GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

Lecturer:

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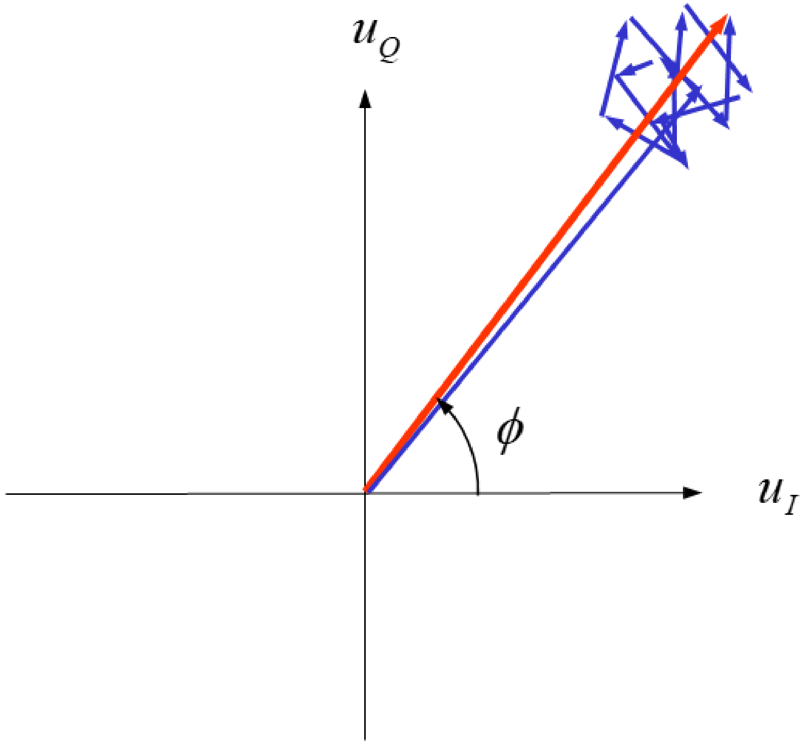
Lecture 9: The SBAS (Short BAseline Subset) Approach to InSAR Time Series Analysis

Before We Start …

Think – Pair – Share

Point Target-based InSAR time series techniques (e.g., PS-InSAR):



Activity 1: Point-Like Scatterers and Coherence:

[Ferretti et al., 2001] found that pixels whose radar signal is dominated by one very bright and stable point-like scatterers tend to be coherent over very long times. Hence, in his PS-InSAR technique, Ferretti first identifies point-like targets using their amplitude signature and then analyzes their phase for high-accuracy deformation monitoring.

- **Discuss why point-like scatterers with high and stable amplitude usually also have stable phase. Complete the sketch to the right in your discussion.**

Activity 2: Limitations of PS-InSAR:

While the point target-based PS-InSAR technique can provide highly accurate surface deformation information in urbanized environments, its performance is often limited when applied to natural environments (e.g., volcano deformation or permafrost subsidence)

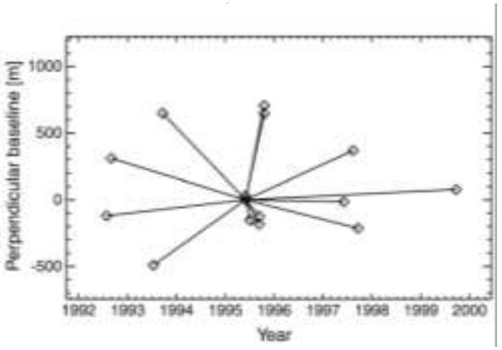
- **Identify least two reasons why PS-InSAR type techniques often underperform in natural setting?**

