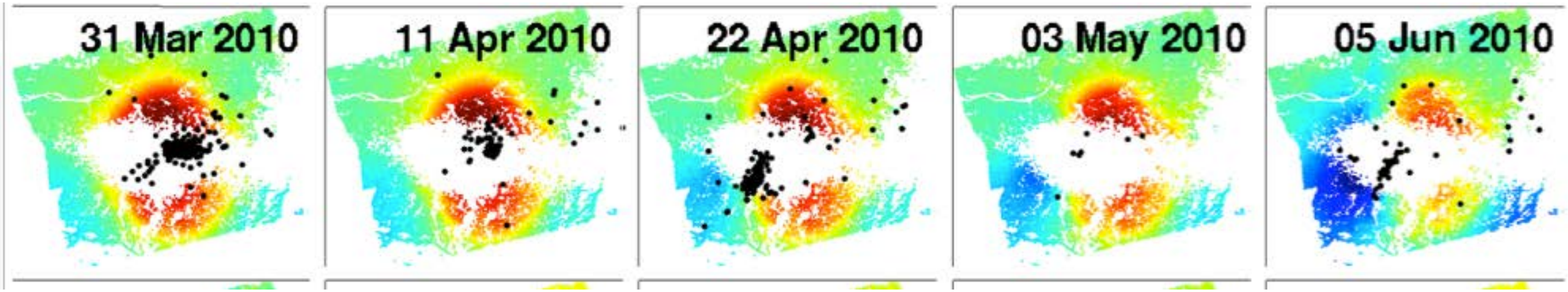
Terrain Motion and Persistent Scatterer InSAR



Andy Hooper
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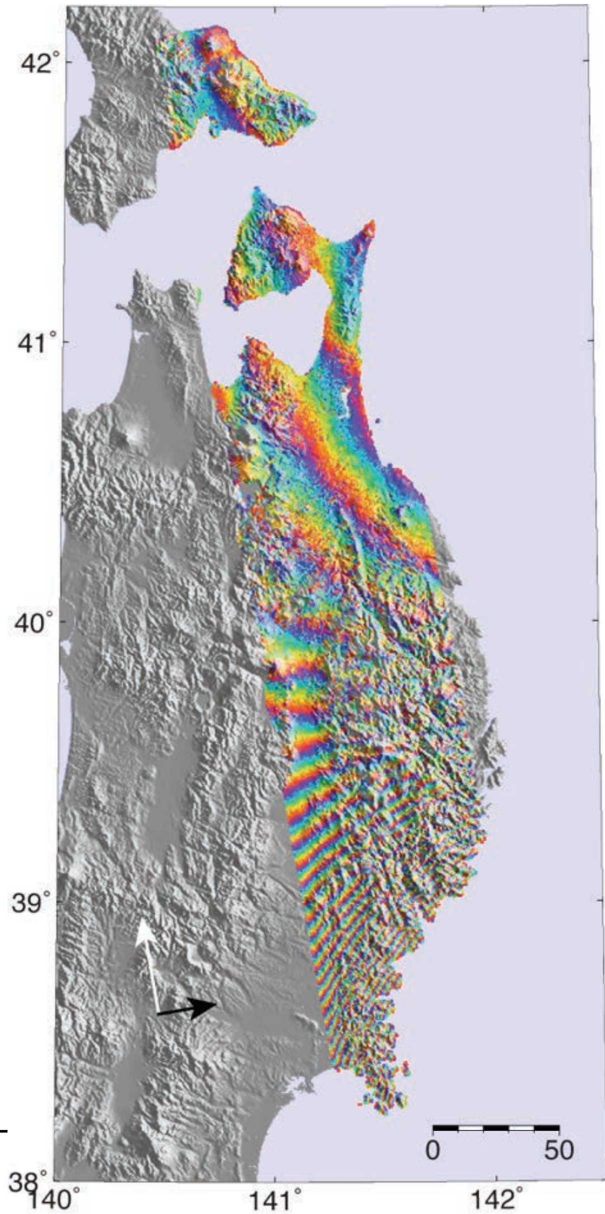
ESA Land Training Course,
Bucharest, 14-18th September, 2015

COMET+
Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics

UNIVERSITY OF LEEDS

Good Interferogram

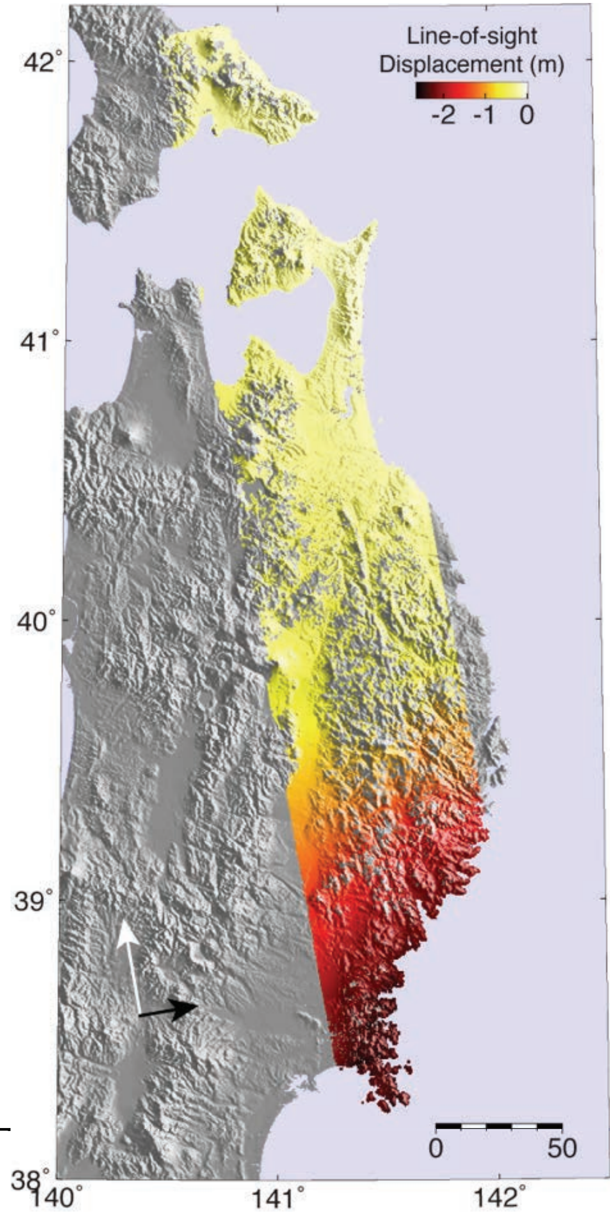


2011 Tohoku earthquake

- Good correlation (low noise)
- Signal is dominated by deformation

ALOS data supplied by JAXA: each colour fringe represents 11.6 cm of displacement away from satellite

Unwarpped Good Interferogram



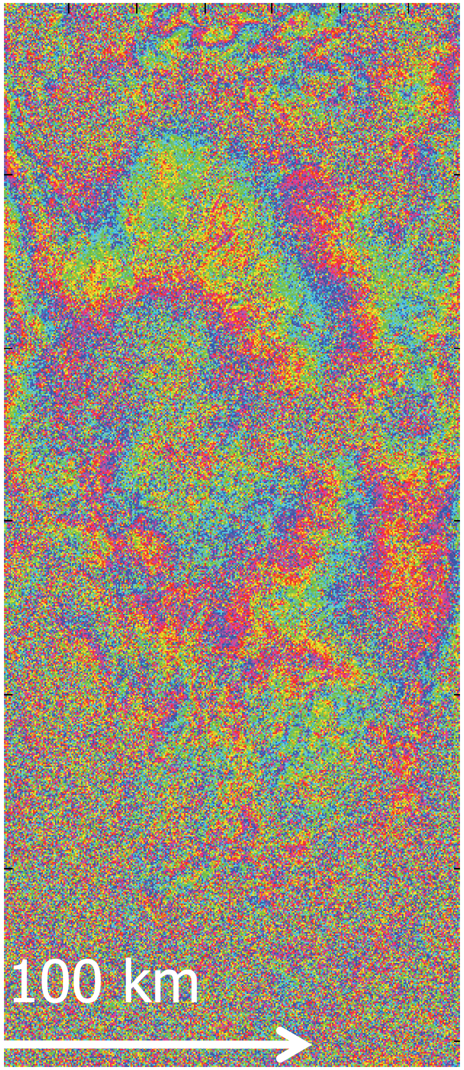
- Can be easily unwrapped
- Deformation dominates

Integrated phase cycles giving 2.5 m relative displacment

Typical interferograms

Signal dominated by amosphere, orbit and DEM errors

(larger than deformation for low strains and short intervals)



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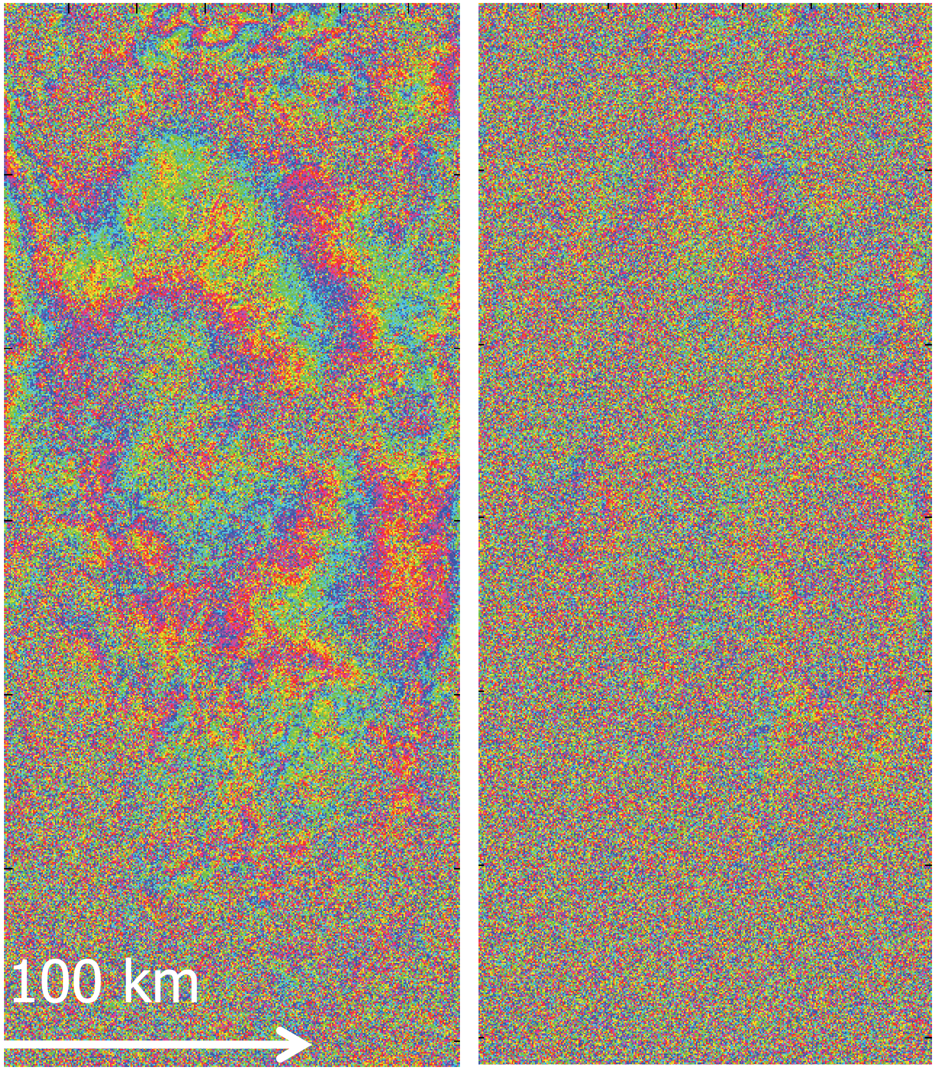


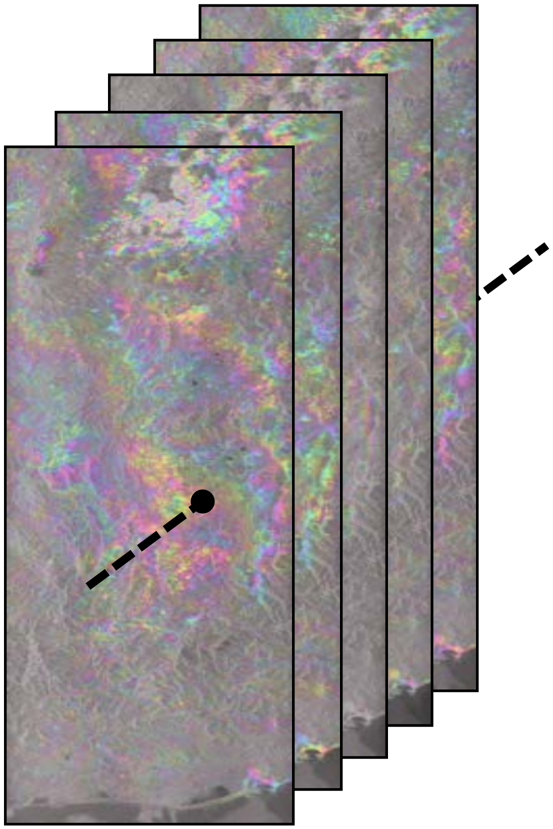
High Decorrelation

(especially for long intervals)

Persistent Scatter (PS) InSAR

Motivation!

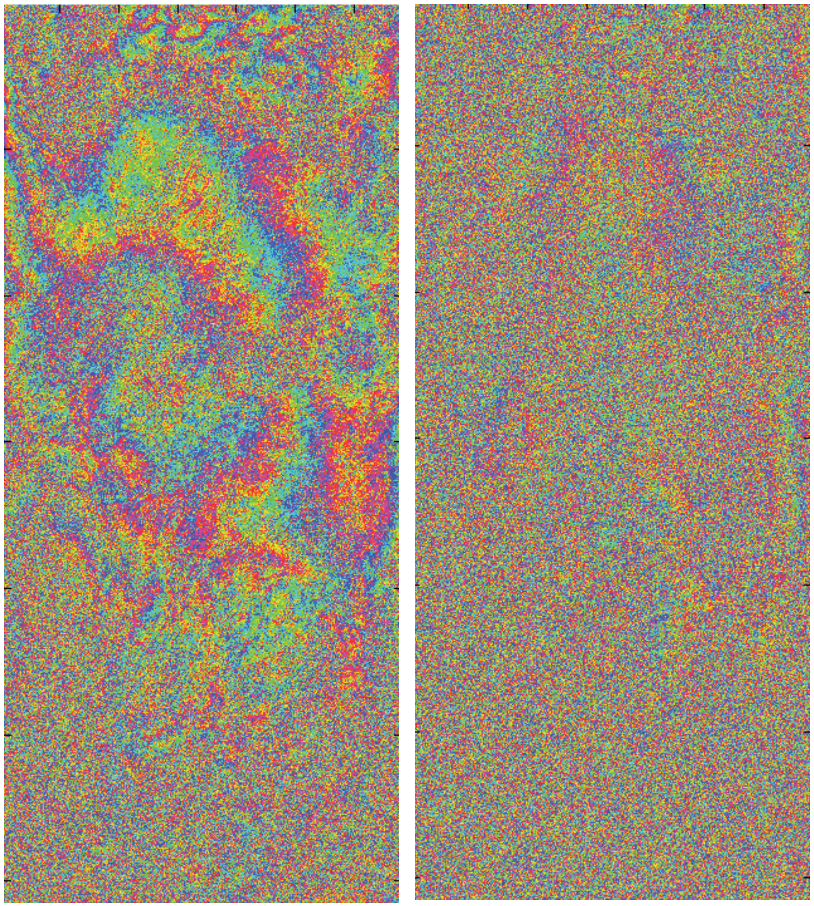
- Allows better selection of coherent pixels
- DEM error estimation possible
- More reliable phase unwrapping possible (3-D)
- Other errors can be reduced by filtering in space and time
- Sub-pixel resolution possible



