SYNTHETIC APERTURE RADAR FOR MAPPING OF FOREST DEGRADATION AND DEFORESTATION

A ONE-WEEK TRAINING ON SAR

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Lecture 2: General Concepts of Interferometric SAR

Outline:

A FIRST INTRODUCTION TO INTERFEROMETRIC SAR (INSAR)

INSAR FOR TOPOGRAPHIC MAPPING

INSAR FOR DEFORMATION MONITORING

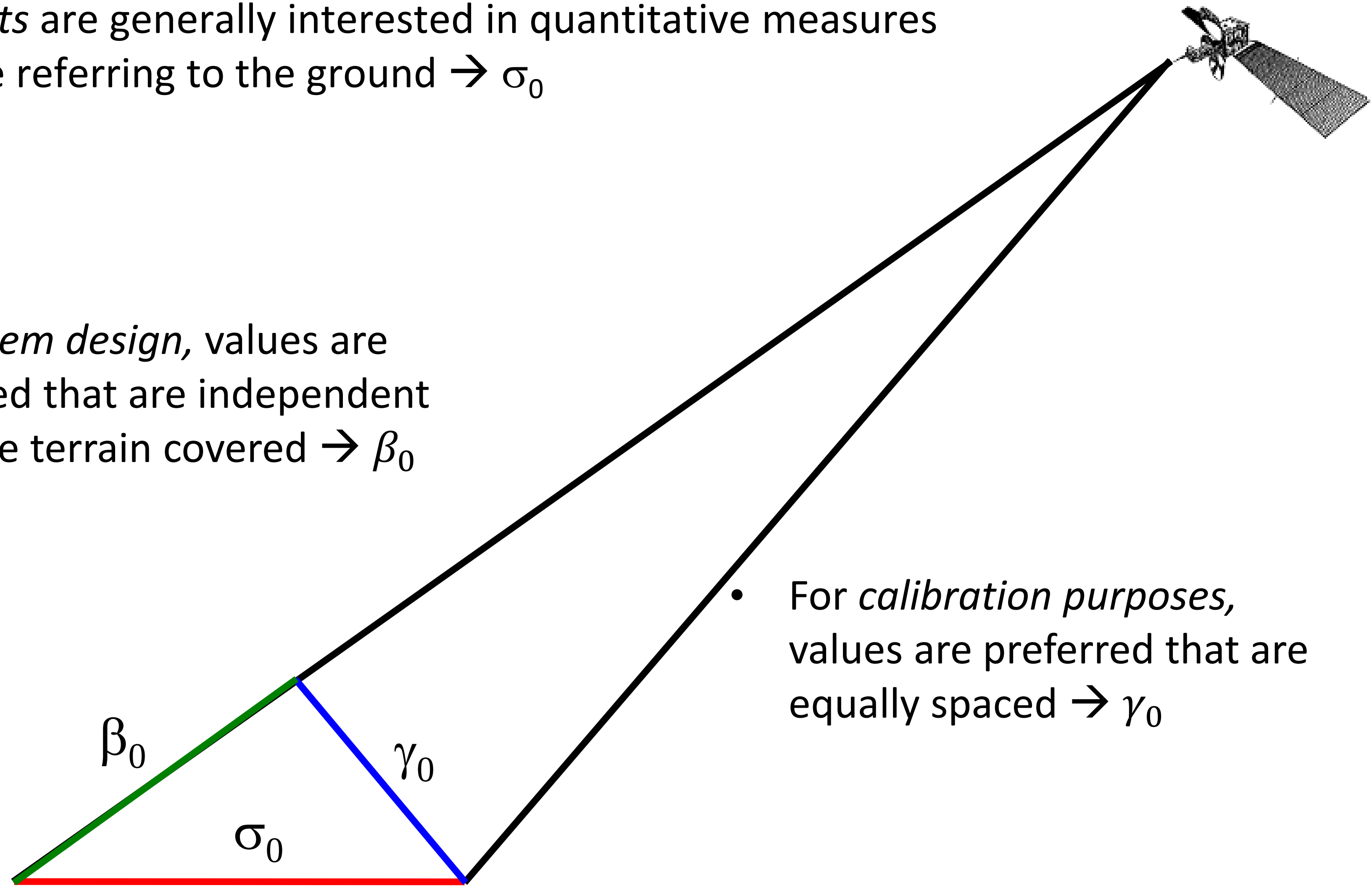
TIPS FOR SELECTING SUITABLE IMAGES FOR INSAR

Geometric View of σ^0, β^0, and γ^0

- *Scientists* are generally interested in quantitative measures that are referring to the ground → σ_0

- For *system design,* values are preferred that are independent from the terrain covered → β_0

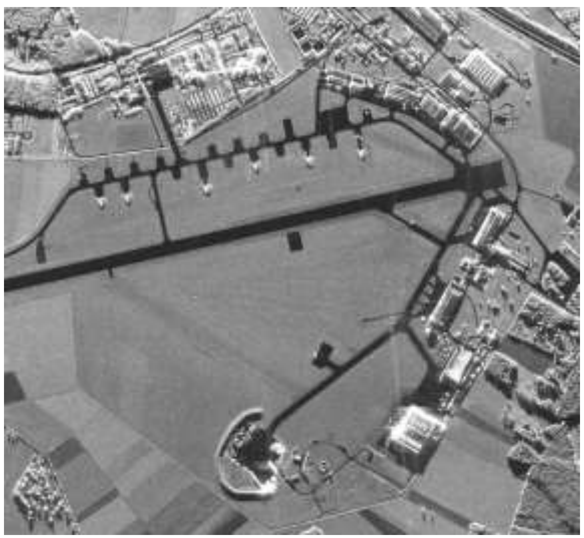
- For *calibration purposes,* values are preferred that are equally spaced → γ_0



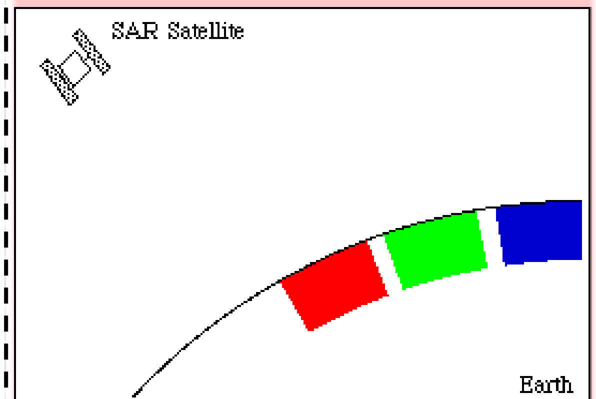
A SAR Acquisition …

… records both **Amplitude** and **Phase** of the reflected **polarized** microwave signals

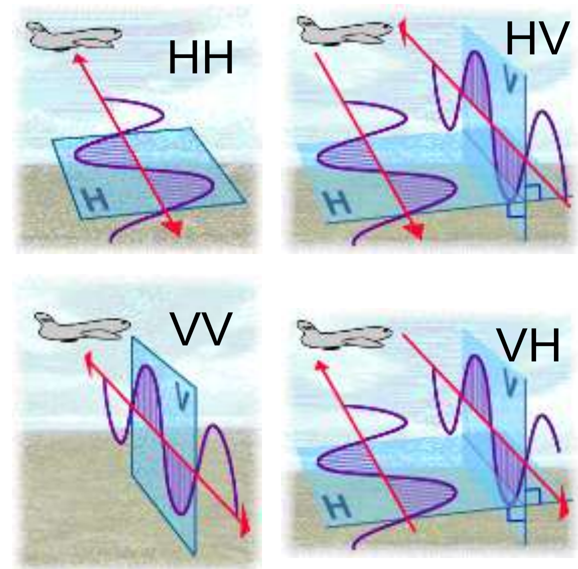
Amplitude forms SAR Image



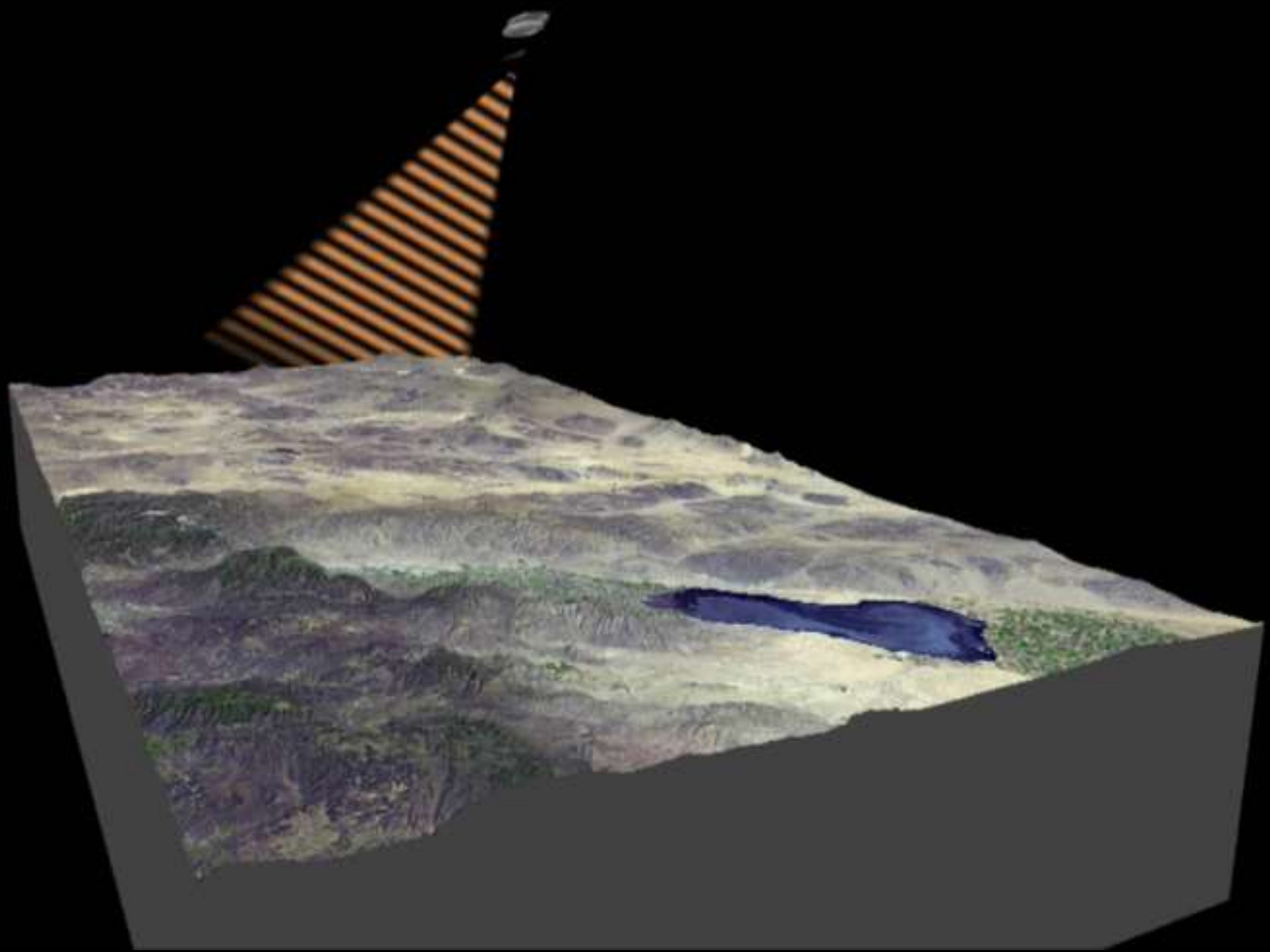
Phase measures the range to objects on ground



Polarization for analyzing surface types



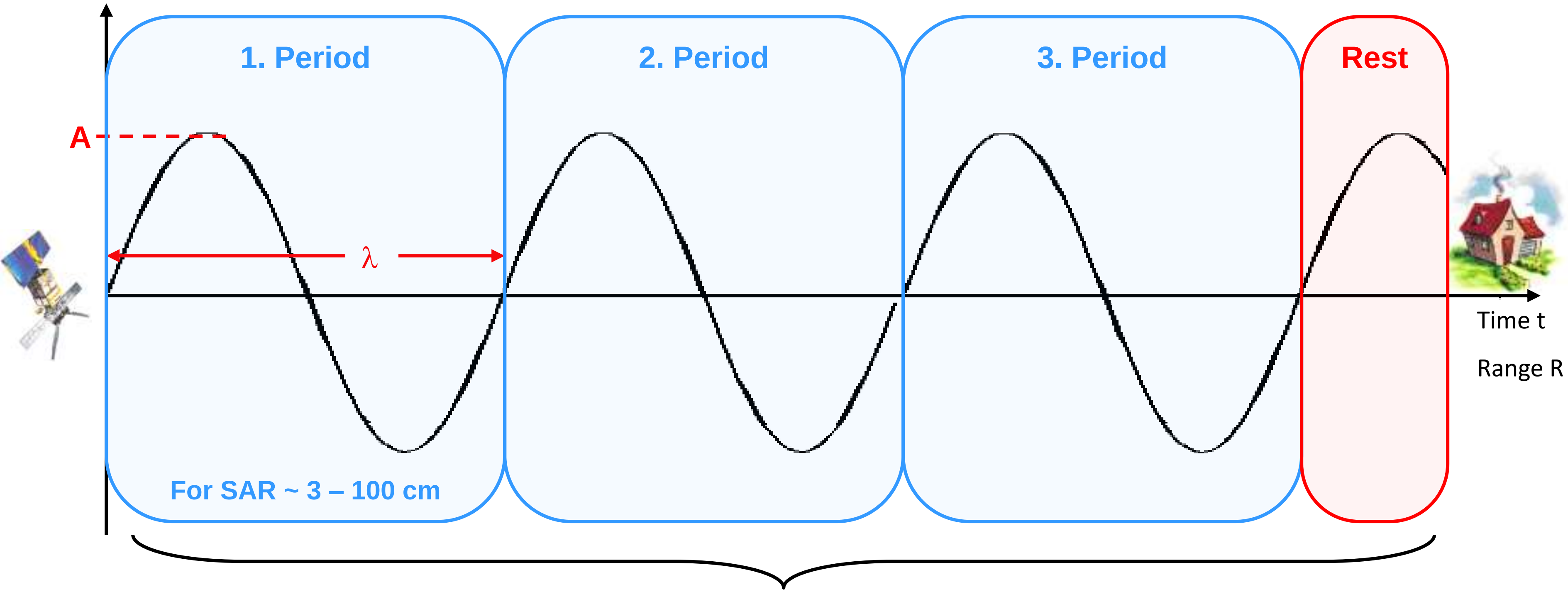
Interferometric SAR Measures Phase Differences Between Repeated Observations to Measure Topography and Deformation



Source: Jet Propulsion Laboratory (JPL)

What is the Phase of a Radar Signal

- A radar transmits electromagnetic waves in the radar spectrum
- The following schematic sketch illustrates a propagating radar wave



Distance = 3 full periods + a fraction of a period

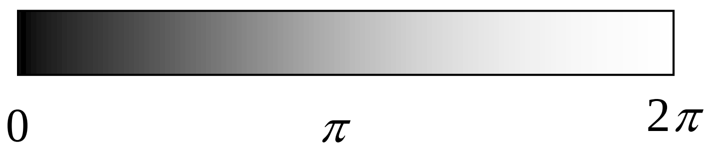
The length of the fractional period is described by the term "Phase"

