InSAR time-series: background and theory

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Overview

- Motivation for time-series interferometry
- Time-series InSAR
  - Persistent Scatterer (PS) Techniques
  - Small Baseline (SB) Techniques
  - Covariance-based Techniques

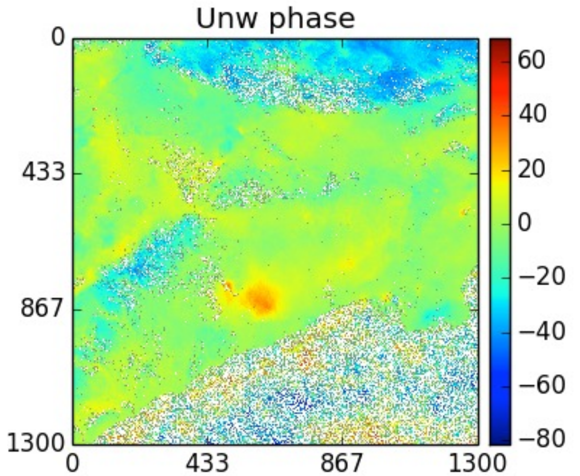
Error Budget (NISAR model)

$$\phi_{ifg} = [\phi_{defo} + \phi_{tropo} + \phi_{iono} + \phi_{dem} + \phi_{base} + \phi_{noise}]_{2\pi}$$

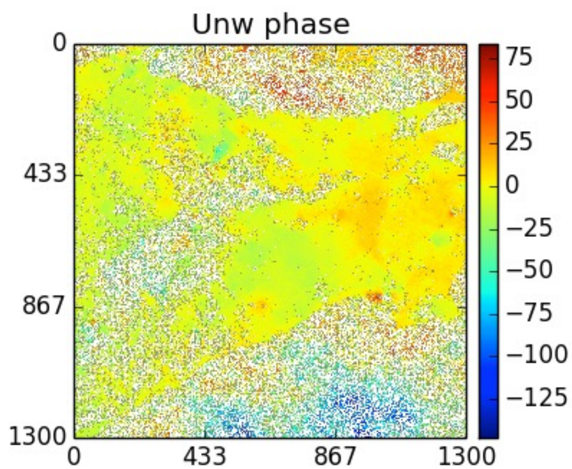
	L-band	
	Bhuj (India)	Barstow (CA)
Troposphere	37.3mm	20.1mm
Ionosphere	0.5mm	0.5mm
DEM Error	Can be mitigated with filtering	
Baseline Error	Negligible	
Decorrelation	3.2mm	2.5mm
Total (RMS)	37.5mm	20.2mm

Northern Summer Period. 100m resolution. 100m Baseline. Two points 50kms apart. 12-day ascending pair.

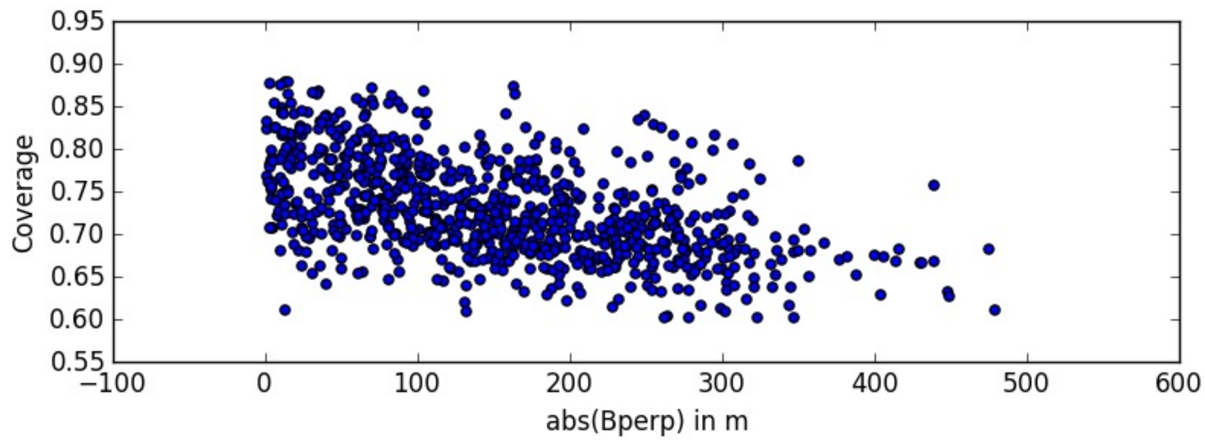
Baseline and decorrelation

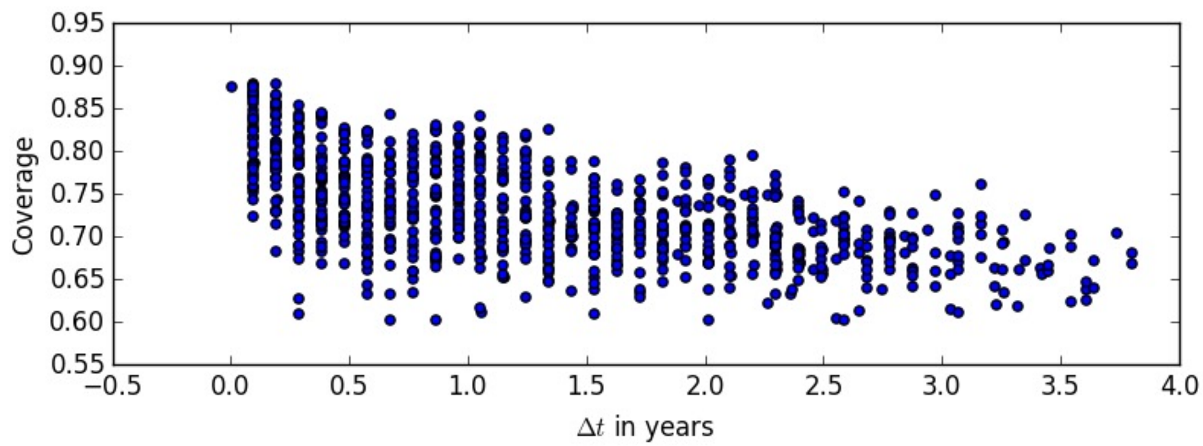


Bperp = 2m, Δt=1yr



Bperp = 400m, Δt=1yr



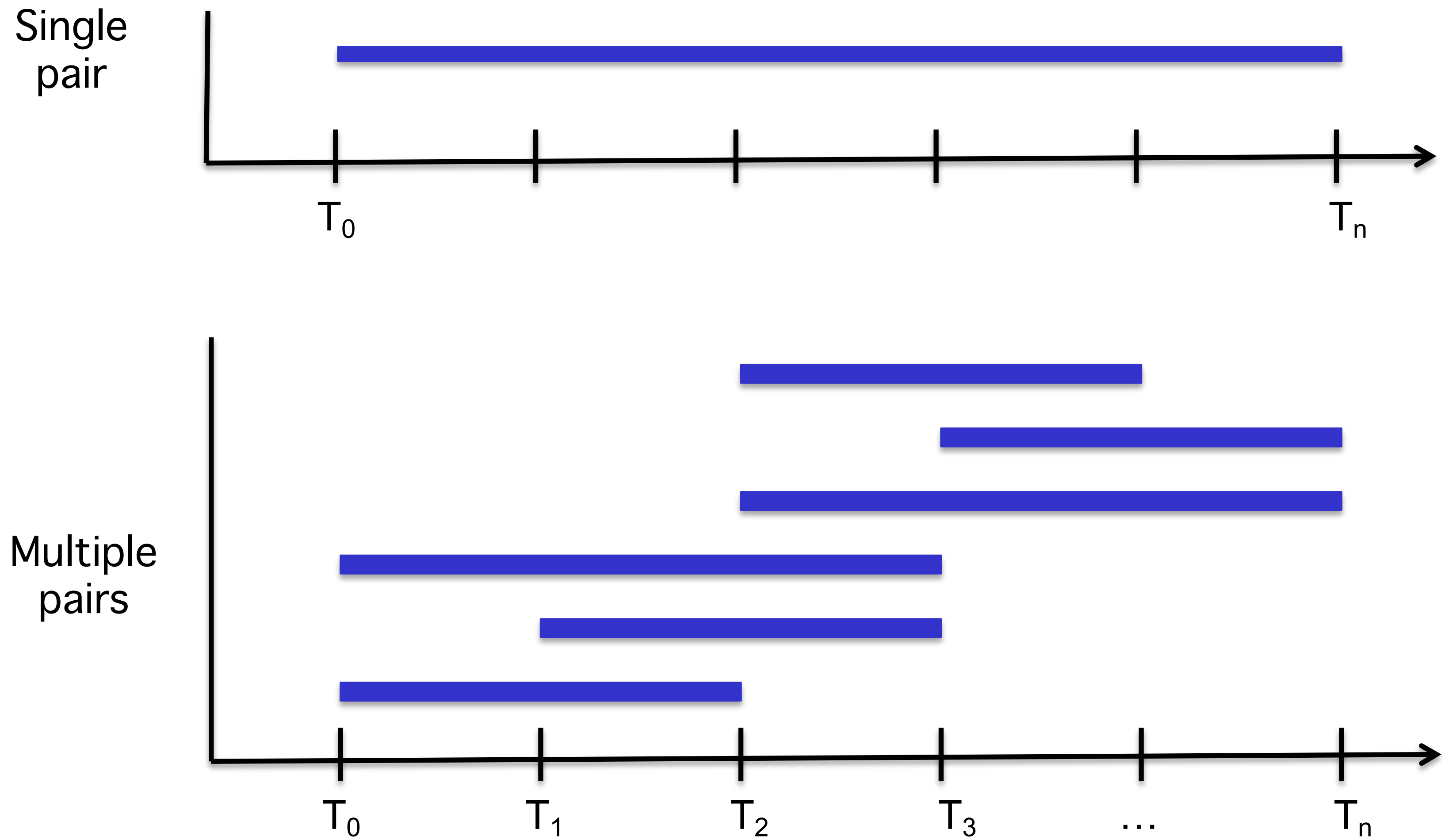


881 ERS + Envisat interferograms over Los Angeles, California

Fraction of image with coherence > 0.4

Limitation 1: Spatial coverage over slowly deforming areas

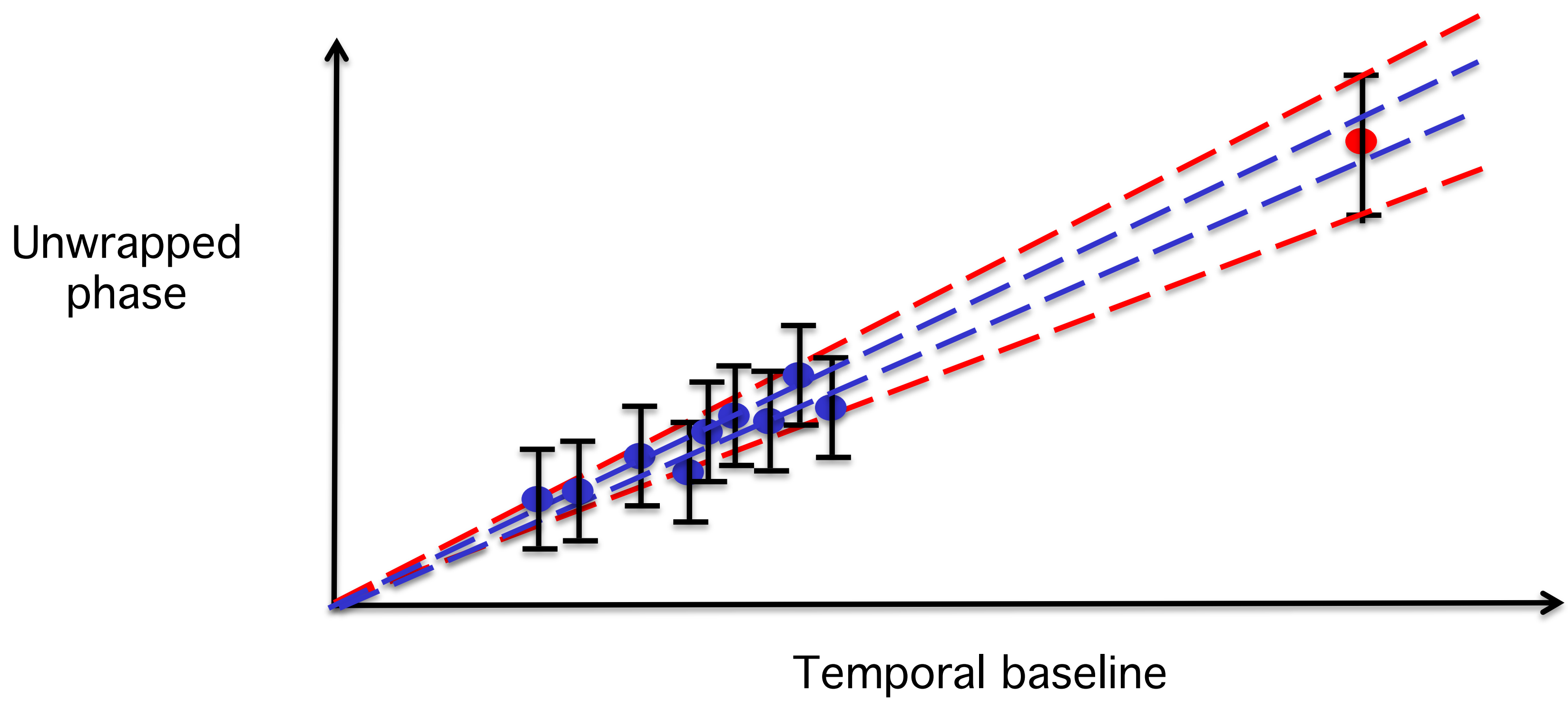
Temporal decorrelation -> Poor spatial coverage



