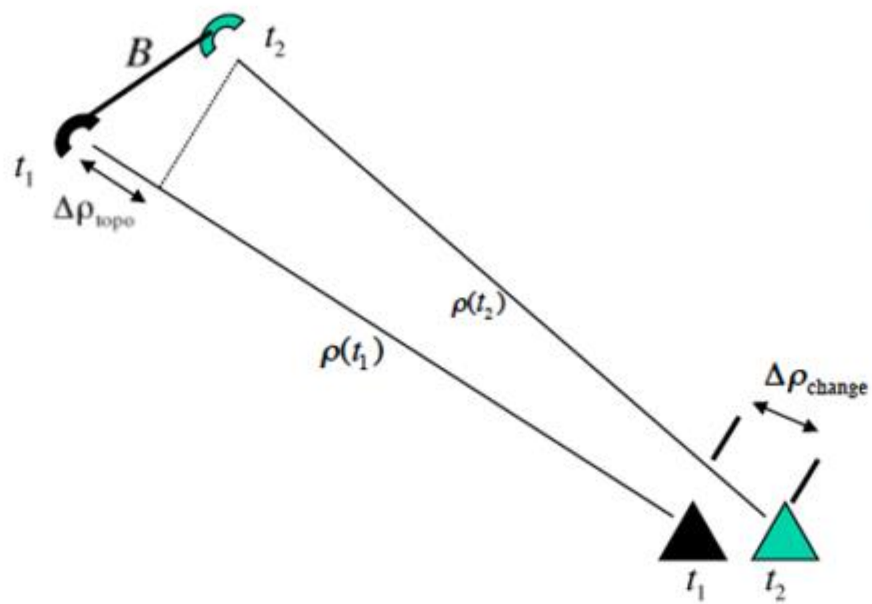
$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{\text{change}}$$



Rosen, 2014

Data Collection (Option II)

- Generally two observations are made from different locations in space and at different times, so the interferometric phase is proportional to topography and topographic change.



$$\Delta\phi = \frac{4\pi}{\lambda}(\Delta\rho_{change} - \Delta\rho_{topo})$$

If topography is known, then second term can be eliminated to reveal surface change

Note: Sensitivity of phase with respect to change is much greater than with respect to topographic relief

Rosen, 2014

InSAR Products

- Note that with two images, we can create two products:
  - An image of the phase information is known as the ***interferogram***
  - An image of the ***coherence*** (i.e. the correlation between the two images)
    - coherence near 1 means the phase information is reliable (and the images have high degree of correlation)
    - coherence < ~ 0.3 means the images have low correlation (noisy). In this case, the phase information is probably not useful.

Interferogram

- The general terms of a single look complex (SLC) image can be written as:

$$C(x) = A(x)e^{i\phi(x)}$$

where $C(x)$ is a complex value, $A(x)$ is amplitude, $\phi(x)$ is phase, e is Euler's number of exponential function and $i = \sqrt{-1}$ is an imaginary number.

- When using two SLC images acquired at different times to produce a complex interferogram, this complex interferogram consists of backscatter amplitude and phase change between observations.

$$C_2C_1^* = A_1A_2e^{i(\phi_2 - \phi_1)}$$

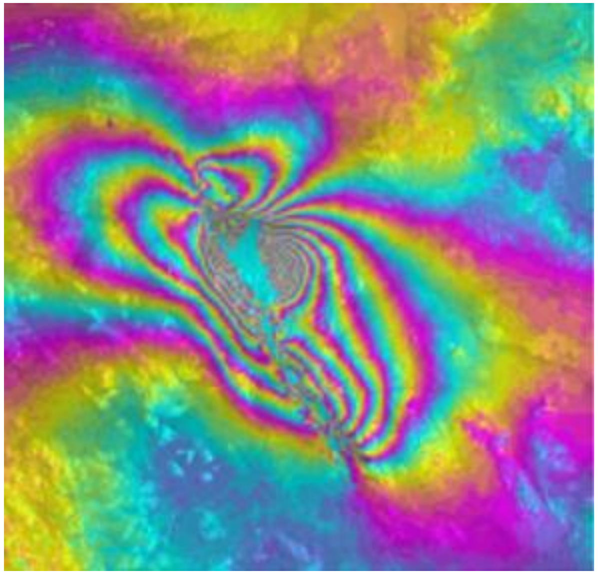
where C_1 and C_2 are master and slave SLC images, A_1 and A_2 are master and slave amplitudes and ϕ_1 and ϕ_2 are master and slave phases. The notation $*$ is the complex conjugation

Interferogram

- The SAR interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second (Bamler, 1998). Thus, the interferogram amplitude is the amplitude of the first image multiplied by that of the second one, whereas its phase (the **interferometric phase**) is the phase difference between the images.