Phase Representation

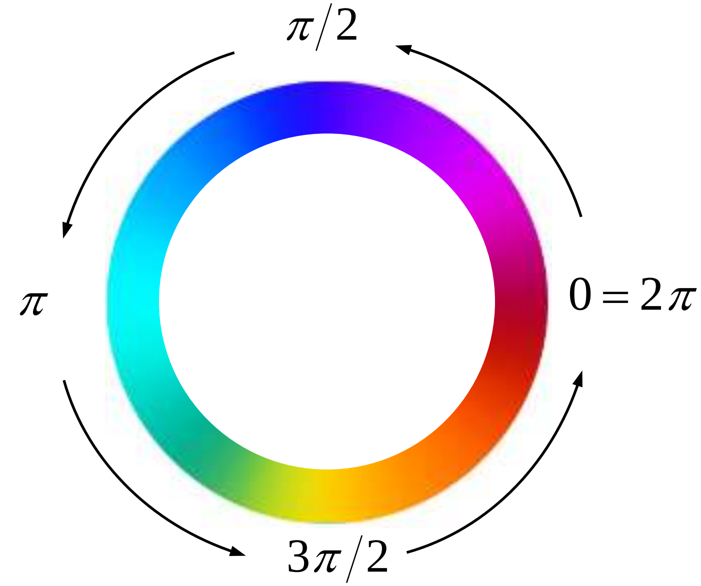
Phase is always ambiguous w.r.t. integer multiples of 2π

pictorial representation of phase:

grey value

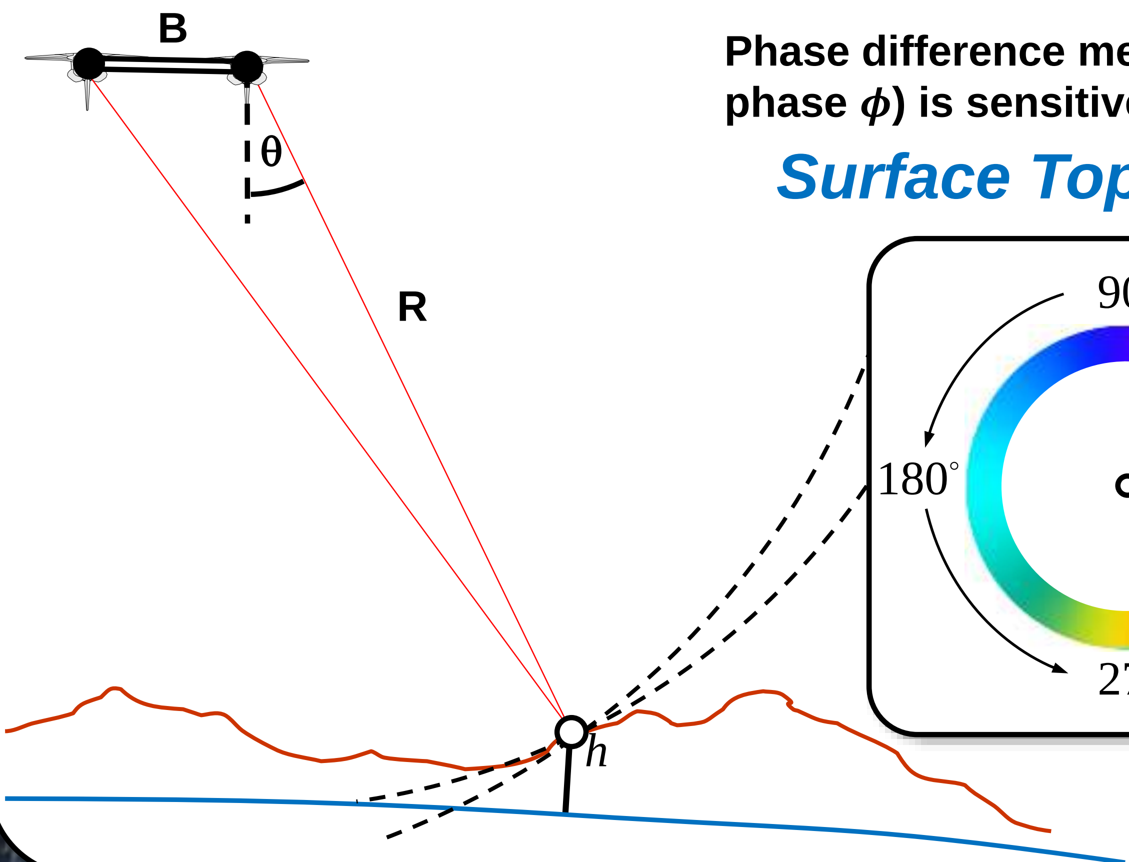


color wheel



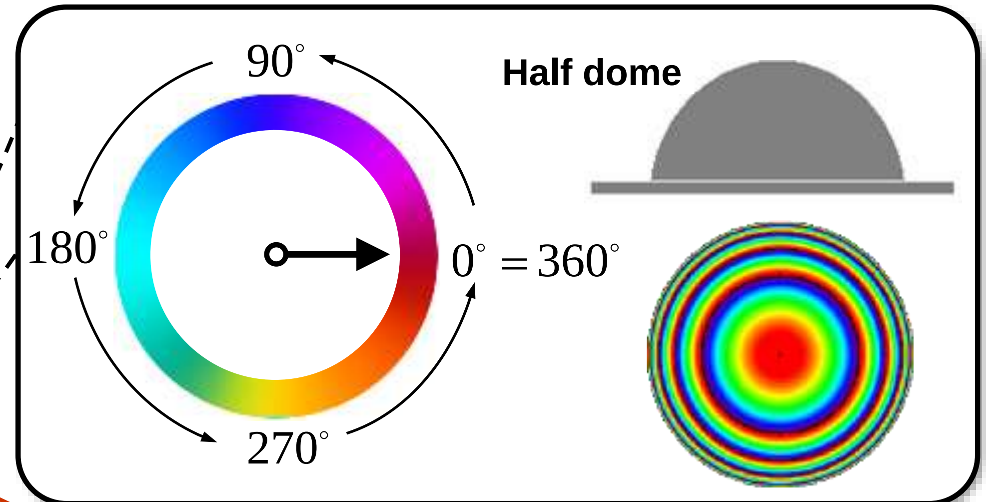
The Concept of Interferometric SAR (InSAR)

Calculation of Phase Difference between Pairs of Radar Remote Sensing Images acquired from similar vantage points

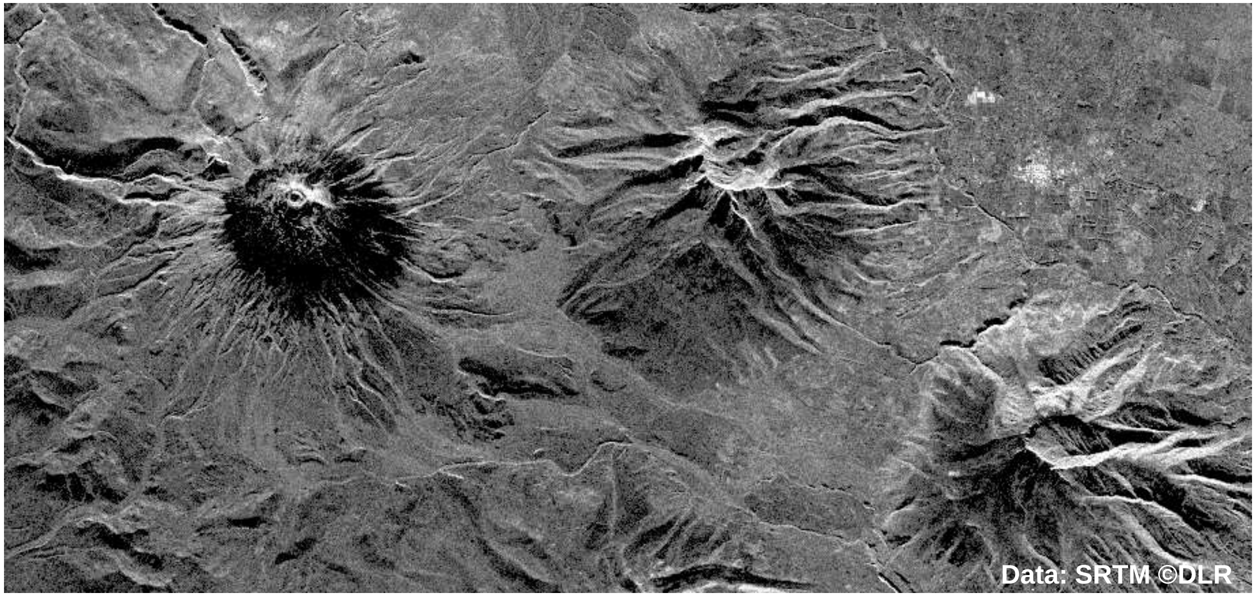


Phase difference measurement (interferometric phase ϕ) is sensitive to:

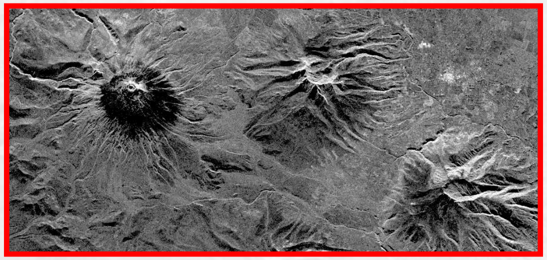
Surface Topography $\boldsymbol{\phi}(\boldsymbol{h}, B, R, \theta)$



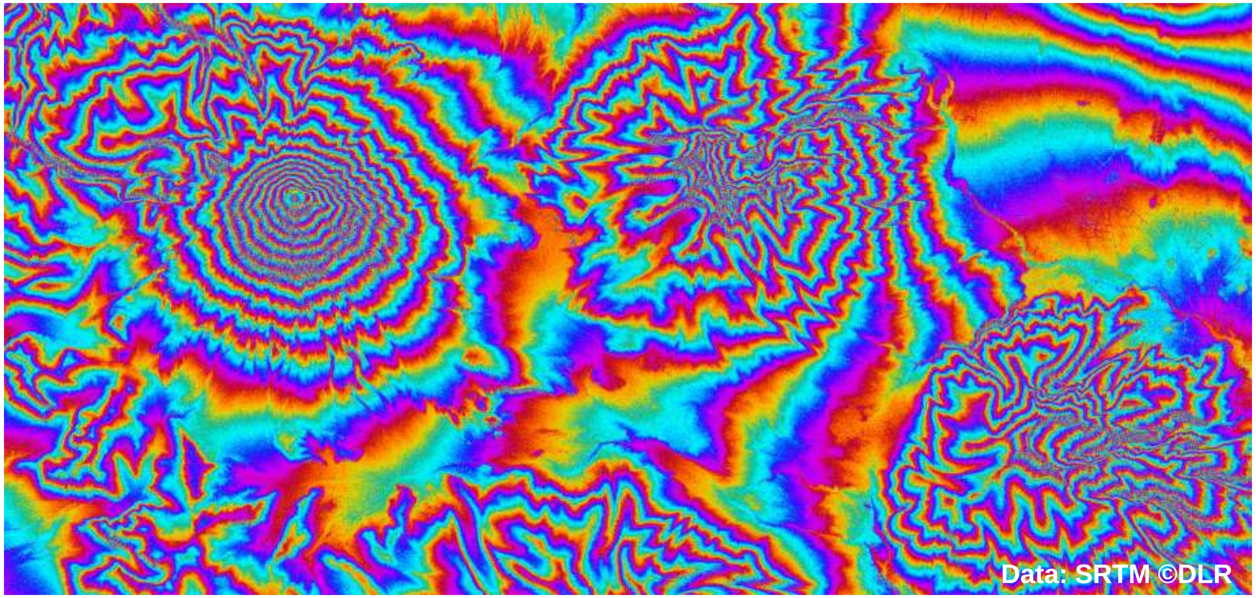
Spaceborne SAR Image



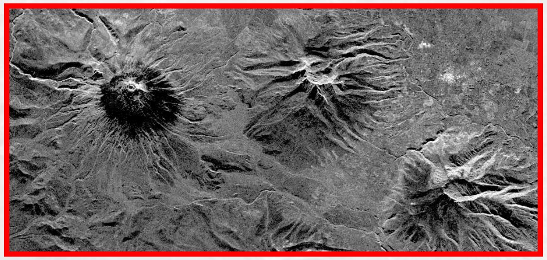
Cotopaxi Volcano Ecuador



Interferometric Phase Image

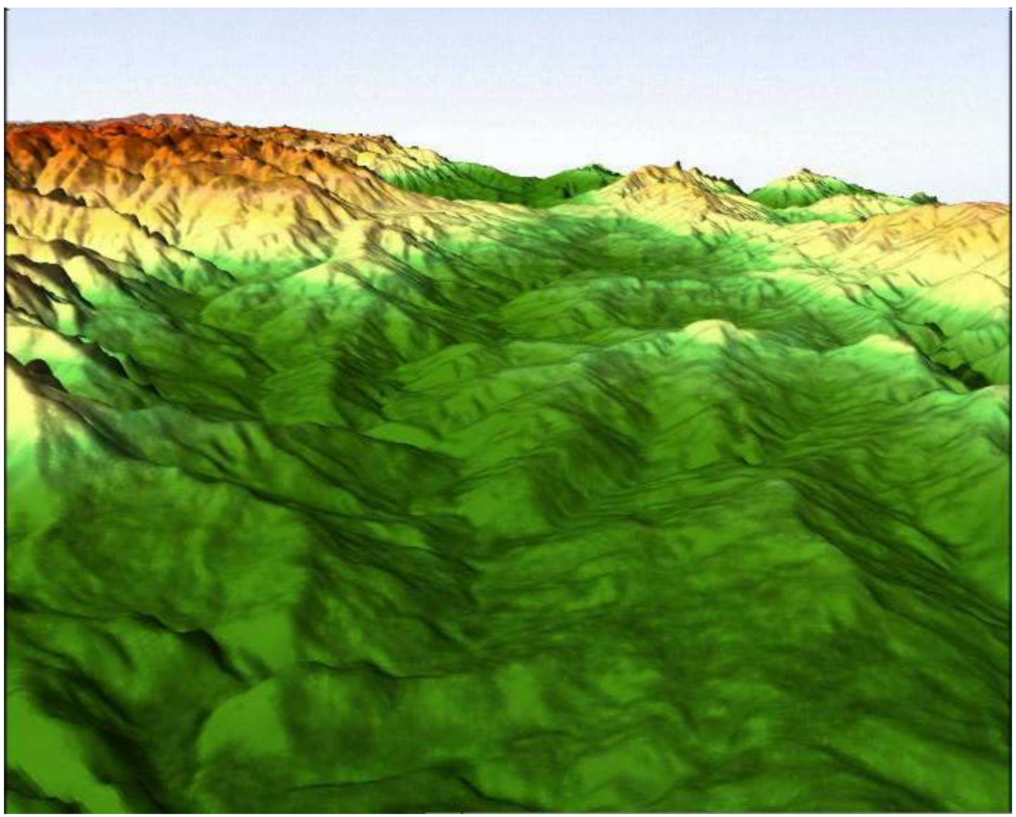


Cotopaxi Volcano
Ecuador



Data: SRTM ©DLR

InSAR-derived DEM, Cotopaxi Volcano, Ecuador



How InSAR Really Works:

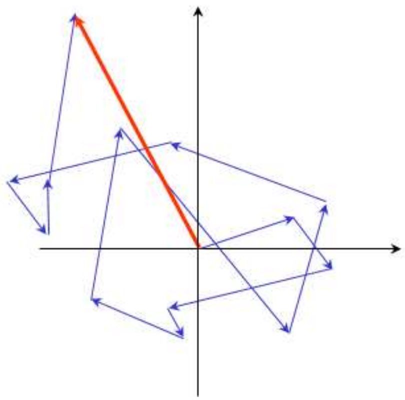
1. What is Contained in a SAR Image's Phase Signal

- **Phase in a pixel of a SAR image is sum of two components:**
  1. A **deterministic** component that is a function of the distance R between satellite and pixel on ground ($\psi(R)$)
  2. A **random** phase change ψ_{scatt} caused by how all scattered signals from one pixel combine together

- **Therefore, the phase signal measured in a SAR pixel is:**

$$\psi = \psi(R) + \psi_{scatt}$$

Remember how individual scatterers sum up to final signal received from a pixel:



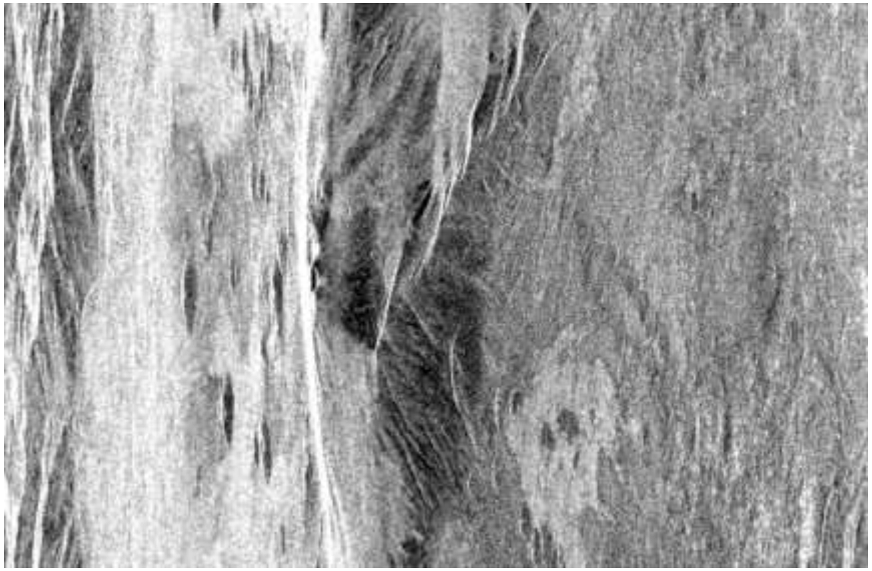
Blue: contribution by one single scattering event

Red: final amplitude and phase of received signal

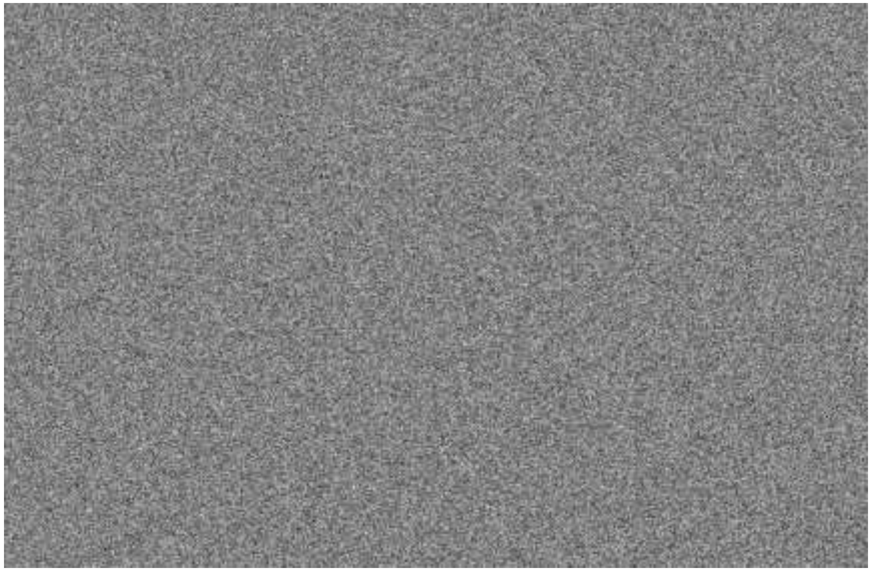
- As ψ_{scatt} is different for every pixel (every pixel contains different combination of scatterers), the **phase in a single SAR image ψ looks random**