Reduced temporal decorrelation -> Better spatial coverage

Limitation 2: Mitigating atmospheric and decorrelation noise

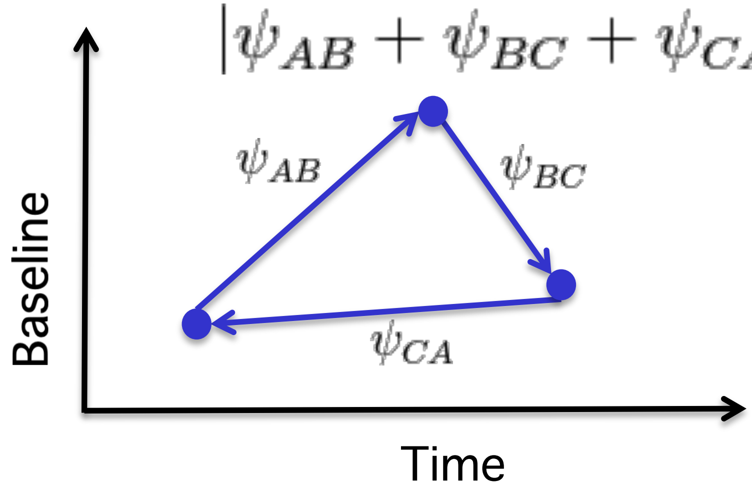
Example: Estimation of average LOS velocity

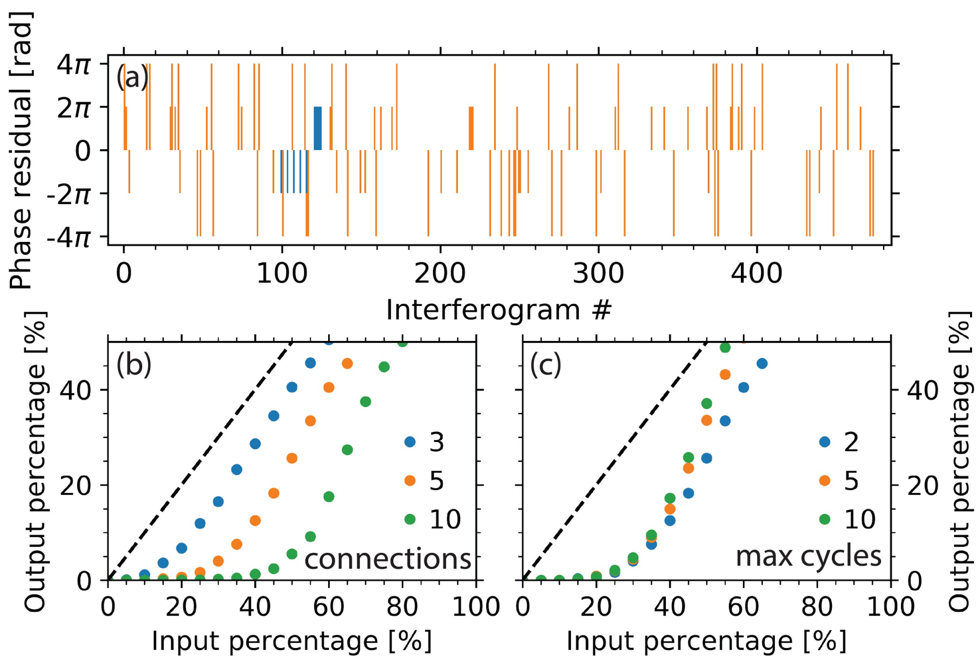


- Atmospheric contributions are uncorrelated in time (difference of > 1 day)
- We can beat down its contribution by combining information from multiple SAR acquisitions instead of just two.
- Decorrelation contributions and unwrapping errors are also less likely for more coherent interferograms.

Limitation 3: Detecting unwrapping errors

$$|\psi_{AB} + \psi_{BC} + \psi_{CA}| < \pi$$





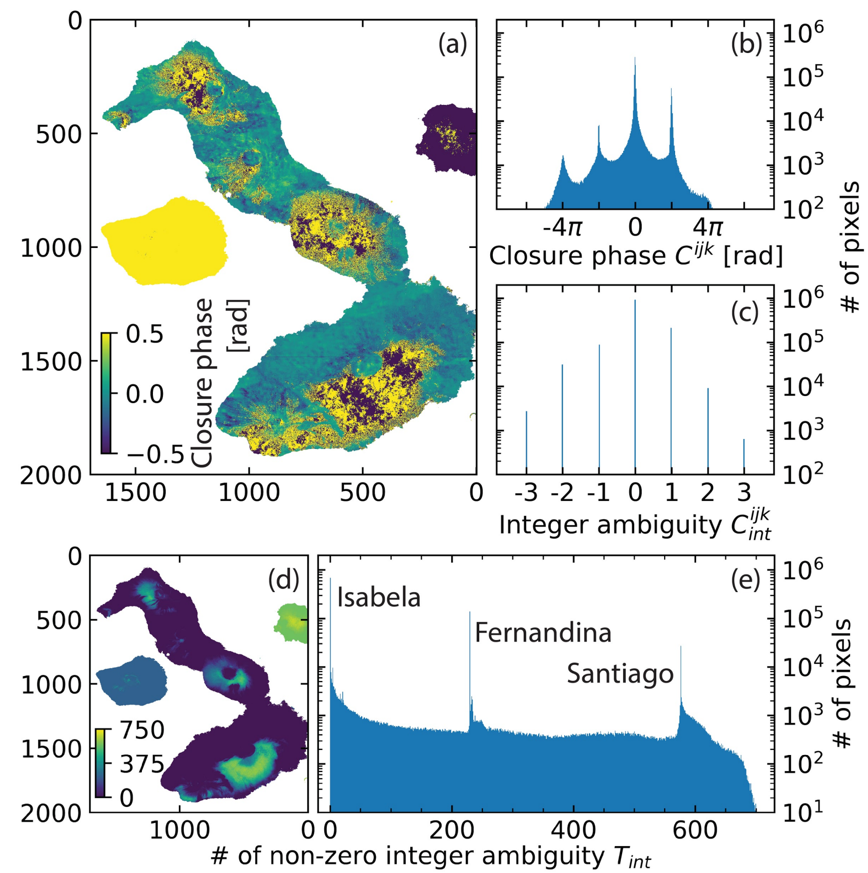
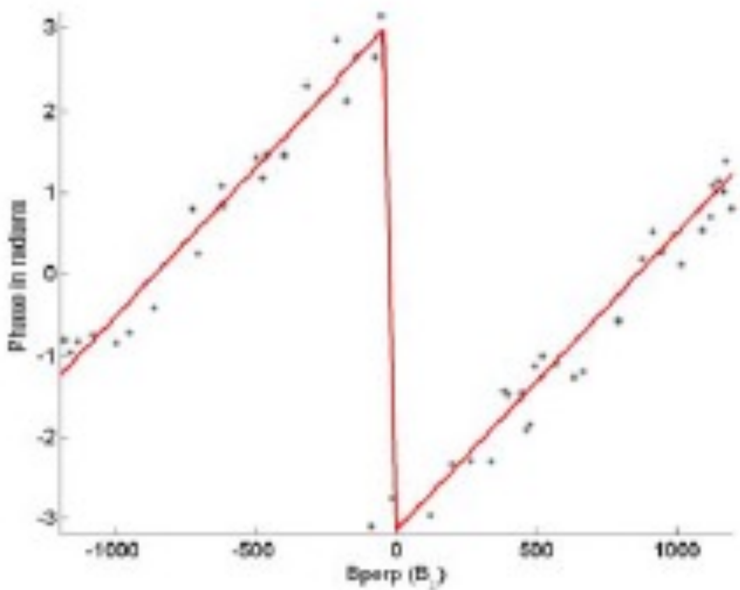


Image: Yunjun et al (2019)

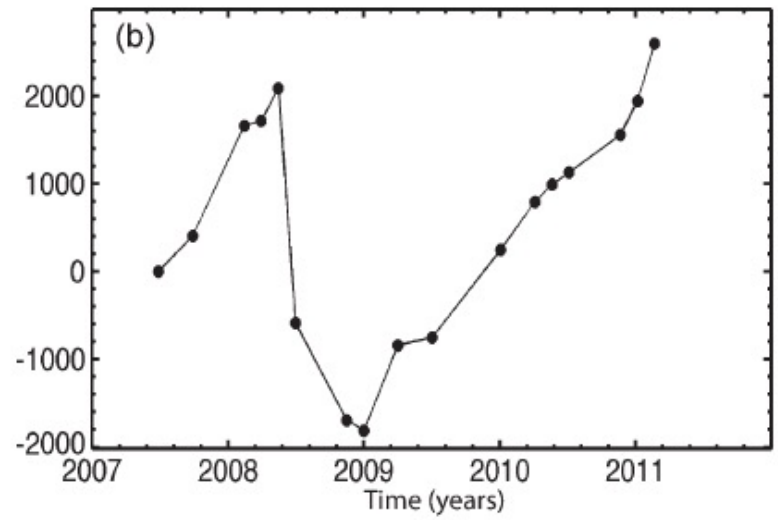
Limitation 4: DEM errors



$$\phi_{dem} = \frac{4\pi}{\lambda} \cdot \frac{B_{\perp}}{r \cdot \sin\theta} \cdot \delta z$$

(Pixel phase – local average) vs Bperp

Image: Fattahi (2014)



Bperp vs Time for ALOS PALSAR

- (Pixel phase – local average) shows a trend w.r.t perpendicular baseline
- DEM error cannot be distinguished from deformation in the case of systematic orbit drift – ALOS PALSAR.

Motivation for Time-series InSAR

- Science argument:
  - Would time-history of surface deformation better inform the scientists about active geophysical phenomena over a given area?
  - Would time-history allow scientists to resolve or decouple contributions from different active phenomena based on associated time-scales?

- Overcoming the limitations of D-InSAR
  - Slowly deforming areas
  - Atmospheric artifacts
  - Unwrapping errors
  - DEM errors

Time-series InSAR techniques

Time-series techniques

Persistent Scatterers (PS) methods

- Popular with engineers
- Analysis at high resolution - single look pixel scale.
- Computationally intensive.
- Typically used for small area analysis and infrastructure monitoring

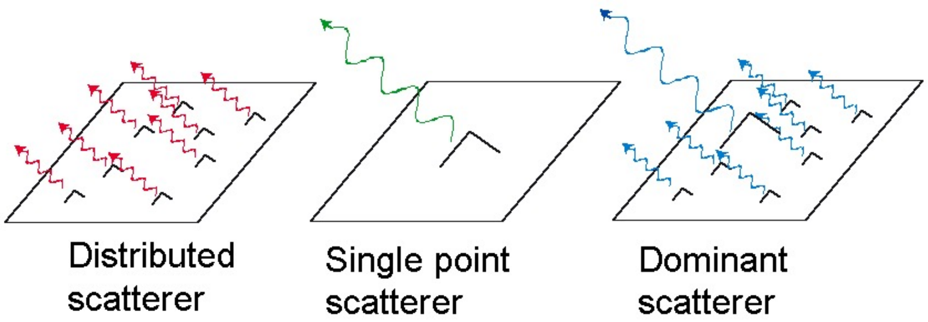
Short Baseline (SB) methods

- Popular with scientists
- Analysis at lower resolution - multi-look pixel scale.
- Typically used for large area analysis.