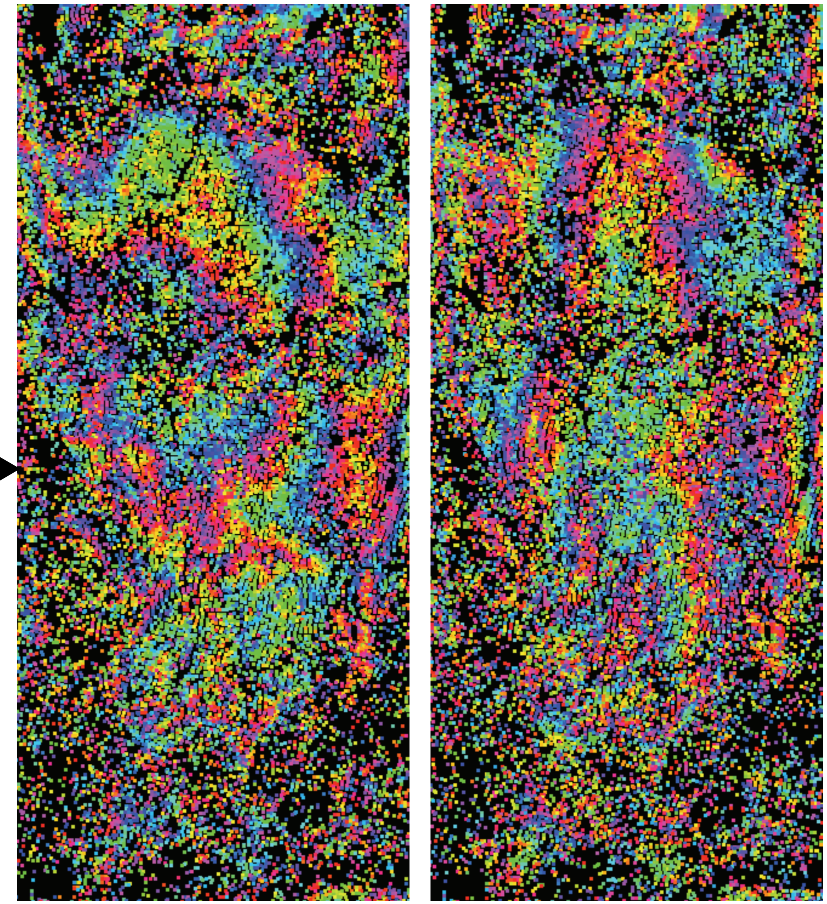
A time series analysis approach

Improvement of coherence

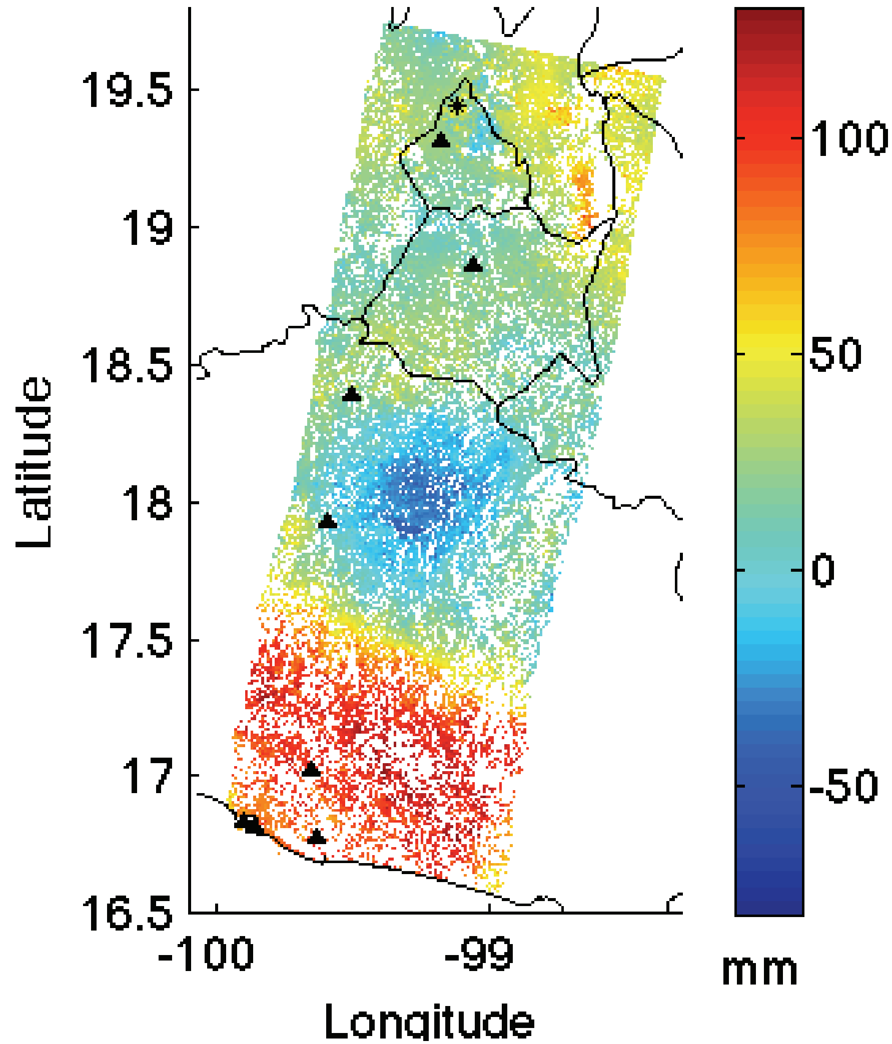
InSAR (80 looks)



Persistent Scatterer InSAR



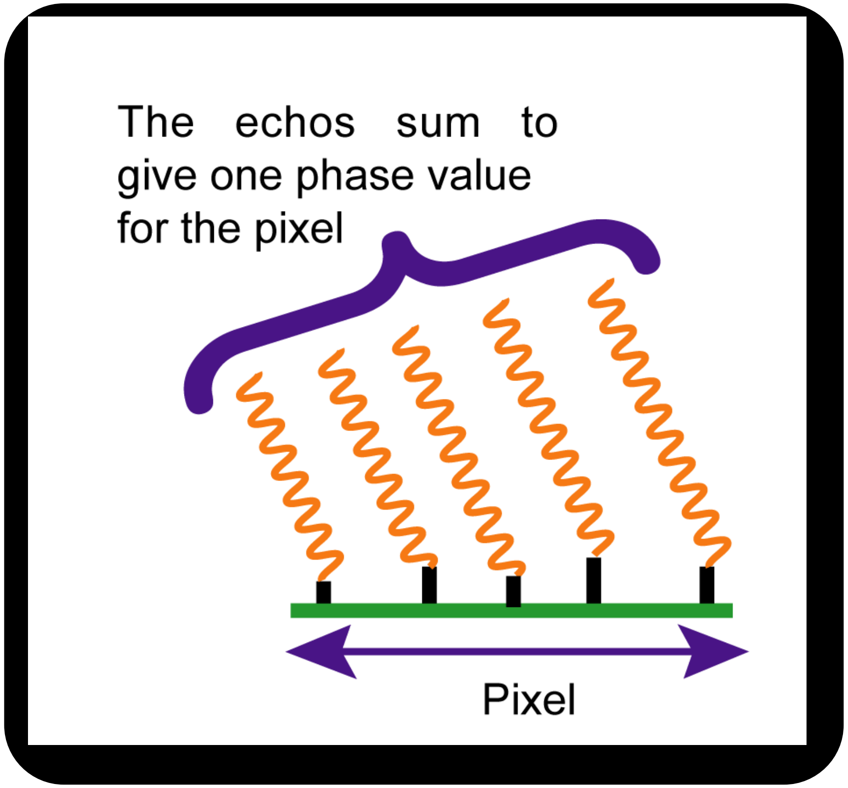
After unwrapping and reduction of non-deformation signals



High resolution PS Processing

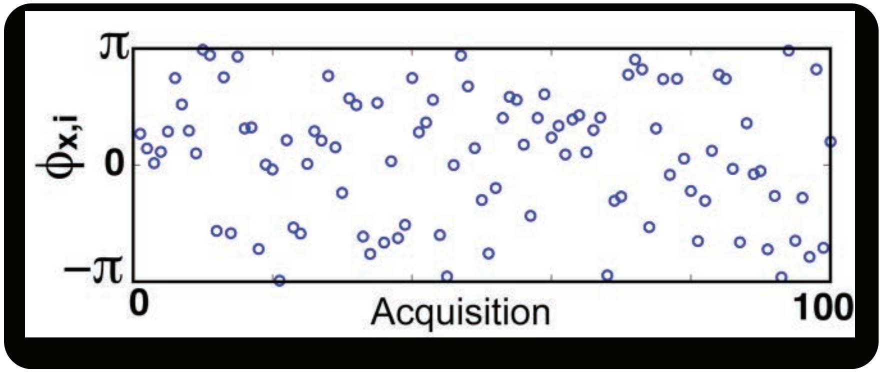
Barcelona Olympic Port (Institut de Geomatica)

Cause of Decorrelation



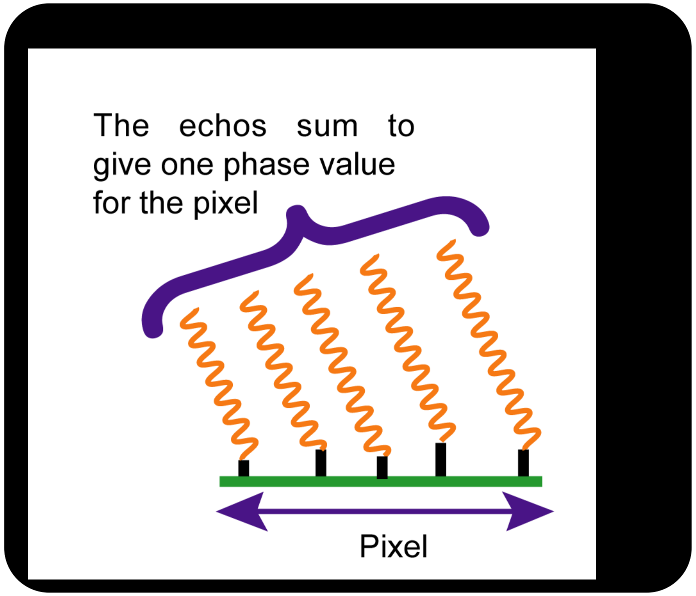
Distributed scatterer pixel

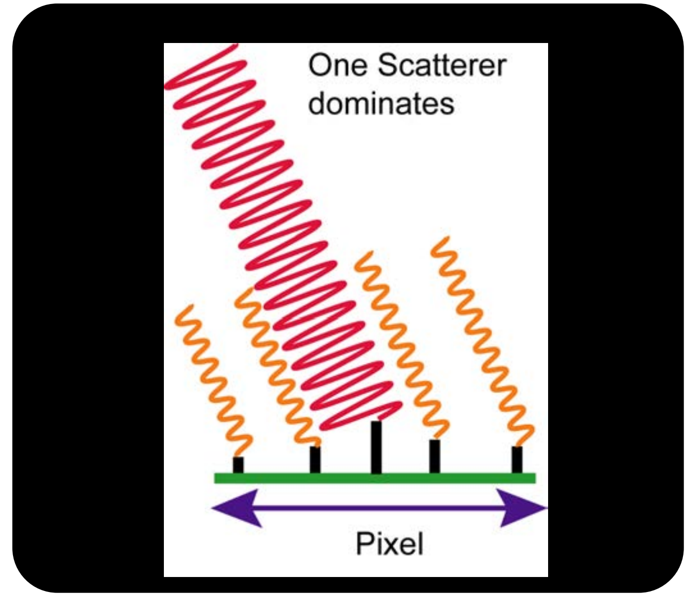
If scatterers move with respect to each other, the phase sum changes

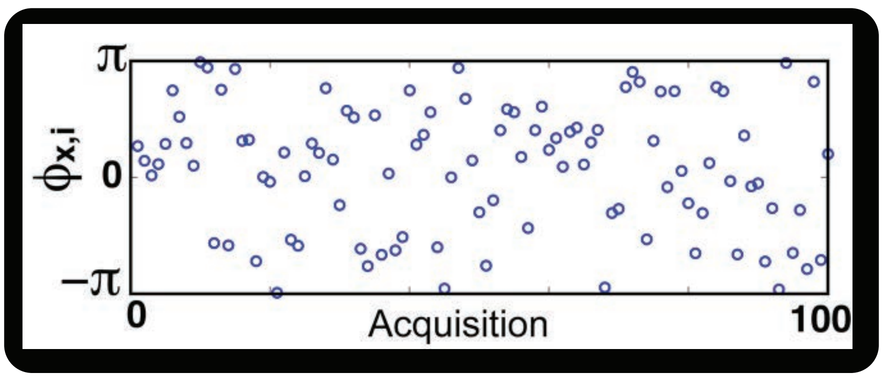


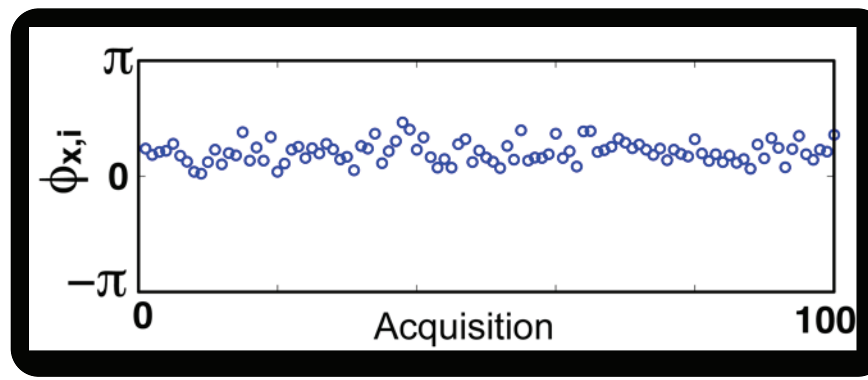
(similar effect if incidence angle changes)