- This phase difference is the result of a path length difference that can be caused by elevation differences, motion, or deformation.

- The interference pattern, also called **FRINGE**, is stored in a range of [-π , π].



One cycle of color represents one cycle of relative phase.

Interferometric Sensitivity as a Function of Wavelength

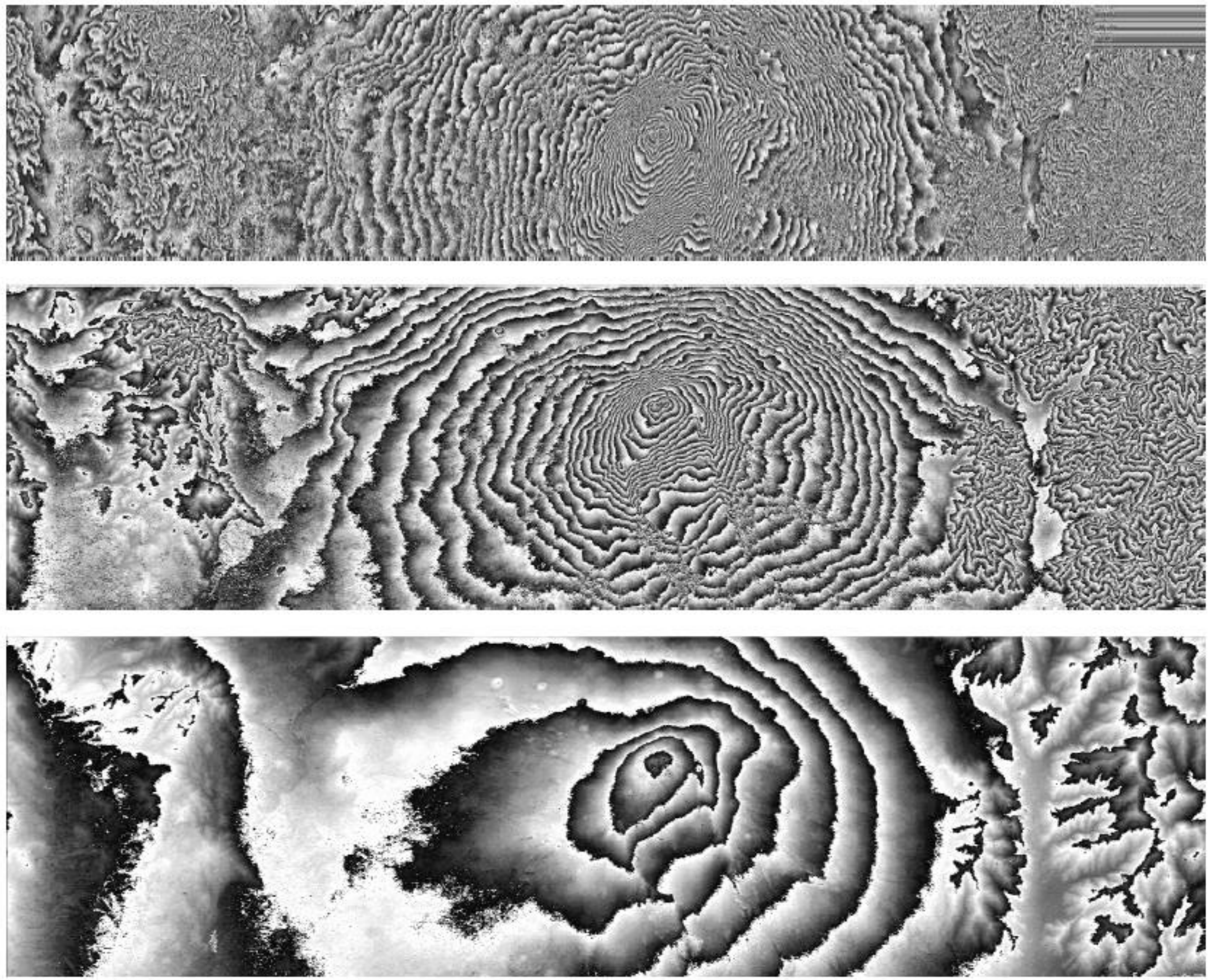
Three simultaneously acquired Interferograms with identical $B_\perp$, R, and θ but varying λ