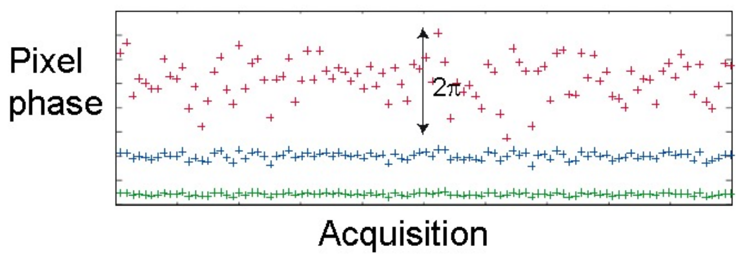
Covariance-based methods

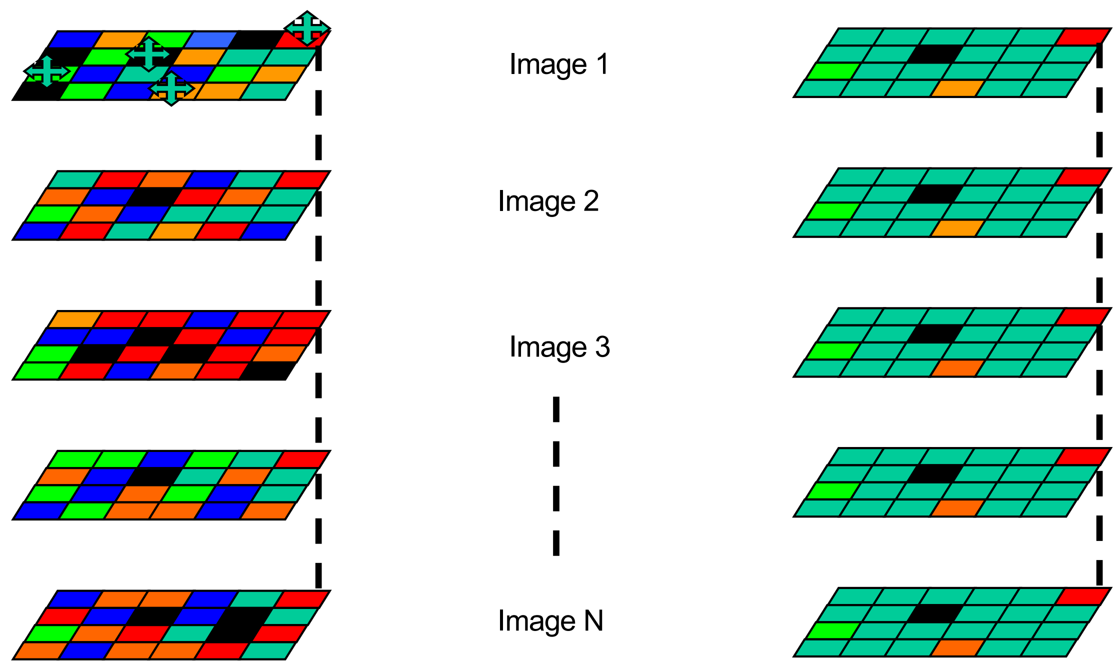
- Popular with engineers
- Best of both worlds – PS and SB
- Extension of PS techniques
- Newer approach and becoming more popular
- More robust approach

What are PS and DS?



PS are corner reflector like resolution elements that are characterized by a dominant scatterer.





Use statistical techniques to identify scattering elements that do not change too much with time or geometric baseline.

PS Interferogram network

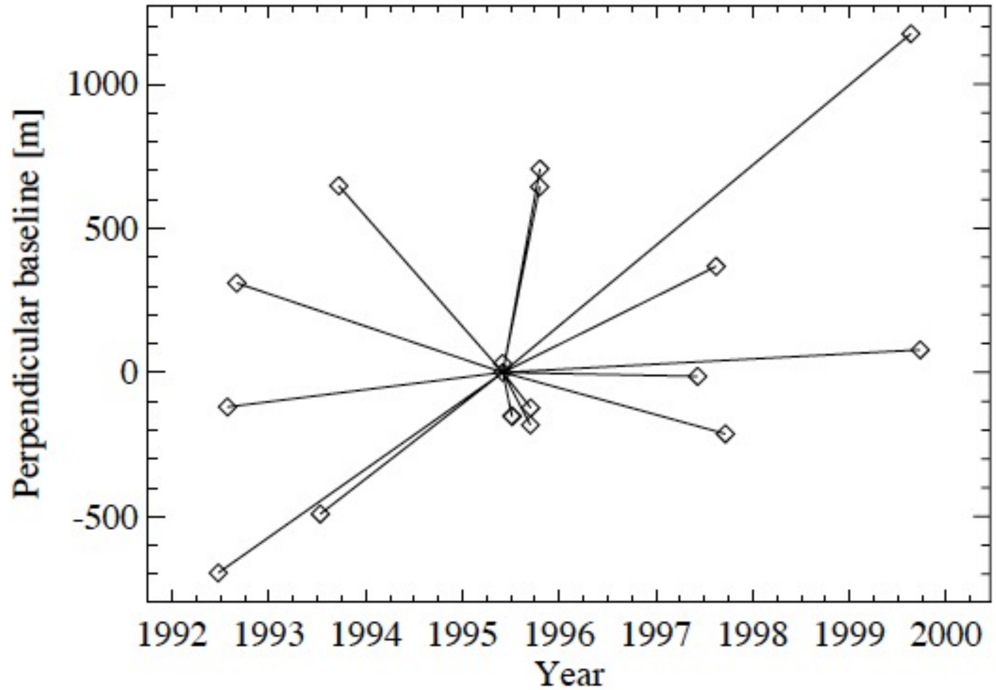


Image: Lauknes et al. (2008)

- Ideal point scatterers do not decorrelate with baseline.
- Common reference network contains the same information as any other interferogram network.
- The reference scene typically is located near the centroid in time-space and baseline space.

Amplitude-based PS identification

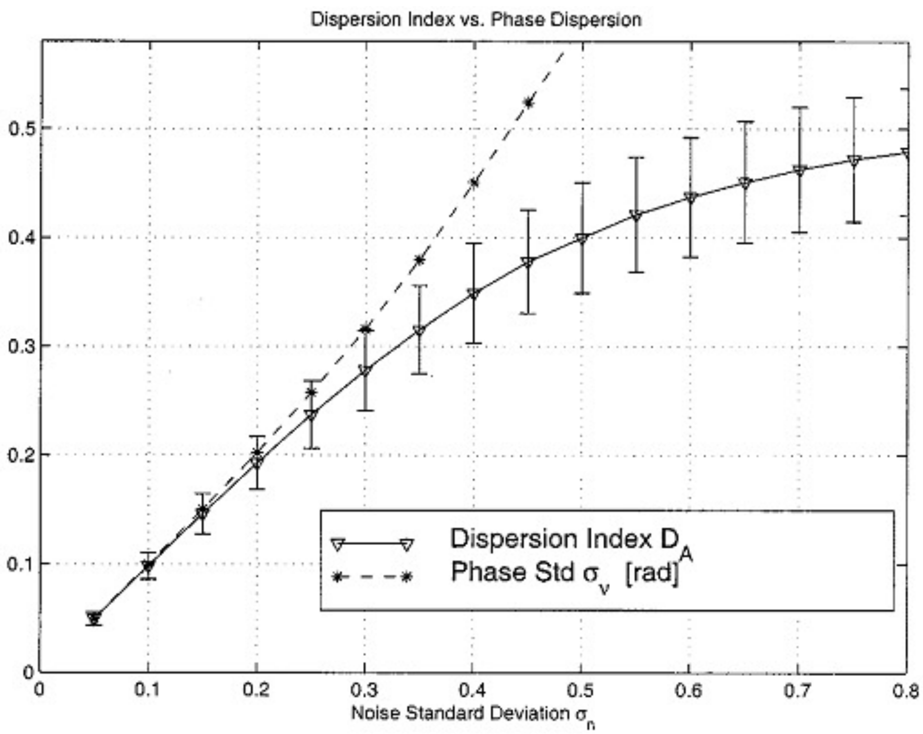


Image: Ferretti et al. (2000)

Simple signal model for observed SAR data.

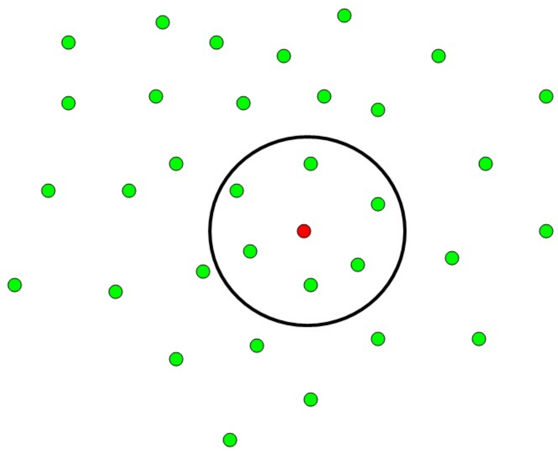
$$s_i = 1 + n_i \qquad \forall i = 0, 1, \cdots, N$$

$$D_A = \frac{\sigma_{|s|}}{\mu_{|s|}}$$

$$\text{Amplitude Dispersion} = \frac{\text{Std. dev of amplitude}}{\text{Mean of amplitude}}$$

- Amplitude stability is used as a proxy for phase stability.
- Can be easily computed using a stack of coregistered SLCs.
- Works very well in urban areas.
- Can be tuned for different scattering models – e.g, two dominant scatterers etc.

Phase-based PS identification



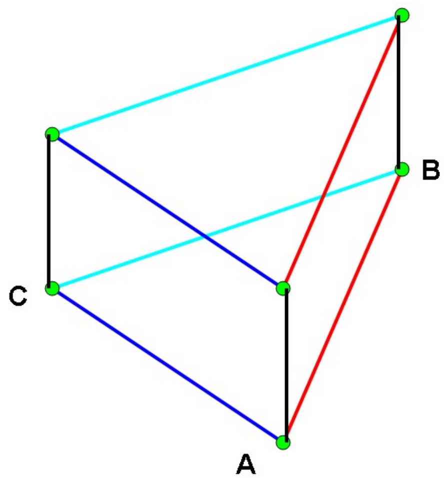
$$\phi_{ifg} = \phi_{defo} + \phi_{aps} + \phi_{orb} + \Delta\phi_{topo} + n$$

Deformation	Spatial $\downarrow$	Temporal $\downarrow$
Atmospheric phase screen	Spatial $\downarrow$	Temporal $\uparrow$
Precise orbit errors	Spatial $\downarrow$	Temporal $\uparrow$
Topo correction error	Spatial $\uparrow$	$\propto$ Baseline
Uncorrelated noise terms	Spatial $\uparrow$	Temporal $\uparrow$

$\uparrow$ High frequency $\downarrow$ Low Frequency

- StaMPS (Stanford Method for PS) framework by Andy Hooper
- Initialize network with reasonably stable pixels
  - Iteratively identify a self-consistent network of stable pixels
  - Weights of pixels based on phase stability
- Usually converges in about 7-8 iterations
- Performs better in natural terrain than amplitude-based methods.

PS - Phase unwrapping



Unwrapping grid is Delaunay triangulation in spatial domain and regular grid in time domain.

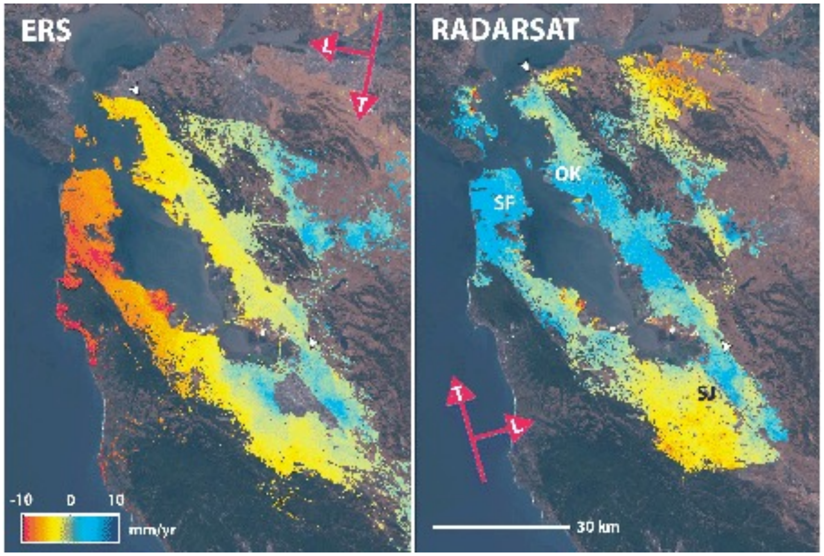
<u>Space first</u>

- Unwrap each interferogram in space using conventional 2D techniques
- Unwrap each edge in time
- Adjust each unwrapped interferogram to accommodate changes.