Persistent Scatterer (PS) Pixel









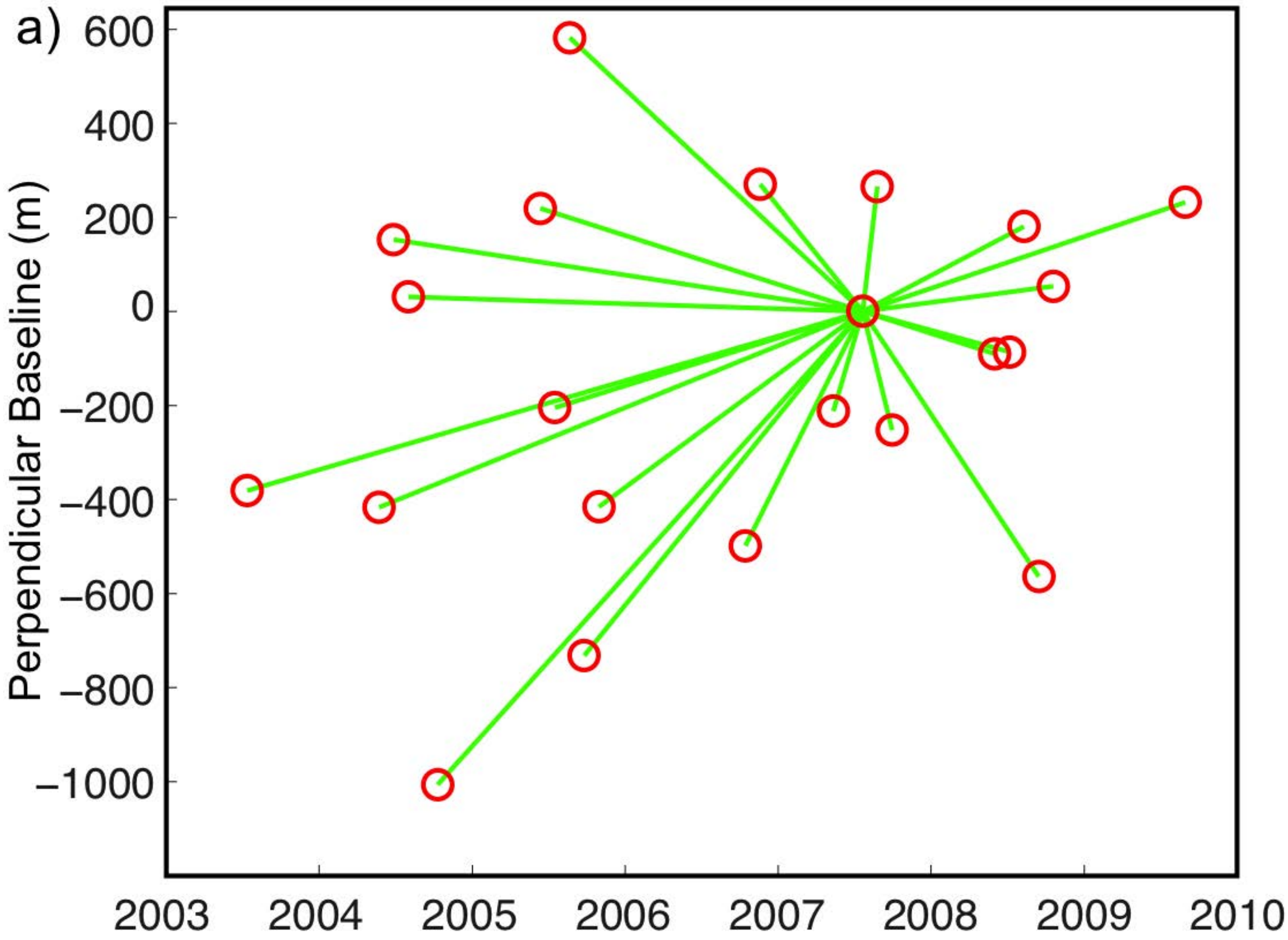
Distributed scatterer pixel

"Persistent scatterer" (PS) pixel

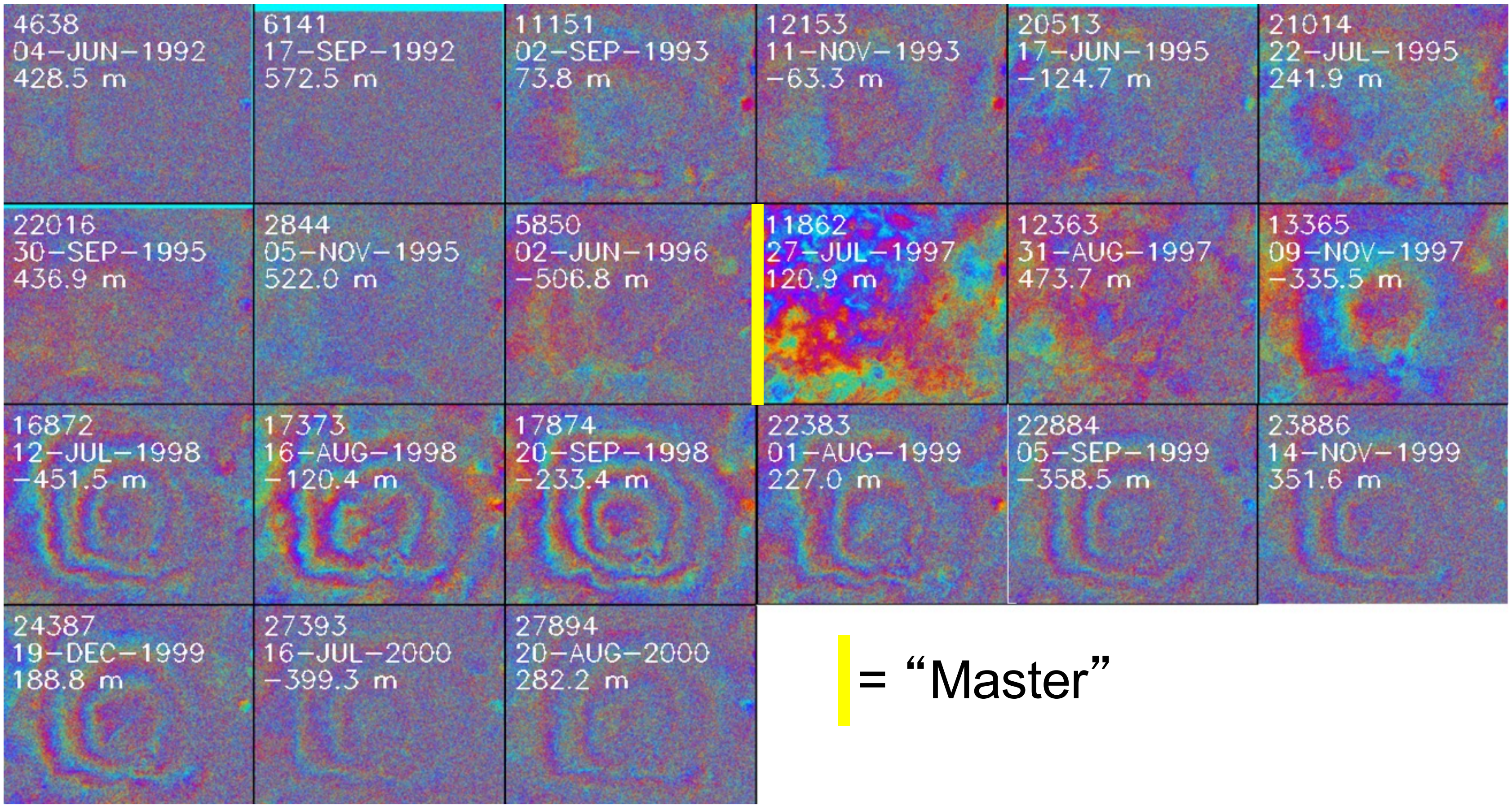
PS Interferogram Processing

- All interferograms with respect to same "master" image
- No spectral filtering applied (maximise resolution)
- Oversampling is preferred to avoid PS being at edge of pixel
- Coregistration can be difficult - use DEM/orbits or slave-slave coregistration
- Reduction of interferometric phase using *a priori* DEM to minimize ambiguities

Interferograms formed



Example: single-master interferograms



= "Master"

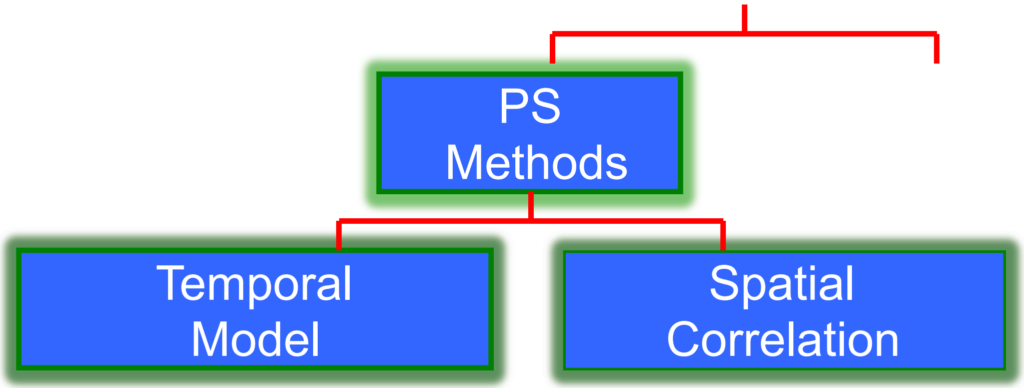
Interferometric Phase

For each pixel in each interferogram:

$$\phi_{int} = W\{\underbrace{\phi_{defo}}_{\text{Deformation in LOS}} + \underbrace{\phi_{atmos}}_{\text{Atmospheric Delay}} + \underbrace{\Delta\phi_{orbit}}_{\text{Orbit Error}} + \underbrace{\Delta\phi_{topo}}_{\text{DEM Error}} + \underbrace{\phi_{noise}}_{\text{“Noise”}}\}$$

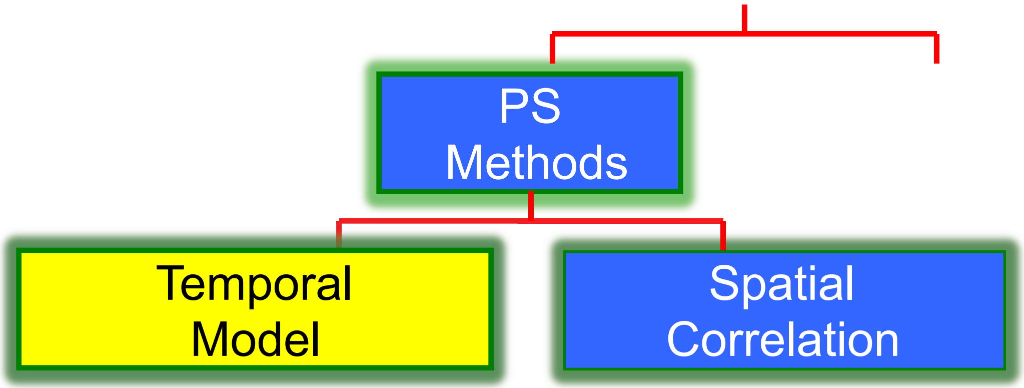
$W\{\bullet\}$ = wrapping operator

PS Processing Algorithms



- Relying on model of deformation in time: e.g. “Permanent Scatterers” (Ferretti et al. 2001), Delft approach (Kampes et al., 2005)
- Relying on correlation in space: StaMPS (Hooper et al. 2004)

PS Processing Algorithms



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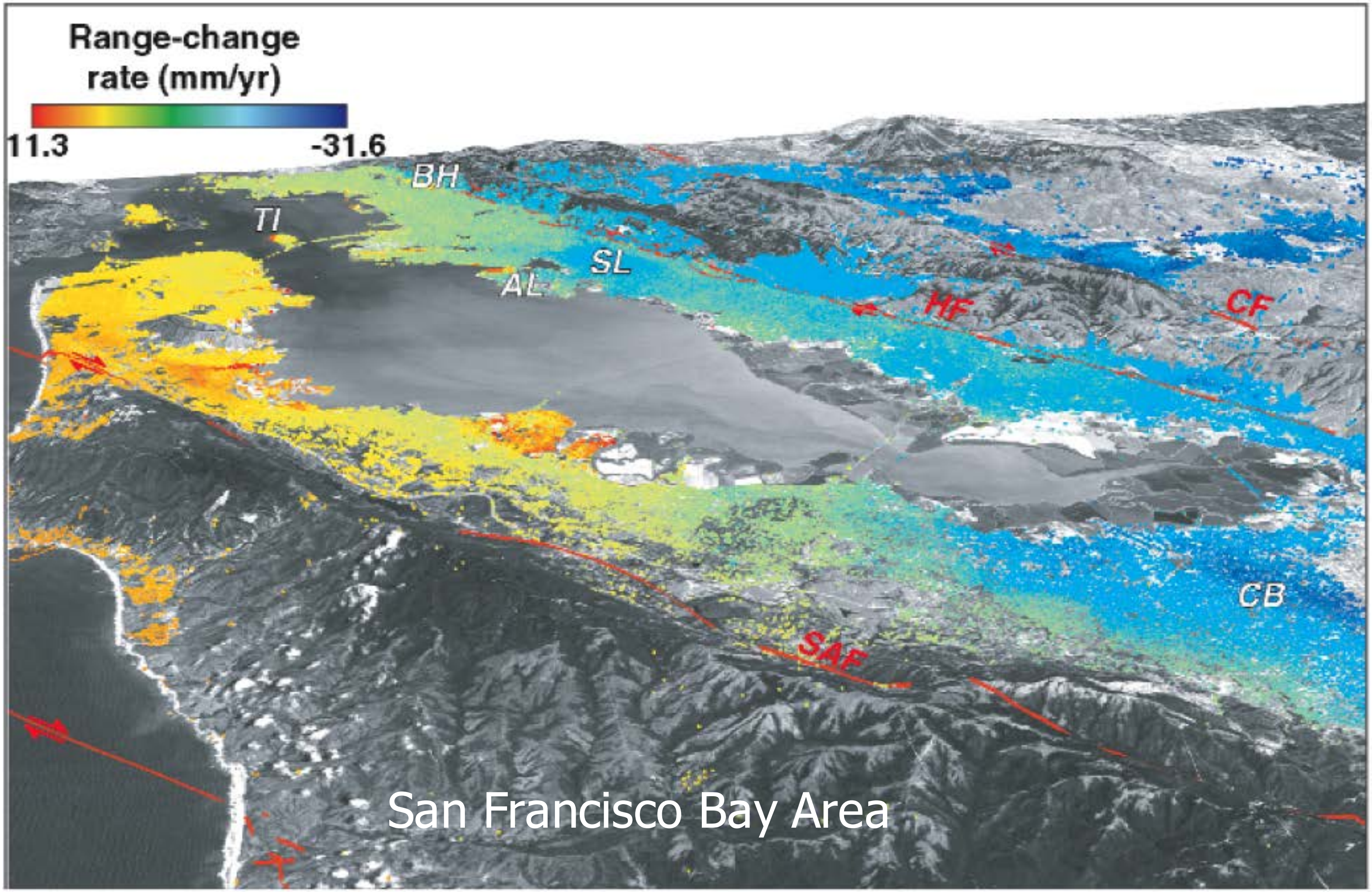
“Permanent Scatterer” Technique



Ferretti et al, 2004

Double-difference phase

For each pair of pixels in each interferogram:

$$\delta\phi_{int} = \delta\phi_{defo} + \delta\phi_{atmos} + \Delta\phi_{orbit} + \delta\Delta\phi_{topo} + \delta\phi_{noise}$$

Deformation in LOS

Atmospheric Delay

Orbit Error

DEM Error

"Noise"

Double-difference phase

If pixel pairs are nearby:

$$\delta\phi_{int} = \delta\phi_{defo} + \cancel{\delta\phi_{atmos}} + \cancel{\Delta\phi_{orbit}} + \delta\Delta\phi_{topo} + \delta\phi_{noise}$$

Atmospheric Delay

DEM Error

Deformation in LOS

Orbit Error

"Noise"

Double-difference phase

If pixel pairs are nearby:

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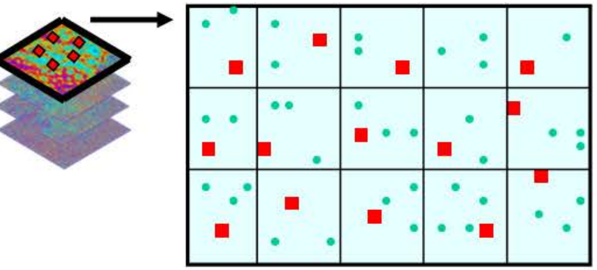
- model these two term

Preliminary Network

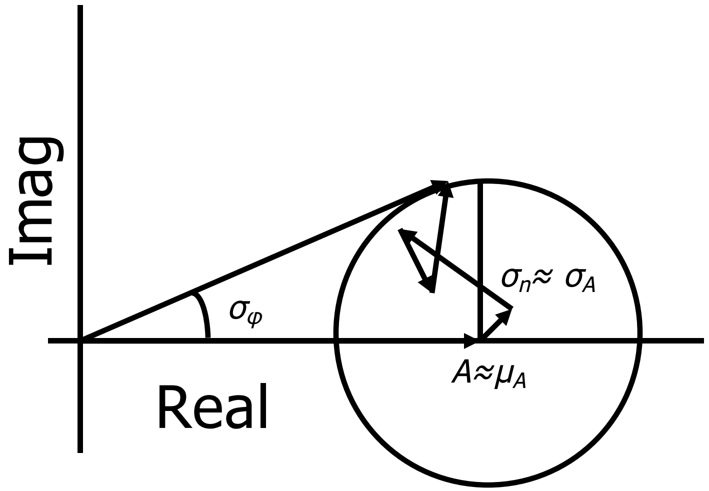


1: SELECTION

Only consider point (-like) scatterers.
Select the ***best points*** (▪) in each grid cell (ca. 250x250 m).

Initial selection

- Initial selection based on **amplitude dispersion** (Ferretti et al., 2001)

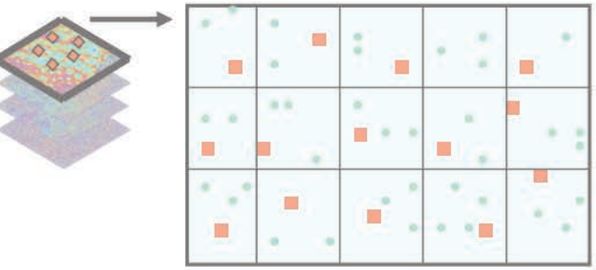


$$\sigma_\varphi \approx \frac{\sigma_n}{A} \approx \frac{\sigma_A}{\mu_A} = D_A$$

Phase noise

Reasonable proxy for small phase noise (<0.25 rad)

Preliminary Network



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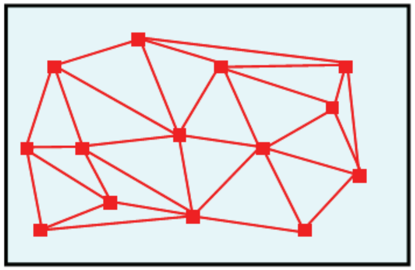
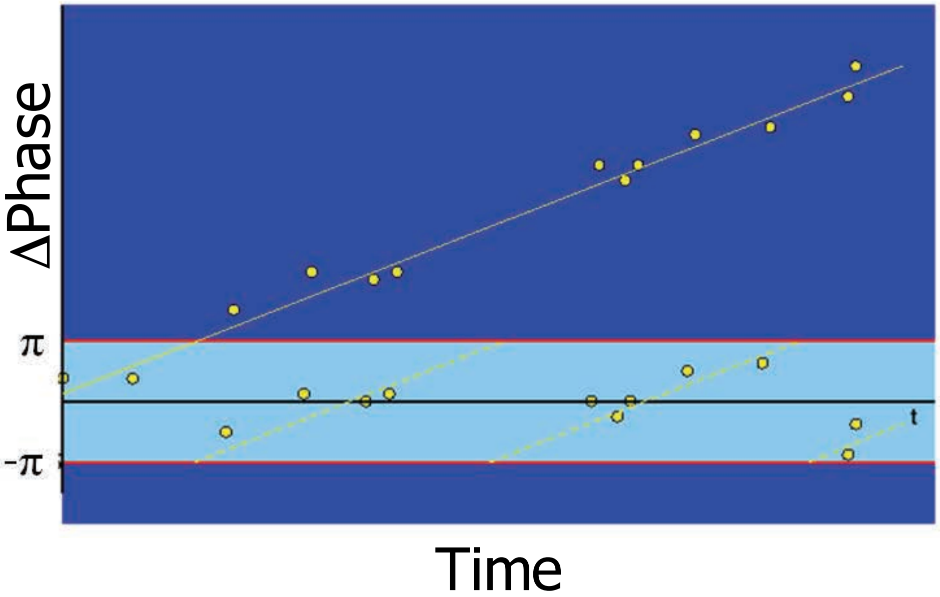


2: ESTIMATION

Construct a "network" to estimate displacement parameters and DEM error differences ***between nearby points*** in order to reduce atmospheric signal.

