GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

Lecturer:

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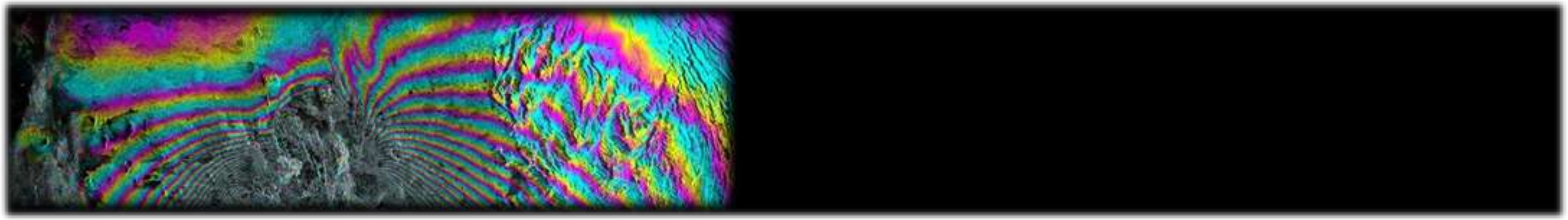
Lecture 7: InSAR for Deformation Monitoring



INSAR – A SHORT RECAP

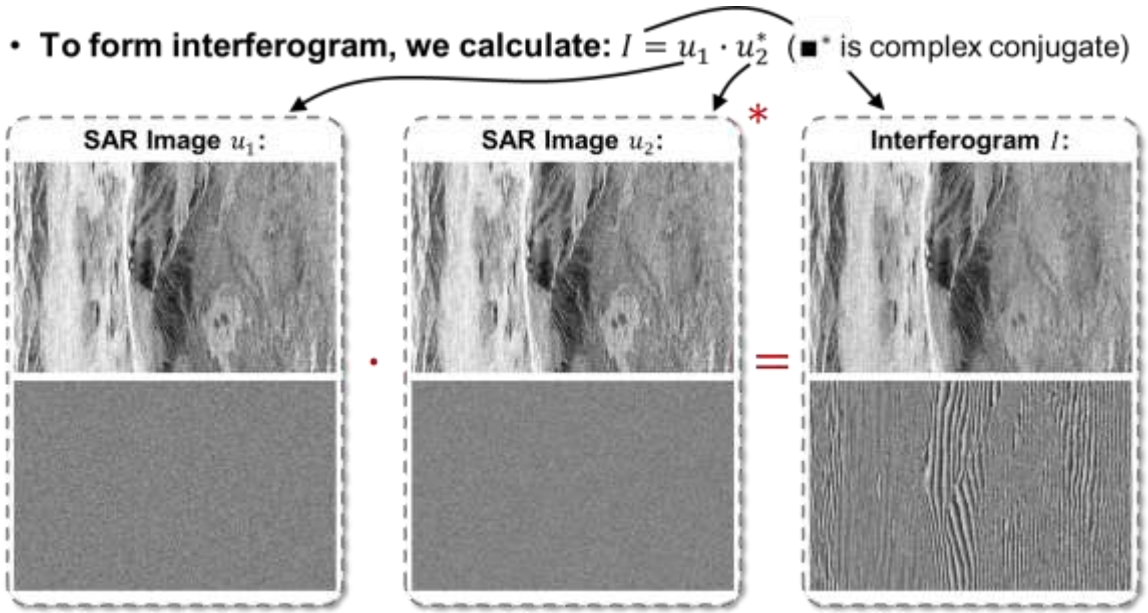
Let's Recap some InSAR Basics

- **Q1:** Even though the SAR phase ψ carries information about the distance between satellite and ground, the phase map of a single SAR image looks like this.

  Why is that?

- **Q2:** InSAR Processing (calculating the phase difference $\phi = \psi_2 - \psi_2$) can remove the noise pattern and extract the desired distance information.

  Under which circumstances does this approach work?



- **Q3:** Which of these observation scenarios allows to map topography using InSAR:
  a) **Images acquired at the same time but from different across-track locations**
  b) **Images acquired from the same location but at different times**
  c) **Images acquired from different along-orbit locations**
  d) **Images acquired at different times and from different across-track locations**

A Typical InSAR Processing Workflow

1. **Select and order InSAR-capable SAR data** from a data server
2. **Import SAR data into an InSAR processing system**
3. **Calculate spatial baseline & apply spectral (wavenumber) shift filtering** (not discussed in the lectures – applied automatically by most available tools)
4. **Determine co-registration parameters**:
   - cross-correlate >100 image chips spread over image
   - use over-sampling and interpolation to locate correlation peaks
   - apply regression to parameterize co-registration (e.g. affine transform)
5. **Co-register images:**
   - Resample slave image(s) to match master image
   - Required accuracy: << 1/10 resolution element

A Typical InSAR Processing Workflow

6. **[Optional Orbit improvement:** If precise orbit information is available.]
7. **Interferogram formation:** $I = u_1 \cdot u_2^*$; optional multi-looking may be applied.
8. **Flat Earth phase removal:** Simulate and subtract phase trend due to the geometry changes from near range to far range.
9. **Coherence Calculation:** Coherence is calculated as described in Lecture 3.
10. **For differential InSAR (d-InSAR):** Using a DEM, simulate and subtract interferogram replicating topography-related phase.
11. **Apply phase filter:** A phase filter is applied to reduce InSAR phase noise and reduce phase unwrapping complexity (see next section).
12. **Phase Unwrapping:** Turns originally ambiguous interferometric phase into unambiguous absolute phase.
13. **Geocoding and Terrain Correction:** Note that flat earth phase needs to be added before geocoding to obtain absolute phase.

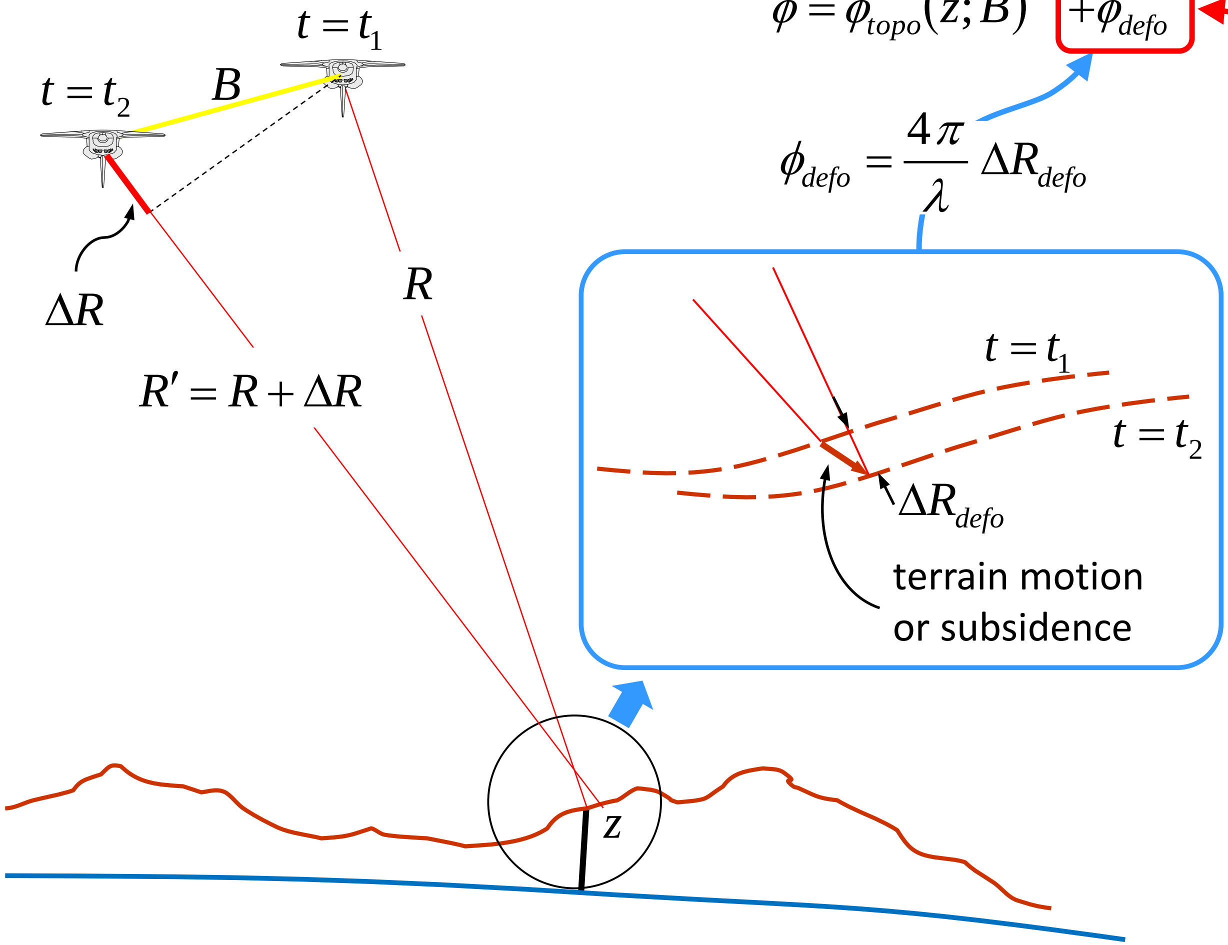
DIFFERENTIAL INSAR – A METHOD FOR CM-SCALE DEFORMATION MONITORING

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, ..., 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}

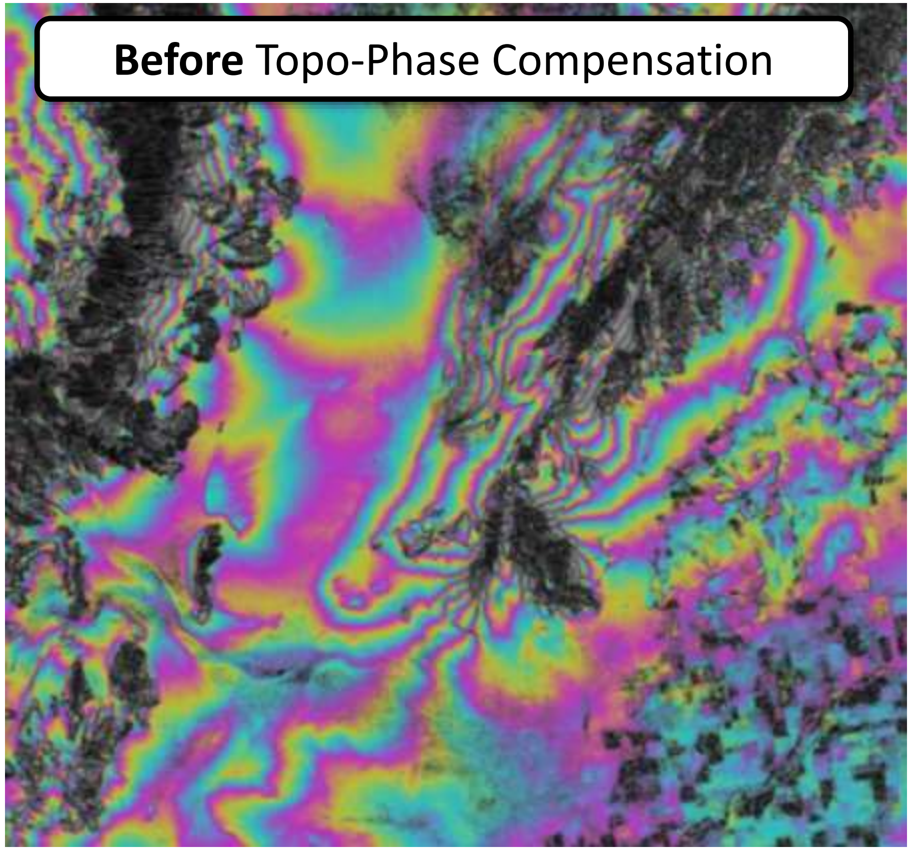
   For signal separation consider:
   - Deformation phase changes only with time
   - Topography phase changes only with Baseline

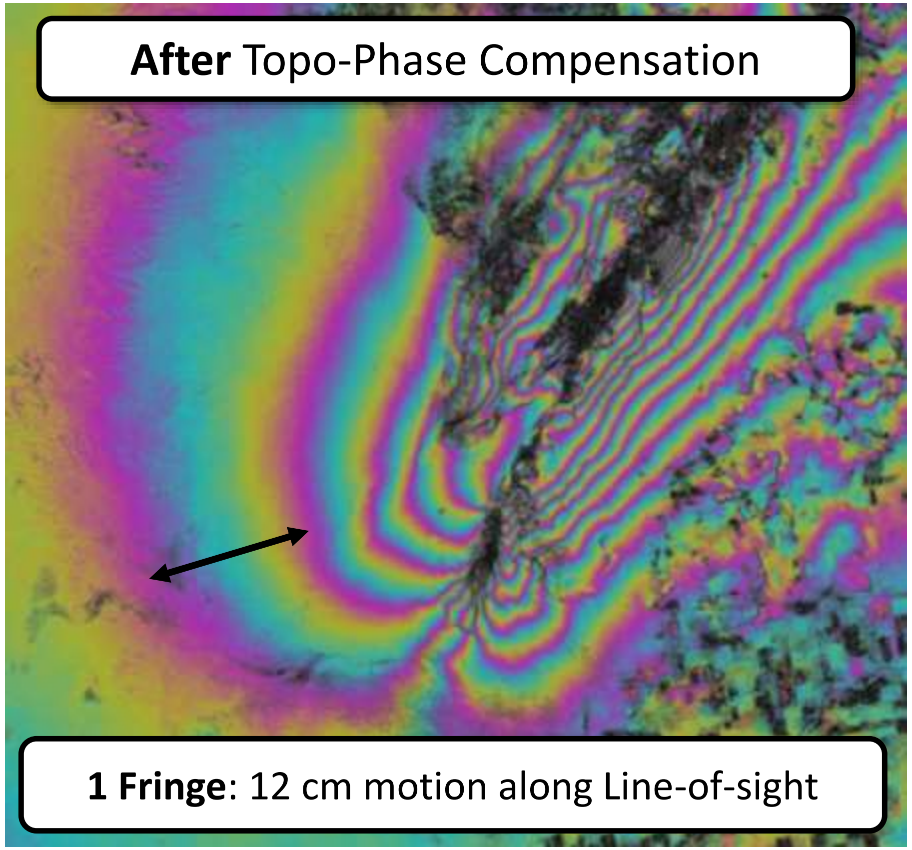
   - For constant velocity: $\boxed{\phi_{n-m}^{defo} = \phi_{n-m} \propto \Delta t_{n-m}}$ and $\boxed{\phi_{n-m}^{topo} = \phi_{n-m} \propto B_{\perp,n-m}}$

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

Example of Topography Compensation

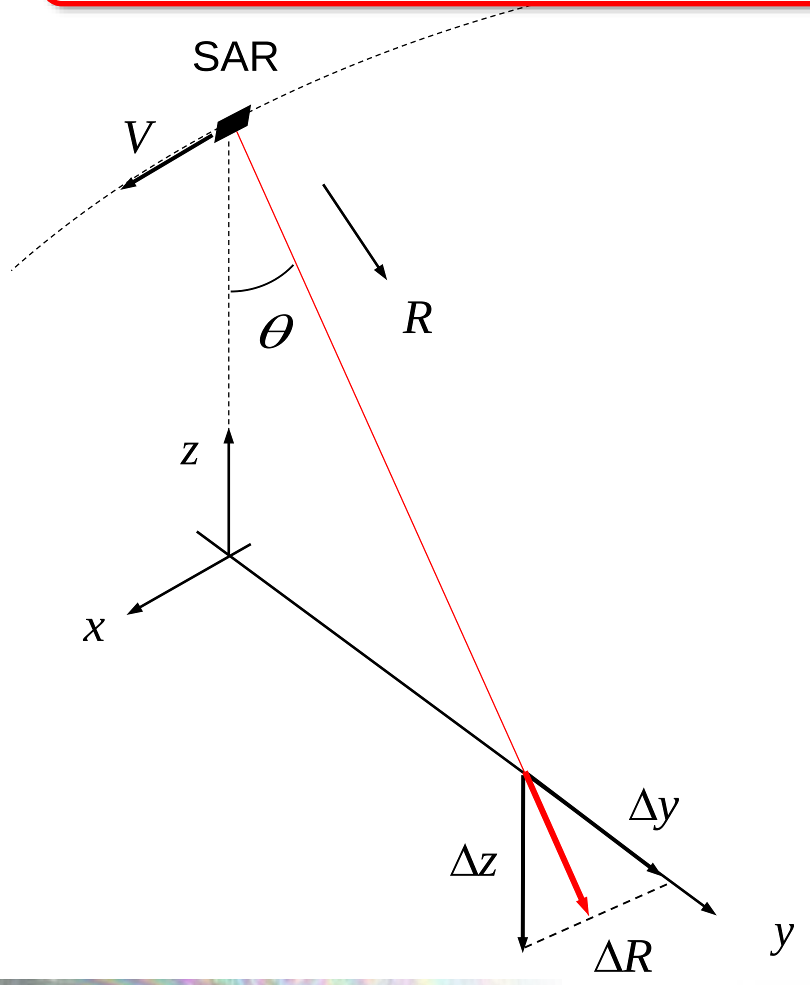
- Compensation using available DEM
- ALOS PALSAR data of Baja Earthquake, 2010





