GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

Lecturer:

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Lecture 3: Interferometric SAR Techniques

The General Concepts of interferometric SAR (InSAR)

SAR Interferometry ....

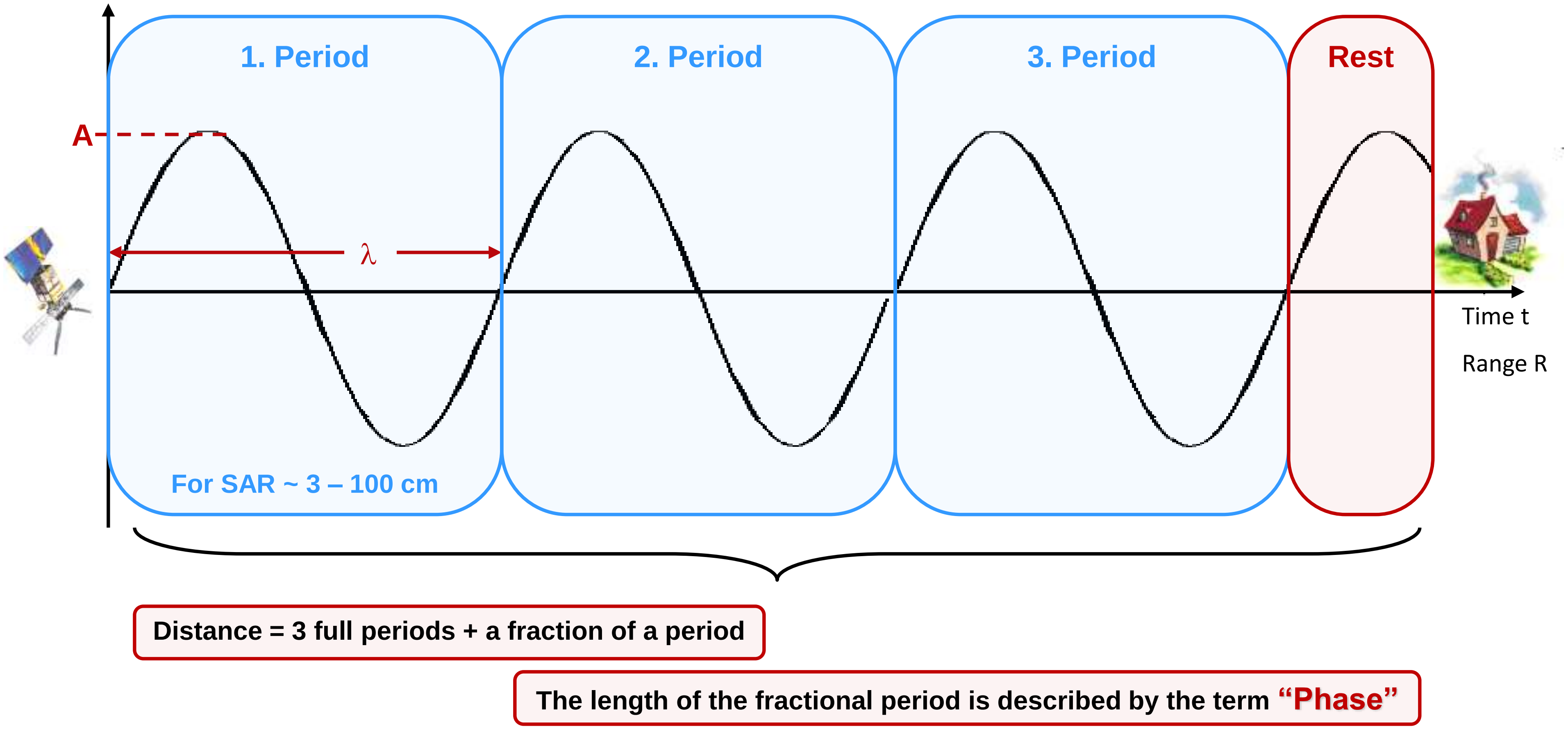
... combines two or more complex-valued SAR images to derive more information about the imaged objects (compared to using a single image) by exploiting phase differences.

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

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

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

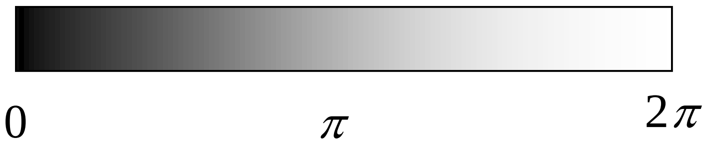


Phase Representation

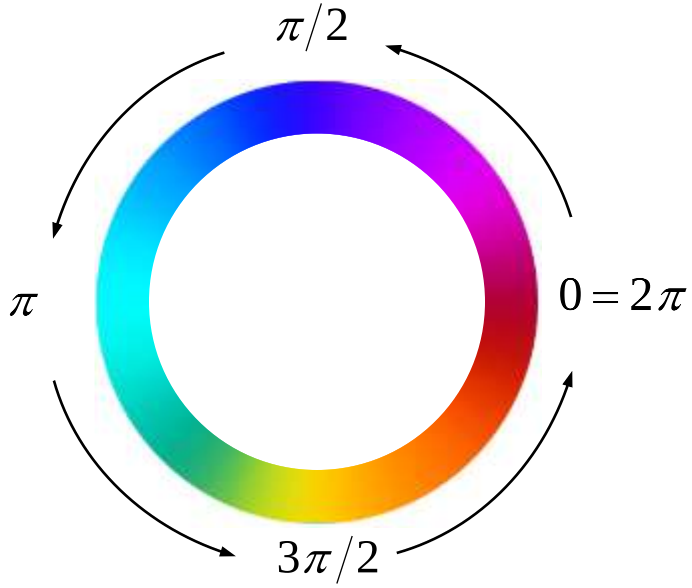
Phase is always ambiguous w.r.t. integer multiples of 2π

pictorial representation of phase:

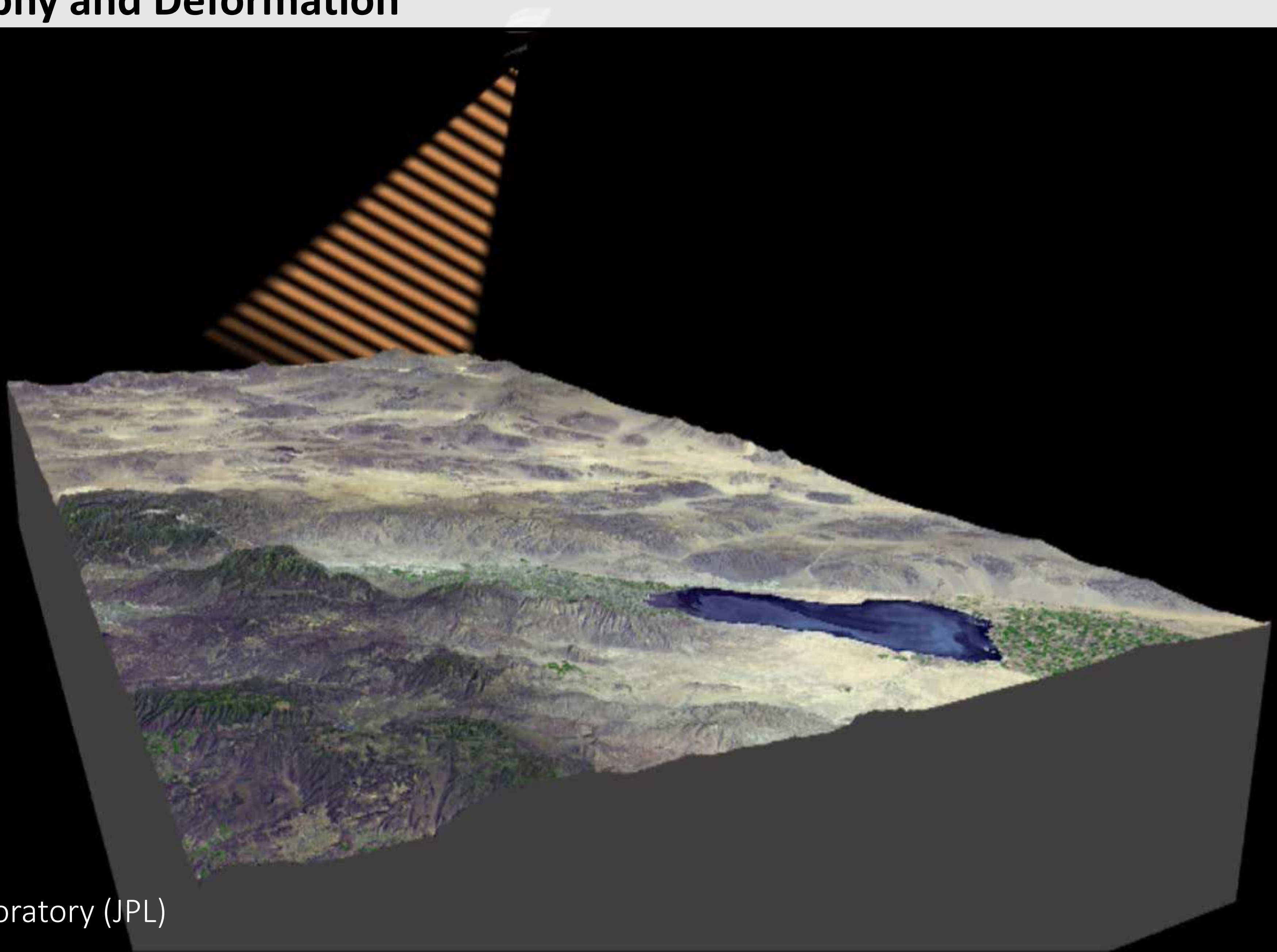
grey value



color wheel



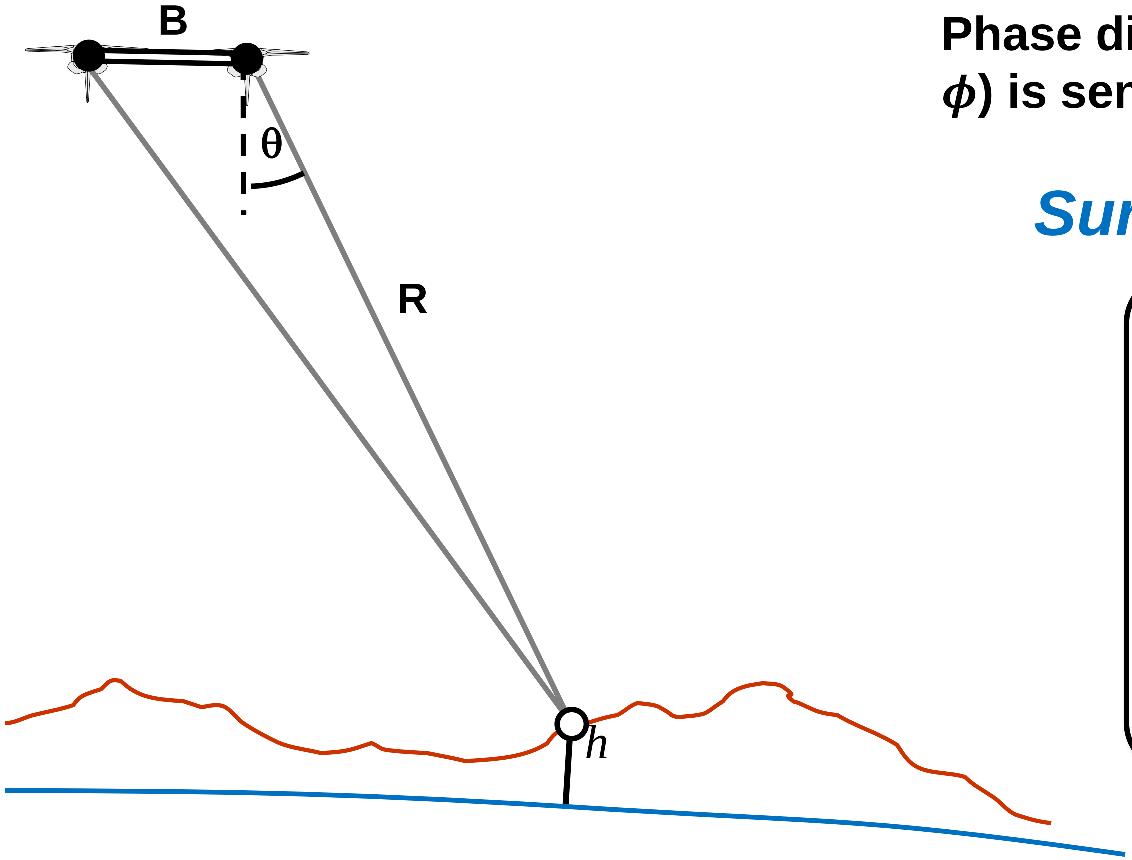
Interferometric SAR Measures Phase Differences Between Repeated Observations to Measure Topography and Deformation



Source: Jet Propulsion Laboratory (JPL)

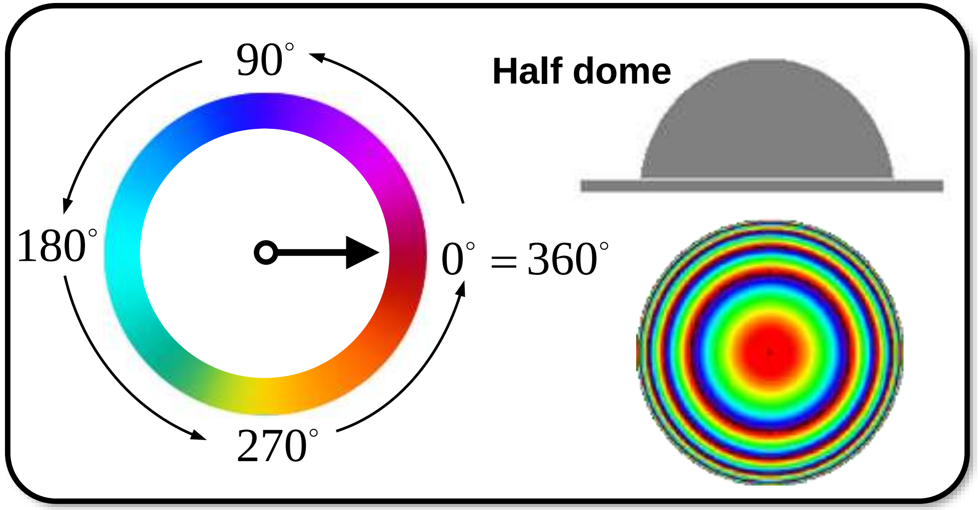
The Concept of Interferometric SAR (InSAR)

- 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 $\phi(h, B, R, \theta)$



The Concept of Interferometric SAR (InSAR)

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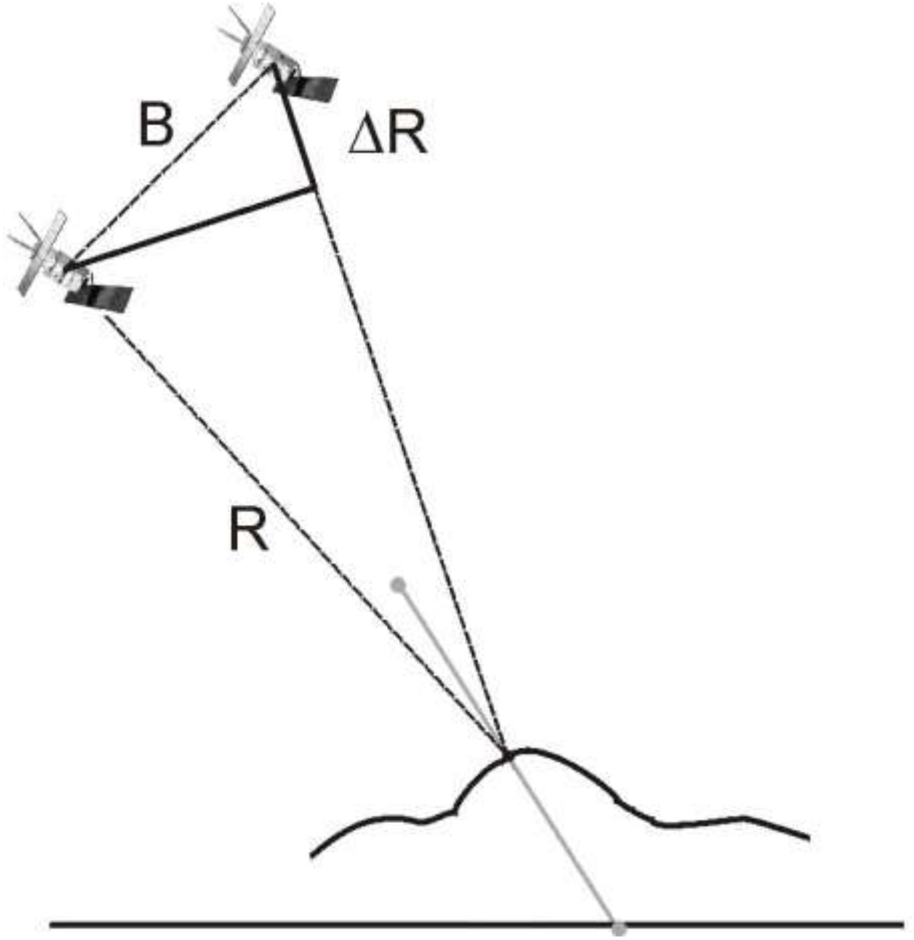

