GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

Lecturer:

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Lecture 8: InSAR Time Series Analysis Basics & PS-InSAR: Time Series Analysis using Point Targets

BEFORE WE START …

Think – Pair – Share:

Remember the Complete d-InSAR Phase Equation:

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

Activity 1: Discuss the Elements of this Equation:

a) What are the variables h_{err}, v, Δt, ϕ_{atmo}, ϕ_{orbit}, and ϕ_{noise} in this phase equation?
Which of them do we typically consider as our target parameters and which one as error sources?

b) What does the symbol $W\{.\}$ represent?

Activity 2: Interferometric Coherence γ:

The amount of phase noise ϕ_{noise} is quantified by the coherence $\gamma(\Delta t)$, which is typically a function of the temporal baseline Δt.

a) Discuss coherence properties of the following *2* surface types in a C-band SAR interferogram:

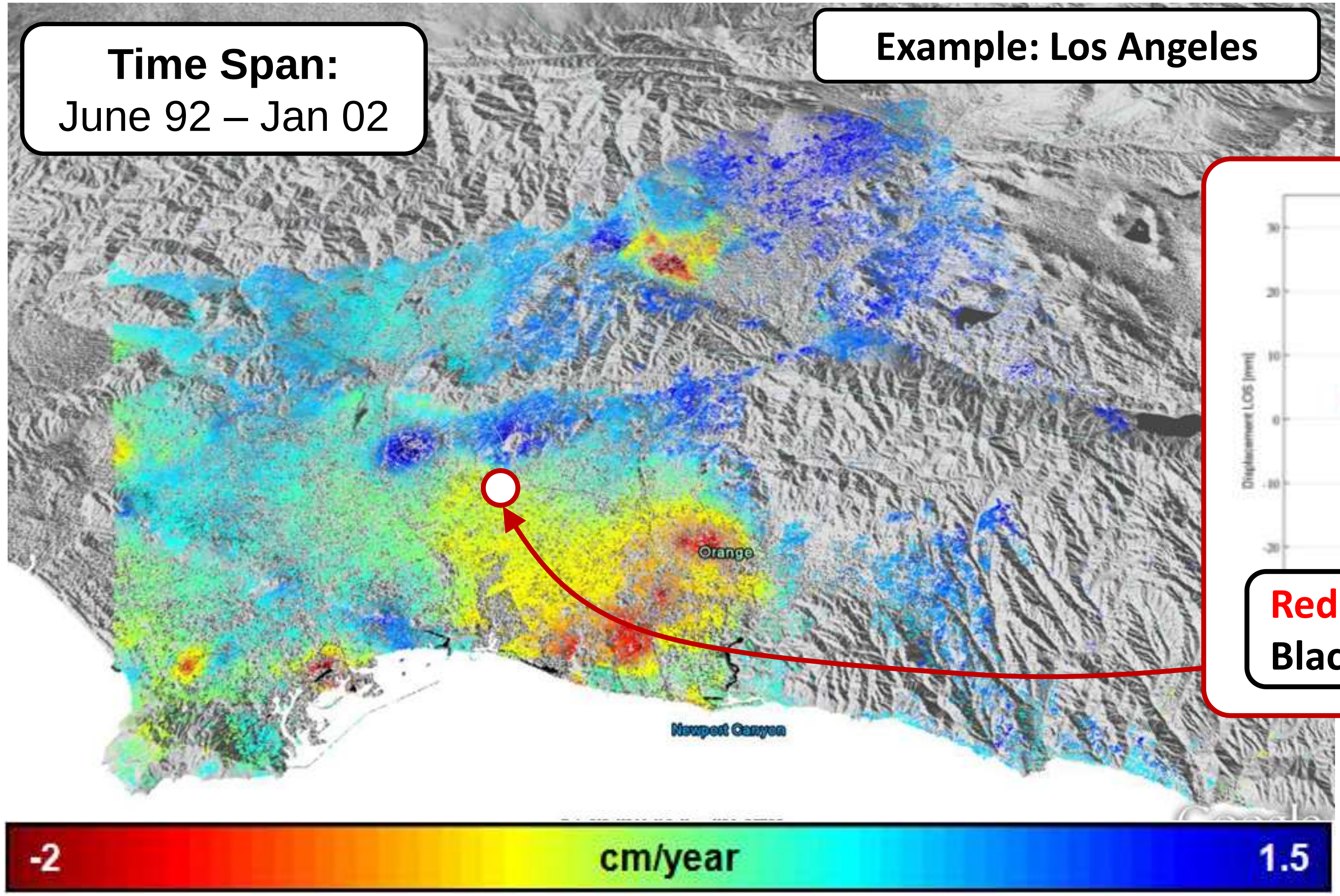
- **Deciduous forest**: Describe qualitatively how coherence $\gamma(\Delta t)$ behaves with Δt. How long may the InSAR phase stay coherent over this area?
- **Urban environment**: Describe the dependence of $\gamma(\Delta t)$ on Δt for this area. How is it different from $\gamma(\Delta t)$ for deciduous forests and why?
- Both areas are subsiding with $v = 1cm/year$. Can a traditional single-pair InSAR approach measure this deformation in both areas?

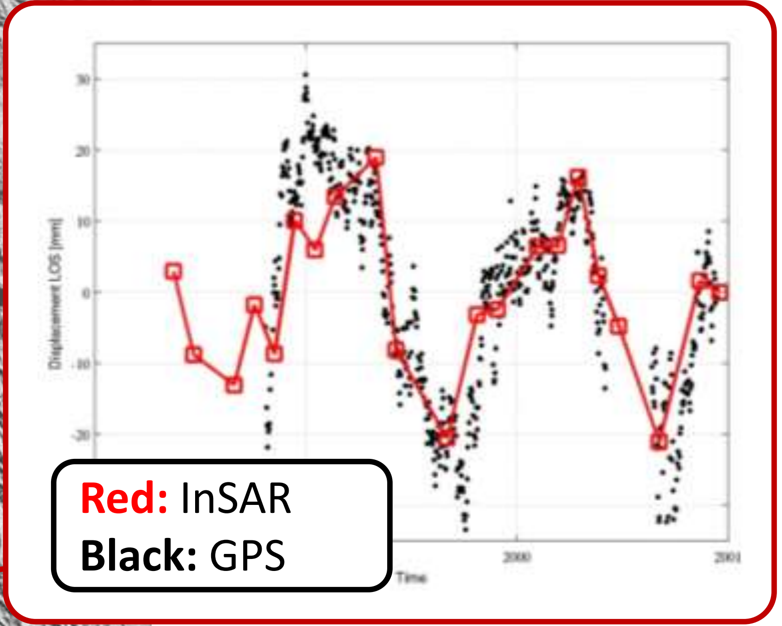
THE BASIC CONCEPT OF INSAR TIME SERIES ANALYSIS

Study Deformation Across Time Scales

Time Span:
June 92 – Jan 02

Example: Los Angeles





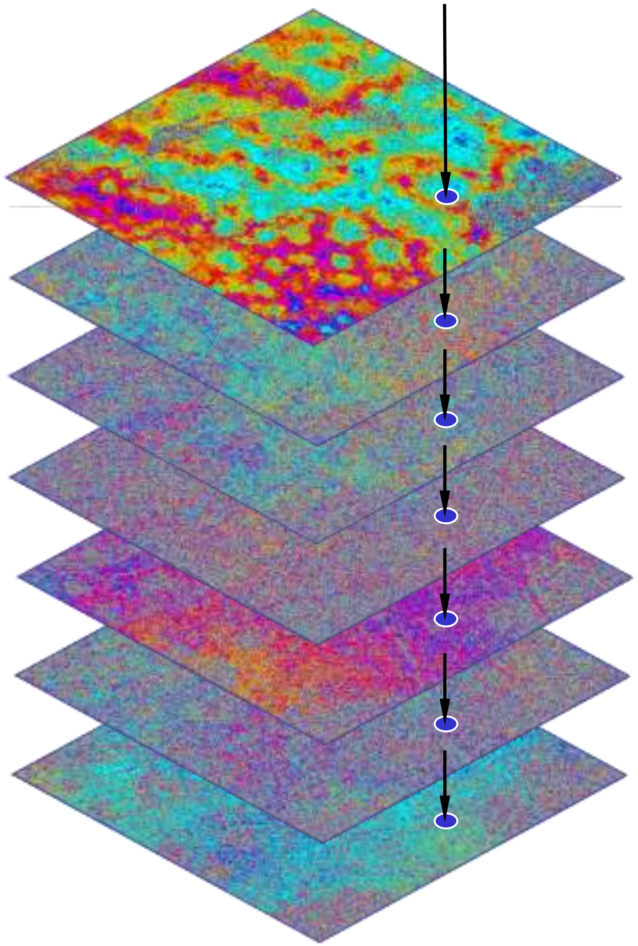
Why Use Time Series Analysis?

Two compelling reasons

1. **Study temporally extended phenomena**
   - Volcanic inflation
   - Landslides
   - Inter-seismic slip
   - Groundwater-related subsidence

2. **Improved estimation of deformation signal** by exploiting time series to remove
   - Atmosphere
   - Topography (DEM errors)
   - and other noise sources

Treatment of Error Sources and Limitations Through InSAR Time Series Analysis



Concepts included in Time Series InSAR

1. **Use many ($N \gg 2$) interferograms (ifgrms) spanning long time span**

   → $N \gg 2$ observations and only two unknowns (topography h; deformation v)

   → Suppression of noise (atmosphere; orbit errors; noise) *[response to Limitation 4 in Lecture 13]*

   → Improve precision of deformation estimates *[response to Limitation 2 in Lecture 13]*

2. **Find patches that are coherent in all ifgrms**

   → Sophisticated algorithm required to identify pixels that are coherent over long time frames *[response to Limitation 2 in Lecture 13]*

3. **Analyze phase of coherent pixels over time & across space**

Separate Phase Components With Time Series Analysis

Main interest — Nuisance

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

smooth in time (usually)

proportional to spatial baseline

random in time – smooth in space
orbit error similar

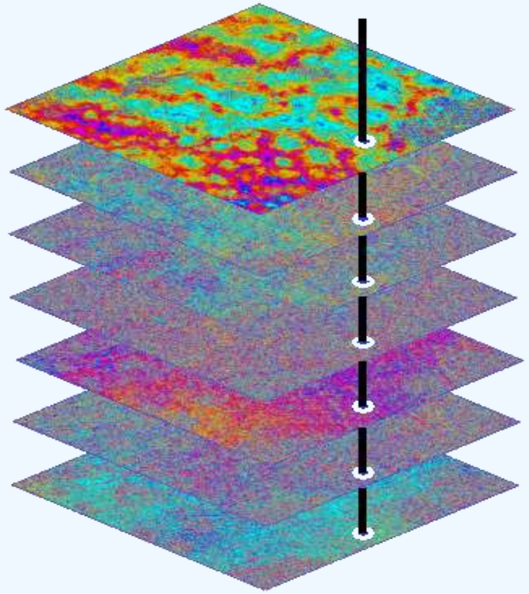
random in time and space

Separate components based on their temporal, spatial and baseline characteristics

Rationale of InSAR Time Series Analysis

Input

Time series of SAR images



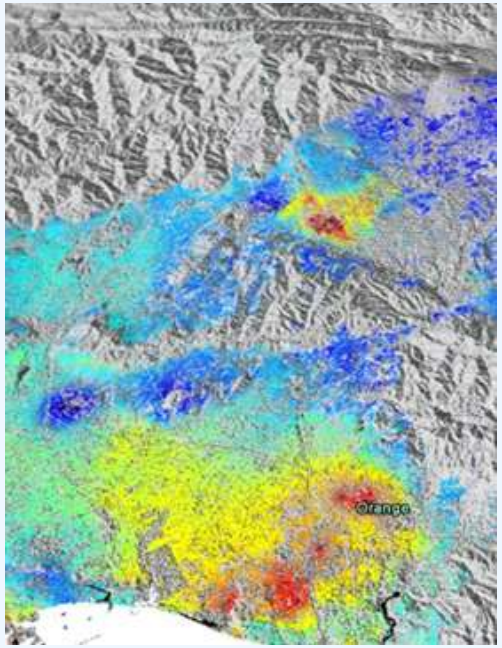
Processing

Key steps

- Interferogram formation
- Unwrapping
- Isolate deformation

Output

Deformation

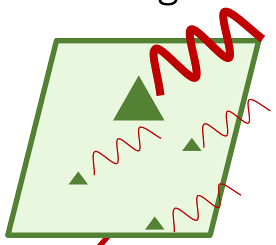


Multiple Approaches to Time Series Analysis

A key distinction is the type of target that is analyzed

Point-like scatterers

One scatter dominates the signal from a SAR resolution cell



Point Target InSAR

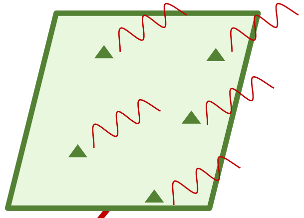
\+ high quality for selected points
\+ retains full resolution