X-band
$\lambda \approx 3.1cm$

C-band
$\lambda \approx 5.6cm$

L-band
$\lambda \approx 24.0cm$

Mt. Etna
data: SRL-2



Meyer, 2016

InSAR Study of 17 August 1999 Mw 7.6 Izmit Earthquake

Image source: Parsons and Walker, 2011

Making an Interferogram

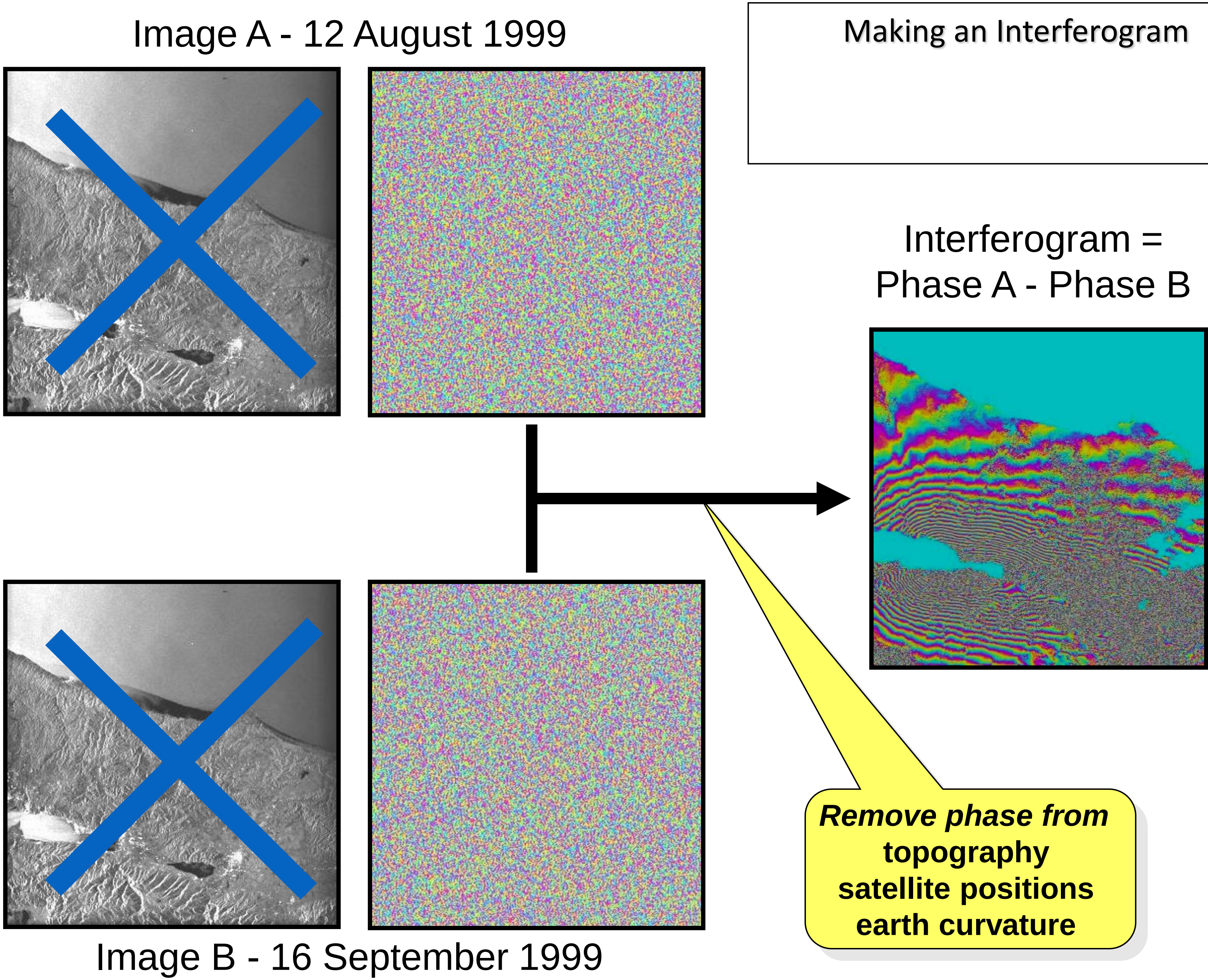
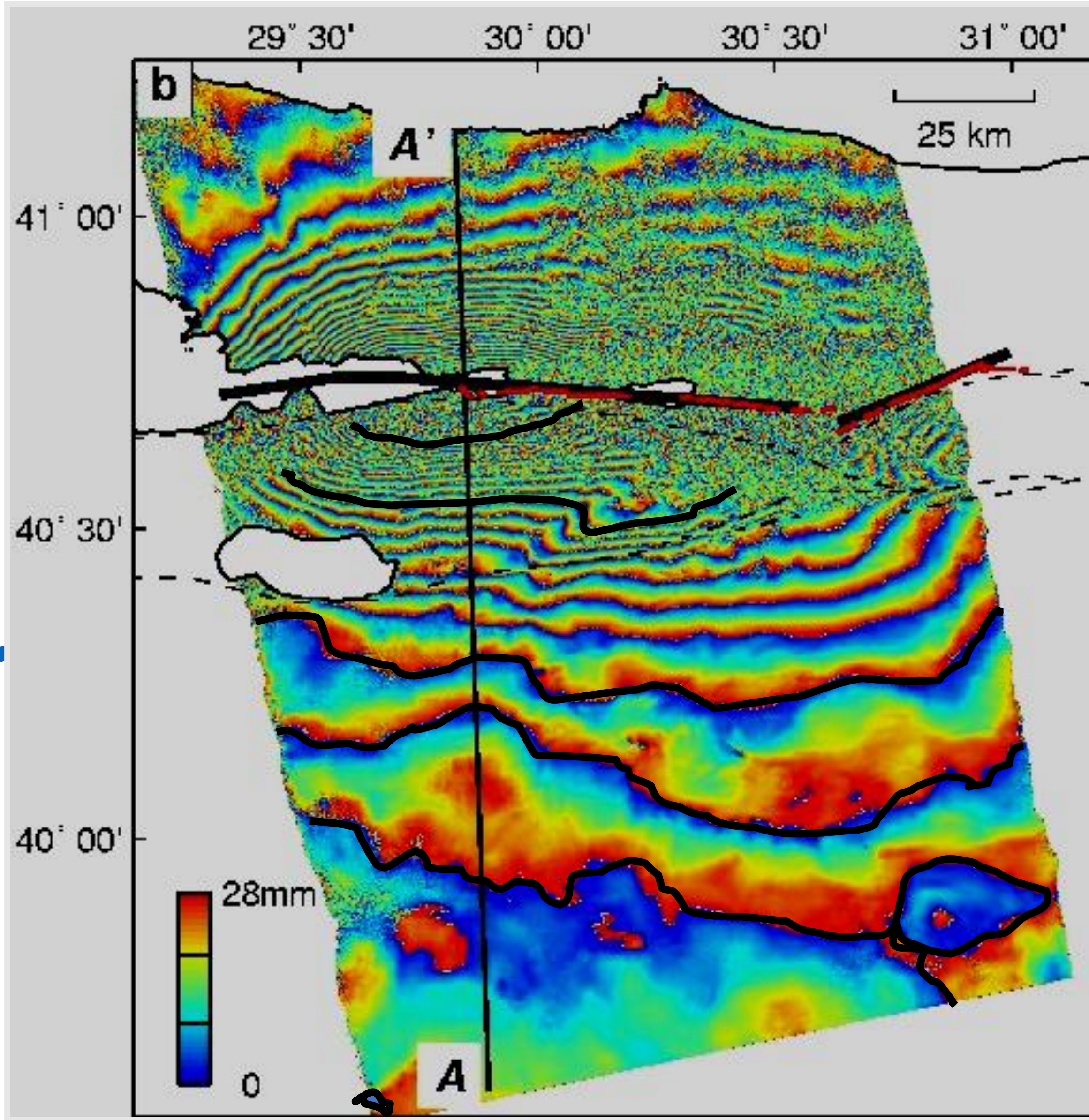