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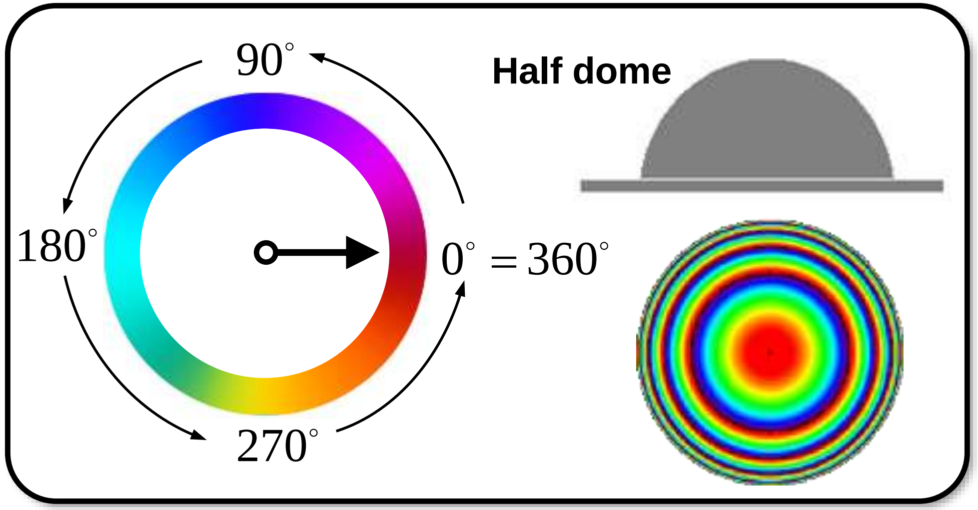
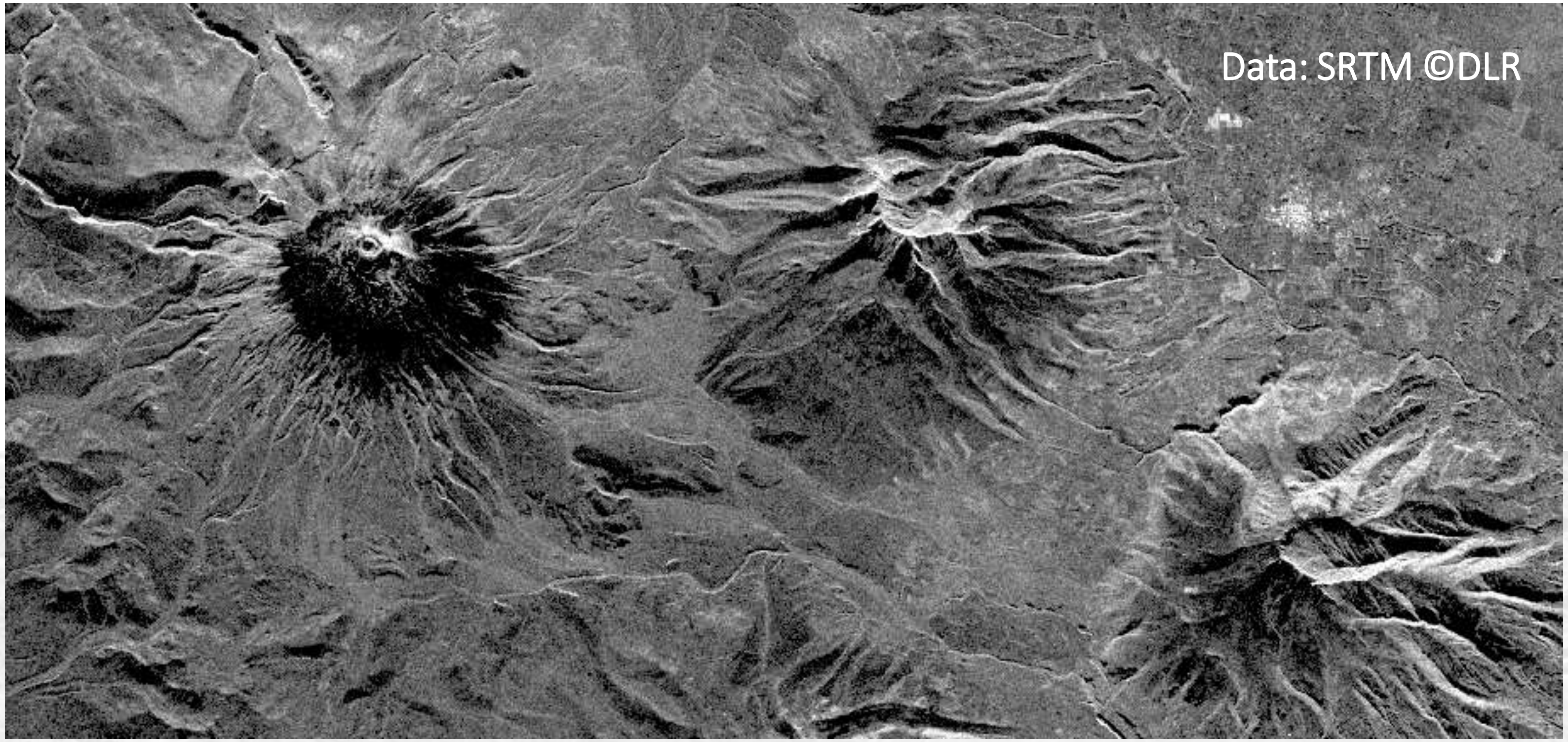
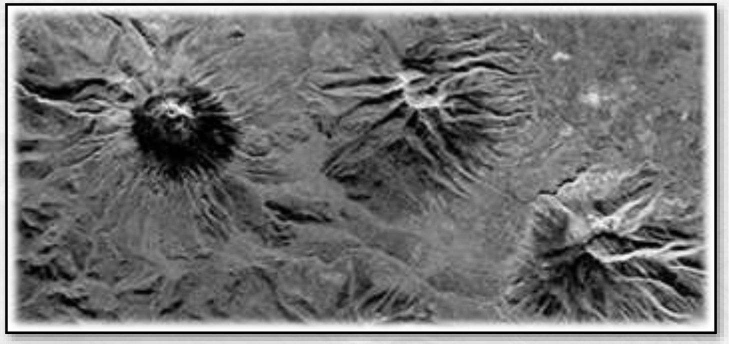


Example of a Spaceborne SAR Image

Cotopaxi Volcano, Ecuador

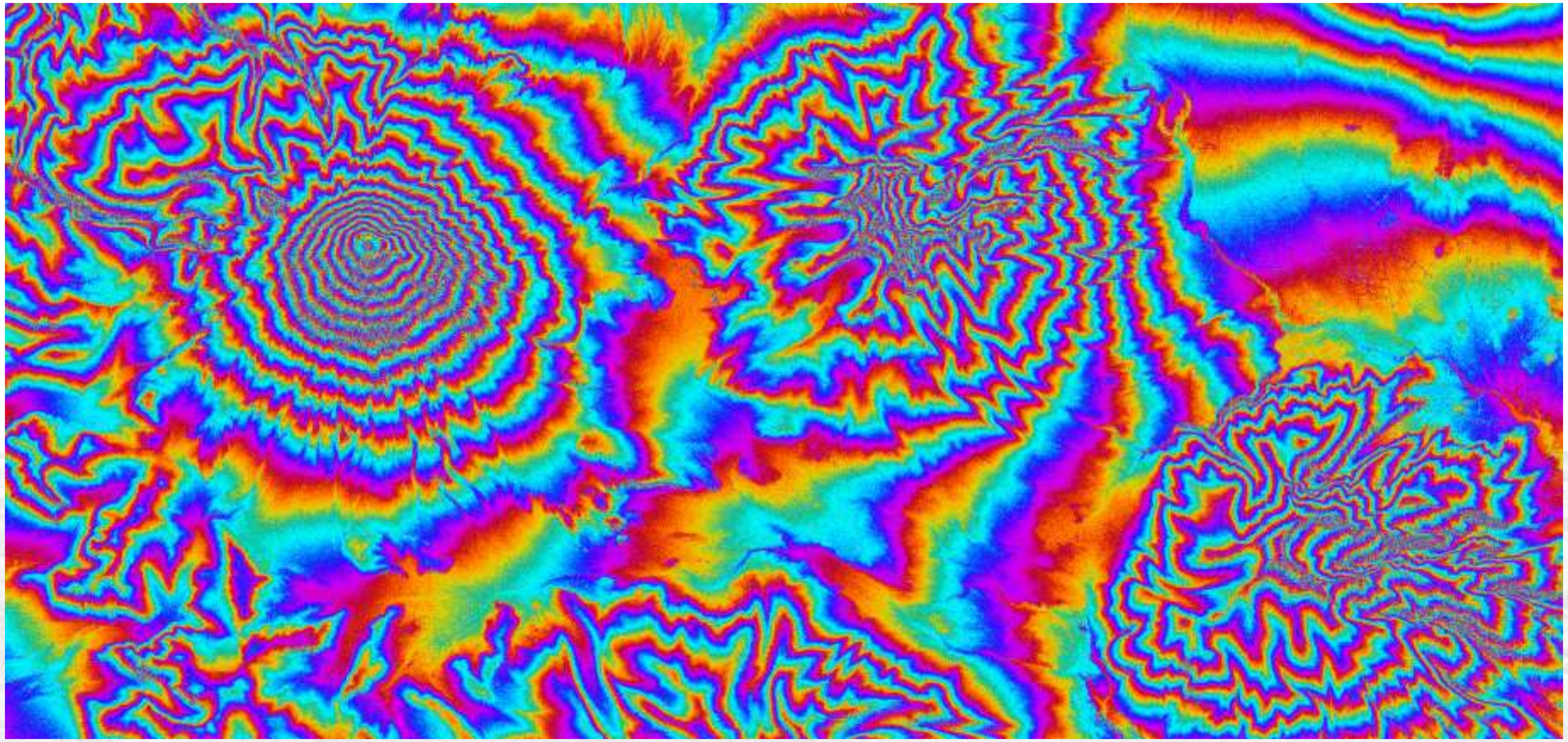


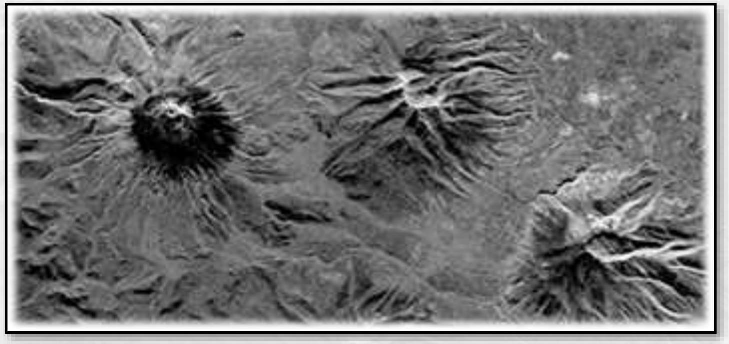


Data: SRTM ©DLR

Example of the Corresponding Interferometric Phase Image

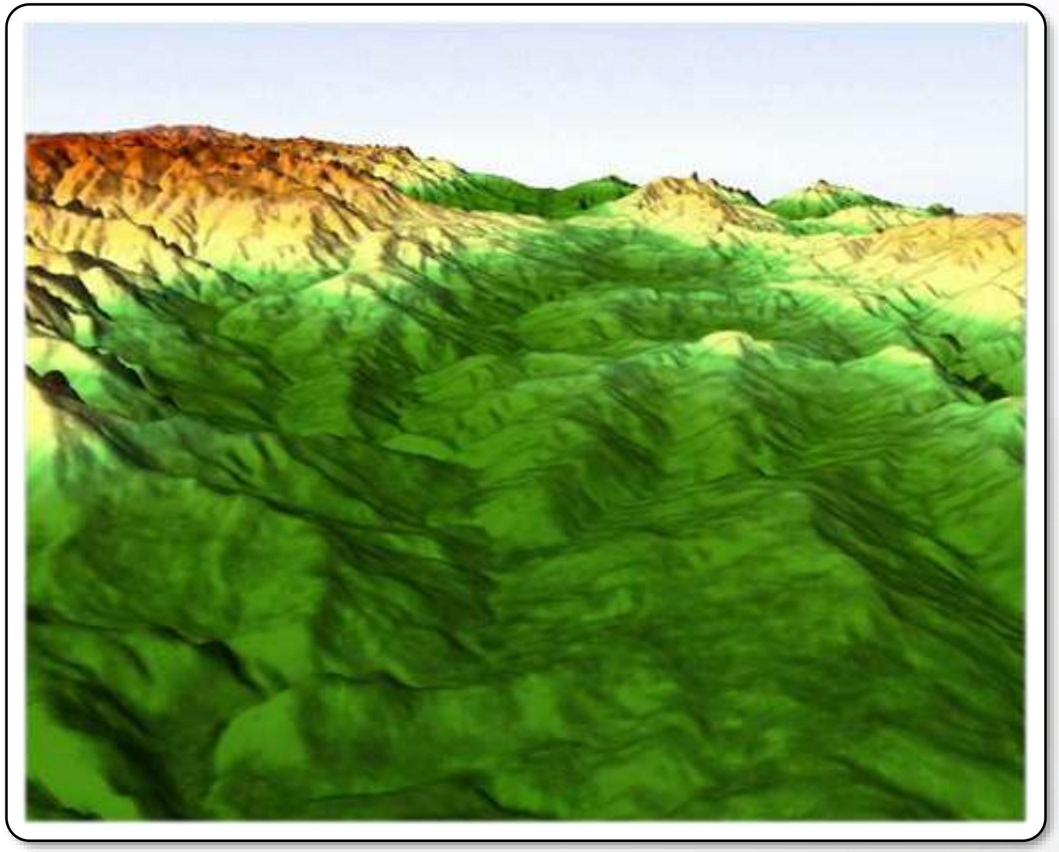
Cotopaxi Volcano, Ecuador





Data: SRTM ©DLR

InSAR-derived DEM, Cotopaxi Volcano, Ecuador



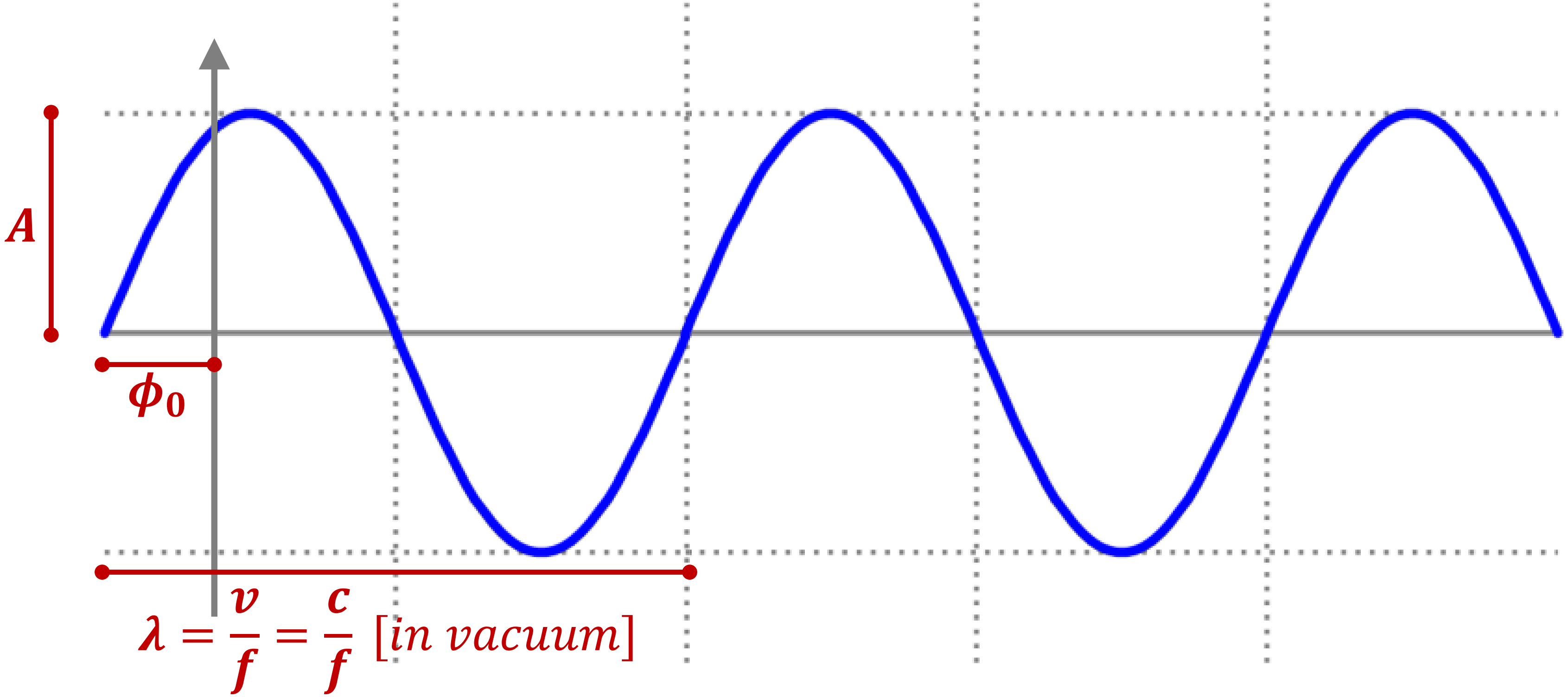
A short Excursion into Wave Propagation, Wave Interference, and Coherence