Example: Amplitude and Phase of a SAR Image of Mount Etna

Amplitude of a segment of an ERS-1 image over Mount Etna, Italy



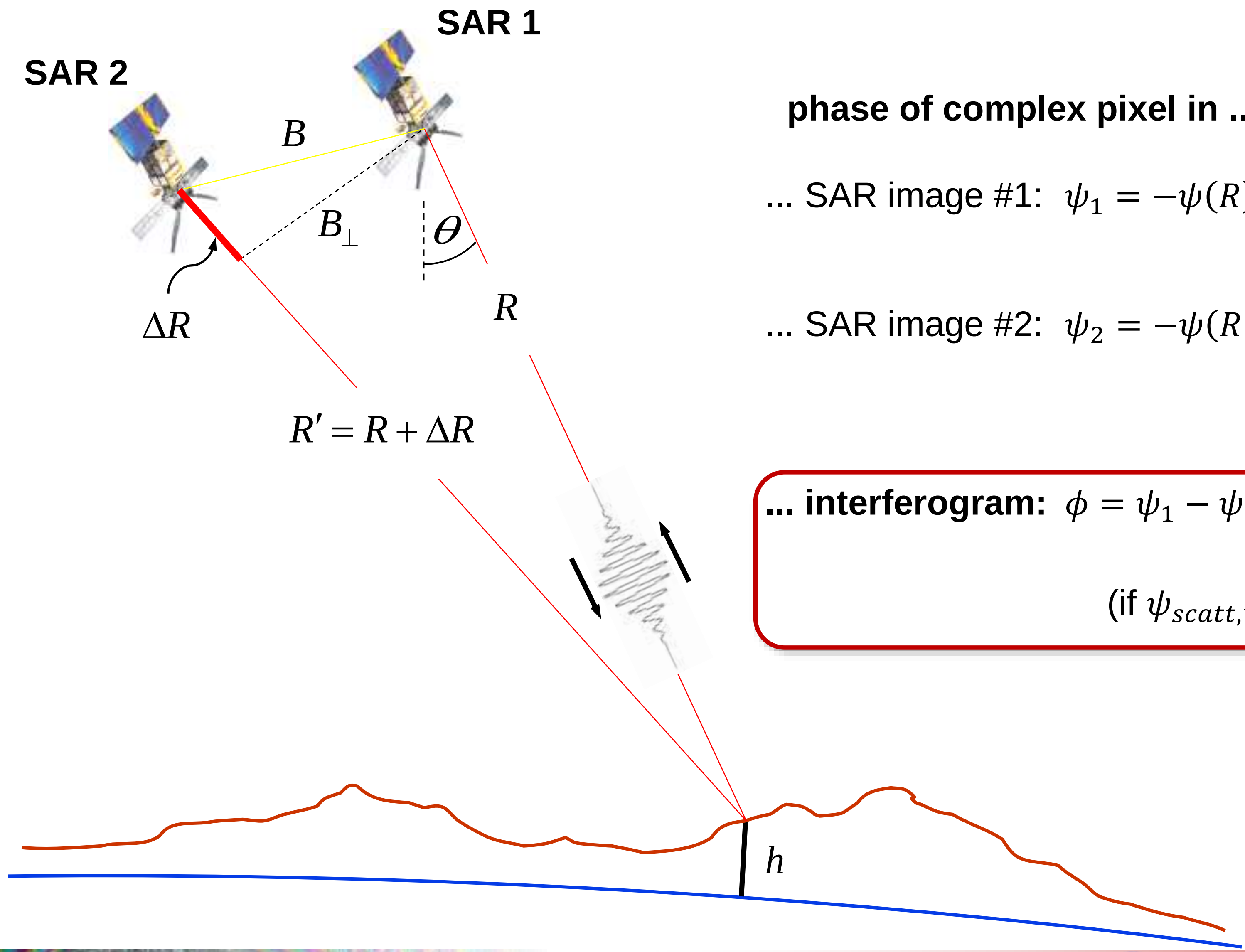
Phase ψ of a segment of an ERS-1 image over Mount Etna, Italy



$$\psi = \psi(R) + \psi_{scatt}$$

How InSAR Really Works:

2. Form Interferogram to Remove Random Phase ψ_{scatt}



phase of complex pixel in ...

... SAR image #1: $\psi_1 = -\psi(R) + \psi_{scatt,1}$

... SAR image #2: $\psi_2 = -\psi(R + \underline{\Delta R}) + \psi_{scatt,2}$

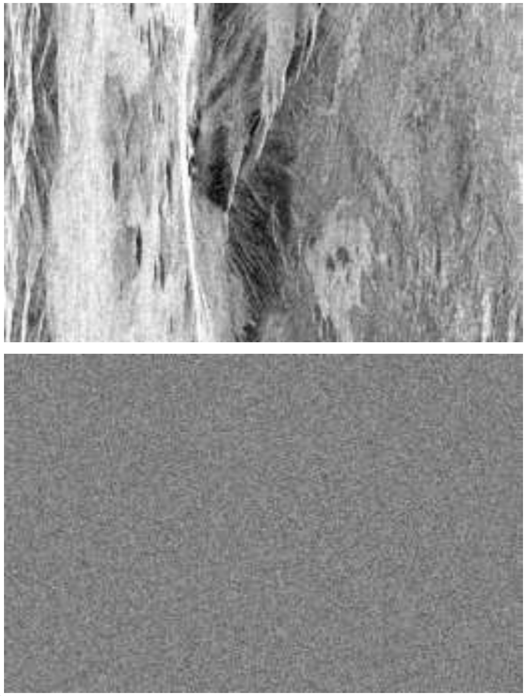
... interferogram: $\phi = \psi_1 - \psi_2 = \phi(R)$

(if $\psi_{scatt,1} = \psi_{scatt,2}$!)

Example: Form Interferogram to Remove Random Phase Component ψ_{scatt}

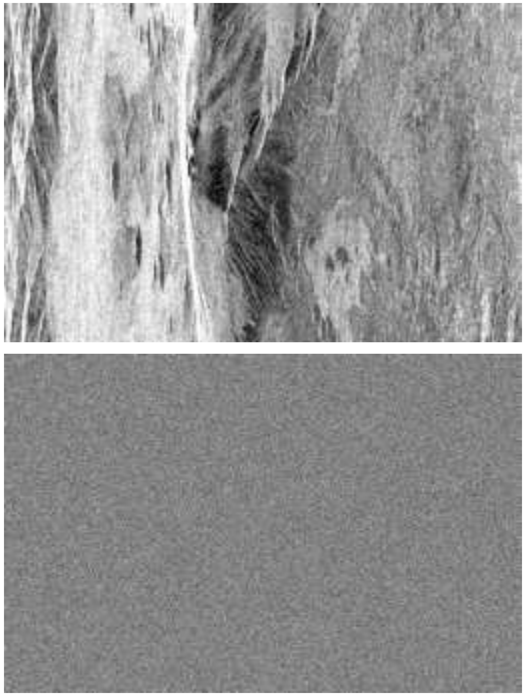
- **To form interferogram, we calculate:** $I = u_1 \cdot u_2^*$ ($\blacksquare^*$ is complex conjugate)

SAR Image u_1:



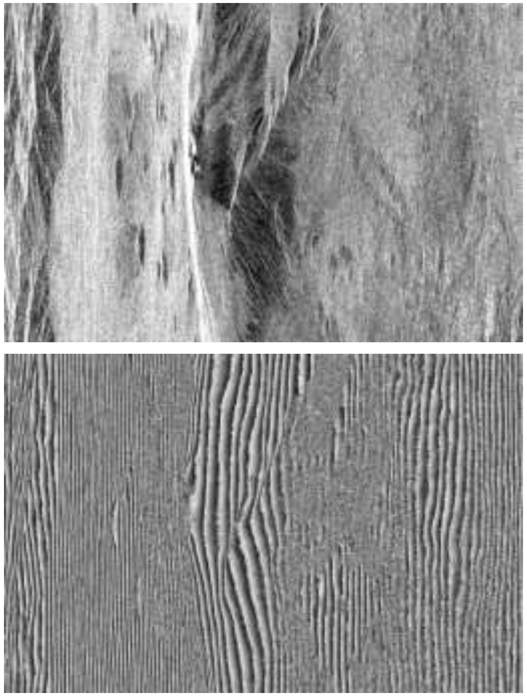
$\cdot$

SAR Image u_2: $*$



$=$

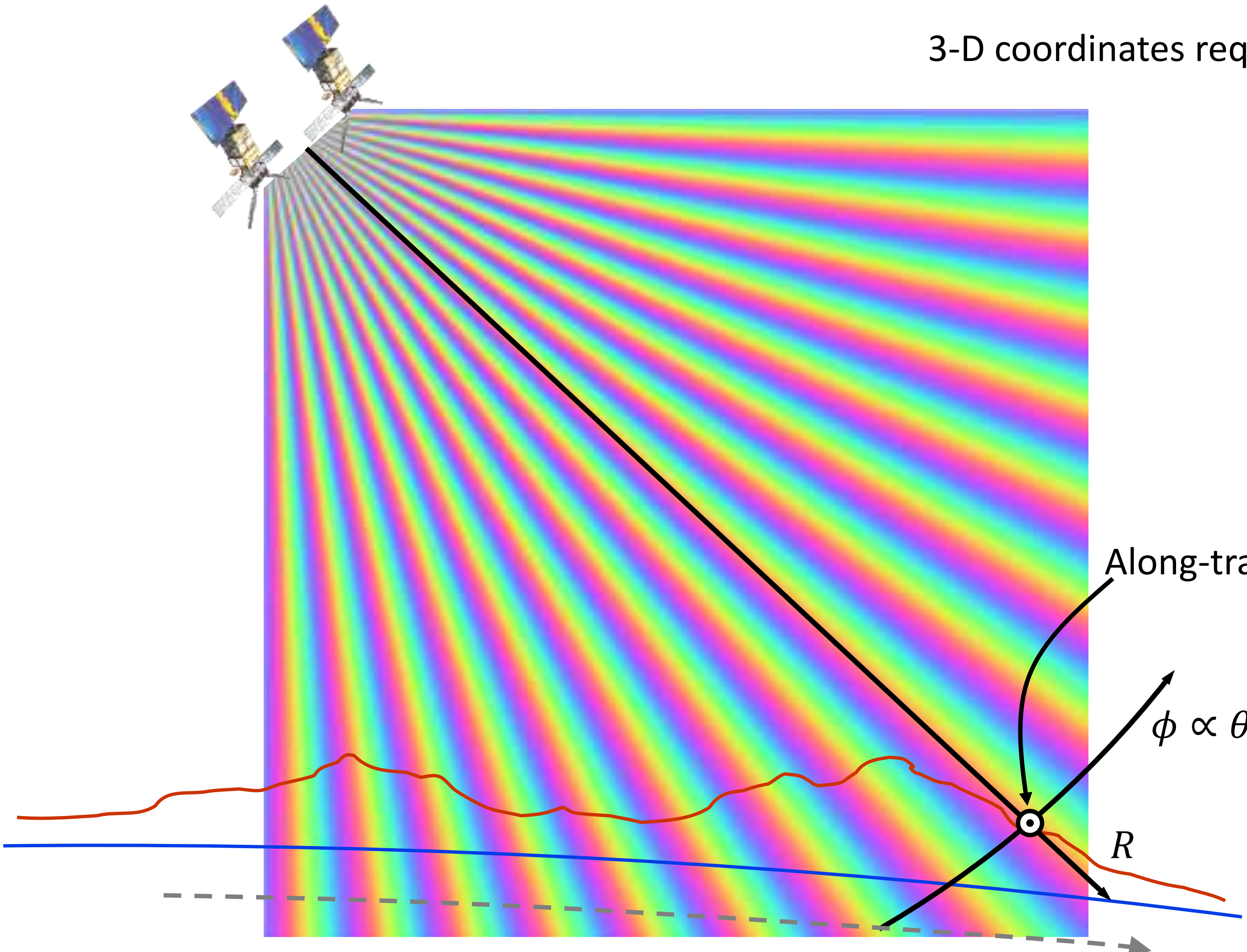
Interferogram I:



How InSAR Really Works:

3. Interferometric Phase ϕ as a Measurement of Angle

3-D coordinates required: R, t, θ

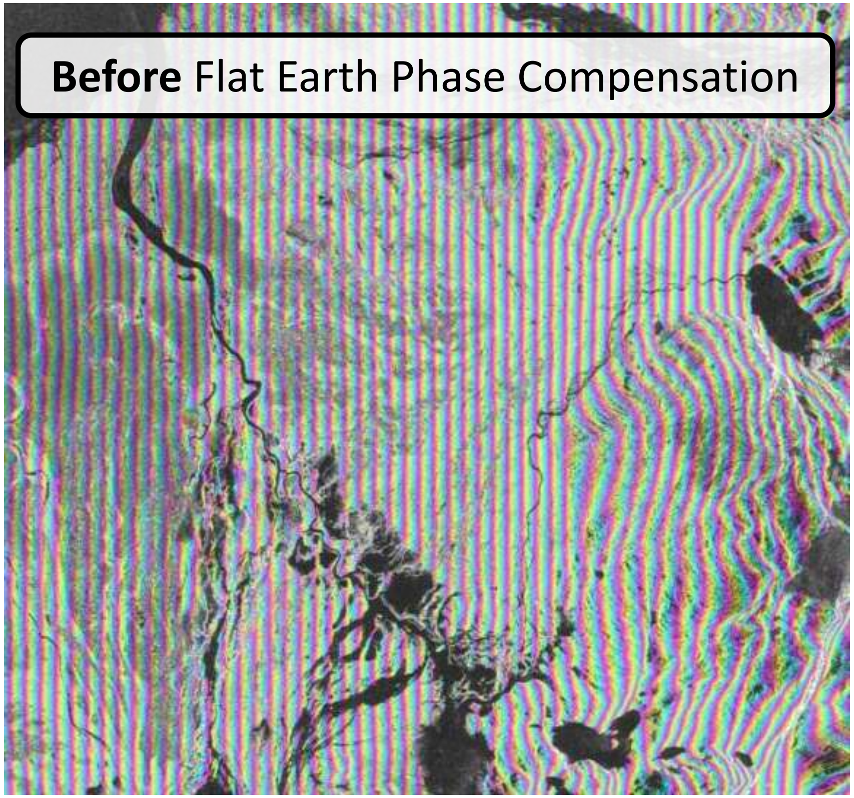


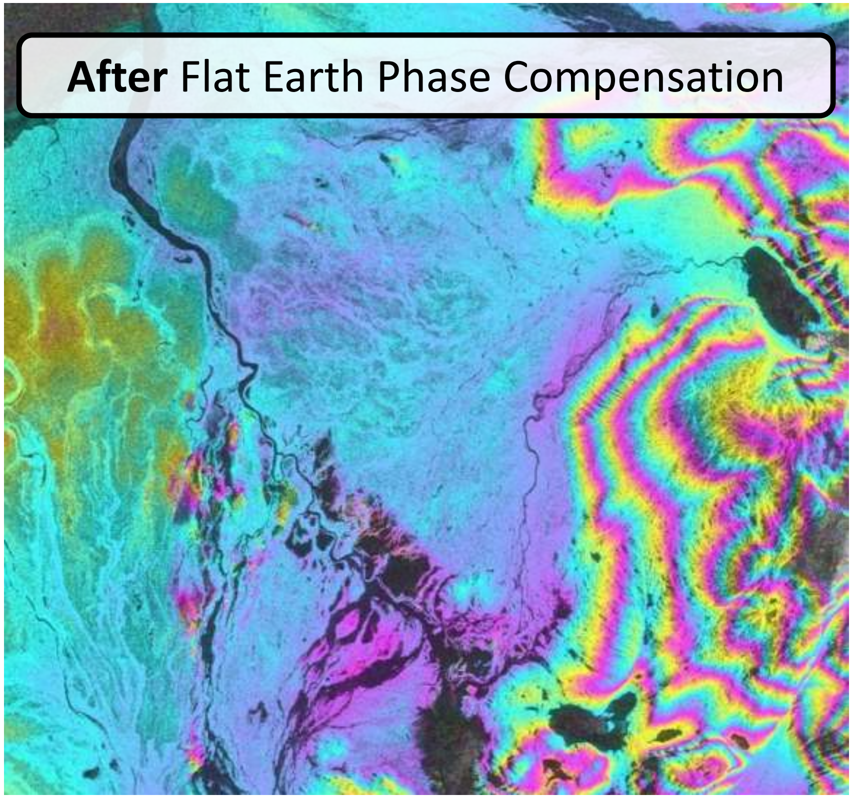
Note: Even for flat terrain: phase varies from near-range to far-range

How InSAR Really Works:

5. Subtraction of Flat Earth Phase

- **Example:**
  - ALOS PALSAR Interferogram near of Drift River Valley, AK (Baseline ~ 400m)