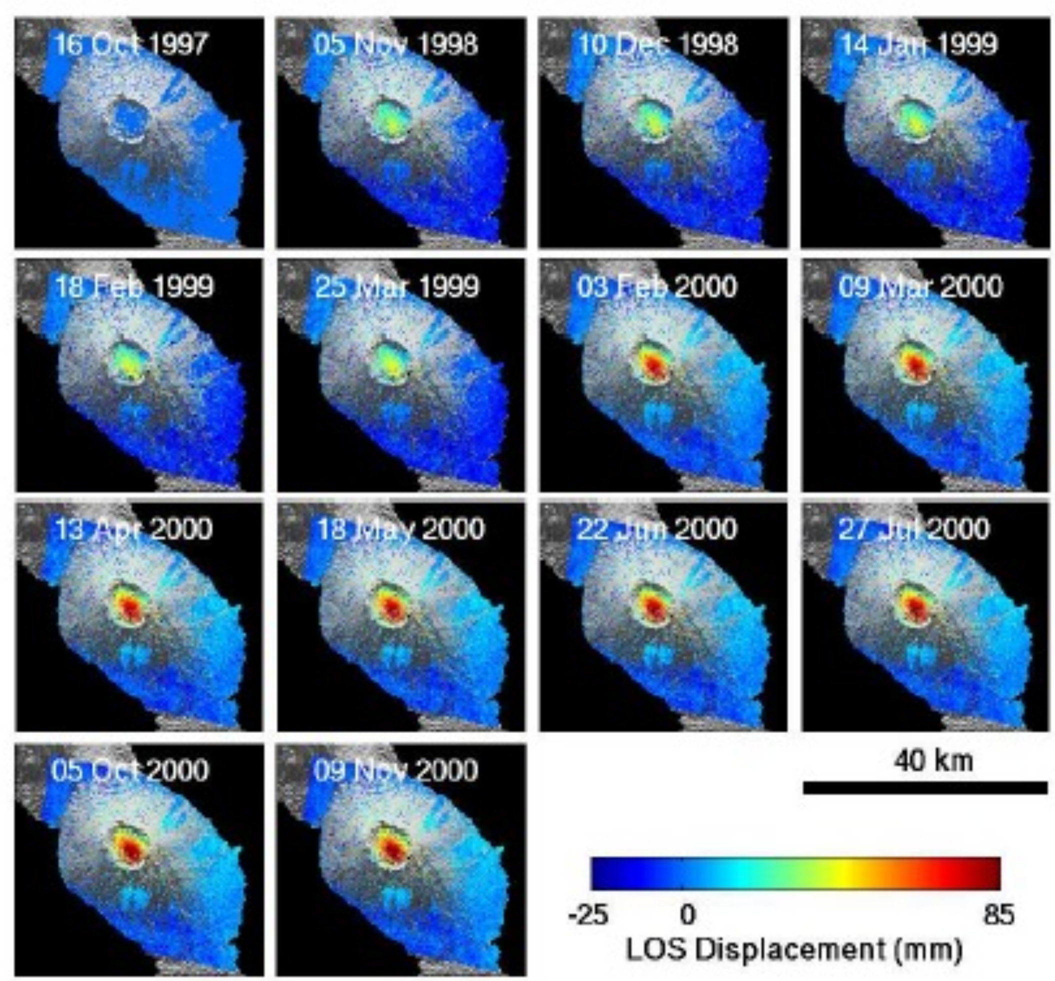
<u>Time first</u>

- Unwrap each edge of Delaunay triangulation in time- i.e, time-series of spatial gradients
- Use unwrapped solution as initial guess to spatial unwrapping using conventional 2D techniques.

Applications of PS



Fault activity in the San Francisco Bay Area (Image: TRE and UC Berkeley)



Deformation time-series for Volcan Alcedo in the Galapagos using ERS-data (Image: Andy Hooper)

Effect of resolution on PS

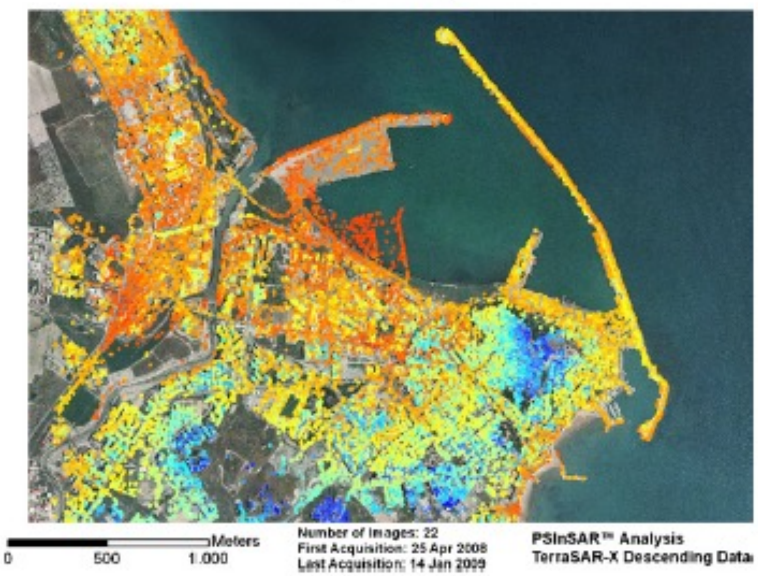


Image: TRE (2010)

- Theory: Higher resolution leads to fewer mixed pixels and hence, higher PS density.
- This has been validated using data from high resolution sensors – TSX, CSK, RSAT2.
- High resolution acquisitions resulted in significantly higher PS density than from older C-band sensors – ERS, Envisat and Radarsat-1.

Building-scale monitoring

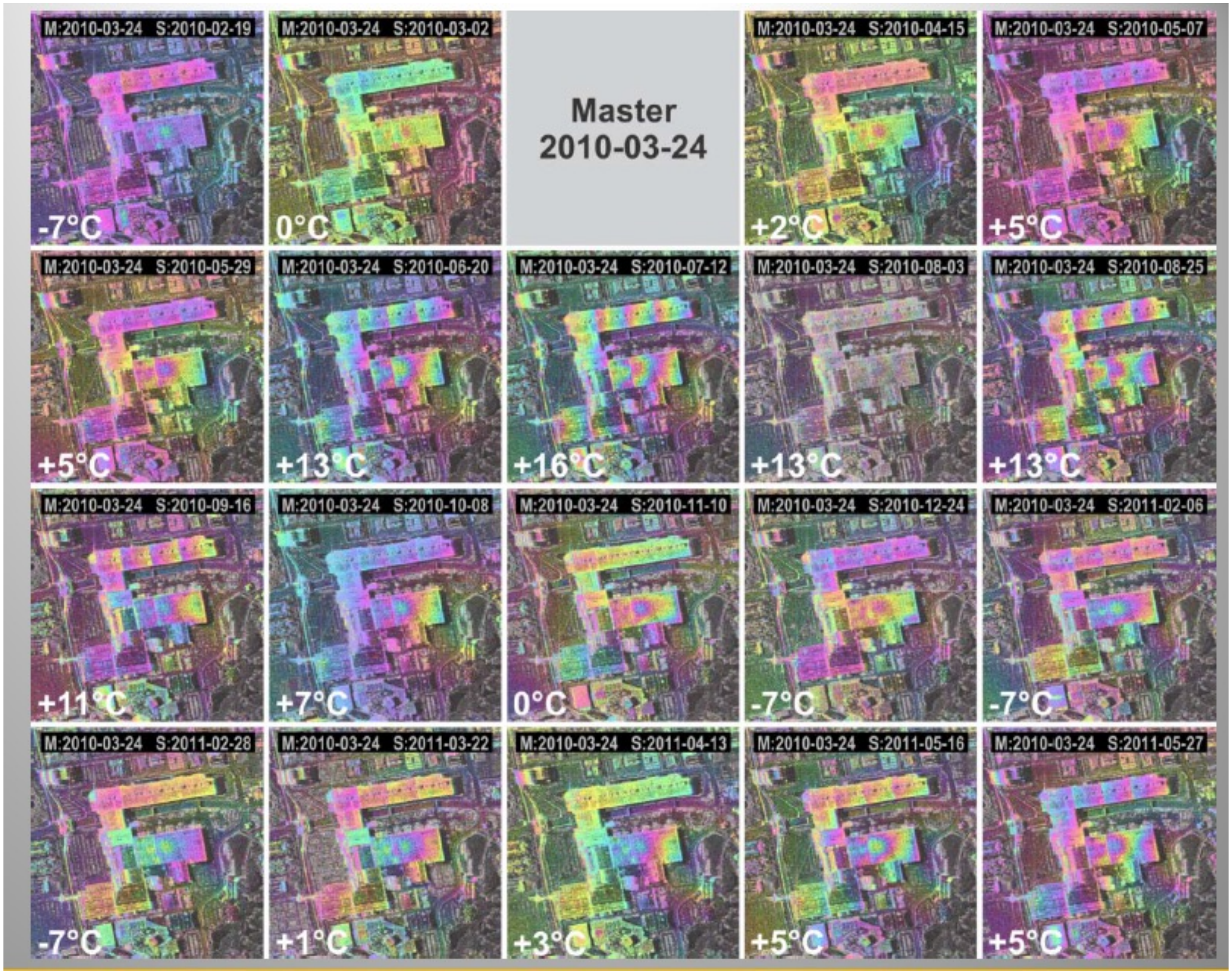


Image: Jendryke et al (2013)

PS: Coregistration drives everything

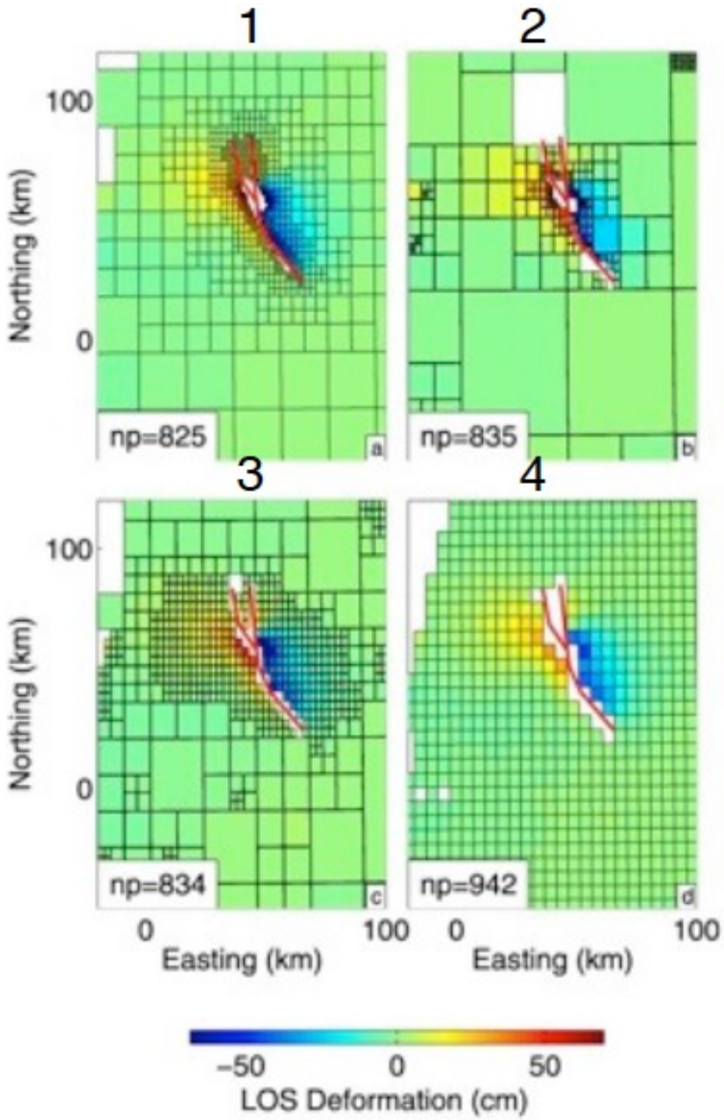
- PS analysis is performed at highest resolution and pixel selection techniques rely on precise coregistration

- Till a couple of years ago, freely available software typically use simple polynomial models to coregister images.

- PS techniques are more popular amongst engineering groups and industry

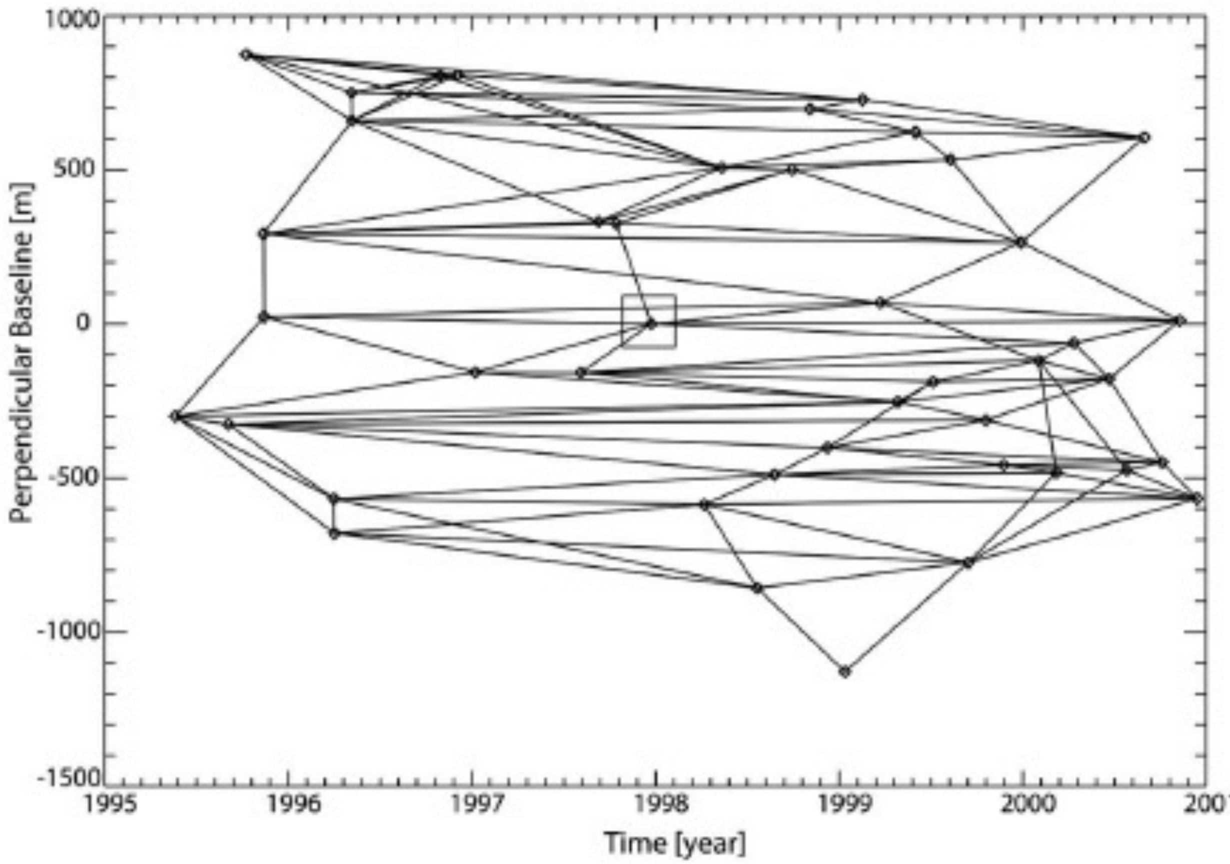
PS: Tectonics applications perspective

Image: Lohman (2013)



