GEOS 657 – MICROWAVE REMOTE SENSING

GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

Lecturer:
Franz J Meyer, Geophysical Institute, University of Alaska Fairbanks, Fairbanks; fjmeyer@alaska.edu

Lecture 16: The SBAS (Short BAseline Subset) Approach to InSAR Time Series Analysis

UAF Course GEOS 657

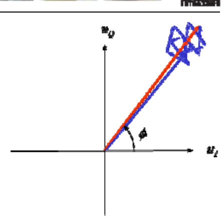
BEFORE WE START …

Think – Pair – Share

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

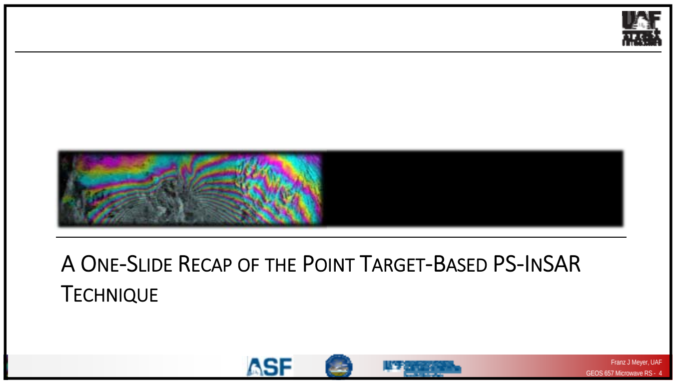
Activity 1: Point-Like Scatterers and Coherence:
[Ferretti et al., 2001] found that pixels whose radar signal is dominated by one very bright and stable point-like scatterers tend to be coherent over very long times. Hence, in his PS-InSAR technique, Ferretti first identifies point-like targets using their amplitude signature and then analyzes their phase for high-accuracy deformation monitoring.

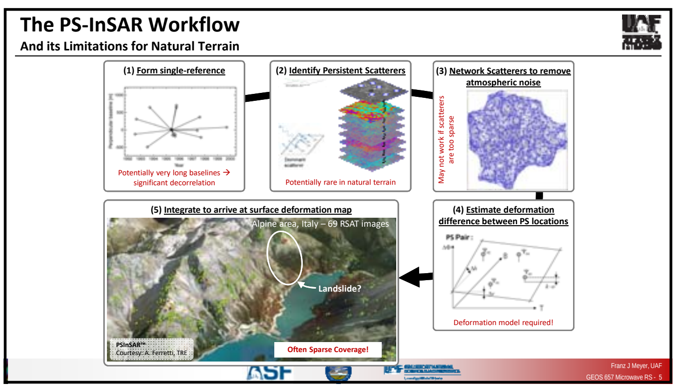
- **Discuss why point-like scatterers with high and stable amplitude usually also have stable phase. Complete the sketch to the right in your discussion.**

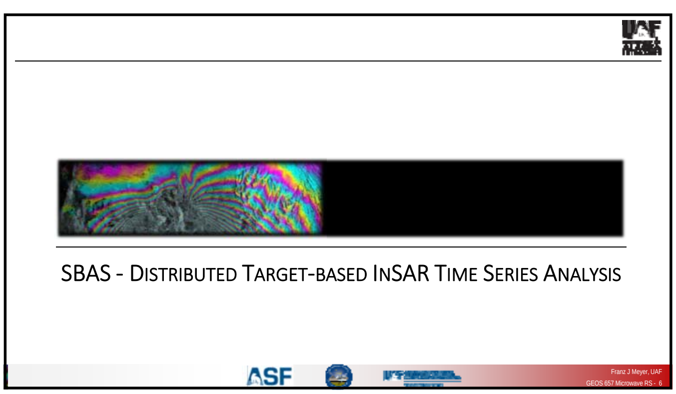


Activity 2: Limitations of PS-InSAR:
While the point target-based PS-InSAR technique can provide highly accurate surface deformation information in urbanized environments, its performance is often limited when applied to natural environments (e.g., volcano deformation or permafrost subsidence)

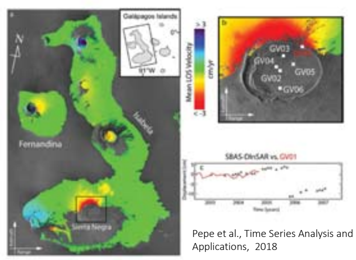
- **Identify least two reasons why PS-InSAR type techniques often underperform in natural setting?**


A ONE-SLIDE RECAP OF THE POINT TARGET-BASED PS-INSAR TECHNIQUE
ASF
Franz J Meyer, UAF
GEOS 657 Microwave RS - 4


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
PS Pair :
Deformation model required!
(5) Integrate to arrive at surface deformation map
Alpine area, Italy – 69 RSAT images
Landslide?
Often Sparse Coverage!
Courtesy: A. Ferretti, TRE
ASF
Franz J Meyer, UAF
GEOS 657 Microwave RS - 5