– **only few coherent points**
– does not work well for short stacks

Persistent Scatterer Interferometry (PSI)

Distributed targets

Many scatterers contribute to signal
Extended targets



Distributed Target InSAR

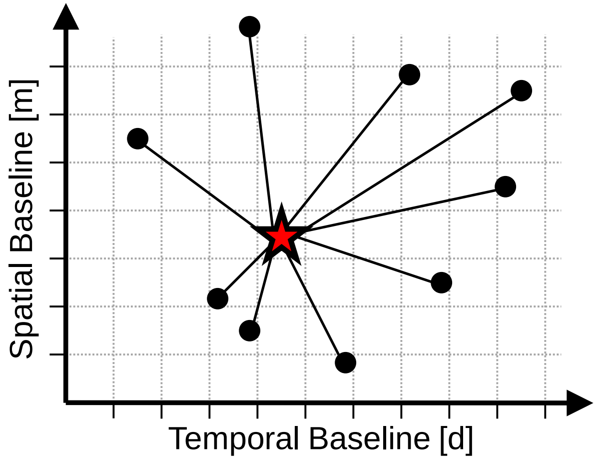
\+ **higher point density**
\+ flexible, easily applicable to large areas

– usually higher noise level
– averaging reduces resolution

Small Baseline Subset (SBAS)

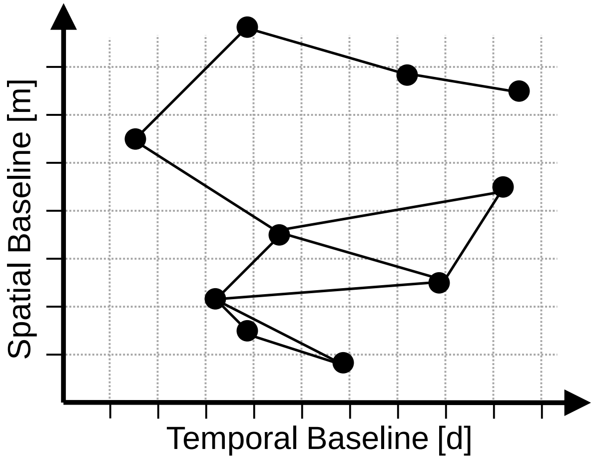
Two Philosophies on How to Form Interferograms from Multiple Images

- **PSI uses single reference image**



  - Ifgrms formed relative to one unique reference image

- **SBAS uses multiple reference images**



  - Igrms formed between all image pairs that fulfill user defined baseline requirements (min – max allowed baselines)

Used in Persistent Scatterer InSAR (PSI) [Lecture 15]

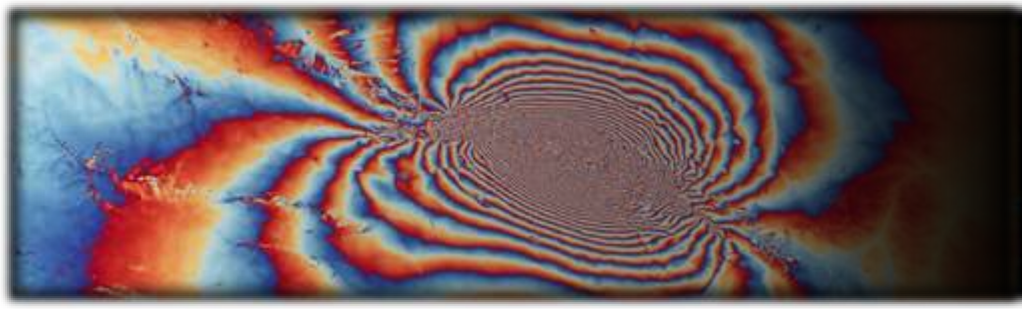
+ solving of equation system “simple”
+ very low noise level of selected points

– **Only few coherent points**
– Long time lag to reach critical number of images in stack

Used in Short Baseline Subset InSAR [Lecture 16]

+ **higher density of coherent point**
+ quicker stack buildup

– equation system underdetermined
– higher phase noise → lower absolute accuracy or filtering required

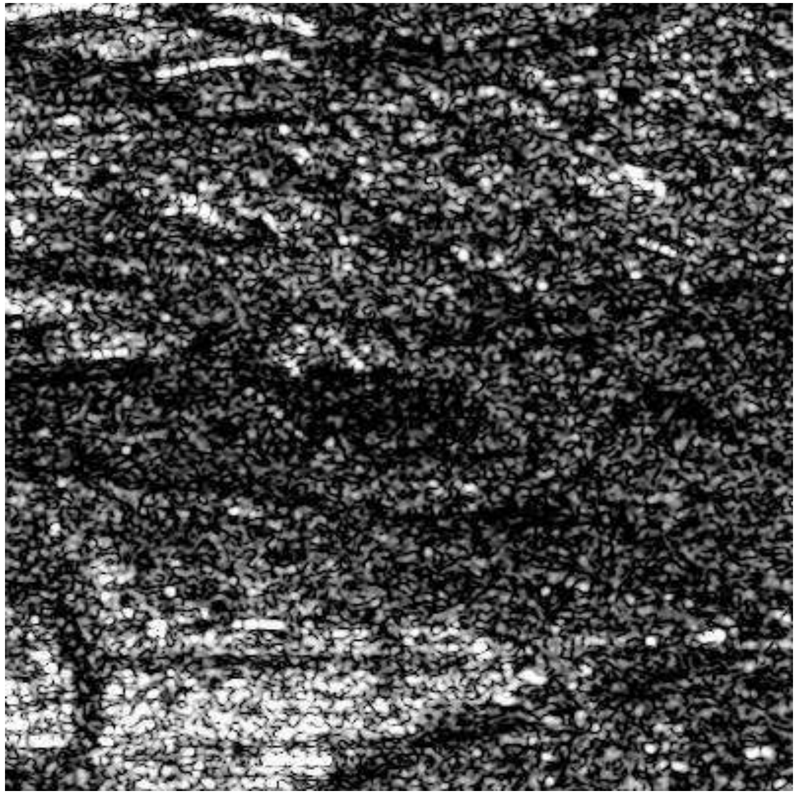


Point Target-Based InSAR Time Series Analysis

Persistent Scatterer Interferometry (PSI)

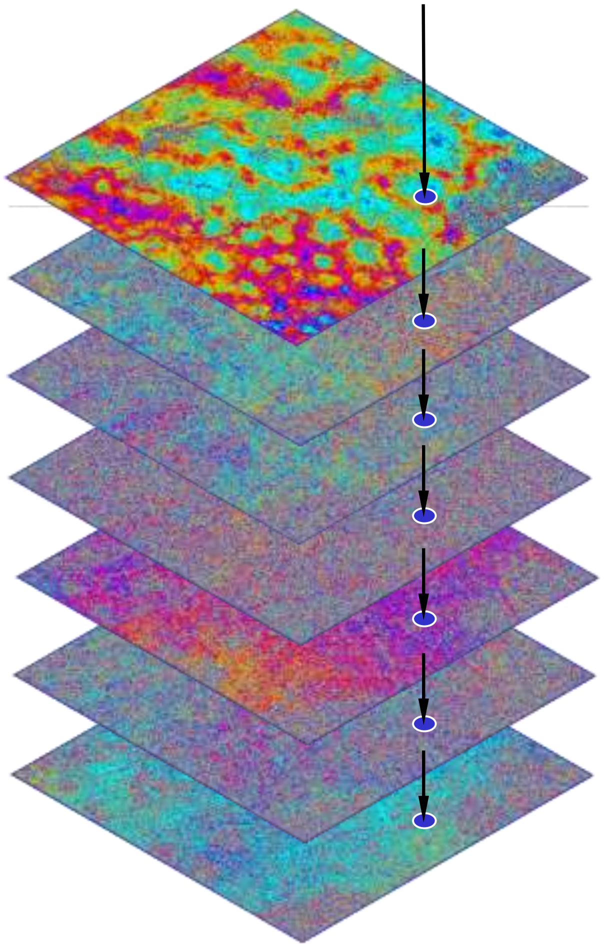
- Developed by A. Ferretti, F. Rocca, and, C. Prati, Politecnica di Milano, Italy
- **Idea:** Every Interferogram ***always*** contains ***a few coherent pixels*** whose phase can be exploited for deformation analysis

incoherent average of 70 ERS SAR images



individual images (9 years)

Persistent Scatterer Interferometry (PSI)



- Many interferograms all referenced to ***single reference image***
- Identification of isolated stable points
- Analyze ***phase difference*** between pixels both in time and space
- Phase difference analysis is a powerful means for noise suppression
- Detectable velocities from cm/day to mm/year

General Scatterer Types in SAR Images

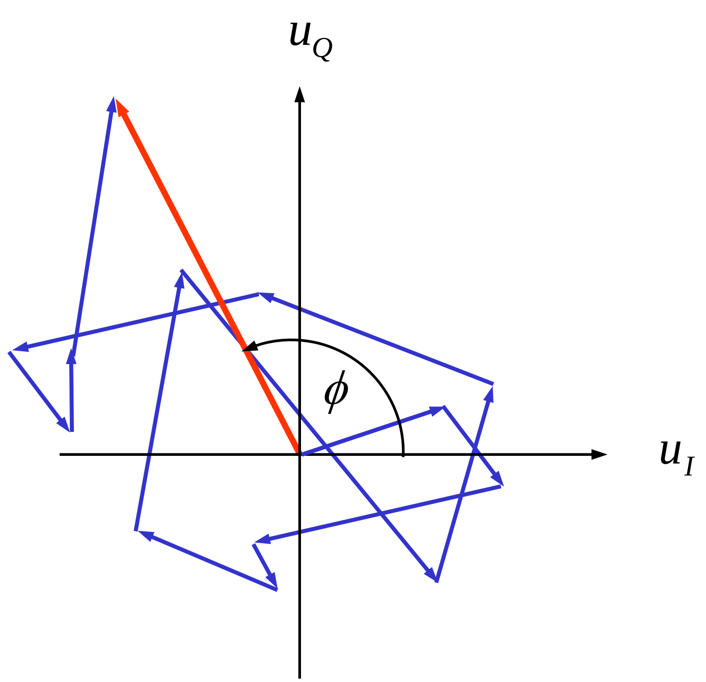
- **Distributed targets:**
  - Many scatterers contributing to the signal from a resolution cell with about equal importance
  - **Examples include**: vegetated surfaces; bare soil; general natural terrain

- **Point-like scatterers:**
  - One scatter dominates the signal from a SAR resolution cell
  - **Examples include**: Corner reflectors; man-made features such as buildings

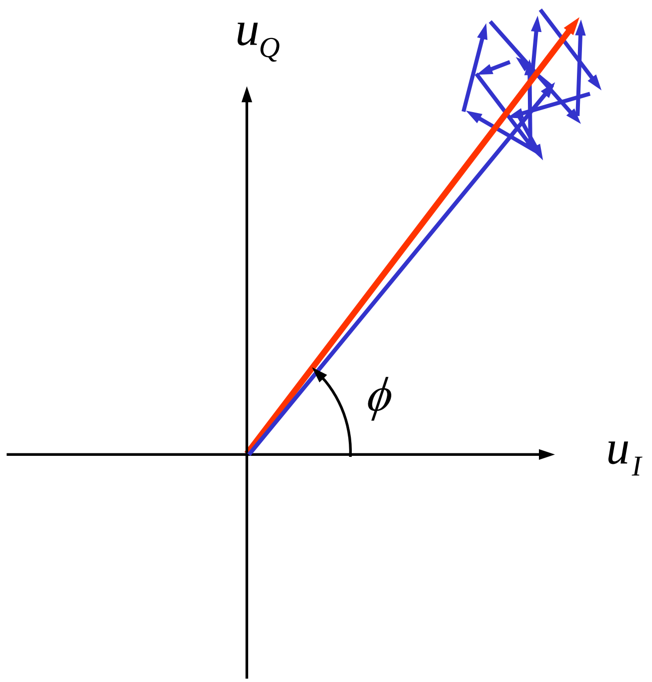
Characteristics of Distributed and Point Targets