A One-Slide Recap of the Point Target-Based PS-InSAR Technique

The PS-InSAR Workflow

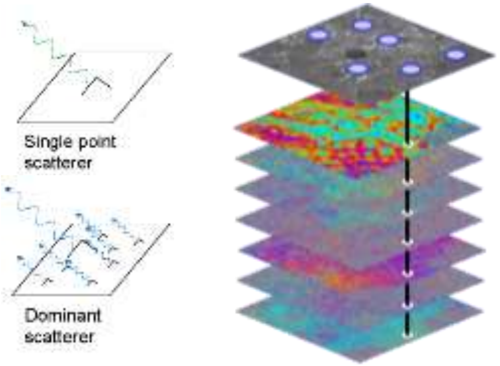
And its Limitations for Natural Terrain

(1) Form single-reference



Potentially very long baselines → significant decorrelation

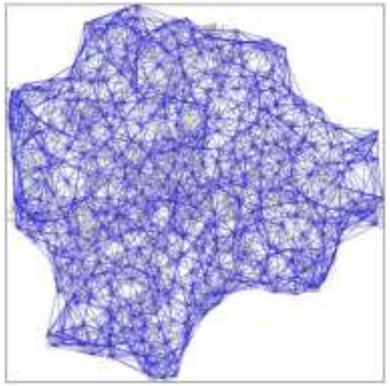
(2) Identify Persistent Scatterers



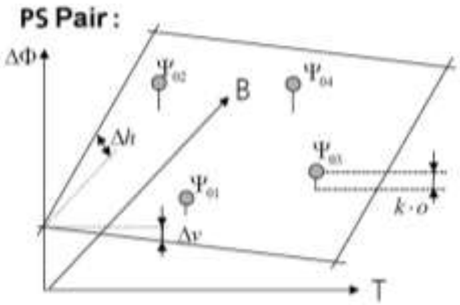
Potentially rare in natural terrain

(3) Network Scatterers to remove atmospheric noise

May not work if scatterers are too sparse

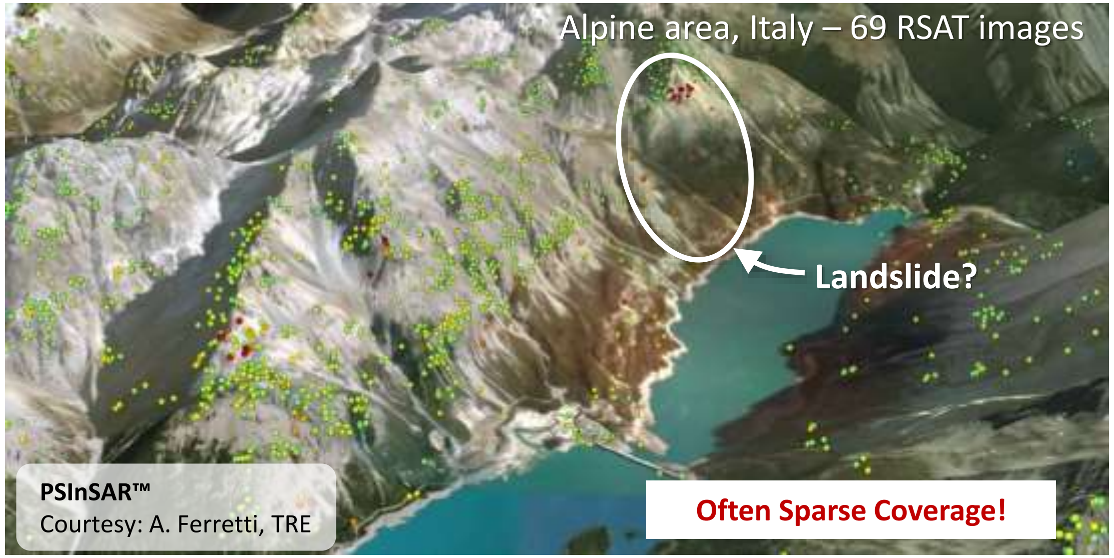


(4) Estimate deformation difference between PS locations



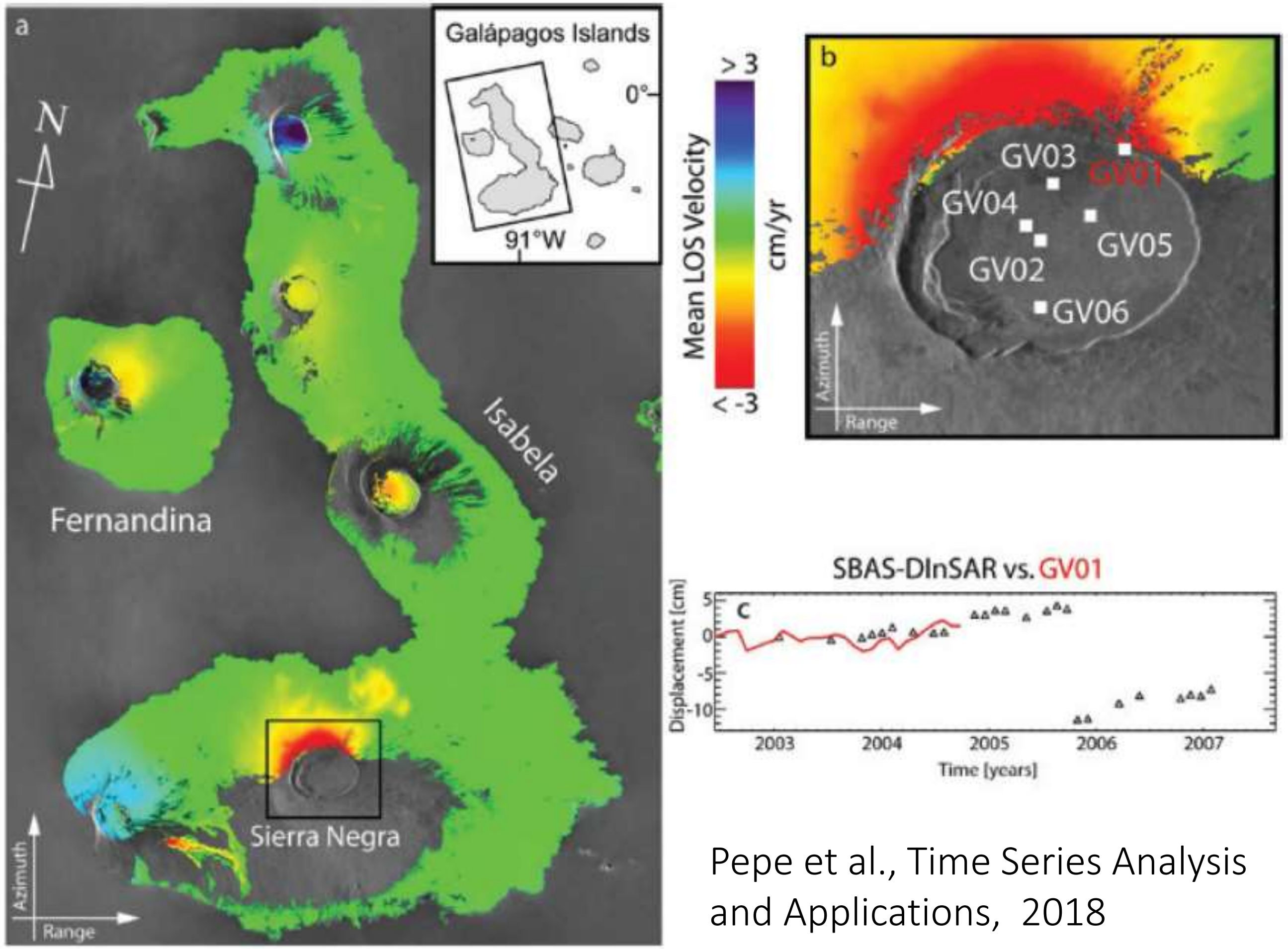
Deformation model required!

(5) Integrate to arrive at surface deformation map



SBAS - Distributed Target-based InSAR Time Series Analysis

Study Deformation Over Natural Terrain

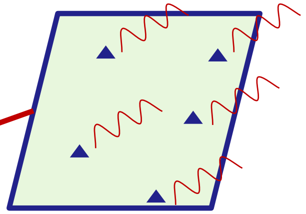


Pepe et al., Time Series Analysis and Applications, 2018

Distributed Target InSAR

+ higher point density in natural terrain
+ flexible, easily applicable to large areas
– usually higher noise level
– averaging reduces resolution

Natural Terrain



Distributed targets

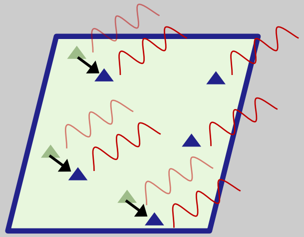
+ widespread (pasture, bare soil, etc.)
+ coherence as quality measure

– averaging reduces resolution
– **typically less stable**: decorrelation

Spatial decorrelation not a major concern for Sentinel-1 and NISAR

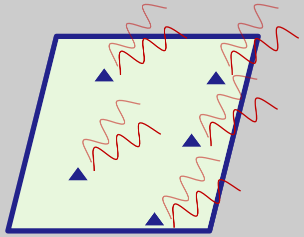
Two important sources of decorrelation

Temporal decorrelation
Sub-resolution scatterers change with respect to one another
Example: branches move in the wind



Adapted from A. Hooper

Spatial decorrelation
If difference in look angle (spatial baseline):
Individual returns add up differently



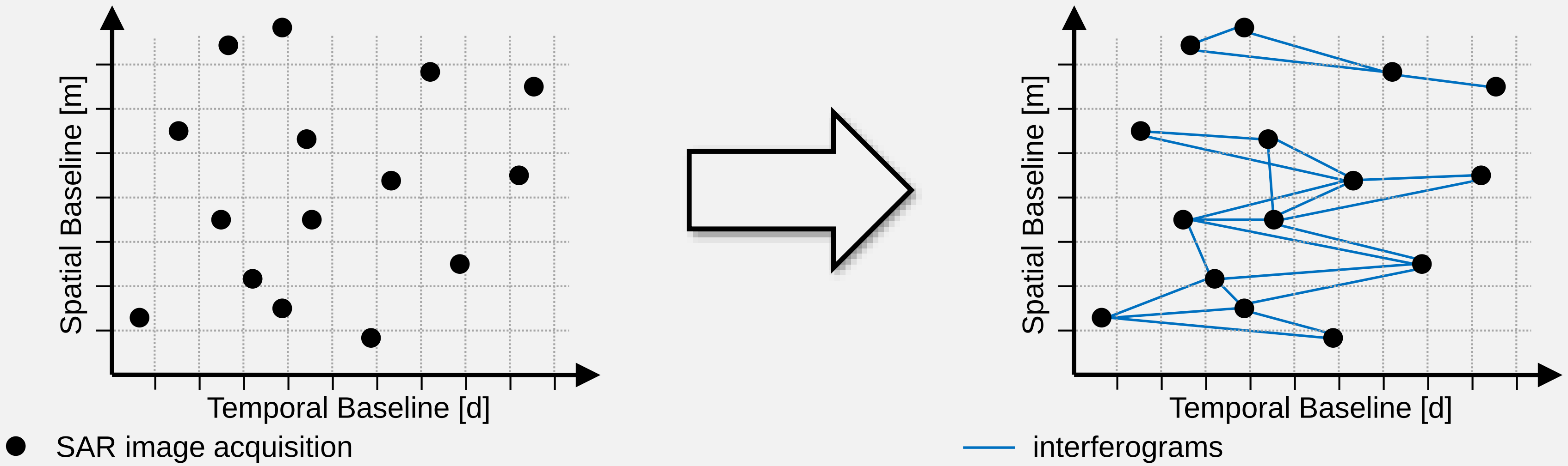
Short Baseline Subset InSAR

- **Original publication:** Berardino, P. et al., (2002): "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms," IEEE TGRS, 40(11), pp.2375-2383.

- **Idea:** Form **many high coherence interferograms** by selecting a **subset** of interferograms with **short spatial** and **moderate temporal baselines**

- **Advantages:**
  - **More coherent information, especially in natural environments!**
  - Large number of interferograms helps in mitigating processing errors and noise

- **Concept sketch:**



PS-InSAR and SBAS InSAR Processing Flows

A Side-By-Side Comparison

PS-InSAR

- Formation of interferograms *relative to unique "reference" image*
- Subtraction of DEM → d-InSAR
- Detection of coherent information
- *No* phase filtering and *no* phase unwrapping
- Estimation of surface motion *requires a model* (e.g., linear motion with time)
- Coherent information are *mostly point-like targets*

SBAS InSAR

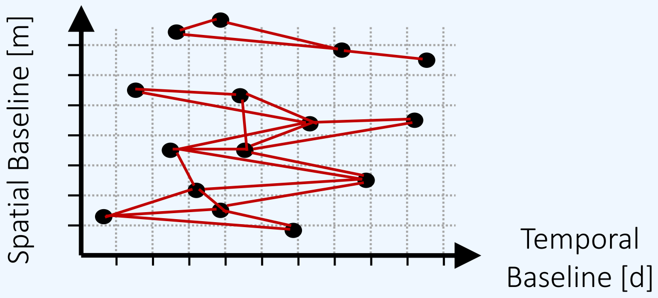
- Formation of *all InSAR pairs with short spatial (& temporal) baseline*
- Subtraction of DEM → d-InSAR
- Detection of coherent information
- Phase filtering and phase unwrapping
- Estimation of surface motion *does not require a model*
- Coherent patches composed of *only distributed targets*

The Small Baseline Subset (SBAS) Method

Critical Processing Steps

Interferogram formation (pairwise)

Form multi-looked interferograms
Unwrap



Phase inversion

Estimate best-fit deformation phase history
Still contaminated by atmosphere etc.