Wave Description of EM Signals

- Simplest way of describing a wave: Harmonic waves (= sine wave)

- Typically we use three parameters to describe harmonic waves:

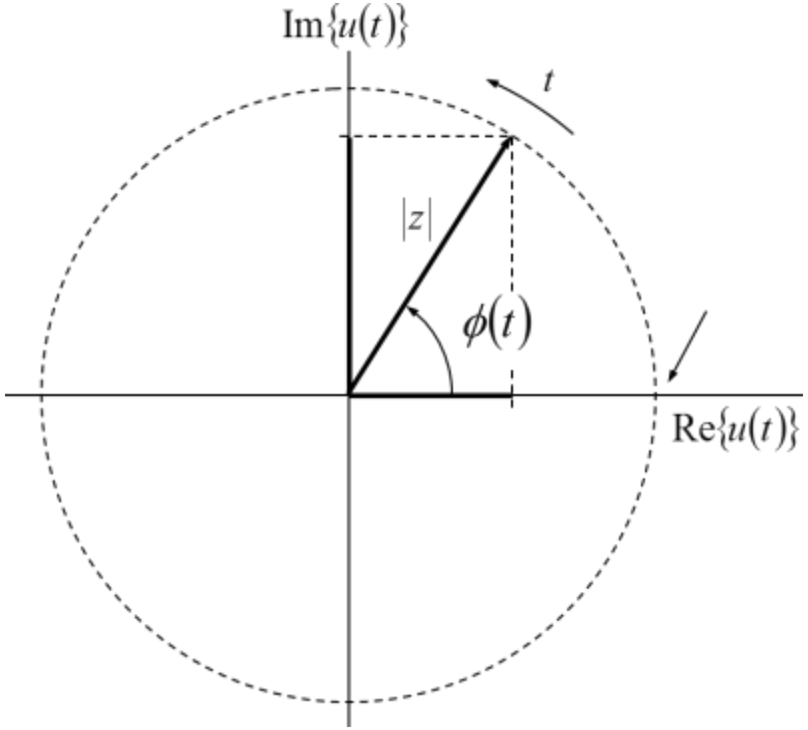
$$\Psi(t) = \boldsymbol{A} \cdot sin(2\pi \boldsymbol{f} t + \boldsymbol{\phi_0})$$

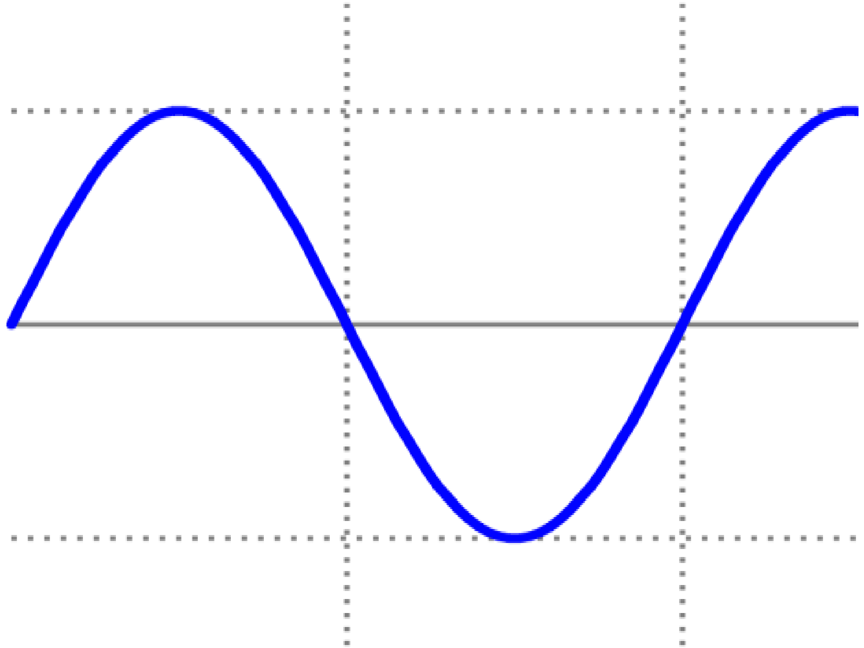


A Compact Way to Visualize Propagating EM Waves

- **Imagine a propagating EM wave as a vector rotating in a plane**
  - The length of the vector describes the amplitude of the signal
  - The orientation describes the phase of the signal
  - The rotation speed describes its frequency

This visualization is a handy way of thinking about propagating waves



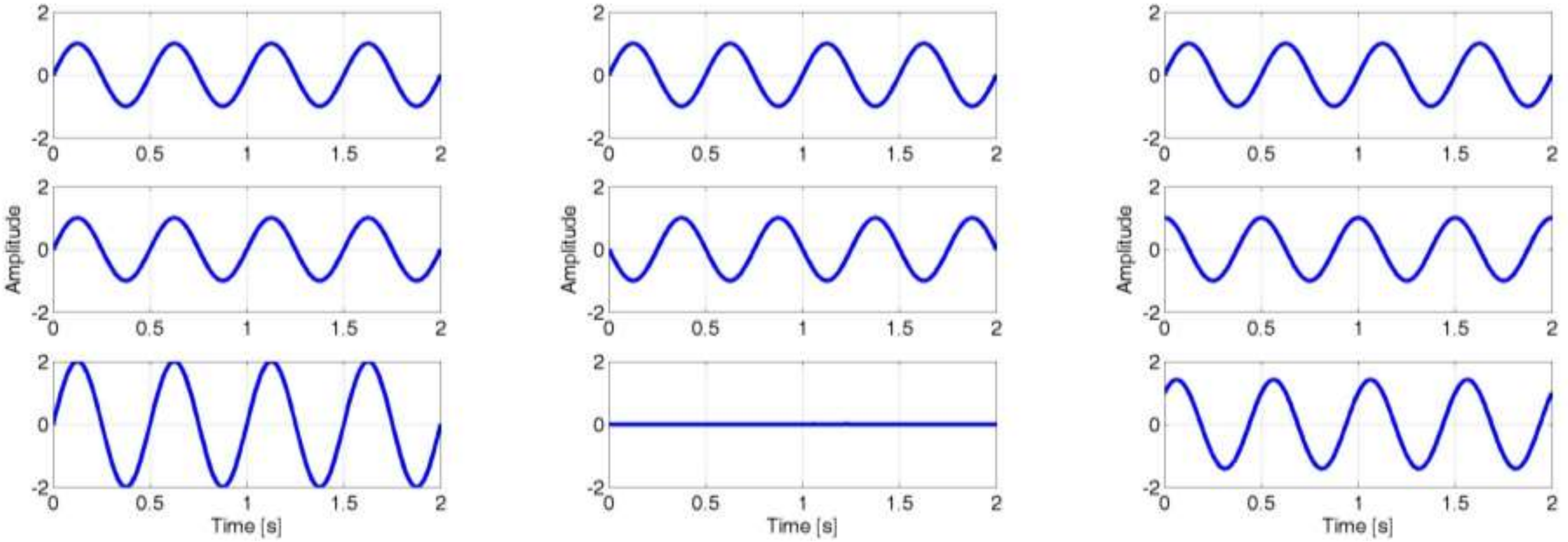


Combination of Waves

- Superposition of waves called *interference* (e.g., two waves: $\psi = \psi_1 + \psi_2$)
- As ψ_1 and ψ_2 can have different amplitude, frequency, and phase, the shape of ψ is not straightforward

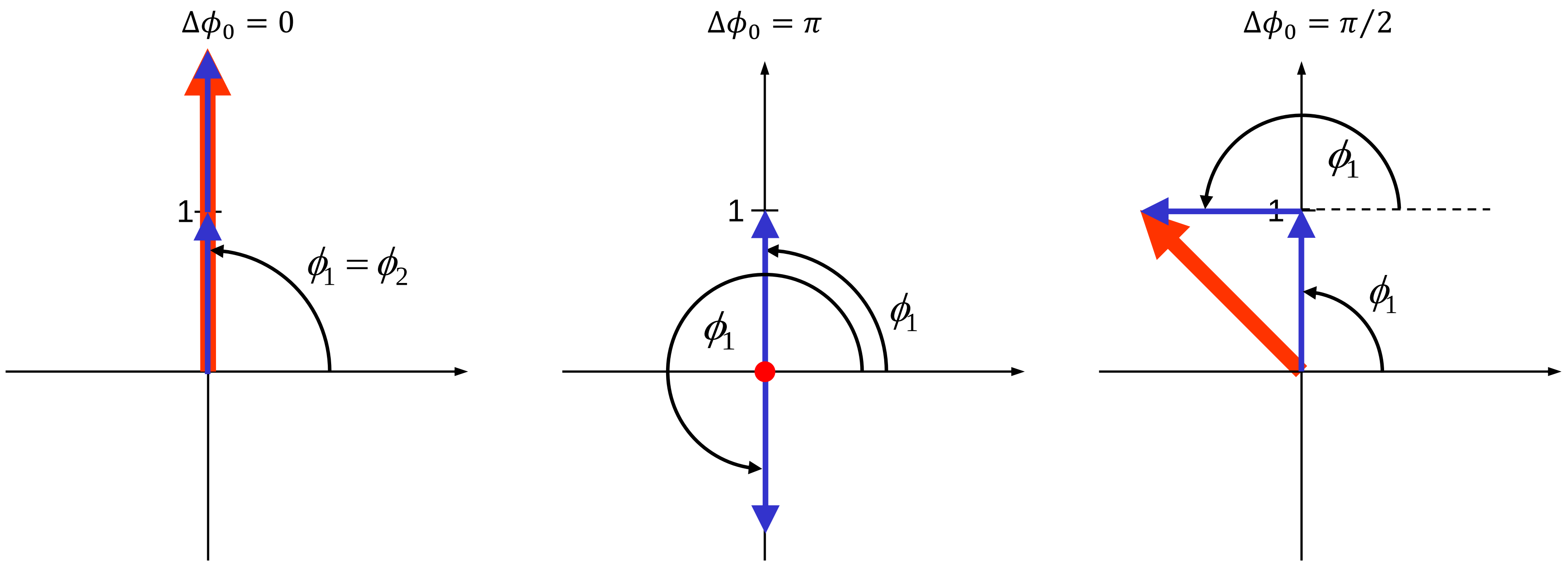
  - **Examples:** A and f of waves kept the same; ϕ_0 can vary

$\Delta\phi_0 = 0$ $\Delta\phi_0 = \pi$ $\Delta\phi_0 = \pi/2$



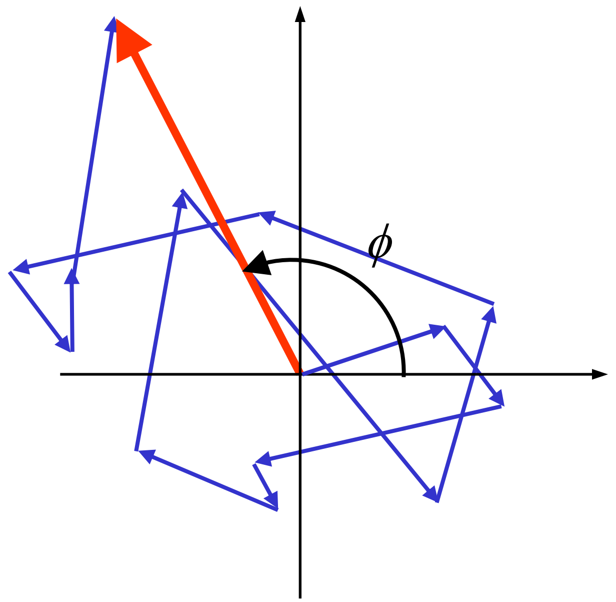
Combination of Waves

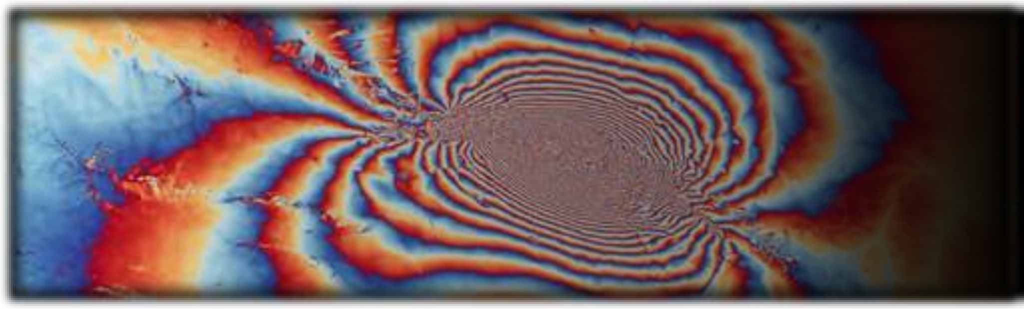
- **The result of interference can be easier calculated in the complex plane**
- In the complex plane, the addition of two waves ψ_1 and ψ_2 is simply their vector sum



Interference and Coherence

- Waves with phase differences that remain constant over time (or space) are said to be ***coherent***
- Coherent waves → combined wave vector is stationary
- If coherence is low, interference effects are less predictable
- Coherence can be seen as measure of predictability

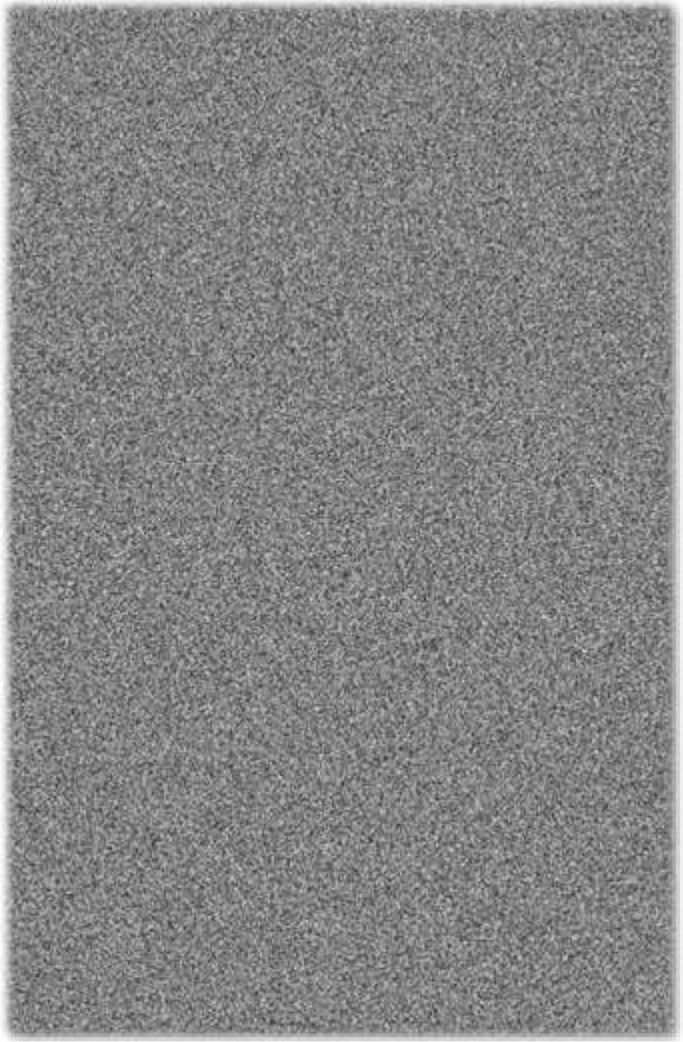




How InSAR Really Works

InSAR, a differential technique (or, interference & coherence is back … again):

- InSAR analyzes the phase difference between two or more SAR images in order to map surface topography and monitor surface deformation.
  - **Q1**: We have to rely on phase differences as the phase of a single SAR image appears spatially random and does not allow access to information. Use the concept of interference to explain why that is.
  - **Q2**: We calculate phase differences between SAR images to extract information about surface topography and/or deformation. For this approach to be successful, we require the data to have sufficient coherence. From your knowledge about coherence, explain how coherence affects this process.