Goal: Understand Nature of Persistent Scatterers

Distributed Targets



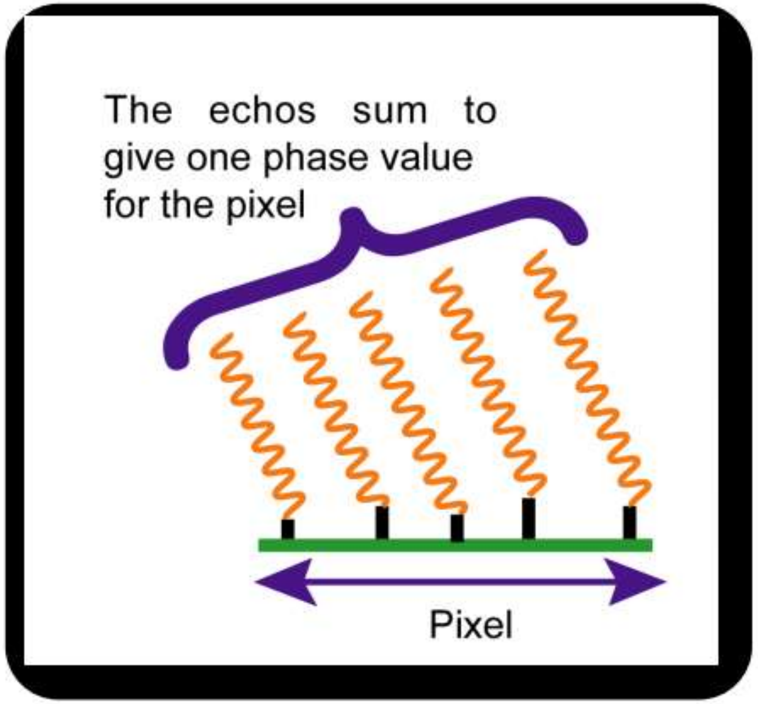
Point Targets



Point Targets are likely to show consistent phase and amplitude over time → **most persistent scatterers are point-like targets (rocks, manmade structures, …)**

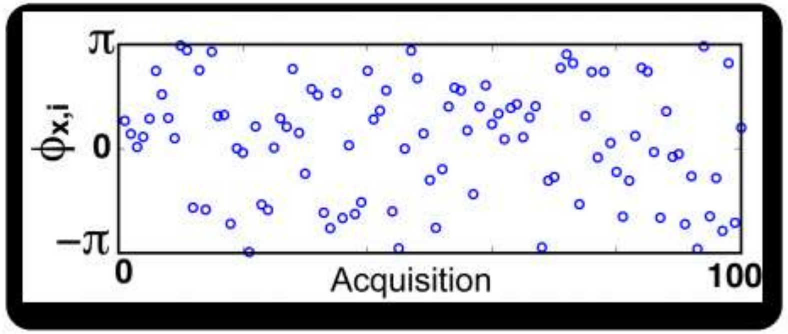
Characteristics of Distributed and Point Targets

Distributed Targets Decorrelate Quickly



Distributed scatterer pixel

If scatterers move with respect to each other, the phase sum changes

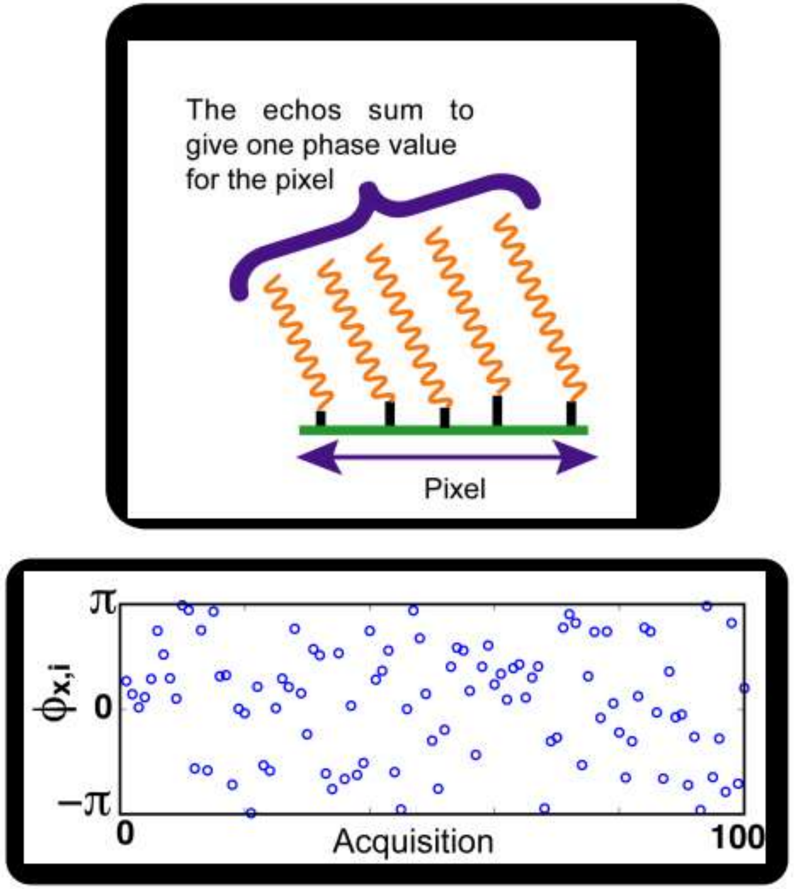


(similar effect if incidence angle changes)

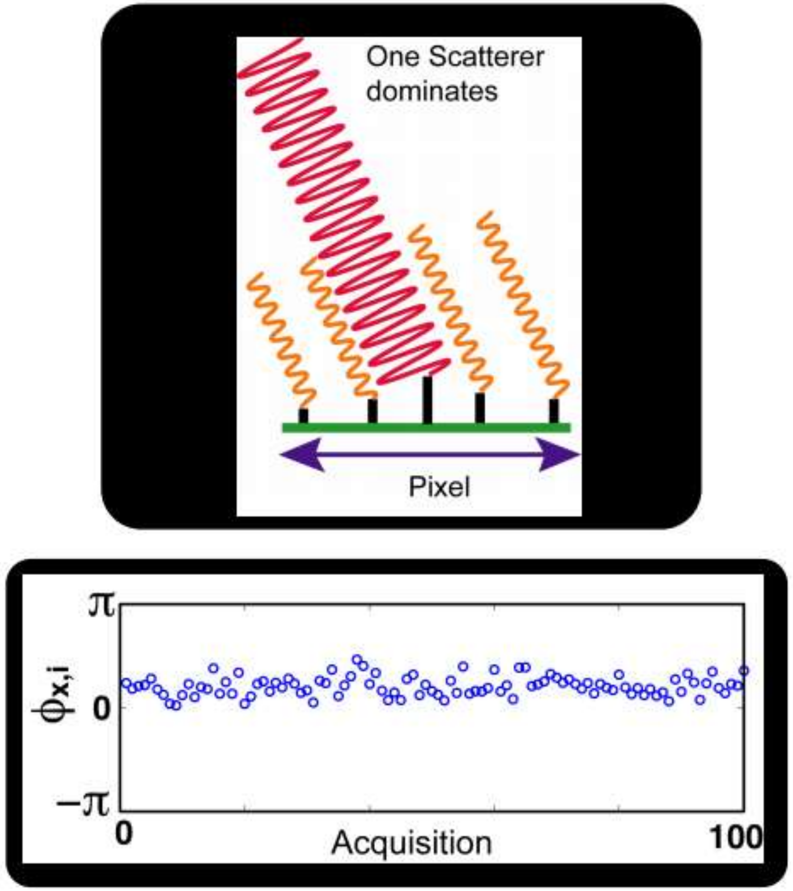
Source: A. Hooper, University of Leeds; UNAVCO InSAR Training

Characteristics of Distributed and Point Targets

Point-Like Targets keep Coherent For Long Times



Distributed scatterer pixel



"Persistent scatterer" (PS) pixel

Source: A. Hooper, University of Leeds; UNAVCO InSAR Training

Persistent Scatterer Interferometry (PSI)

- **Phase of an interferogram:**

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

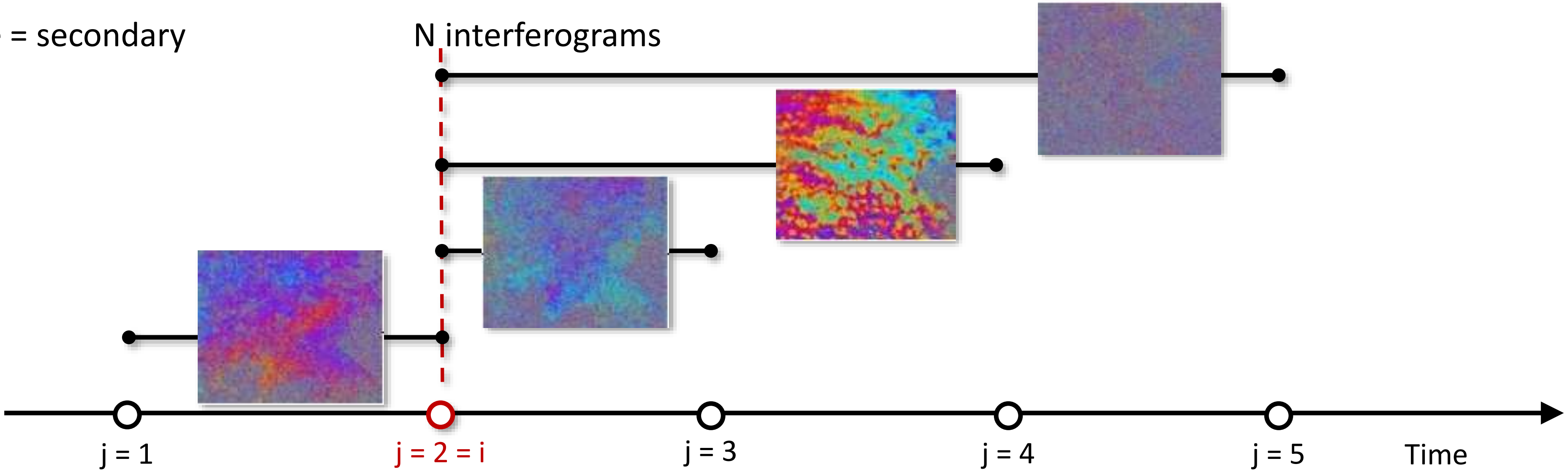
$$\boxed{= W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot sin(\theta)}h + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}}$$

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

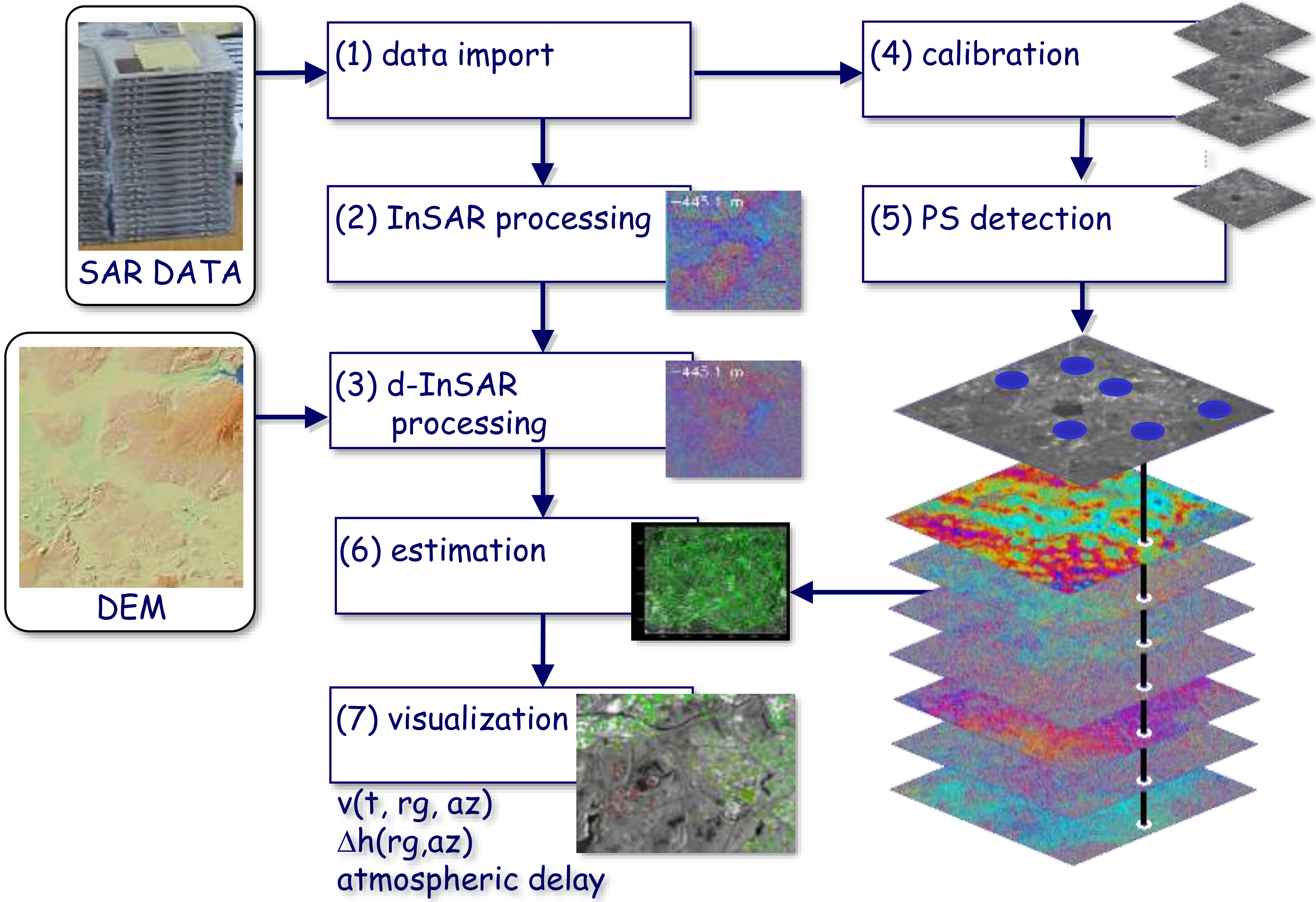
- **Form several interferograms referenced to a unique "reference" image**
  - *ith* image = reference
  - *jth* image = secondary