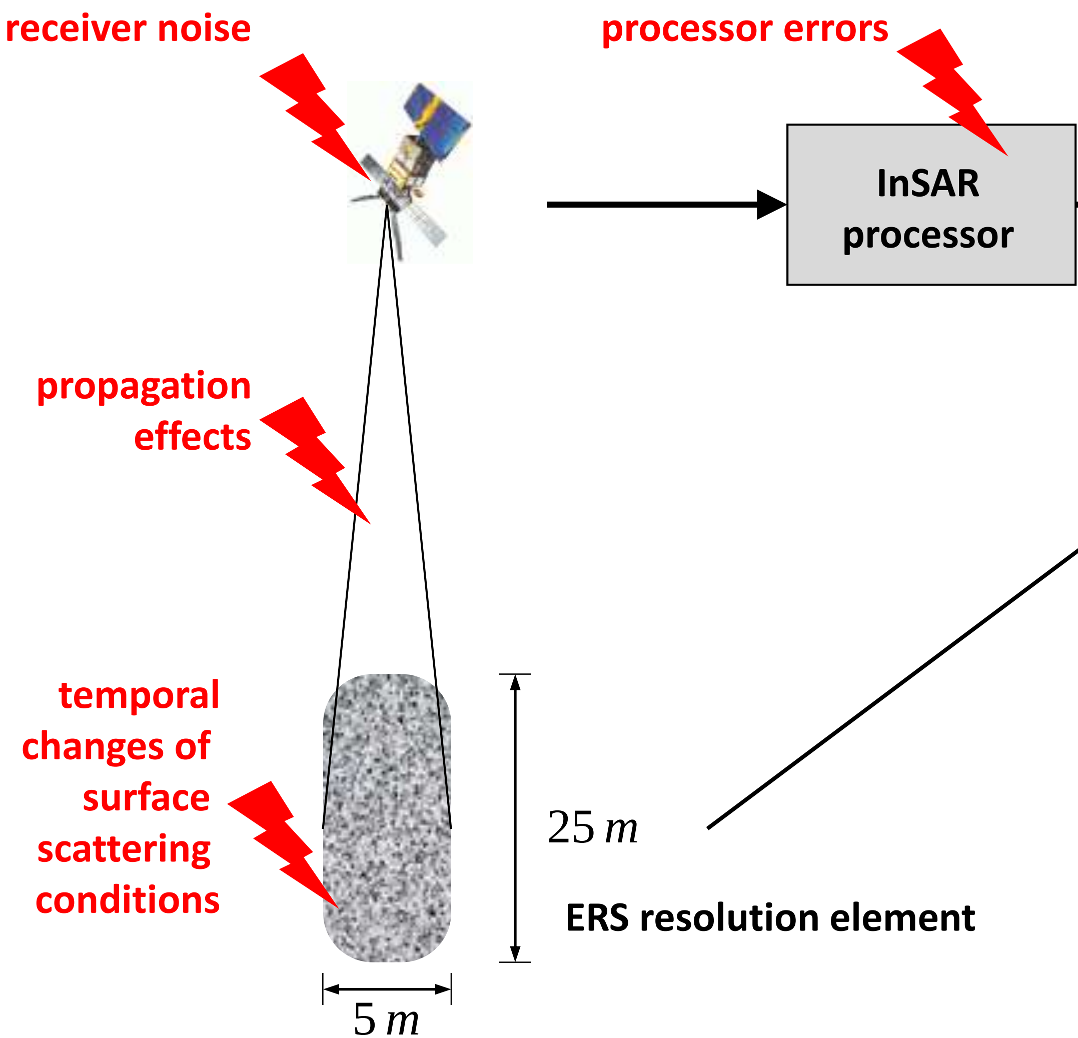


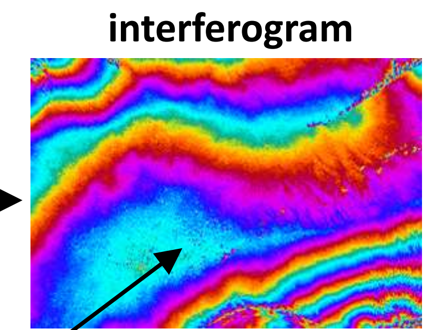


How InSAR Really Works:

6. Coherence: A Phase Quality Descriptor

- **Contributions to Phase Noise:**



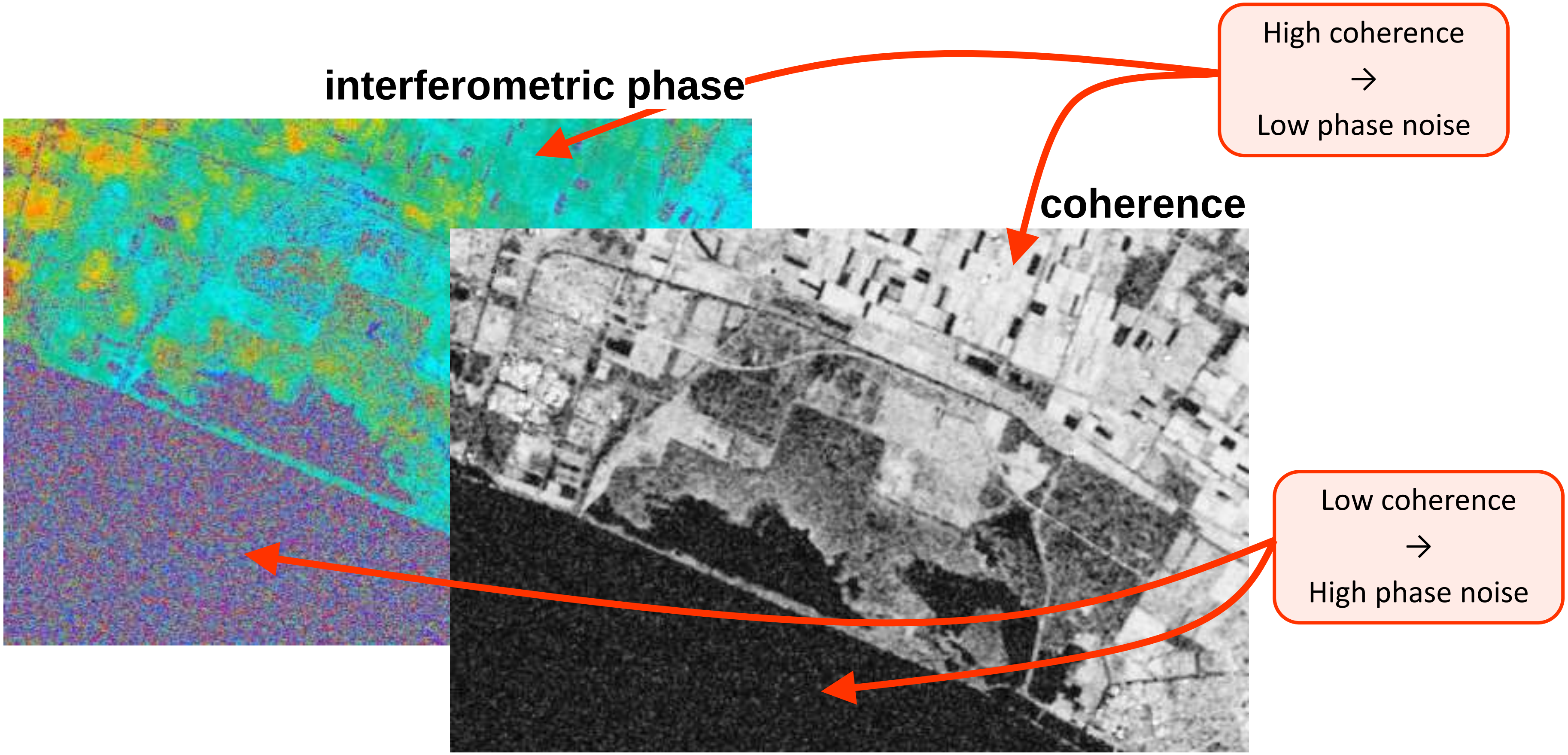


Coherence:
- Quality measure describing noise level of InSAR phase

Useful for:
- How accurate is a topography or deformation estimate from InSAR

Interferometric Coherence - Example

- **This example compares interferometric phase quality and coherence side-by-side**



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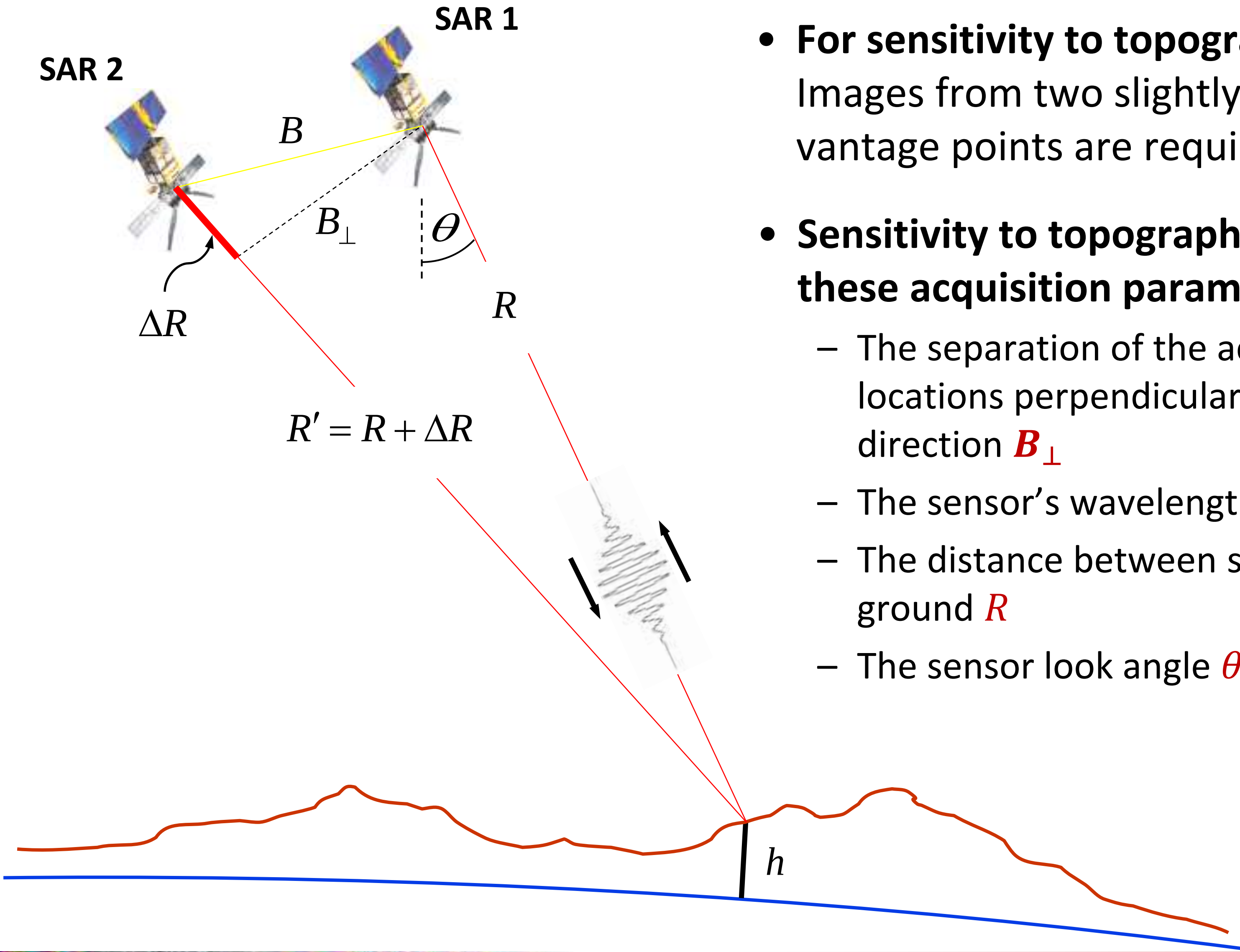
Across-Track InSAR Geometry To Enable Topographic Mapping



- **For sensitivity to topography:** Images from two slightly different vantage points are required
- **Sensitivity to topography depends on these acquisition parameters:**
  - The separation of the acquisition locations perpendicular to the sensor look direction $\boldsymbol{B}_{\perp}$
  - The sensor's wavelength $\boldsymbol{\lambda}$
  - The distance between satellite and ground R
  - The sensor look angle θ

Measuring Topography using InSAR

How to measure topographic height from the InSAR phase: $$\phi_{topo} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{R \sin\theta} h$$

How well can we measure height: $$\sigma_h = \frac{\lambda}{4\pi} \frac{R \sin\theta}{B_{\perp}} \cdot \sigma_{\phi}$$

example ALOS PALSAR: $\lambda \approx 25\,\mathrm{cm}$

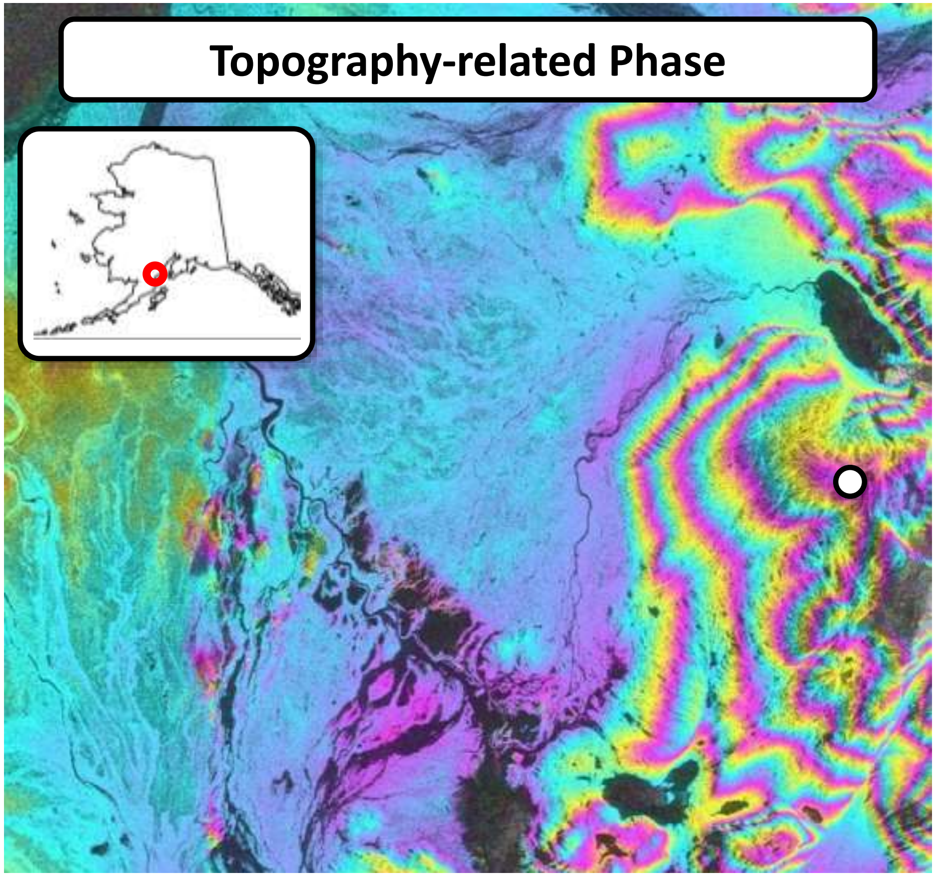
$R \approx 800\,\mathrm{km}$

$\theta = 30^{\circ} \rightarrow \sin\theta = 0.5$

baseline	**height for 1 phase cycle (2π)**
50 m	≈ 1000 m
100 m	≈ 500 m
200 m	≈ 250 m

Topographic Mapping with InSAR - Example

- **Example:**
  - ALOS PALSAR Interferogram near of Drift River Valley, AK (Baseline ~ 400m)



What is the altitude of the highlighted peak?