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

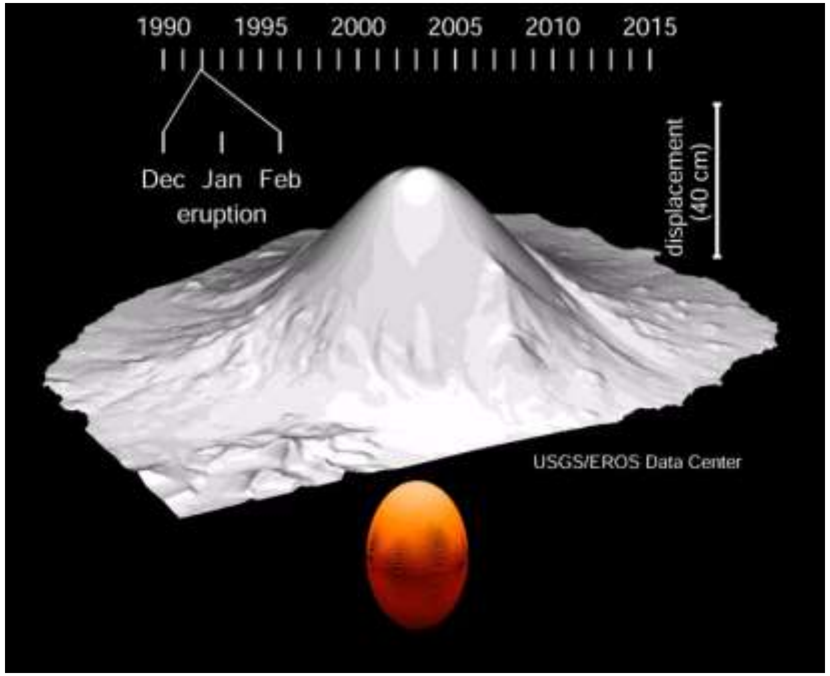
14.5 cm in z (e.g. subsidence)

25.0 cm in y (motion)

Monitoring Volcanoes with InSAR

Principle

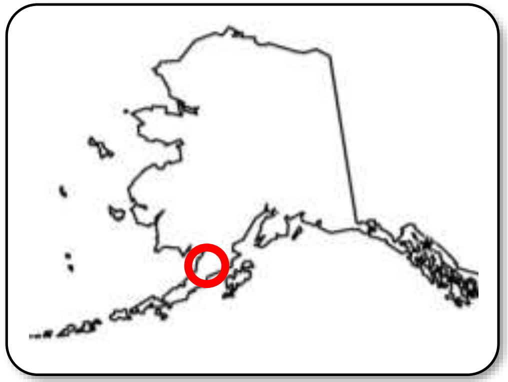
- InSAR is capable of observing inflation and deflation of volcanoes
- Inflation and deflation is triggered by changes of magma pressure in magma chamber (see animation)
- These phenomena precede volcanic eruptions and are potentially interesting for predicting eruptive behavior



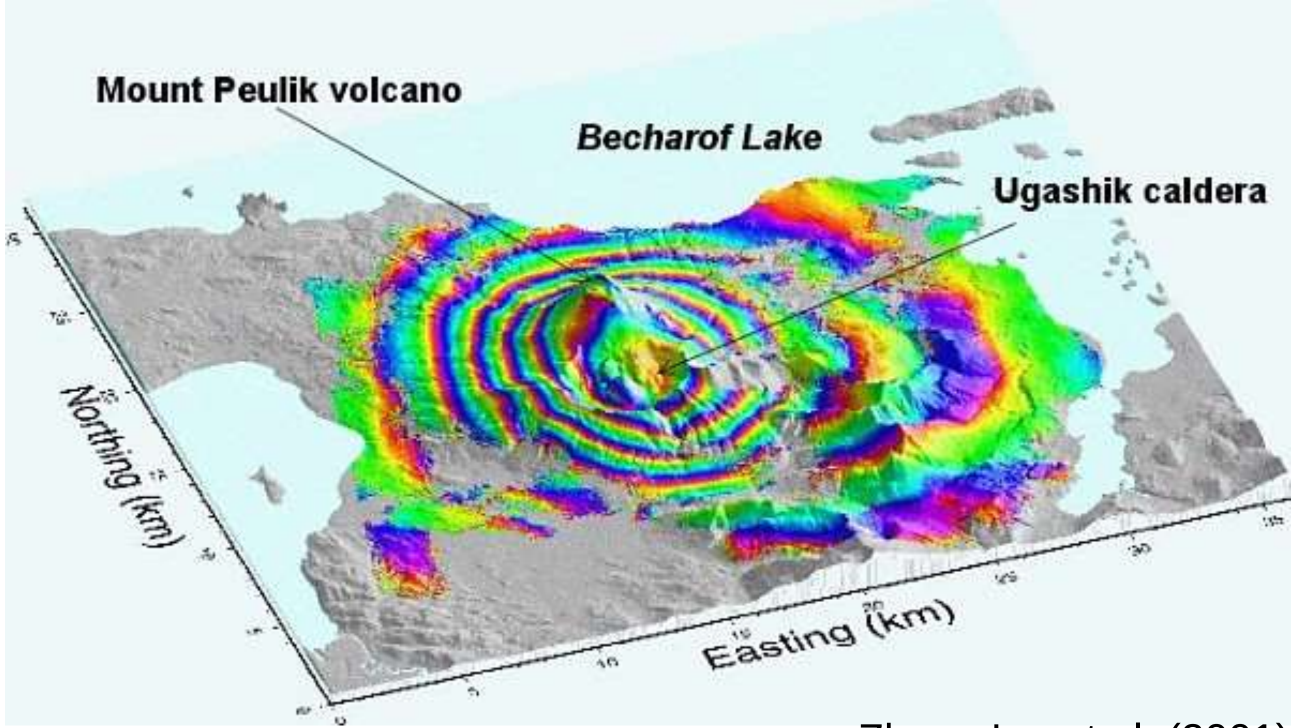
Westdahl Volcano Deformation Movie

Interferometric Phase Interpretation

Example: Surface Deformation at Mt. Peulik, Alaska

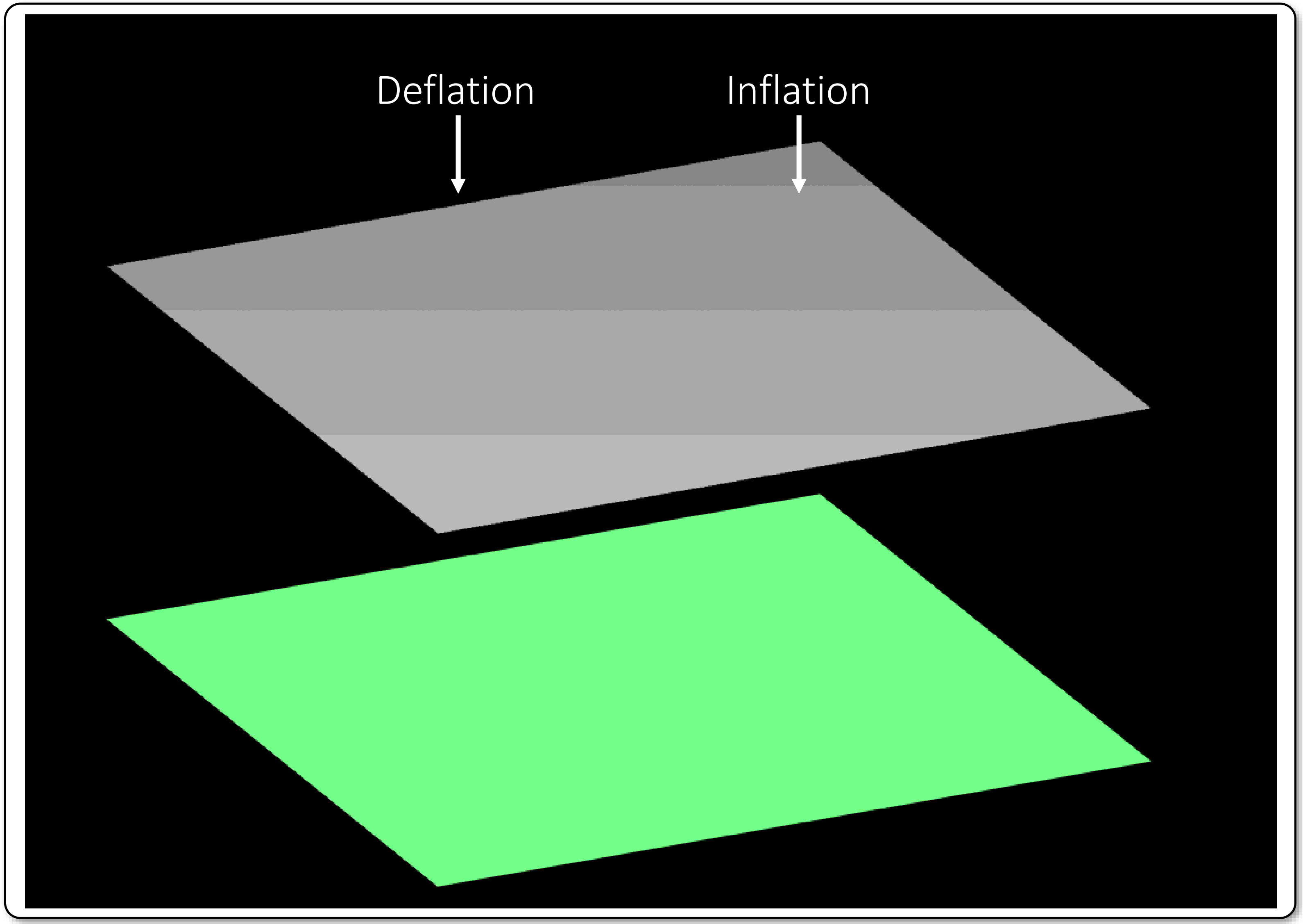


17-cm inflation, Sept. 1996 to Oct. 1997



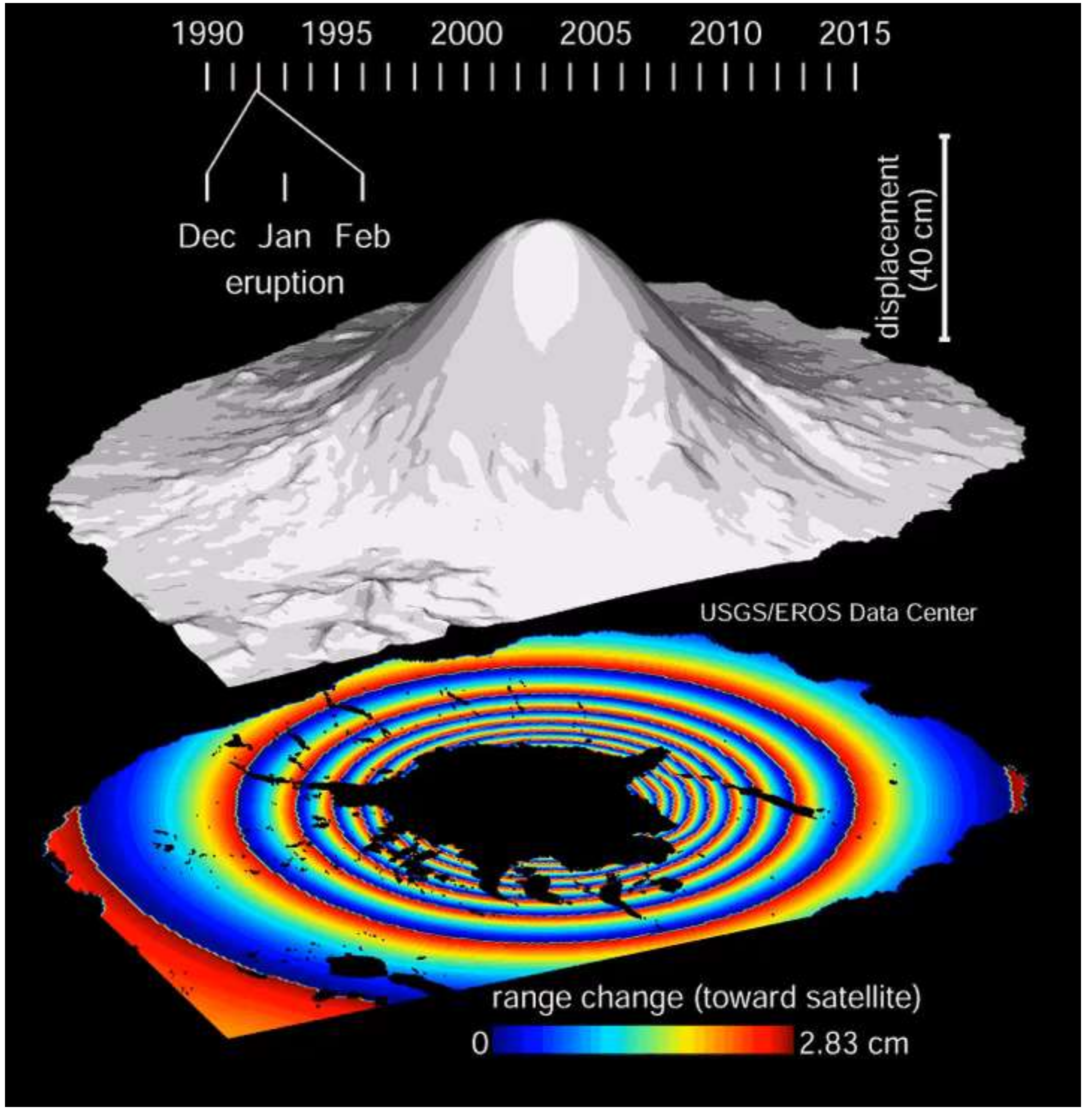
Zhong Lu, et al. (2001)