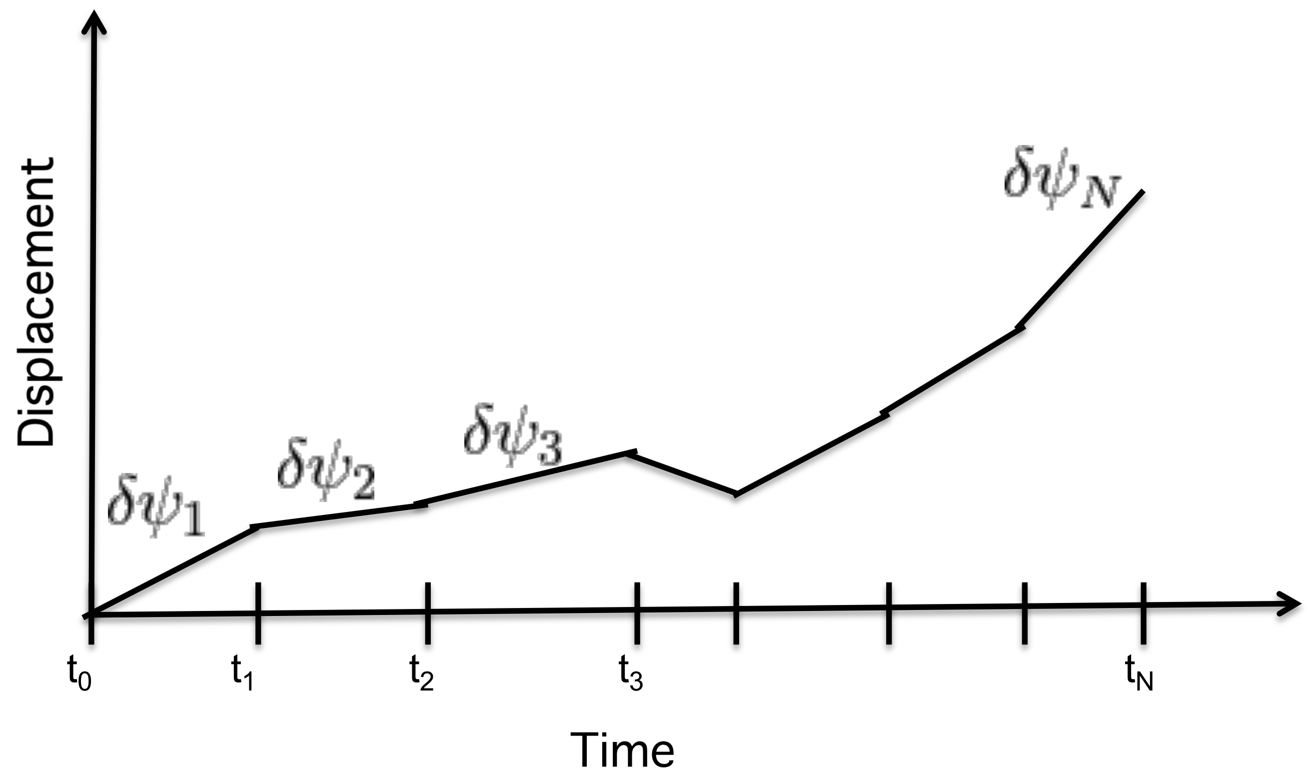
- Tectonic studies typically interested in areas of few 100 km x few 100 km.
- PS used for targeted studies – landslides, volcanoes etc.
- For modeling, scientists often reduce data from 10^6-10^7 observations to 10^2-10^3 points.
- Modeling tools use fault patches of few km. High resolution features not captured by these models.
- Resolution of few 100m more than sufficient for tectonic applications.
- PS-InSAR typically used after other methods fail to perform satisfactorily

Short Baseline Subset (SBAS) method



Time-baseline plot for San Francisco ERS dataset
(Agram et al., 2011)

Simple formulation



$$\psi(t_N) = \sum_{i=1}^{N} \delta\psi_i$$

Estimated time-series is sum of piece-wise terms

$$\psi_{ifg}(t_i, t_j) = \sum_{k=i}^{j} \delta\psi_k$$

Interferometric unwrapped phase is sum of piece-wise terms spanned by the acquisitions

Variants of SBAS

- Original SBAS implementation (Berardino et al., 2002) demanded similar amount of rigor in coregistration as PS methods.

- Modifications can be easily implemented
  - Reuse of already existing D-InSAR tools
  - Heavy filtering of interferograms reduces resolution and relaxes strict coregistration requirements
  - Simpler workflows possible for certain applications

- Most modifications at the inversion stage
  - Inversion of wavelet coefficients / data
  - Use of GPS-like model including seasonal terms, step functions, polynomials etc

- Example: NSBAS, MInTS etc.

Applications of SBAS

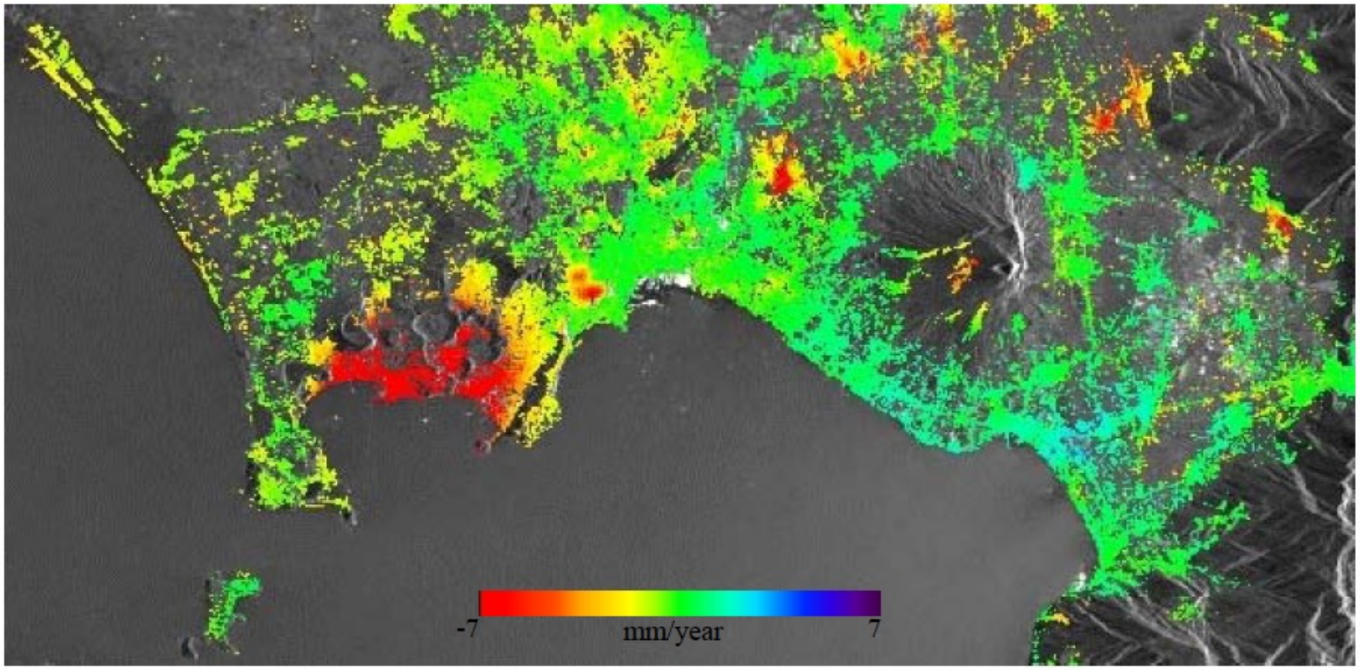


Fig.1 False-color map of the measured deformation superimposed on the SAR image amplitude of Napoli Bay (Italy).

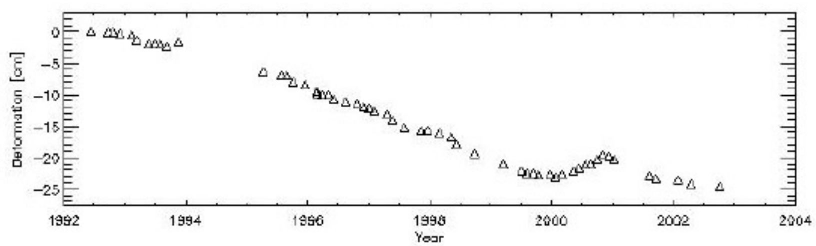
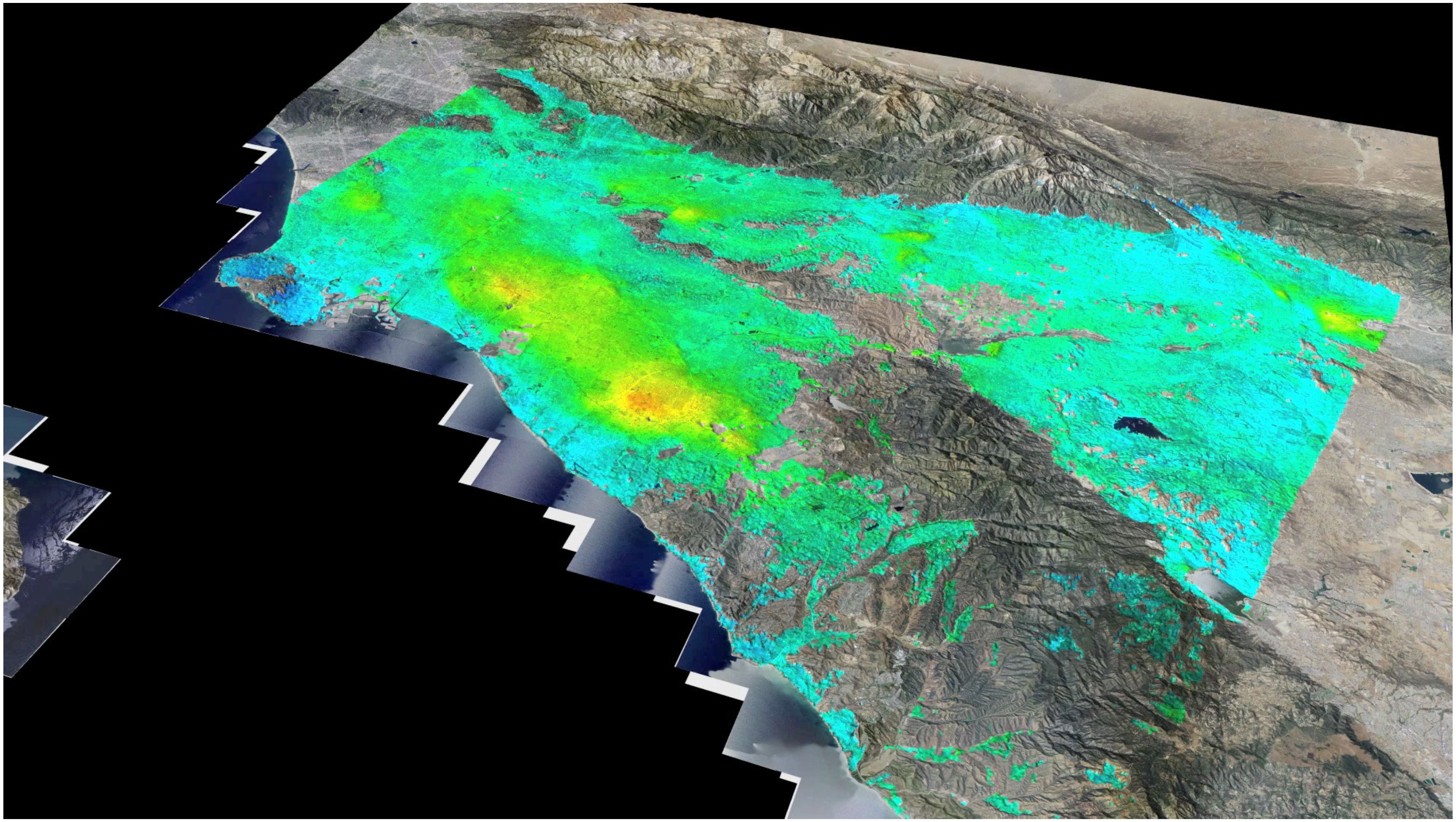


Fig.2 Time-series deformation measured in the area of maximum subsidence/uplift of the Campi Flegrei caldera.