Image source: Parsons and Walker, 2011

Izmit Earthquake Interferogram



1 fringe = 28 mm line of site deformation for ERS

(-20) 567 mm range decrease

(-10) 283 mm range decrease

(-3) 85 mm range decrease

(-2) 57 mm range decrease

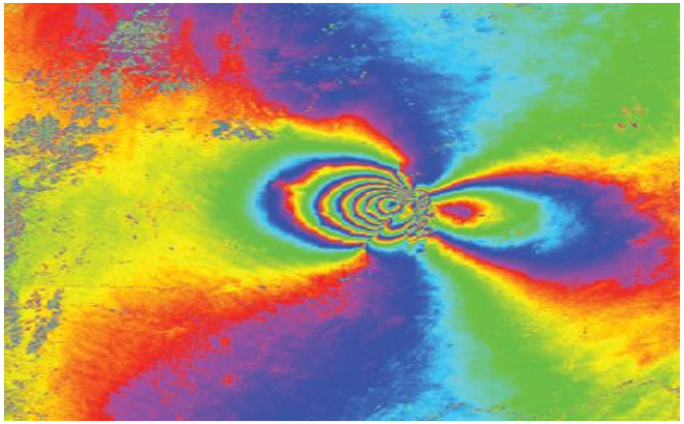
(-1) 28 mm range decrease

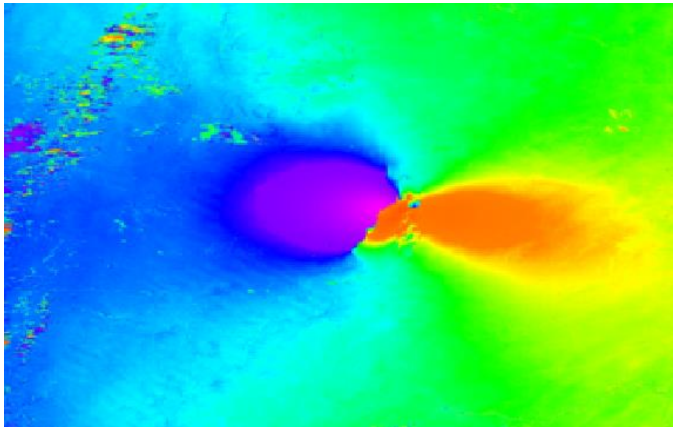
(0) 0 mm range change

Image source: Parsons and Walker, 2011

Phase unwrapping

Phase can only be detected between –π and π but the actual phase shift between two waves is often more than this. Phase unwrapping is the process of reconstructing the original phase shift from this "wrapped" representation. It consists of adding or subtracting multiples of 2π in the appropriate places to make the phase image as smooth as possible. To convert interferometric phase into elevation, you must perform phase unwrapping.





Mellors et al., 2017

Coherence

The coherence is a measure of the correlation of the phase information of two corresponding signals and varies in the range of 0 to 1.