Representation of Interferometric Phase

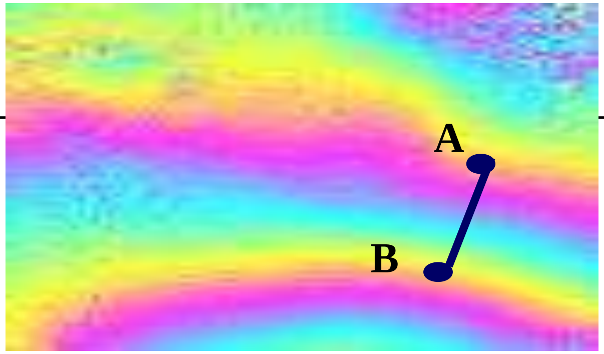


Representation of Interferometric Phase

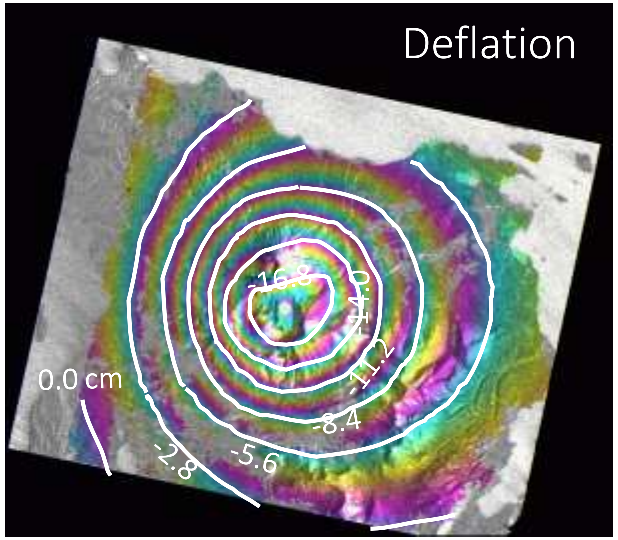
The Westdahl Case

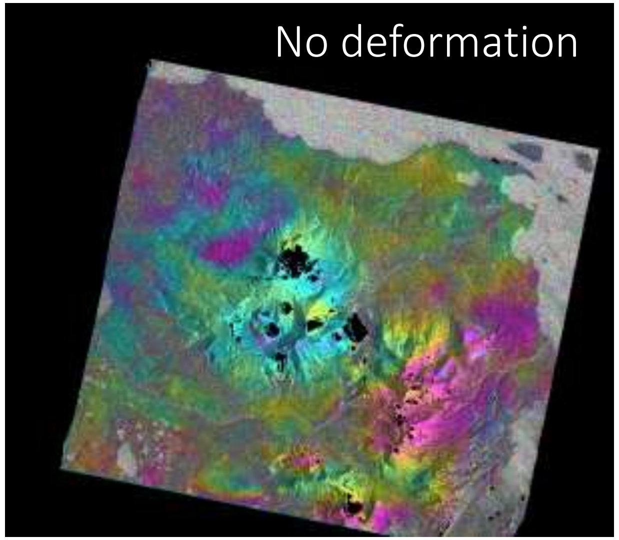


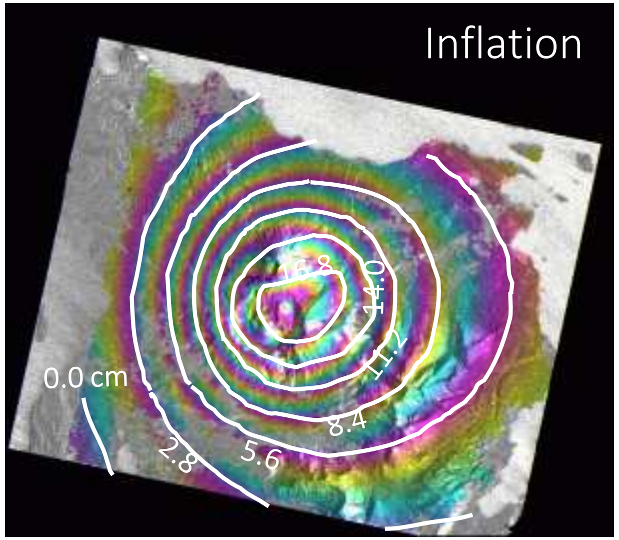
Interpretation of Interferometric Phase



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





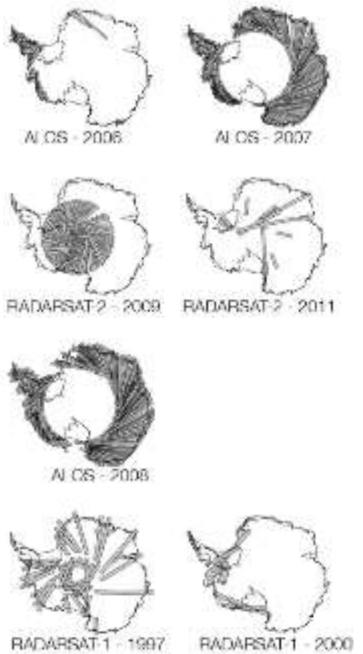


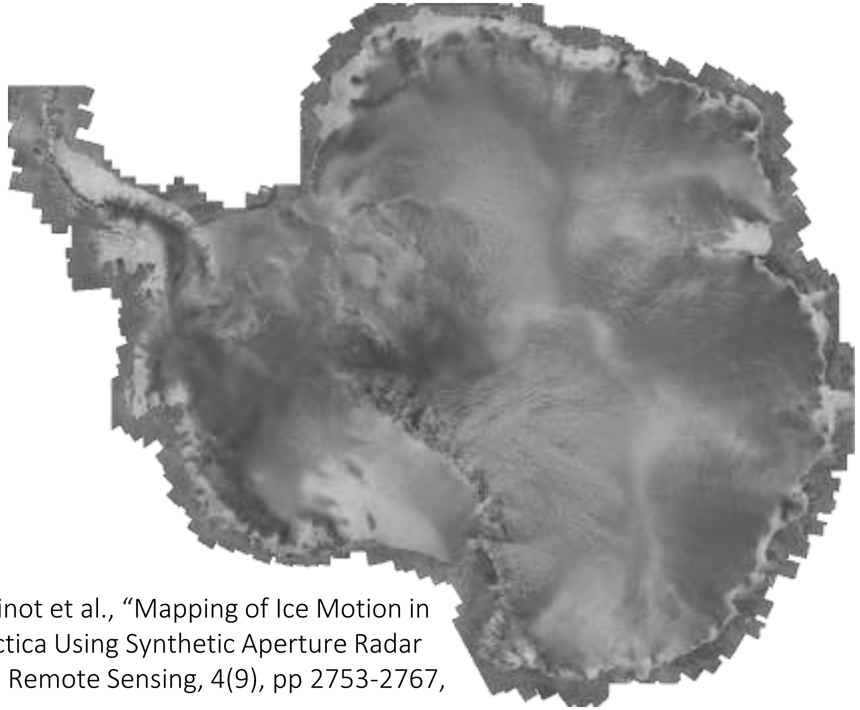
Dr. Z. Lu, USGS

Continent-Wide Deformation Mapping from InSAR

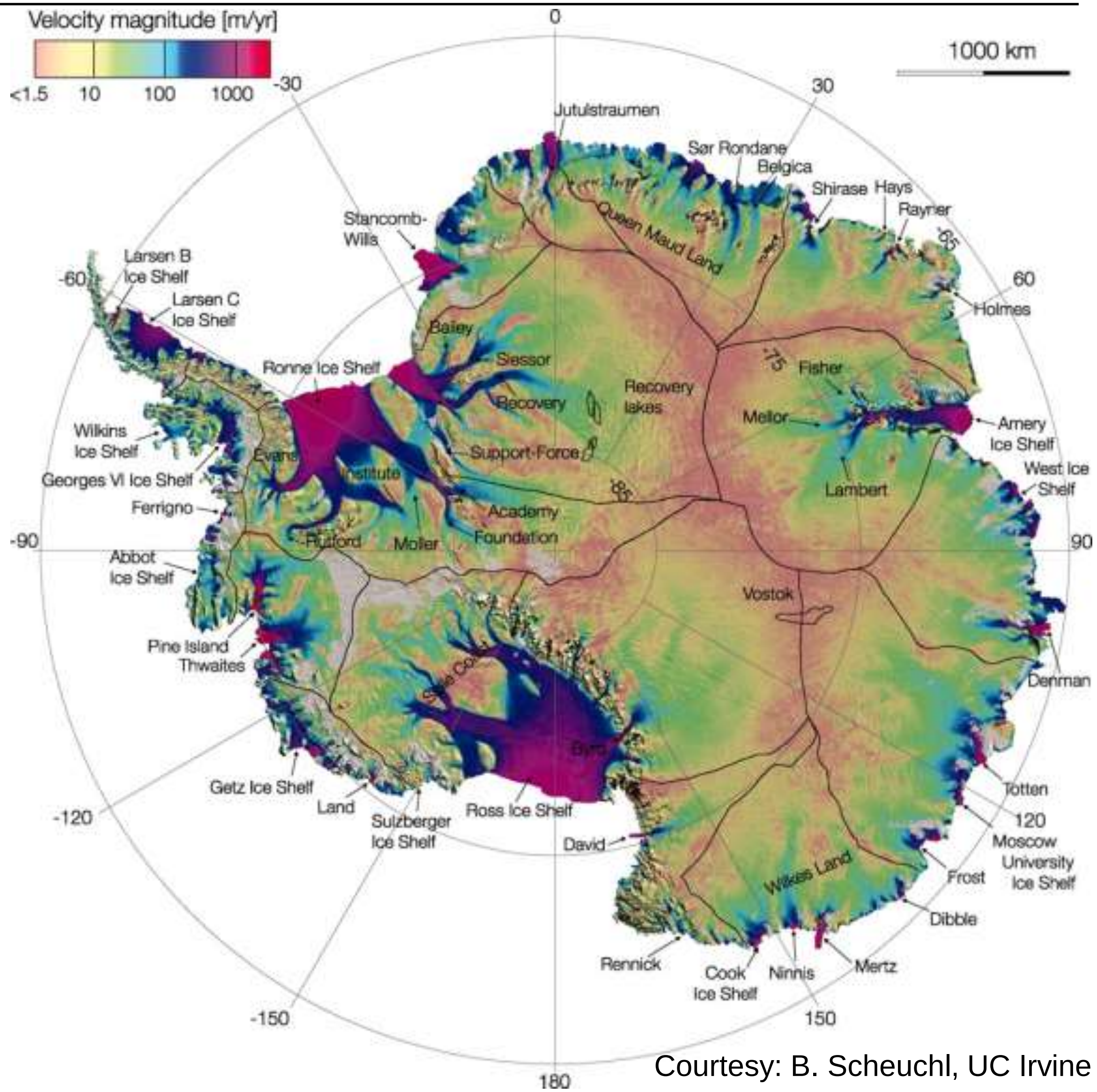
Example: Antarctica

- 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





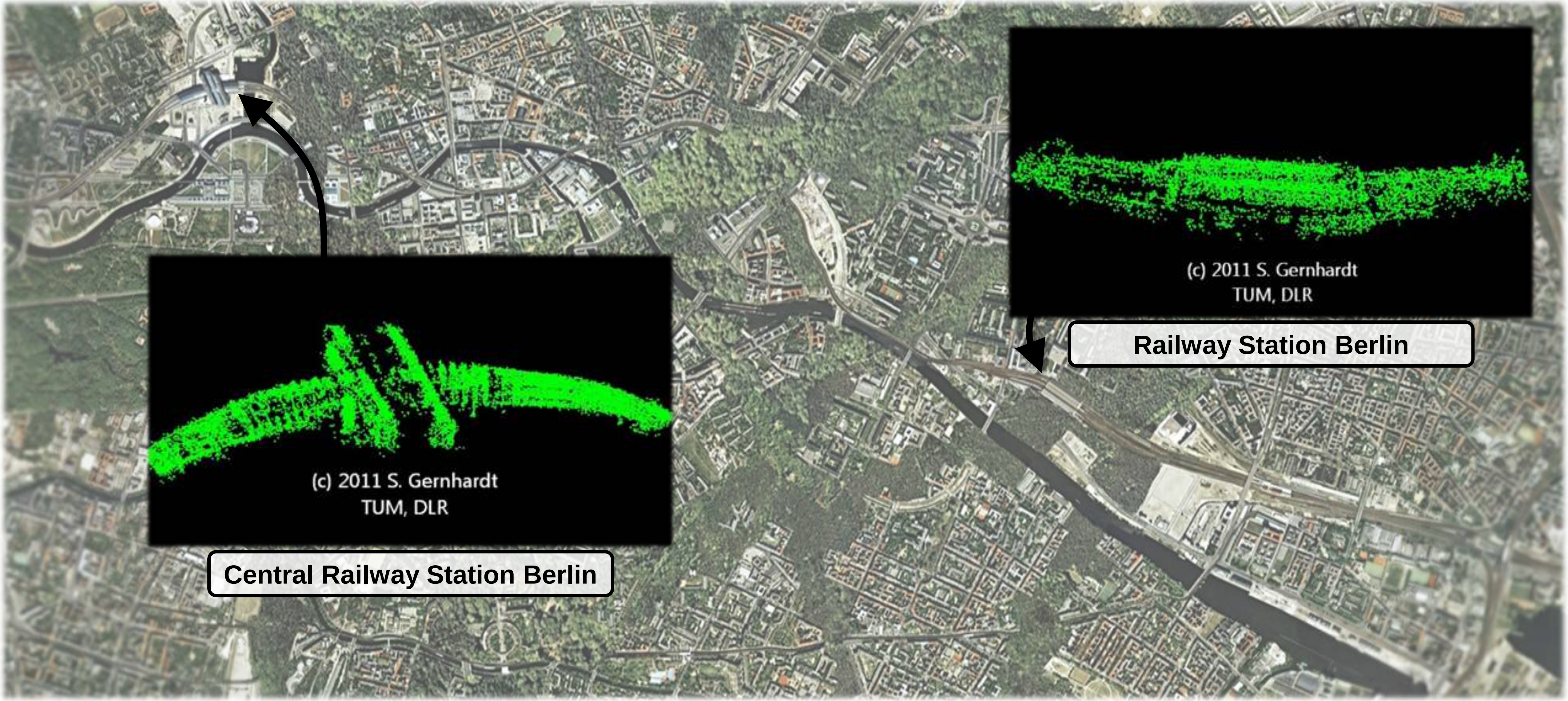
Mouginot et al., “Mapping of Ice Motion in Antarctica Using Synthetic Aperture Radar Data”, Remote Sensing, 4(9), pp 2753-2767, 2012



Courtesy: B. Scheuchl, UC Irvine

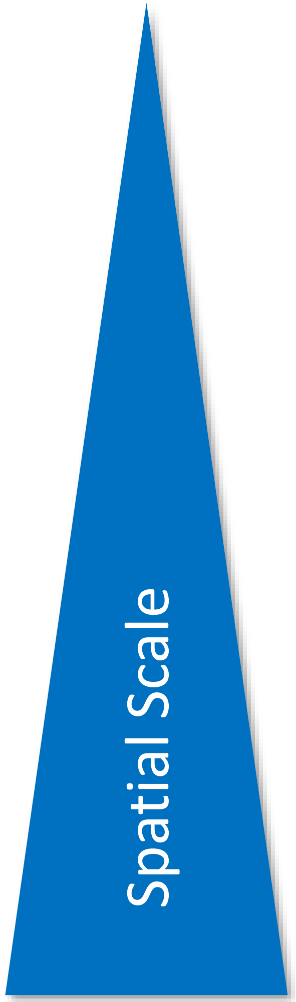
Sub-Milimeter Surface Analysis

Building Deformation in Berlin, Germany



Typical Applications of Differential InSAR

Application	Notes
• Infrastructure (buildings; roads; levees) deformation	X-band
• Sink holes	X-band
• Landslides	X- or C-band
• Oil/gas extraction	
• Glacier motion mapping	
• Volcano monitoring	
• Permafrost-related surface deformation	C- or L-band
• Soil moisture variation	L-band
• Co-seismic earthquake deformation	L-band
• Post & inter-seismic deformation	L-band
• Ice sheet monitoring	C- or L-band



Think – Pair – Share

Picking the right data for your InSAR analysis:

- Okmok is a volcano in Alaska's Aleutian Chain.
- Since its last eruption in 2008, the volcano has been re-inflating at a rate of ~10cm/year
- **Activity: Pick the most suitable interferogram for measuring this deformation. Motivate your answer!**
  a) L-band data; $\Delta t = 24$ days; June - July
  b) L-band data; $\Delta t = 48$ days; June - August
  c) L-band data; $\Delta t = 144$ days; July – December
  d) C-band data; $\Delta t = 24$ days; June - July
  e) C-band data; $\Delta t = 48$ days; June - August
  f) C-band data; $\Delta t = 144$ days; July - December
- Please consider the expected coherence γ and phase noise σ_ϕ in your answer

Okmok Volcano, Alaska

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

AUTOMATIC INSAR PROCESSING SERVICES

Why Is There a Need For Automatic SAR Processing Services?