SBAS - DISTRIBUTED TARGET-BASED INSAR TIME SERIES ANALYSIS
ASF
Franz J Meyer, UAF
GEOS 657 Microwave RS - 6

Study Deformation Over Natural Terrain



Distributed Target InSAR

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

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

Natural Terrain

Distributed targets

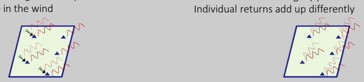
- \+ widespread (pasture, bare soil, etc.)
- \+ coherence as quality measure
- – averaging reduces resolution
- – **typically less stable**: decorrelation

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

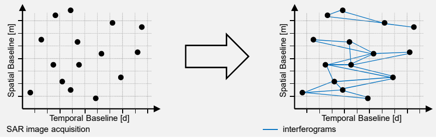
Spatial decorrelation
If difference in look angle (spatial baseline):
Individual returns add up differently



Adapted from A. Hooper

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

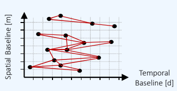
- Formation of interferograms *relative to unique "reference" image*
- Subtraction of DEM → d-InSAR
- Detection of coherent information
- *No* phase filtering and *no* phase unwrapping
- Estimation of surface motion *requires a model* (e.g., linear motion with time)
- Coherent information are *mostly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

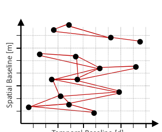


Phase inversion
Estimate best-fit deformation phase history
Still contaminated by atmosphere etc.

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



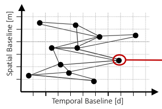
Select M interferograms
Maximize estimated coherence
Temporal baseline most critical for Sentinel-1

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



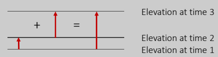
Key idea

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):**

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

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

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

The Small Baseline Subset (SBAS) Method
Mathematics of SBAS Phase Inversion

Problem statement

Given

For each location: observed unwrapped phase vector
$\boldsymbol{\phi} = [\phi_{1,2}, \ldots, \phi_{N-1,N}]$
M interferograms: $\boldsymbol{\phi}$ is M-dimensional

We assume no phase unwrapping errors

Wanted

Consistent phase history
For each location: an N-dimensional vector
$\boldsymbol{\varphi} = [\varphi_1, \ldots, \varphi_N]$
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 $\boldsymbol{\varphi}$

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

$\boldsymbol{A}$ 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:

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

- **Design matrix A:**

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

The Small Baseline Subset (SBAS) Method
Design Matrix in SBAS Phase Inversion

Design matrix

Describes how the changing surface position is reflected in each interferogram

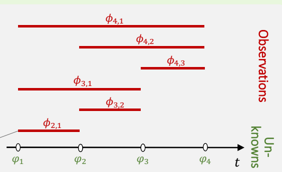
Parameterization

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

Example:
N = 4 images, M = 6 Interferograms

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

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

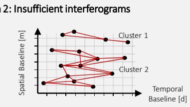
Only sensitive to *differences* in path length such as deformations

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.

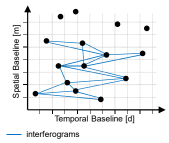
The Small Baseline Subset (SBAS) Method
How to Calculate ϕ_{defo} from $\Delta\phi$

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 $\Delta\phi$

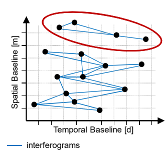
Advanced Materials

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 $A^T A$, 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?

Advanced Materials

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

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

Target parameters — nuisance parameters

- **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

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

- ϕ_{defo}: **smooth in time (usually)**
- ϕ_{topo}: proportional to spatial baseline
- ϕ_{atmo}: random in time – smooth in space; orbit error similar
- ϕ_{noise}: random in time and space

Separate components based on their temporal, spatial and baseline characteristics

Filtering for Mitigation of Errors

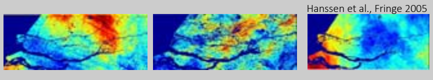
Key idea

Atmospheric error is smooth in space
High-pass in space: Subtract spatially smoothed φ_s from φ

Atmospheric error is random in time
Low-pass filter in time: Smooth φ in time

φ from inversion: $\varphi_{defo}, \varphi_{atmo}, \cdots$ → Filtering → Filtered φ: mainly φ_{defo}

Hanssen et al., Fringe 2005



Turbulent tropospheric phase

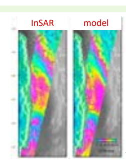
Spatially correlated
But independent between acquisitions

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

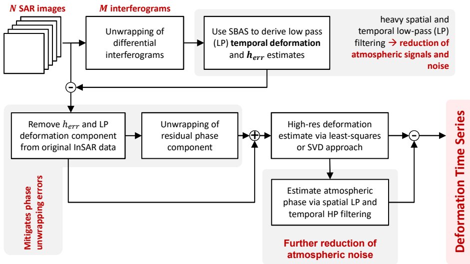
$\phi_{topo} \sim B_{\perp}$

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

The Small Baseline Subset (SBAS) Method

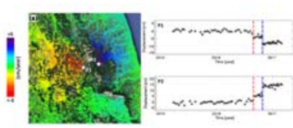
An Example on How To Deal with Nuisance Signals?