Filtering

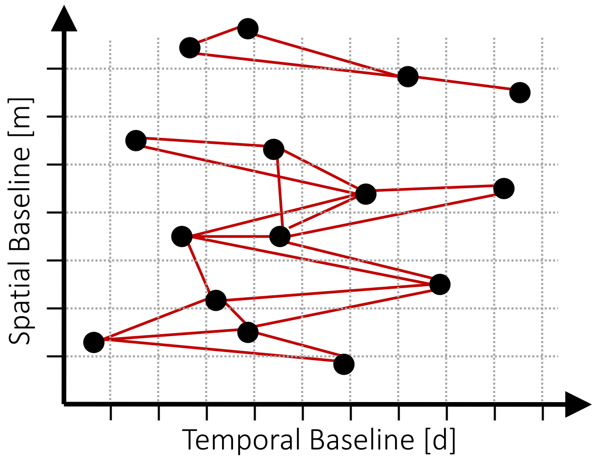
Mitigate atmospheric phase by spatial and temporal filtering

SBAS processing workflow

Many variants exist; for instance, the phase inversion step may detect unwrapping errors
There are also non-SBAS distributed-target approaches that form all interferograms

The Small Baseline Subset (SBAS) Method

Interferogram Formation



Select M interferograms

Maximize estimated coherence
Temporal baseline most critical for Sentinel-1

Computational efficiency vs. improved estimation:
N images: N (N-1)/2 possible interferograms

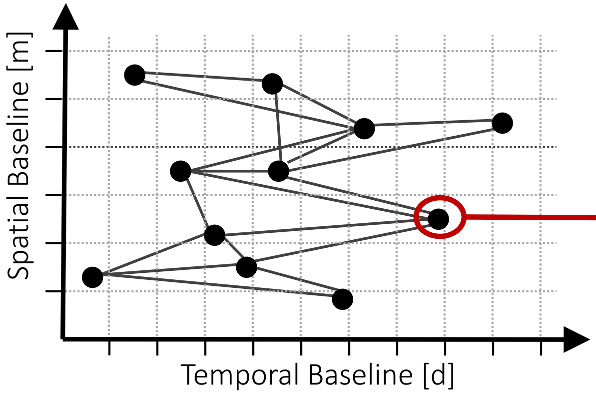
Interferogram computation

Can use standard pairwise processor (e.g. ISCE)
Remove topographic phase using reference DEM

Unwrap

The Small Baseline Subset (SBAS) Method

SBAS Phase Inversion



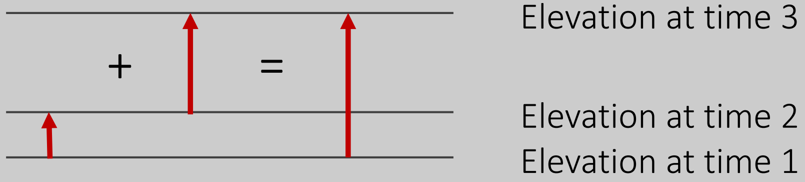
Key idea

We have partially redundant interferograms
One time instance contributes to multiple interferograms

Exploit redundancy to reduce noise

Reducing noise by enforcing consistency (or phase closure)

Deformation is temporally consistent[1]



Zwieback 2016

Decorrelation noise is not

Reduce noise by making redundant, inconsistent interferograms consistent

Problem: Atmosphere (& DEM error[1]) also consistent

1: Deformation and terrain need to be homogeneous

The Small Baseline Subset (SBAS) Method

Mathematics of SBAS Phase Inversion

- **In a stack of N images, number of potential interferograms M is:**

$$\frac{N+1}{2} \leq M \leq N\left(\frac{N+1}{2}\right)$$

For $N = 100$:
between 51 and 5100 interferograms

- **For simplicity, we will initially make the following assumptions:**
  - $\phi^k_{x,atmo}$, $\phi^k_{x,orbit}$, and $\phi^k_{x,\Delta DEM}$ can be ignored
  - Phase of individual M interferograms is unwrapped without unwrapping error

Main estimation problem to be solved:

- **Estimate:** **Vector of N unknown deformation phases (at N acquisition times):**

$$\varphi^T_{defo} = \left[\varphi_{defo}(t_1), \dots, \varphi_{defo}(t_N)\right]$$

- **From:** **Vector of M observed d-InSAR phase values**:

$$\Delta\phi^T = [\phi(t_1), \dots, \phi(t_M)], \quad \text{where} \quad \phi(t_j) = \left(\varphi_{reference,j} - \varphi_{secondary,j}\right)$$

The Small Baseline Subset (SBAS) Method

Mathematics of SBAS Phase Inversion

Problem statement

Given

For each location: observed unwrapped phase vector

$$\boldsymbol{\phi} = [\phi_{1,2}, \dots, \phi_{N-1,N}]$$

M interferograms: $\boldsymbol{\phi}$ is M-dimensional

We assume no phase unwrapping errors

Wanted

Consistent phase history

For each location: an N-dimensional vector

$$\boldsymbol{\varphi} = [\varphi_1, \dots, \varphi_N]$$

where $\boldsymbol{\varphi}$ is proportional to path length at each time step (surface position but also atmosphere, etc.)

Solution strategy

Model noisy $\boldsymbol{\phi}$ as function of unknown $\boldsymbol{\varphi}$

$$\boxed{\boldsymbol{\phi} = \boldsymbol{A}\,\boldsymbol{\varphi}}$$

$\boldsymbol{A}$ is a design matrix that encodes which phases contribute to each interferogram

Solve using least squares

Minimize quadratic misfit between the observations $\boldsymbol{\phi}$ and the model predictions $\boldsymbol{A}\,\boldsymbol{\varphi}$

The Small Baseline Subset (SBAS) Method

A Word about Design Matrix A

- **Matrix A describes how deformation history ϕ_{defo} maps into InSAR phase $\Delta\phi$**
- **Example:**
  - $N = 4$ SAR acquisition times t_N at which ϕ_{defo} was sampled; $M = 6$ ifgrms ($\Delta\phi$)

We can write this problem as:

$$\underbrace{\begin{bmatrix} \phi_{defo}(t_2) - \phi_{defo}(t_1) \\ \phi_{defo}(t_2) - \phi_{defo}(t_3) \\ \phi_{defo}(t_3) - \phi_{defo}(t_1) \\ \phi_{defo}(t_3) - \phi_{defo}(t_4) \\ \phi_{defo}(t_4) - \phi_{defo}(t_2) \\ \phi_{defo}(t_4) - \phi_{defo}(t_1) \end{bmatrix}}_{\text{Observations } \Delta\phi} = A \cdot \overbrace{\begin{bmatrix} \phi_{defo}(t_1) \\ \phi_{defo}(t_2) \\ \phi_{defo}(t_3) \\ \phi_{defo}(t_4) \end{bmatrix}}^{\text{Unknowns } \phi_{defo}}$$

- **Design matrix A:**

$$A = \underbrace{\overbrace{\begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & -1 & 0 & 1 \\ -1 & 0 & 0 & 1 \end{bmatrix}}^{N = 4 \text{ columns}}}_{M = 6 \text{ rows}}$$

Design Matrix in SBAS Phase Inversion

Design matrix

Describes how the changing surface position is reflected in each interferogram

Parameterization

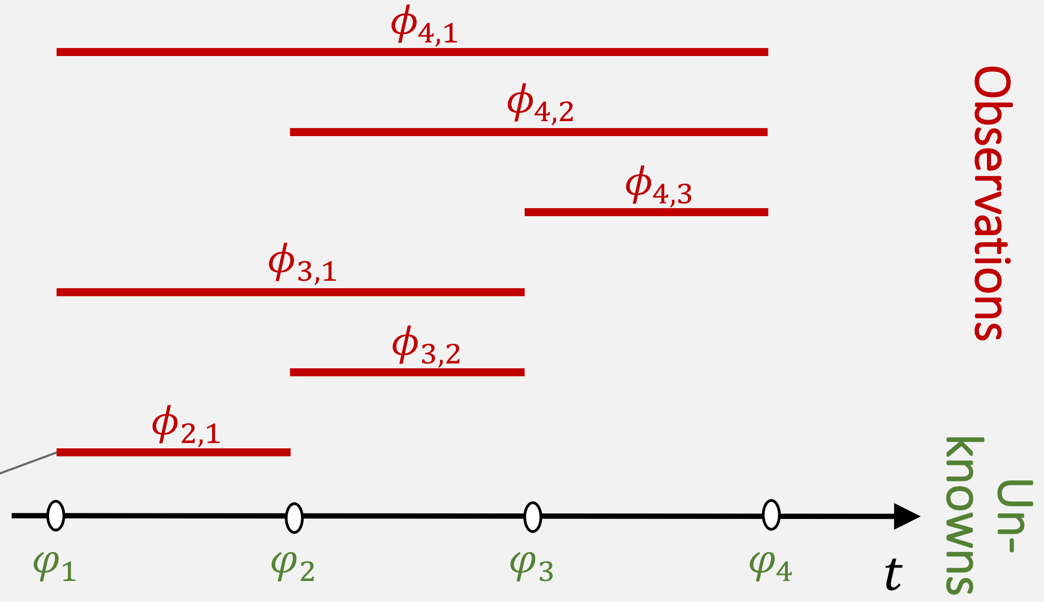
One can also include a deformation model and the DEM error here (how?)