- **Processing Flows for Generating Value-Added Products Are Often Complicated**
  - Difficult and heterogeneous data types and data formats
  - SAR data typically do not come geocoded and have strong geometric distortions
  - Strong noise effects require complex filtering approaches
  - InSAR processing is complicated and error prone

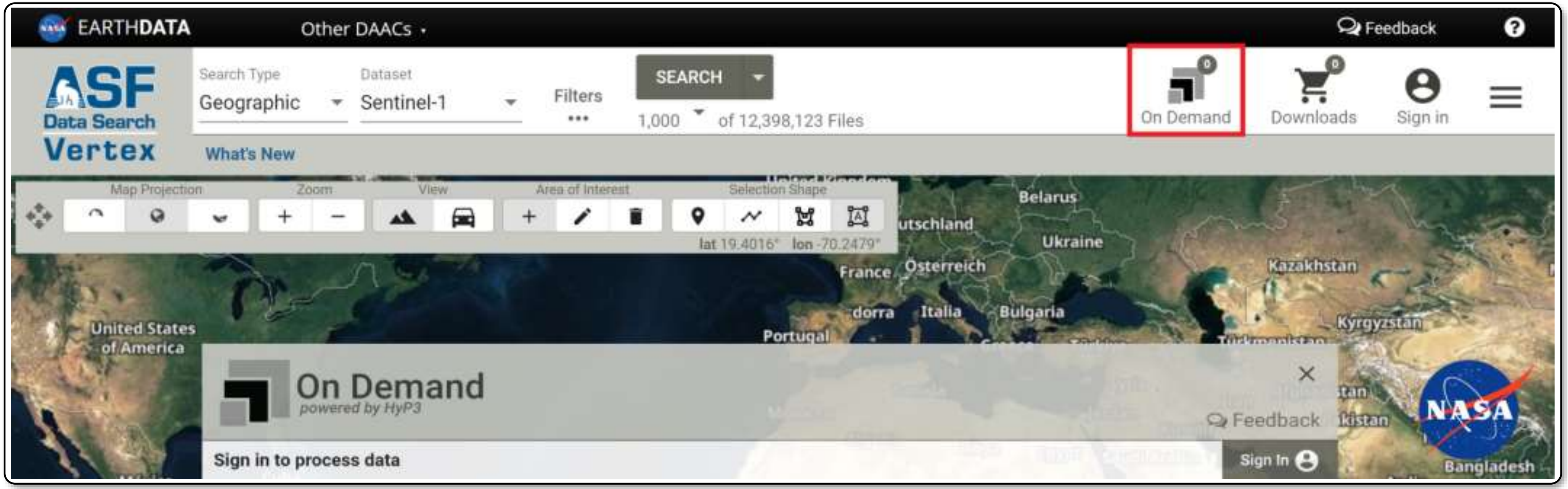
- **Large Data Volume of SAR Requires Powerful Processing Machines**

- **SAR Processing Software is Often Not User Friendly**

→Several automatic processing tools are in development to make SAR data more accessible especially to new users from the disaster monitoring communities

Sentinel-1 On-Demand Processing offered by ASF

- **Requirements for requesting On-Demand Data**:
  - Earthdata Login credentials (EOSDIS User Registration; https://urs.earthdata.nasa.gov/users/new)
  - Accept the ASF End User License Agreement (EULA) on Vertex (https://search.asf.alaska.edu/)



Currently Available S1 On-Demand Products at ASF

RTC

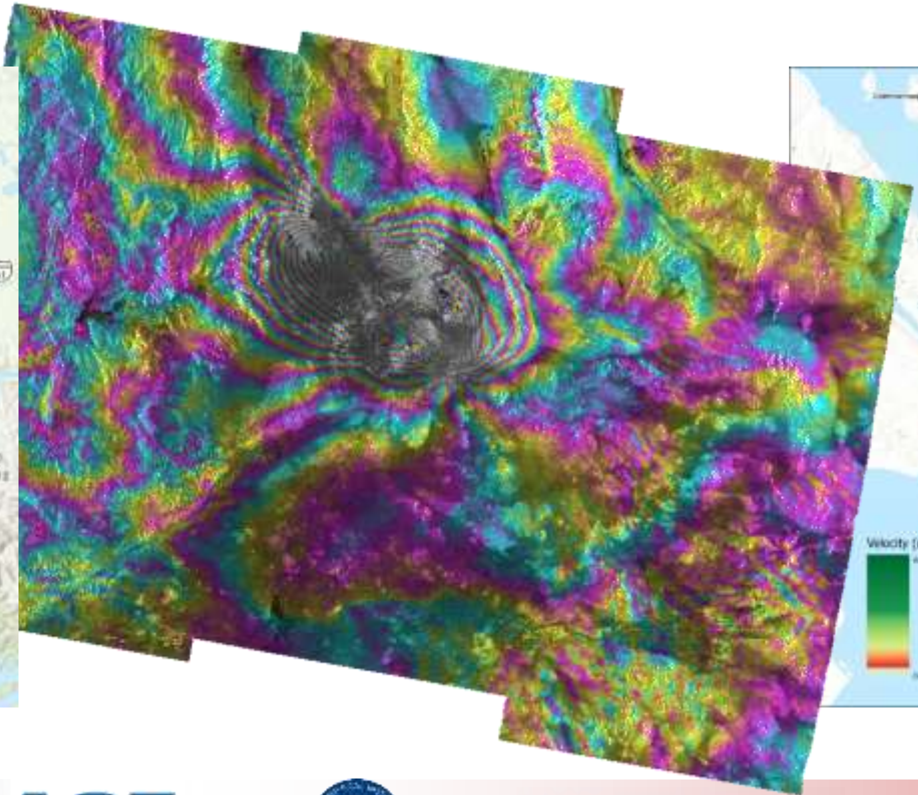
- Radiometric Terrain Correction
- Amplitude Data in multiple polarizations
- Processed using GAMMA software
- Easy to use in GIS workflows

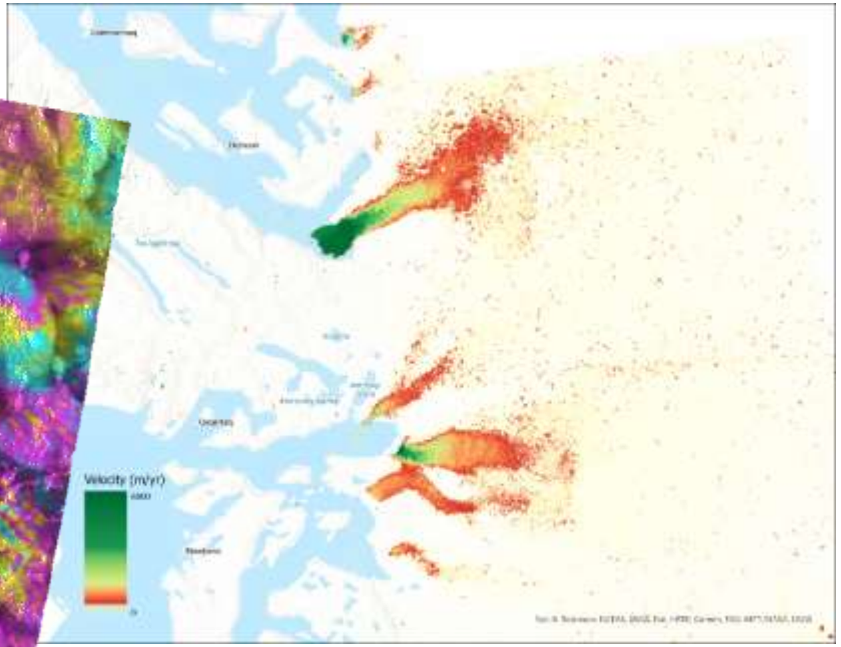
InSAR

- SAR Interferometry (phase differencing)
- Wrapped and unwrapped phase, coherence, displacement maps
- Processed using GAMMA software

autoRIFT

- Glacier velocity tracking
- Part of NASA MEaSUREs ITS_LIVE: Inter-mission Time Series of Land Ice Velocity and Elevation

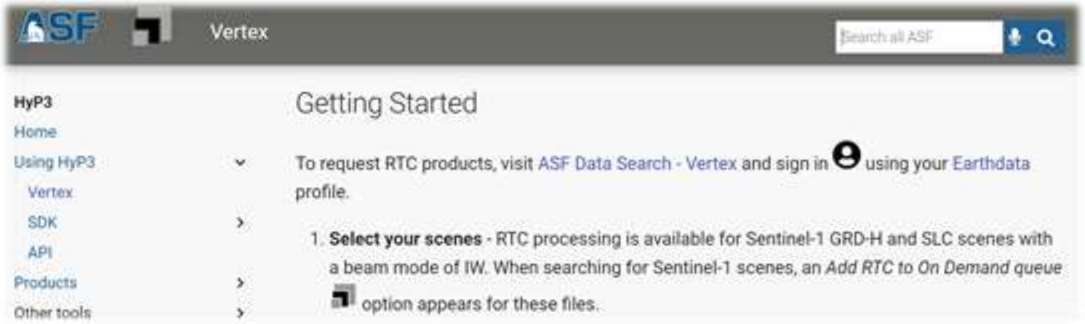




On-Demand Processing Resources

HyP3 Documentation:
https://hyp3-docs.asf.alaska.edu/

Vertex Documentation:
https://docs.asf.alaska.edu/vertex/manual/



Story Map Tutorial - InSAR:
https://storymaps.arcgis.com/stories/68a8a3253900411185ae9eb6bb5283d3

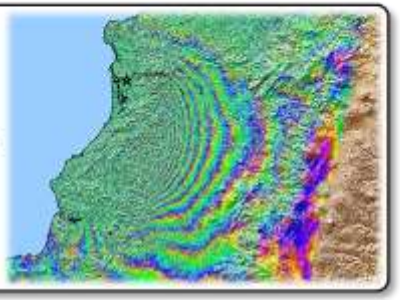
Story Map Tutorial - RTC:
https://storymaps.arcgis.com/stories/2ead3222d2294d1fae1d11d3f98d7c35

ASF's Level-2 Data Processing Platforms: The SARVIEWS Service

Automating ARD Generation for Hazard Events

Volcanoes

Earthquakes



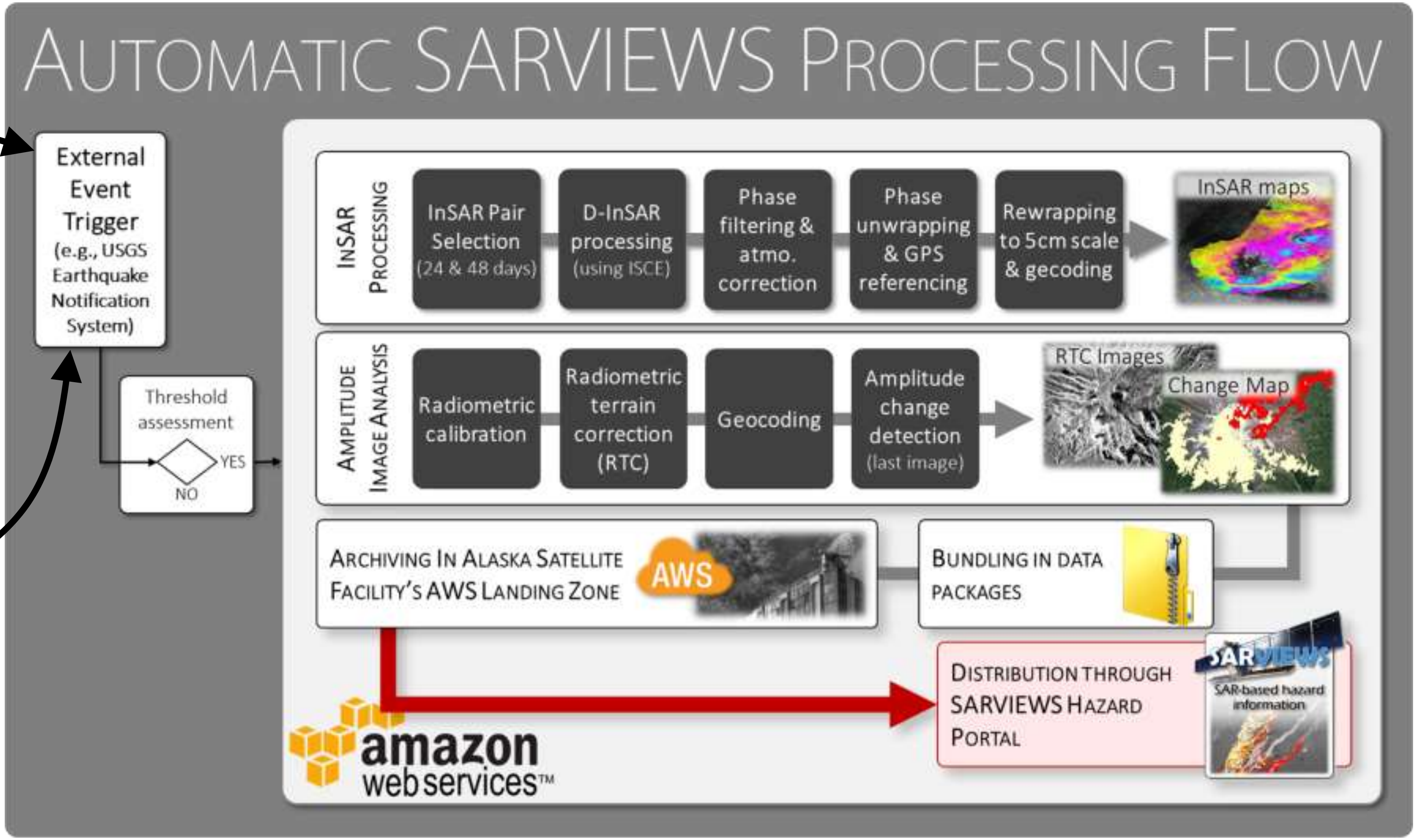
USGS Earthquake & Volcano Feeds

Fully Automatic

Flooding

Manual

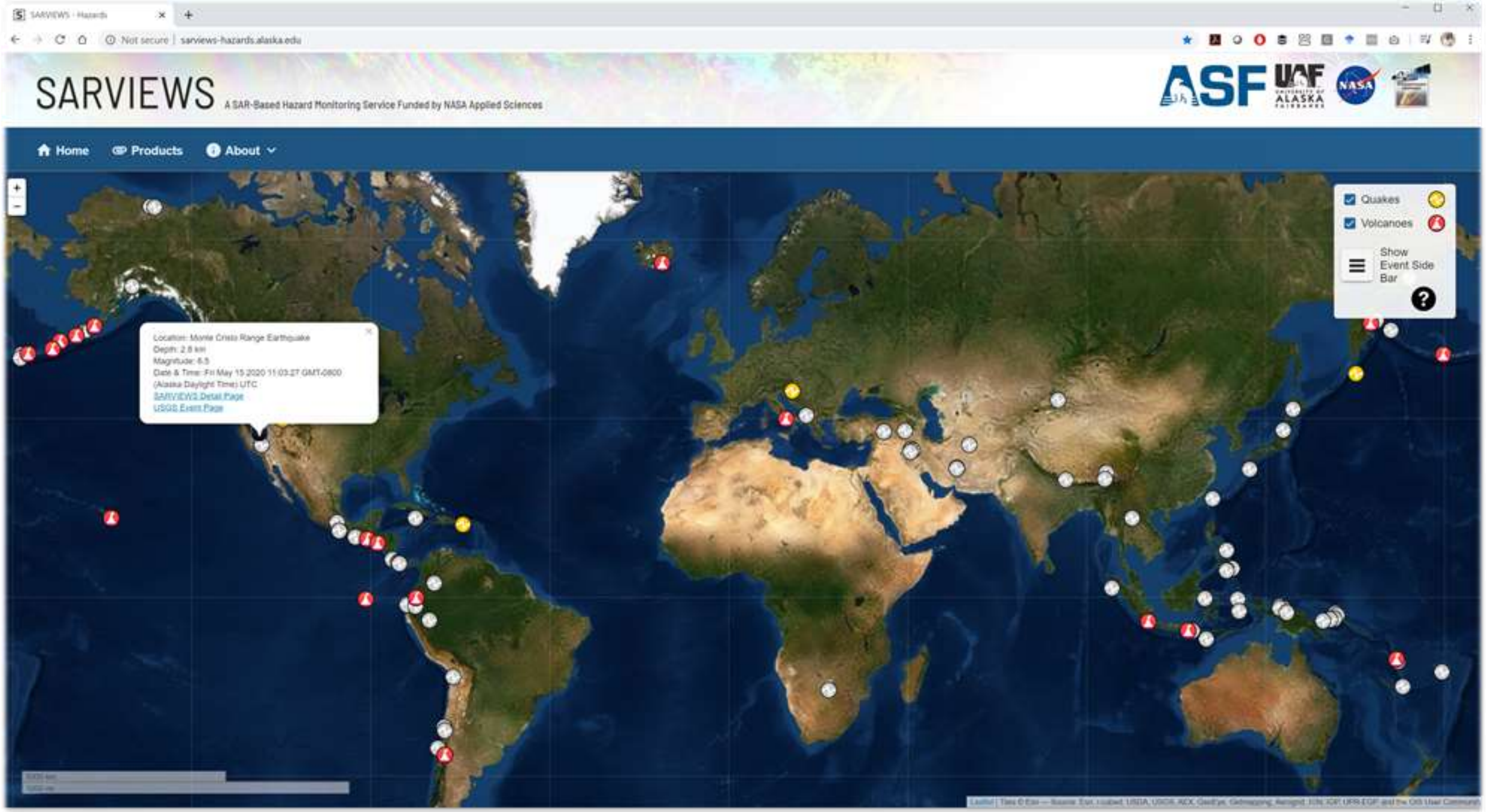
Response Agencies



The SARVIEWS Hazard Portal

Funded by: Applied Sciences Program

Visit Us @ [HTTP://SARVIEWS-HAZARDS.ALASKA.EDU/](http://sarviews-hazards.alaska.edu/)