Phase signature of a single SAR image

How InSAR Really Works:

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

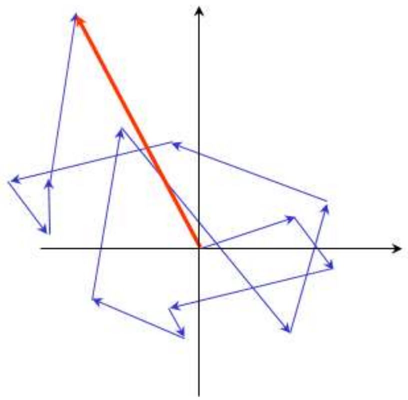
- **Phase in a pixel of a SAR image is sum of two components:**
  1. A **deterministic** component that is a function of the distance R between satellite and pixel on ground ($\psi(R)$)
  2. A **random** phase change ψ_{scatt} caused by how all scattered signals from one pixel combine together

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

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

- 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**

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

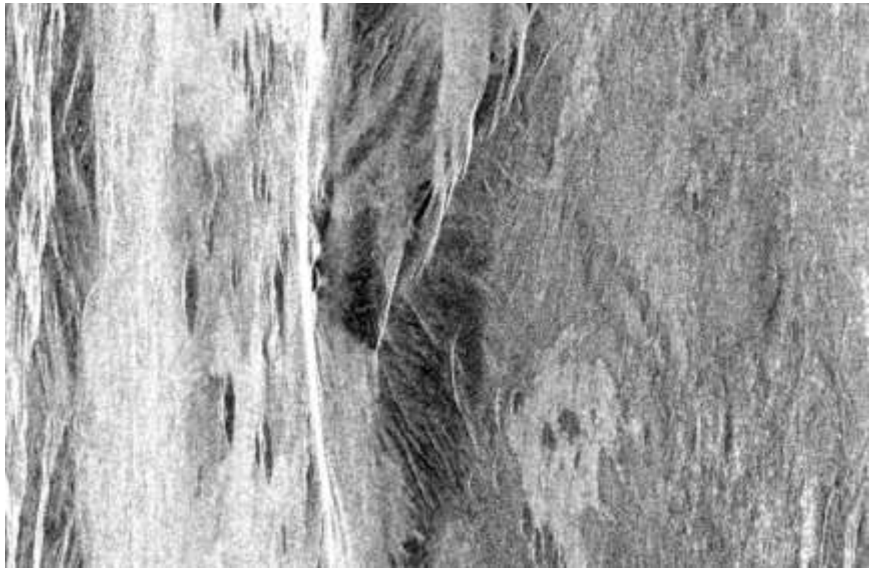


Blue: contribution by one single scattering event

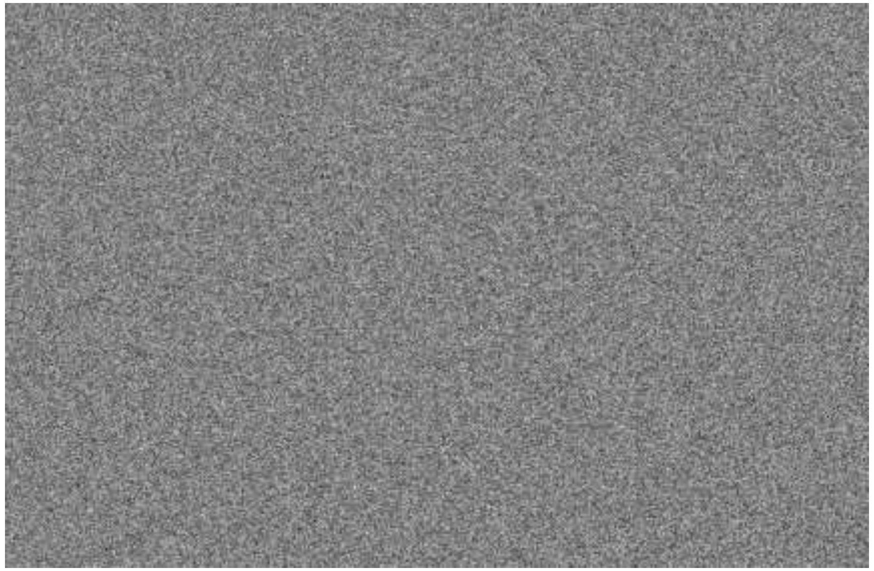
Red: final amplitude and phase of received signal

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

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



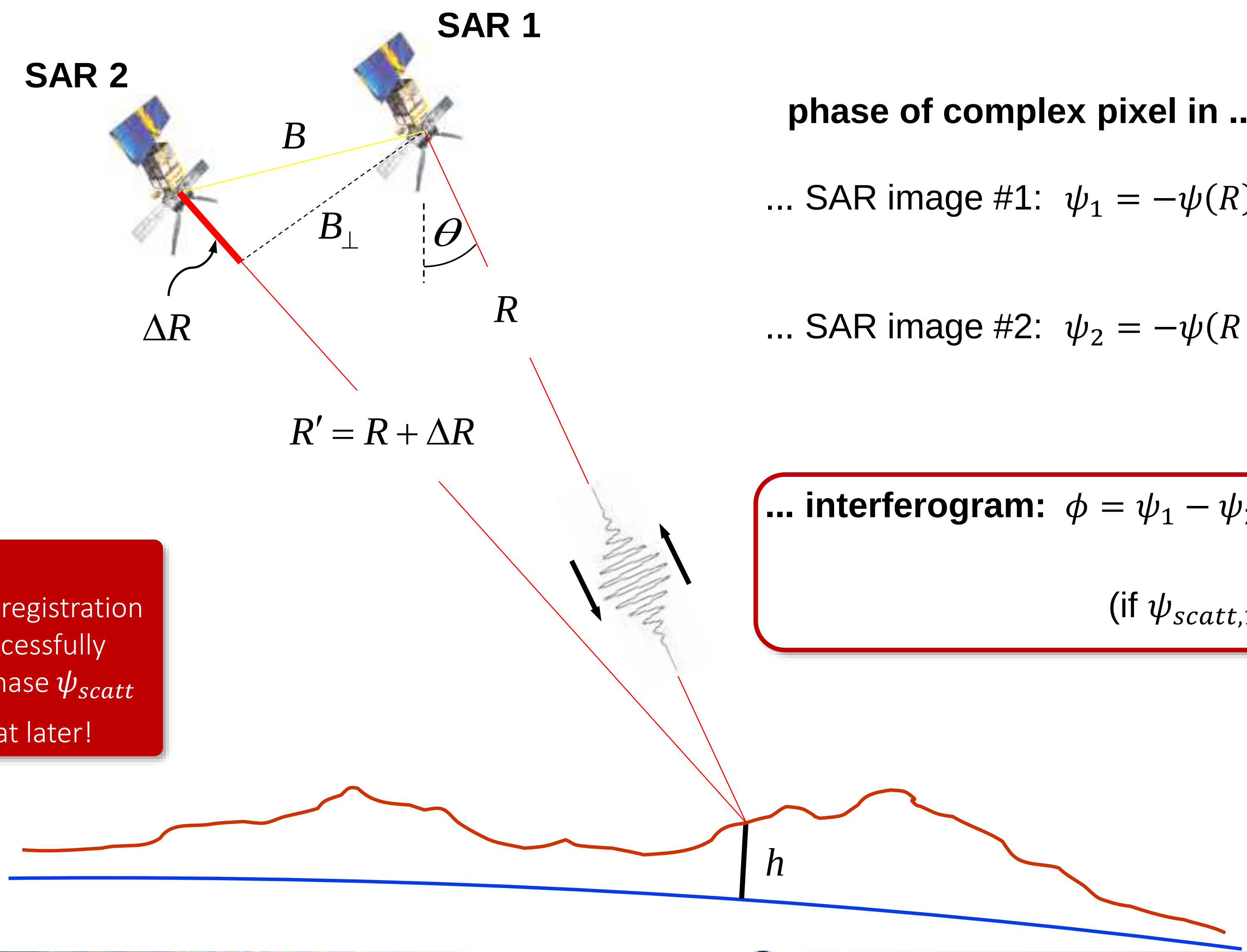
Phase ψ of a segment of an ERS-1 image over Mount Etna, Italy



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

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: $\phi = \psi_1 - \psi_2 = \phi(\Delta R)$

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

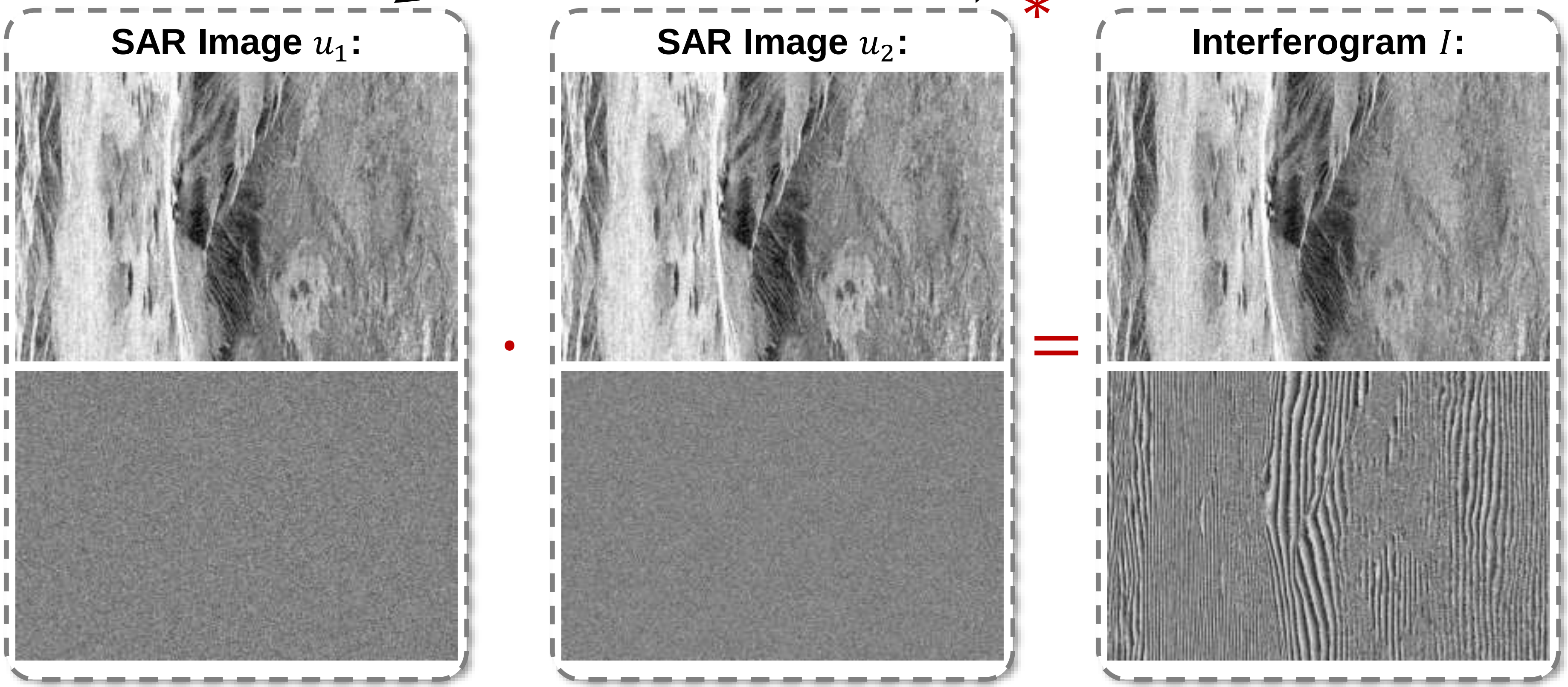
Note:

Accurate Image co-registration is needed to successfully remove random phase ψ_{scatt}

More about that later!

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

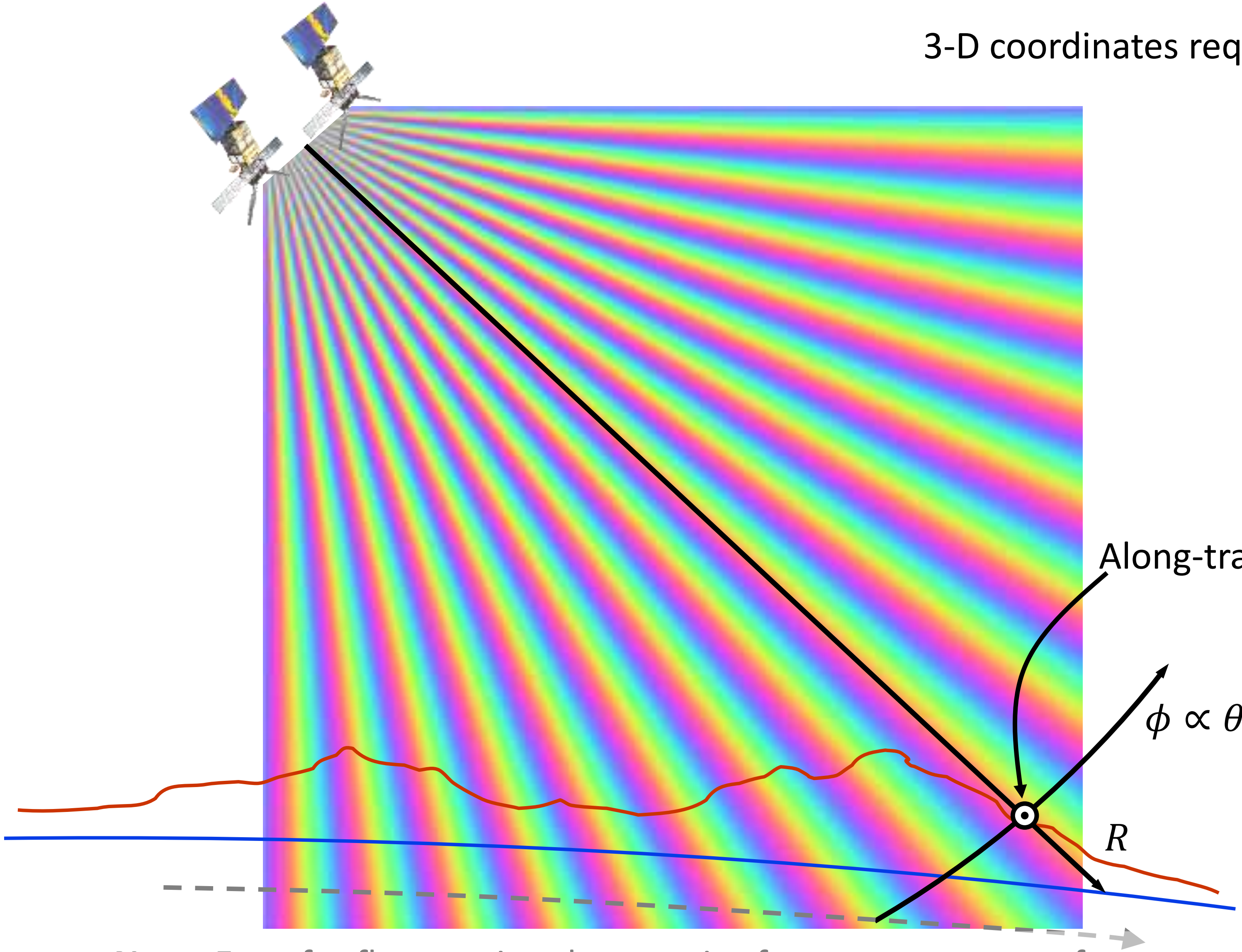
- **To form interferogram, we calculate:** $I = u_1 \cdot u_2^*$ ($\blacksquare^*$ is complex conjugate)



How InSAR Really Works:

3. Interferometric Phase ϕ as a Measurement of Angle

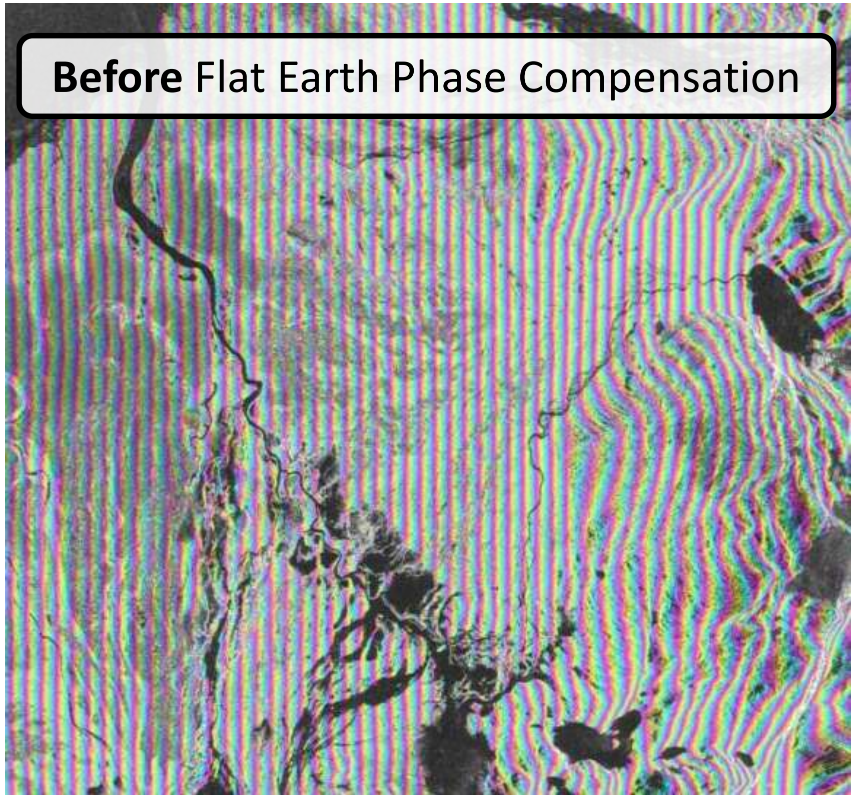
3-D coordinates required: R, t, θ

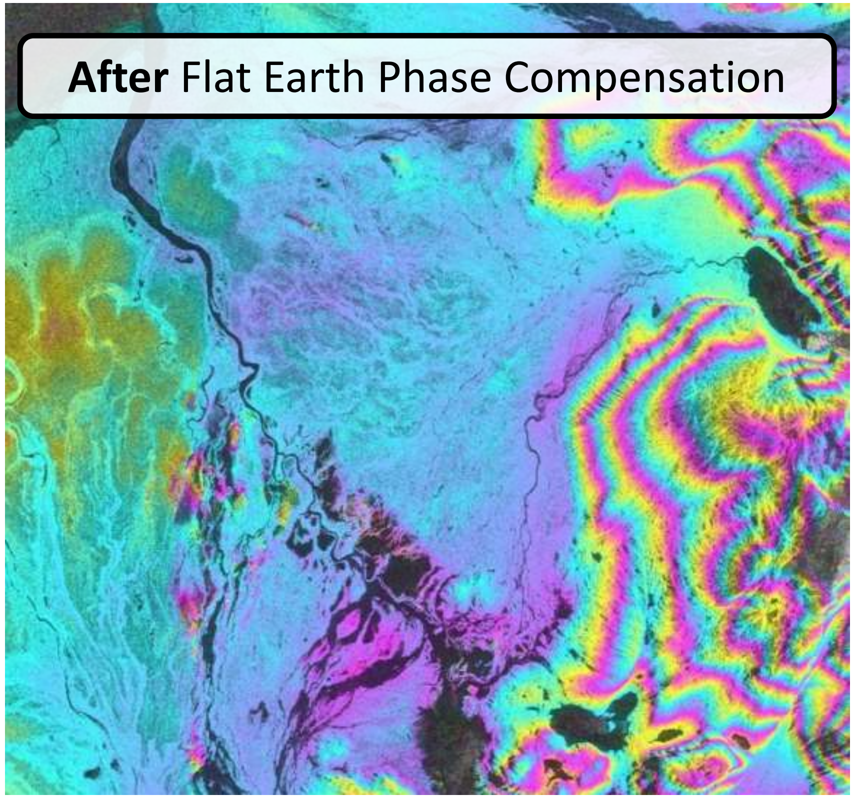


Note: Even for flat terrain: phase varies from near-range to far-range

How InSAR Really Works:
4. Subtraction of Flat Earth Phase

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

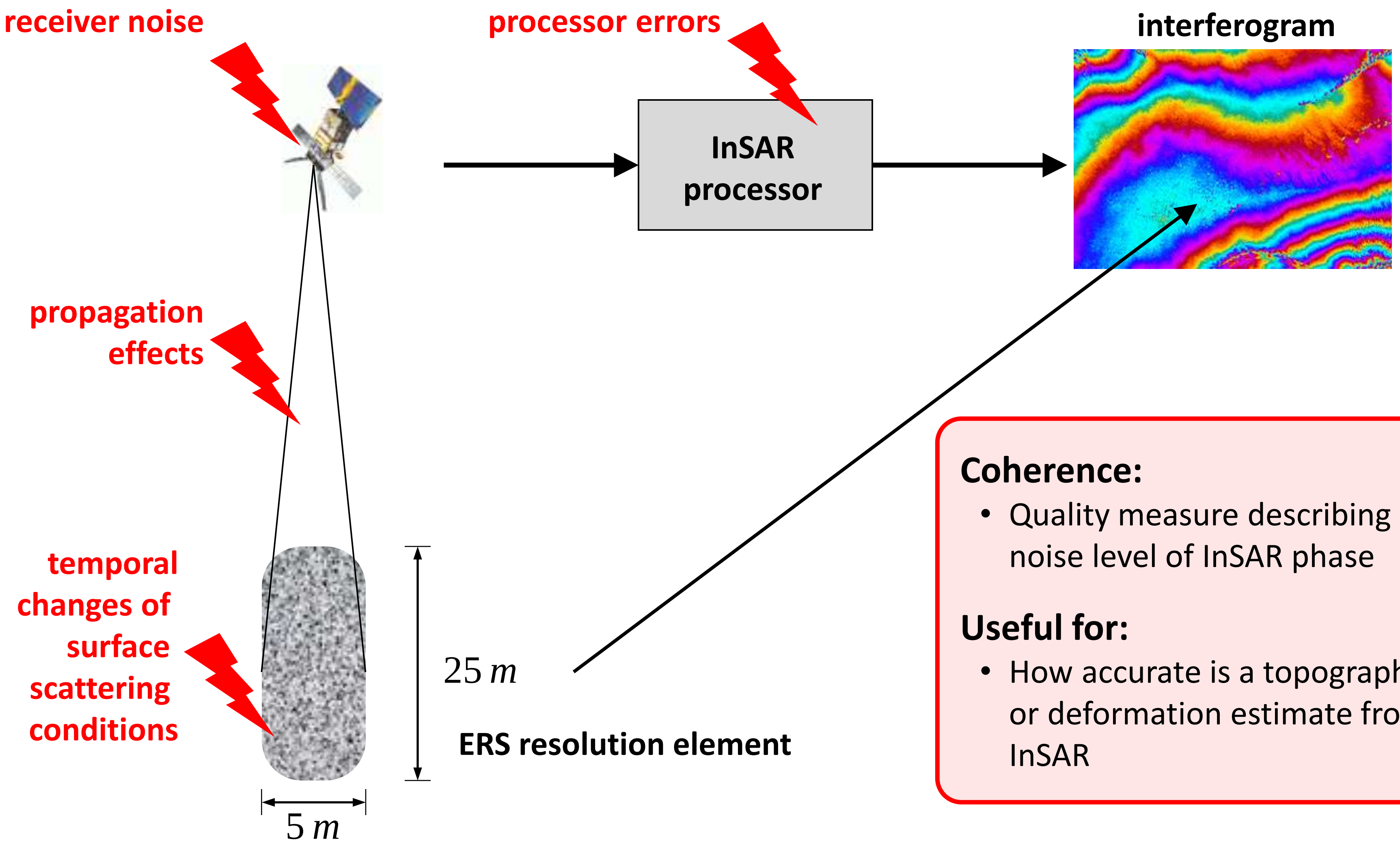




How InSAR Really Works:

5. 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

How InSAR Really Works:

5. Coherence: A Phase Quality Descriptor

- **We can calculate coherence using the following approach:**

$$|\hat{\gamma}[i,k]| = \frac{\left|\sum_W u_1[i,k] \cdot u_2^*[i,k]\right|}{\sqrt{\sum_W |u_1[i,k]|^2 \cdot \sum_W |u_2[i,k]|^2}}$$

W: small window centered around pixel $[i,k]$

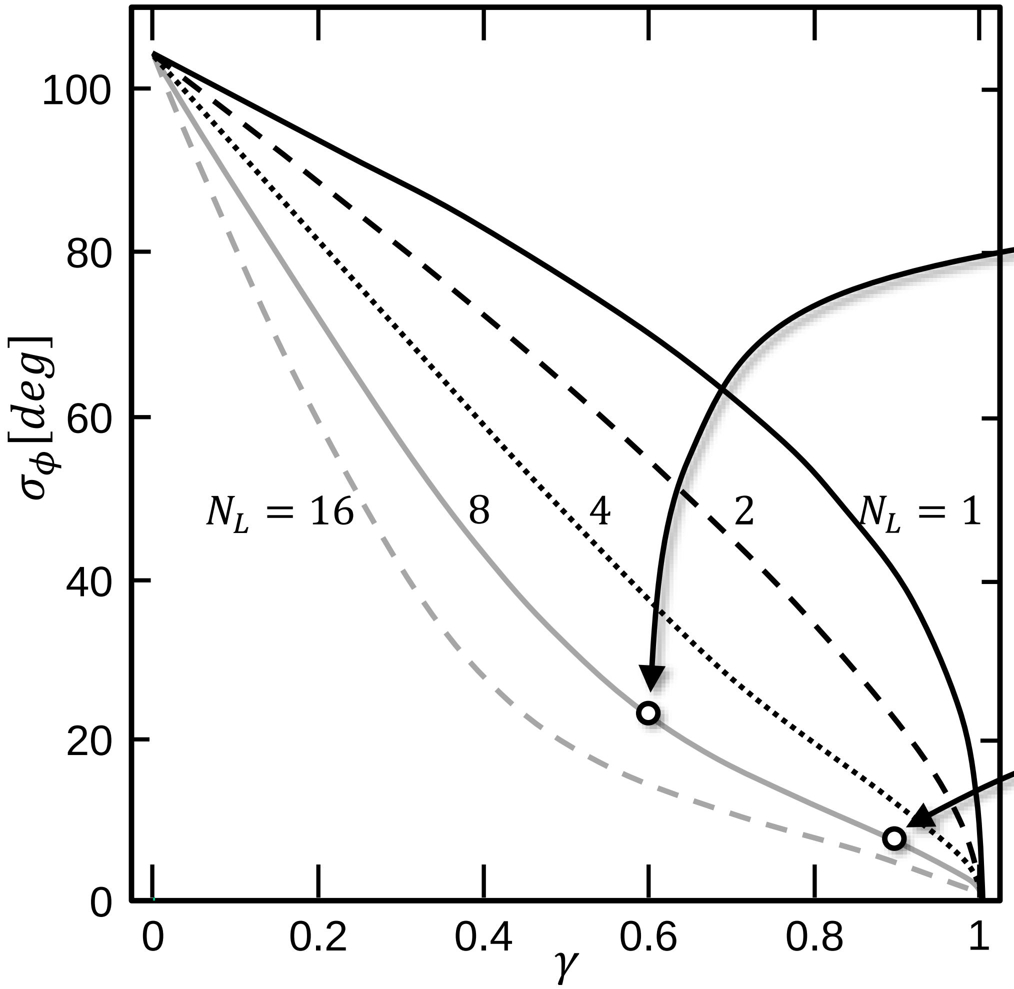
- **Coherence** is an indicator for the **level of noise in phase** $\phi[i,k]$ of interferogram pixel $[i,k]$

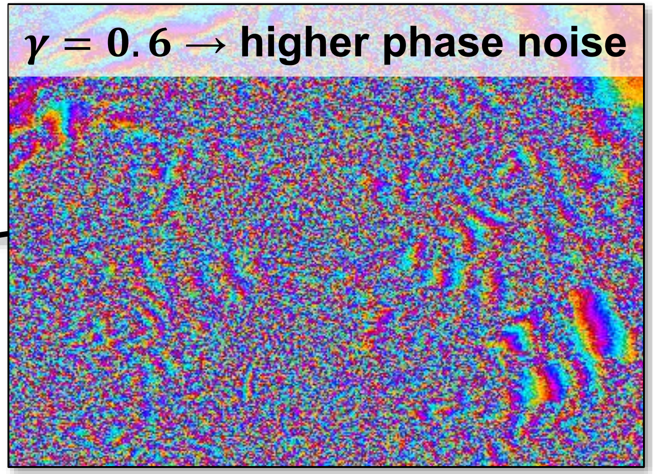
- **Coherence is defined between 0 (high phase noise) and 1 (low phase noise)**

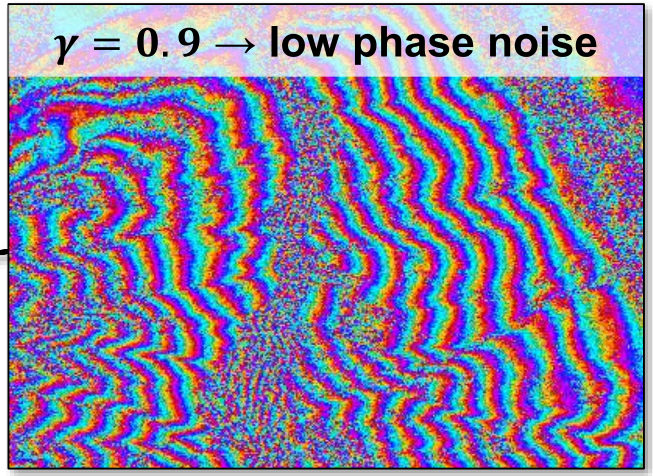
- **Coherence can be converted to a phase standard deviation** $\sigma_\phi[i,k]$

Coherence and Phase Noise - Theory

- How Coherence γ converts into phase standard deviation σ_ϕ depends on the number of looks N_L (how much we average)