Example:

N = 4 images, M = 6 Interferograms

$$\boldsymbol{A} = \underbrace{\left\{\right.}_{\boldsymbol{M}\,=\,6\text{ rows}} \overbrace{\begin{bmatrix} -1 & 0 & 0 & 1 \\ 0 & -1 & 0 & 1 \\ 0 & 0 & -1 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 1 & 0 & 0 \end{bmatrix}}^{\boldsymbol{N}\,=\,4\text{ columns}}$$

Interferogram phase $\phi_{2,1}$ contains the deformation between time 2 and time 1, i.e. $-\varphi_1 + \varphi_2$.



The Small Baseline Subset (SBAS) Method

Uniqueness of Solution (advanced material)

Is there always a unique solution?

Problem 1: InSAR is a differential technique

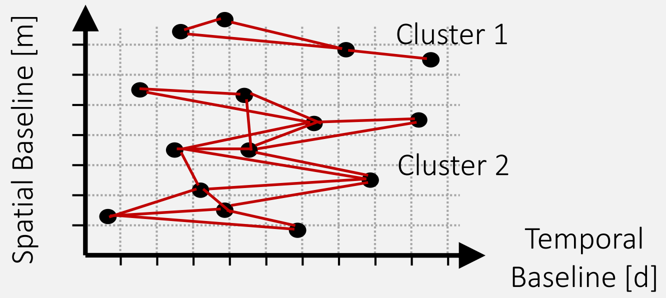
Only sensitive to *differences* in path length such as deformations

What happens if you add a constant shift to $\boldsymbol{\varphi}$?

$\boldsymbol{\phi} = \boldsymbol{A}\,\boldsymbol{\varphi}$ does not change!

We say that $\boldsymbol{A}$ has a rank defect (or a non-trivial kernel or nullspace). The solution $\boldsymbol{\varphi}$ to the least-squares problem is not unique. We can make it unique by fixing e.g. φ_1 and referencing all deformation relative to this time instance. Then φ_2, say, corresponds to a cleaned interferometric phase $\phi_{2,1}$ with reduced decorrelation noise but still contaminated by atmosphere etc.

Problem 2: Insufficient interferograms



Can you spot the problem?

How would your measurements change if there was a shift to all the time instances in cluster 1?

This is another rank defect. One needs additional conditions or constraints to deal with it.

The Small Baseline Subset (SBAS) Method

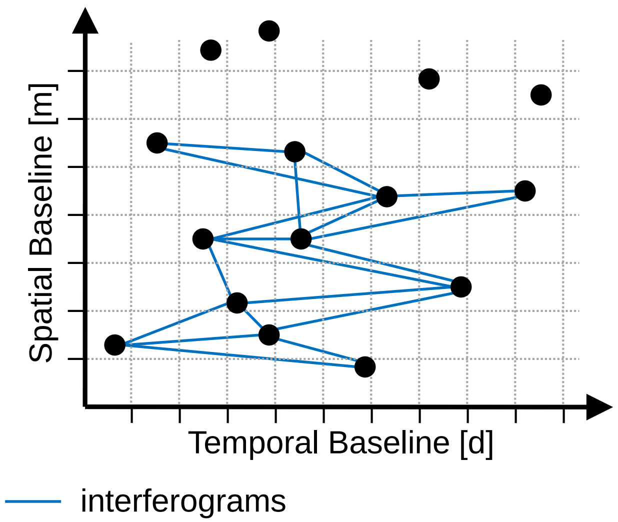
How to Calculate ϕ_{defo} from $\Delta\phi$

Advanced Materials

The Least-Squares Solution:

- **Requirement for Applying Least Squares:**
  - All acquisitions have to belong to one single set of interconnected interferograms
- **If requirement is met:**
  - $M \geq N$ and A is of rank N
  - In this case solution is found using Least-Squares methods

$$\hat{\phi} = \left(A^T A\right)^{-1} A^T \delta\phi$$ Normal Equation



The Small Baseline Subset (SBAS) Method

How to Calculate ϕ_{defo} from $\Delta\phi$

The Singular Value Decomposition (SVD) Approach

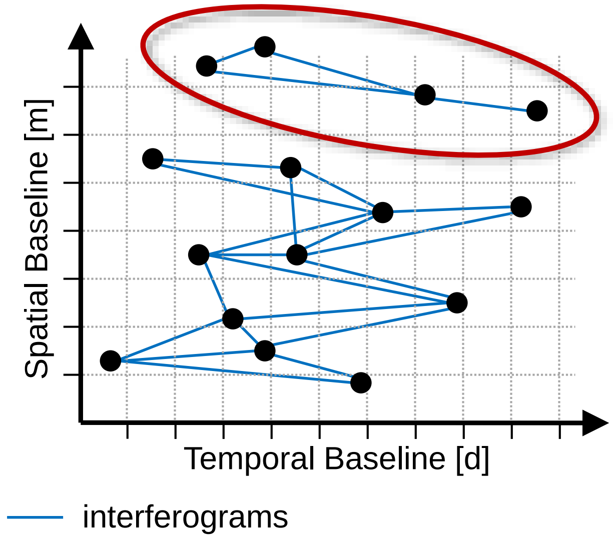
- **Required** if acquisitions belong to $L > 1$ different interferogram sets

- **In the case of** $L > 1$, matrix A is rank deficient (rank: $N - L + 1$) meaning we have less independent observations than unknowns

- **Solution through SVD decomposition of A :**

$$A = USV^T$$

U: eigenvectors of AA^T, V: Eigenvectors of A^TA, and S is matrix of eigenvalues



- Solution for $\hat{\phi}_{defo}$ is found through: $\hat{\phi}_{defo} = A^{+}\Delta\phi$ with $A^{+} = VS^{+}U^{T}$

The Small Baseline Subset (SBAS) Method

How To Deal with Nuisance Signals?

- **Reminder of the full interferometric phase equation:**

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

- **Also remember that SBAS is operating on unwrapped interferograms → unwrapping errors may occur**

- **Hence, the following nuisance signals must be treated in SBAS InSAR:**
  - Atmospheric noise ϕ_{atmo}
  - DEM errors $\phi_{h_{err}}$
  - Phase unwrapping errors
  - Orbit errors (ϕ_{orbit}) and noise (ϕ_{noise}; due to heavy filtering) are largely ignored

Filtering for Mitigation of Errors

Properties of the phase history φ

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

Filtering for Mitigation of Errors

Key idea

Atmospheric error is smooth in space
High-pass in space: Subtract spatially smoothed $\boldsymbol{\varphi}_S$ from $\boldsymbol{\varphi}$

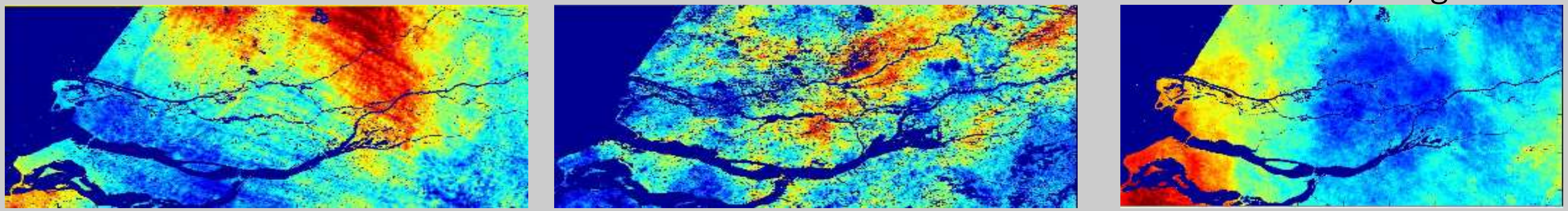
Atmospheric error is random in time
Low-pass filter in time: Smooth $\boldsymbol{\varphi}$ in time