Campi Flegrei caldera in Napoli Bay with 55 ERS acquisitions.

Berardino et al (2003)

More SBAS applications ....



Brian Riel et al.,

Covariance-based methods

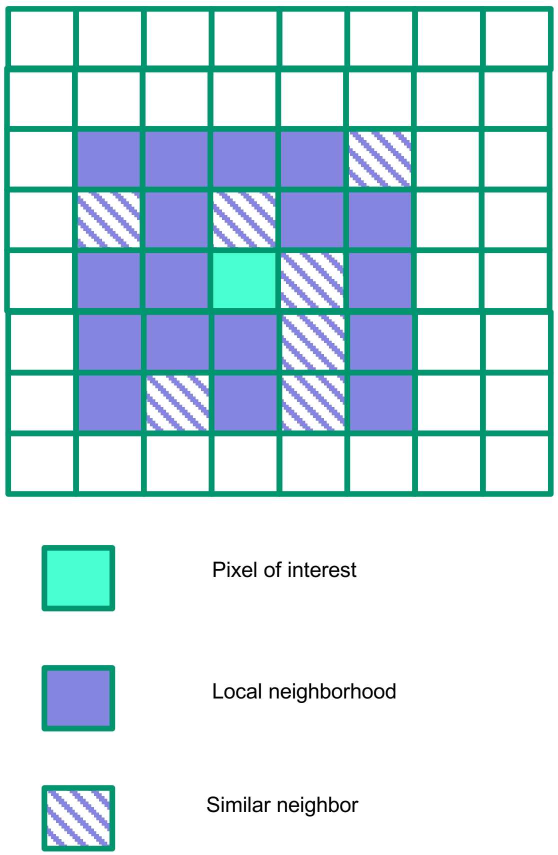
- Best of both worlds.
  - Phase linking (Guarneiri & Tebaldini, 2008)
  - SqueeSAR™ approach (Ferretti, 2011)

- Adaptive feature preserving multilooking
  - PS at full resolution
  - DS multi-looked based on similar neighbors.
  - Resolution of time-series product depends on location.

- Neighbors typically identified by comparing SAR amplitude distributions.

- By design, an extension of PS techniques and relies heavily on precise coregistration
  - Computationally intensive

Methodology



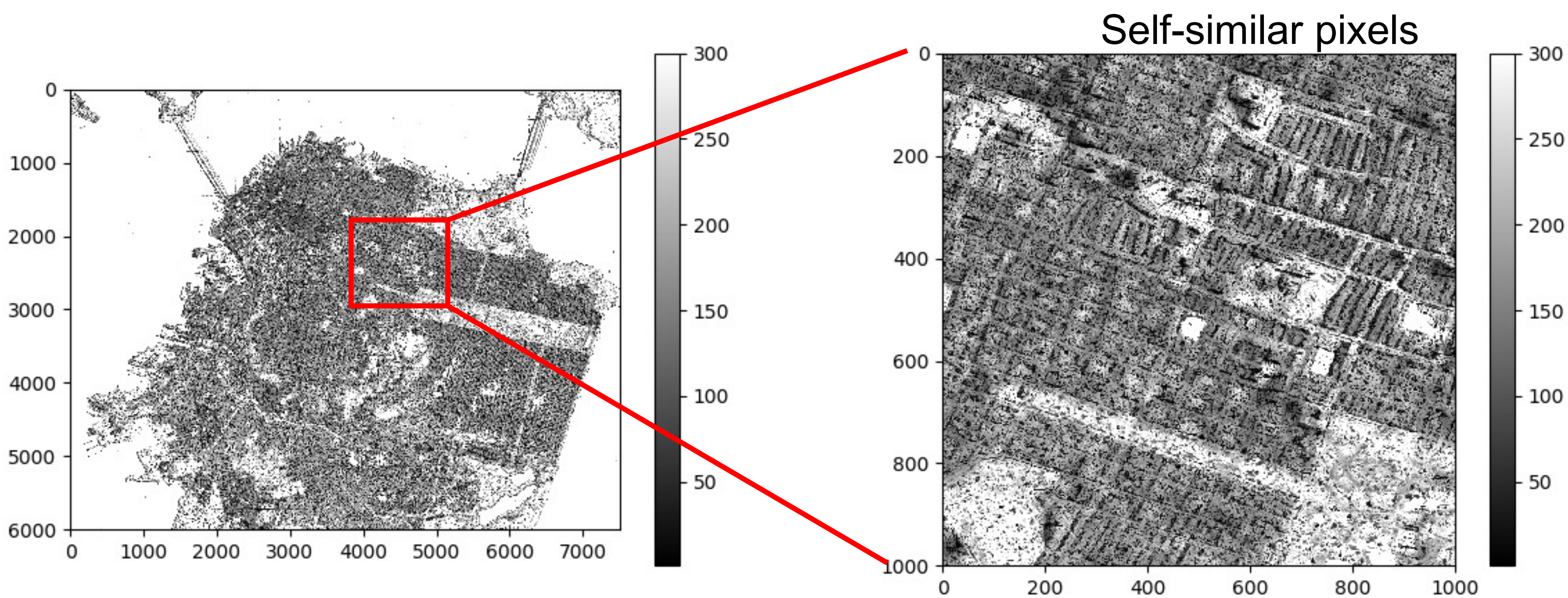
Similarity comparison of Pixels

- Compare histograms of amplitudes for given pixels in stack of coregistered SLCs
- Histogram comparison is more robust than direct comparison of values in SAR data due to speckle
- Variations
  - Self-similar statistical tests
  - Contiguous neighborhood

Self-similar neighbor selection

Example CSK stack of 200 SLCs over San Francisco

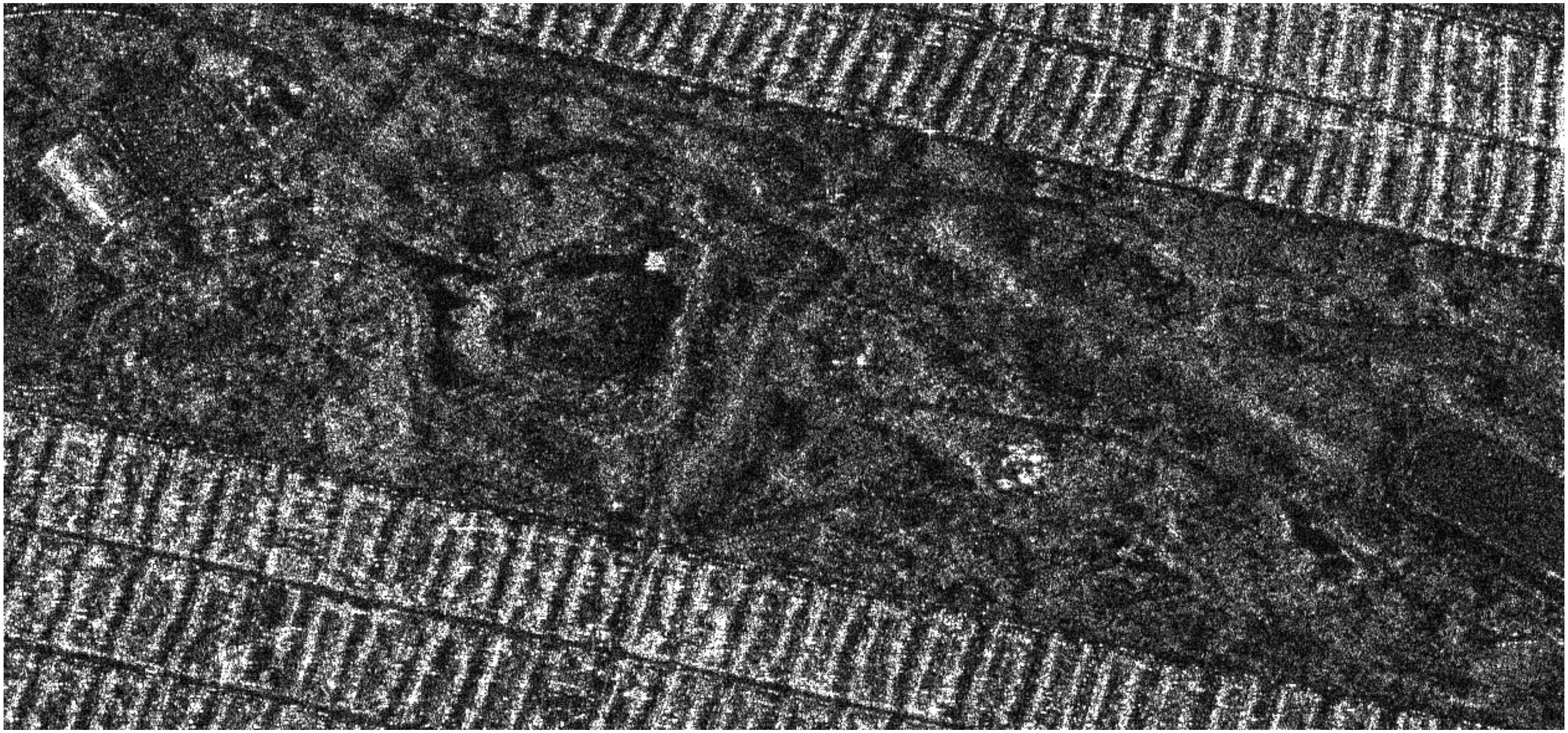
Images from Fattahi, Agram and Bekaert (JPL)



- Neighbors identified with Anderson-Darling tests on amplitude histograms

Original SLC at full resolution

Golden gate park



Despecked SLC – preserves features

Golden gate park

Covariance/Correlation matrix

- Covariance methods extract information from all possible pairs for each pixel
  - Considers every possible pair (Nsar x Nsar)

- Covariance matrix is just adaptively multilooked interferogram for each pair

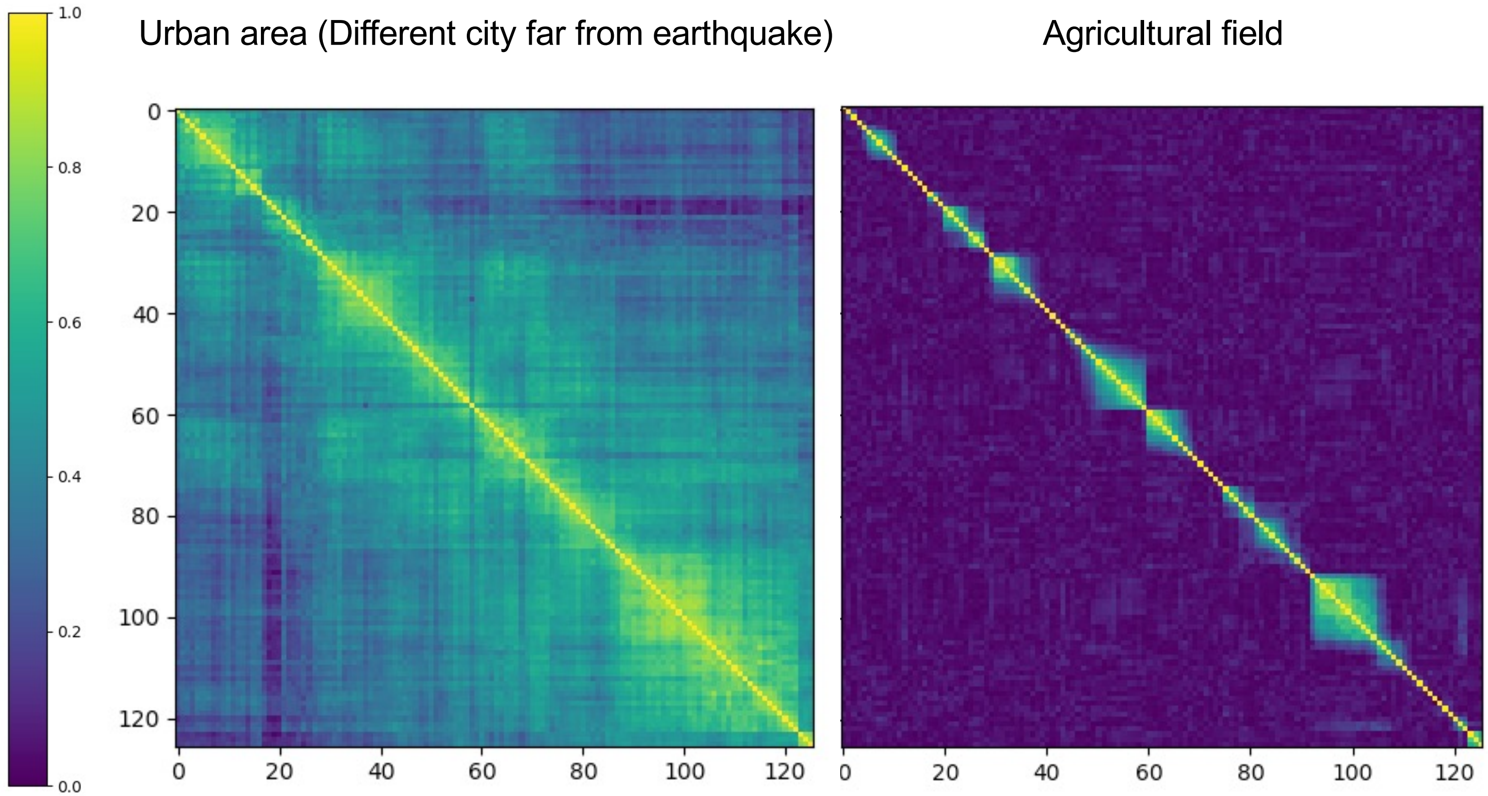
$$C_{ij} = \sum_{L} z_{i,p} \cdot z_{j,p}^{*} \quad \text{for p} \in L$$