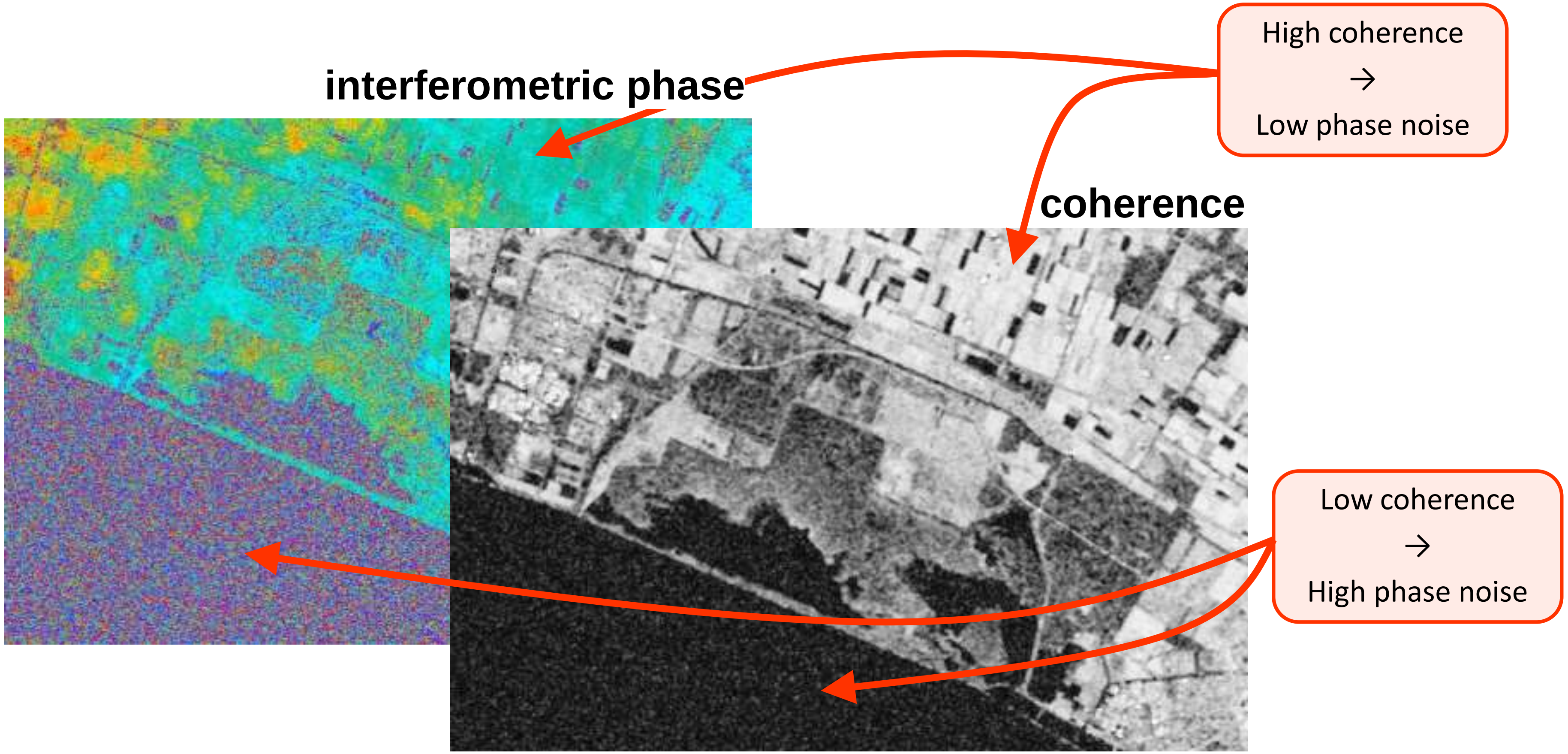


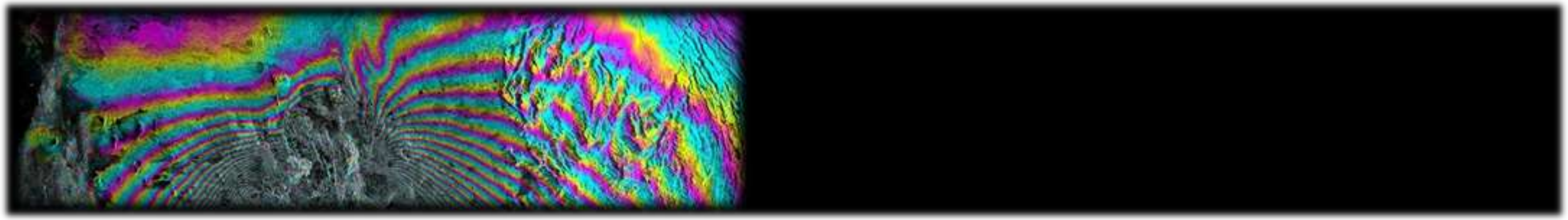




Interferometric Coherence - Example

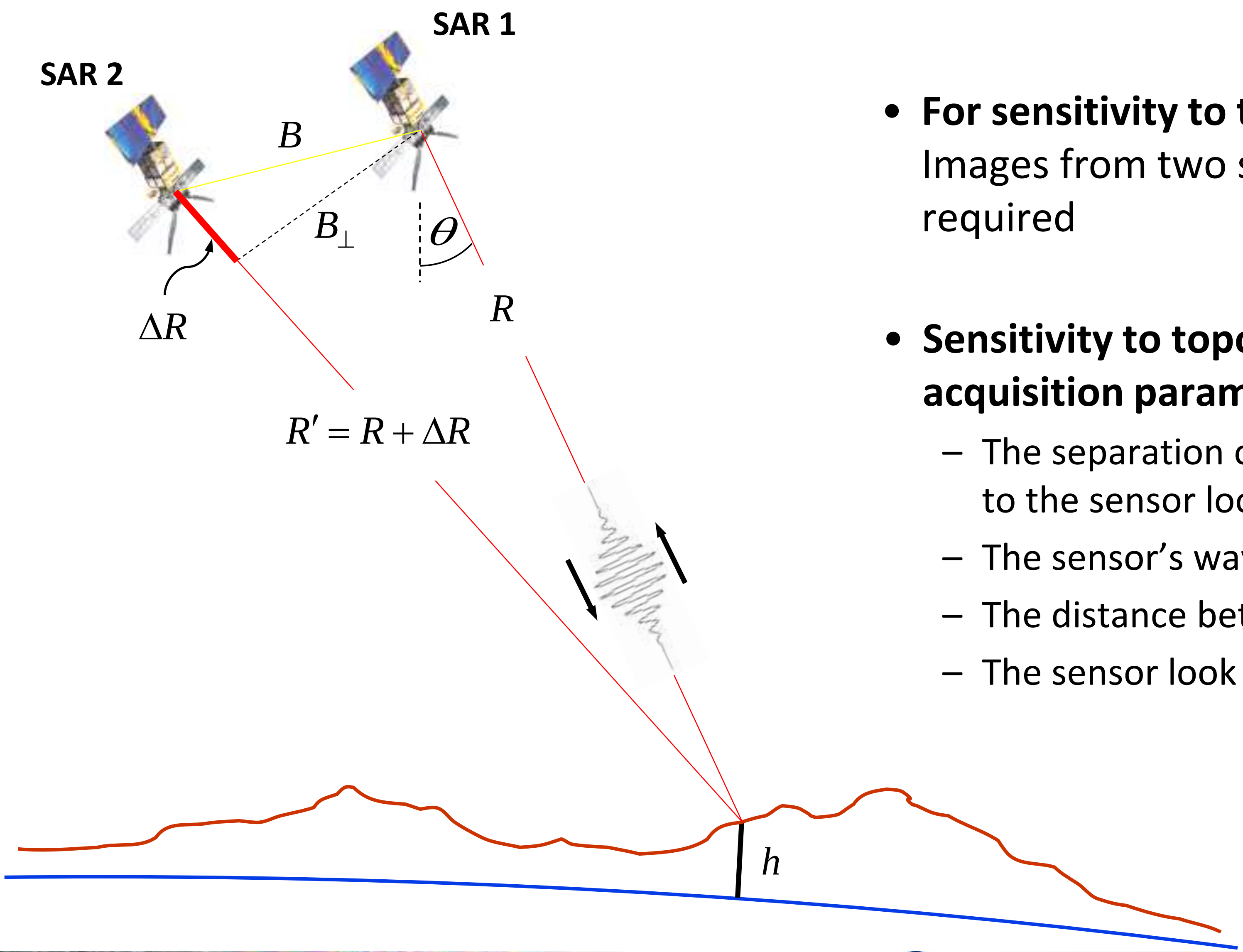
- **This example compares interferometric phase quality and coherence side-by-side**





INSAR FOR TOPOGRAPHIC MAPPING

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

Interferometric Sensitivity as a Function of Wavelength

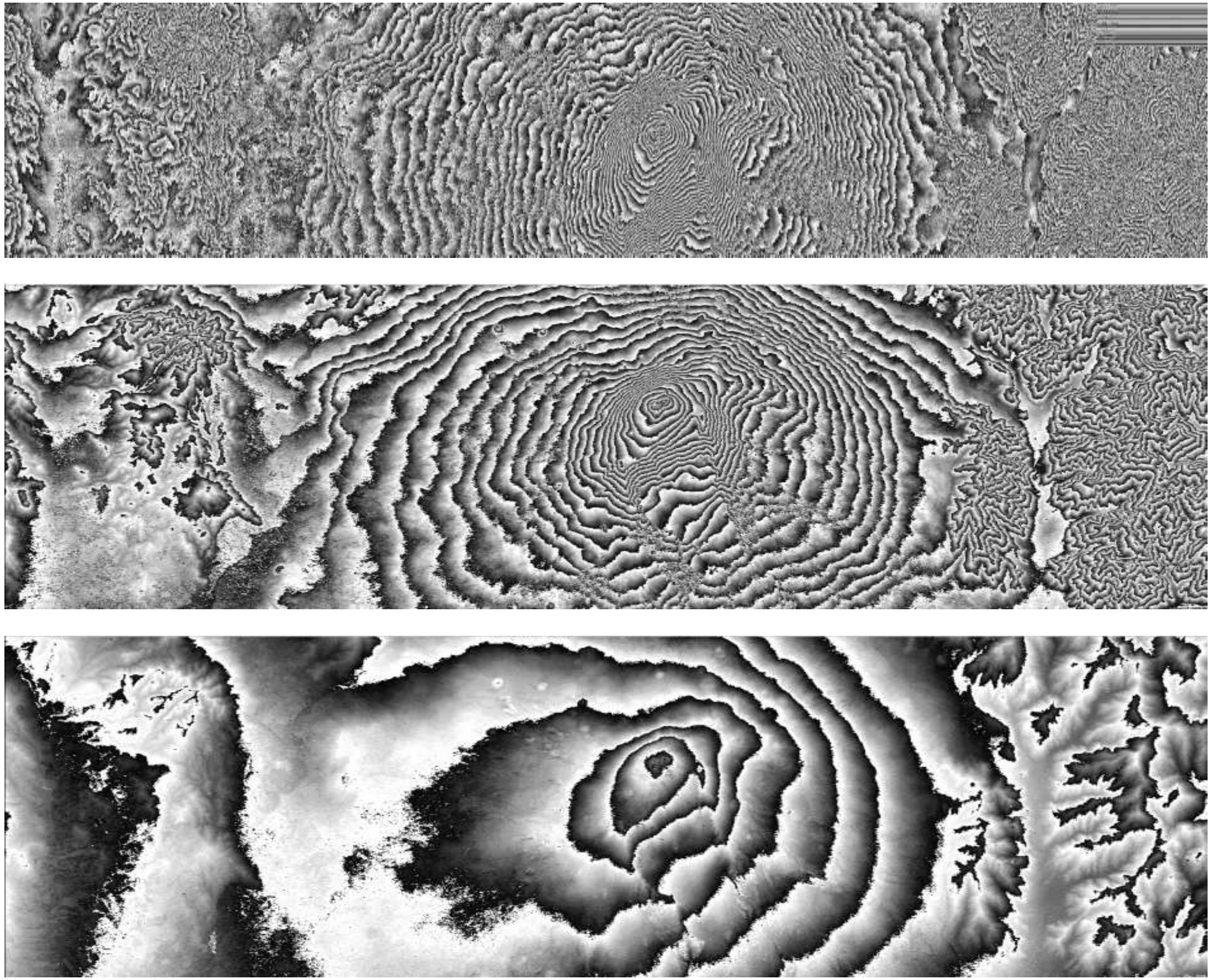
Three simultaneously acquired Interferograms with identical $B_\perp$, R, and θ but varying λ

X-band
$\lambda \approx 3.1cm$

C-band
$\lambda \approx 5.6cm$

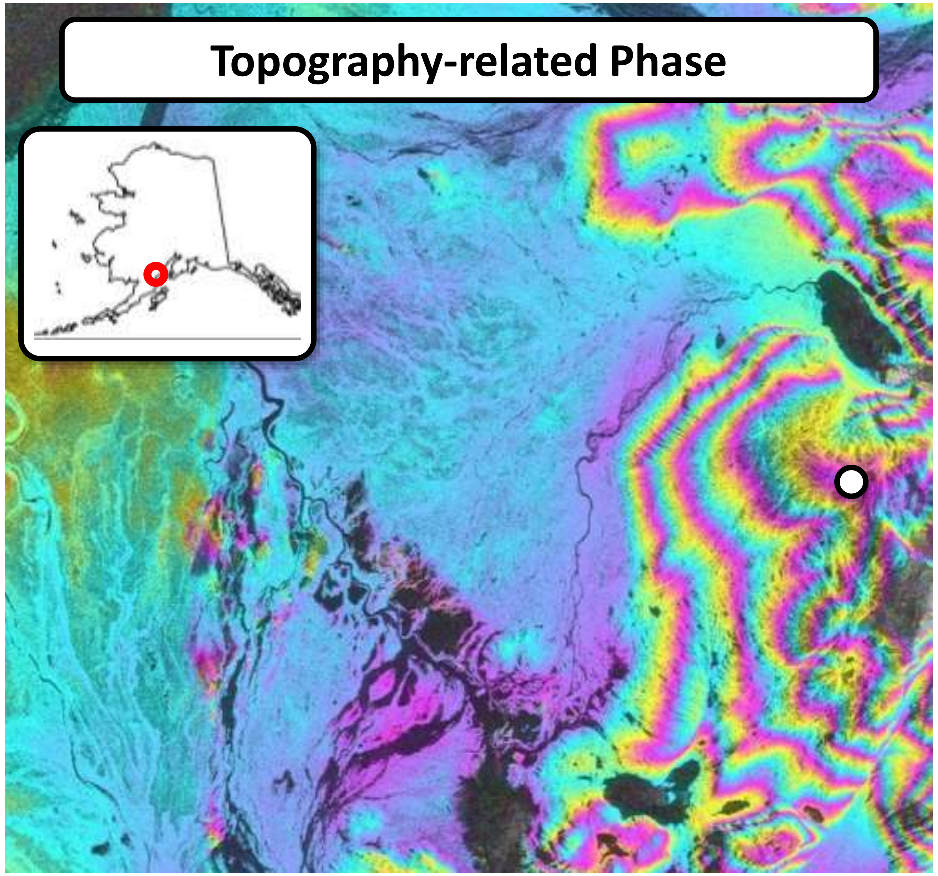
L-band
$\lambda \approx 24.0cm$

Mt. Etna
data: SRL-2



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): $h_{2\pi} = \frac{\lambda}{2} \frac{R \sin\theta}{B_\perp}$

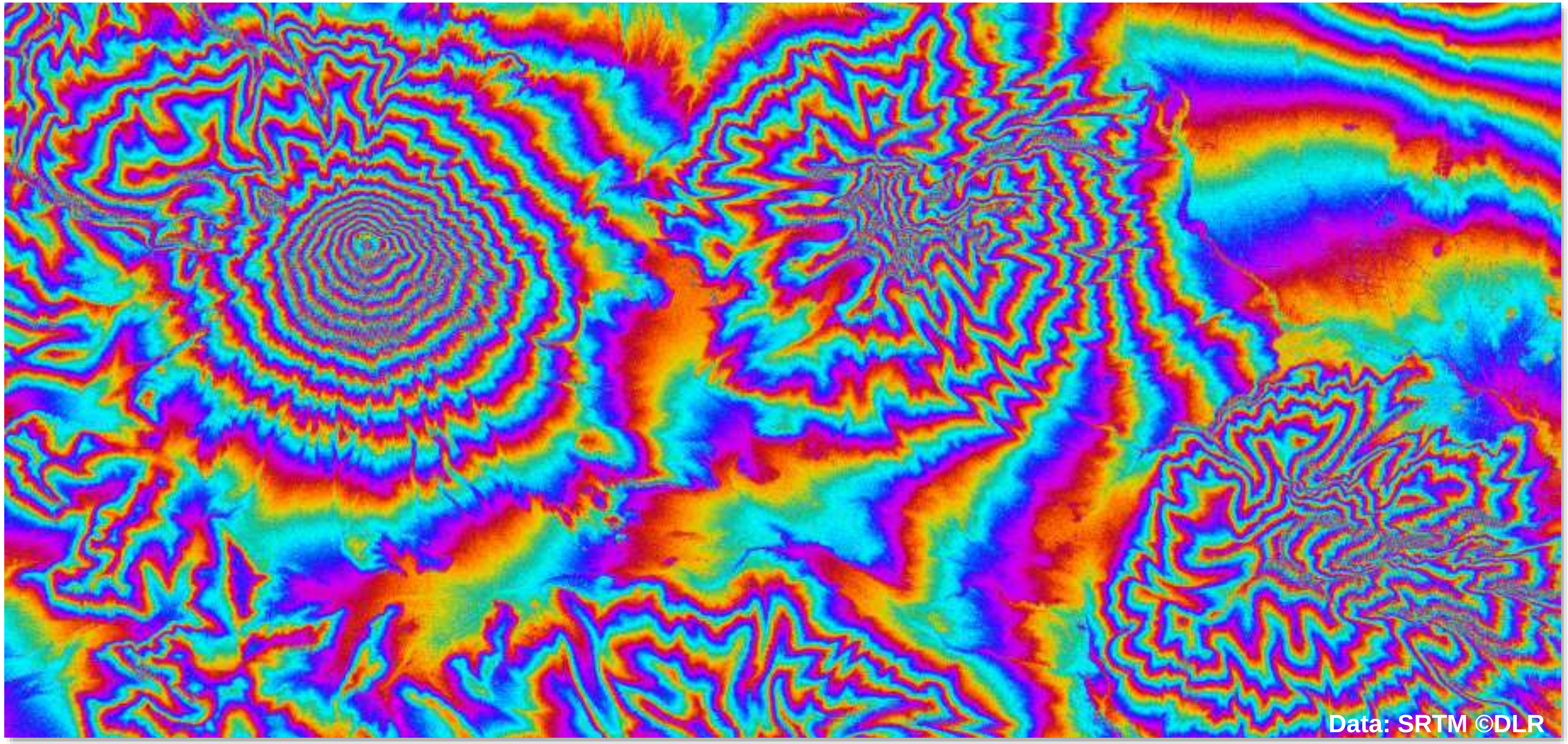
Parameters:

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

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

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

Problem of InSAR: Interferometric Phase is Ambiguous

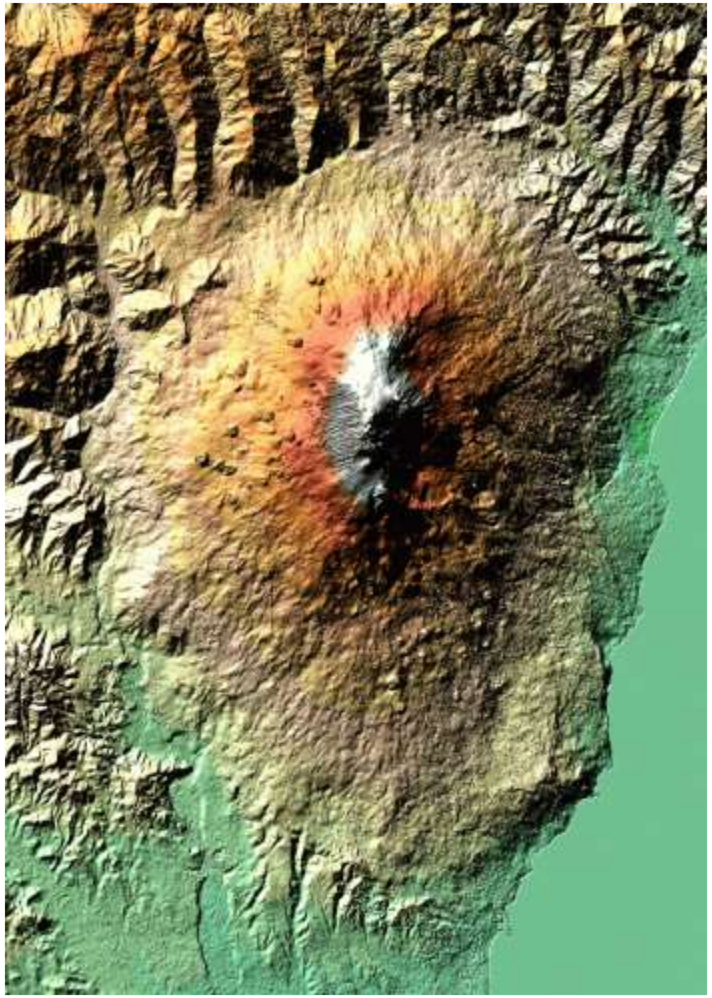


A specific interferometric phase value matches several topographic height values!