$\boldsymbol{\varphi}$ from inversion
$\varphi_{defo}, \varphi_{atmo}, \dots$

Filtering

Filtered $\boldsymbol{\varphi}$
mainly φ_{defo}

Hanssen et al., Fringe 2005



time

Turbulent tropospheric phase

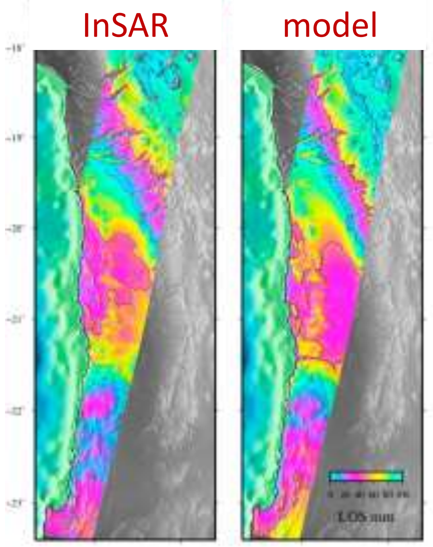
Spatially correlated
But independent between acquisitions

Further Error Mitigation Steps

Tropospheric errors

Systematic elevation dependence
Remove based on dependence of phase on elevation

Regional variability
Use weather models to mitigate regional trends and stratified elevation-dependent errors