N+1 scenes

N interferograms



PSI Processing Chain

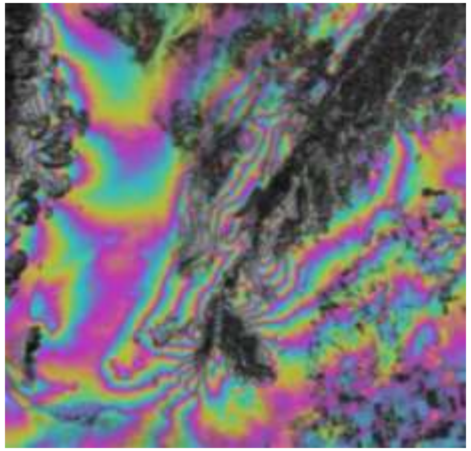


PSI Processing Chain
Steps (1) – (3): InSAR and D-InSAR Processing

1. **Interferogram generation:**

$$\phi_x^k = W\left\{\frac{4\pi}{\lambda}\frac{B_\perp^k}{R\cdot sin(\theta)}h_x + \frac{4\pi}{\lambda}v_x\Delta t^k + \phi_{x,atmo}^k + \phi_{x,orbit}^k + \phi_{x,noise}^k\right\}$$

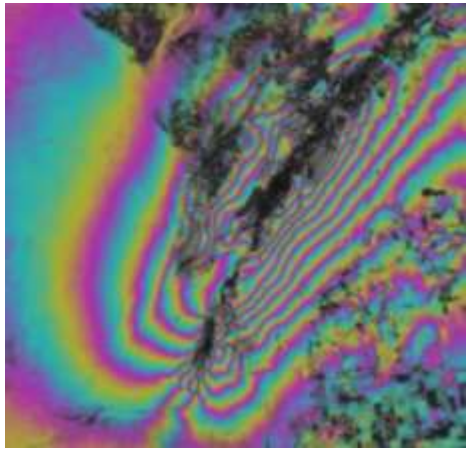
$$h = h_{DEM} + h_{ERR}$$



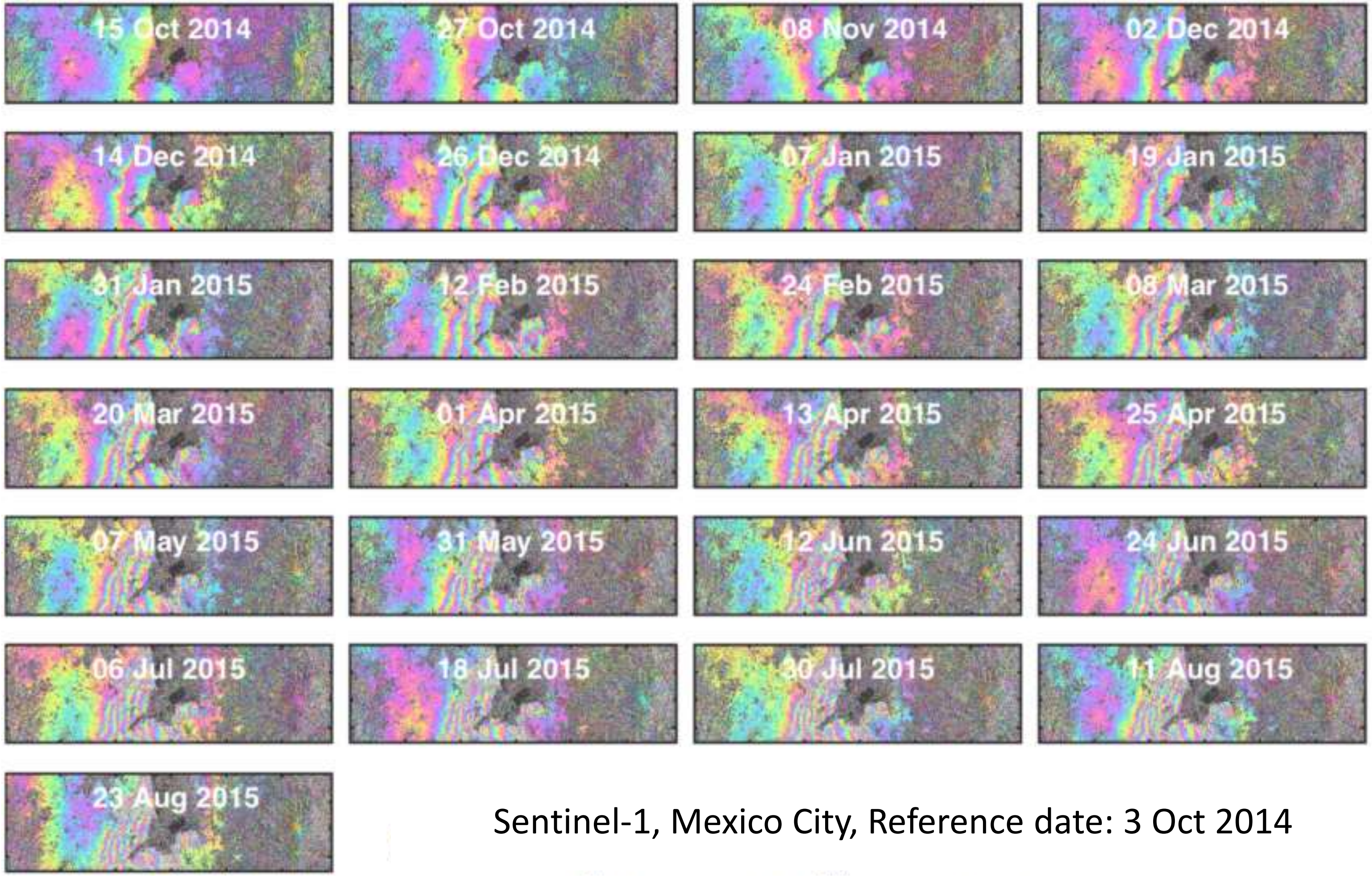
2. **Remove DEM via D-InSAR processing:**

$$\Delta\phi_x^k = W\left\{\frac{4\pi}{\lambda}\frac{B_\perp^k}{R\cdot sin(\theta)}h_{x,err} + \frac{4\pi}{\lambda}v_x\Delta t^k + \phi_{x,atmo}^k + \phi_{x,orbit}^k + \phi_{x,noise}^k\right\}$$

- $h_{x,err}$ remains due to
  - Imperfect interferometric baseline
  - Imperfect DEM



Example of Single-Reference d-InSAR Stack



Sentinel-1, Mexico City, Reference date: 3 Oct 2014

Source: A. Hooper, University of Leeds; UNAVCO InSAR Training

PSI Processing Chain

Steps (4) & (5): Selection of Persistent Scatterer (PS) Candidates

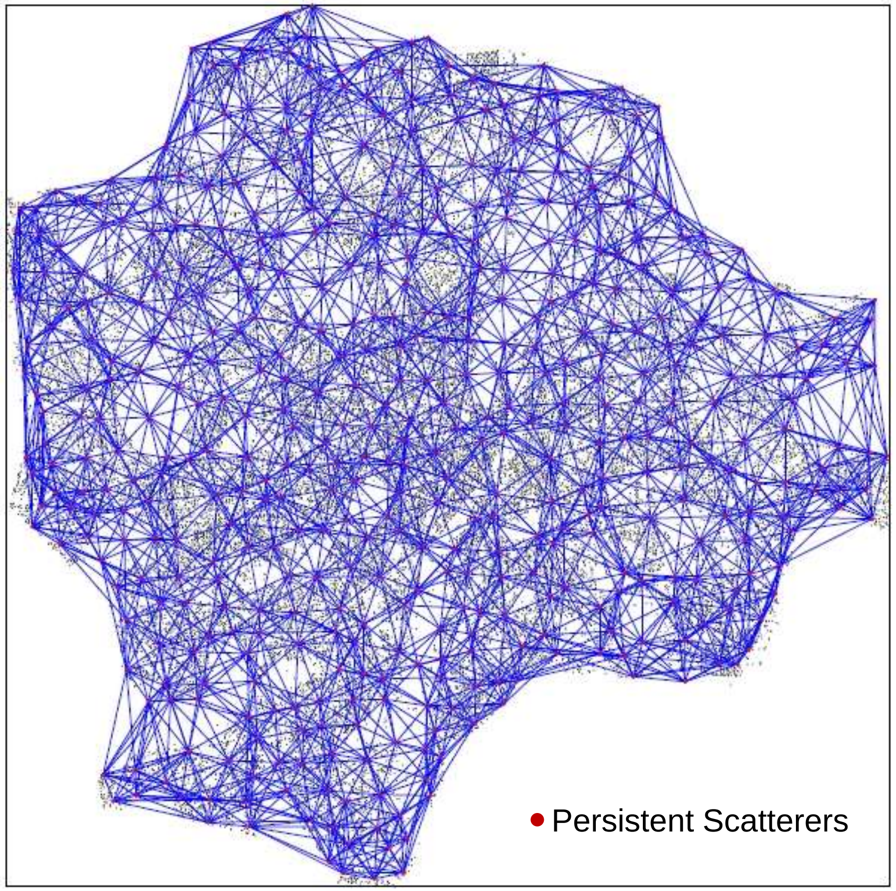
- **Various ways for detecting PS:**
  - **Amplitude dispersion index:** $D_A = \frac{\sigma_A}{\mu_A} \rightarrow$ points with stable amplitude A over time
  - **Points with high signal-to-clutter ratio**
  - …

- **Features of Persistent Scatterers**:
  - No temporal decorrelation
  - Very low phase noise

- **Goal: Dense spatial distribution of high quality PS**

  ⇨ Favorable description of spatial deformation signal

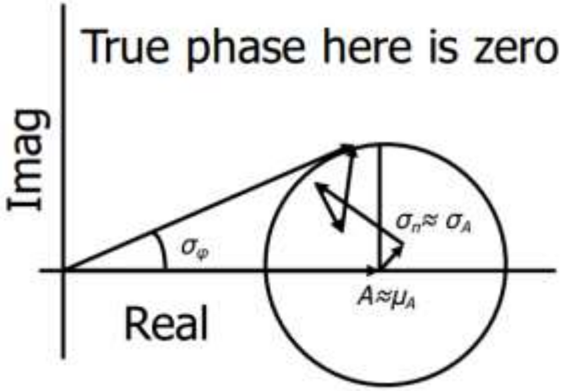
  ⇨ Easier phase unwrapping



PSI Processing Chain

A Few Words on the Amplitude Dispersion Index

- Amplitude Dispersion Index initially published in (Ferretti et al., 2001)

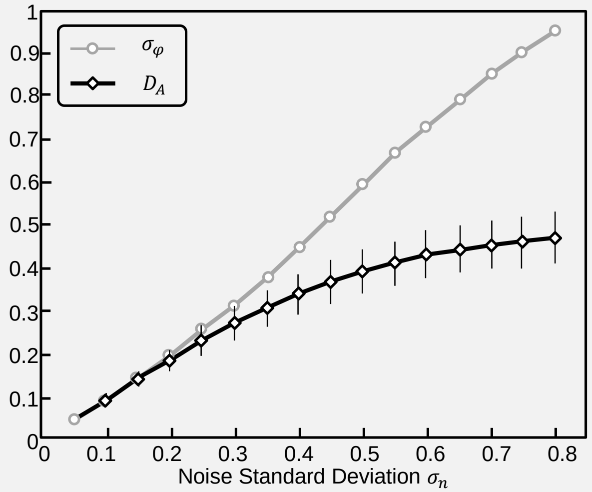


$$\sigma_\varphi \approx \frac{\sigma_n}{A} \approx \frac{\sigma_A}{\mu_A} = D_A$$

Phase noise

- **Approach**: Calculate D_A per pixel and use points with $D_A <$ threshold

- Data analysis has shown that D_A is a good approximation for σ_φ for low values of D_A