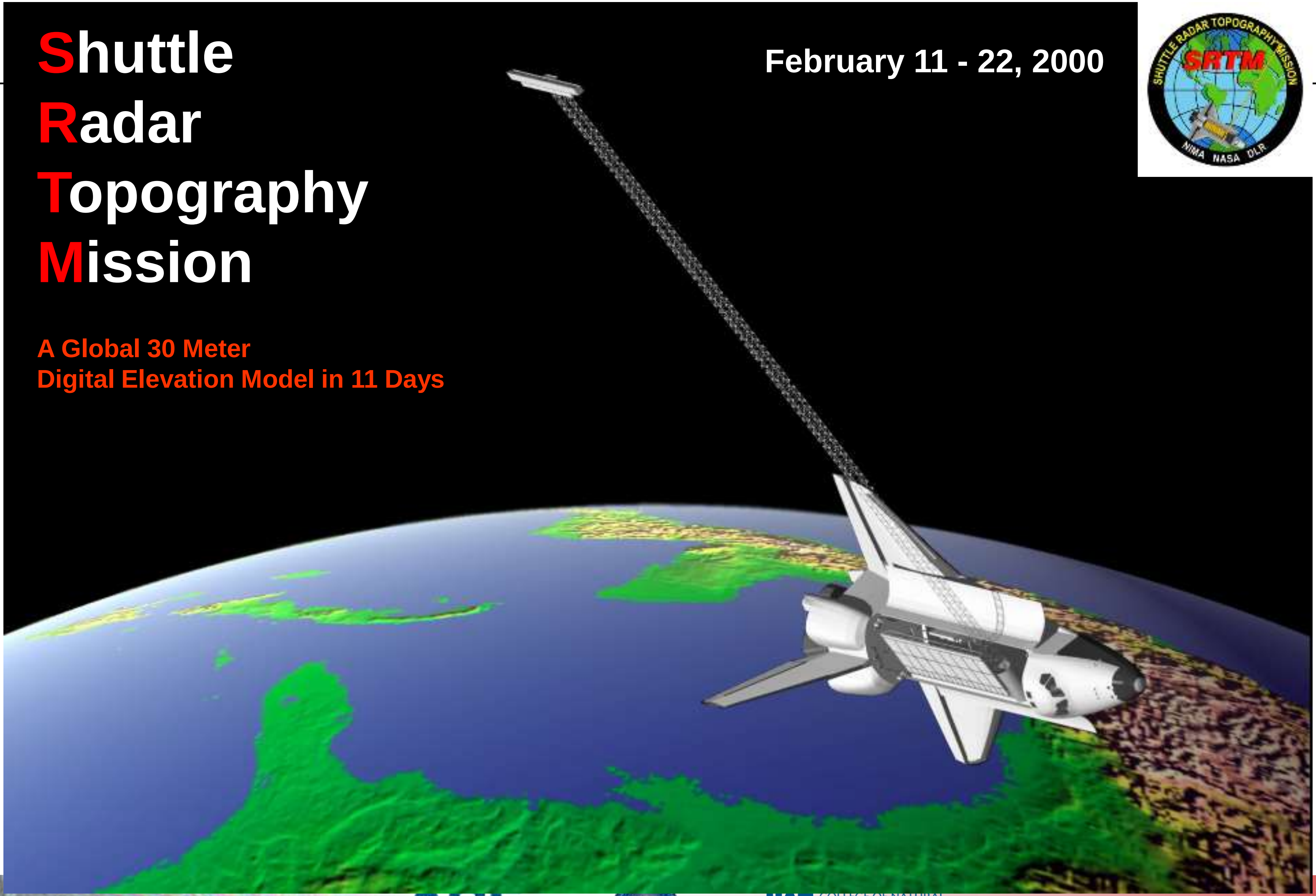
Phase Unwrapping: Find “Most Likely” Absolute Phase Given Measured Ambiguous Phase

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

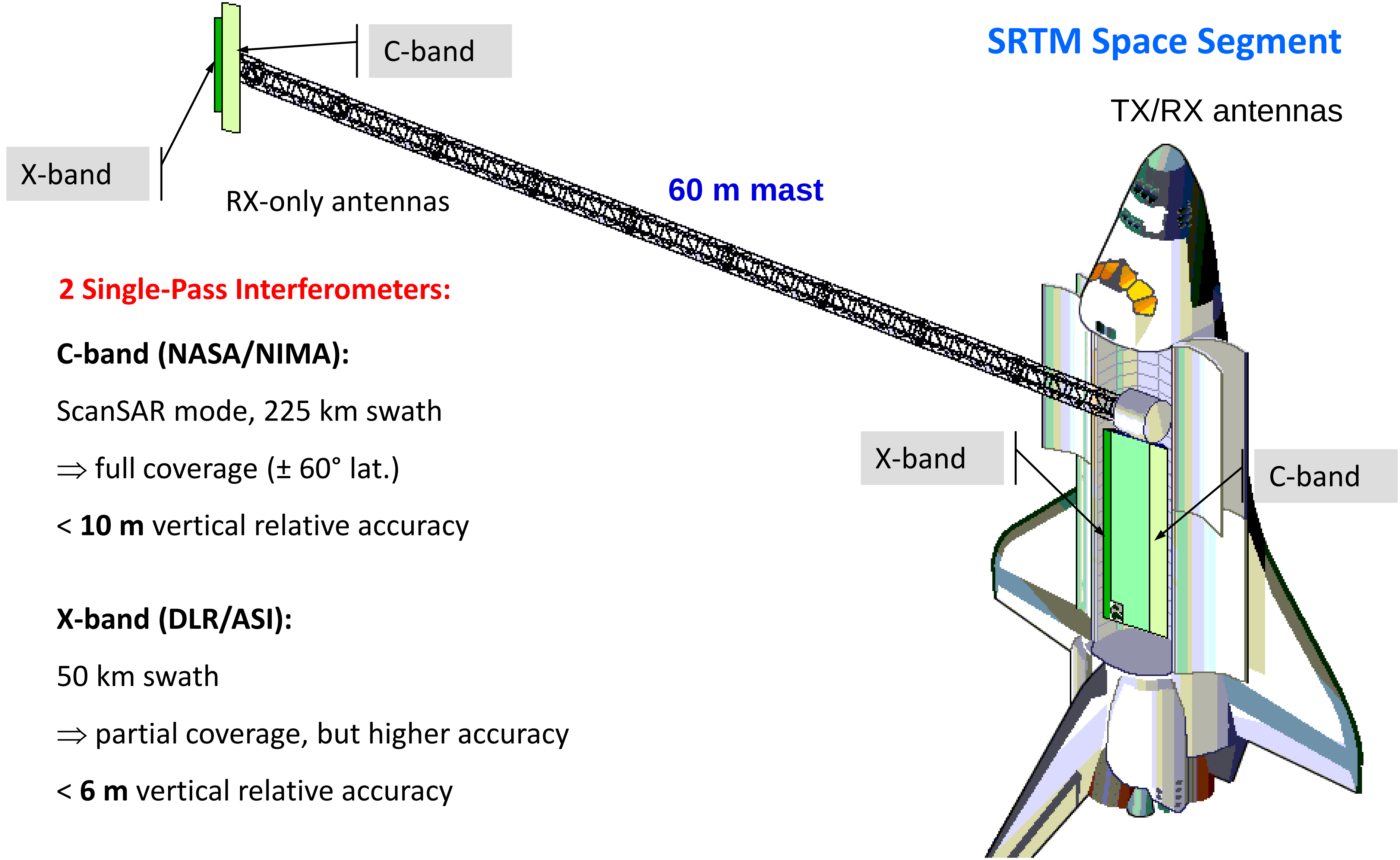
this is much more likely …



… than this


Shuttle
Radar
Topography
Mission
February 11 - 22, 2000
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):

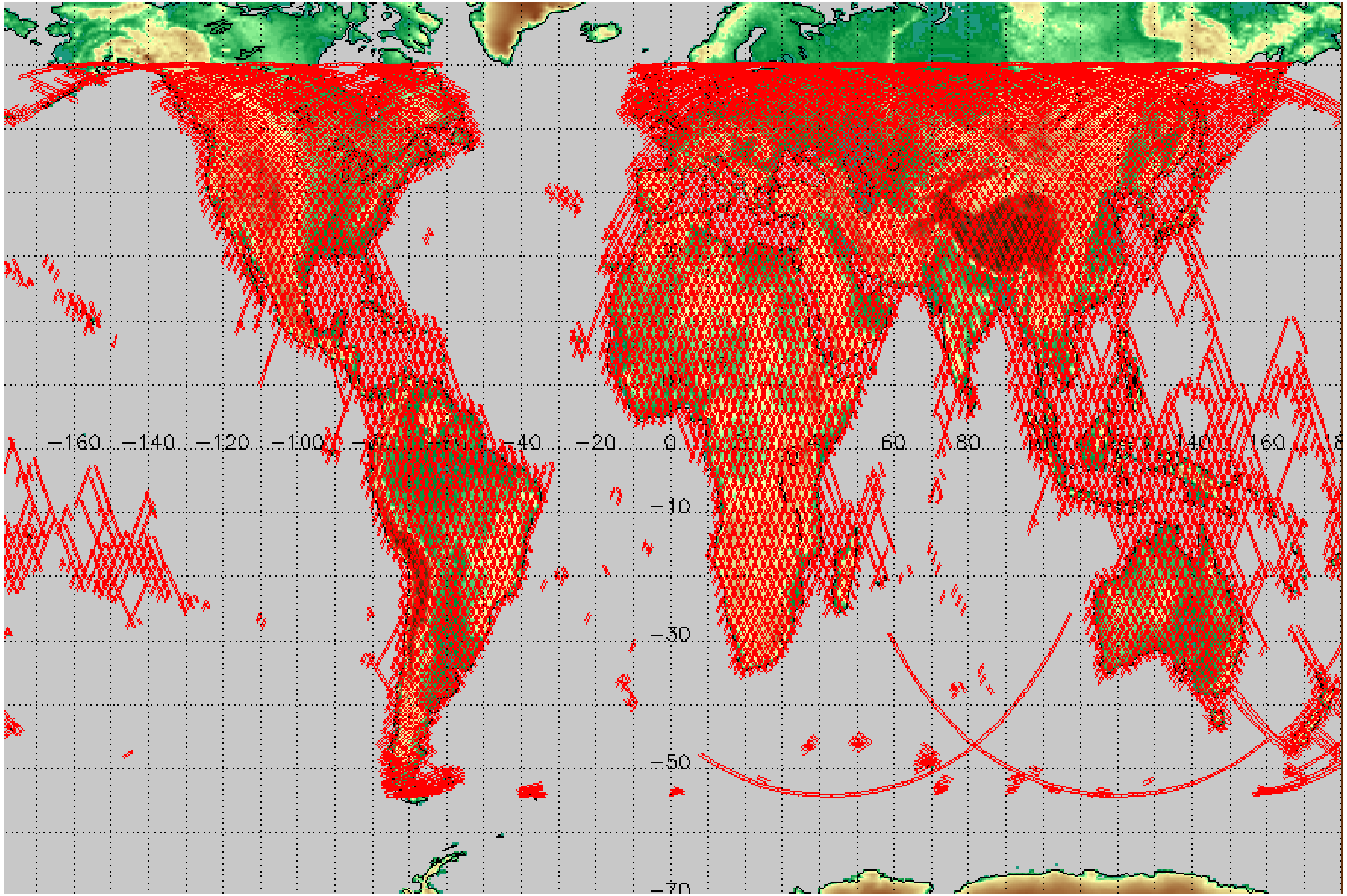
50 km swath

⇒ partial coverage, but higher accuracy

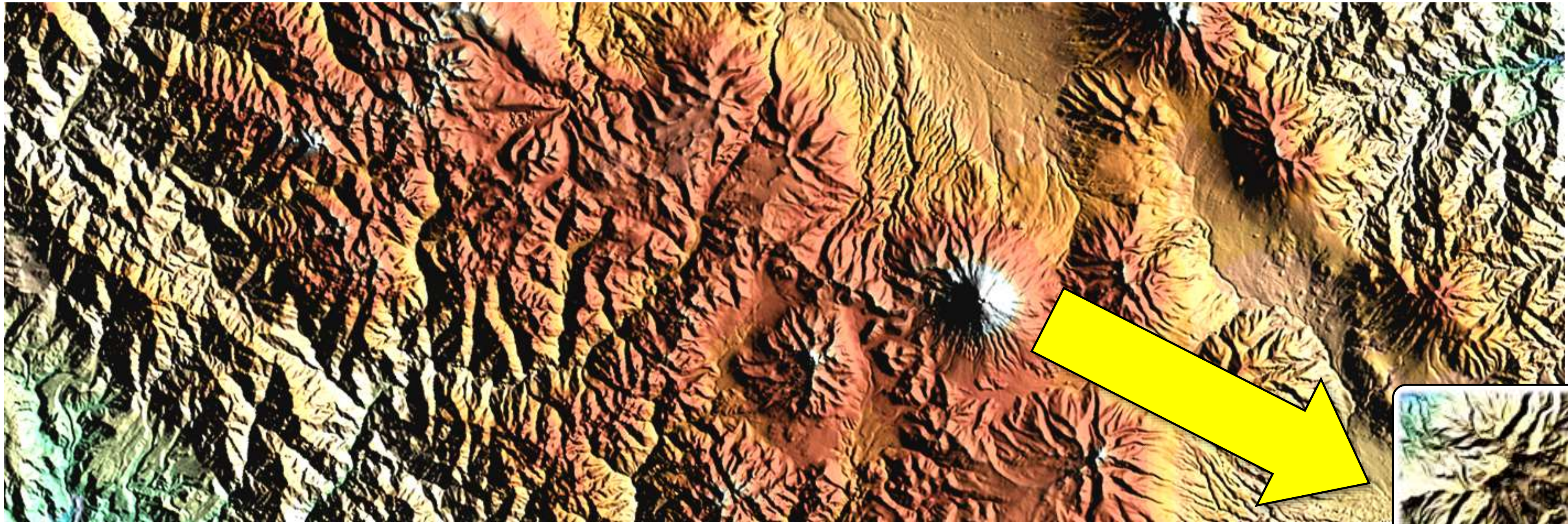
< **6 m** vertical relative accuracy

SRTM – Deployment of Mast

SRTM Coverage

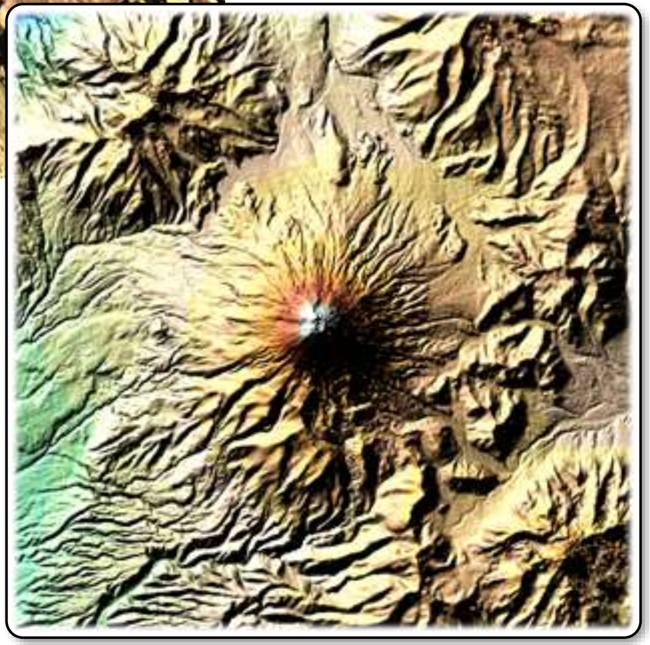


SRTM Example, Cotopaxi Volcano, Ecuador



Cotopaxi Volcano
Ecuador

SRTM/X-SAR

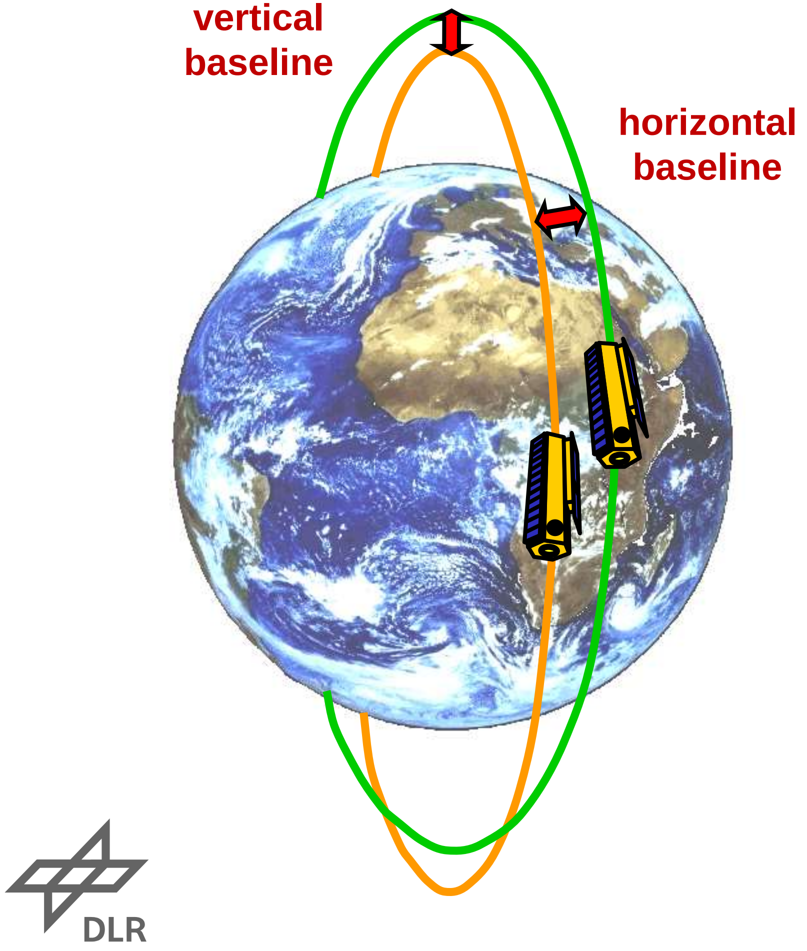


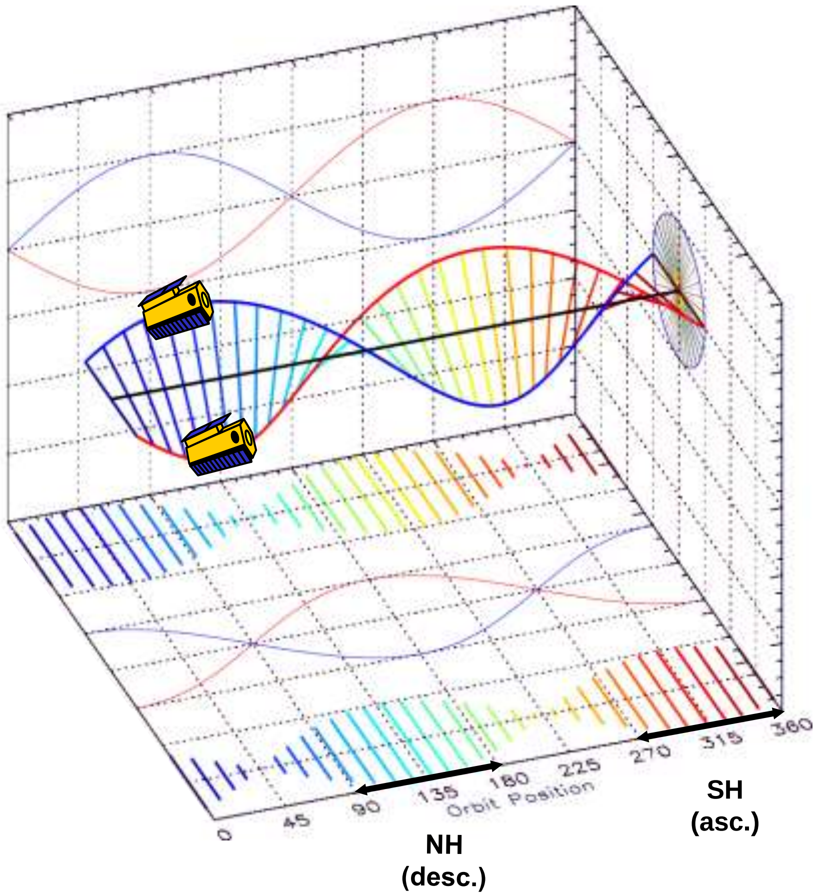
Digital Elevation Model (DEM)