Weather model

Remove predicted delay
- Large scale
- Stratified

Jolivet et al., JGR 2014

DEM errors

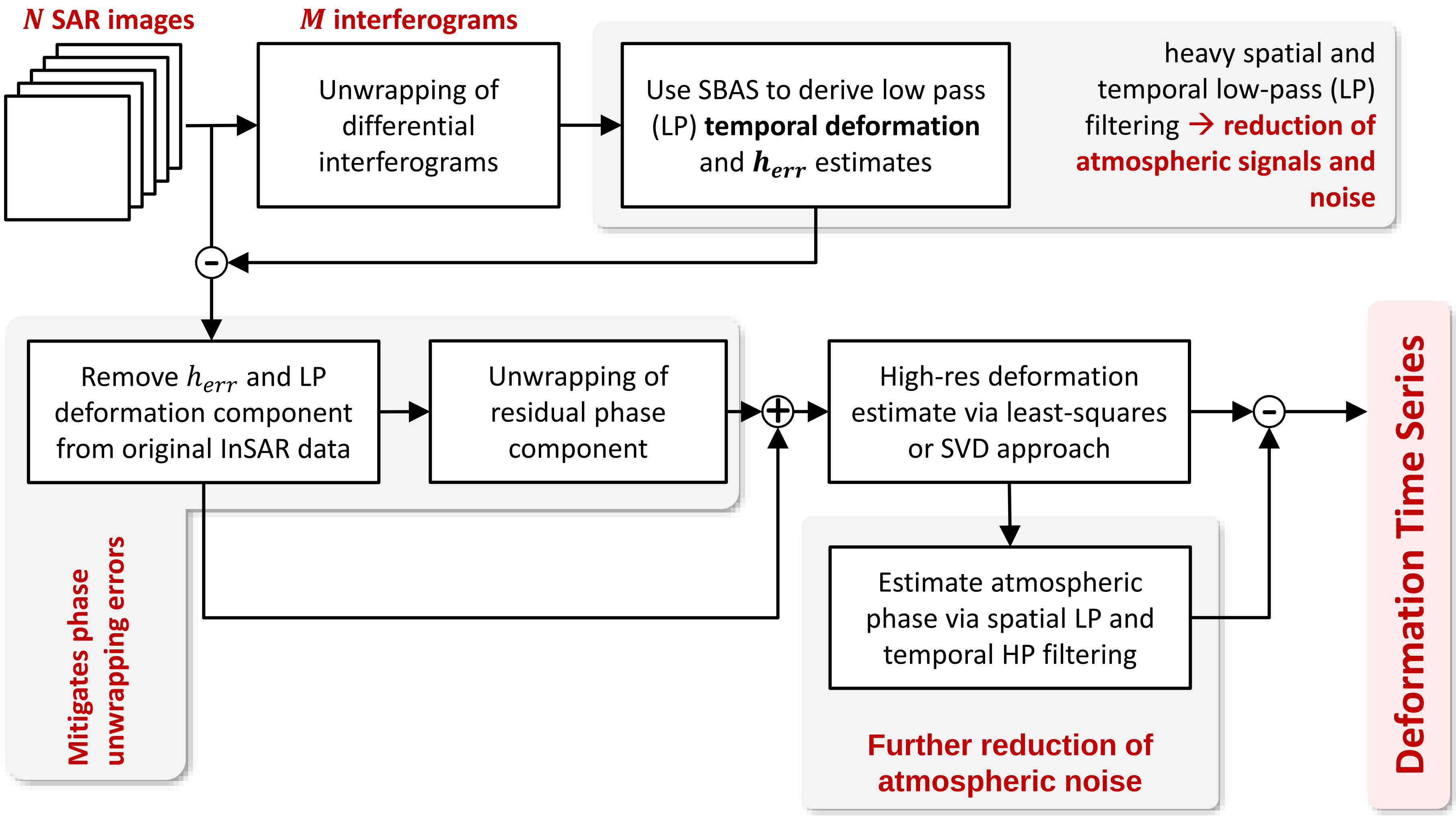
Exploit dependence on baseline

Not so critical for small baselines (Sentinel-1) and accurate DEMS

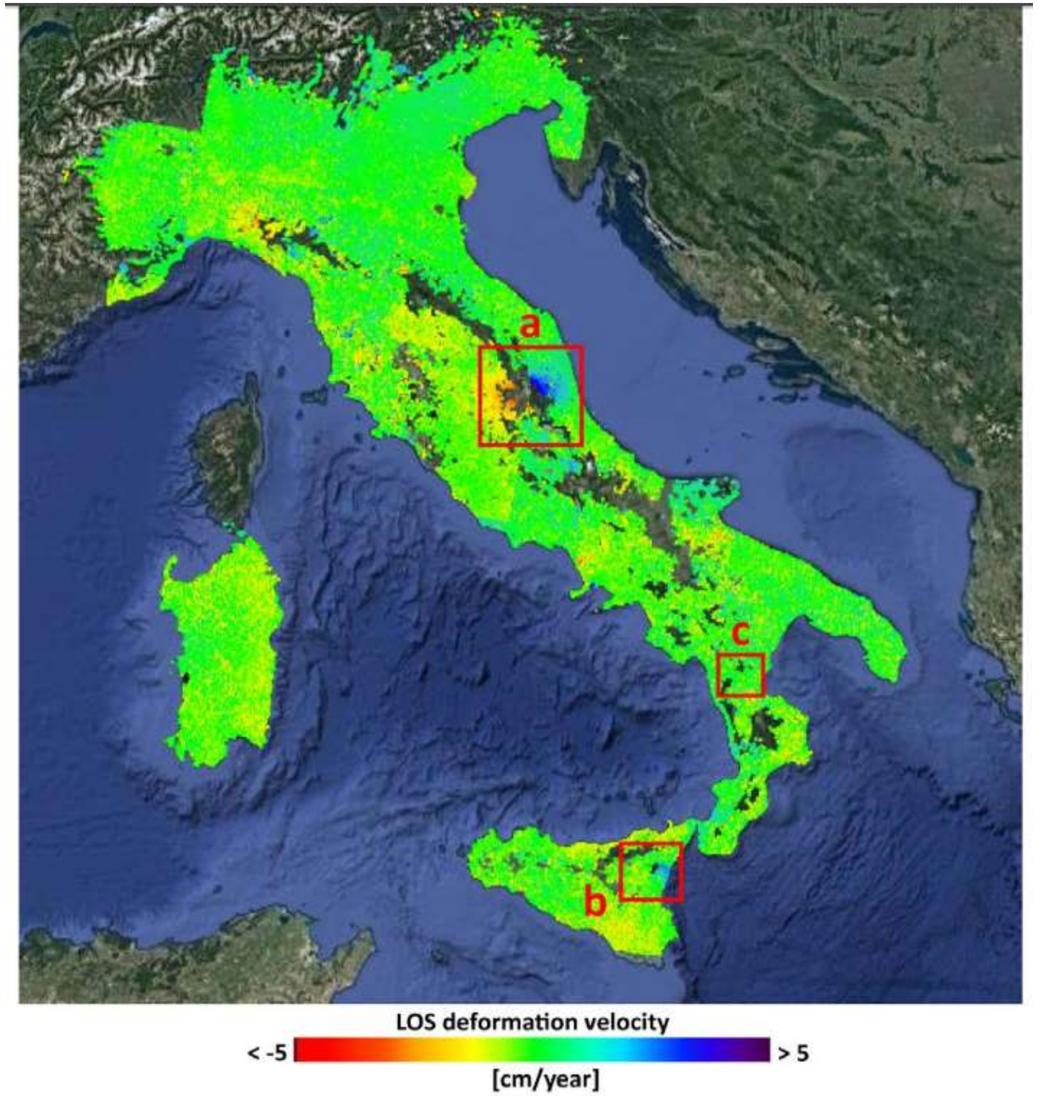
$$\phi_{topo} \sim B_{\perp}$$

The Small Baseline Subset (SBAS) Method

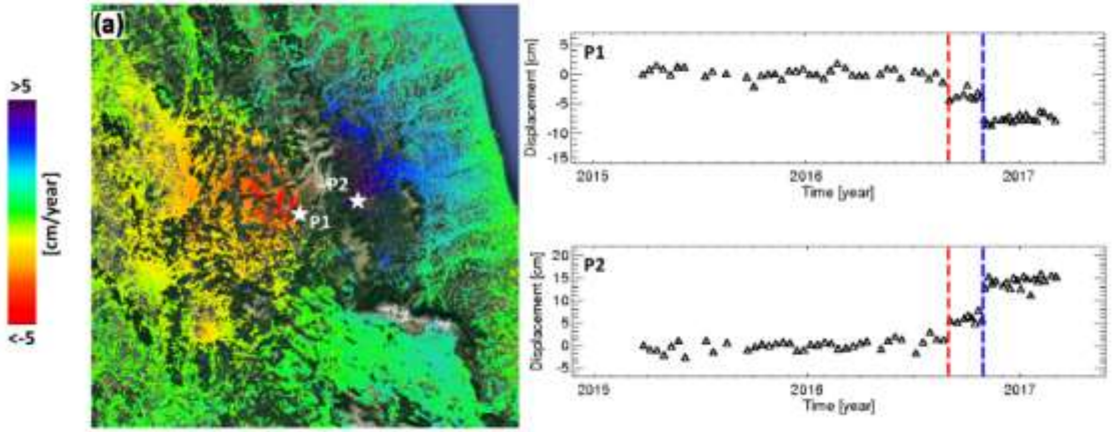
An Example on How To Deal with Nuisance Signals?