Height per phase cycle (fringe): $h_{2\pi} = \frac{\lambda}{2} \frac{R \sin\theta}{B_{\perp}}$

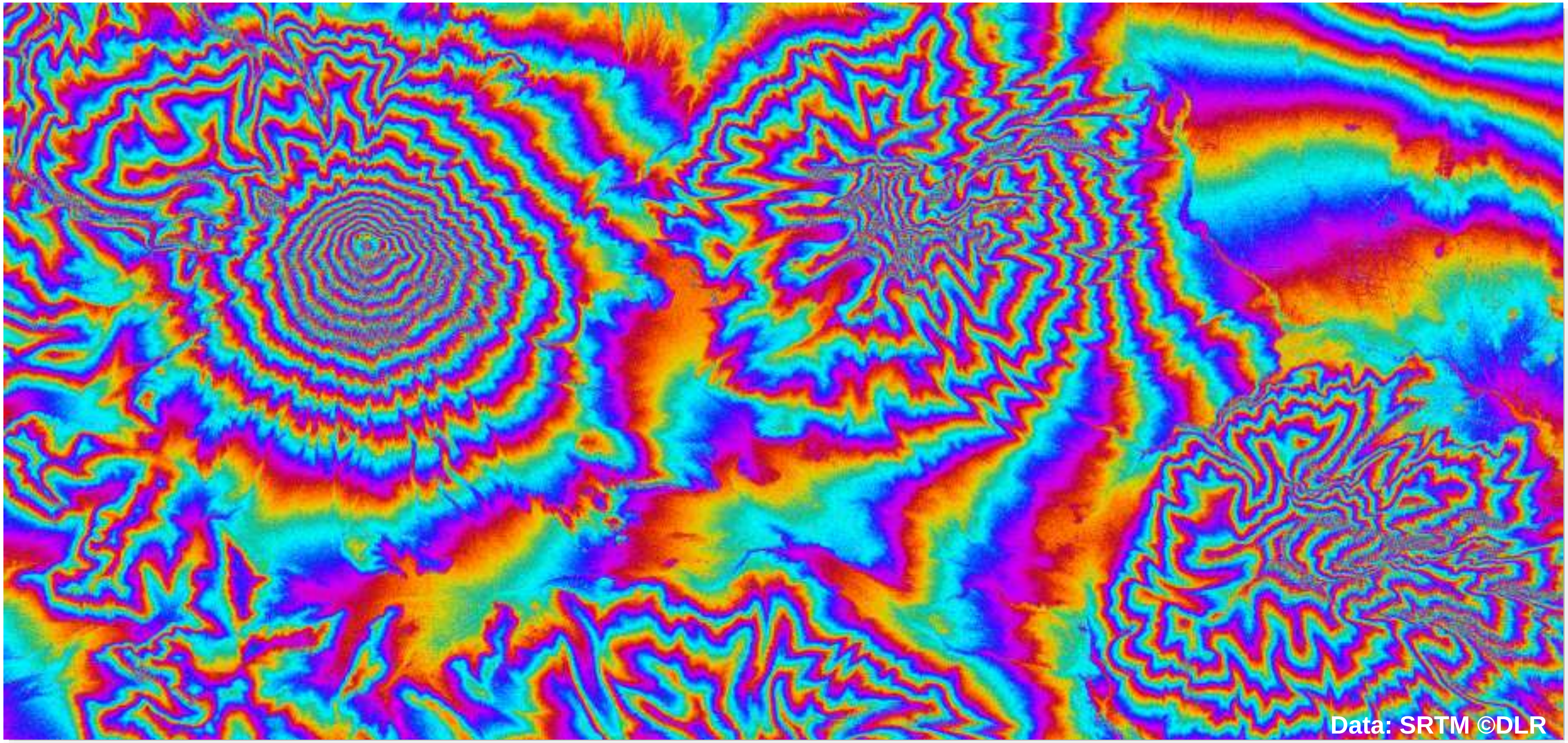
Parameters:

$$\begin{aligned} B &= 400m \\ R &= 800{,}000m \\ \sin\theta &= 0.5 \\ \lambda &= 0.25m \end{aligned}$$

Height per fringe: $h_{2\pi} = 125m$

About 4 fringes → $h_{peak} \approx 125m \cdot 4 = 500m$

Problem of InSAR: Interferometric Phase is Ambiguous

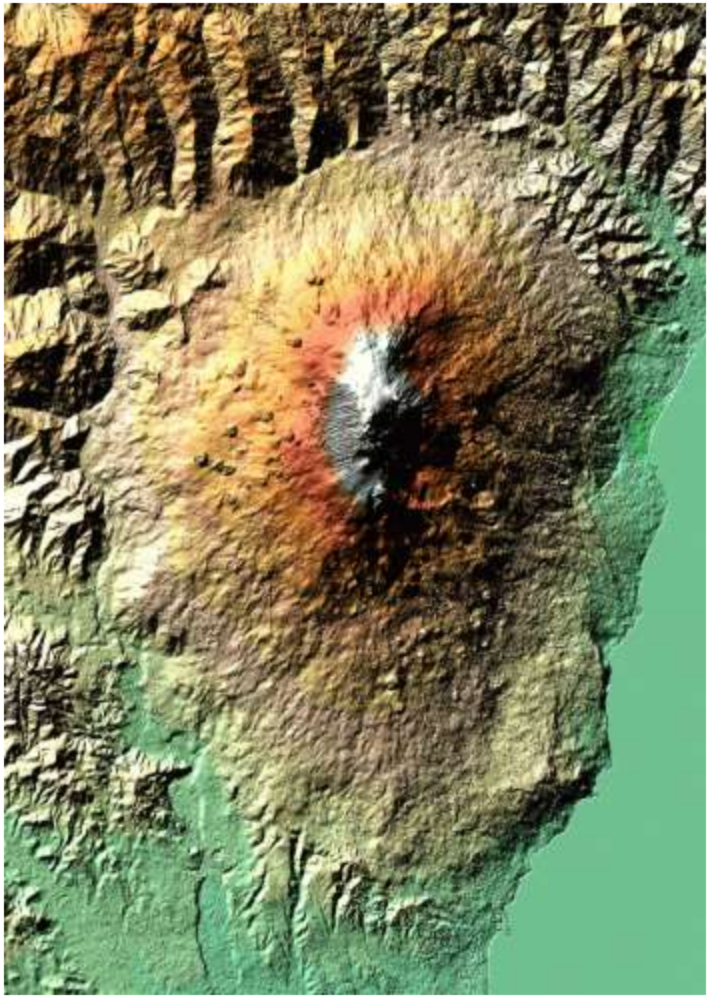


A specific interferometric phase value matches several topographic height values!

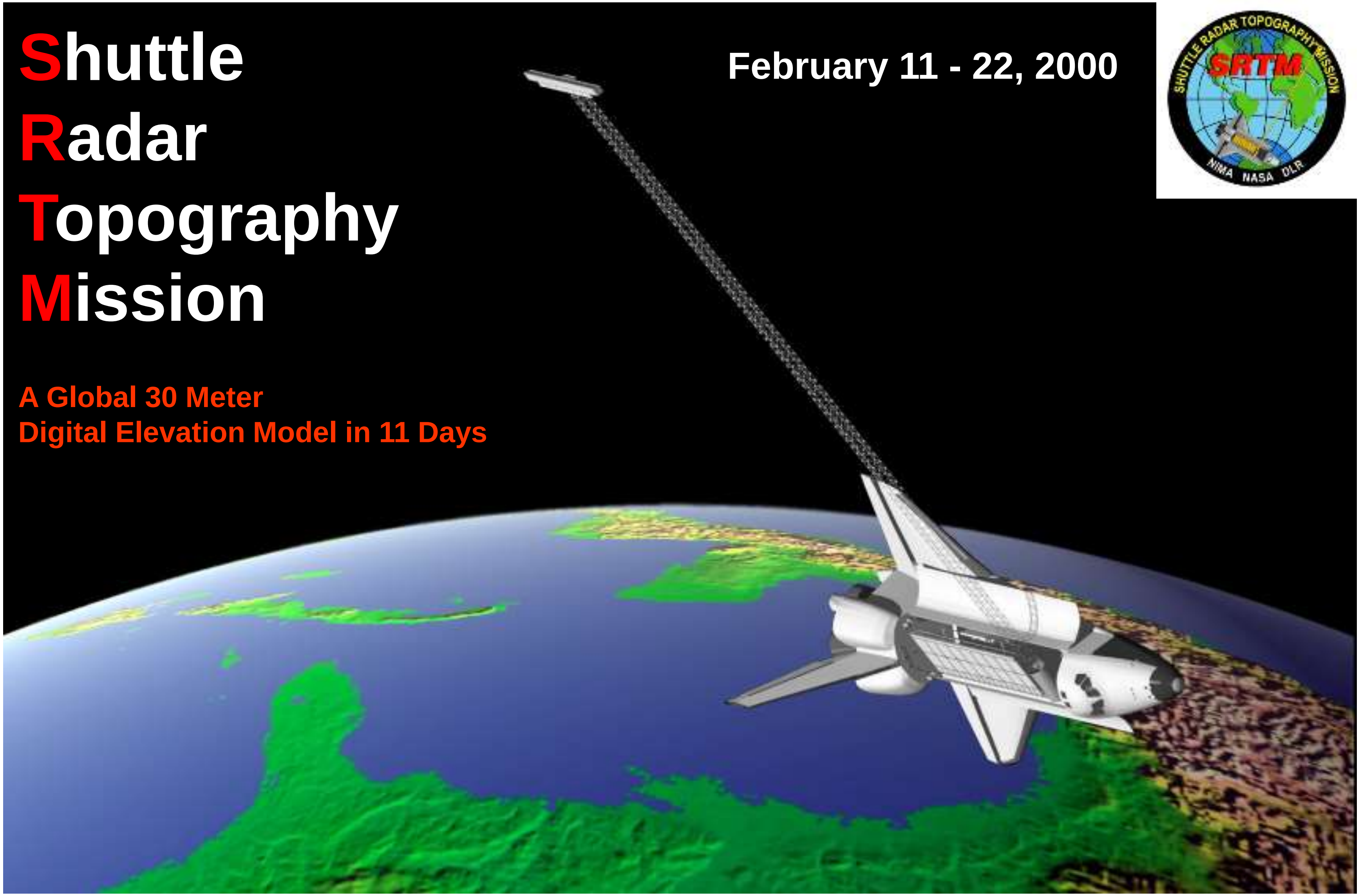
Phase Unwrapping: Find "Most Likely" Absolute Phase Given Measured Ambiguous Phase

- **Phase Unwrapping algorithms find mathematical ways of describing that …**

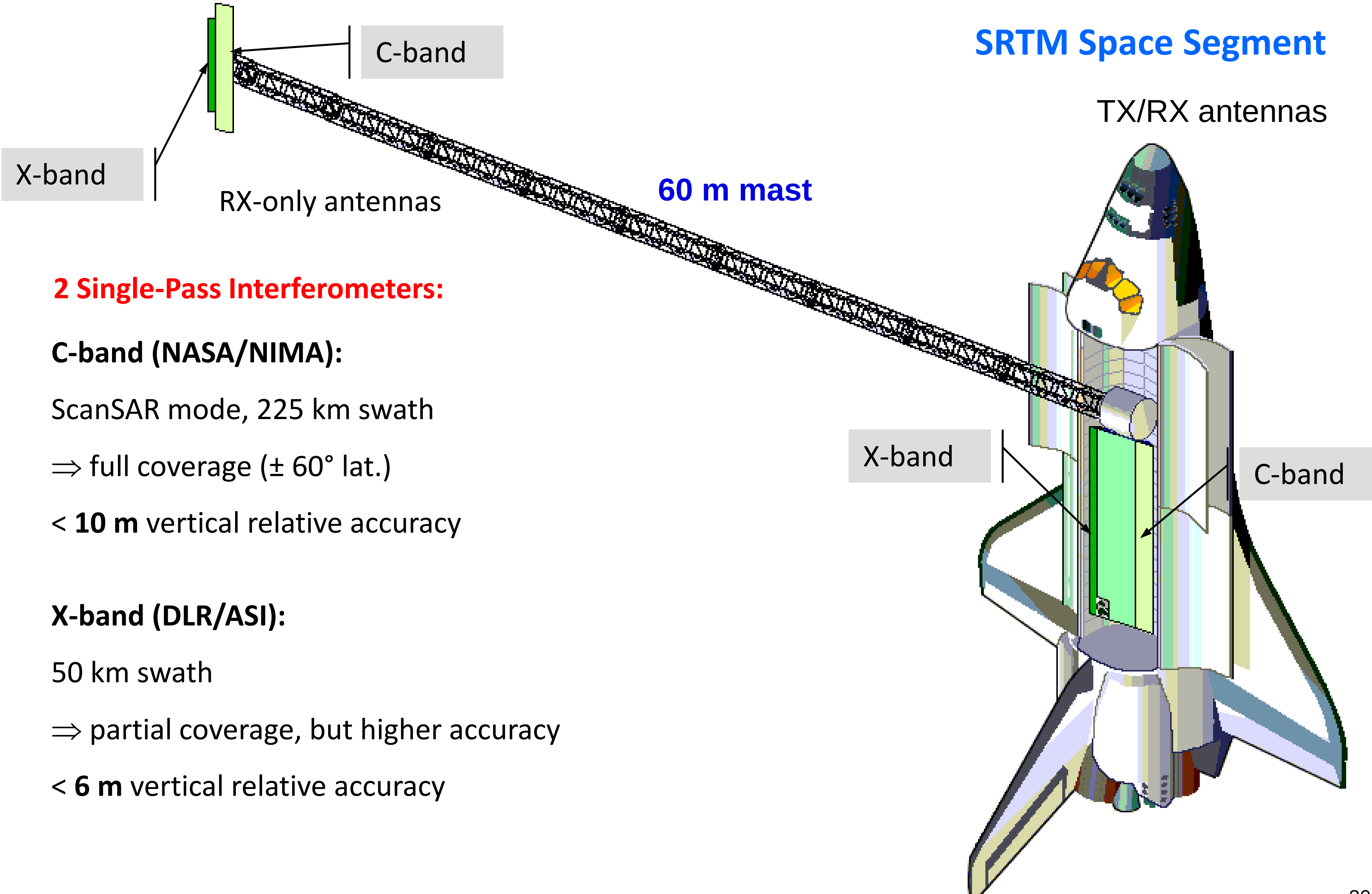
this is much more likely ...



... than this


Shuttle
Radar
Topography
Mission
February 11 - 22, 2000
SHUTTLE RADAR TOPOGRAPHY MISSION
SRTM
NIMA NASA DLR
A Global 30 Meter
Digital Elevation Model in 11 Days

SRTM – A Dedicated Topographic Mapping 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):