TanDEM-X - An X-Band Mission for Global Topographic Mapping

- **Mission Goals:**
  - Acquisition of a global DEM according to HRTI-3 standard
  - Generation of Local DEMs with HRTI-4 quality
  - Demonstration of innovative bistatic imaging techniques and applications

Helix Orbit of TanDEM-X





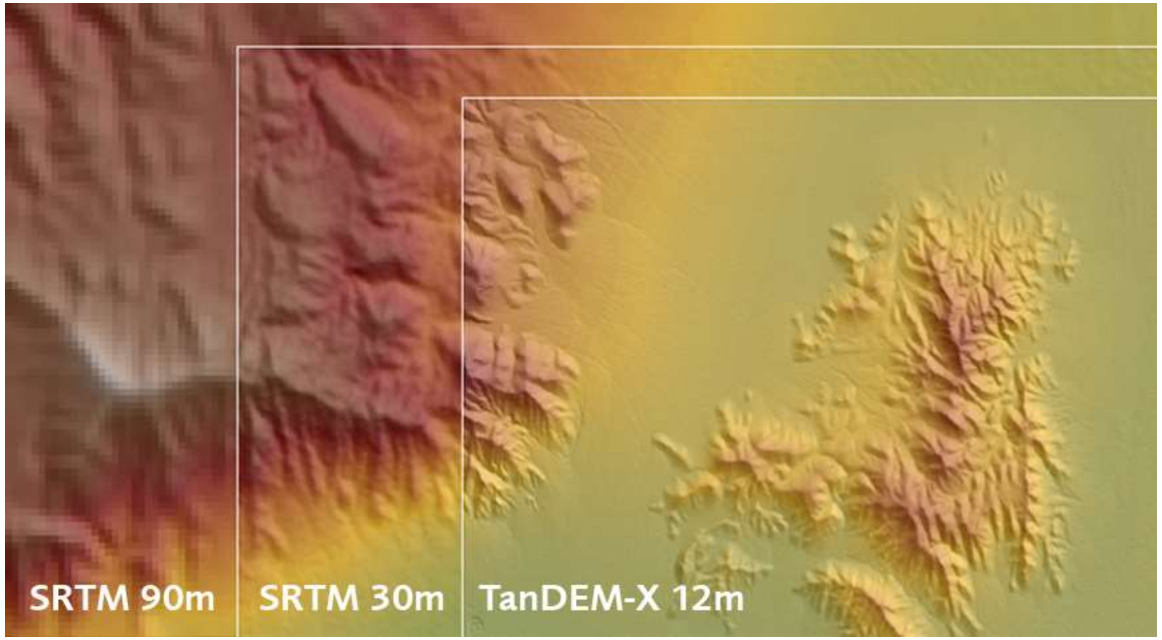
TanDEM-X

DEM Vertical Accuracy

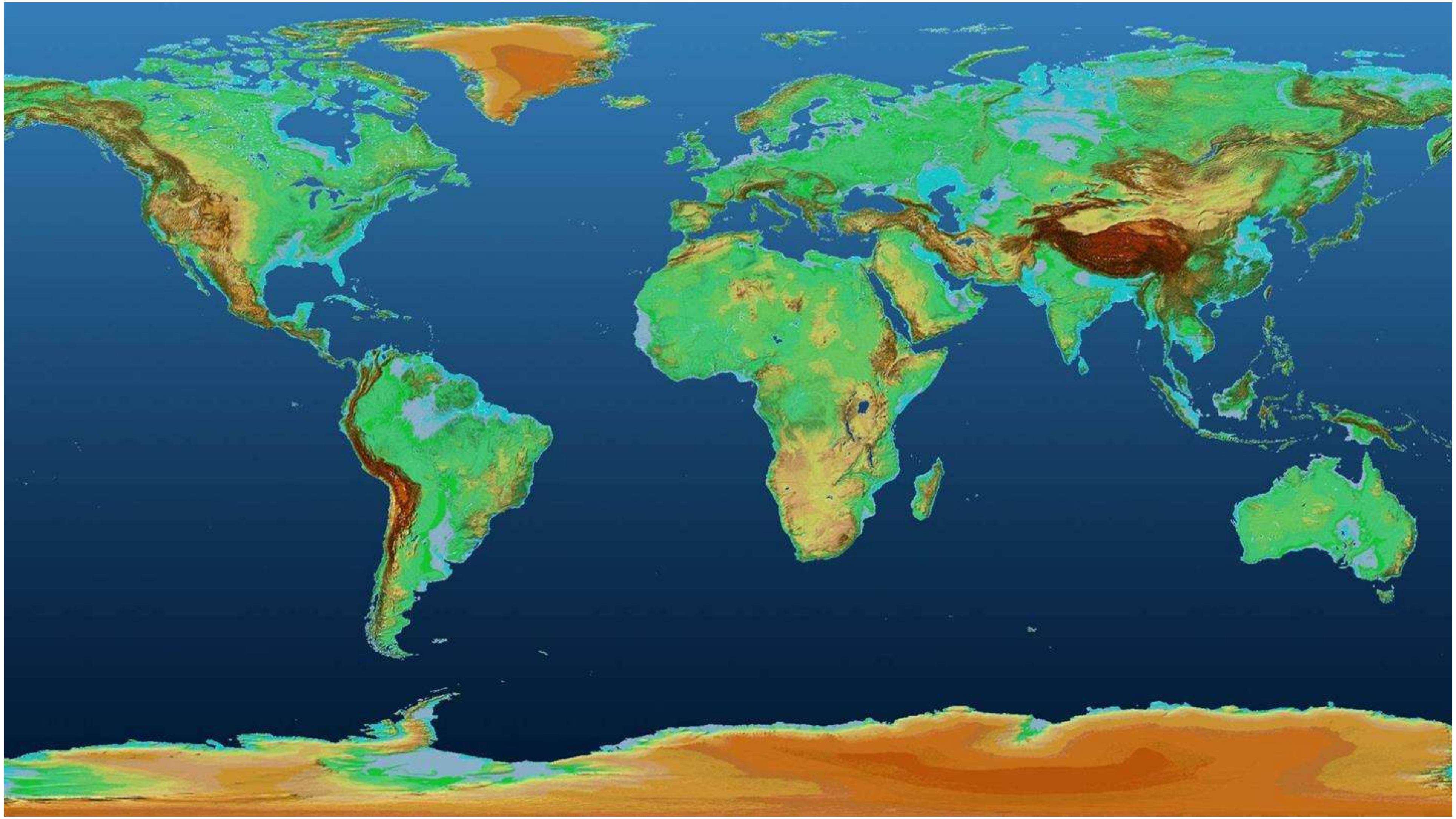
	Spatial Resolution	Absolute Vertical Accuracy (90%)	Relative Vertical Accuracy (point-to-point in 1° cell, 90%)
DTED-1	90 m x 90 m	< 30 m	< 20 m
DTED-2	30 m x 30 m	< 18 m	< 12 m
TanDEM-X	12 m x 12 m	< 10 m	< 2 m
Level-4	6 m x 6 m	< 5 m	< 0.8 m

Visualization of improved DEM quality:

TanDEM-X vs. SRTM DEMs

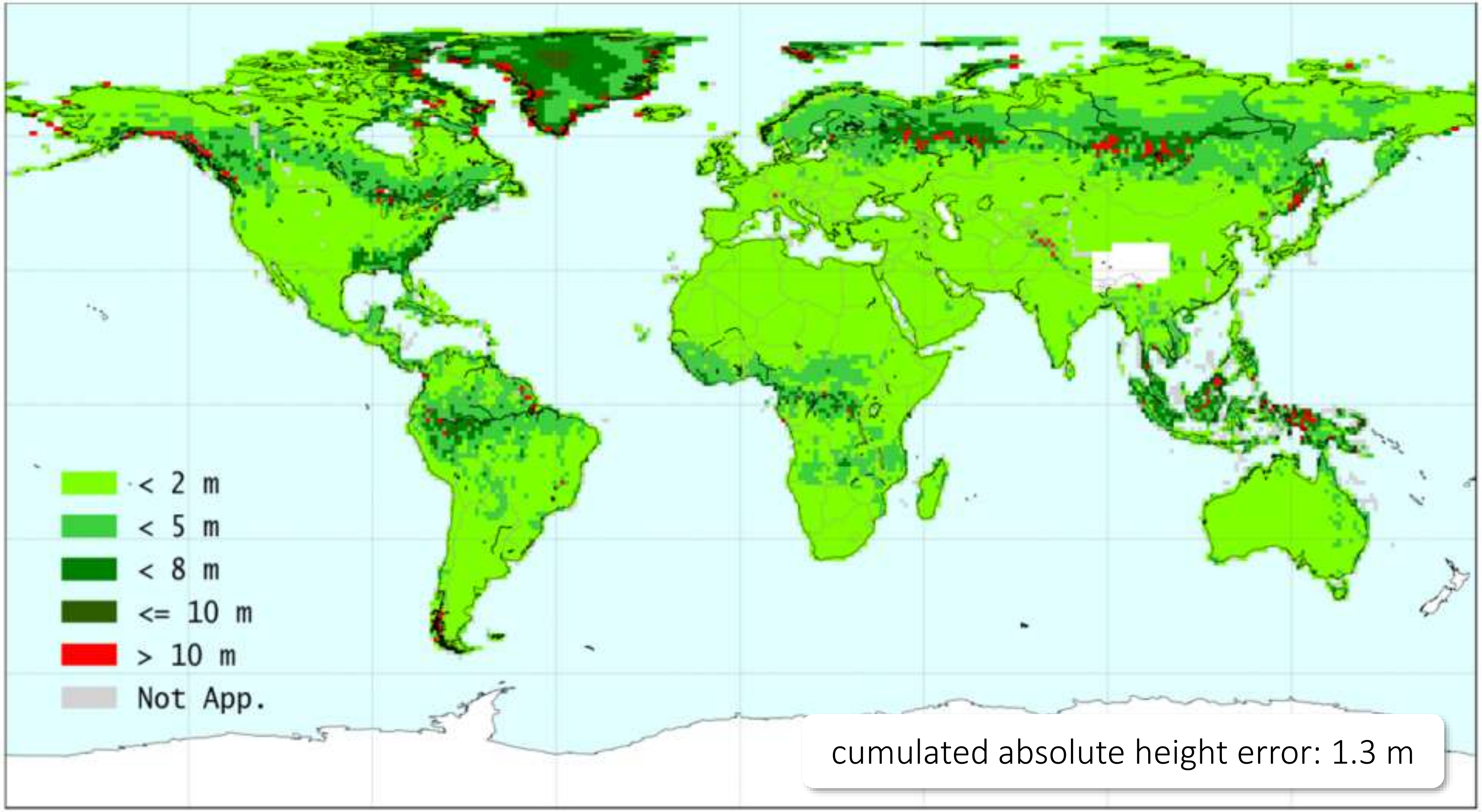


Global TanDEM-X DEM



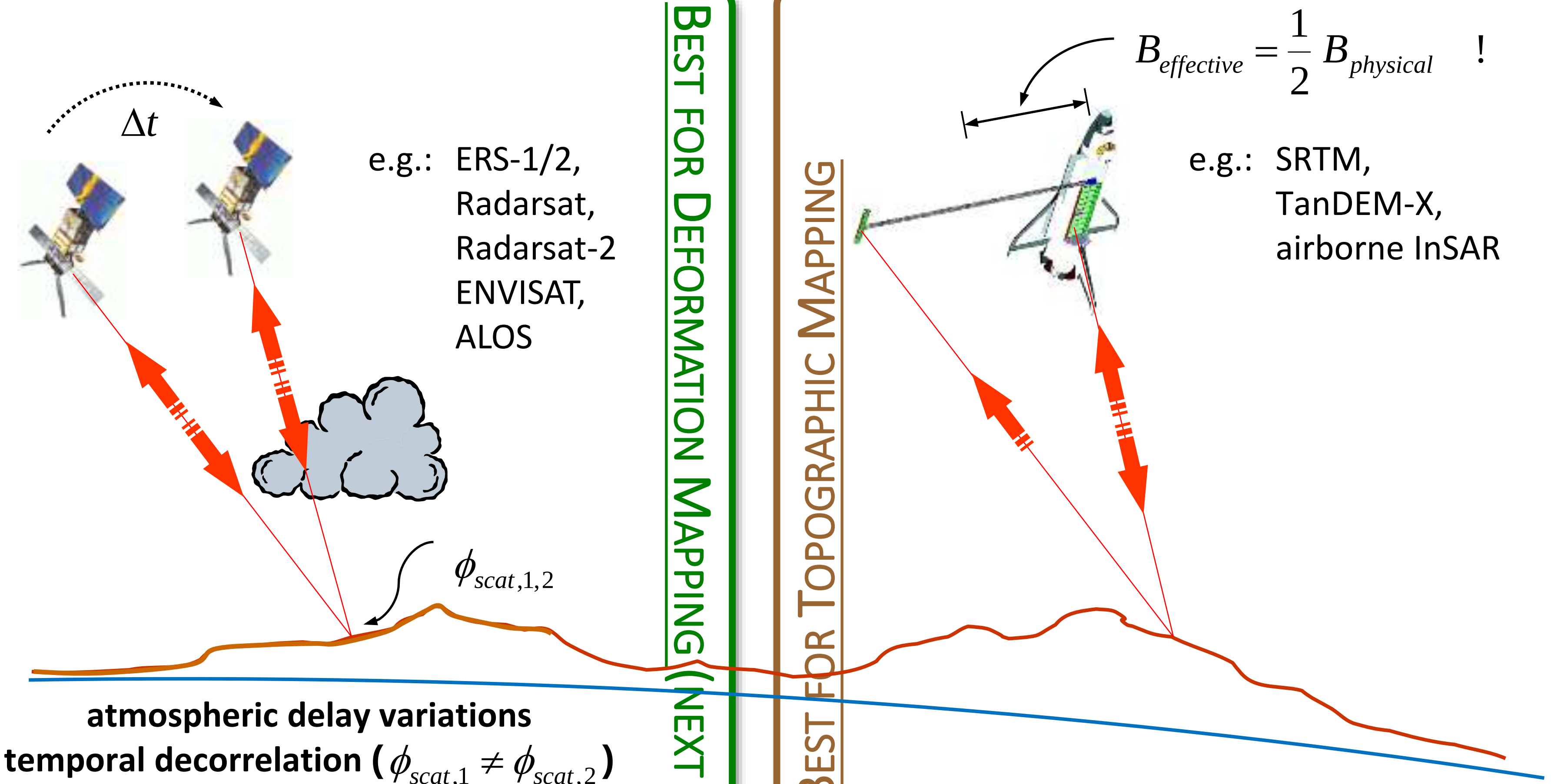
Global TanDEM-X DEM

Absolute Height Error



Zink, Manfred, et al. "TanDEM-X mission status: the complete new topography of the Earth." *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. IEEE, 2016.

Repeat-Pass vs. Single-Pass Interferometry



atmospheric delay variations
temporal decorrelation $(\phi_{scat,1} \neq \phi_{scat,2})$

- **reduced & variable quality**
- **sensitive to surface deformation**

- **high and constant quality DEMs**
- **not sensitive to surface deformation**

What’s Next?

- This is what awaits next:
  - Lab on DEM generation using InSAR