Examples: Mapping Italy from Multiple Sentinel-1 Swaths

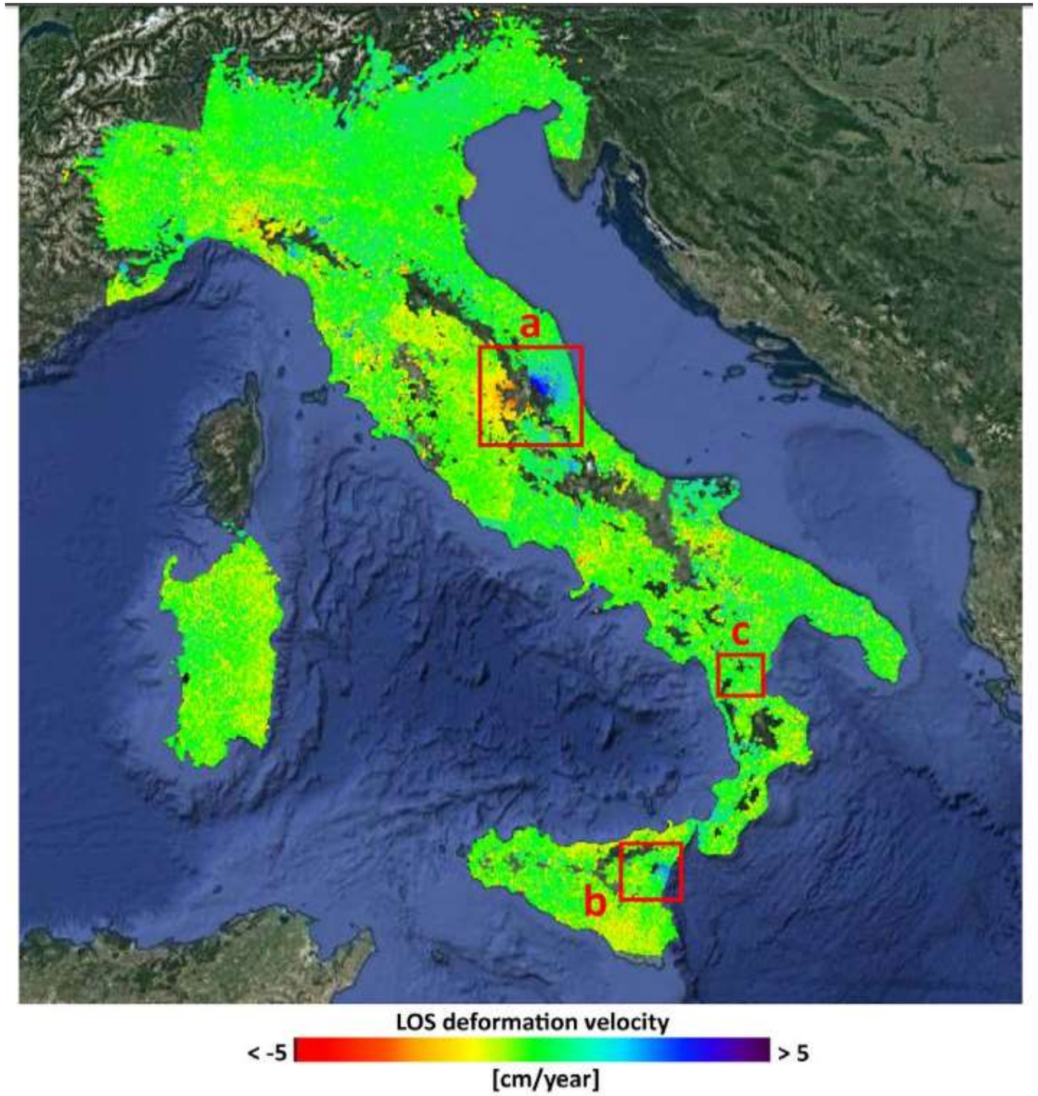


a) 2016 Norcia Earthquake

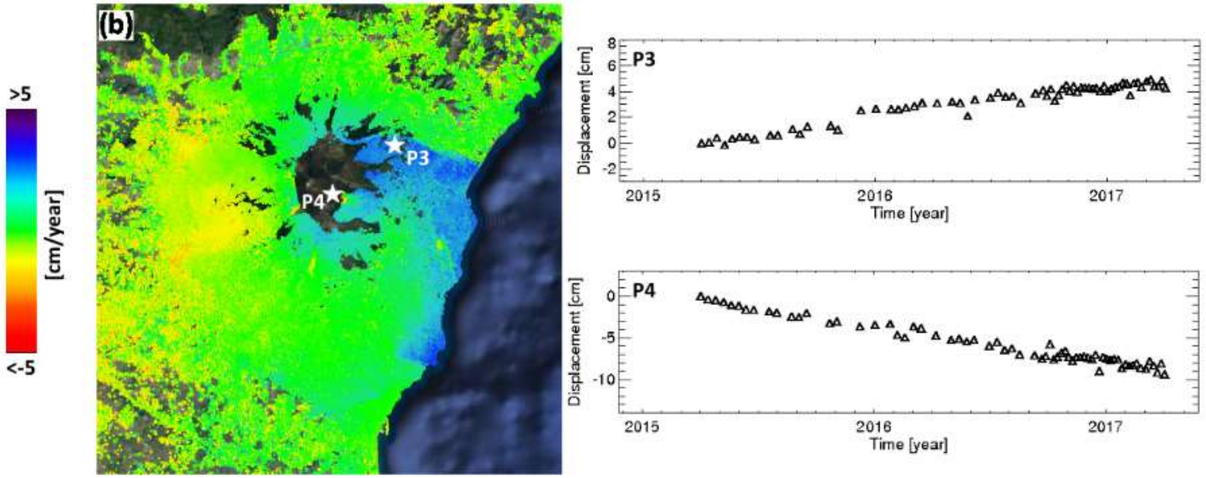


Zinno et al., TGRS, 2019

Examples: Mapping Italy from Multiple Sentinel-1 Swaths

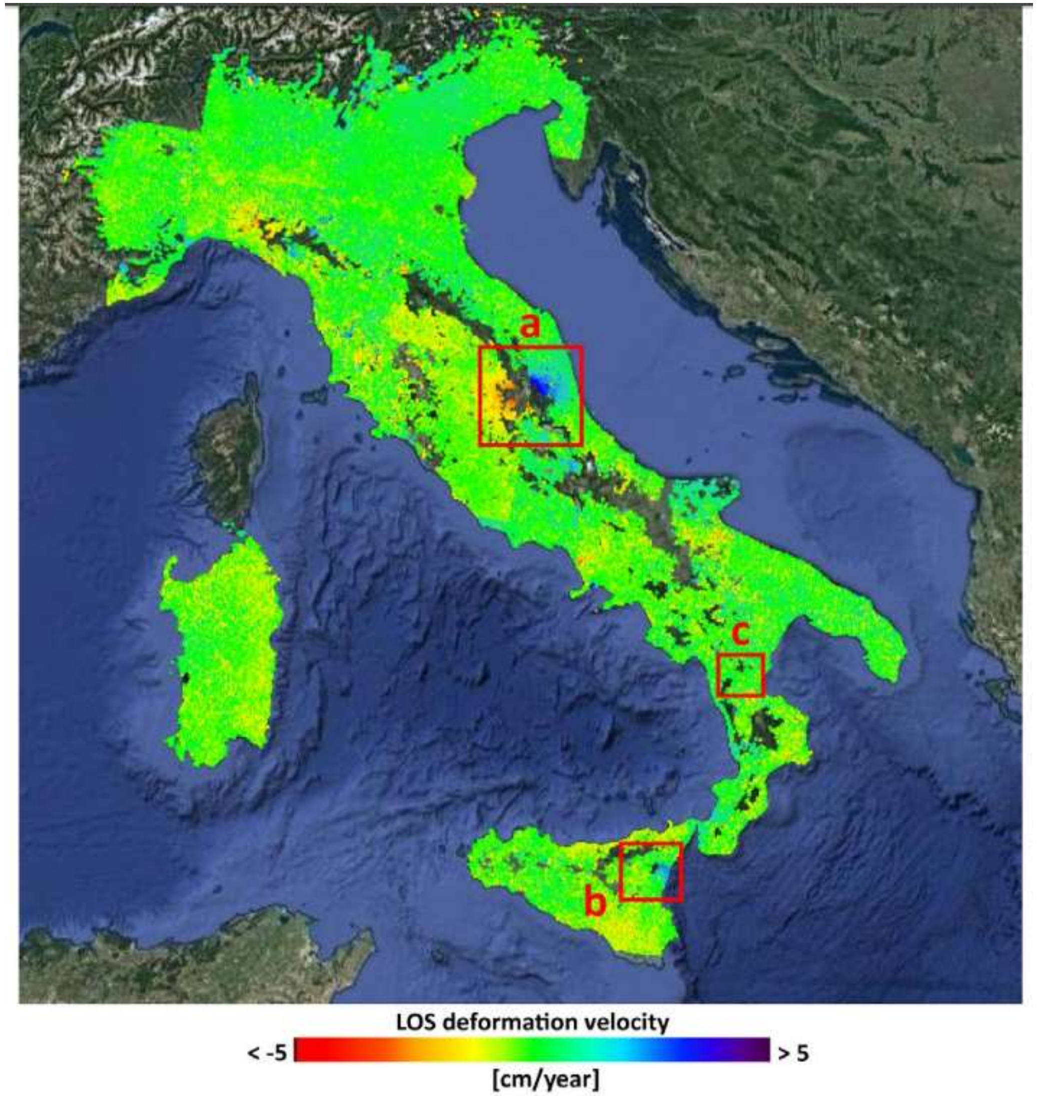


b) Etna Volcano

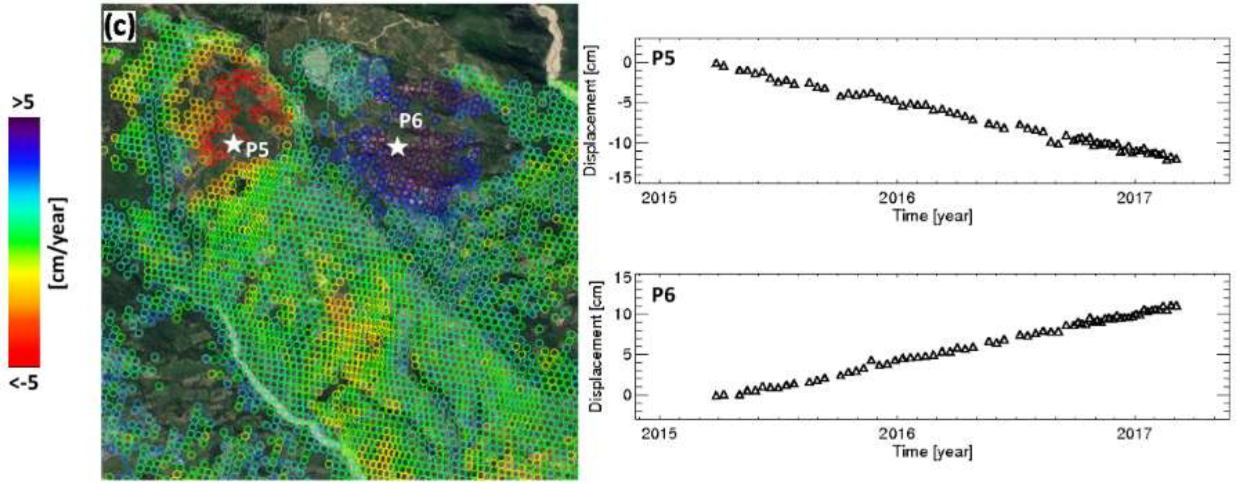


Zinno et al., TGRS, 2019

Examples: Mapping Italy from Multiple Sentinel-1 Swaths

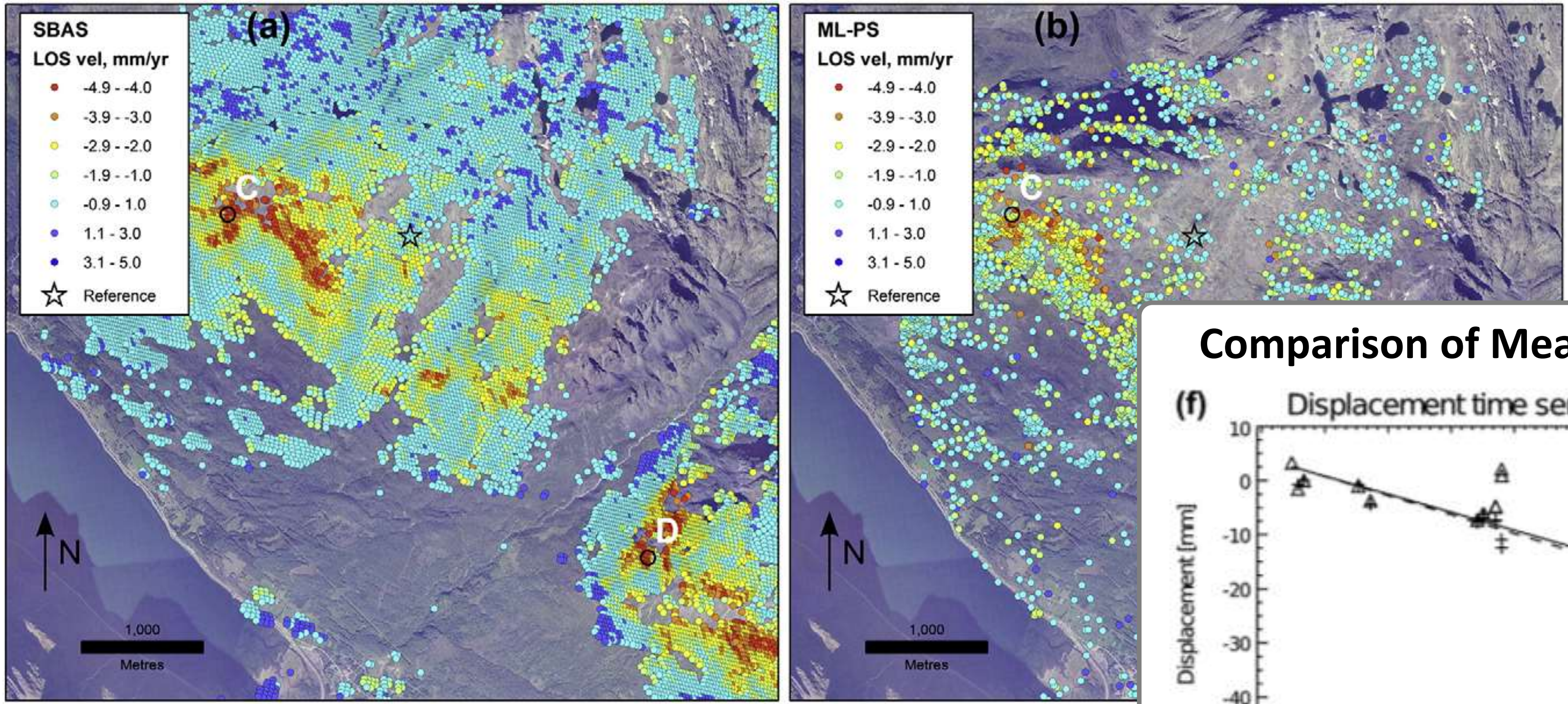


c) Pernicana Fault System



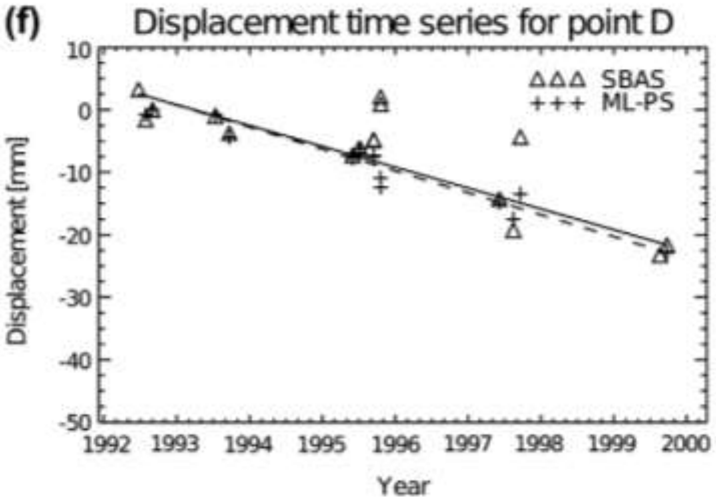
Zinno et al., TGRS, 2019

Comparison SBAS vs. PSI



Lauknes et al. (2010). *Remote Sensing of Environment*, *114*(9), 2097-2109.

Comparison of Measurements



Advantages and Disadvantages of SBAS

- **Advantages:**
  - Usually more coherent points → better description of deformation
  - No motion model required → better for geophysical signals
- **Disadvantages:**
  - More noise in the estimates (less accurate compared to PS-InSAR)
  - Spatial averaging → lower spatial resolution
  - More interferograms → significantly higher computational effort
- **Other Notes:**
  - SBAS requires that there are no temporal gaps in the time series
  - A deformation model can be integrated into SBAS to constrain the solution. Variations of SBAS that contain models are often referred to as NSBAS (Doin et al., 2011)

Summary

Input

Time series of SAR images

Processing

- Interferogram formation
- Isolate deformation

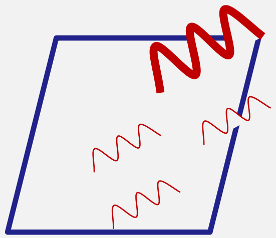
Output

Deformation

Point Target InSAR

+ high quality for selected points
+ retains full resolution

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