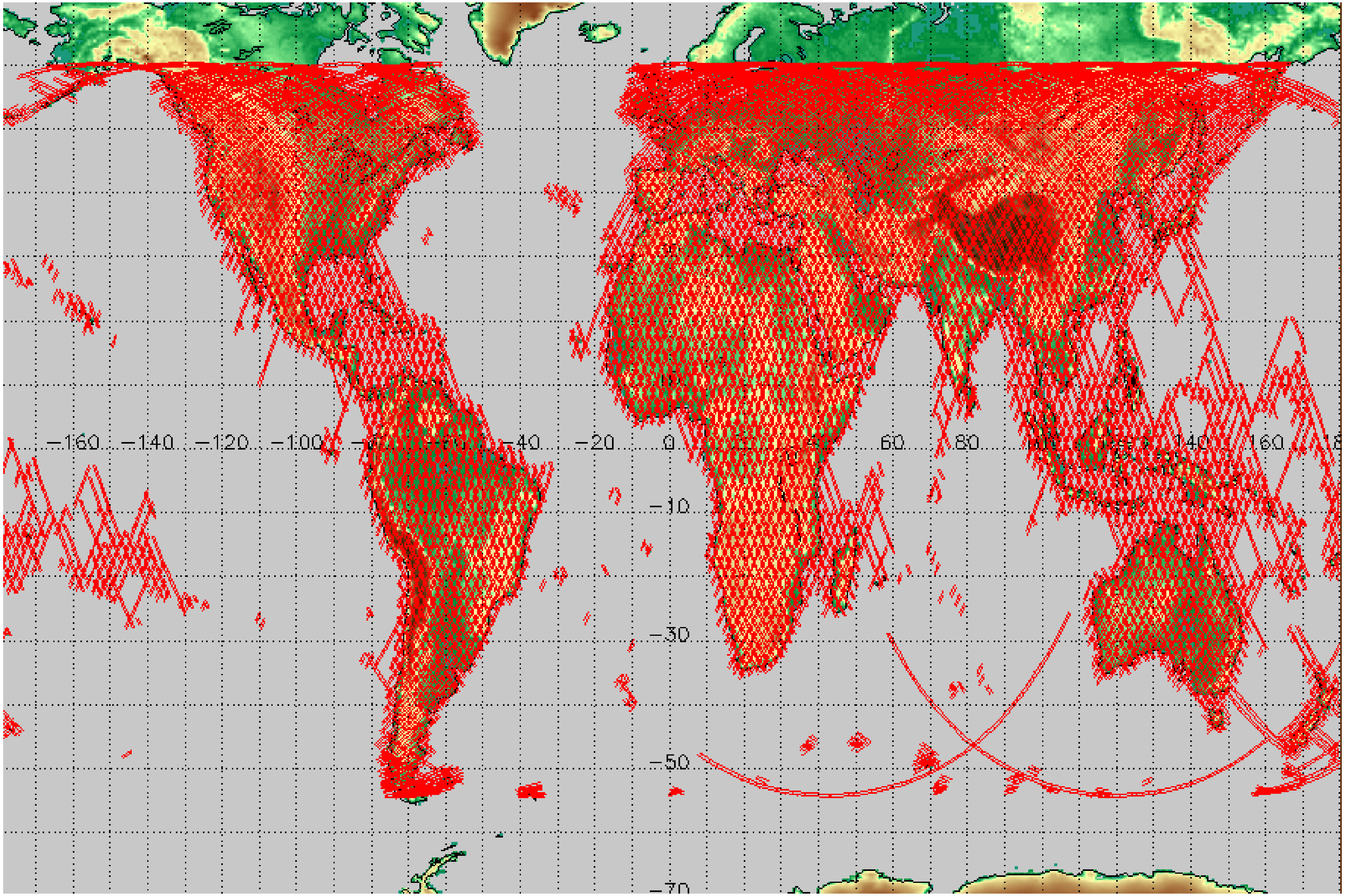
50 km swath

⇒ partial coverage, but higher accuracy

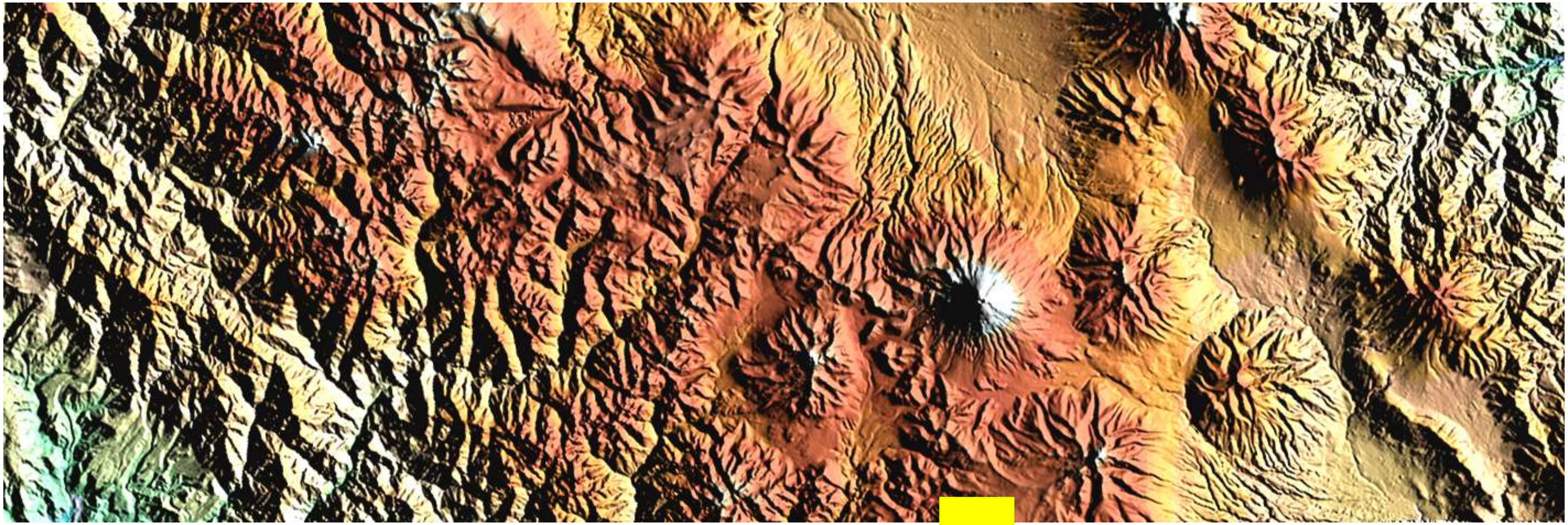
< **6 m** vertical relative accuracy

SRTM – Deployment of Mast

SRTM Coverage



SRTM Example, Cotopaxi Volcano, Ecuador



Cotopaxi Volcano
Ecuador

SRTM/X-SAR

Digital Elevation Model (DEM)

geocoded

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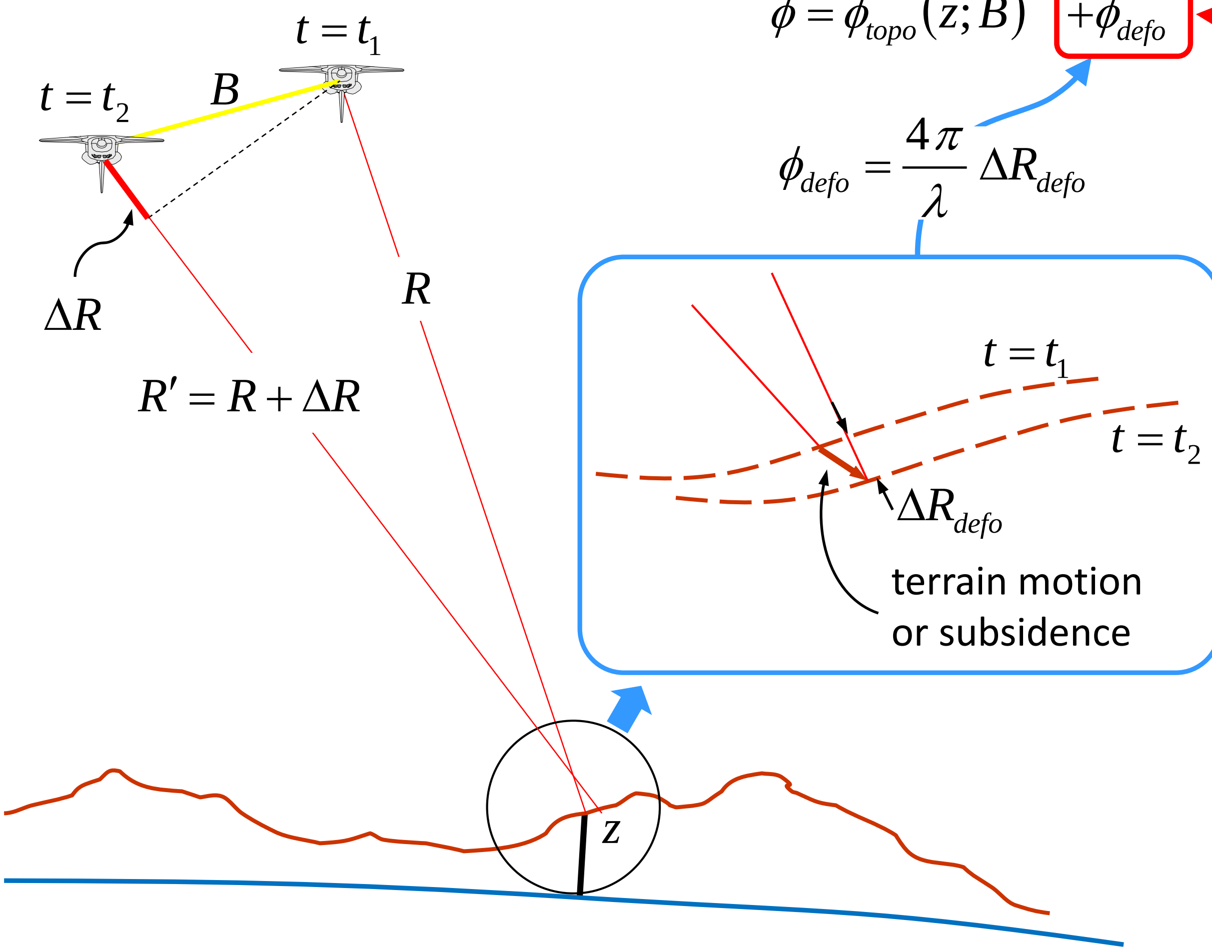
The Concept of Differential InSAR (d-InSAR)

Interferometric Phase:

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

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



d-InSAR Goal:

extraction of deformation signal from interferometric phase

How to Separate Topographic and Deformation Phase?

1. **If reliable DEM is available, use DEM to compensate for topography.**

2. **Else, ≥ 3 complex SAR images at times $t_1, t_2, \ldots, t_n$ are required:**

- Form several interferograms:
  - time lag: $\Delta t_{n-m} = t_n - t_m$
  - baseline: $B_{\perp,\, n-m}$
  - phase: ϕ_{n-m}

For signal separation consider:

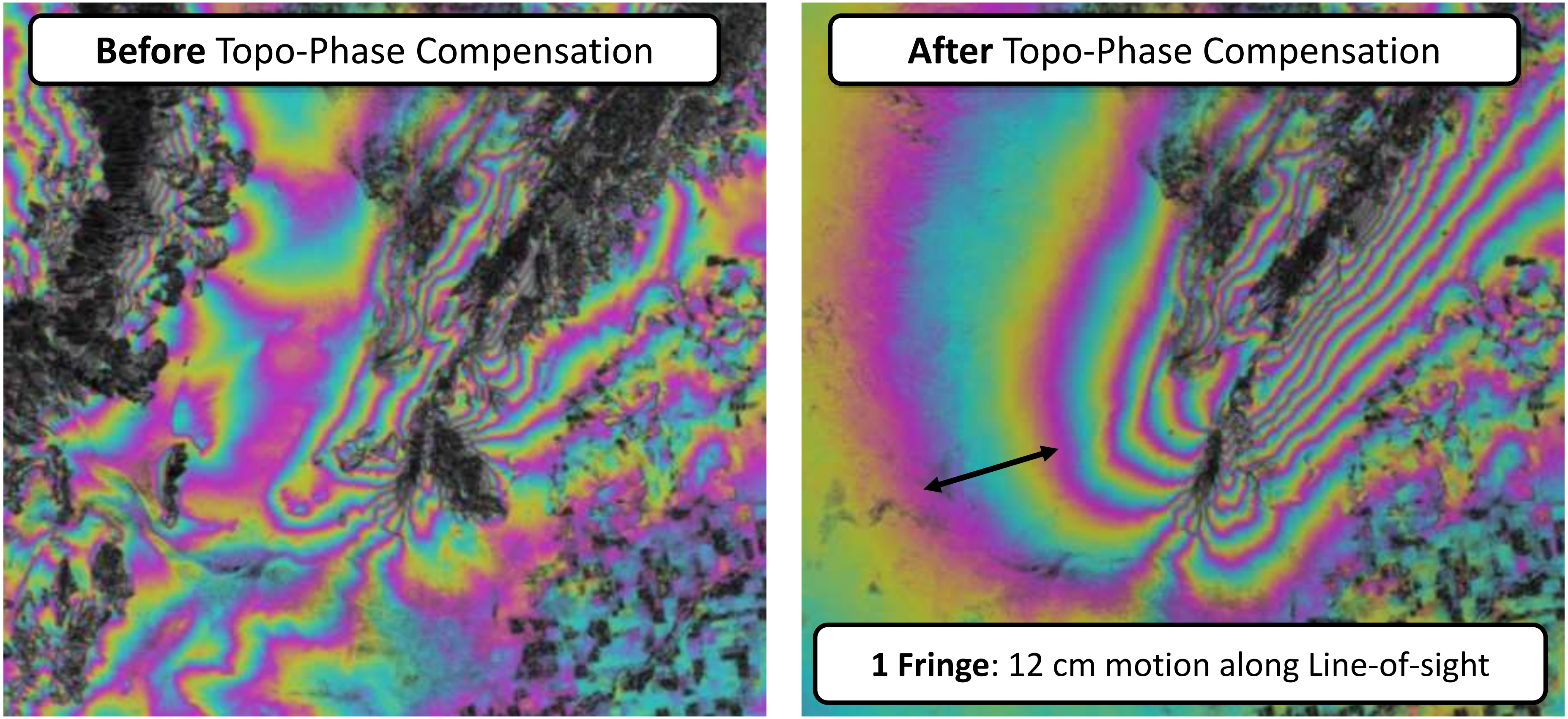
- Deformation phase changes only with time
- Topography phase changes only with Baseline

- For constant velocity: $\boxed{\phi_{n-m}^{defo} = \phi_{n-m} \propto \Delta t_{n-m}}$ and $\boxed{\phi_{n-m}^{topo} = \phi_{n-m} \propto B_{\perp,n-m}}$

3. **For singular displacement event:** use $\phi_{n-m} \propto B_{\perp,n-m}$ to derive topography

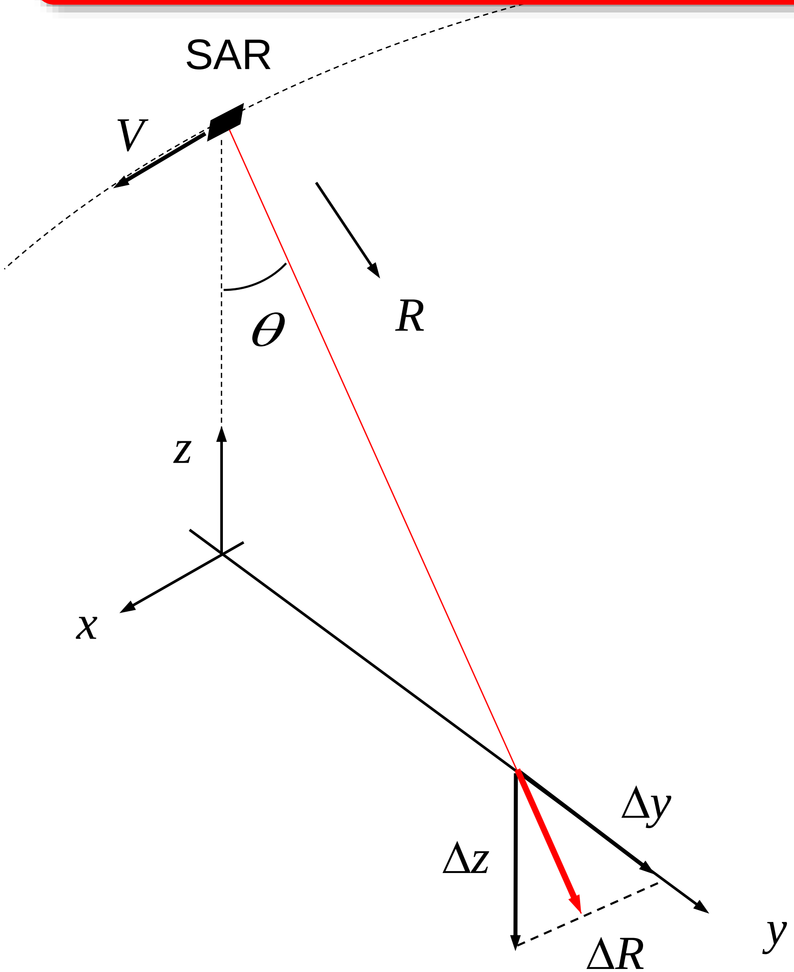
Example of Topography Compensation

- Compensation using available DEM
- ALOS PALSAR data of Baja Earthquake, 2010



How well can we measure deformation?

How to measure surface motion from the InSAR phase: $\phi_{defo} = \frac{4\pi}{\lambda} \Delta R_{defo}$



ΔR is motion in sensor look direction

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

For previous PALSAR example:

1 fringe (2π) corresponds to

12.5 cm in R

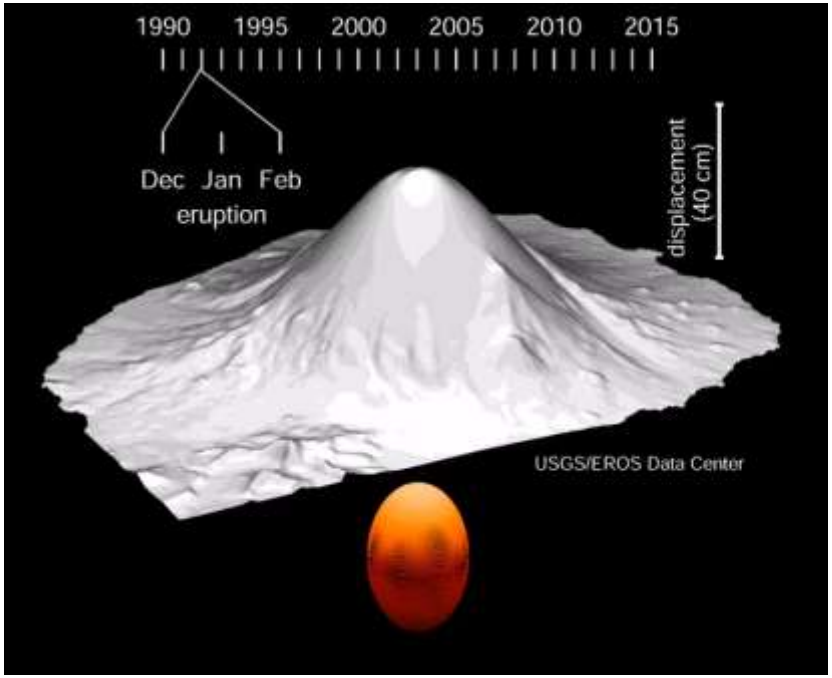
14.5 cm in z (e.g. subsidence)

25.0 cm in y (motion)

Monitoring Volcanoes with InSAR

Principle

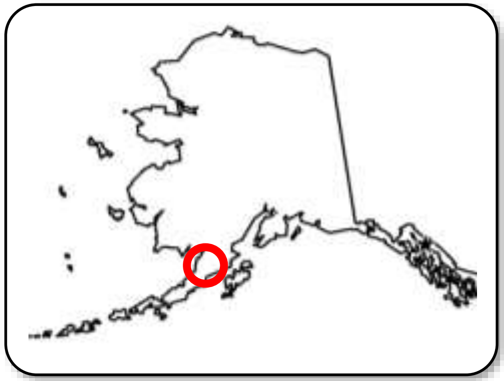
- InSAR is capable of observing inflation and deflation of volcanoes
- Inflation and deflation is triggered by changes of magma pressure in magma chamber (see animation)
- These phenomena precede volcanic eruptions and are potentially interesting for predicting eruptive behavior