PSI Processing Chain

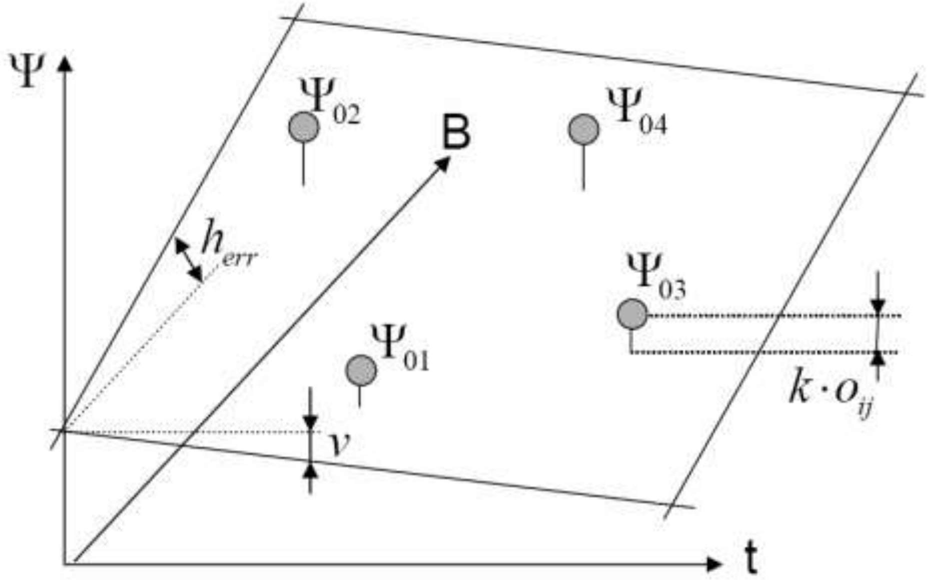
Step (6a): Spatio-Temporal Modeling

- **Linear deformation model:** phase $\phi^k_{x,defo}$ of pixel x of ifgrm k

$$\phi^k_{x,defo} = \frac{4\pi}{\lambda} v_x \Delta t^k$$

- **Linear dependence of DEM error on interferometric baseline →**

$$\phi^k_{x,topo} = \frac{4\pi}{\lambda} \frac{B^k_{\perp}}{R \cdot sin(\theta)} h_{x,err}$$



- **Estimation of DEM error and deformation using spatio-temporal model**:
  - **Fitting of a 2-d plane into the phase observations in the spatio-temporal baseline plot (see above)**

PSI Processing Chain

Step (6b): Persistent Scatterer Estimation I

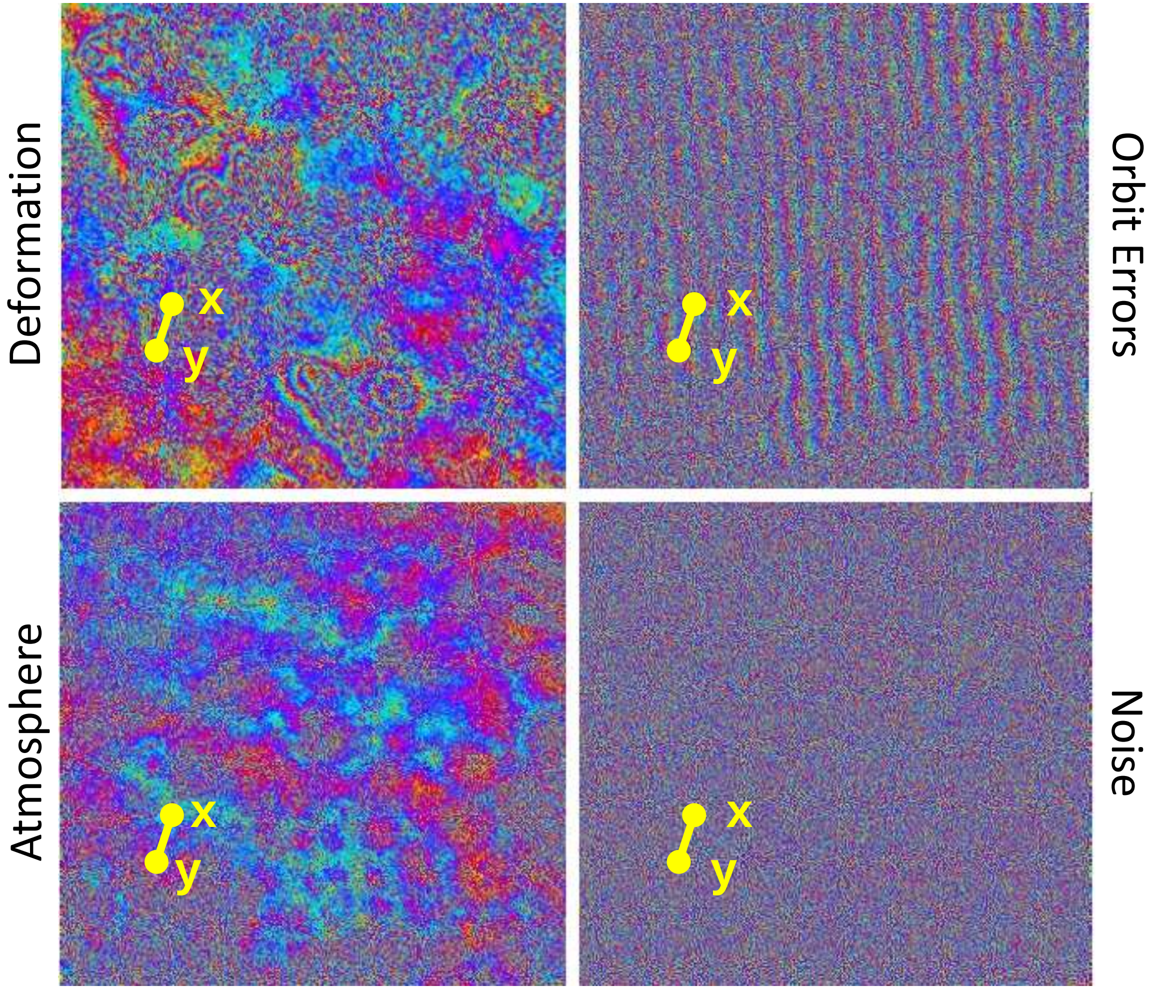
- **Goal:**
  Estimation of
  - DEM error
  - Surface deformation

  at the position of the Persistent Scatterers

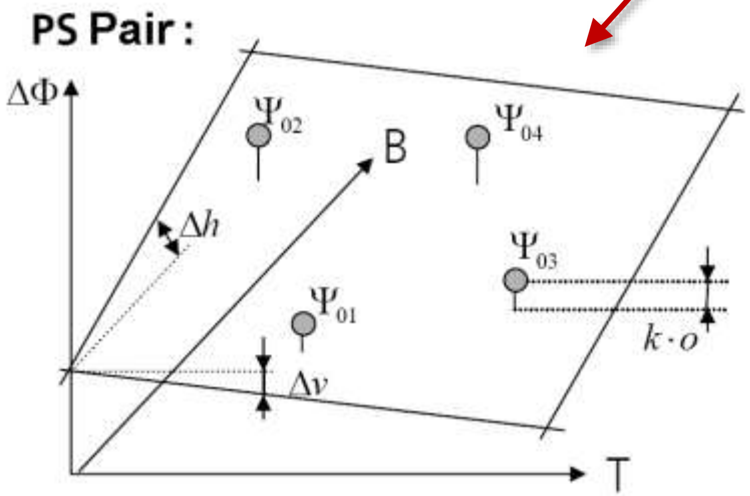
- **Problem:**
  - Noise contributions at the PS positions may mask desired signal
  - Some phase components are random in time and prevent successful estimation

Step (6b): Persistent Scatterer Estimation II

Calculation of Phase Differences between Nearby Points



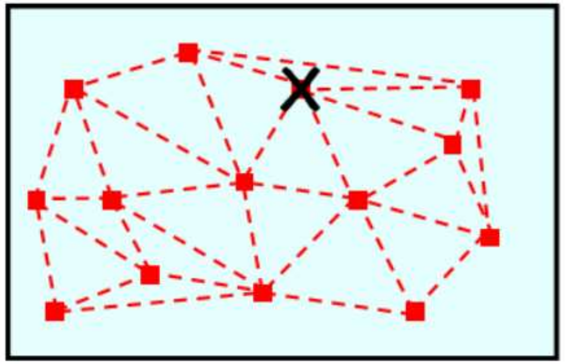
$$\Delta\phi^k_{x-y} = \boxed{\frac{4\pi}{\lambda}\frac{B^k_\perp}{R\cdot\sin(\theta)}\Delta h_{x-y,err} + \frac{4\pi}{\lambda}\Delta v_{x-y}\Delta t^k +} \left.\begin{array}{l}\phi^k_{x-y,atmo} + \\ \phi^k_{x-y,orbit} + \\ \phi^k_{x-y,noise}\end{array}\right\}\text{small}$$



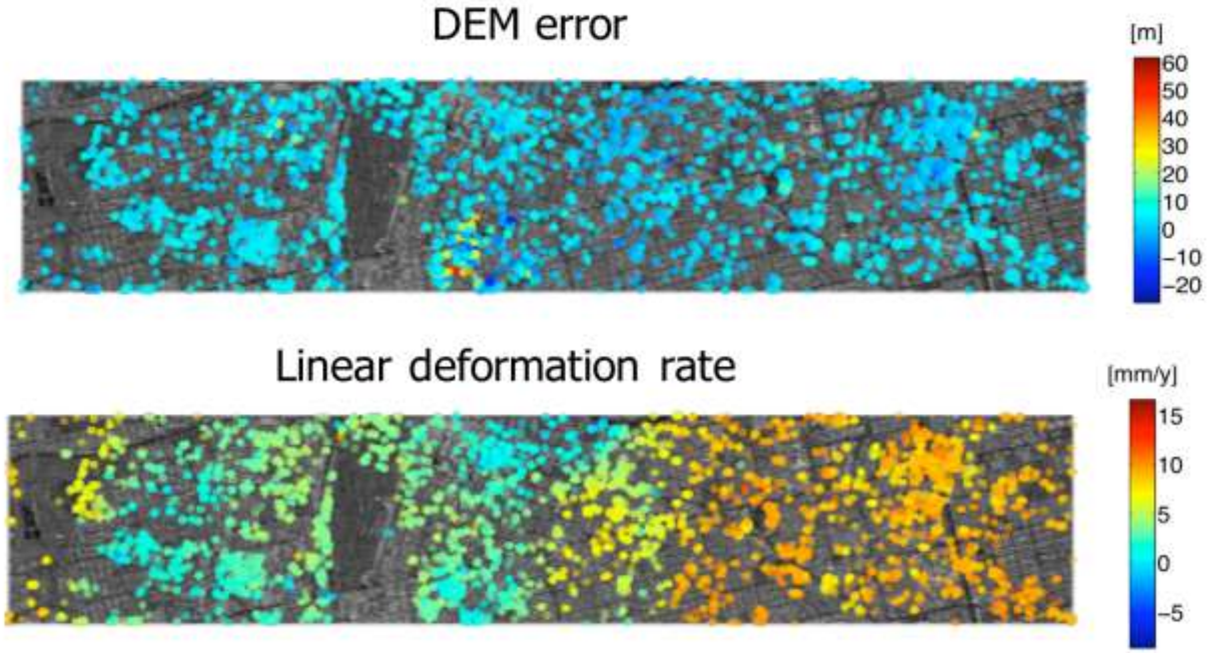
PSI Processing Chain

Step (7c): Integration Step

- We now have estimated $\Delta h_{x-y,err}$ and Δv_{x-y} corresponding to the height-error and deformation velocity **differences between pairs of PS points**
- To obtain parameters at the PS locations ($h_{x,err}$ and v_x), we **perform a least-squares integration** with respect to a reference point (**X**)



- **Example:**
  - Integration Result for InSAR Stack over Las Vegas



Source: A. Hooper, University of Leeds; UNAVCO InSAR Training

Analysis of Residuals to Separate Atmospheric Delay from Noise

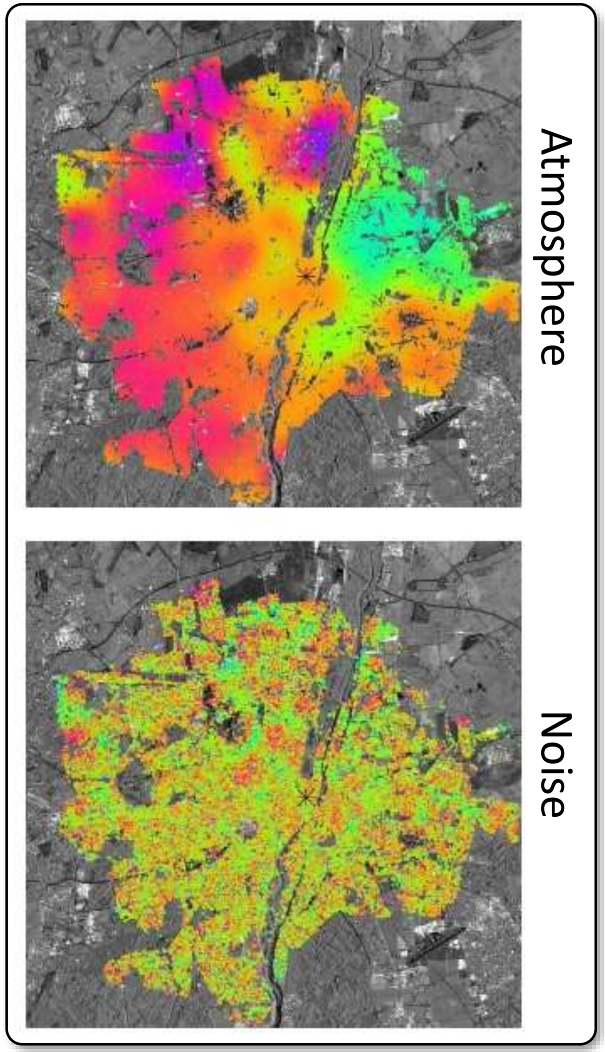
- Residuals:

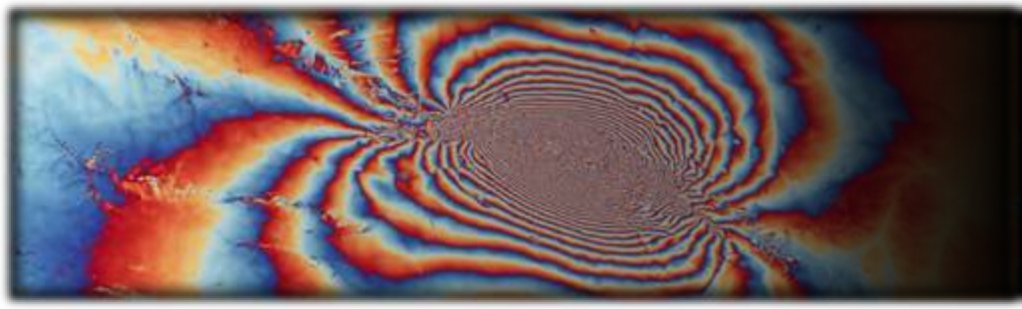
$$\phi^k_{x,res} = \phi^k_{x,atmo} + \phi^k_{x,noise} + \cancel{\phi^k_{x,orbit}}$$

- **Properties:**
  - Atmosphere correlated in space and uncorrelated in time
  - Noise uncorrelated in both space and time

→ Separation:

– Spatial filtering and subsequent interpolation



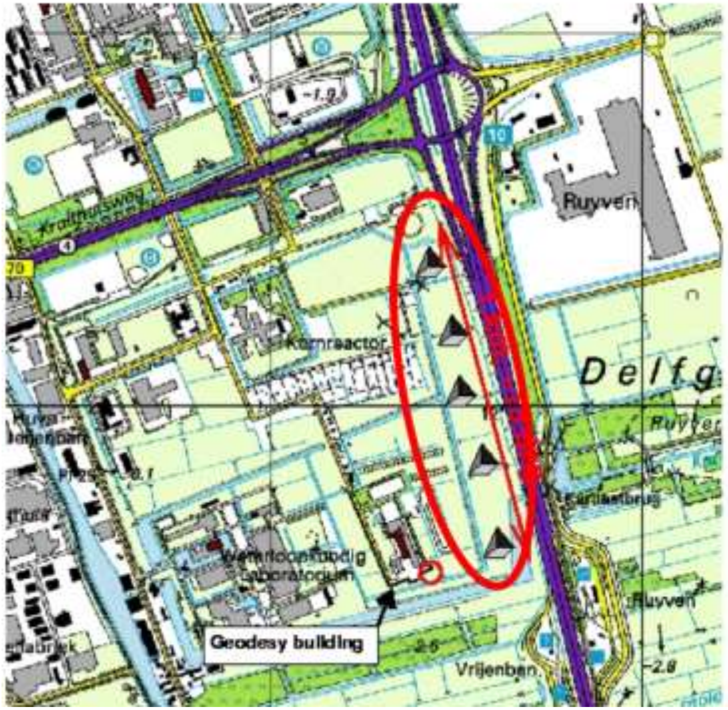


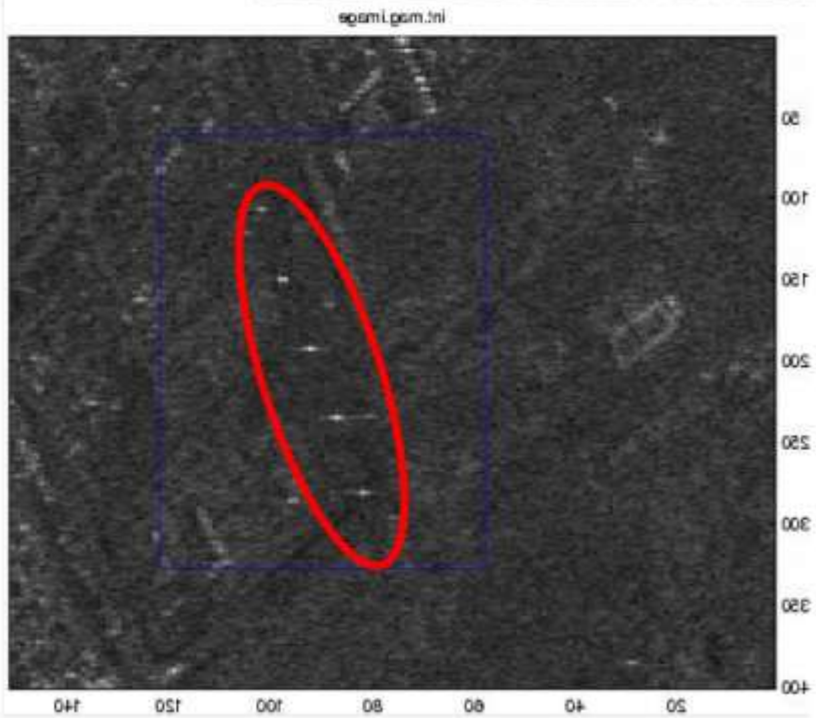
PS-InSAR (PSI): Accuracy Assessment and Examples

Assessment of Accuracy of PS-InSAR

Corner Reflector Experiment Conducted by Delft University, NL

- **Experiment Setup:**
  - Row of oriented corner reflectors
  - Surveyed using levelling for validation of PSI results

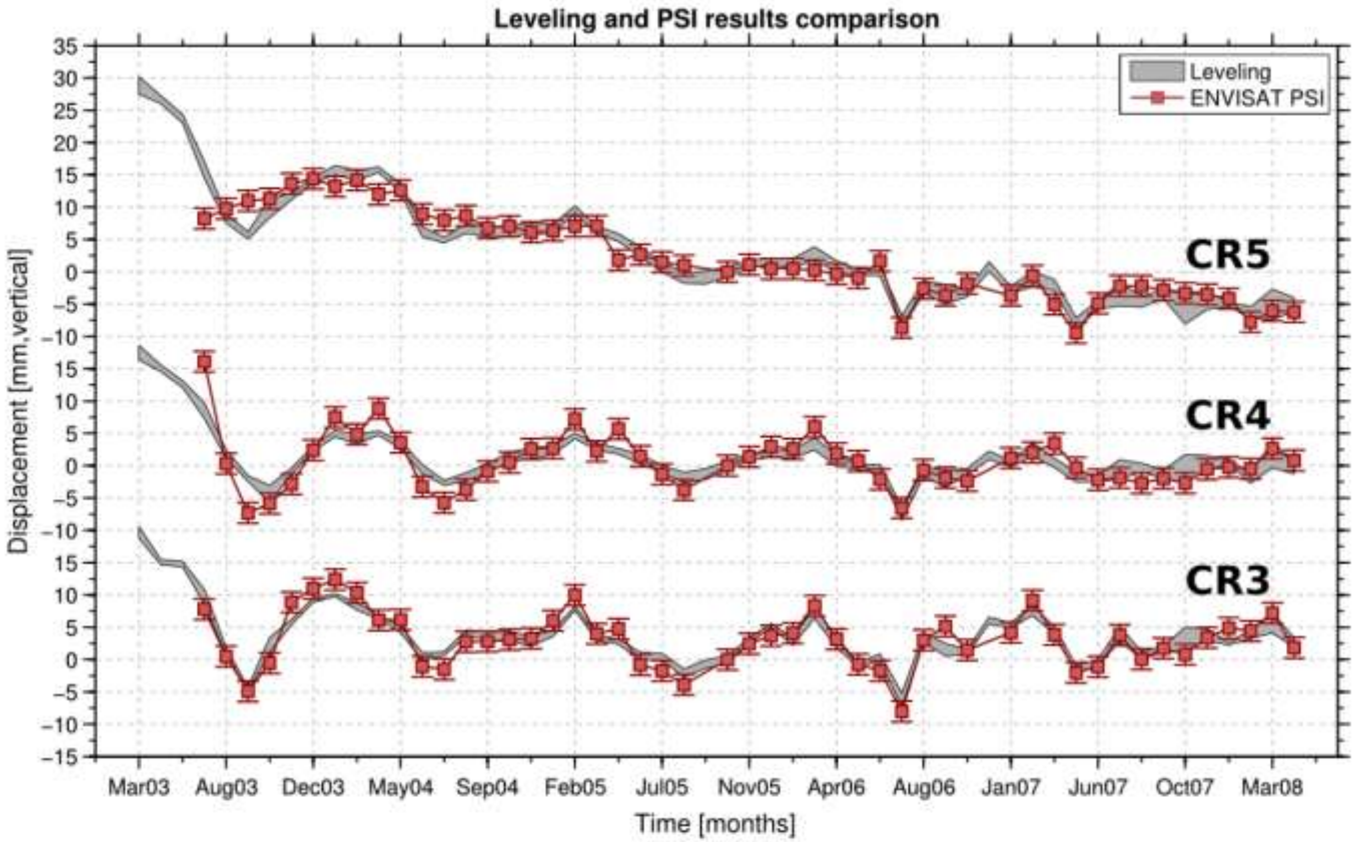




Assessment of Accuracy of PS-InSAR

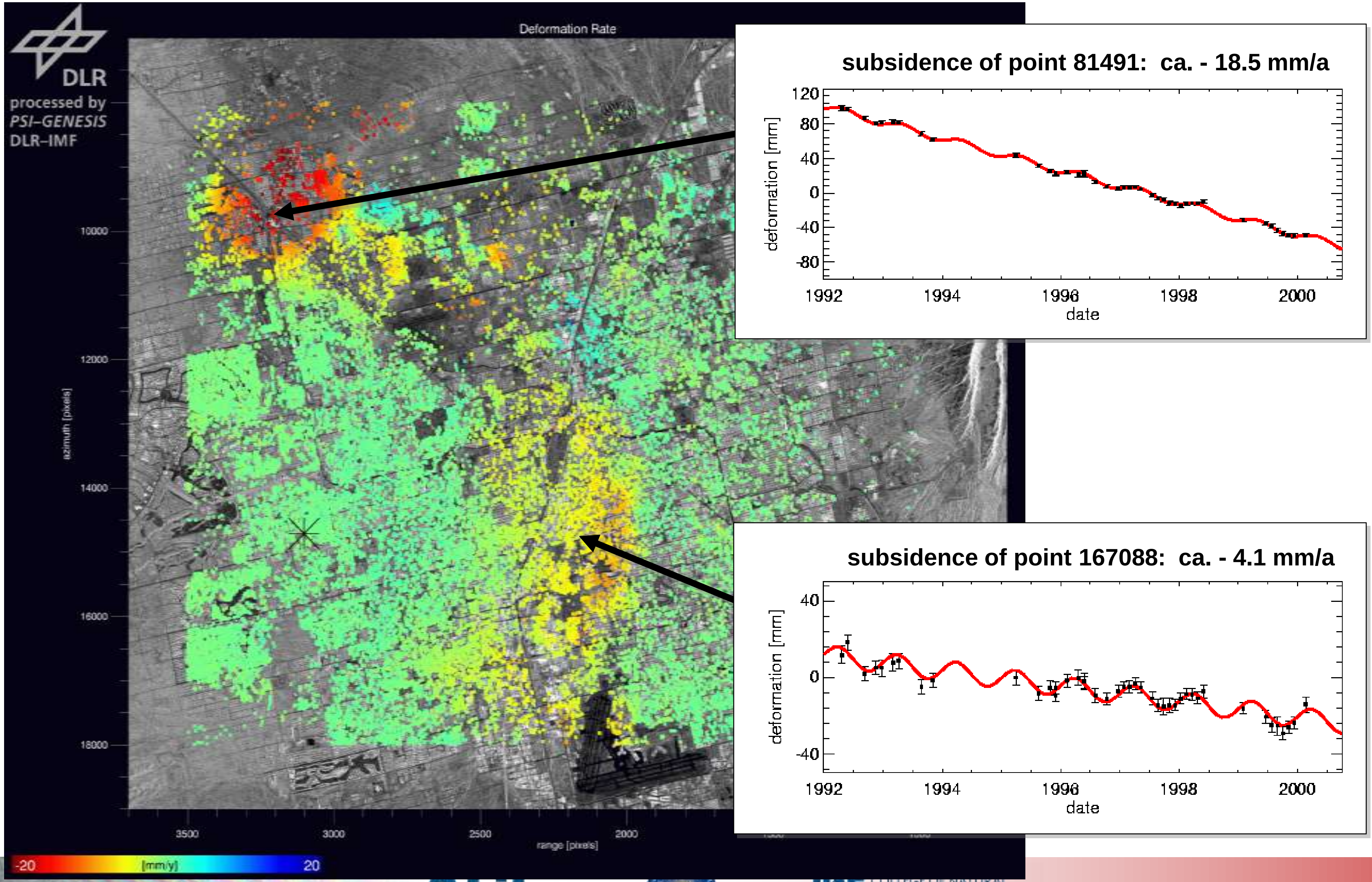
Corner Reflector Experiment Conducted by Delft University, NL