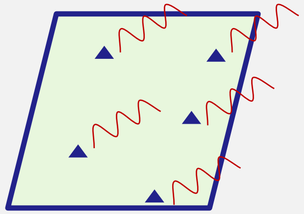


Persistent Scatterer Interferometry (PSI)

Distributed Target InSAR

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

– usually higher noise level
– averaging reduces resolution



Small Baseline Subset (SBAS)

More about InSAR Time Series Analysis

- **InSAR time series analysis is current ongoing research topics**
- Many advanced methods have been developed in recent years including:

  - Traditional PS-InSAR (Politecnica di Milano, Italy)
  - StaMPS (Stanford University)
  - DePSI (University of Delft, NL)
  - Coherent Target InSAR (IPTA) (GAMMA Remote Sensing)

Point Target InSAR-Type

  - Traditional SBAS InSAR (University of Napoli, Italy)
  - StamPS SBAS InSAR (Stanford University)
  - GIAnT (Generic InSAR Analysis Toolbox; http://earthdef.caltech.edu/projects/giant/wiki)
  - MintPy (Miami InSAR time-series software in Python; https://github.com/insarlab/MintPy)

SBAS-Type

  - SqueeSAR (TRE, Italy)

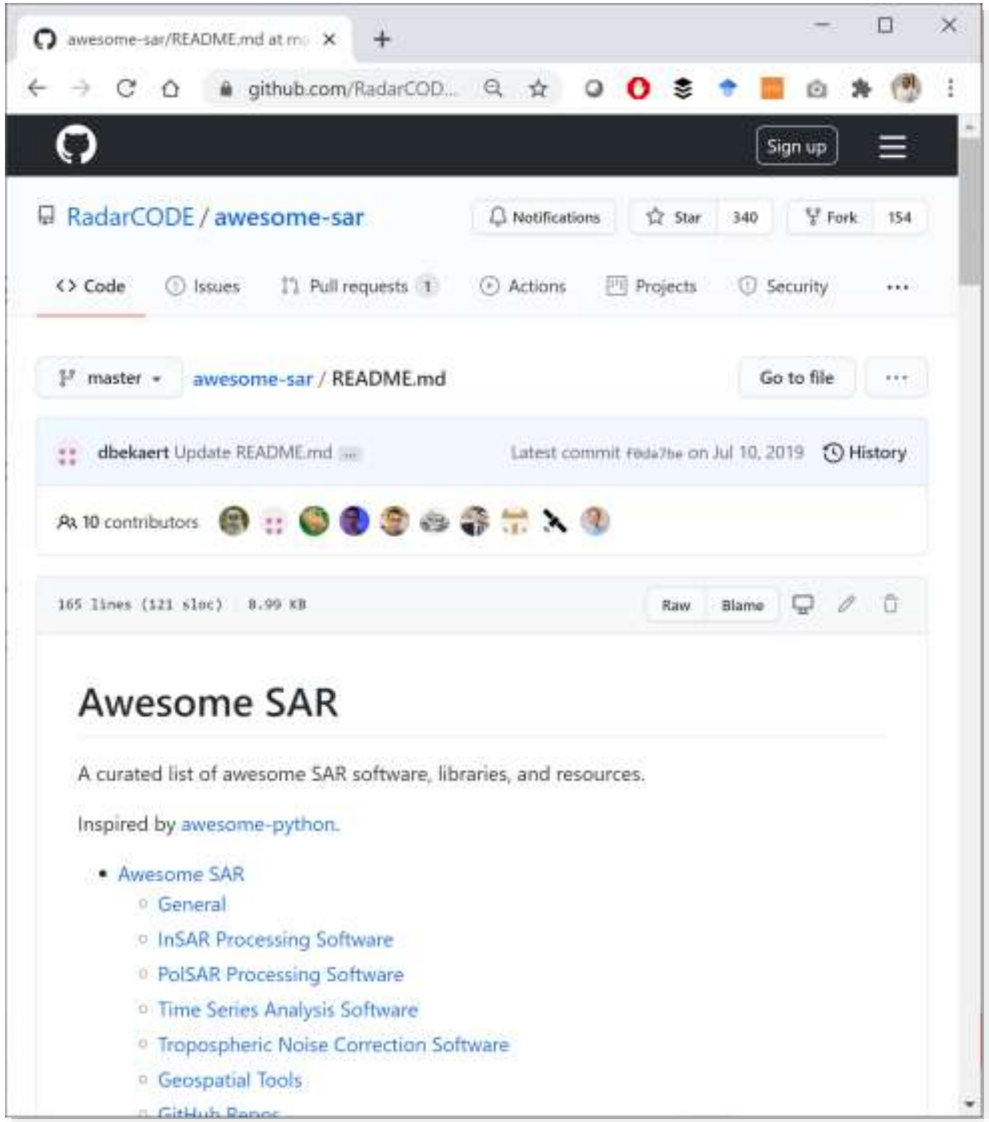
Combination of PS and SBAS

  - MInTS (Multiscale InSAR Time Series) (CalTec)

Independent Approach

Open Source InSAR Time Series Analysis Software

- **Nowadays, there are a number of publicly available open source Time Series Analysis tools available.**
- Together with a few community members, we provide coordinated access to these tools via the [RadarCODE]() (Radar COordinated DEvelopment) initiative



Some InSAR Time Series Analysis Literature

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What's Next?

- **This is what awaits next:**
  - **Tuesday :** Lab on InSAR Time Series Analysis for Volcano Applications