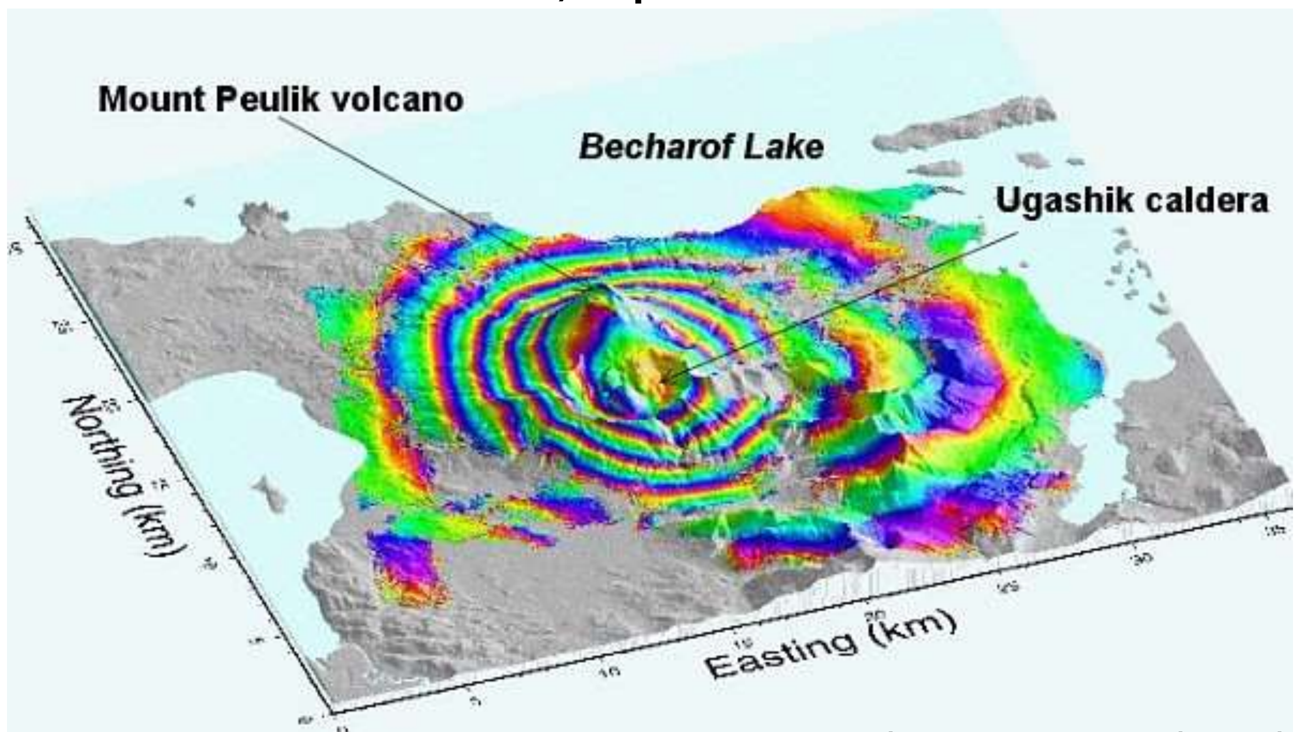
Westdahl Volcano Deformation Movie

Interferometric Phase Interpretation

Example: Surface Deformation at Mt. Peulik, Alaska

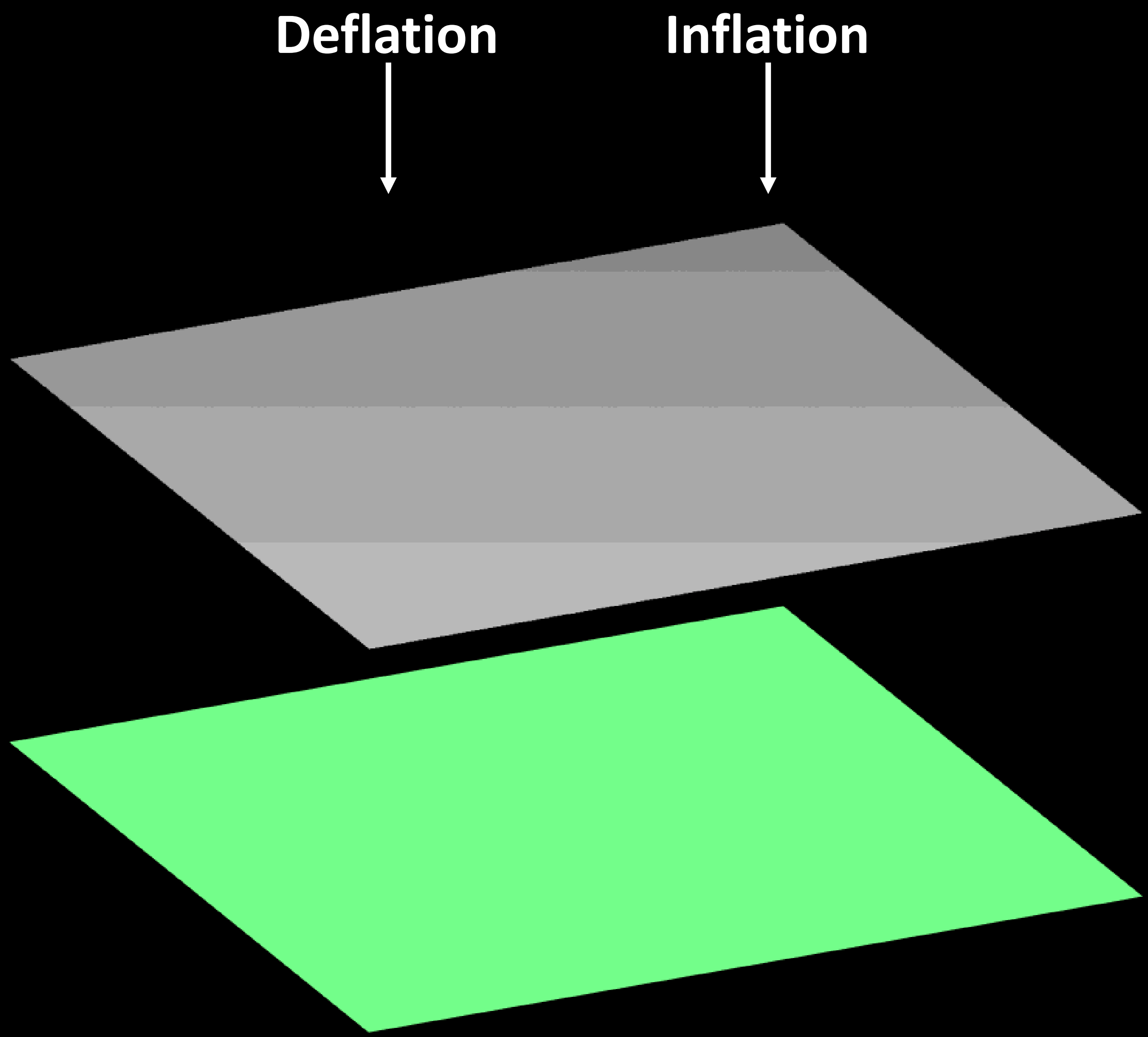


17-cm inflation, Sept. 1996 to Oct. 1997



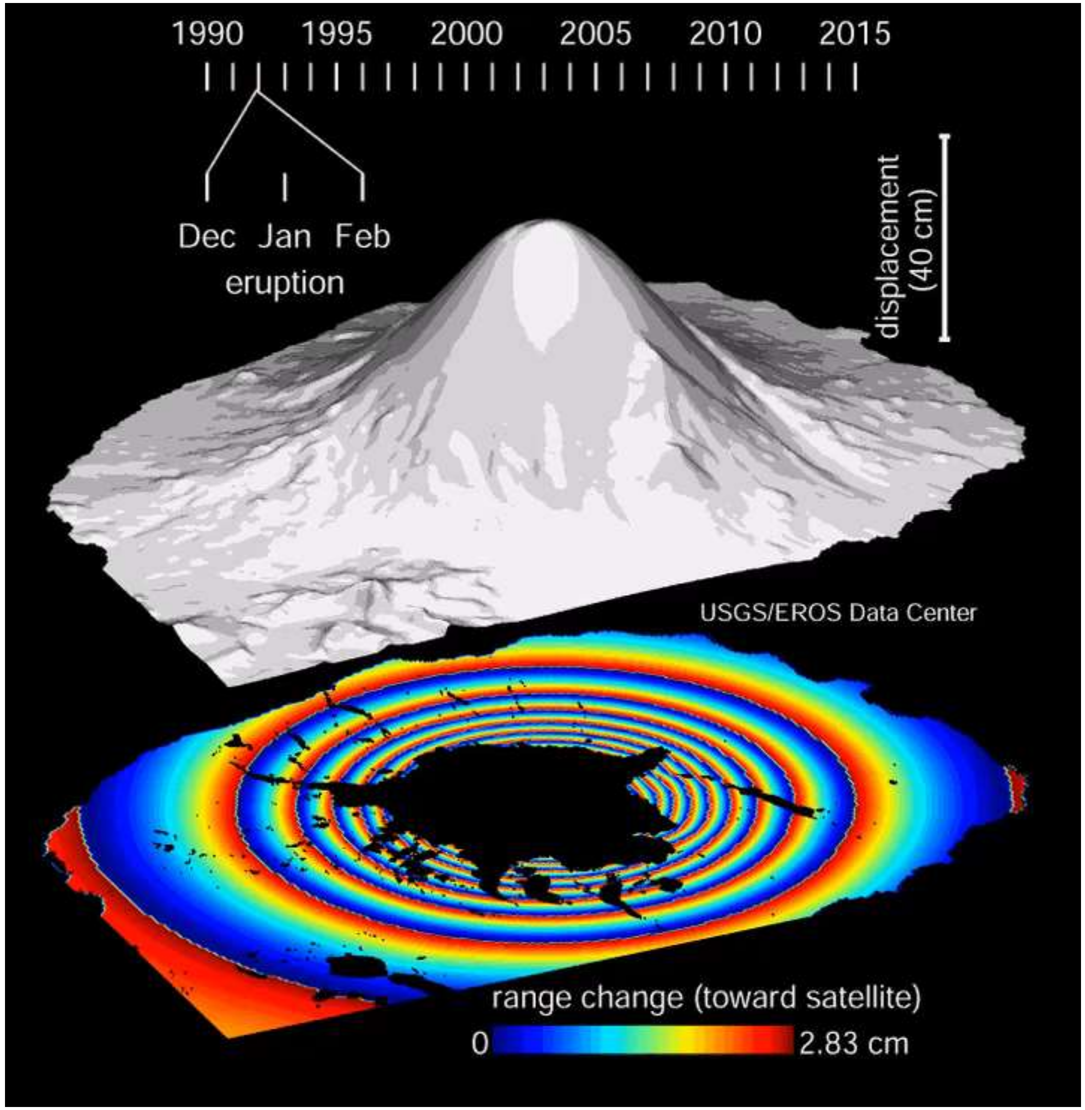
Zhong Lu, et al. (2001)

Representation of Interferometric Phase

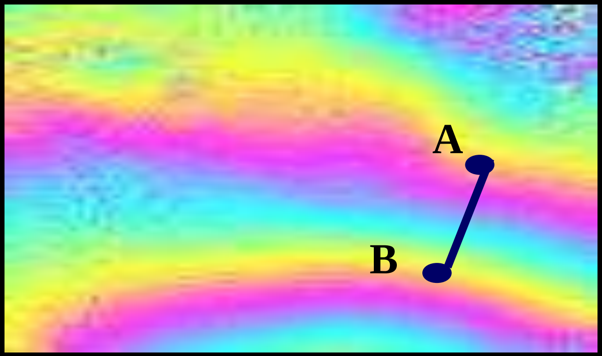


Representation of Interferometric Phase

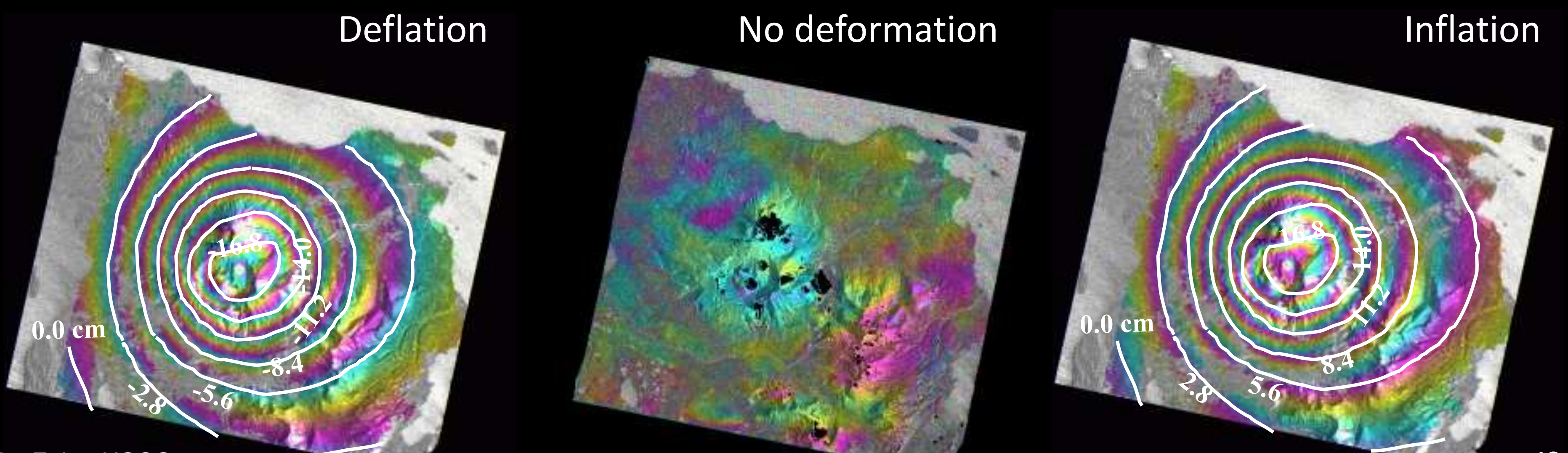
The Westdahl Case



Interpretation of Interferometric Phase

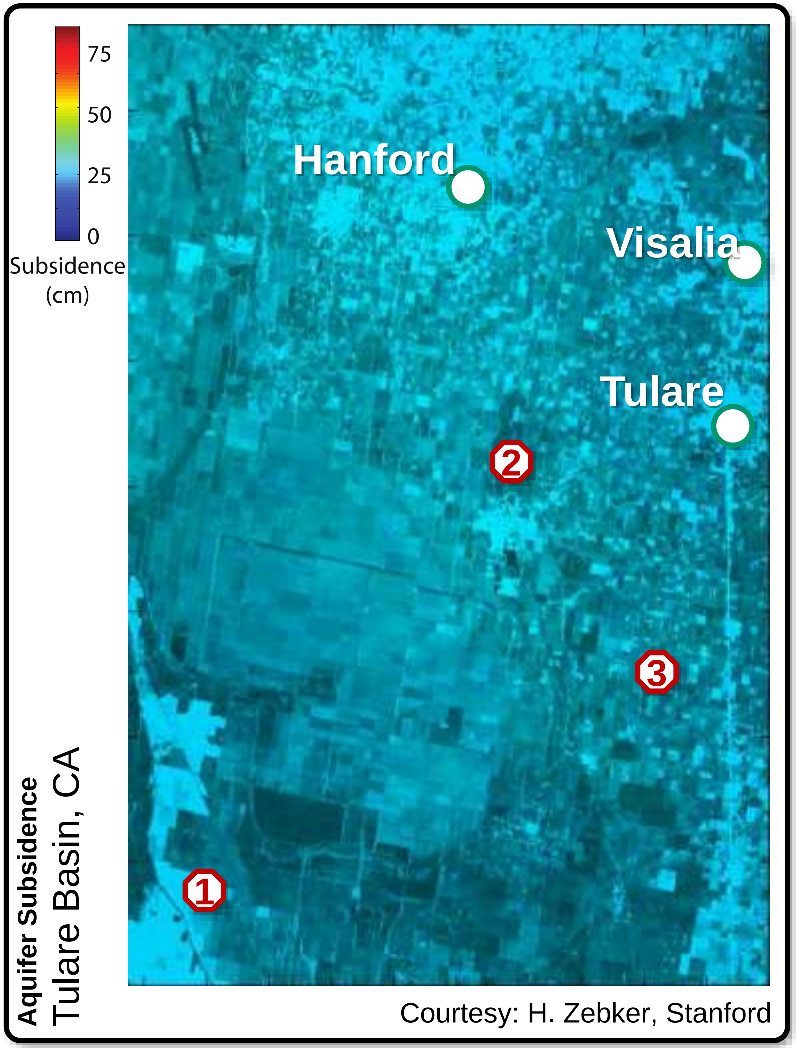


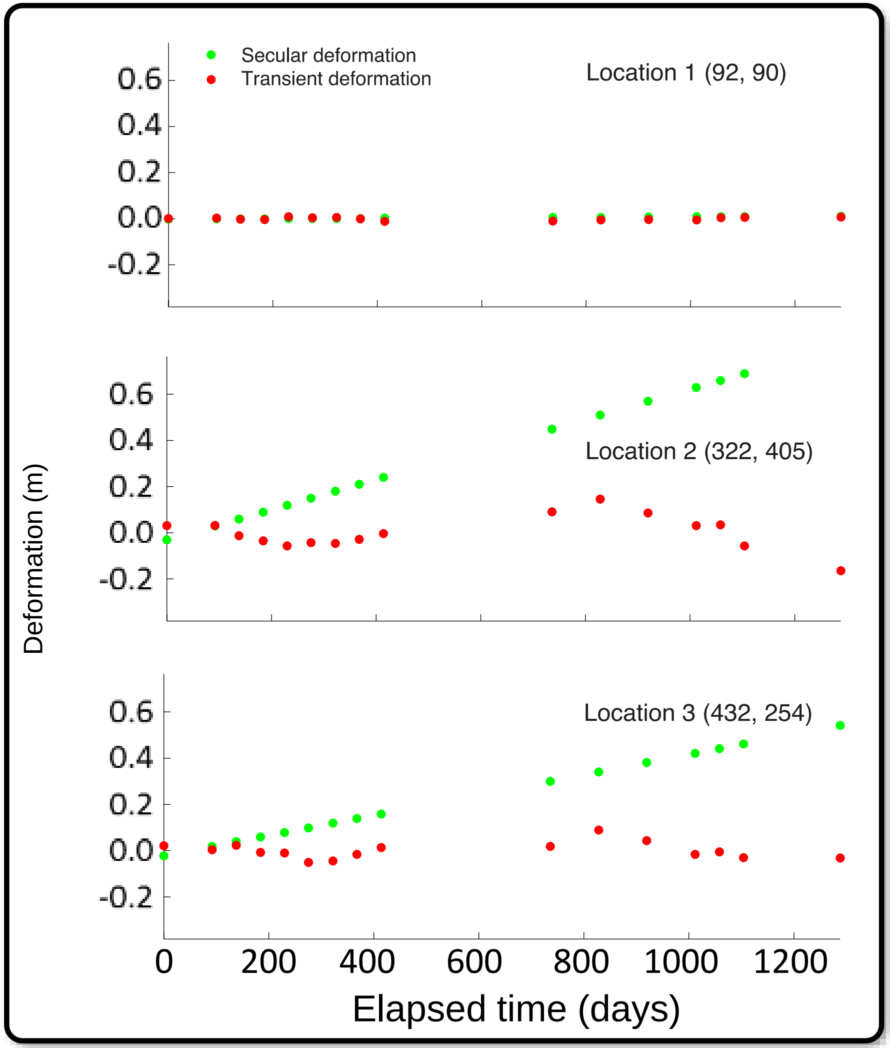
- **Phase Difference from A to B**: -2π (one fringe)
- **Deformation**: B inflates 2.83 cm relative to A.