Estimation in Time



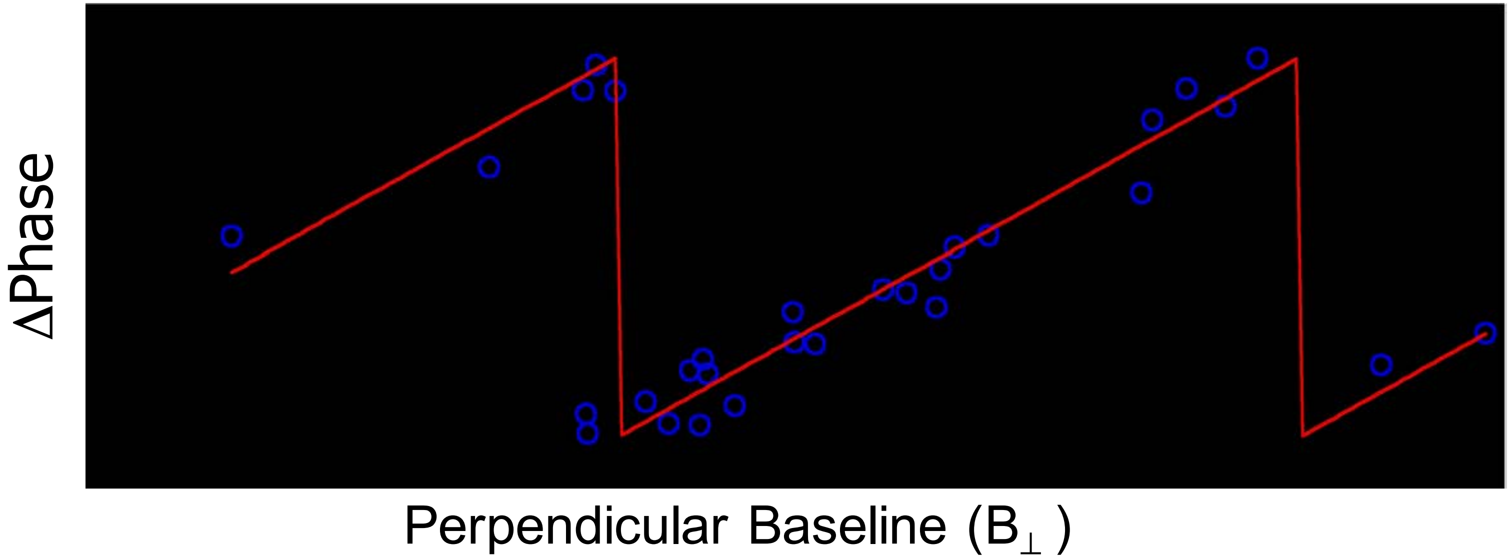
(for each arc between 2 points)

- Linear deformation model
- Phase is function of time
  $d(t) = a * t$
- Observed is wrapped phase
  $-\pi < \text{phase} < \pi$
- Goal is to unwrap the phase time series, supported by the model

- There are many possibilities.

- A norm must be used to decide which solution best.

Simultaneous Estimation of DEM Errors

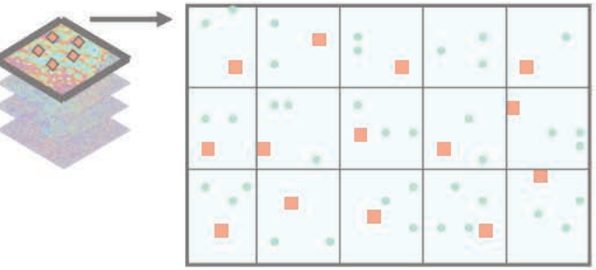


Constant for each interferogram

$$\Delta\varphi = \frac{4\pi B_{perp} \sin(\theta) \Delta h}{\lambda}$$

θ is incidence angle, Δh is DEM error,

Preliminary Network



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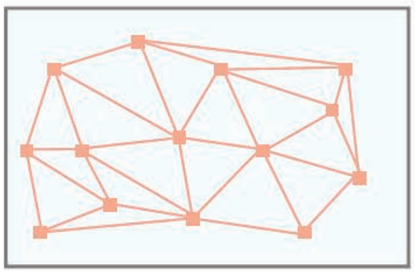

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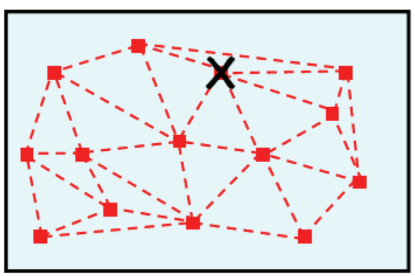
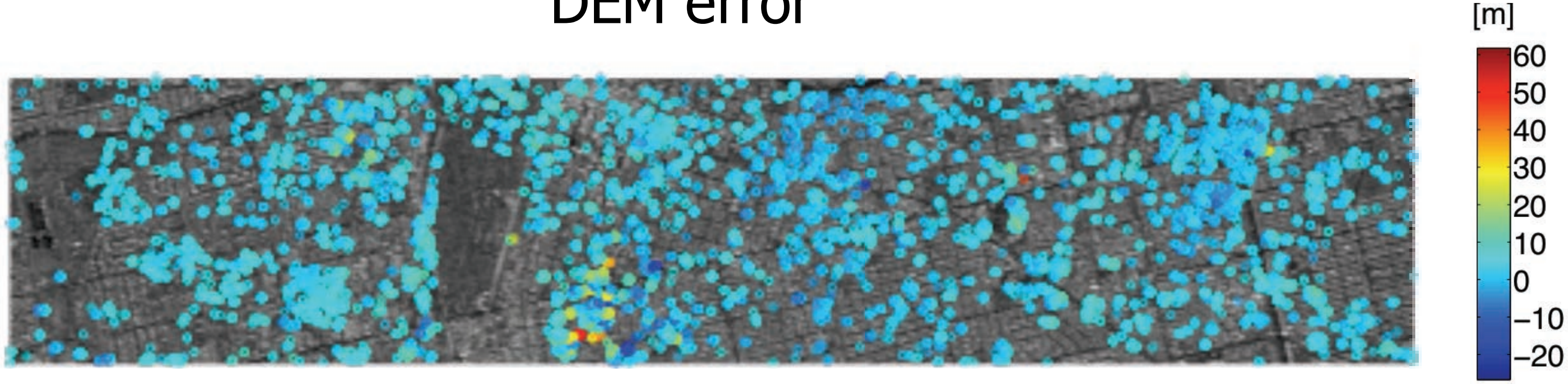


3: INTEGRATION

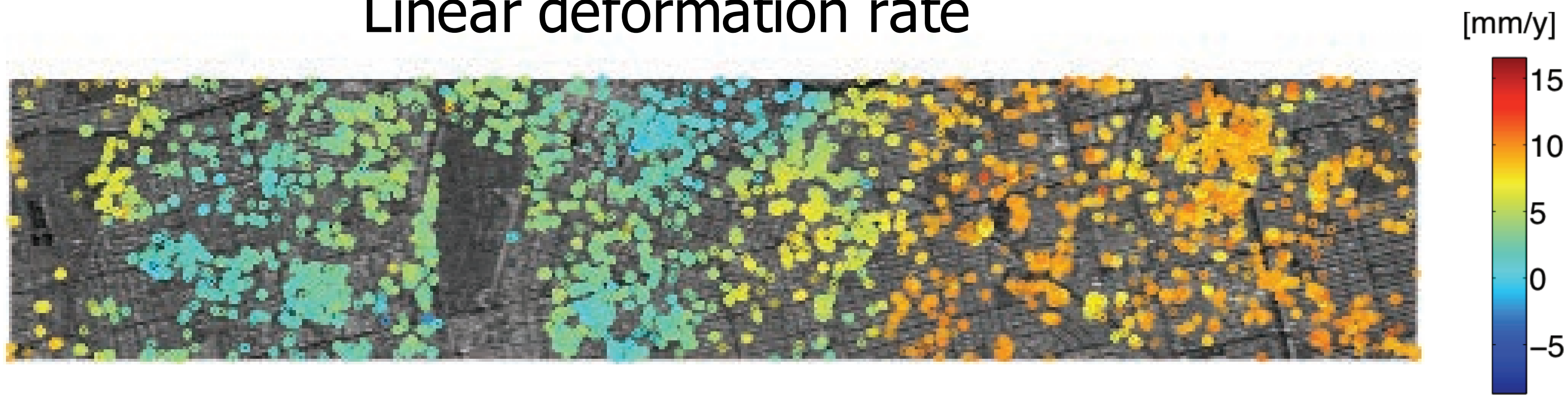
Obtain the ***parameters at the points*** by LS integration w.r.t. a reference point (**X**).
Identify incorrect estimates and/or incoherent points using alternative hypothesis tests.

Integrated results (Las Vegas)

DEM error



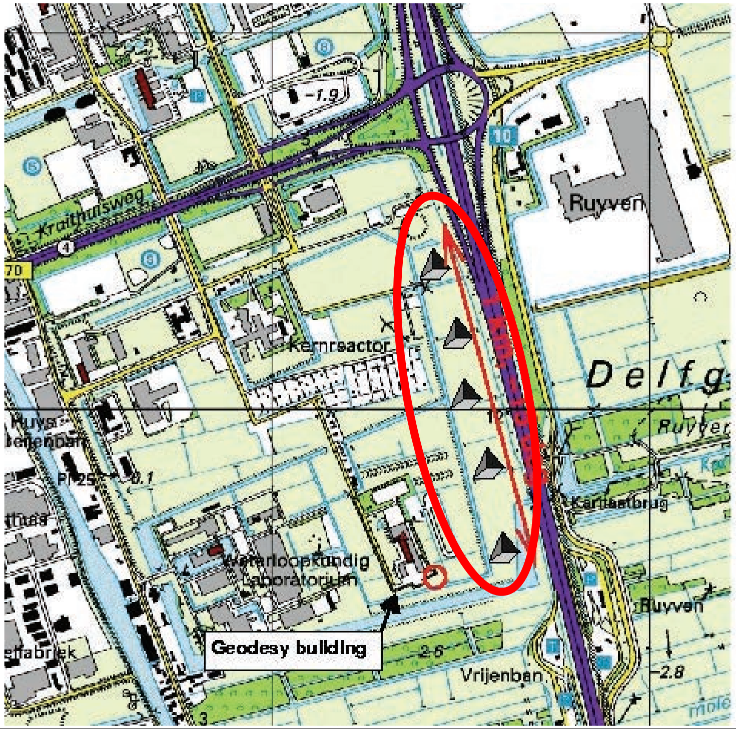
Linear deformation rate

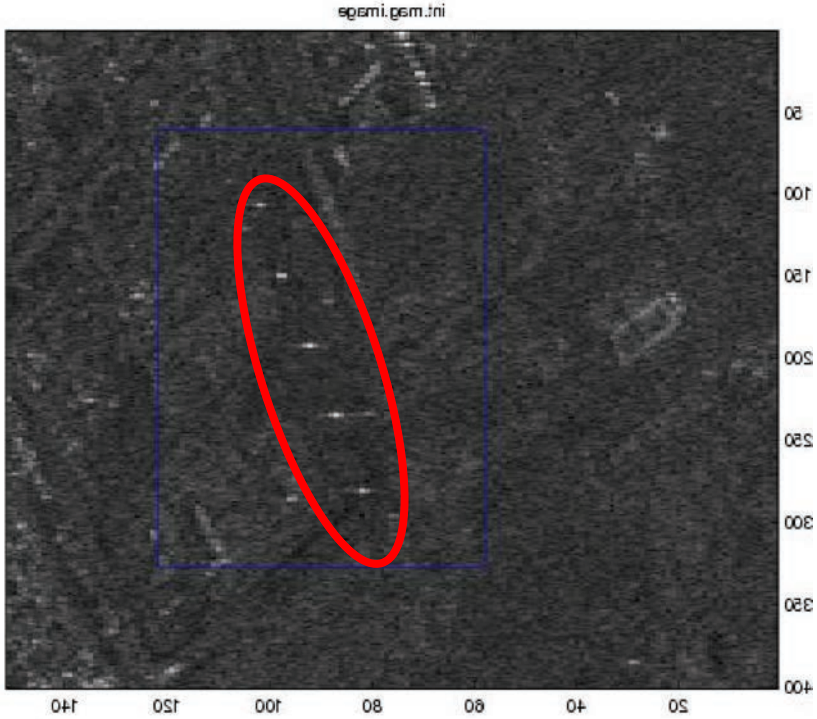


Next steps…

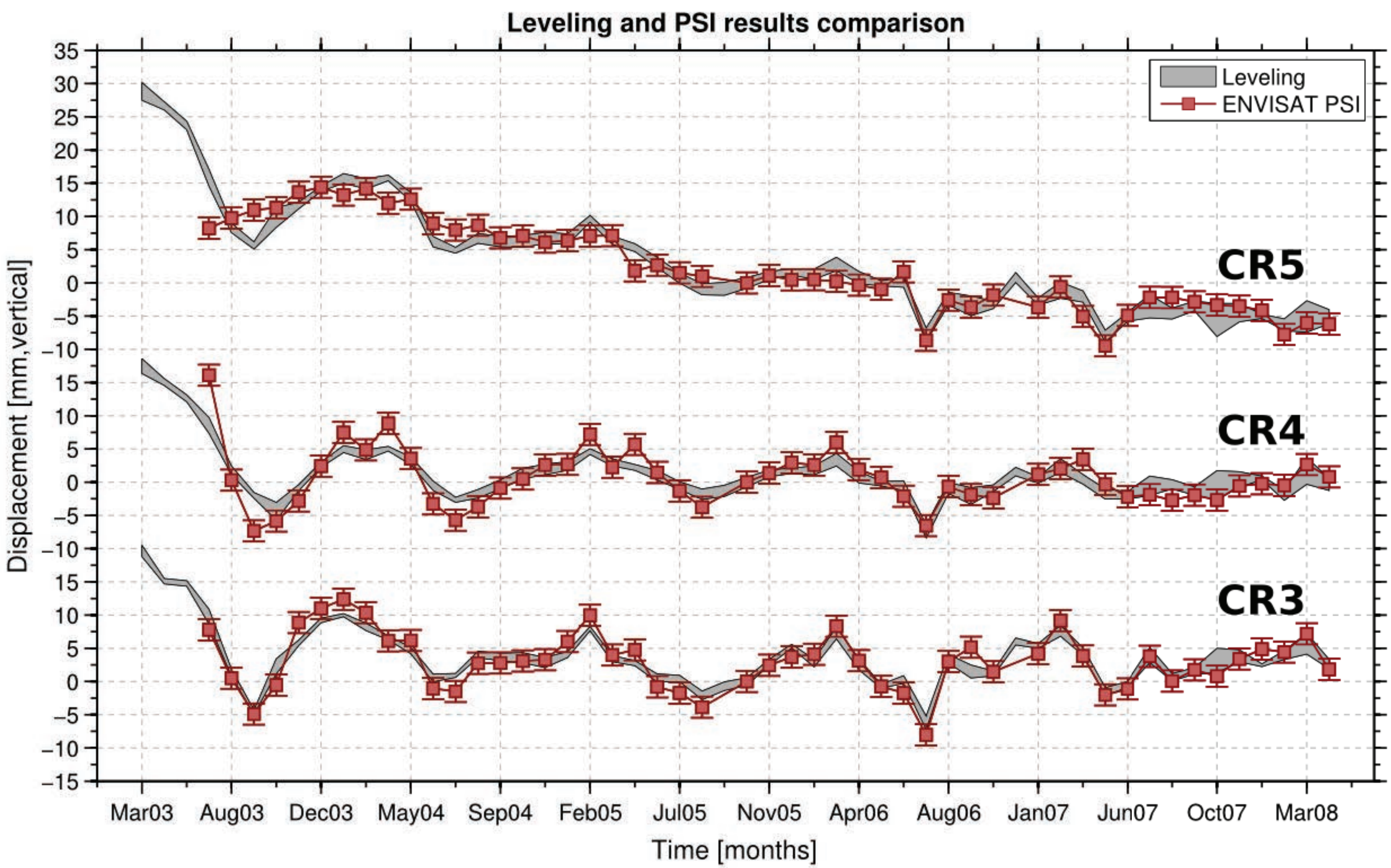
- Estimation and interpolation of atmospheric delay from initial network. This is subtracted from all pixels
- Testing of all other pixels by forming arcs to initial network
- Filtering in time and space to try and separate unmodelled deformation from atmosphere