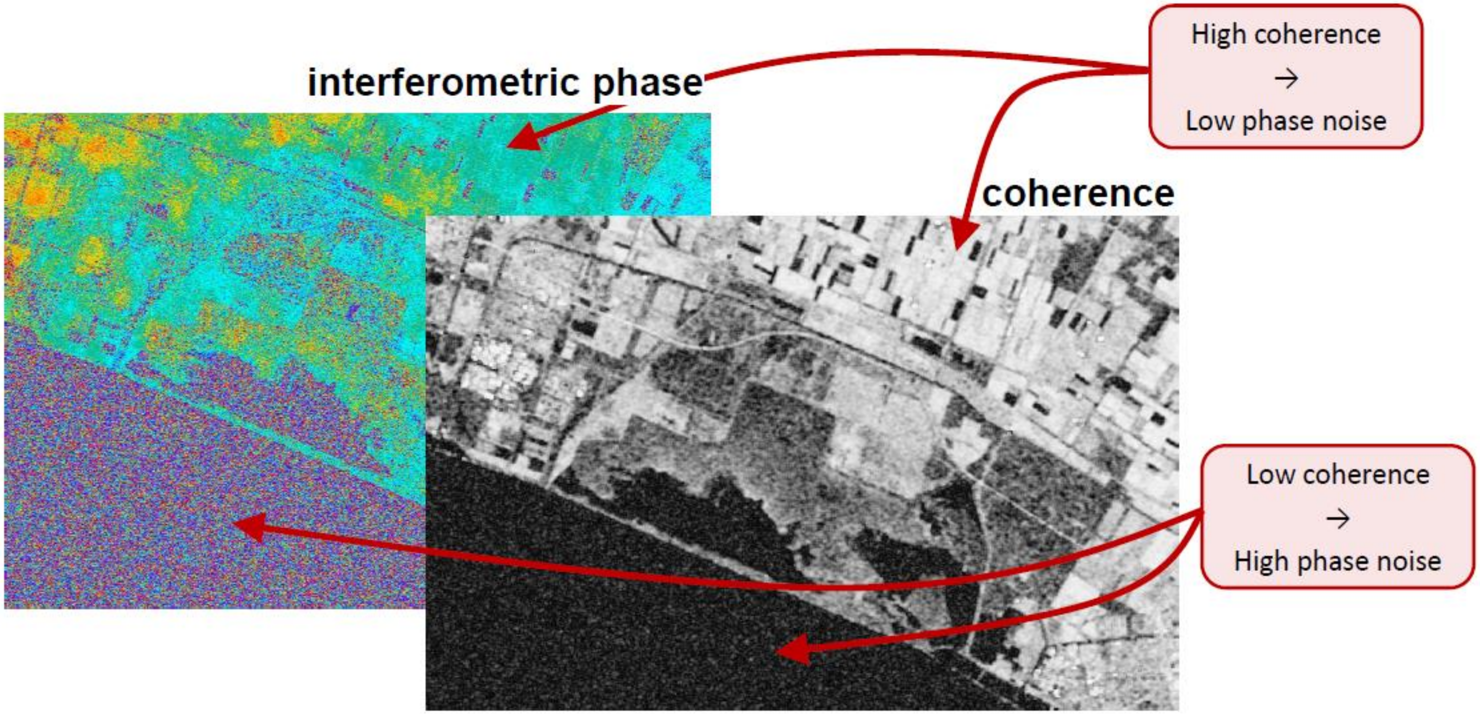
It is derived by estimating the cross-correlation coefficient of the SAR image pair estimated over a small window (a few pixels in range and azimuth), once all the deterministic phase components (mainly due to the terrain elevation) are compensated for.

The degree of coherence can be used as a quality measure because it significantly influences the accuracy of phase differences and height measurements.

Bright areas indicate regions of high coherence, whereas dark areas represent low coherence regions.

Coherence

- **Coherence** is an indicator for the **level of noise in phase** of interferogram pixel.
- Coherence is defined between 0 (high phase noise) and 1 (low phase noise)