InSAR-based Aquifer Monitoring

- Time series of aquifer subsidence from L-band ALOS PALSAR observations



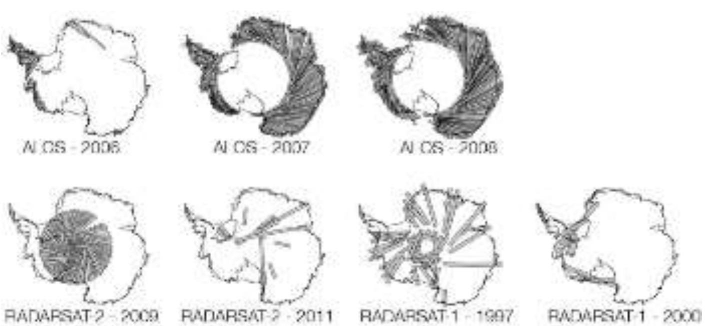


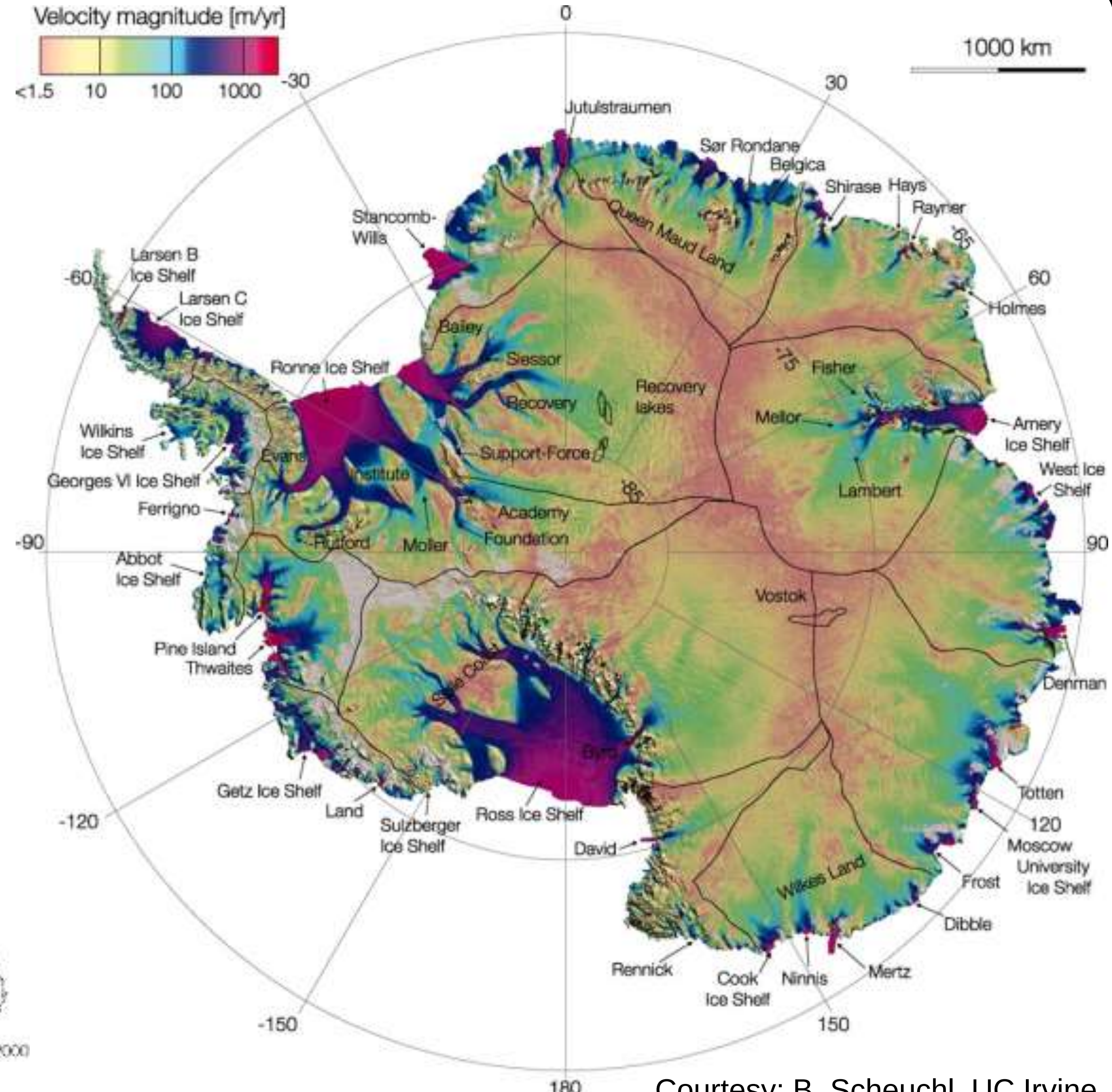
Continent-Wide Deformation Mapping from InSAR

Example: Antarctica

- First Antarctic-wide glacier velocity map in history
- Full coverage by merging data from a wide range of satellite systems
- Accuracy varies with number of multiple coverage per area and coherence

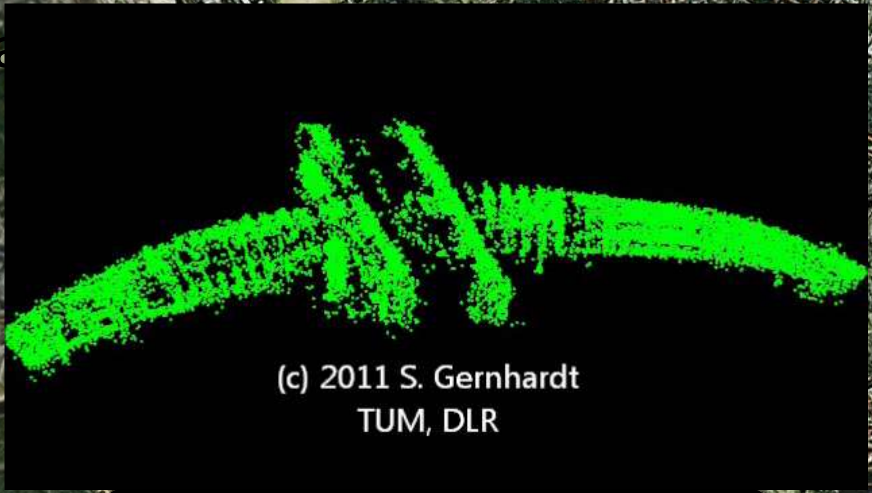
Mouginot et al., "Mapping of Ice Motion in Antarctica Using Synthetic Aperture Radar Data", Remote Sensing, 4(9), pp 2753-2767, 2012



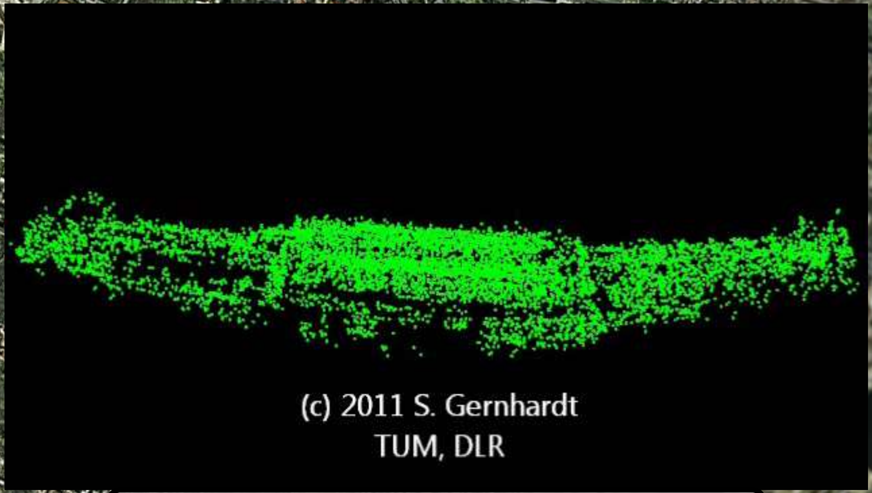


Courtesy: B. Scheuchl, UC Irvine

Sub-Milimeter Surface Analysis
Building Deformation in Berlin, Germany



Central Railway Station Berlin

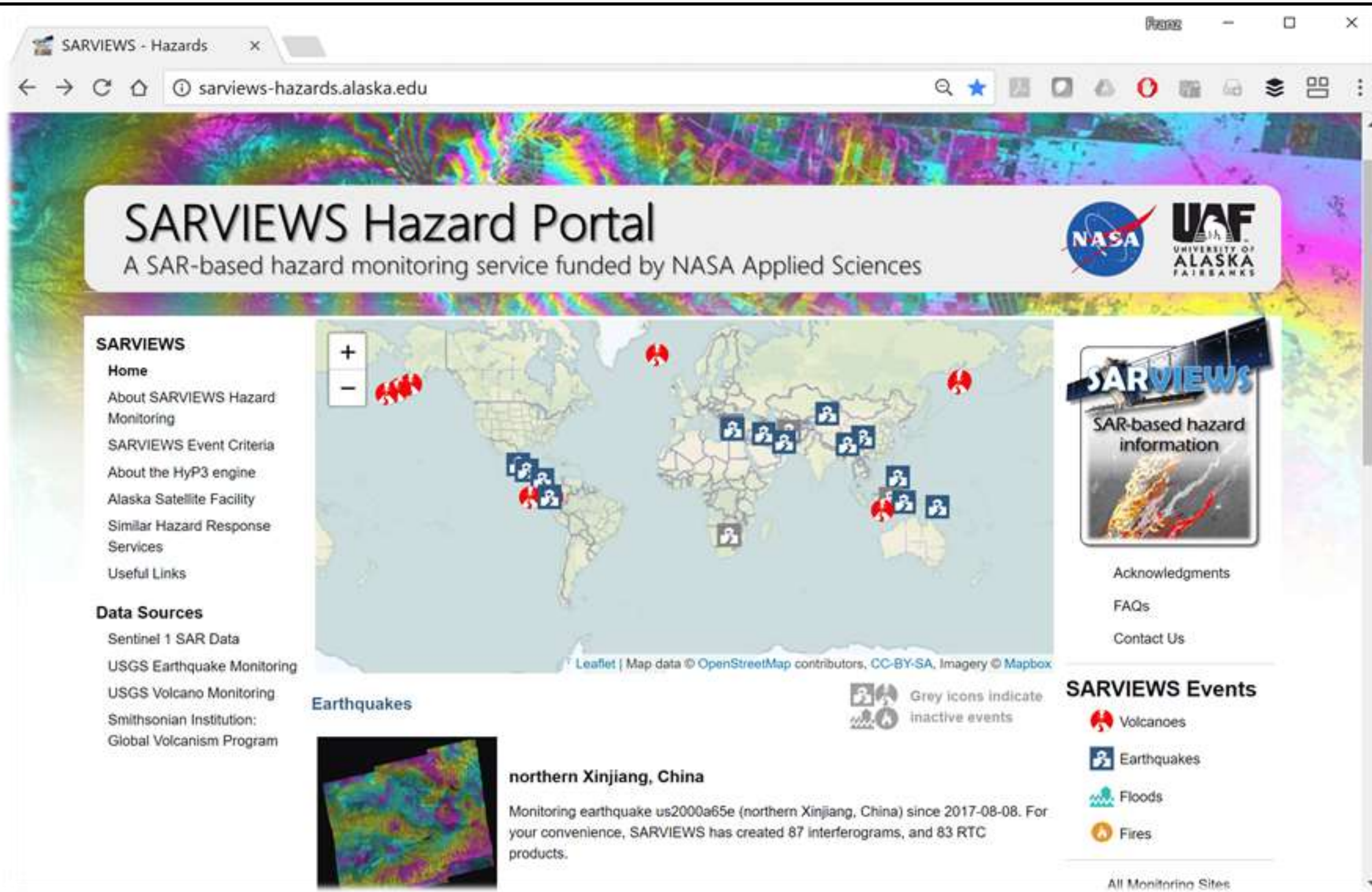


Railway Station Berlin

The SARVIEWS Hazard Portal

An Automatic InSAR Processing System for Geohazards

VISIT US @ HTTP://SARVIEWS-HAZARDS.ALASKA.EDU/



Outline:

A FIRST INTRODUCTION TO INTERFEROMETRIC SAR (INSAR)

INSAR FOR TOPOGRAPHIC MAPPING

INSAR FOR DEFORMATION MONITORING

TIPS FOR SELECTING SUITABLE IMAGES FOR INSAR

Tips for Selecting Suitable Images for InSAR

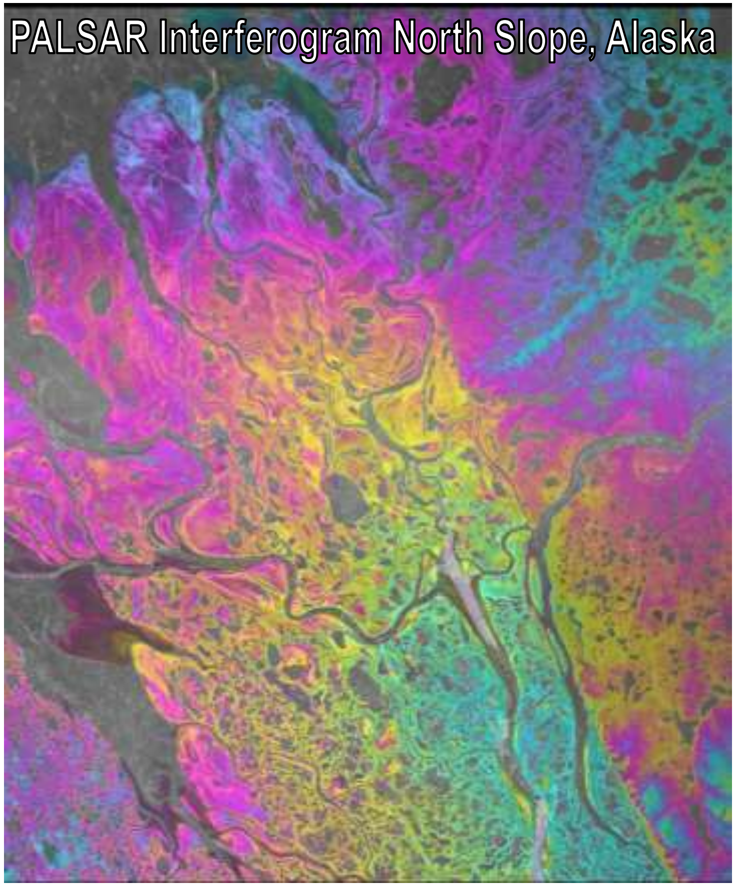
How to select a suitable image pair for successful InSAR processing

- **Required conditions:**
  - Images from identical orbit direction (both ascending or both descending)
  - Images with identical incidence angle and beam mode
  - Images with identical resolution and wavelength (usually: same sensor)
  - Images with same viewing geometry (same track/frame combination)

- **Recommended conditions:**
  - For topographic mapping: Limited time separation between images (temporal baseline)
  - For deformation mapping: Limited spatial separation of acquisition locations (spatial baseline)
  - Images from similar seasons / growth / weather conditions

Conclusion and Take-Home Points

- InSAR very powerful method for mapping surface topography and cm-scale surface deformation
- InSAR has strong potential to improve understanding and predictability of geodynamic processes, especially when combined with modeling
- InSAR is limited by
  - One-dimensionality of the measurement
  - signal decorrelation (reduction of similarity), which is caused by physical change of the surface (e.g. water, vegetation, strong surface change)



QUESTIONS?

UP NEXT: LET'S LOOK AT SAR DATA