Corner Reflector Experiment



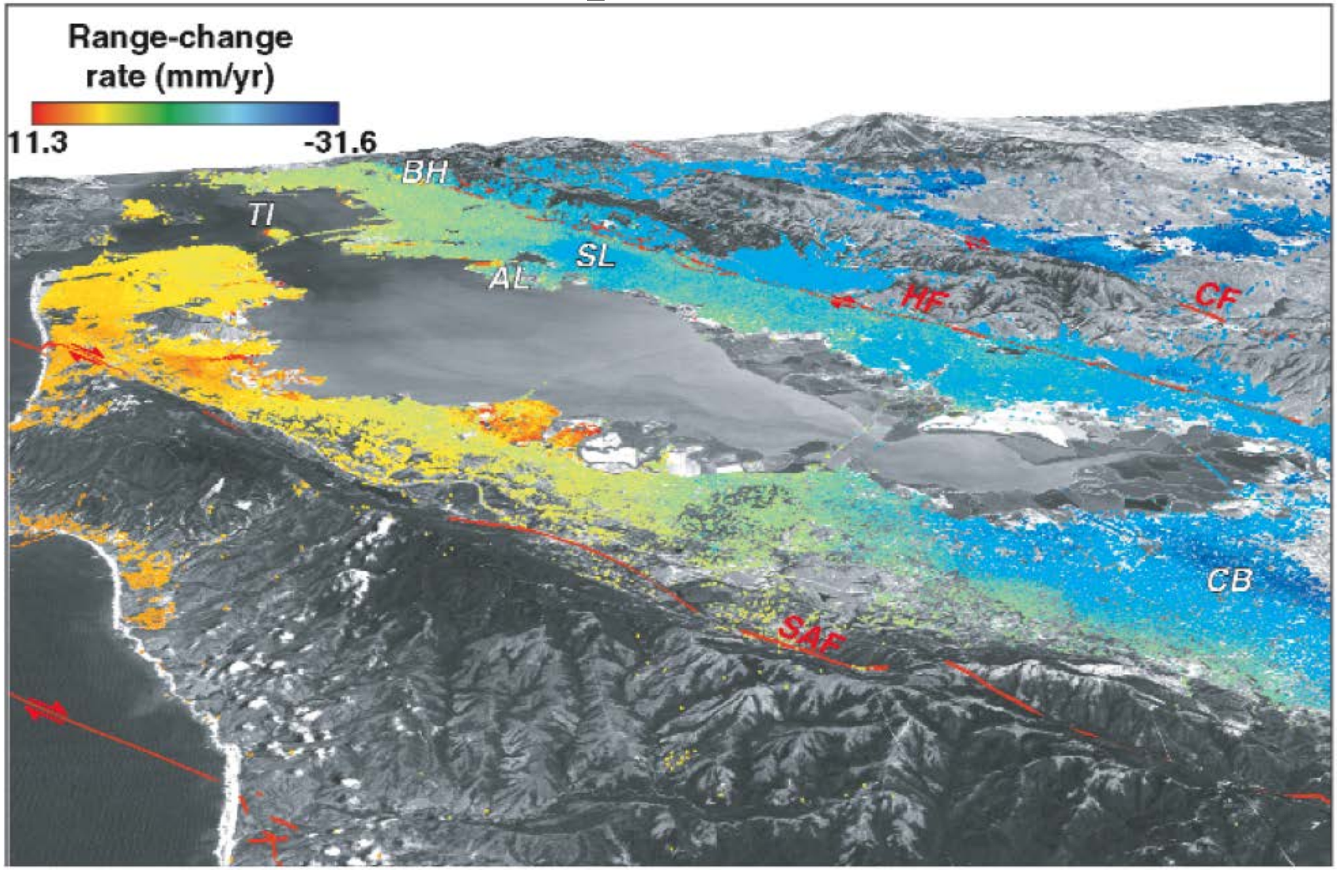


Corner Reflector InSAR vs Leveling



Marinkovic et al, CEOS SAR workshop, 2004

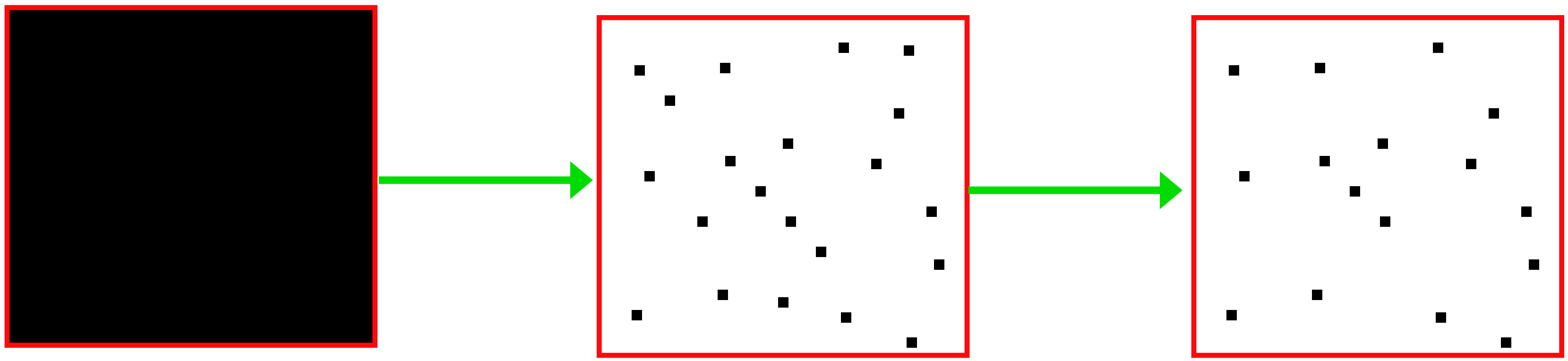
Results: Bay Area, California



San Francisco Bay Area (Ferretti et al., 2004)

- Works well in urban areas, but not so well in areas without man-made structures. Why?

Initial Selection

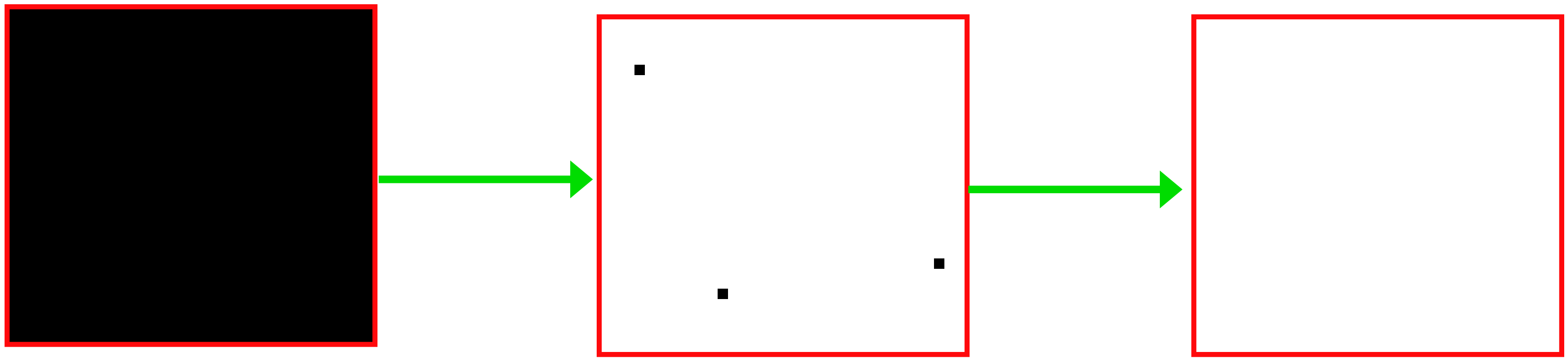


All pixels

Best candidates picked
e.g. Amplitude

Bad candidates rejected using phase model for pixel pairs

Why few pixels picked in rural areas



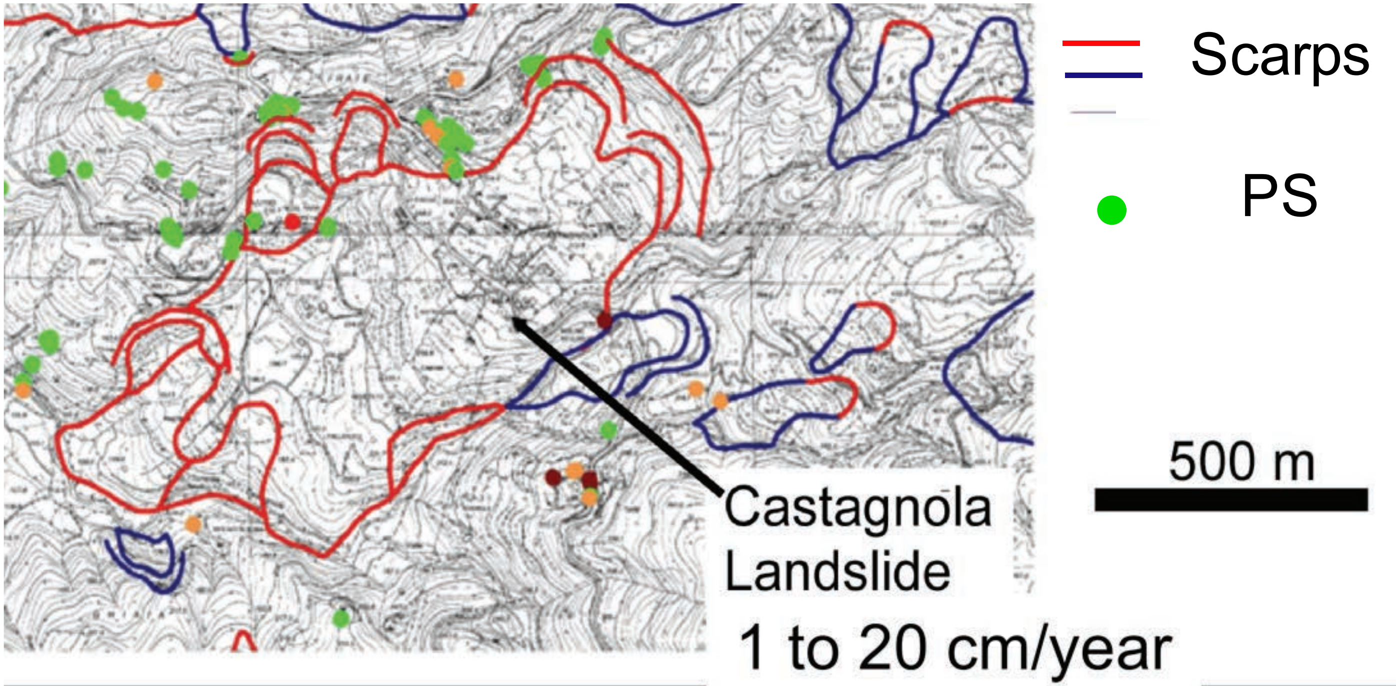
All pixels

Too few “best” candidates

Difference in atmospheric noise between pixels is large, so unable to reliably estimate velocity and DEM error: All pixels rejected

- Lowering the bar for candidate pixels also leads to failure: too many “bad” pixels for network approach.

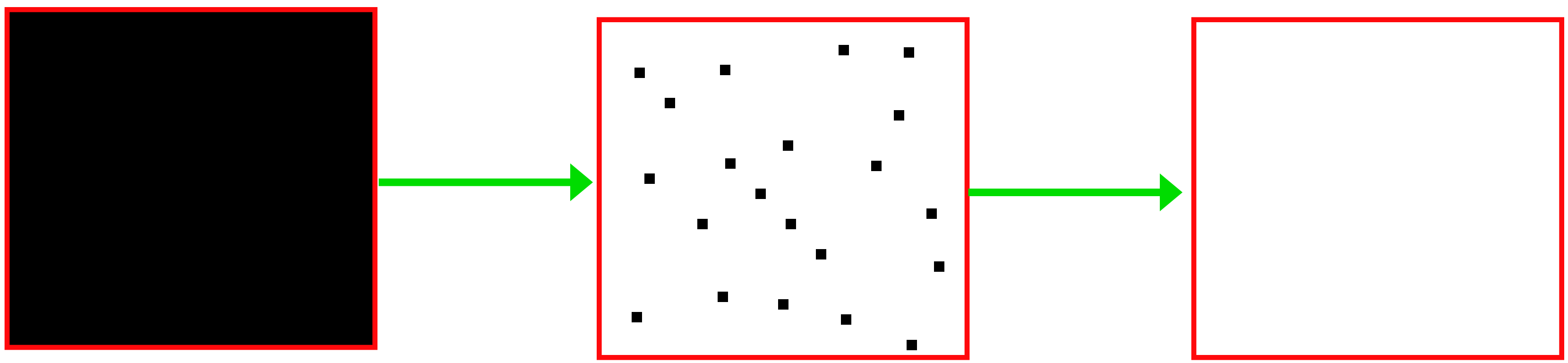
Results for Castagnola, Italy



Castagnola, Northern Italy (from Paolo Farina)

➢ Algorithm rejects pixels whose phase histories deviate too much from a predetermined model for how deformation varies with time

Why few pixels picked when deformation rate is irregular



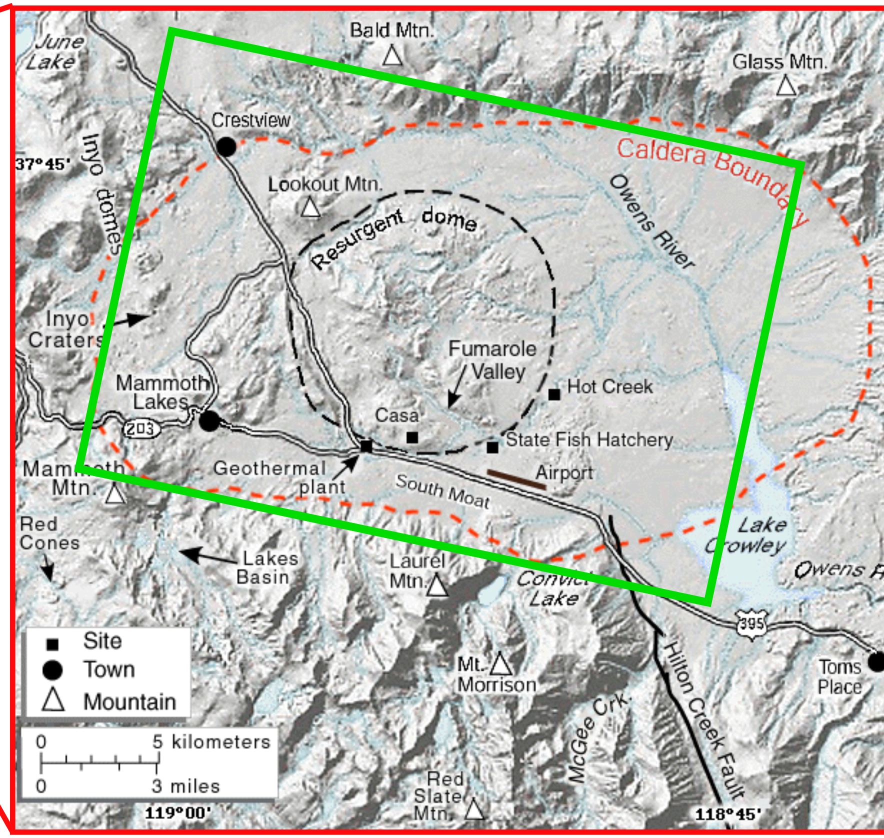
All pixels

Best candidates picked
e.g. Amplitude

Phase model inadequate due to deformation

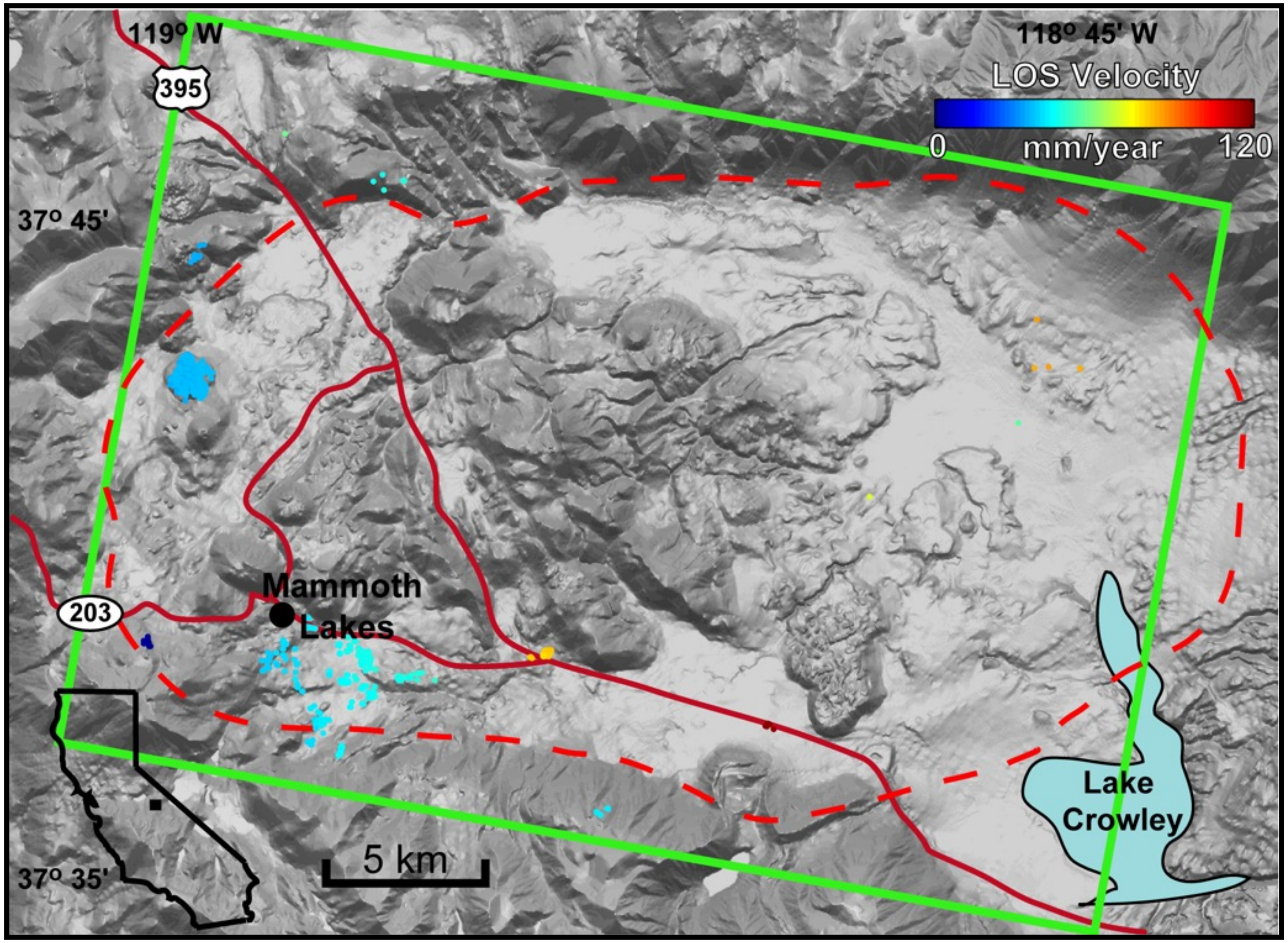
Example of rural area with irregular deformation