- **Comparison of leveling and PSI deformation measurements**
  - Excellent match of measurements

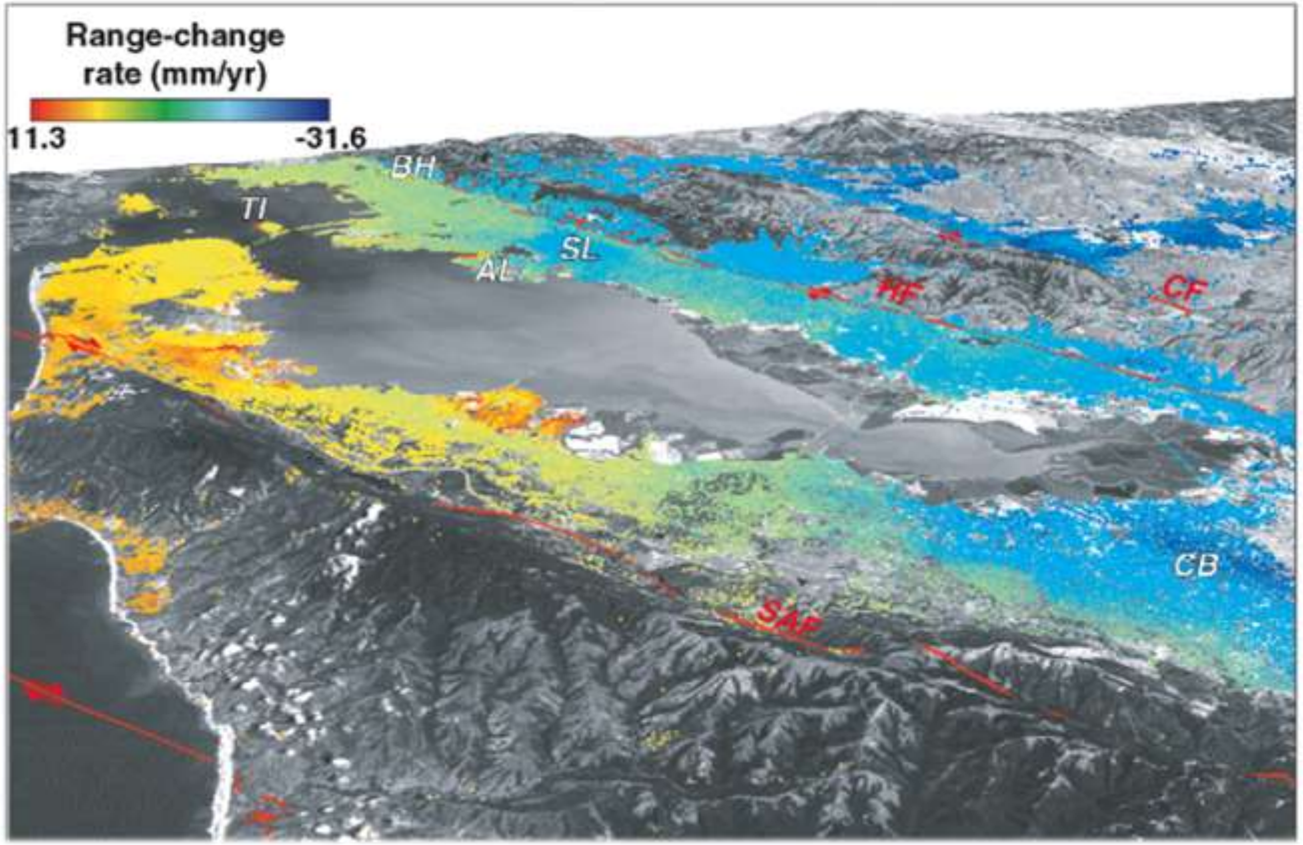


Marinkovic et al, CEOS SAR workshop, 2004

PSI Example: Subsidence in Las Vegas



PSI Example: Bay Area, California

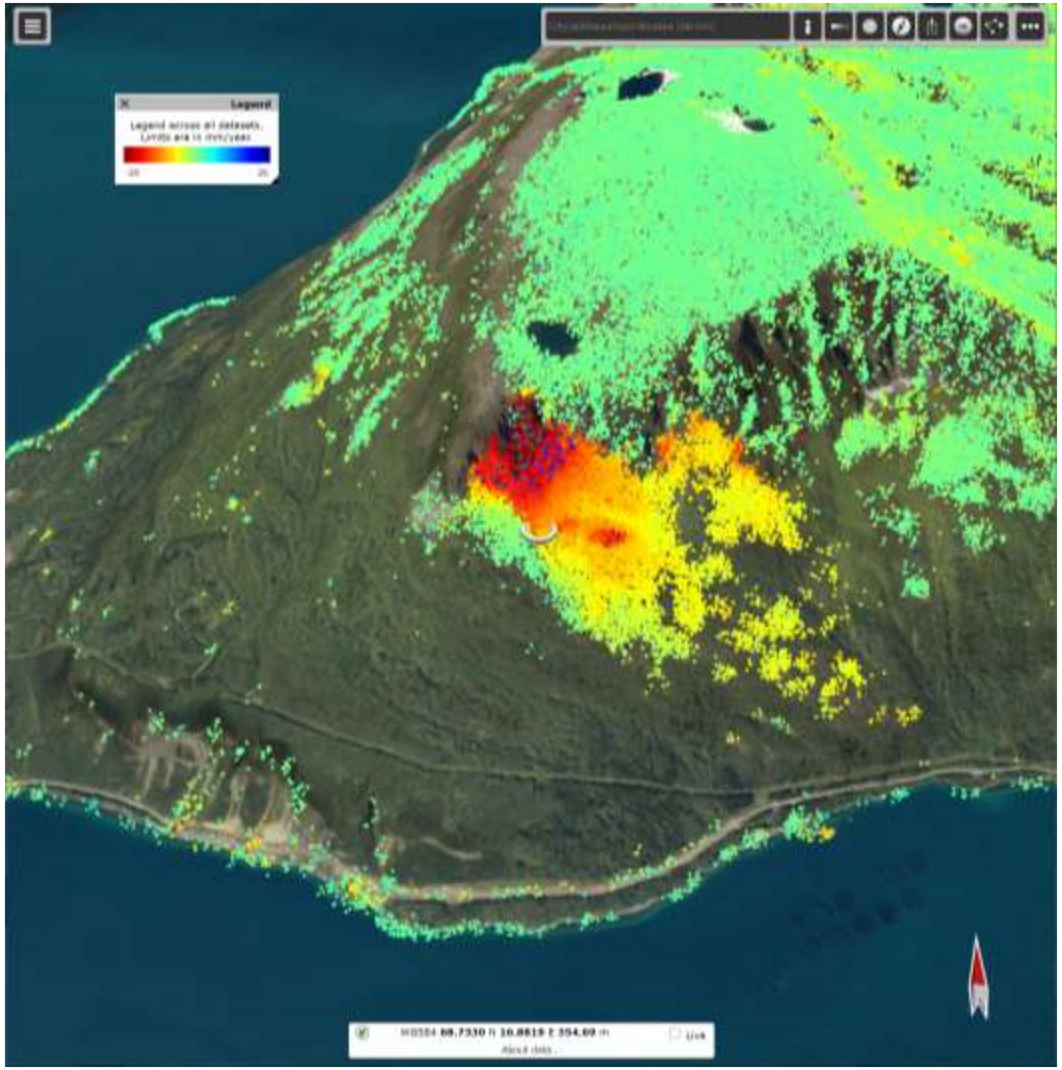


San Francisco Bay Deformation ([Ferretti et al., 2004](#))

- These results indicate that PSI works well in **urban areas**, but not so well in areas without man-made structures. **Why?**

Think – Pair – Share:

Let's look at some PS-InSAR Data: Explore [the following deformation site]on the InSAR Norway PSI Portal



Activity 1: Explore and compare ascending and descending deformation data:

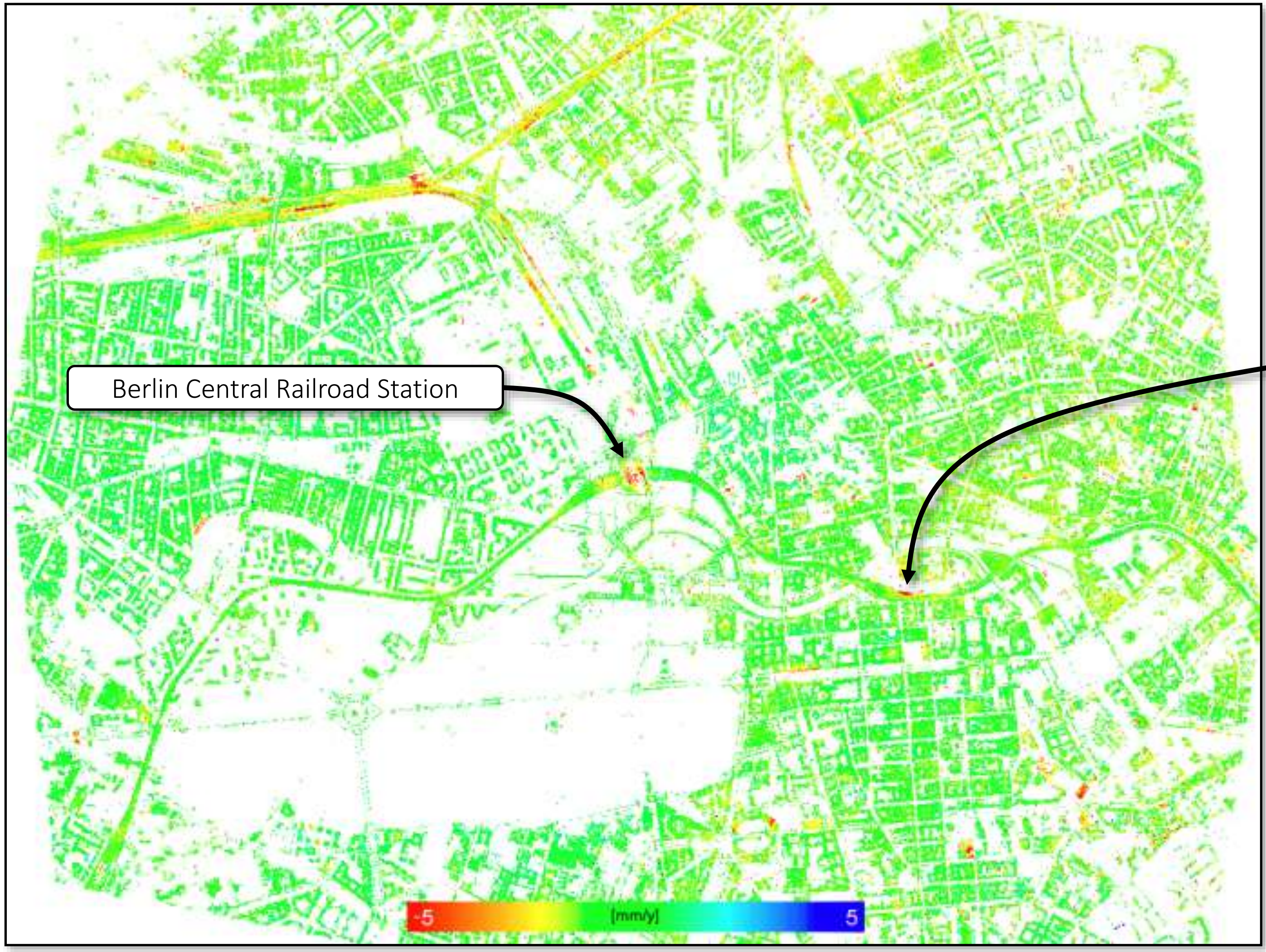
- How do the deformation features for ascending and descending compare.
- What do ascending and descending data tell you about the direction of surface motion?