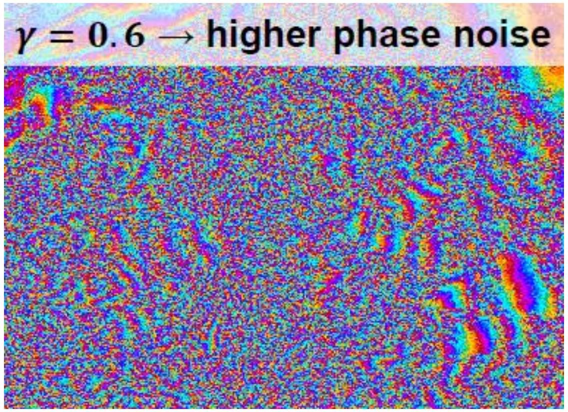


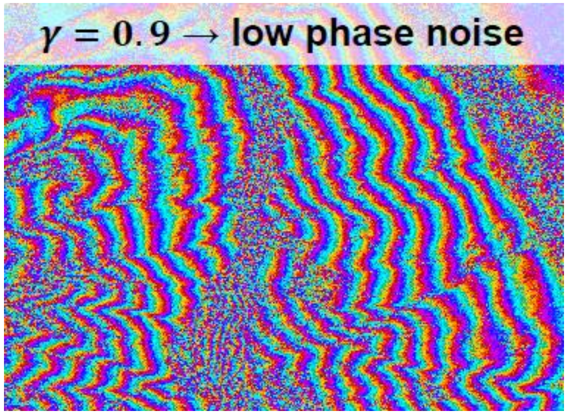
Meyer, 2016

Effective Factors on Coherence

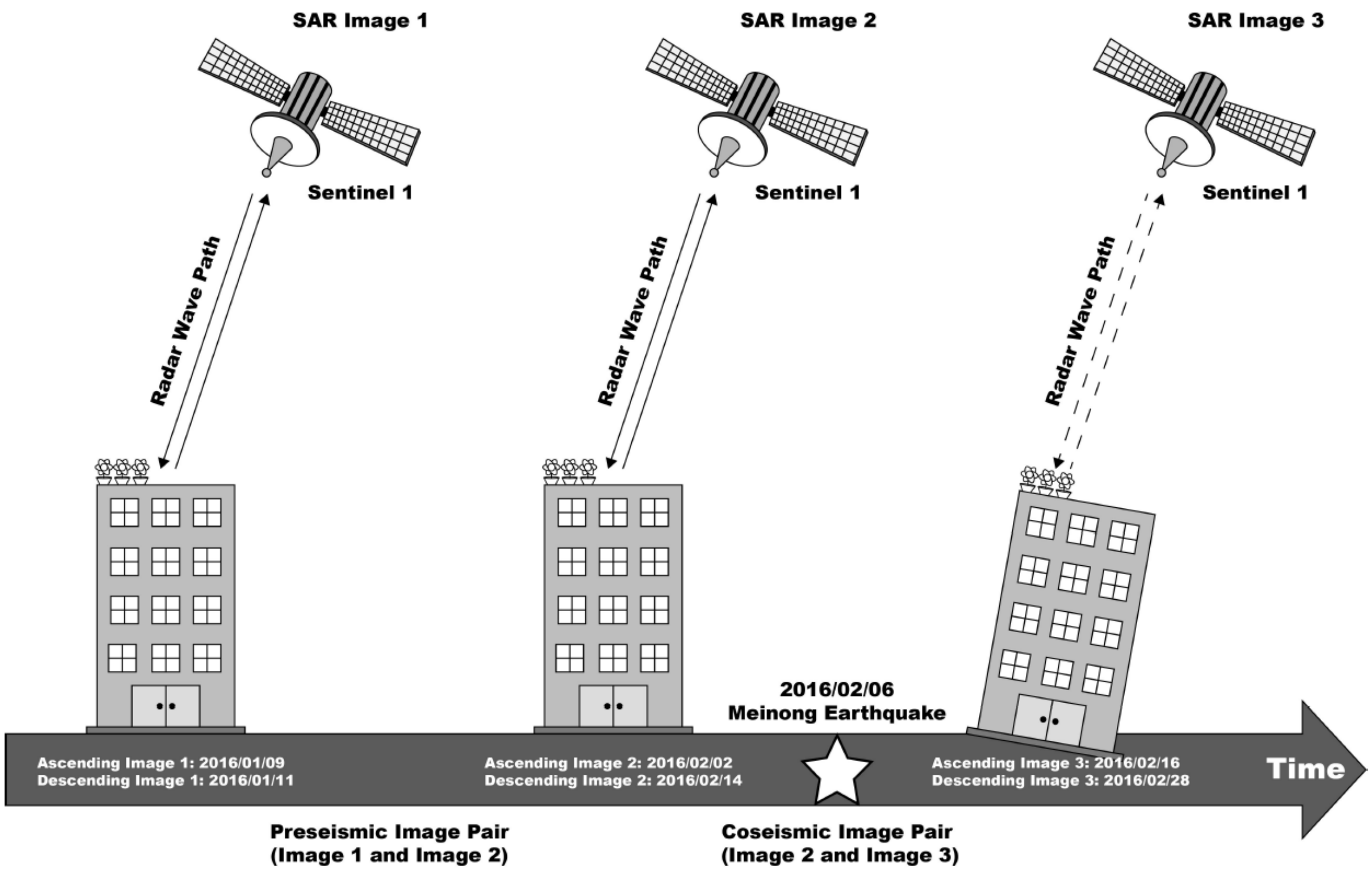
There are several factors decreasing the coherence. In approximate order:

- Properties of the surface being imaged (vegetated or moving surfaces have low coherence).
- Time difference between the passes in an interferogram (long time difference lead to low coherence)
- The baseline (large baselines lead to low coherence)
- Technical details of the generation of the interferogram (poor co-registration or resampling leads to low coherence)