Long Valley Volcanic Caldera



5km

Using Temporal Model Algorithm



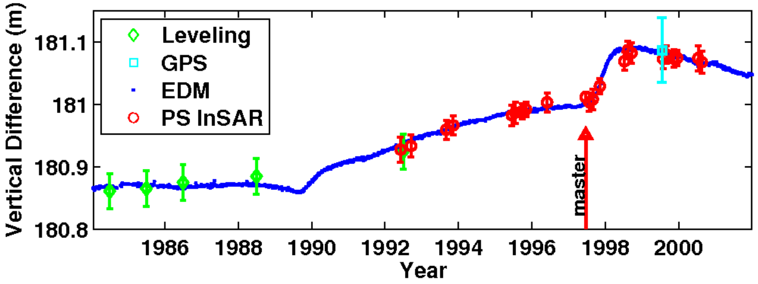
- 300 high-amplitude persistent scatterers

StaMPS PS Approach

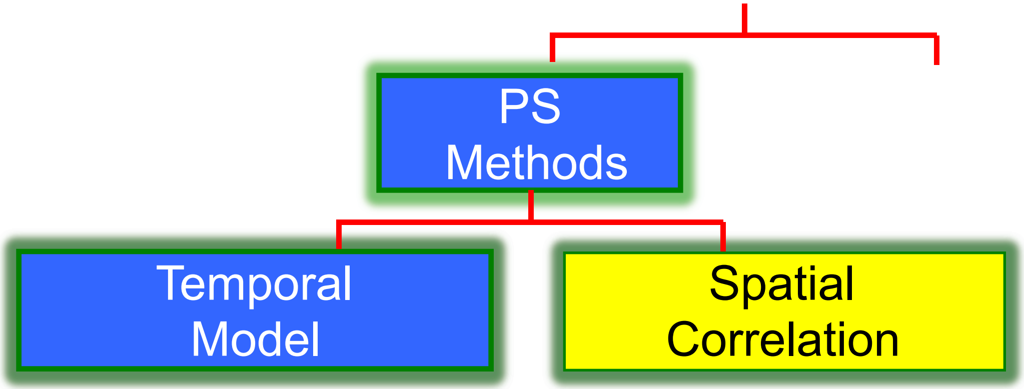
Developed for more general applications, to work:

a) in rural areas without buildings (low amplitude)

b) when the deformation rate is very irregular



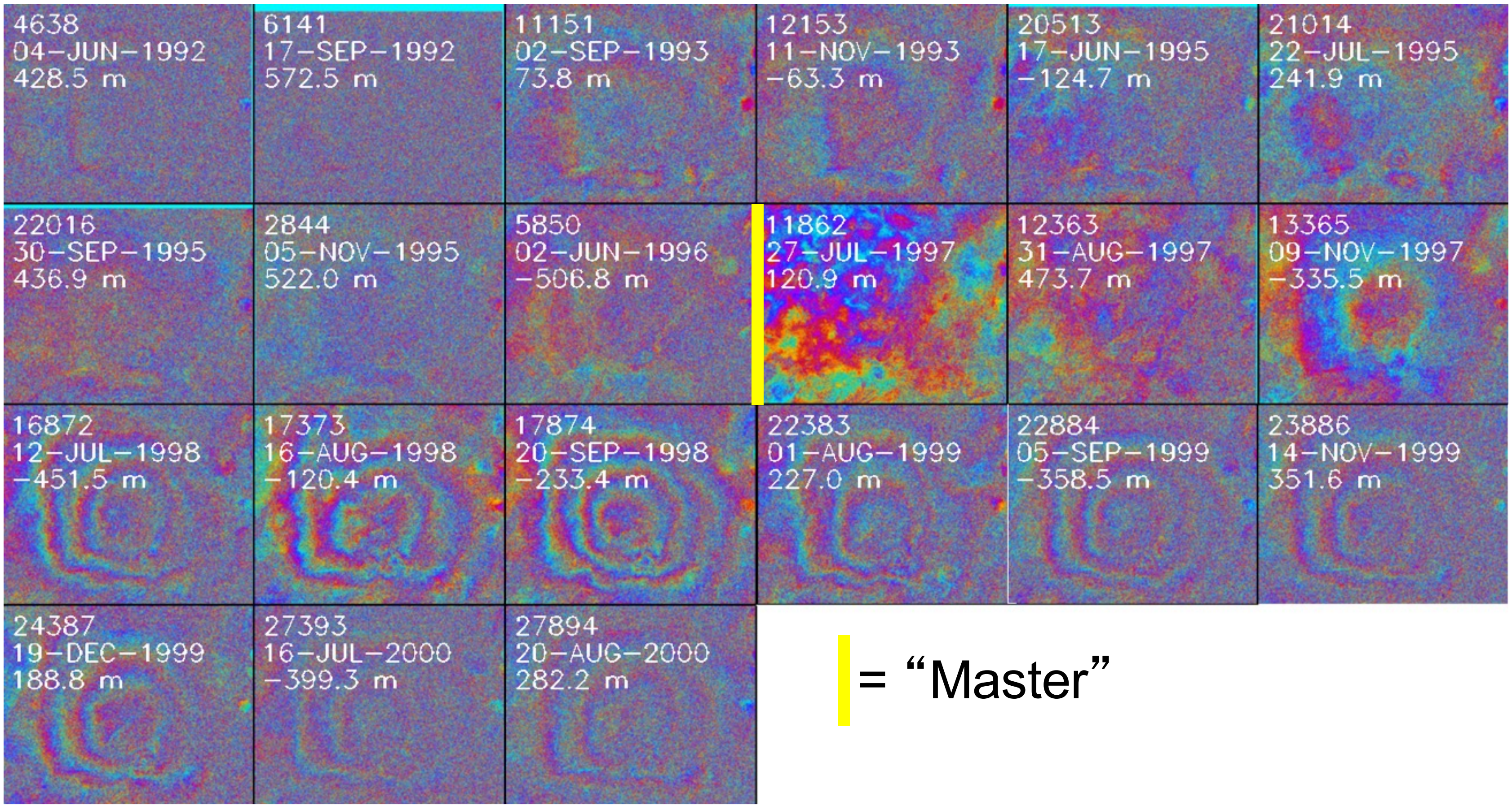
PS Processing Algorithms



- Relying on correlation in space: StaMPS Hooper et al. (2004, 2007, 2012)

Series of single-master interferograms

- Pre-Processing as for Temporal Model Algorothm



Spatial Correlation PS Algorithm

Exploits spatial correlation of the deformation signal.

Interferometric phase terms as before:

$$\underbrace{\phi_{int}}_{} = \underbrace{\phi_{defo}}_{\text{Deformation in LOS}} + \underbrace{\phi_{atmos}}_{\text{Atmospheric Delay}} + \underbrace{\Delta\phi_{orbit}}_{\text{Orbit Error}} + \underbrace{\Delta\phi_{topo}}_{\text{DEM Error}} + \underbrace{\phi_{noise}}_{\text{“Noise”}}$$

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Spatial Correlation PS Algorithm

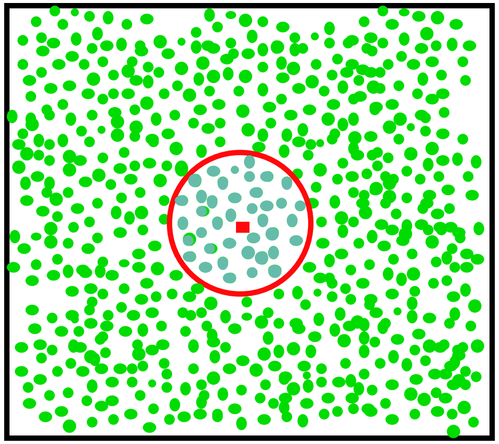
Exploits spatial correlation of the deformation signal.

Interferometric phase terms as before:

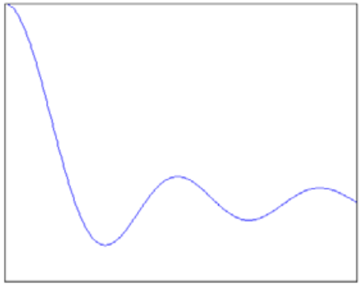
$$\phi_{int} = \phi_{defo} + \phi_{atmos} + \Delta\phi_{orbit} \begin{matrix} + \Delta\phi_{topo}^{uncorr} \\ + \Delta\phi_{topo}^{corr} \end{matrix} + \phi_{noise}$$

- Correlated spatially - estimate by iterative spatial bandpass filtering

Estimation of Spatially Correlated Terms



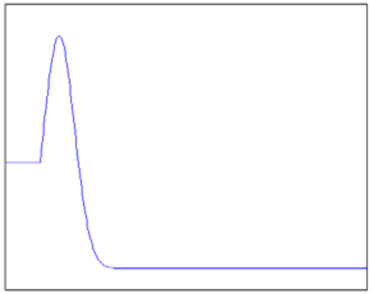
= crude low-pass filter in spatial domain (Hooper et al., 2004)



Frequency response

Better (Hooper et al., 2007)

- Low frequencies plus dominant frequencies in surrounding patch are passed.



Example frequency response

e.g., low-pass + adaptive “Goldstein” filter (Goldstein and Werner, 1998)

Spatial Correlation PS Algorithm

$$\phi_{int} = \phi_{defo} + \phi_{atmos} + \Delta\phi_{orbit} \begin{matrix} + \Delta\phi_{topo}^{uncorr} \\ + \Delta\phi_{topo}^{corr} \end{matrix} + \phi_{noise}$$

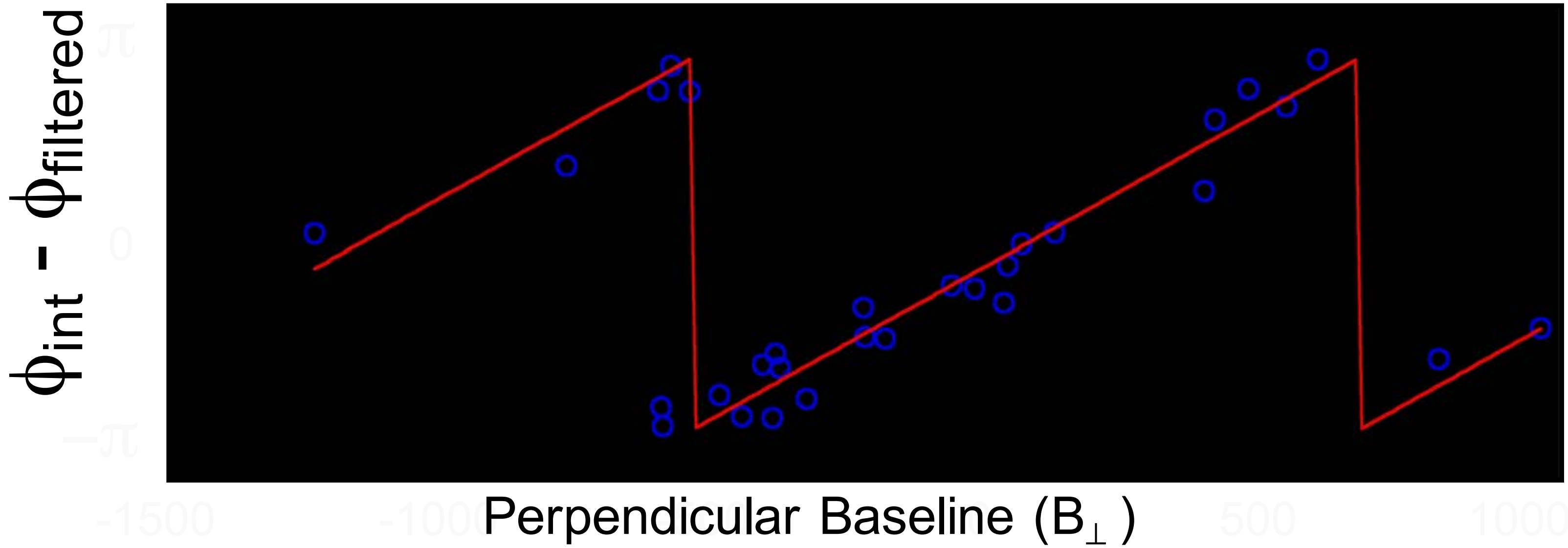
- Correlated spatially - estimate by iterative spatial bandpass filtering

Spatial Correlation PS Algorithm

$$\phi_{int} = \phi_{defo} + \phi_{atmos} + \Delta\phi_{orbit} \begin{array}{l} + \Delta\phi_{topo}^{uncorr} \\ + \Delta\phi_{topo}^{corr} \end{array} + \phi_{noise}$$

- Correlated spatially - estimate by iterative spatial bandpass filtering
- Correlated with perpendicular baseline - estimate by inversion

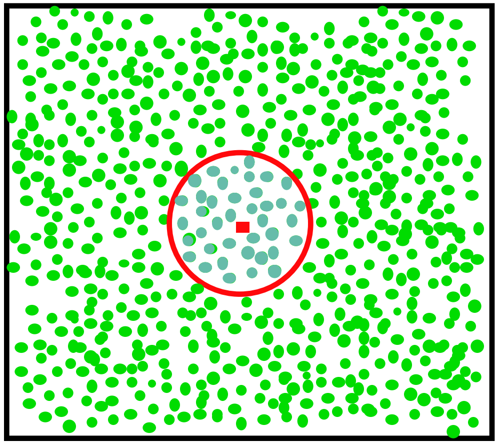
Spatial Correlation PS Algorithm



- 1-D problem (as opposed to 2-D with temporal model approach)

Temporal coherence is then estimated from residuals

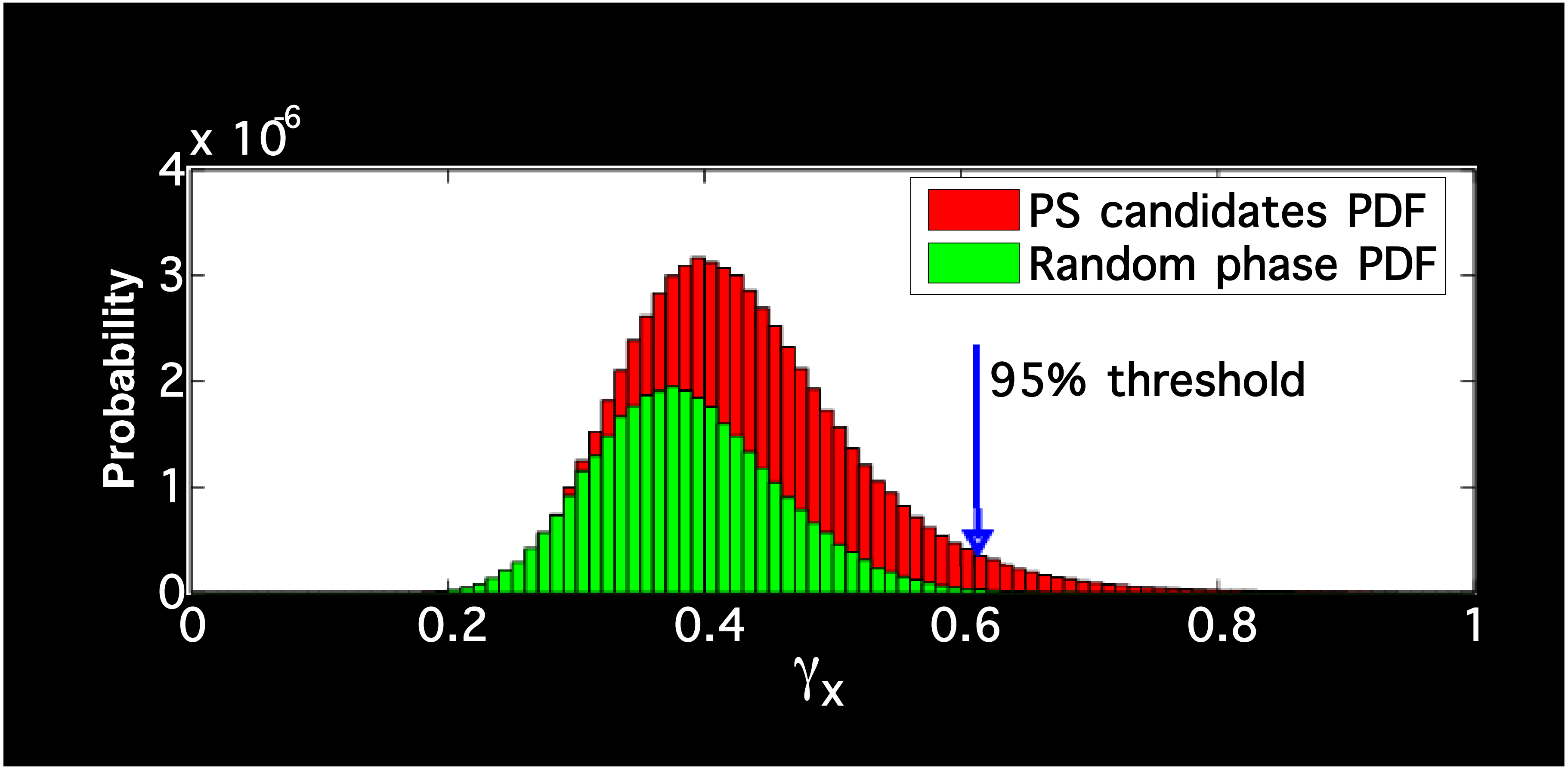
Re-estimation of Spatially Correlated Terms