Advanced Materials



Examples: Mapping Italy from Multiple Sentinel-1 Swaths

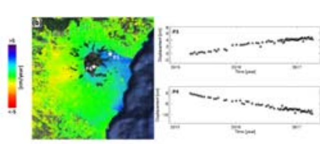
a) 2016 Norcia Earthquake



Zinno et al., TGRS, 2019

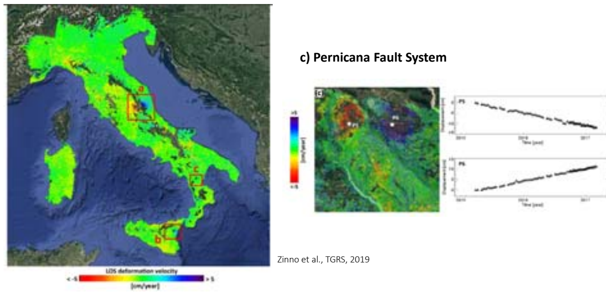
Examples: Mapping Italy from Multiple Sentinel-1 Swaths

b) Etna Volcano



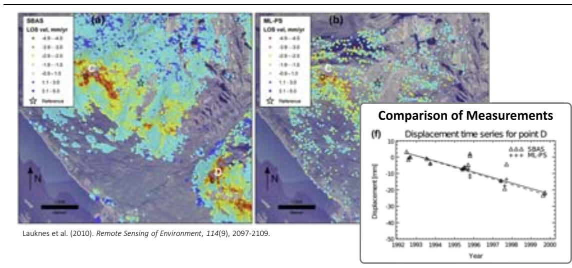
Zinno et al., TGRS, 2019

Examples: Mapping Italy from Multiple Sentinel-1 Swaths



Zinno et al., TGRS, 2019

Comparison SBAS vs. PSI



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

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

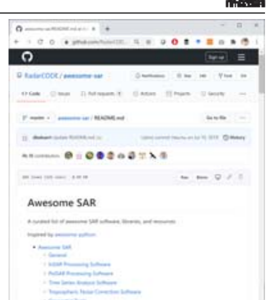
  - Traditional SBAS InSAR (University of Napoli, Italy)
  - StamPS SBAS InSAR (Stanford University)
  - GIAnT (Generic InSAR Analysis Toolbox; http://earthdef.caltech.edu/projects/giant/wiki)
  - MintPy (Miami InSAR time-series software in Python; https://github.com/insarlab/MintPy)

  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

- Ferretti, A.; Prati, C.; Rocca, F., "Permanent scatterers in SAR interferometry," *Geoscience and Remote Sensing, IEEE Transactions on* , vol.39, no.1, pp.8,20, Jan 2001
- Lanari, R.; Mora, O.; Manunta, M.; Mallorqui, J.J.; Berardino, P.; Sansosti, E., "A small-baseline approach for investigating deformations on full-resolution differential SAR interferograms," *Geoscience and Remote Sensing, IEEE Transactions on* , vol.42, no.7, pp.1377,1386, July 2004
- Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E., "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms," *Geoscience and Remote Sensing, IEEE Transactions on* , vol.40, no.11, pp.2375,2383, Nov 2002
- Hooper, A, Zebker, H., Segall, P., Kampes, B., "A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers," Geophysical Research Letters, 31(23), 2004
- Hooper, A,, "A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches," Geophysical Research Letters, 35, 2008
- Ferretti, A.; Fumagalli, A.; Novali, F.; Prati, C.; Rocca, F.; Rucci, A., "A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR," *Geoscience and Remote Sensing, IEEE Transactions on* , vol.49, no.9, pp.3460,3470, Sept. 2011
- Joaquim J. Sousa, Andrew J. Hooper, Ramon F. Hanssen, Luisa C. Bastos, Antonio M. Ruiz, Persistent Scatterer InSAR: A comparison of methodologies based on a model of temporal deformation vs. spatial correlation selection criteria, Remote Sensing of Environment, Volume 115, Issue 10, 17 October 2011
- Hetland, E., Musé, P., Simons, M., Lin, Y. N., Agram, P. S., DiCaprio, C. J., "Multiscale InSAR Time Series (MInTS) analysis of surface deformation," Journal of Geophysical Research: Solid Earth, 117(B2), 2012

What's Next?

- **This is what awaits next:**
  - **Tuesday :** Lab on Change Detection in SAR Amplitude Time Series Stacks
  - **Thursday**: Lab on SBAS-type InSAR Time Series Analysis using MintPy