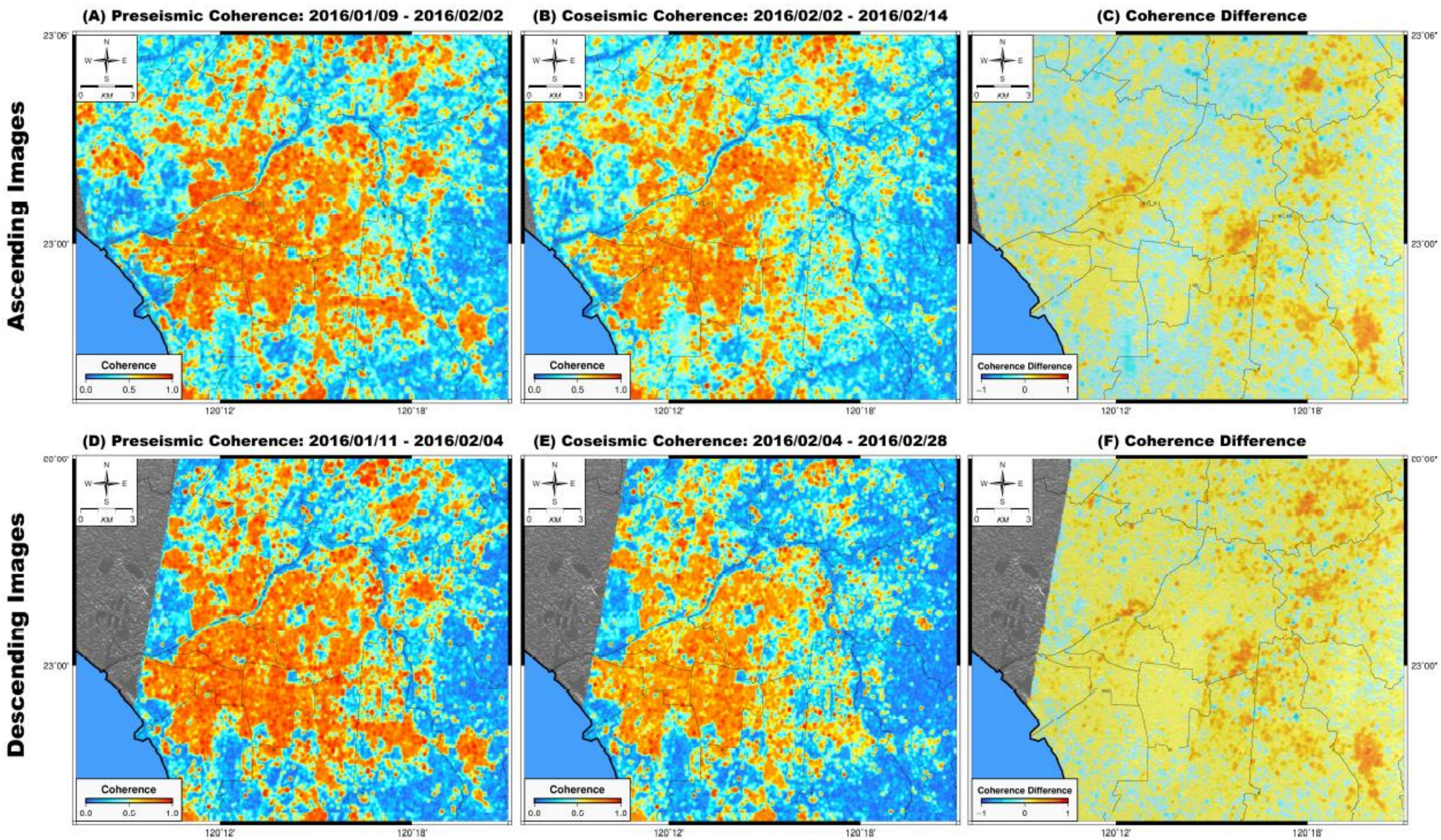


Coherence Difference Example: Meinong Earthquake 2016



Lu et al., 2018

Example: Meinong Earthquake 2016



Lu et al., 2018

Satellite Options

Satellite	Band	Precision	Vegetation	Resolution	Revisit Time (days)
Cosmo-SkyMed	X	3 mm	Poor	3 m	4-16
TerraSAR-X/TanDEM-X/PAZ	X	2 mm	Poor	2-3 m	4-11
RCM	C	4 mm	Moderate	3 m	4
Sentinel-1	C	4 mm	Moderate	20 m	6-12
RADARSAT-2	C	4 mm	Moderate	3 m	24
SAOCOM-1A	L	2 cm	Excellent	1 m	16
ALOS-2	L	2 cm	Excellent	3 m	14

Acknowledgment

Carleton UNIVERSITY
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Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

CSA ASC

Natural Resources Canada
Ressources naturelles Canada

PCI GEOMATICS

Environment and Climate Change Canada
Environnement et Changement climatique Canada

INRS
Institut national de la recherche scientifique