Contribution of each pixel weighted based on its estimated temporal coherence

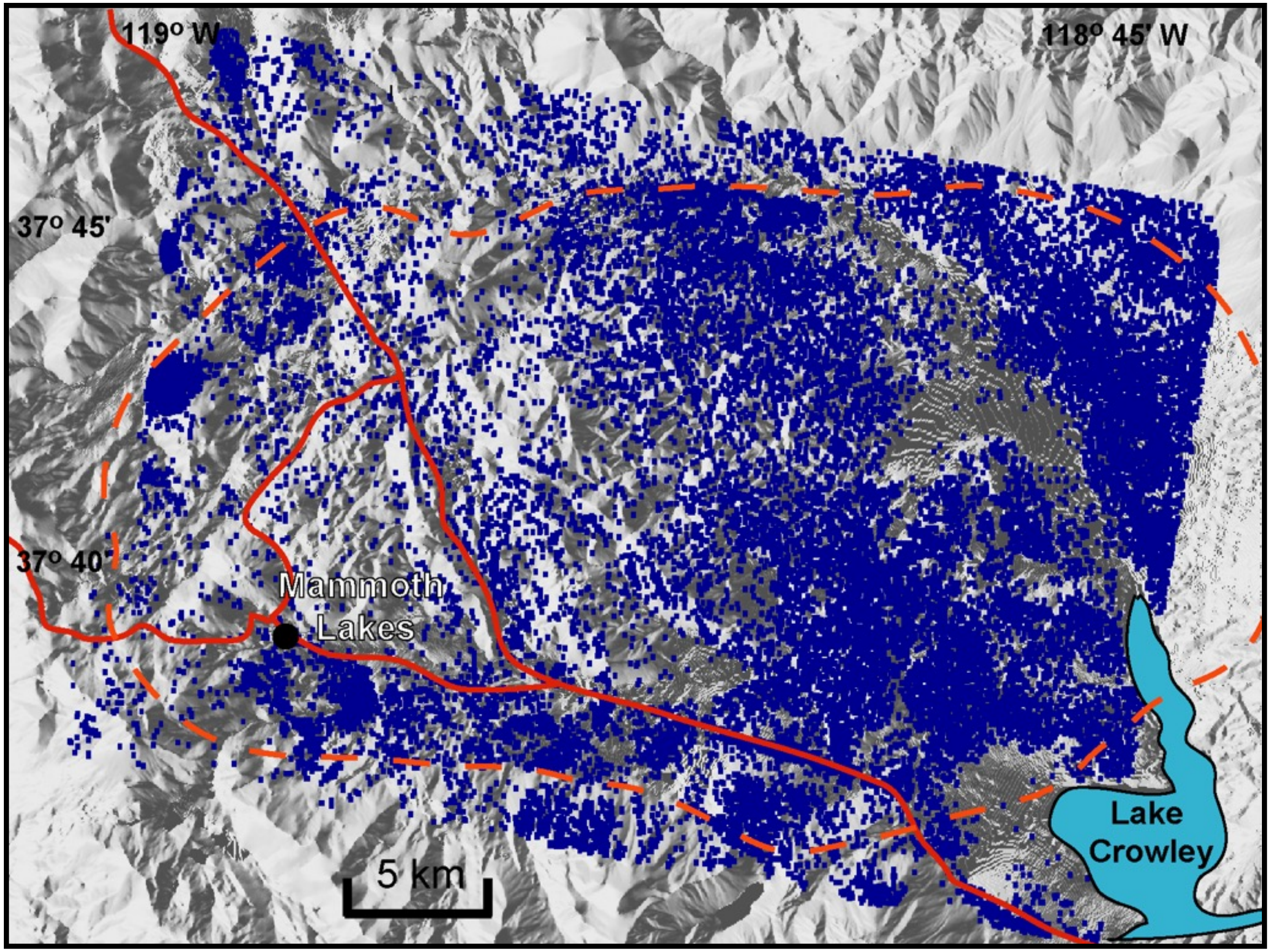
- Followed by restimation of DEM error and temporal coherence
- Iterated several times

Selecting PS



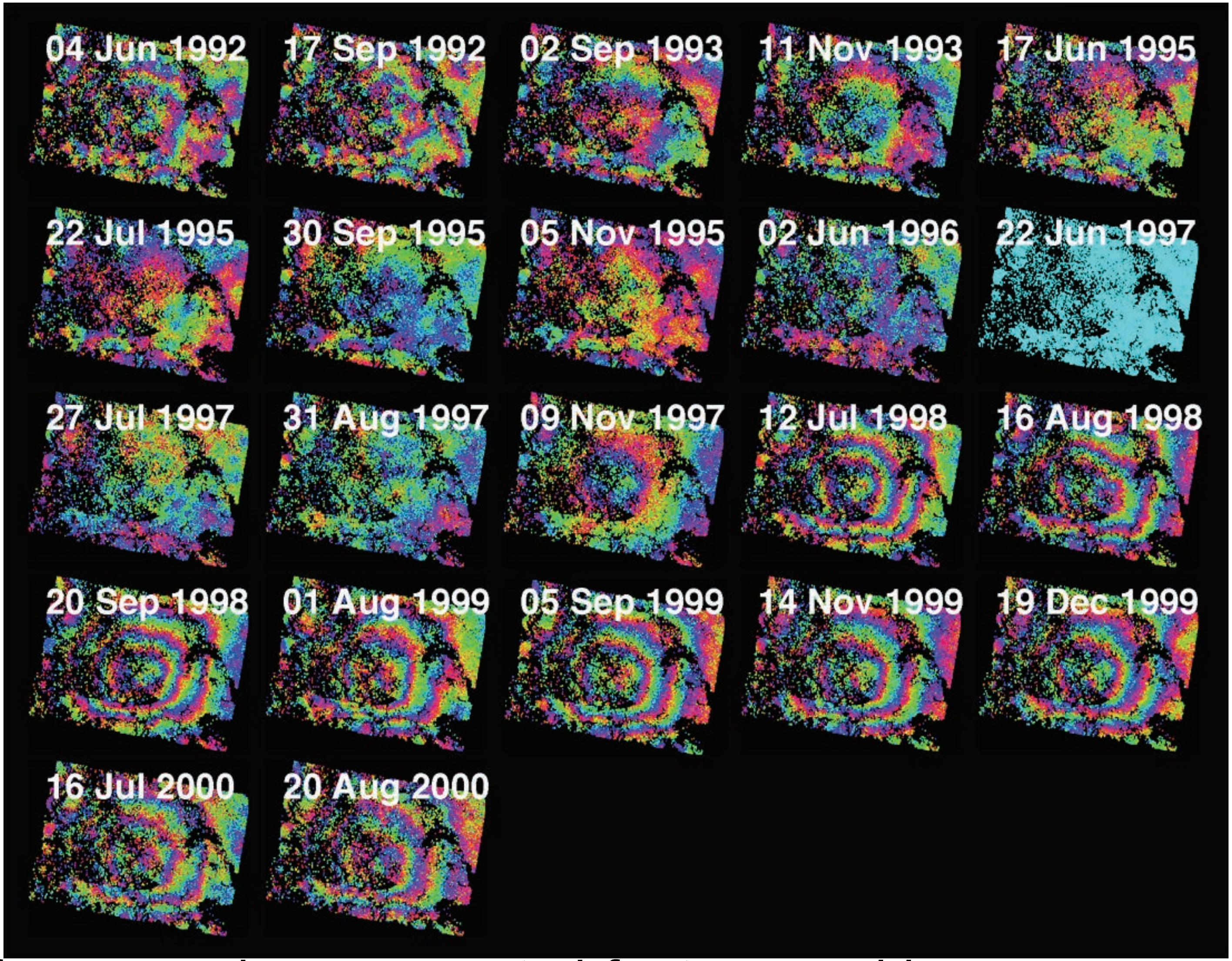
Where γ_x is the temporal coherence

Results in Long Valley



• 29,000 persistent scatterers

Wrapped PS Phase



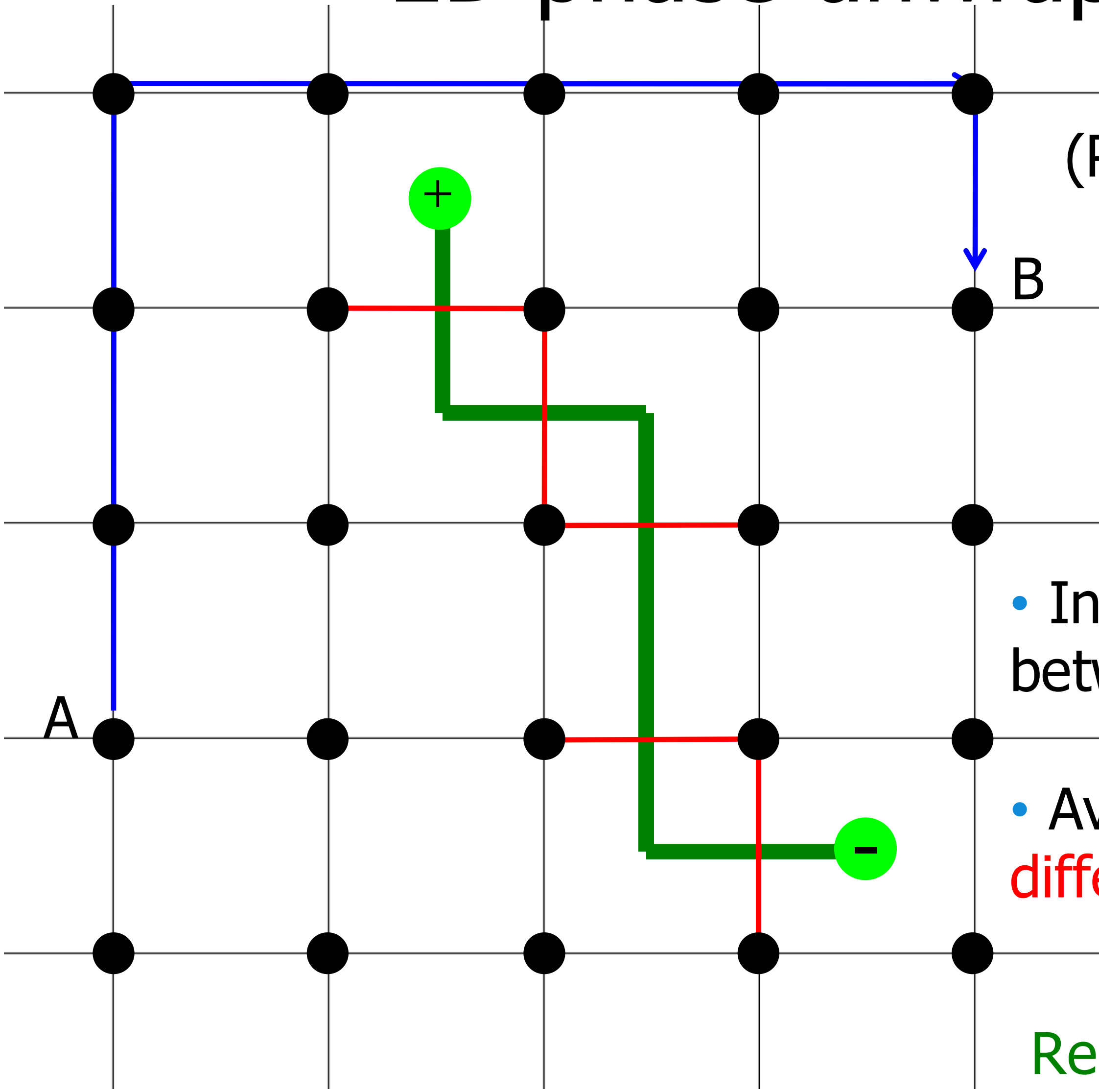
- Interferogram phase, corrected for topographic error

Phase unwrapping

- With temporal model, phase is unwrapped by finding model parameters that minimise the wrapped residuals between double difference phase and the model

- If we do not want to assume a temporal model of phase evolution we need another strategy

2D phase unwrapping

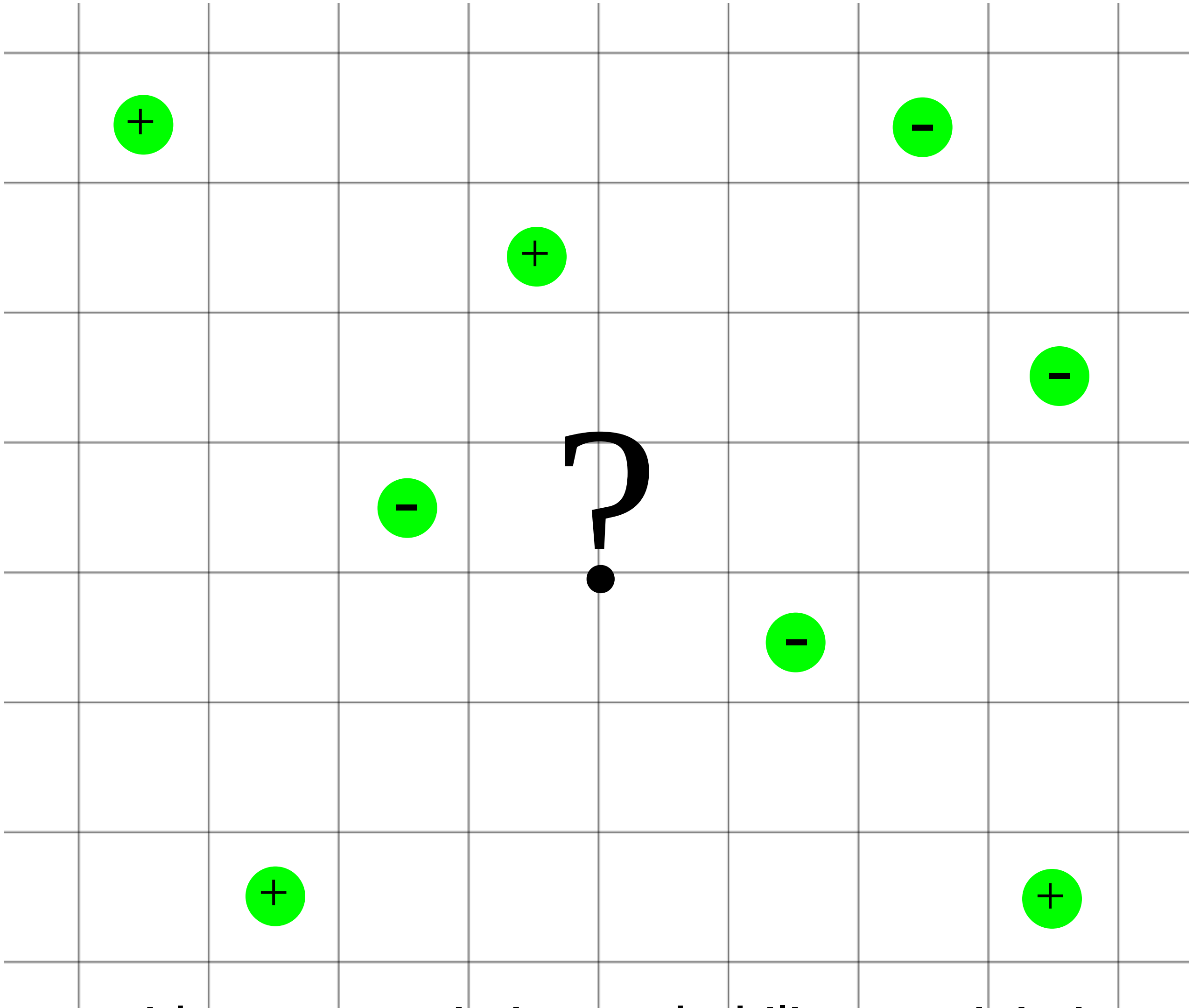


(Points represent PS)