- Correlation matrix is just adaptively estimate complex coherence for each pair

$$\gamma_{ij} = \frac{C_{ij}}{\sqrt{\sum_L \left\| z_{i,p} \right\|^2 \cdot \sum_L \left\| z_{j,p} \right\|^2}} \text{for p} \in L$$

Examples of full coherence matrix

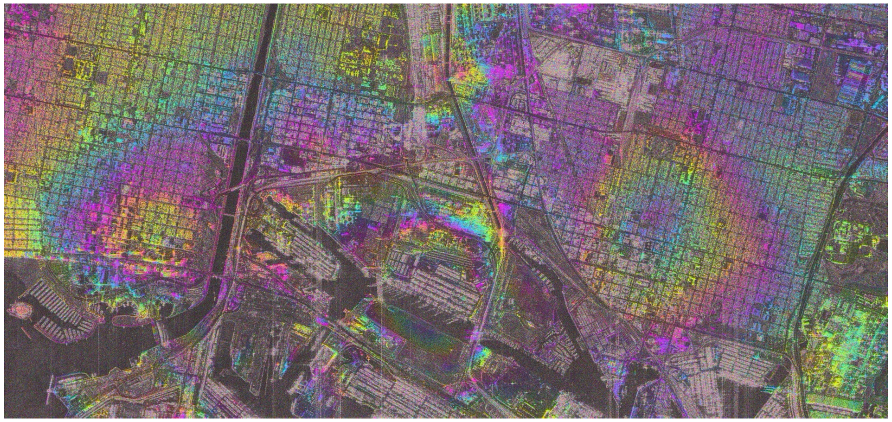
Example from S1 data over Kurdistan EQ (Fattahi)



Extracting information from cov/cor matrix

- Lot of this work was first accomplished in Polarimetric multi-baseline applications (tomography)
  - Directly relevant for InSAR stacking
- Simple PCA-like Eigen Value Decomposition
- More accurate inversion – Phase linking
  - Guarneiri and Tebaldini (2008)
  - Basis of all covariance-based approaches
- Coregistered SLC stack -> Clean SLC stack
  - Option to keep rest of processing the same
  - Phase unwrapping often lot faster

Interferogram despeckling



Unfiltered single look interferogram

Jul 22, 2013 – Oct 7, 2012

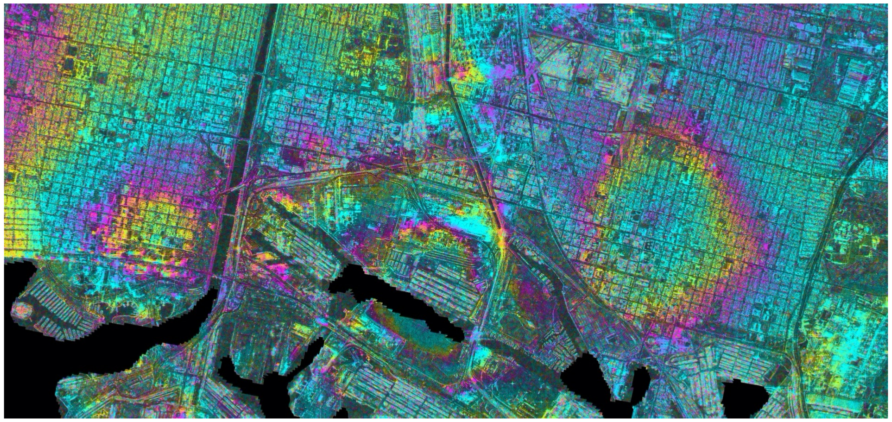
Deformation due to oil extraction clearly visible

Despeckled single look interferogram

Jul 22, 2013 – Oct 7, 2012

Each pixel is coherently averaged with its self-similar neighbors

Results in significantly faster unwrapping at full resolution

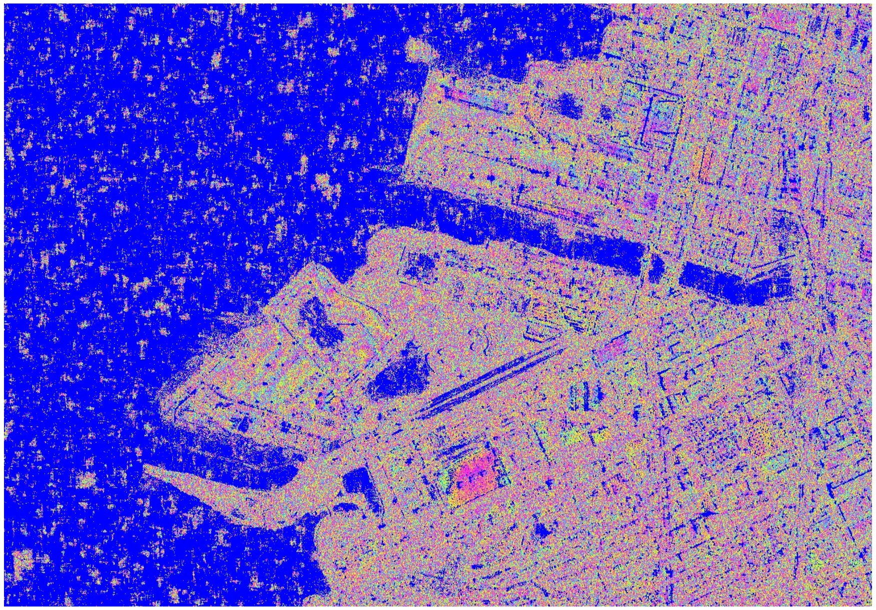


CSK dataset over Long Beach, CA

Latest developments: Updating Stacks

- Sequential Estimator: Towards Efficient InSAR Time-Series Analysis
  - Ansari et al (2017)
- Break up large stacks into mini-stacks
  - Covariance-based approach on mini-stack
  - Compress phase residual of mini-stack to single SLC
  - Covariance-based approach on compressed SLCs to obtain relative phase corrections between mini-stacks
  - Add new mini-stack when sufficient new images are acquired
- Computationally efficient
  - Performs well in terrain where some long term coherence is retained

Example: CSK data over San Francisco



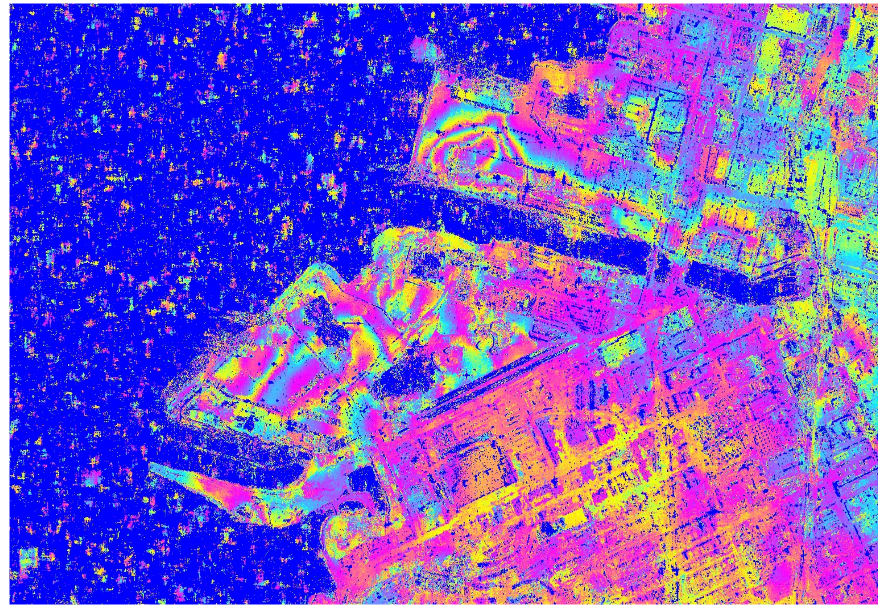
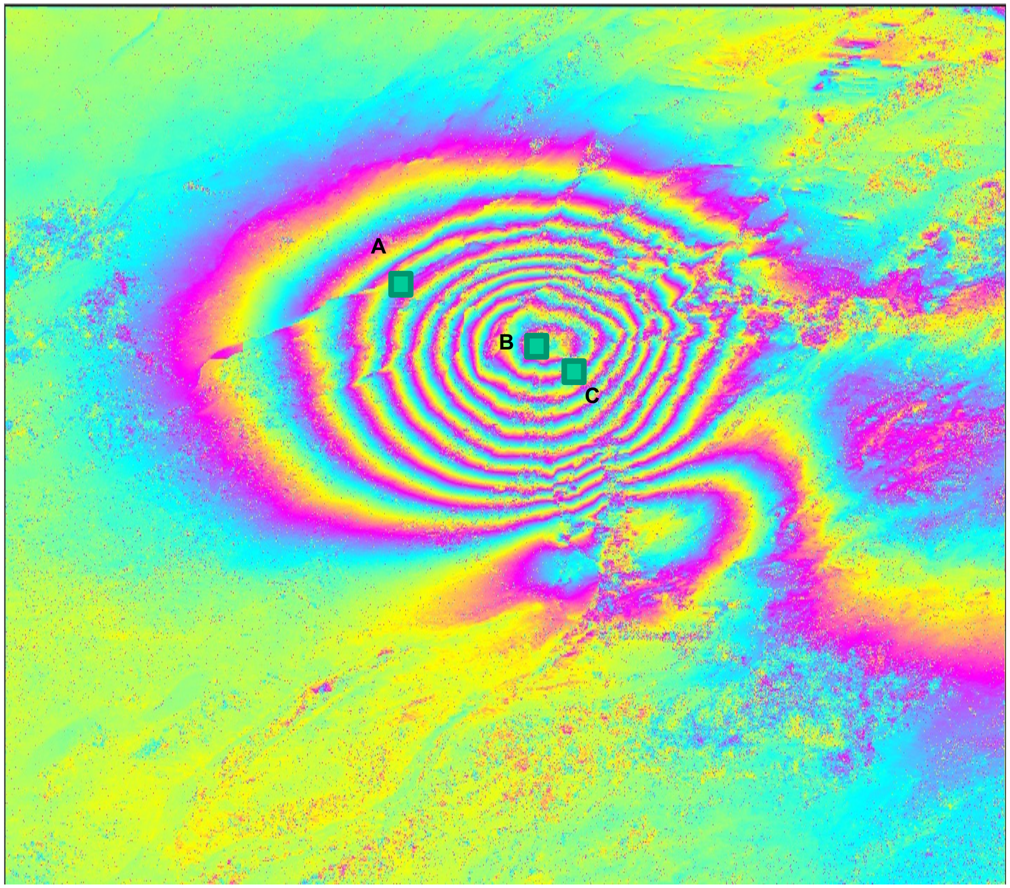


Image from Fattahi, Agram and Bekaert (JPL)

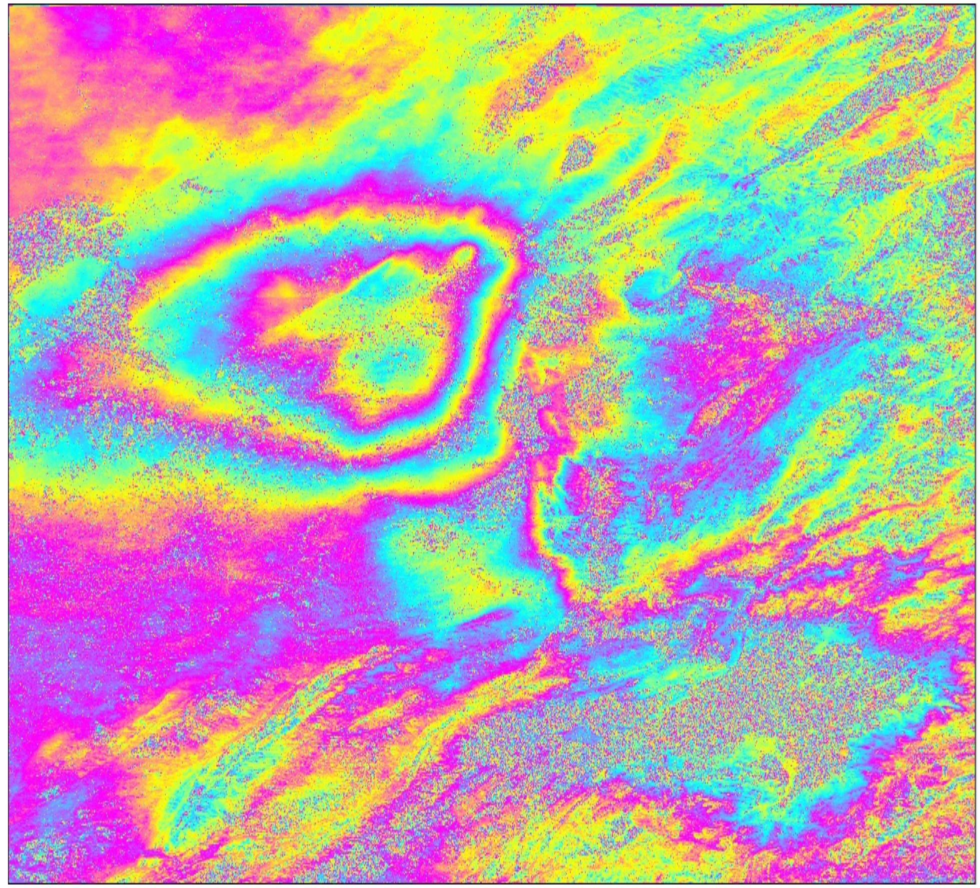
(Left) Conventional 2-pass interferometry between 2 CSK SAR scenes acquired on 2011-06-24 and 2013-10-11 over the Central Waterfront in San Francisco, CA. Subsidence features are not clear due to the large time separation between the 2 images. (Right) Interferogram generated from Sequential EVD estimator which uses the full covariance matrix in time for each pixel. Subsidence features, including sharp boundaries, are clearly preserved in this approach. The interferograms have not been corrected for troposphere and DEM error terms.