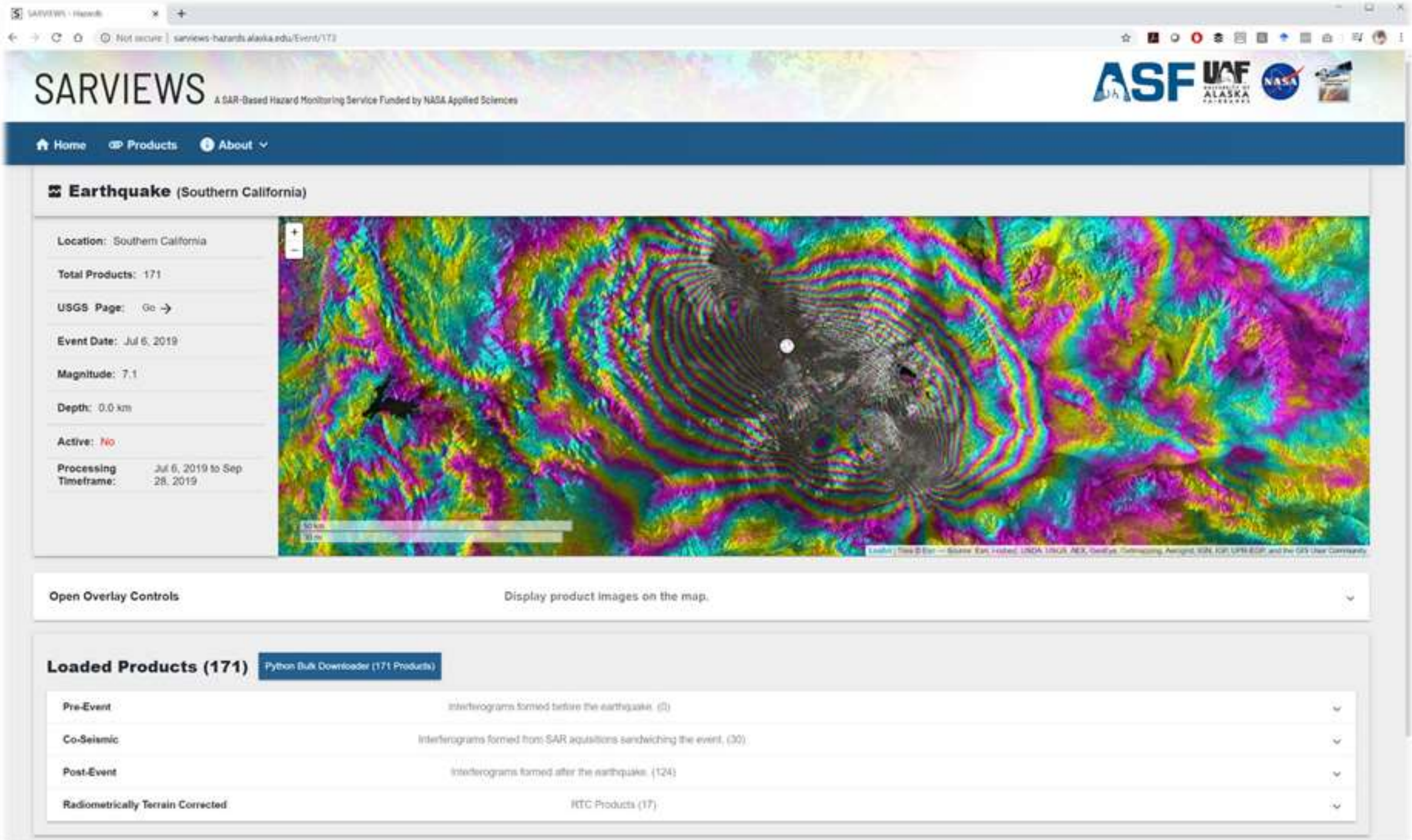


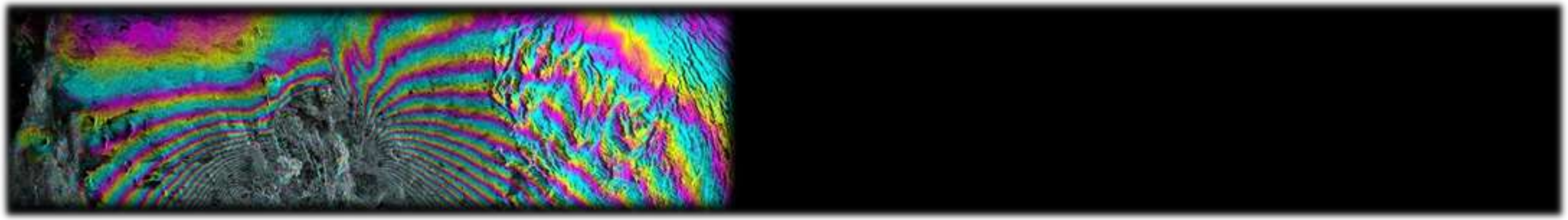
The SARVIEWS Hazard Portal

Funded by: Applied Sciences Program

SEPARATE PAGES PER MONITORED EVENT:

- View data
- Overlay products on map
- Individual download
- Bulk download



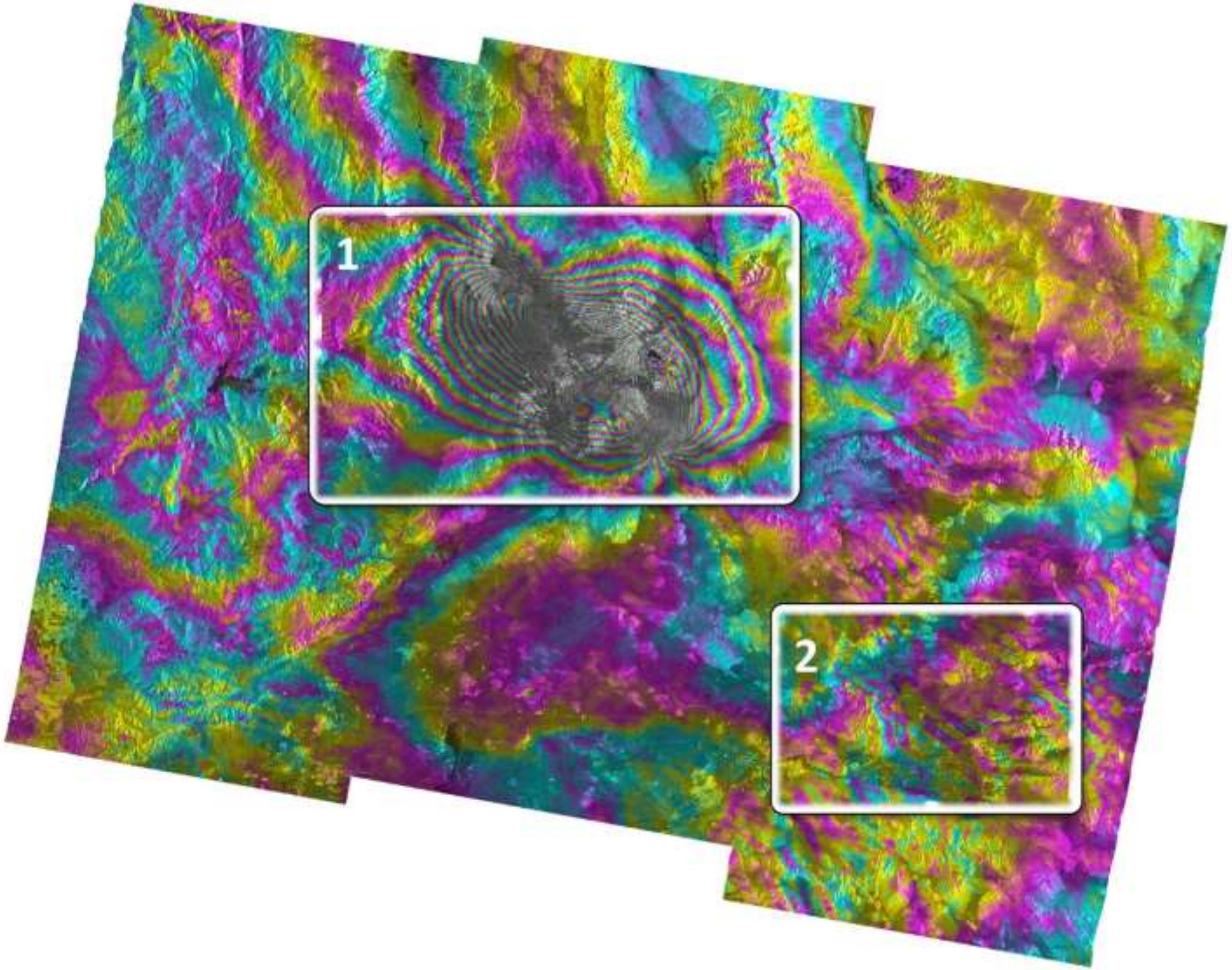


Limitations of Conventional InSAR

Think – Pair – Share: Take 1

Phase Interpretation: Analyze the phase content of this interferogram

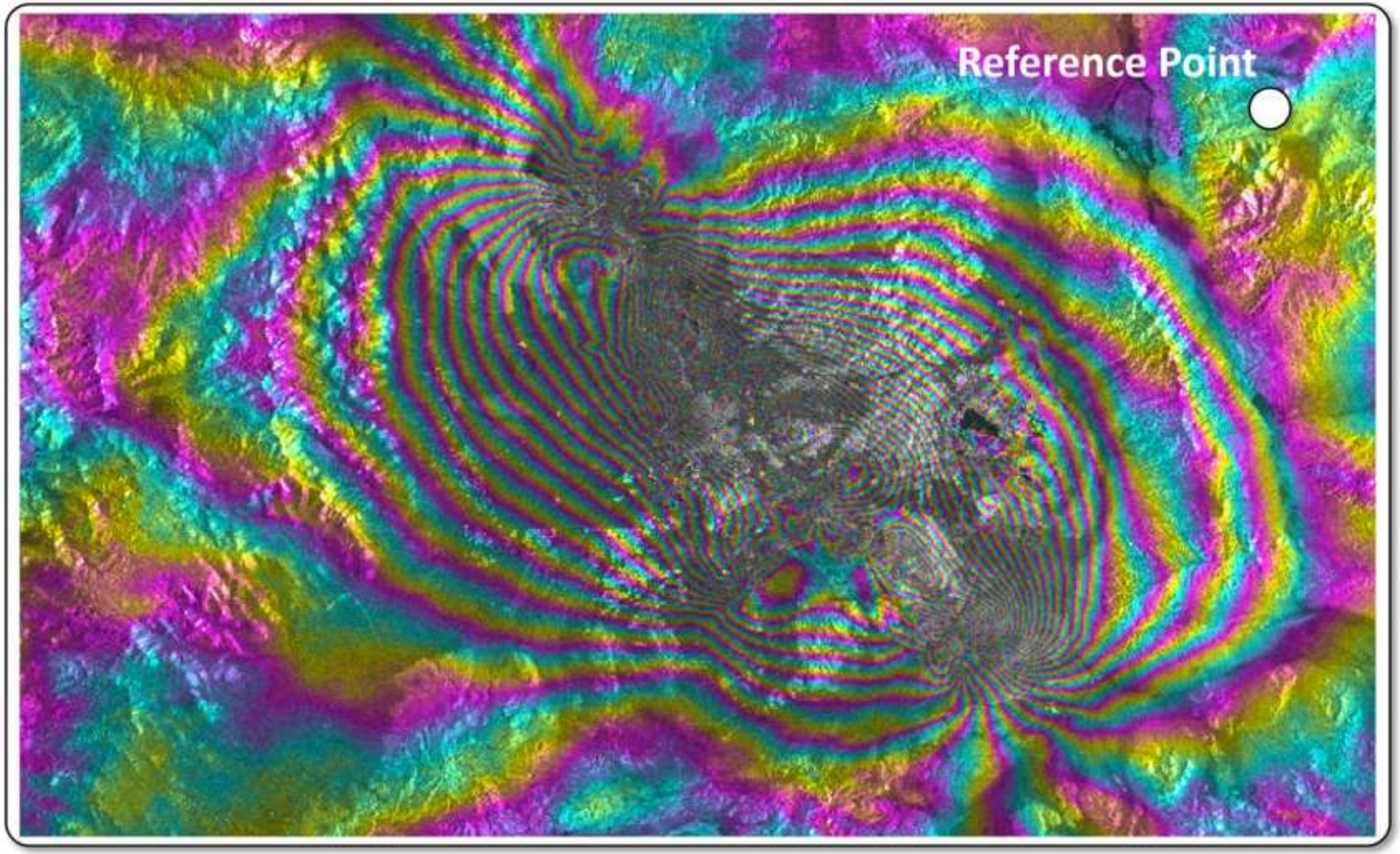
- Activity 1: What do the phase patterns in Area 1 represent?
  a) Displacement phase most likely related to an earthquake
  b) Topographic signal
  c) Atmospheric delay
- Activity 2: What is the main phase contribution in Area 2?
  a) Displacement phase most likely related to an earthquake
  b) Topographic signal
  c) Atmospheric delay



Think – Pair – Share: Take 2

Quantify What's in the Interferogram

- Activity: Based on the interferogram and following the instructions above, what is the amount of line-of-sight deformation contained in the image?
    a) 0-25 cm
    b) 60-80 cm
    c) 100-150 cm

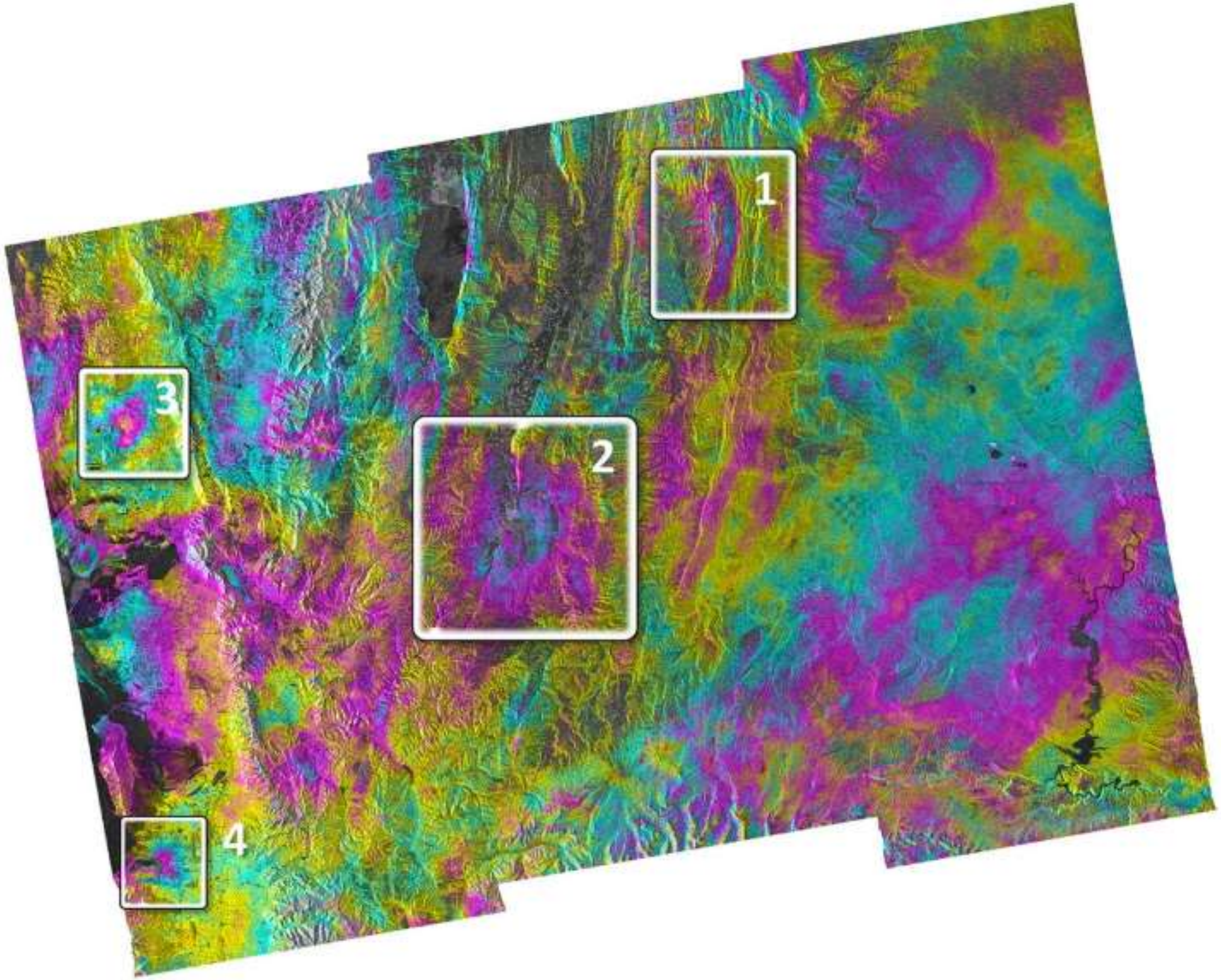


Think – Pair – Share: Take 3

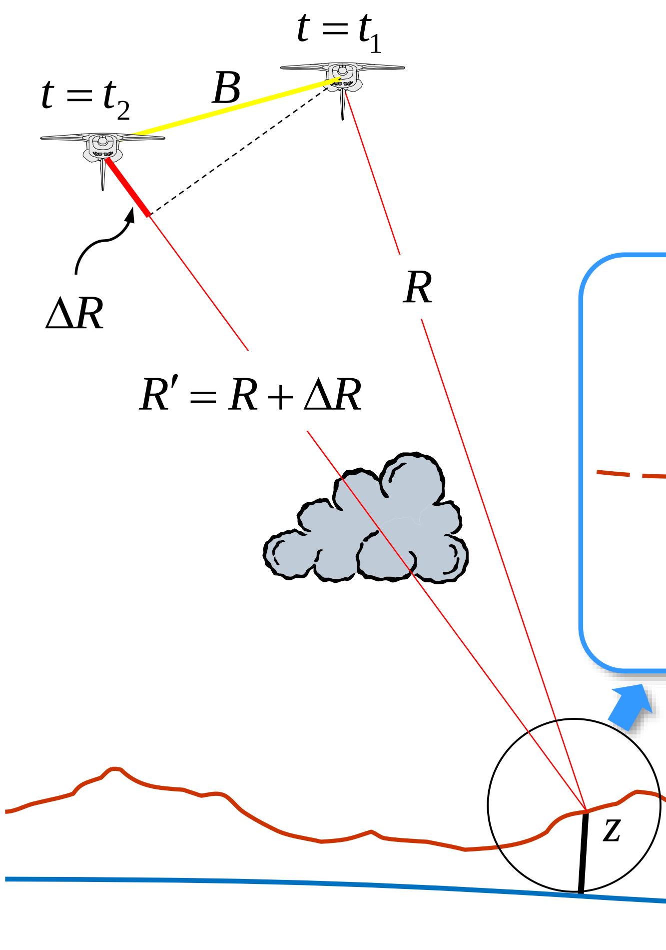
Spot the Deformation Signal

The interferogram shown here contains a deformation signal related to a M5.7 earthquake. Despite it's magnitude, the surface expression of this earthquake is rather small, making it very difficult to spot the location of the event against the noise background in the interferogram.