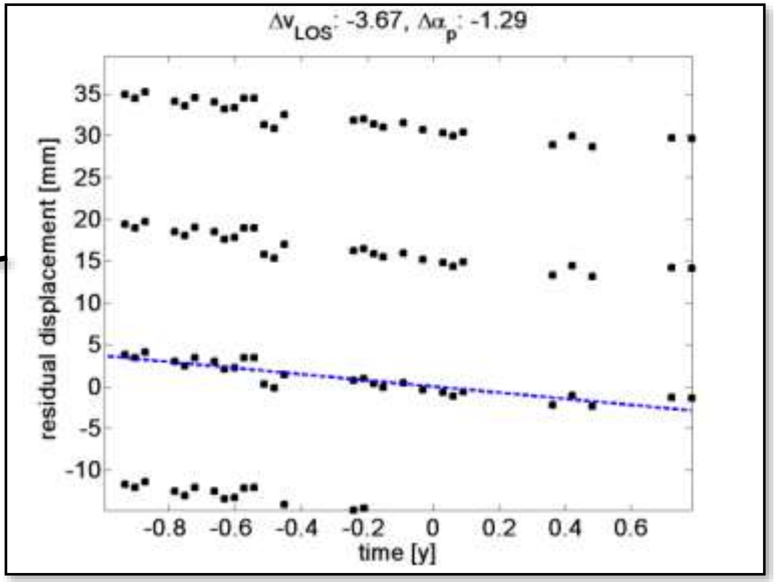
Activity 2: Analyze data gaps / point density variations:

- The PSI point density varies throughout this site.
- Look at ascending and descending data. You may notice distinct differences in the point coverage between these geometries.
- Formulate two reasons why point densities may vary between these geometries.

High-Resolution PS-InSAR Study in Berlin, Germany

Linear deformation rate (Gernhardt, 2011)





High-Resolution PS-InSAR Study in Berlin, Germany

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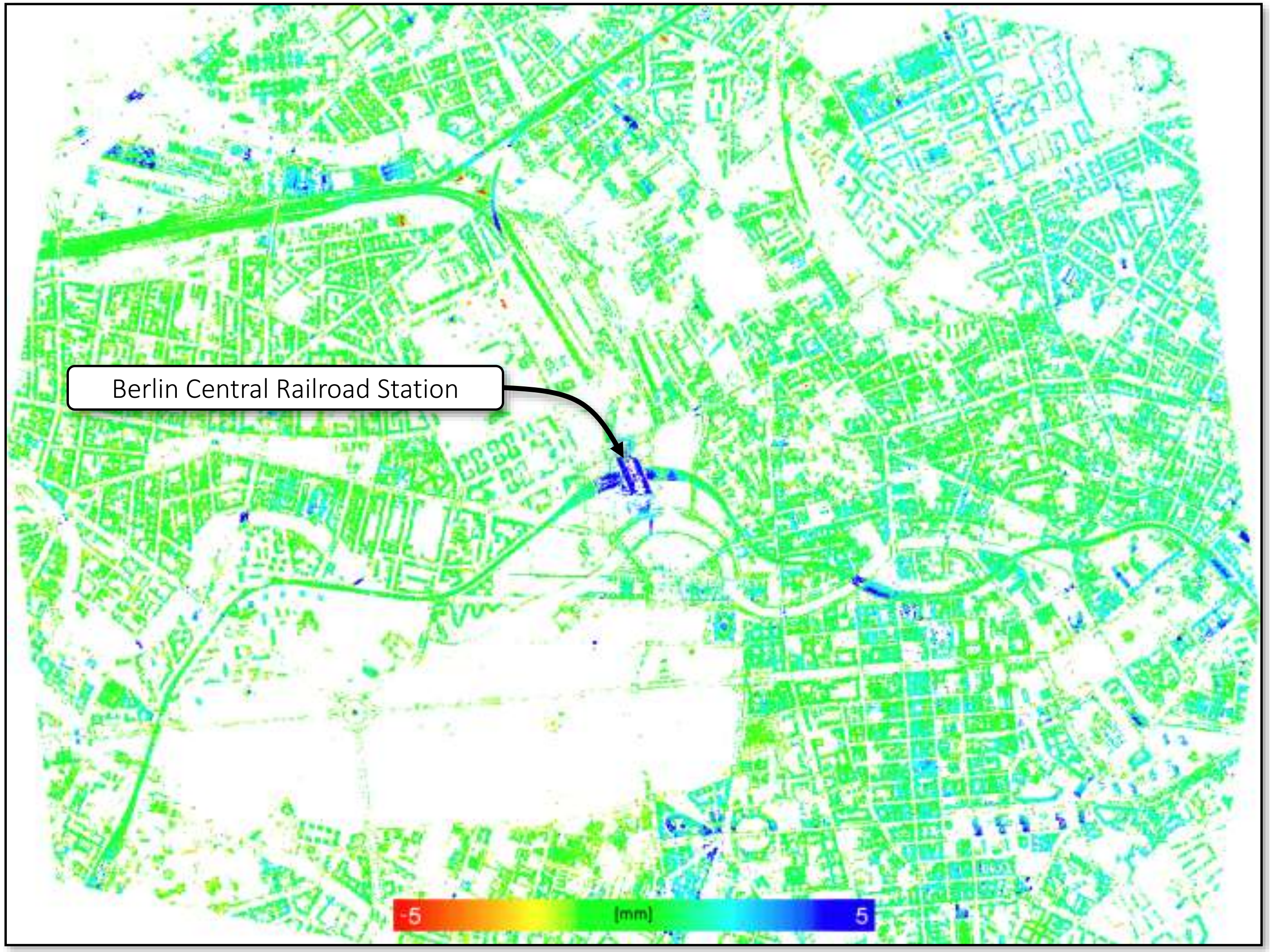


Subtle phenomenon

Seasonal deformation (vertical)

High-Resolution PS-InSAR Study in Berlin, Germany

Point density depends on sensor properties and land cover

Case Study Berlin: ERS-2 Data (resolution ~ 20m)

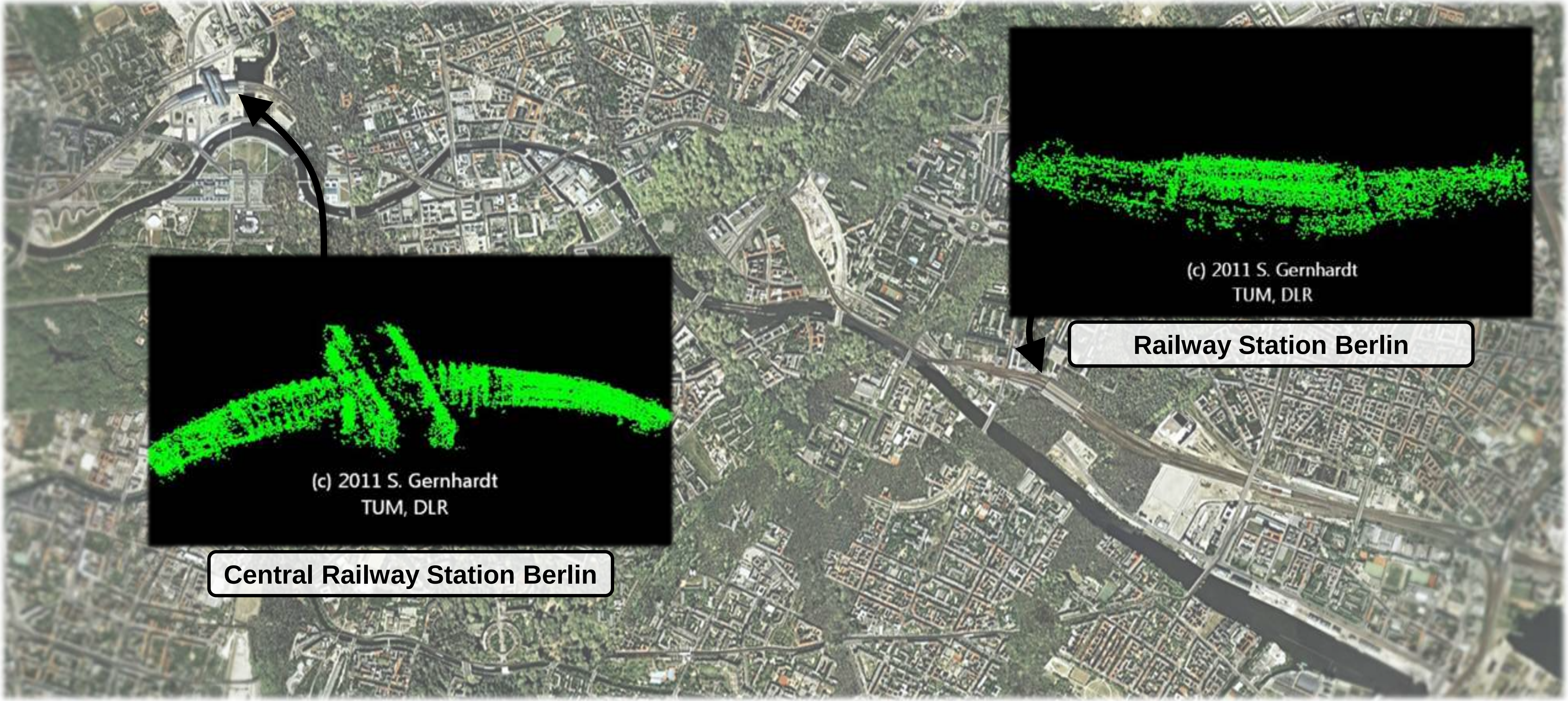
Case Study Berlin: TerraSAR-X Spotlight data (resolution ~ 1m)

Vegetated areas

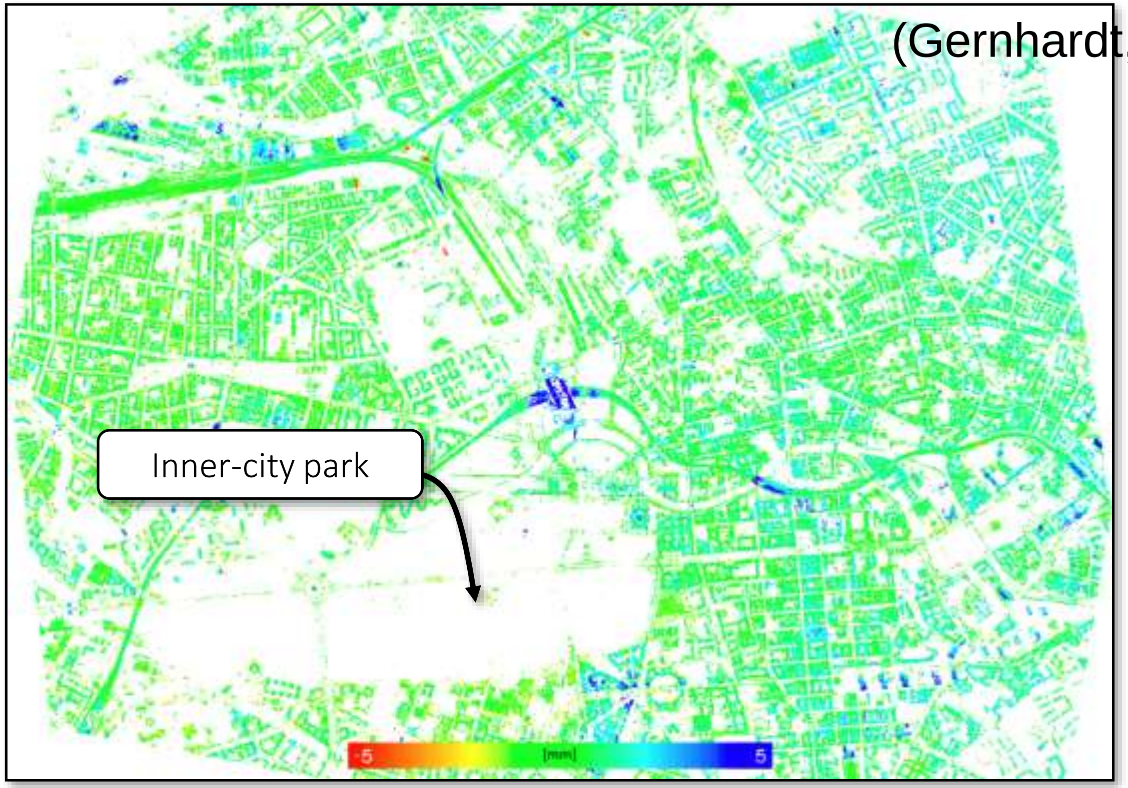
Gerhardt, 2011

Sub-Milimeter Surface Analysis

Building Deformation in Berlin, Germany



Summary of PSI



Key features

1. **PSI exploits and requires stable scatterers**
   - Such as buildings, rock outcrops
   - Hence works well in e.g. urban environments
   - High precision at full resolution

2. **Drawbacks**
   - Point density dependent on environment
   - Point density dependent on sensor
   - Computational cost

Most large-scale geohazard applications focus on distributed targets, using medium-resolution SAR imagery.

For More on PS-InSAR Please Read …

- Look at the papers listed in the "**InSAR Time Series Analysis**" Section of the Relevant Literature element of the class website (radar.community.uaf.edu/relevant-literature/)

- **Specifically, read the following paper:**
  - Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1), 8-20.

What’s Next?

- **This is what awaits next:**
  - **Thursday: Lab on Interpreting differential Interferograms**

- **Next week:**
  - **Tuesday: InSAR Time Series Analysis: Short Baseline Subset InSAR**
  - **Thursday: Lab on InSAR Time Series Analysis Using MintPy**