Example: : Kurdistan EQ

Co-seismic



Post-seismic



Wrap to 20 radians

Wrap to 2PI

Image and analysis
by Fattahi

Kurdistan EQ – Sequential Estimatortime-series

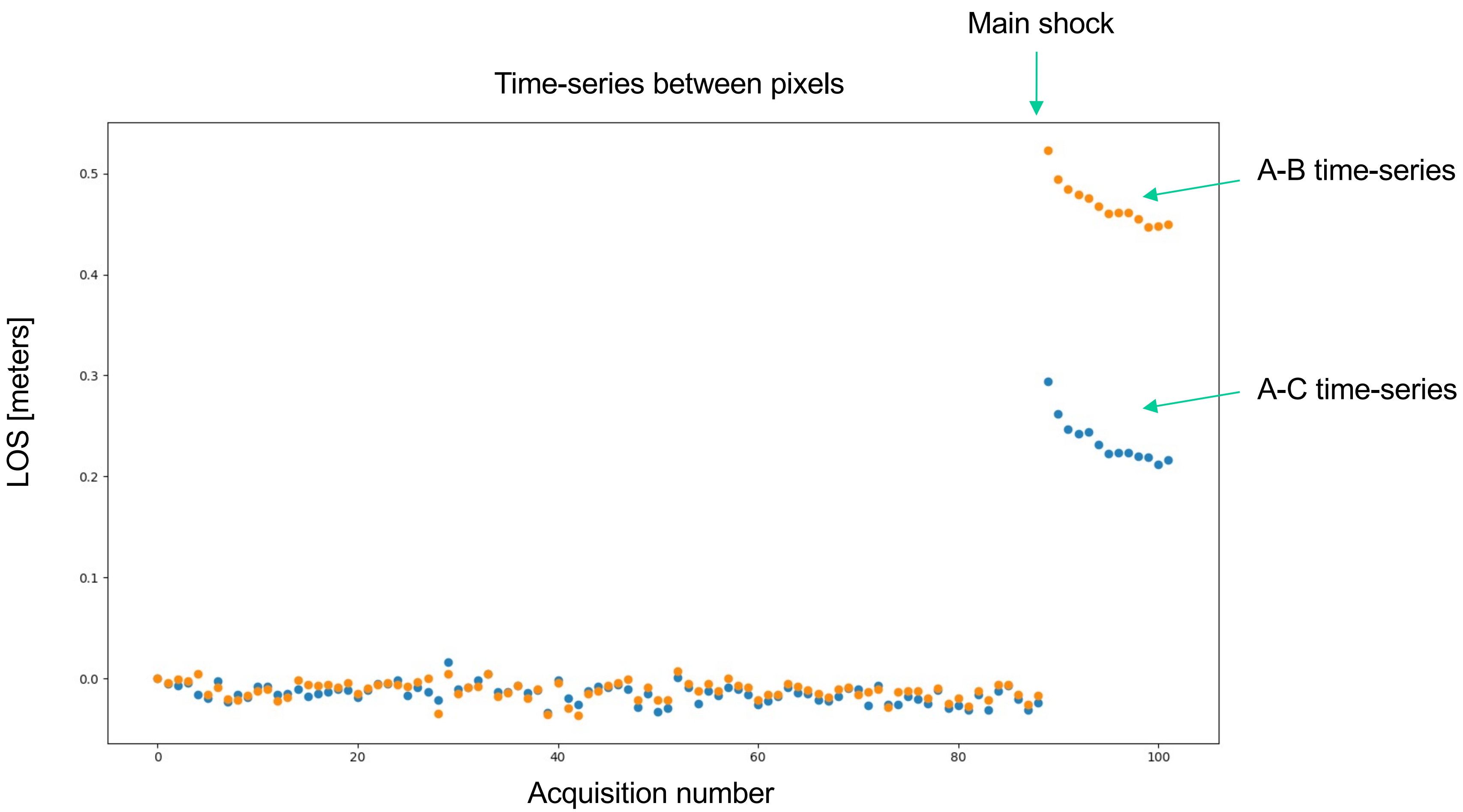


Image and analysis
by Fattahi

Kurdistan EQ – SBAS time-series

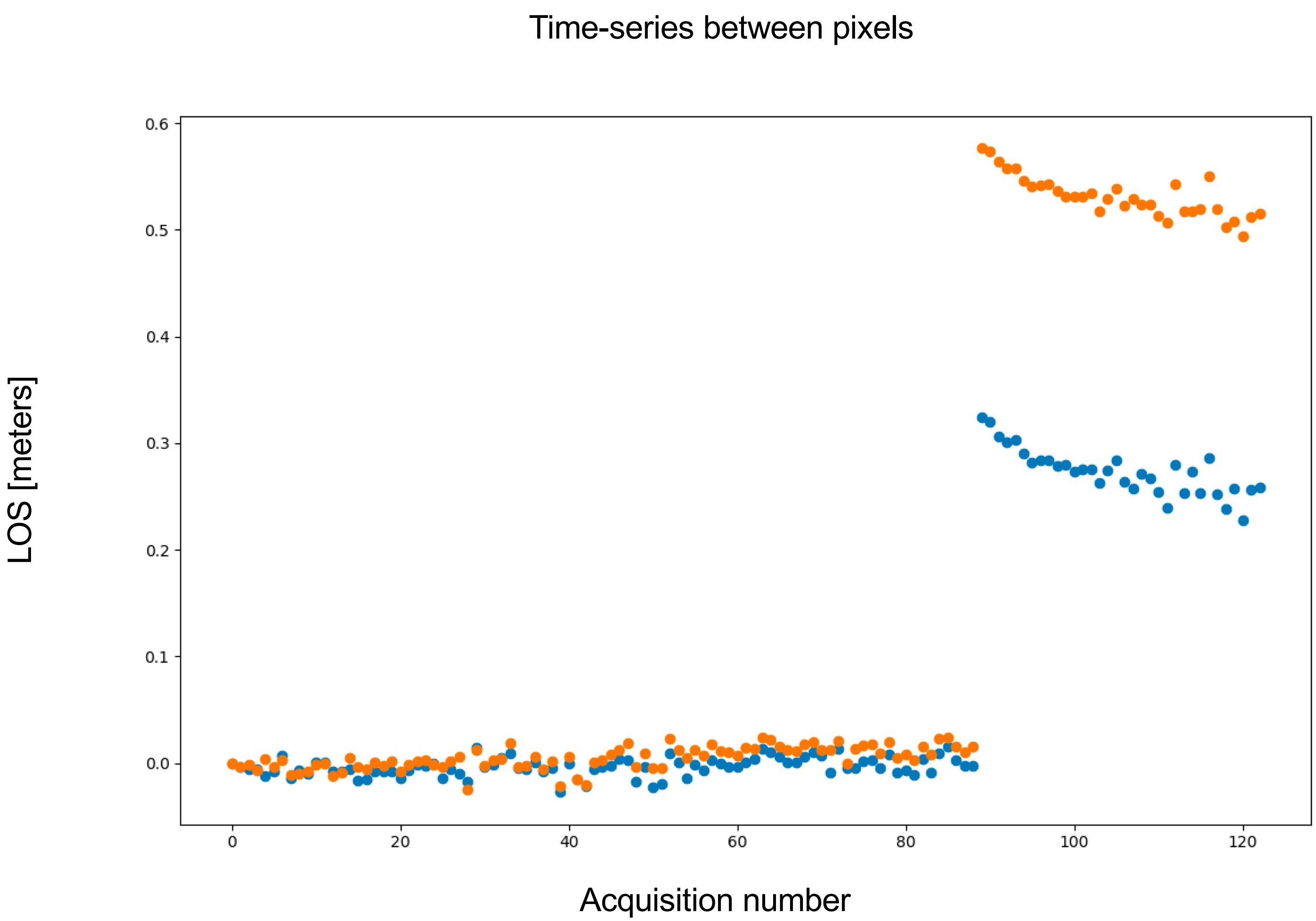
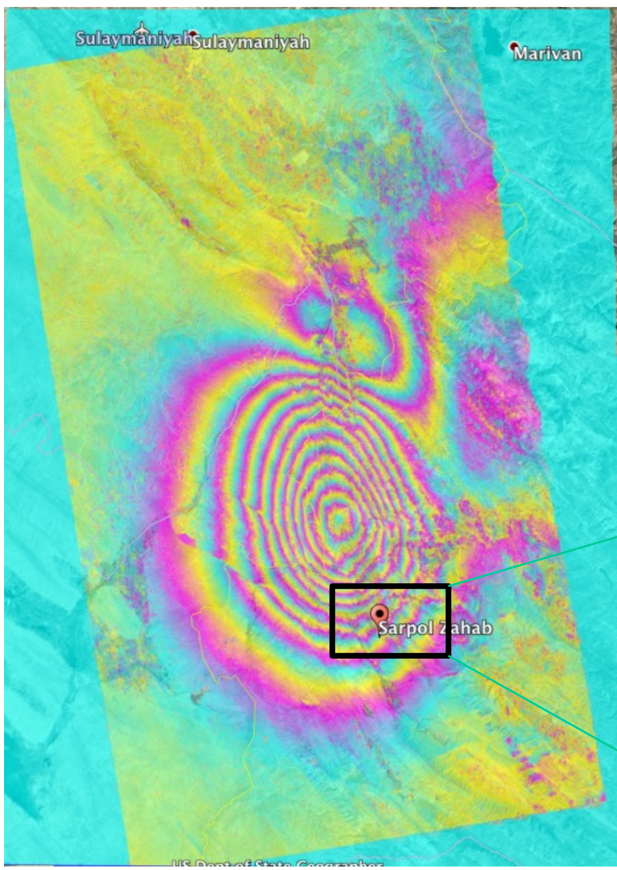


Image and analysis
by Fattahi

Potential for coherence-based Change Detection



Earthquake

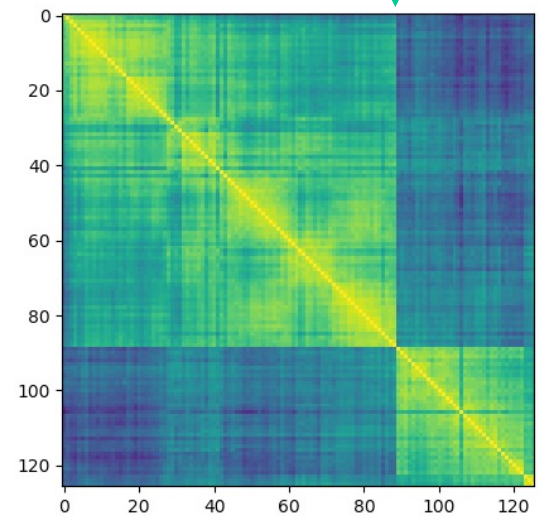


Image and analysis
by Fattahi

Challenges for time-series InSAR

- Phase unwrapping
  - Particularly for high resolution analysis
- Troposphere
- Mission continuity
  - Longer time-series needed to discriminate between different geophysical phenomena
- Multi-dimensional time-series by combining stacks from different geometries
- Computational and storage needs
  - Ability to update stacks with new acquisitions
- Uncertainty products
  - Time-series uncertainties not typically reported