- Activity: Look at the four suggested locations above. Which of the four do you think shows the earthquake?
    a) Area 1
    b) Area 2
    c) Area 3
    d) Area 4



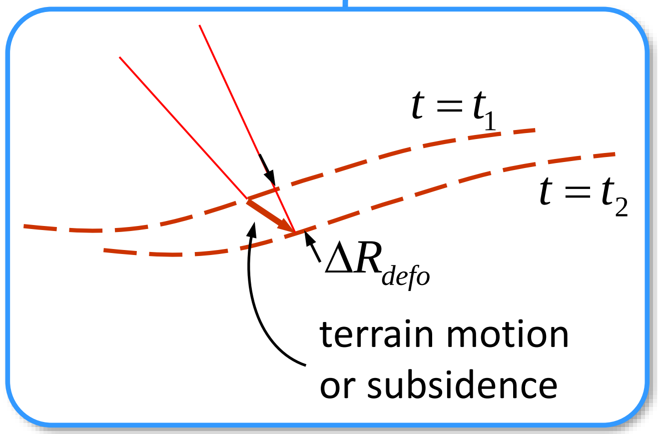
Recap of InSAR Acquisition Scenario



Interferometric Phase:

$$\phi = \phi_{topo}(z;B) \quad + \phi_{defo} \quad + \phi_{atmo} \quad + \phi_{orbit} \quad + \phi_{noise}$$

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



Error Sources from:

- Variation of atmospheric signal delays ϕ_{atmo}
- Uncertainties of the orbit geometry ϕ_{orbit}
- Noise from signal decorrelation ϕ_{noise}

The Complete InSAR Phase Equation

- **Phase of an interferogram:**

$$\phi = W\{\phi_{topo} + \phi_{defo} + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\}$$

$$= W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot sin(\theta)}h + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}$$

(W: wrapping operator $\rightarrow \phi$: $[-\pi, \pi[$)

- **Phase of a differential interferogram** (after compensation of topography phase)**:**

$$\Delta\phi = W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot sin(\theta)}h_{err} + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}$$

(where $h_{err} = h_{true} - h_{DEM}$ is a residual topography phase due to errors in the DEM)

Limitations and Error Sources of InSAR

Overview

1. **Only sensitive to motion in sensor's line-of-sight → does not provide 3D motion fields**

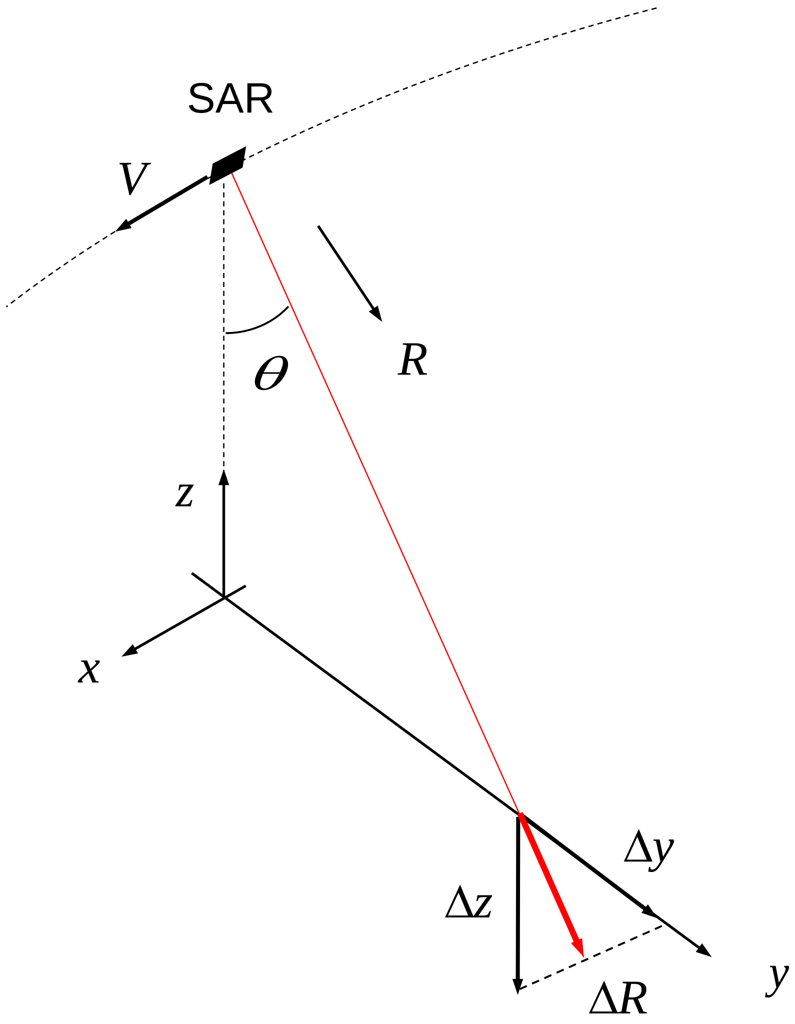
2. **Temporal baseline is limited, leading to limited sensitivity to very slow surface motion:**
   - Limitation is due to temporal decorrelation, leading to increase of phase noise with time

3. **Atmospheric phase patterns may mask signal of interest, limiting sensitivity of InSAR to very small motion (or topography) signals**

4. **Orbit errors may cause ramp-like phase distortions** [usually small]

Limitations of InSAR:

1. Only Line-of-Sight Motion Sensitivity



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

for ERS:

1 fringe (2π) corresponds to

2.8 cm in R

3.0 cm in z (e.g. subsidence)

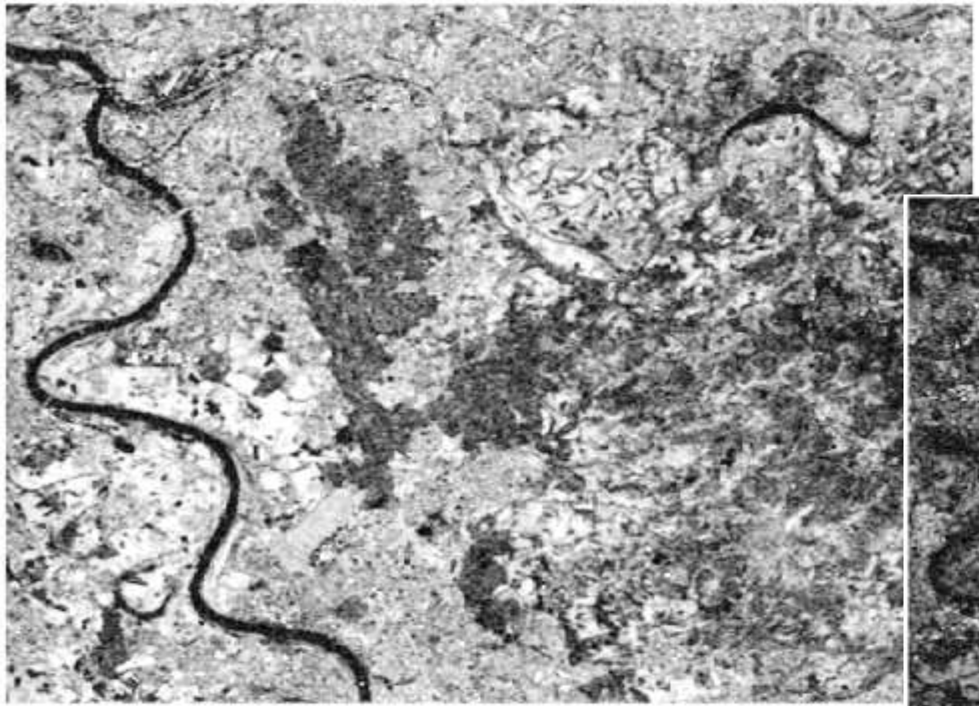
7.2 cm in y (motion)

! only 1 dimension of 3-d motion accessible

! no sensitivity to motion in x direction

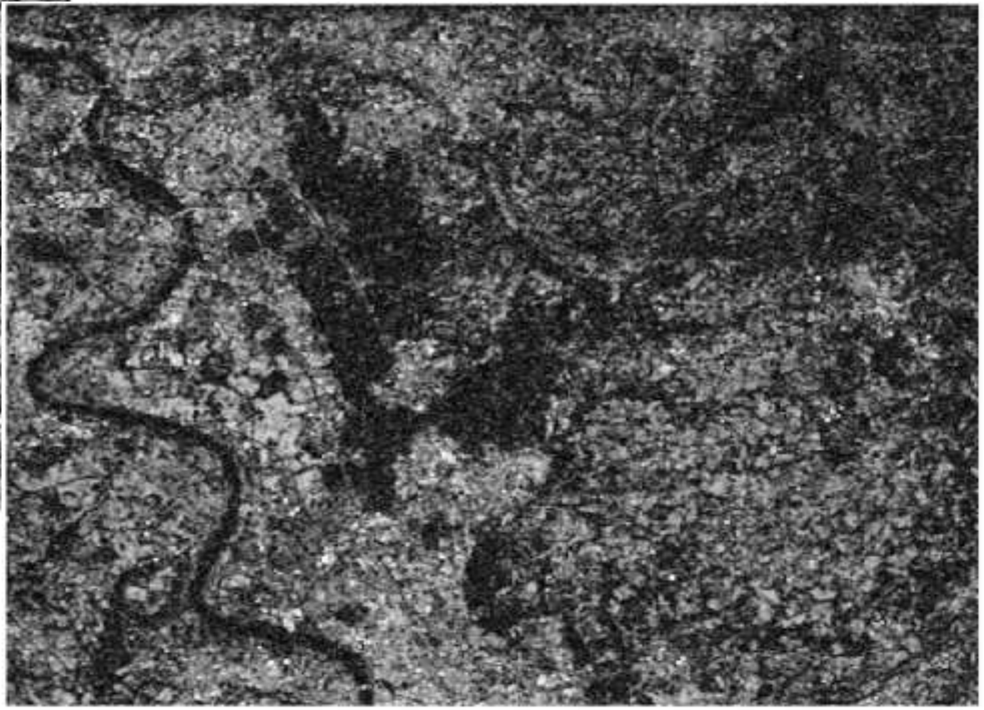
Limitations of InSAR:
2. Temporal Signal Decorrelation

- **Changes of the ground scattering properties are main source of signal decorrelation with time**
  - **Example:** Airborne C-band SAR over vegetated environments



short term interferogram (15.01 – 21.01)

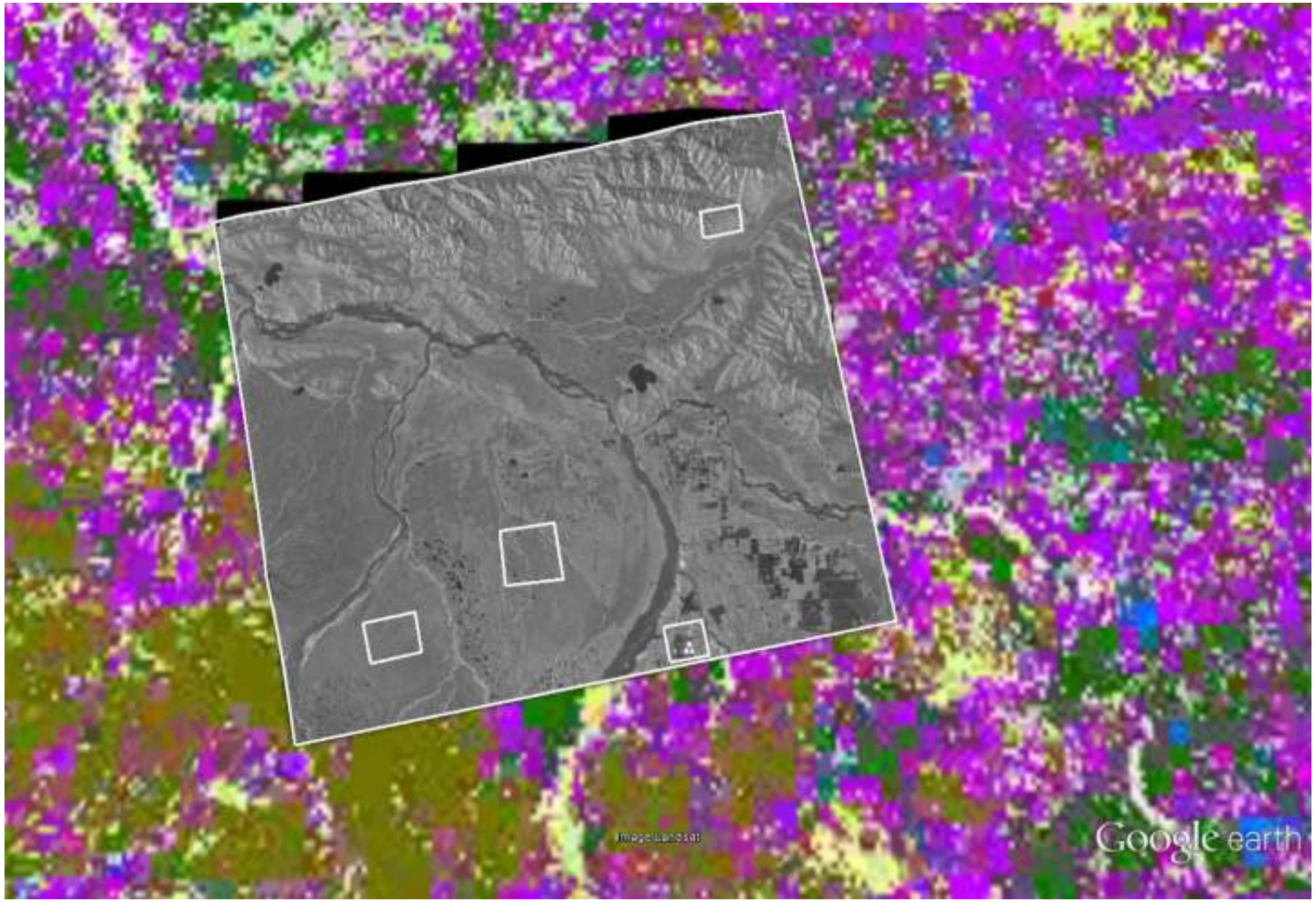
long term interferogram (15.01 – 20.02)



Examples of Coherence Change with Time

Boreal Dry Climate

- **Example**: Delta Junction – L-band SAR (ALOS PALSAR)

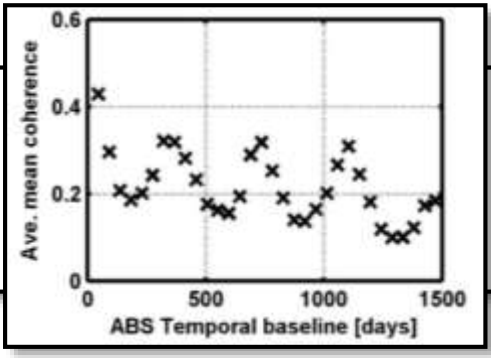


Color	Label
	Water
	Evergreen Needleleaf forest
	Evergreen Broadleaf forest
	Deciduous Needleleaf forest
	Deciduous Broadleaf forest
	Mixed forest
	Closed shrublands
	Open shrublands
	Woody savannas
	Savannas
	Grasslands
	Permanent wetlands
	Croplands
	Urban and built-up
	Cropland/Natural vegetation mosaic
	Snow and ice
	Barren or sparsely vegetated

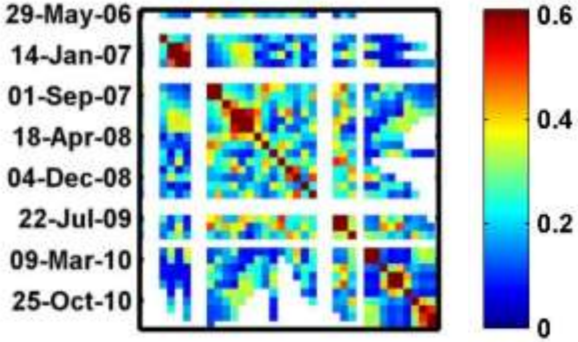
Examples of Coherence Change with Time

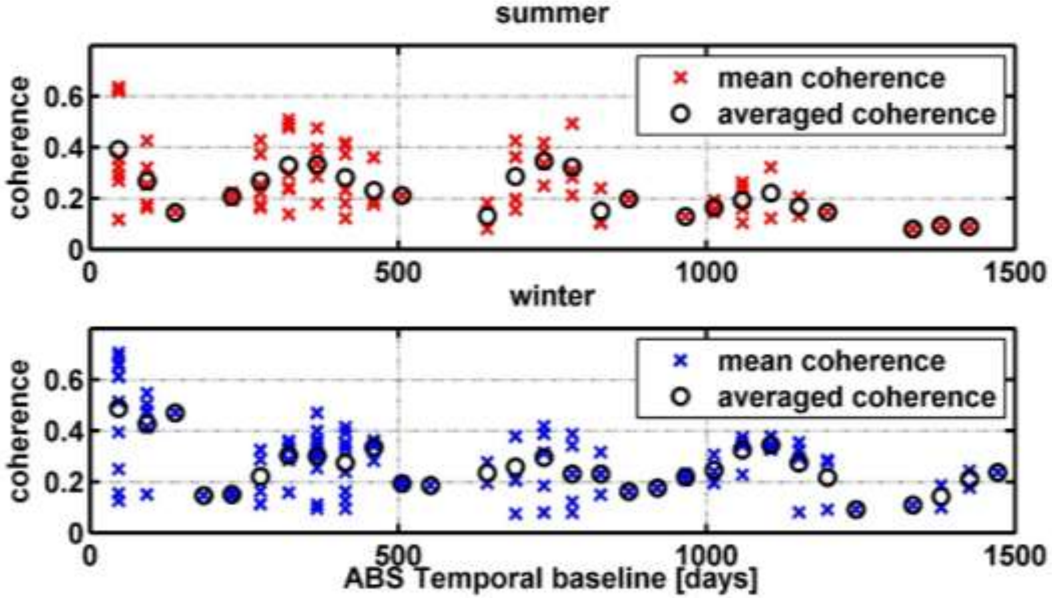
Boreal Dry Climate

- **Delta Junction – Example for Subset-1**



- **LULC:** Woody Savannas
- Flat region
- Summer (June to Oct), Winter (Nov. to May)

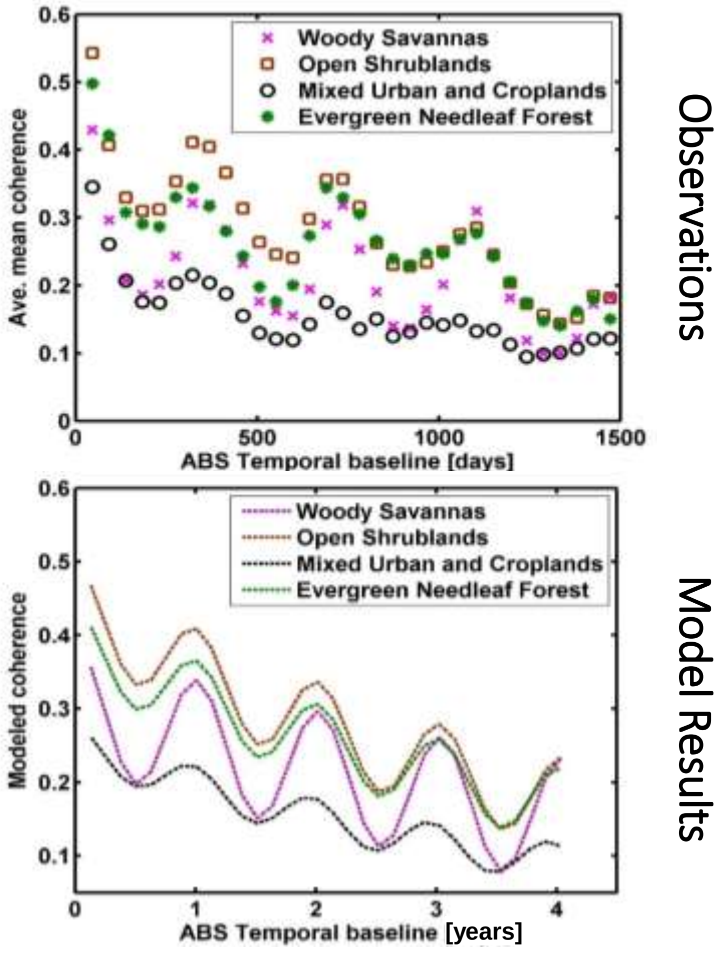




Examples of Coherence Change with Time

Boreal Dry Climate

- **Estimated Coherence Models – Delta Junction; L-band**



LULC type	A	λ (1/yr)	ϕ	B	d (1/yr)	R^2
1. Woody Savannas	0.08 ± 0.01	0.99 ± 0.01	0.00 ± 0.17	0.31 ± 0.01	0.18 ± 0.02	0.89
2. Open Shrublands	0.06 ± 0.01	0.99 ± 0.02	0.03 ± 0.23	0.44 ± 0.01	0.23 ± 0.02	0.92
3. Urban & Croplands	0.03 ± 0.01	1.01 ± 0.03	0.00 ± 0.47	0.25 ± 0.01	0.26 ± 0.03	0.80
4.Evergreen Forest	0.05 ± 0.01	0.99 ± 0.03	0.00 ± 0.43	0.39 ± 0.02	0.21 ± 0.03	0.76

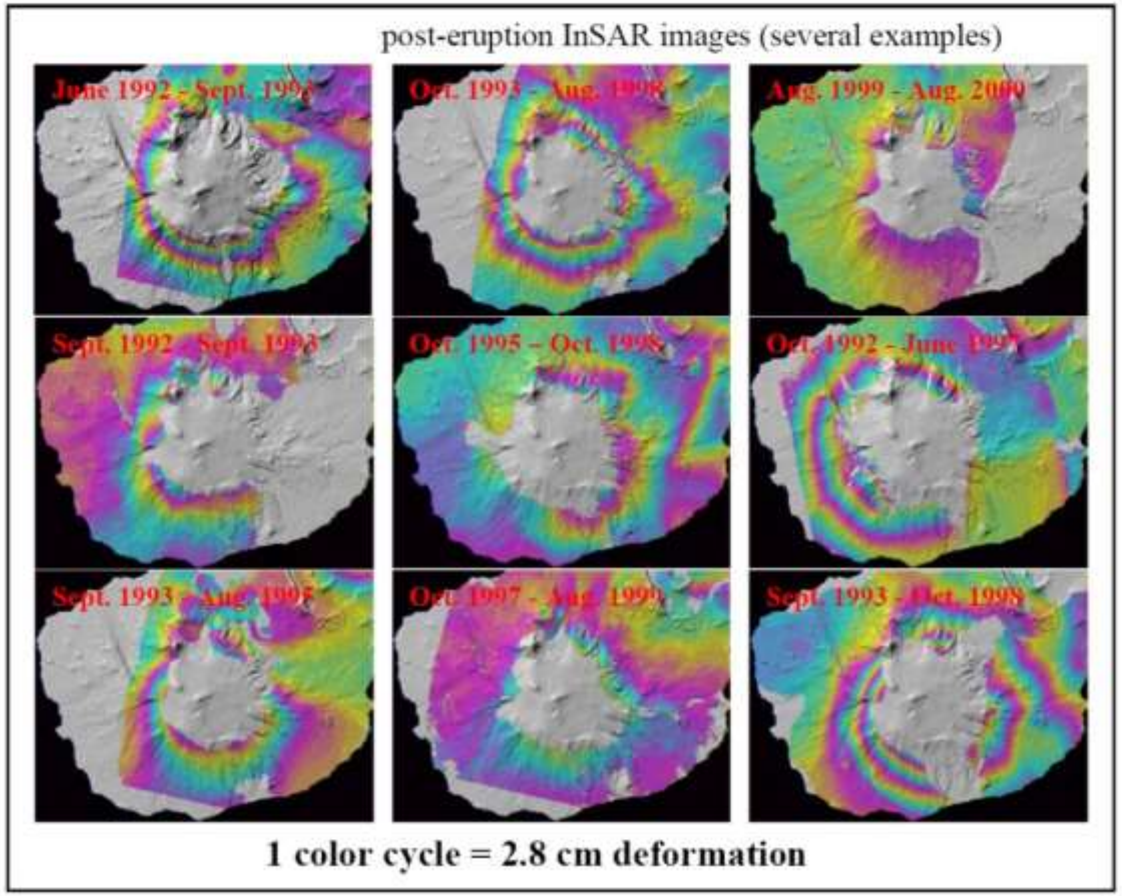
- **Coherence Model Characteristics:**

$$\bar{\gamma}(t) = \boldsymbol{A} \cdot \boldsymbol{cos}(2\pi\boldsymbol{\lambda} \cdot \boldsymbol{t} + \boldsymbol{\phi}) + \boldsymbol{B} \cdot \boldsymbol{exp}(-\boldsymbol{d} \cdot \boldsymbol{t})$$

- Different exponential decay parameters (d & B)
- **Significant** & similar **periodic cycle** $\boldsymbol{\lambda}$ for analyzed land covers
- Differences in amplitude A of periodic signal
- Periodicity λ closely one year → near-seasonal signatures
- Good model fit (high R^2)

Limitations of InSAR:
2. Temporal Signal Decorrelation

Caldera of Westdahl Peak is decorrelated in all interferograms



Example: Volcano Monitoring

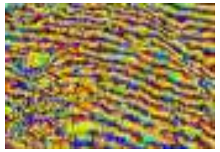
- Often, caldera of active volcanoes is decorrelated due to constant change (snow and ice melt; ash fall; lahars; lava flows; …).
- **Consequence**:
  - Area with strongest signals inaccessible
  - In modeling, shape of source model as well as horizontal location of source hard to define
  - combination with GPS is advised

Decorrelation and Fringe Washing

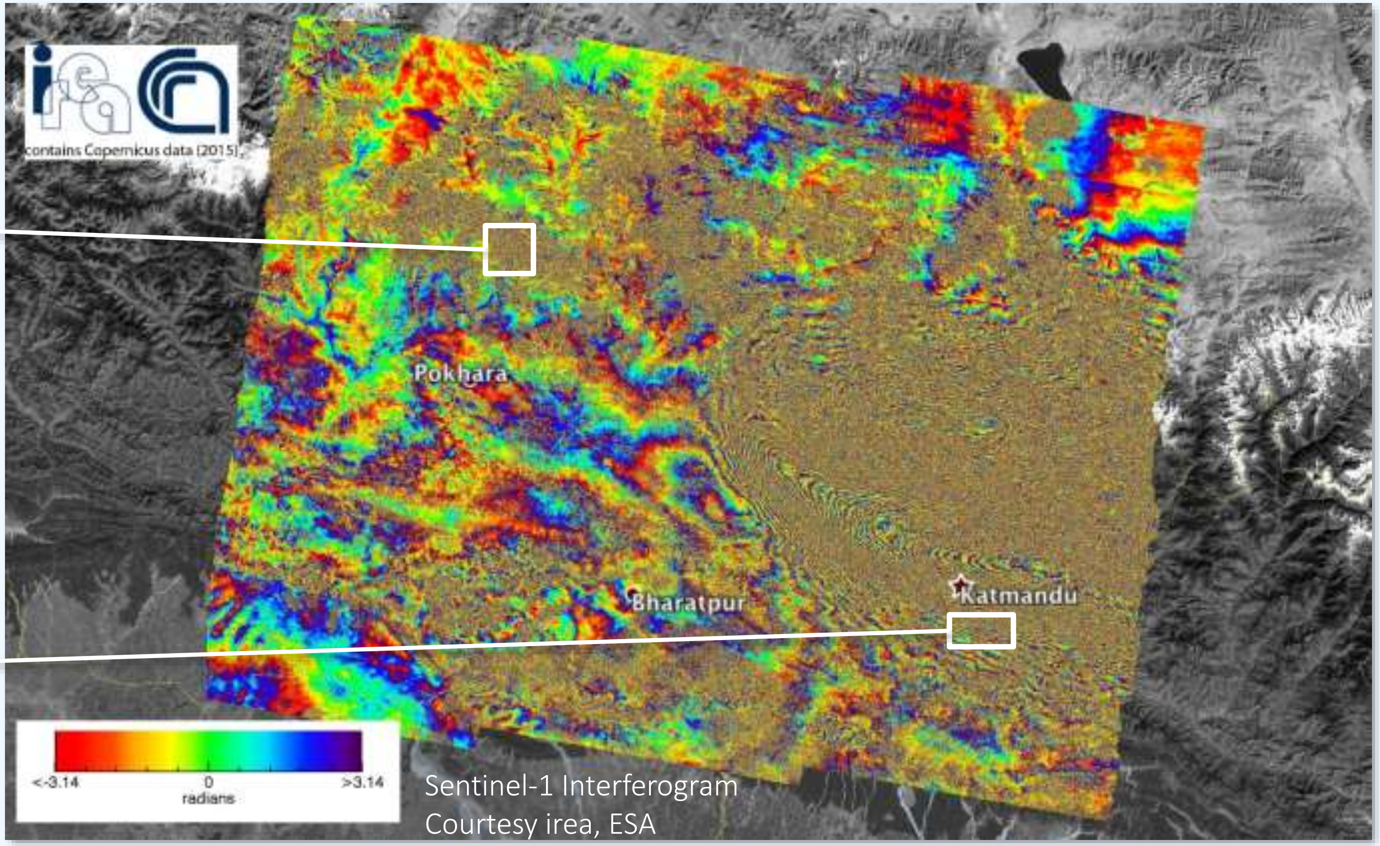
Gorkha Earthquake, Nepal, April 2015

Decorrelation:
phase essentially random

Fringe Washing
Large strain: fringes closely spaced, difficult to unwrap



Can decrease coherence



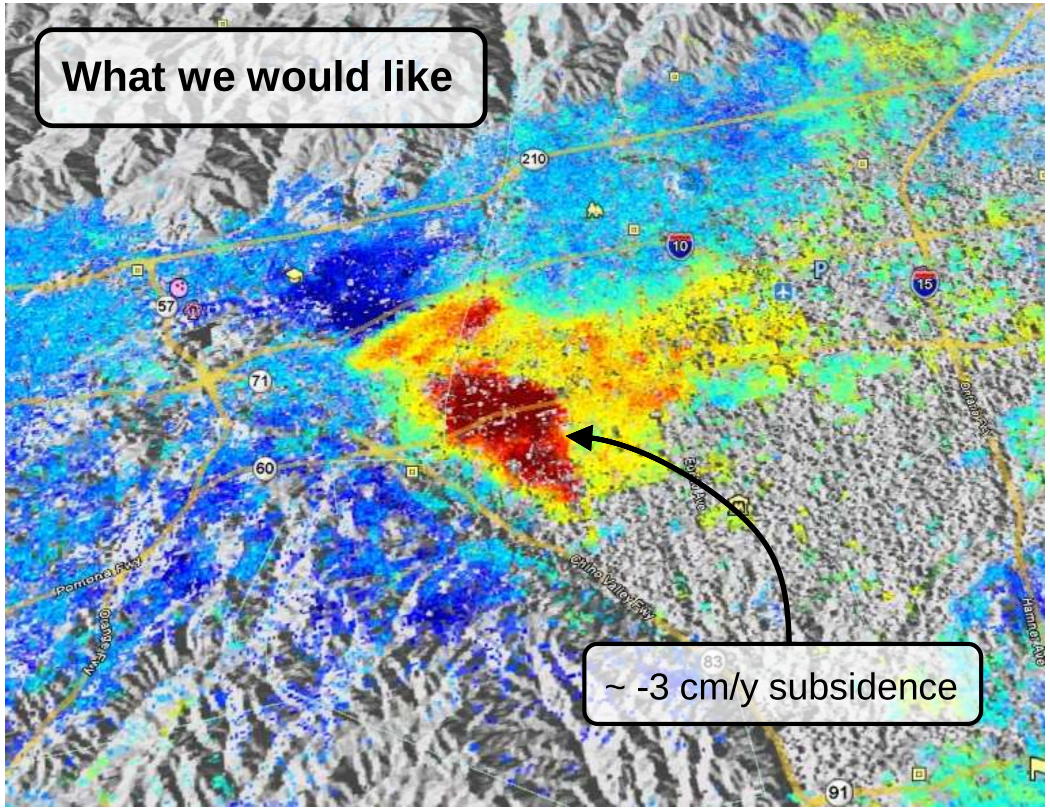
Sentinel-1 Interferogram
Courtesy irea, ESA

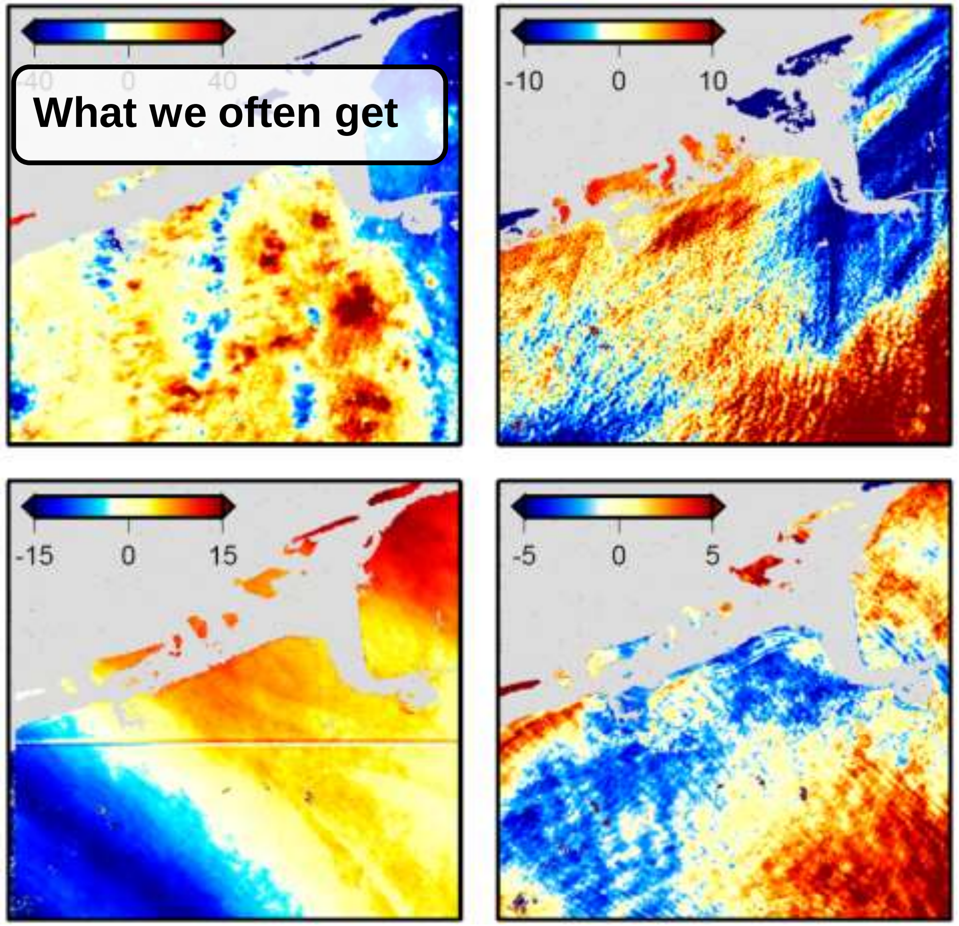
InSAR Time Series Analysis is mitigating the impact of signal decorrelation

Limitations of InSAR:

3. Atmospheric Distortions

- **Atmospheric propagation influence:**
  - Masks deformation signals in InSAR
  - Increases data requirements and latency times for InSAR analyses





Limitations of InSAR:

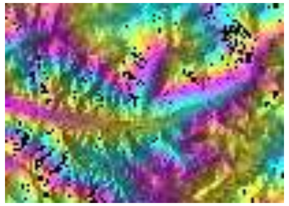
3. Atmospheric Distortions

Coquimbo Earthquake, Chile, April 2018, M6

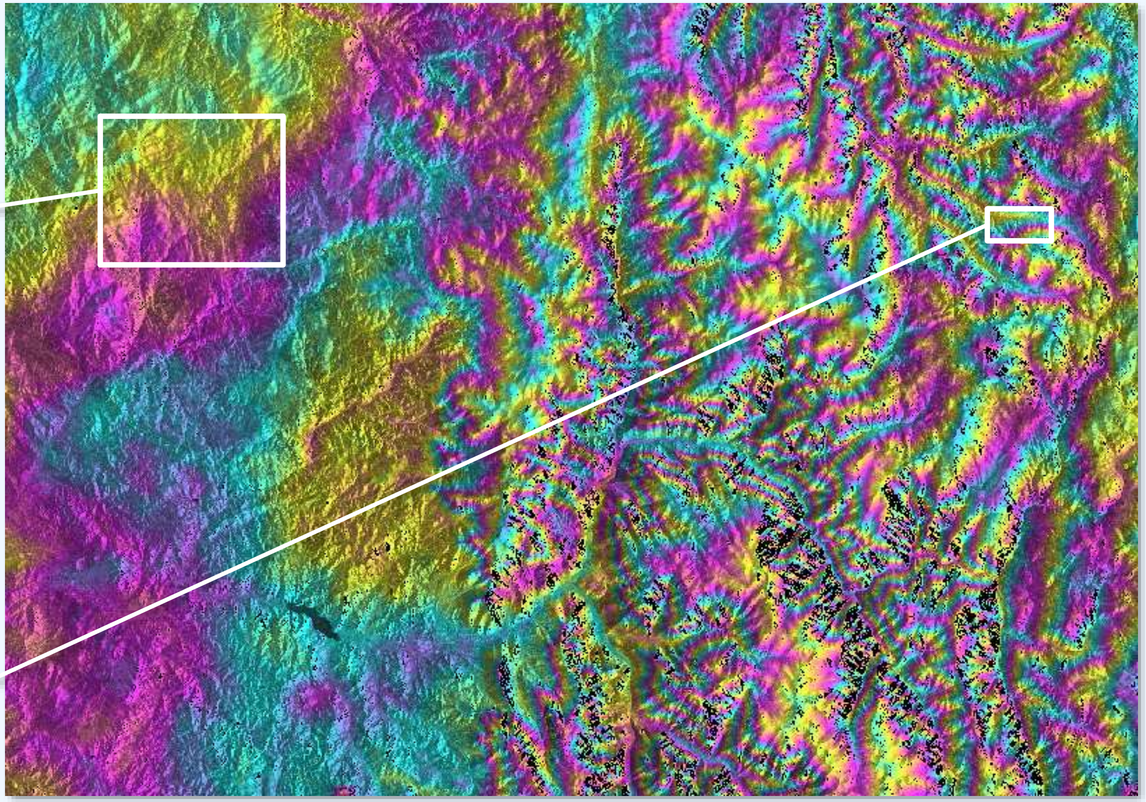
Turbulent Troposphere:
Horizontal variation in refractive index, esp. in water vapor
Variable across spatial scales
Can mask small earthquake

Correction:
- Regional scale: weather model, GPS, etc.
- Small scale: filtering in space and time

Stratified troposphere
Signal path decreases with elevation
Phase correlated with topography



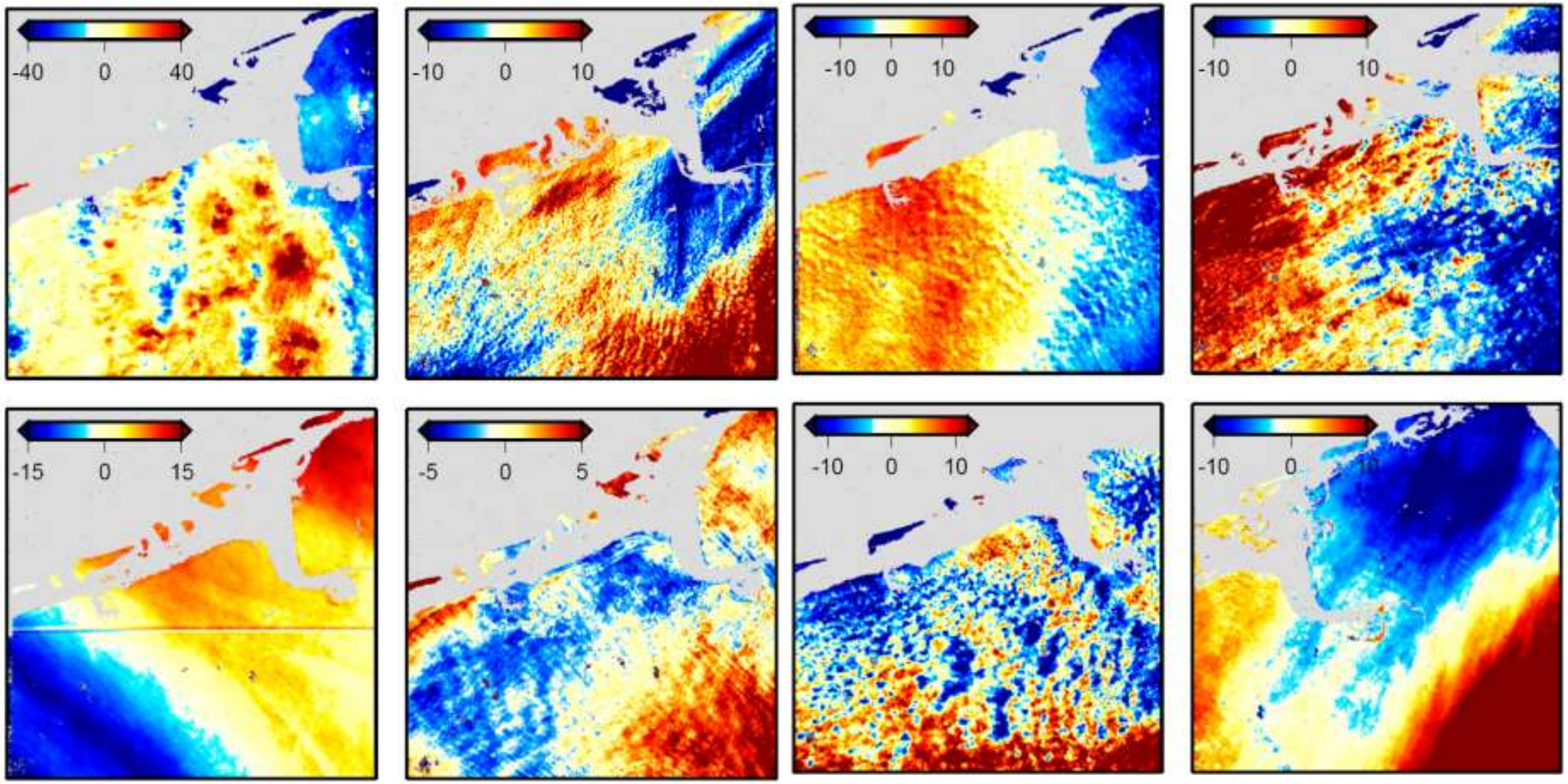
Correction: weather models, data-driven



Sentinel-1 Interferogram
Courtesy SARVIEWS, ESA

Examples of Turbulent Atmospheric Phase Distortions in InSAR Data

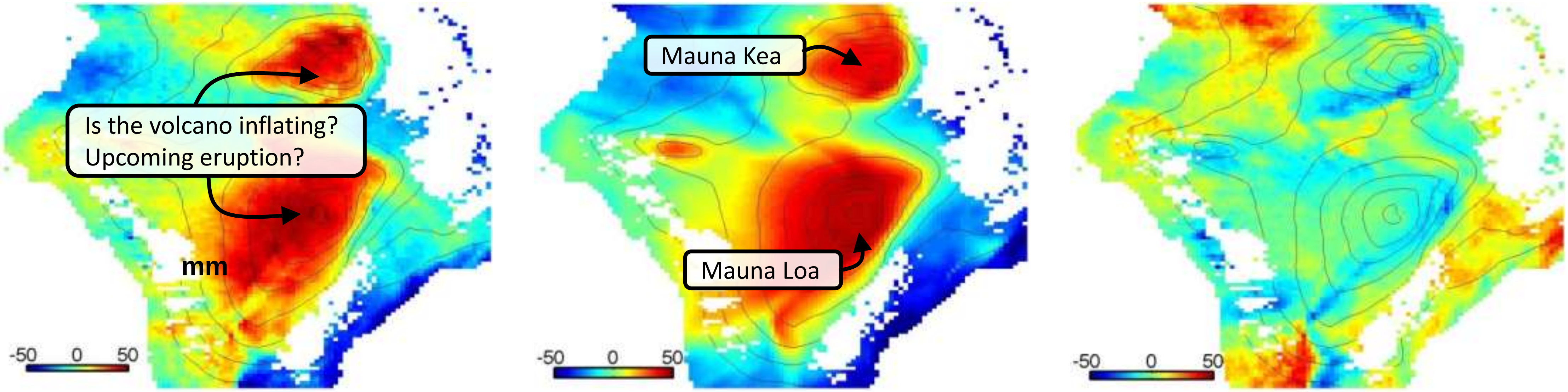
- 8 100x100 km interferograms showing atmospheric distortions [cm]



Courtesy: R. Hansen, TU Delft

Example and Impact of Stratified Atmospheric Phase Distortions

Atmospheric Signals can lead to incorrect interpretation of observations:



d-InSAR Observations, Big Island, Hawaii

Atmospheric Model

Phase after subtracting the Atmospheric Model

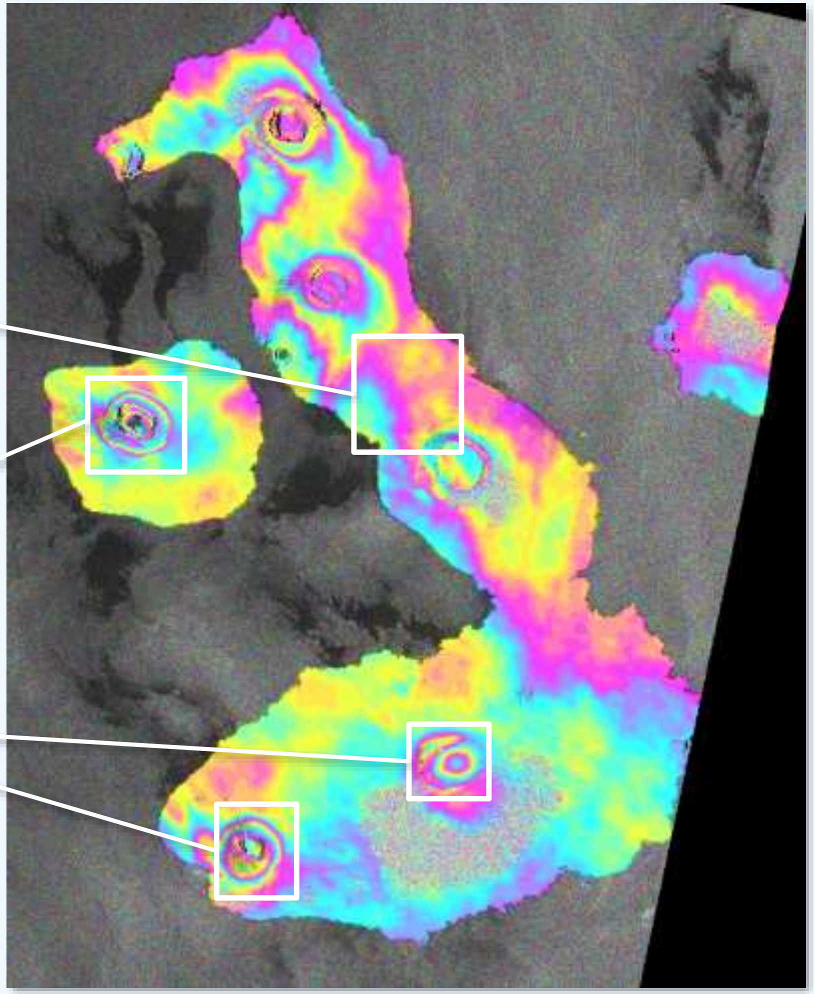
Limitations of InSAR:
3. Atmospheric Distortions

Isabela Island, Galapagos, Ecuador, September 2019, M6

Troposphere or volcanic origin?

Stratified troposphere or volcanic origin?

How could you quantify the relative contributions?



Sentinel-1 Interferogram
Courtesy SARVIEWS, ESA

InSAR Time Series Analysis is mitigating the impact of atmospheric phase delay

What’s Next?

- **This is what awaits next:**
  - **InSAR Time Series Analysis**