- Integrate phase differences between neighboring pixels
- Avoid paths where phase difference > half cycle

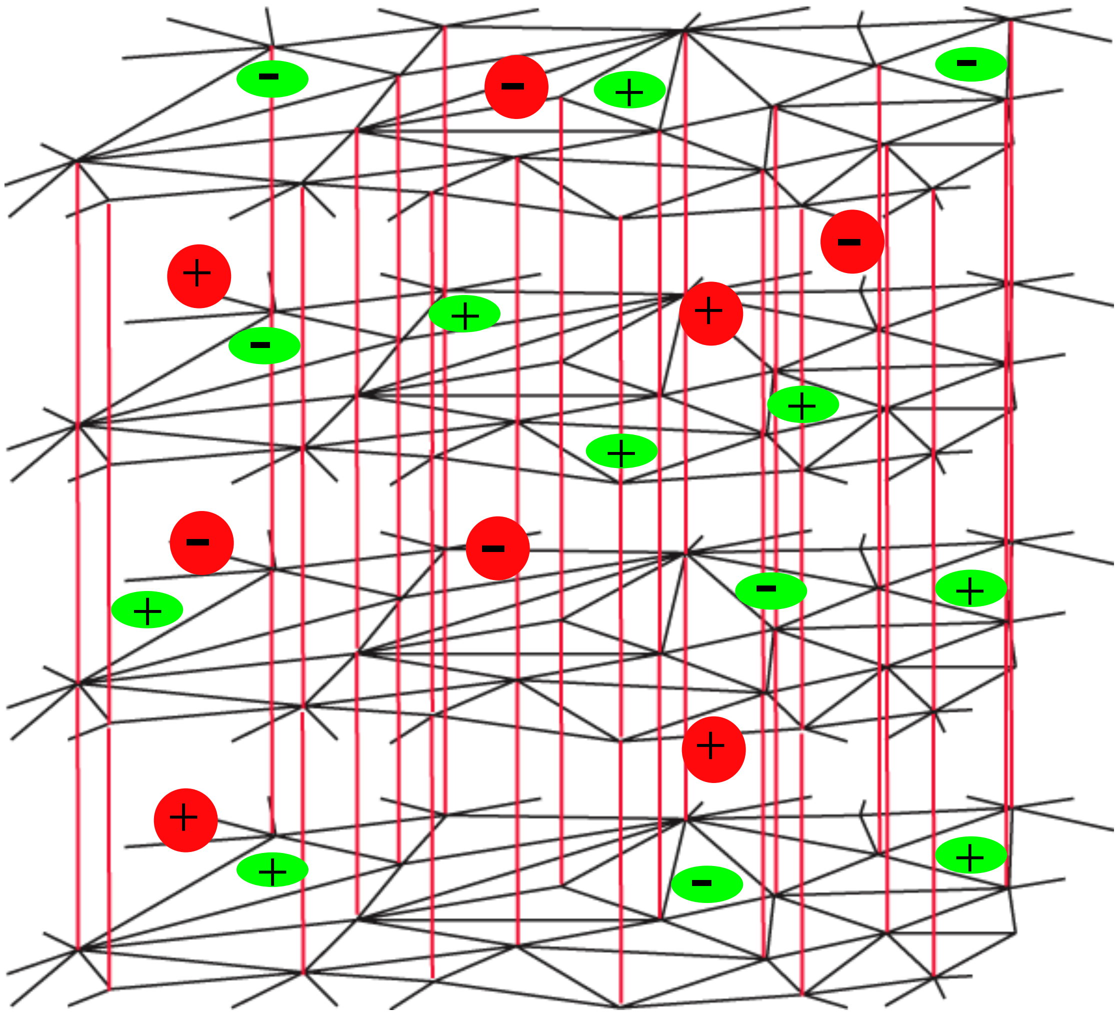
Residues lie on branch cuts

2D Inverse Problem



- Connect residues to maximise probability or minimise some norm

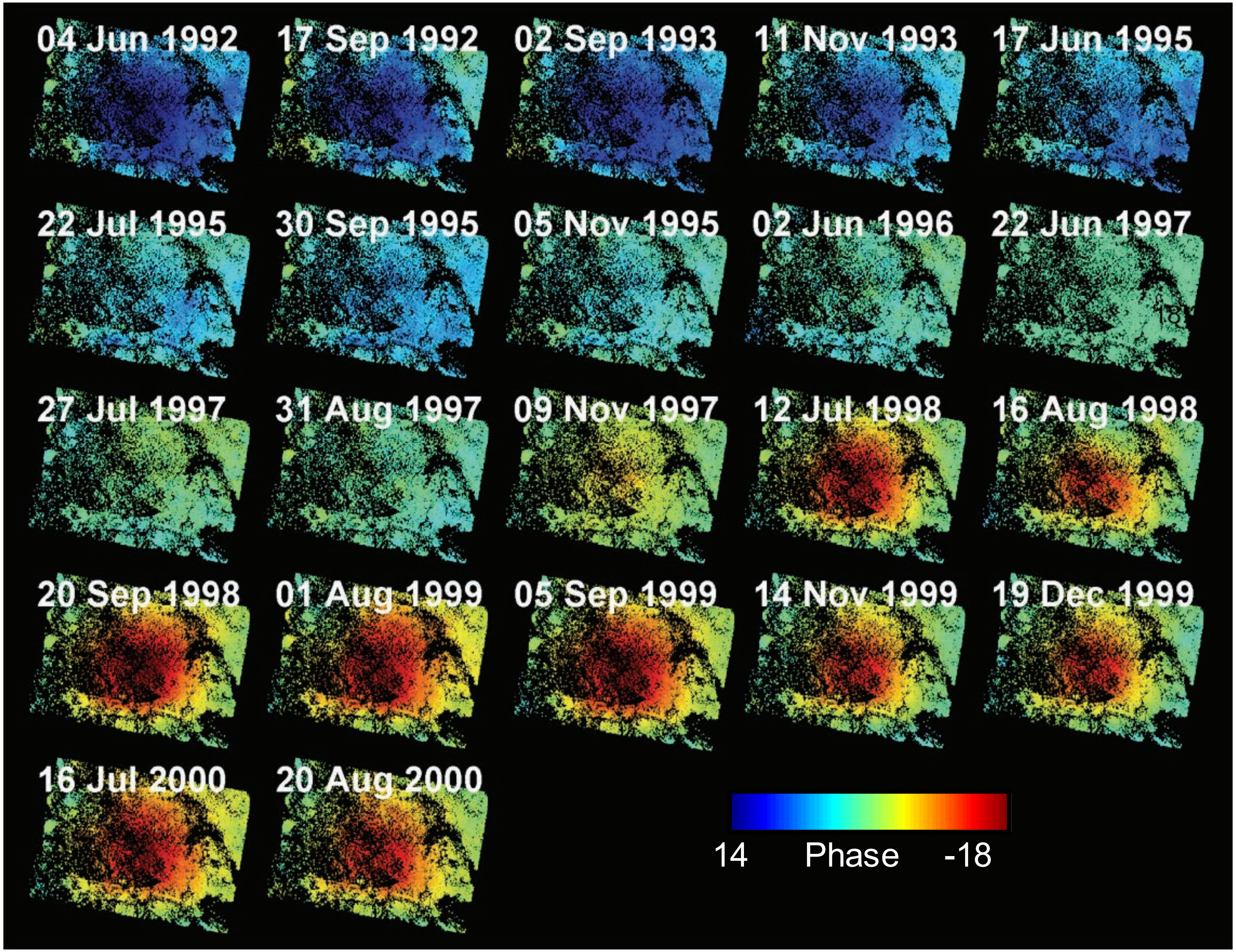
3D Problem (Sparse)



residues in space-space

residues in space-time

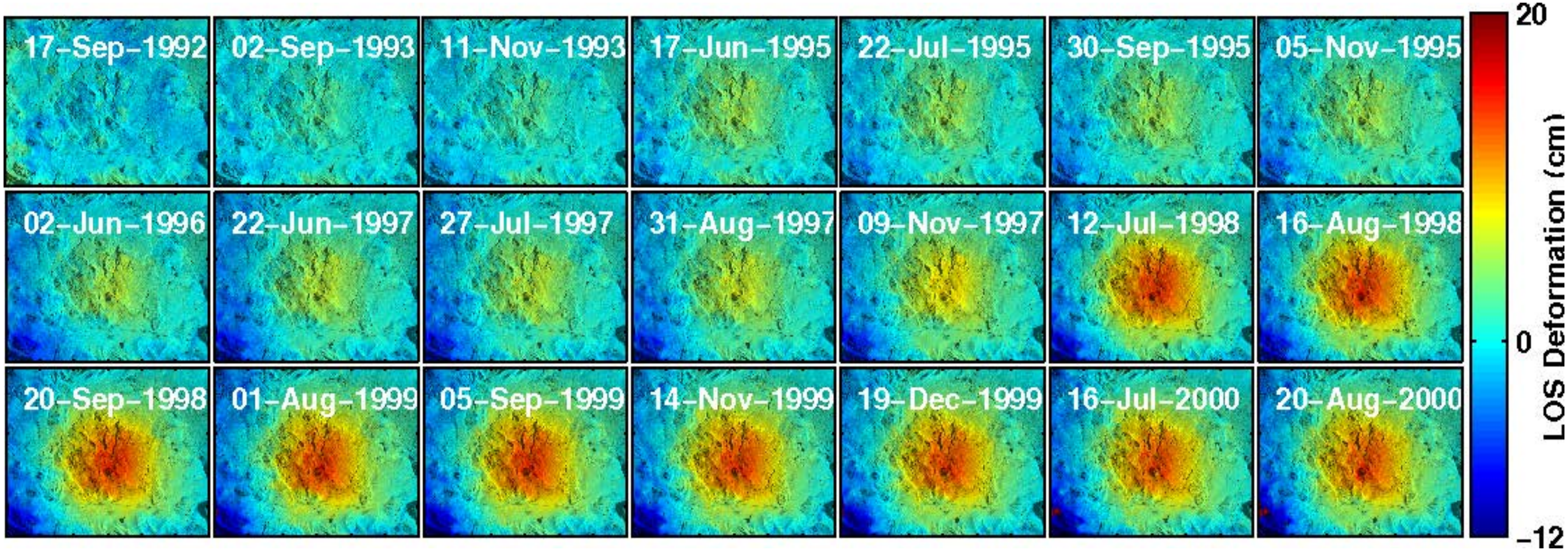
Unwrapped PS Phase



- Not linear in time

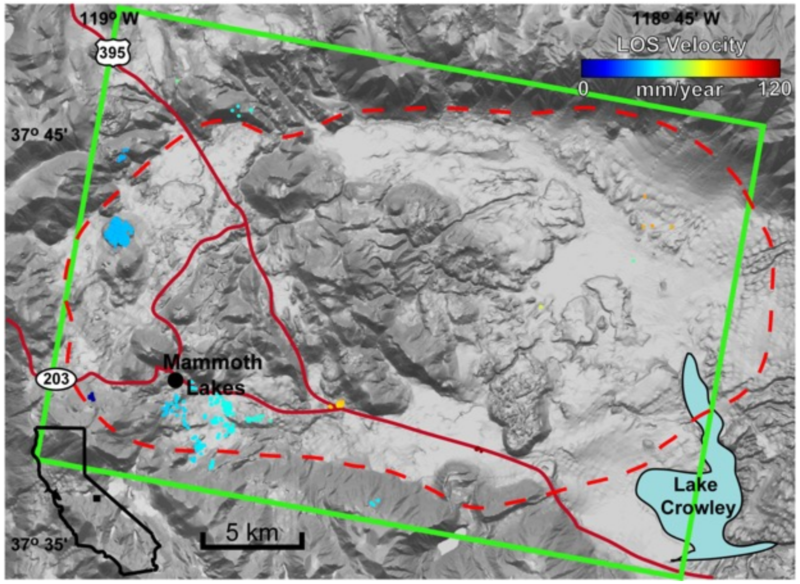
Estimation of Atmospheric Signal And Orbit Errors

- Filtering in time and space, as for temporal model approach

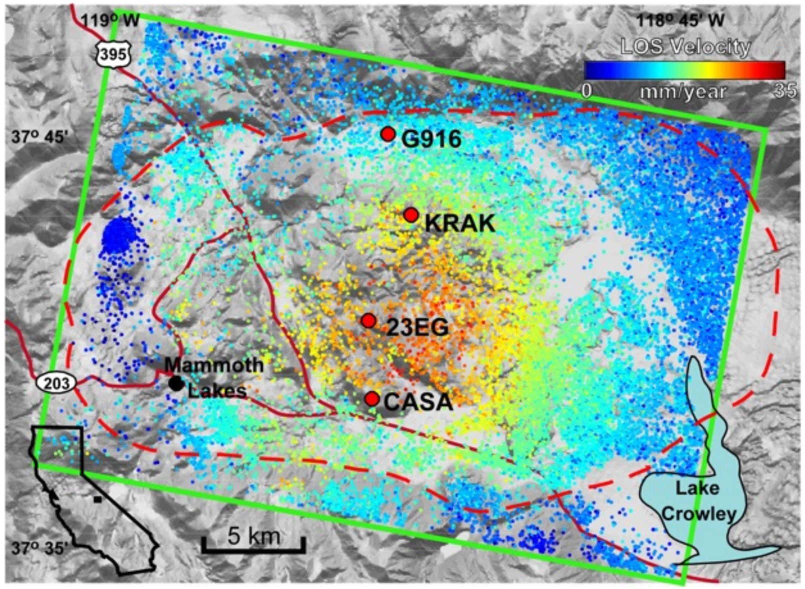


Estimate of atmospheric and orbit errors subtracted, leaving deformation estimate (not necessarily linear).

Comparison of approaches



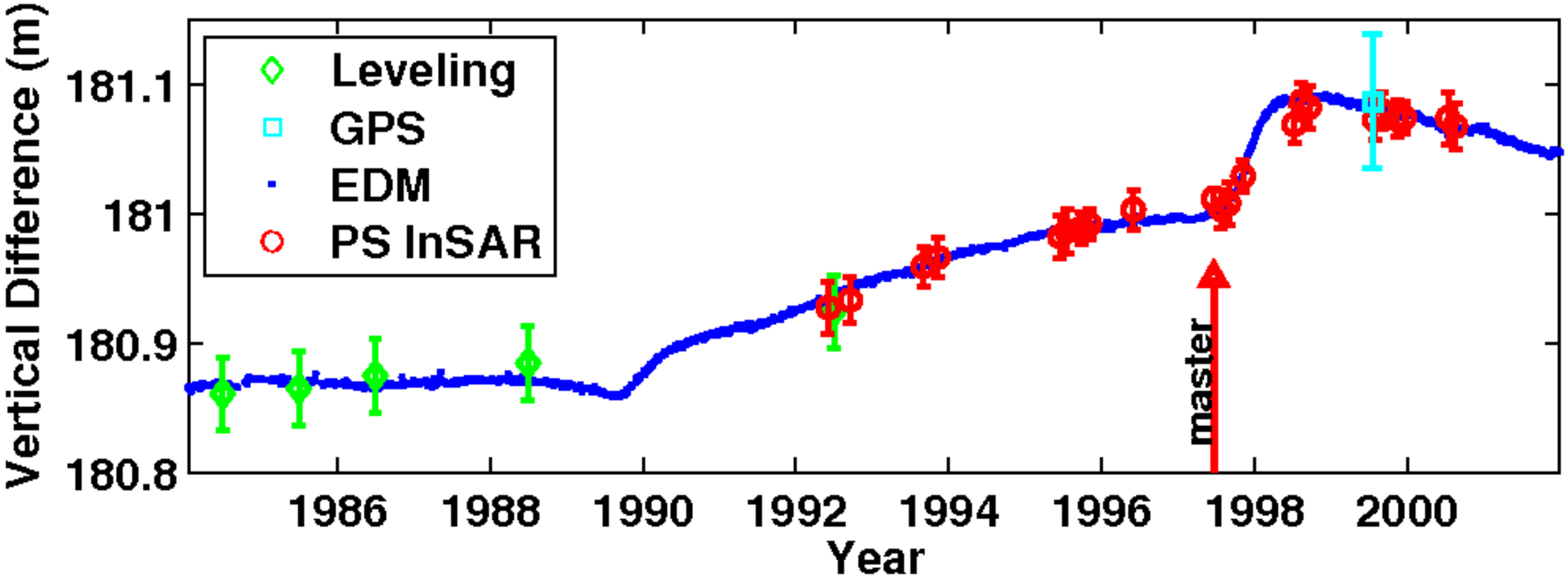
Temporal model approach



Spatial correlation approach

Long valley caldera

Validation with Ground Truth

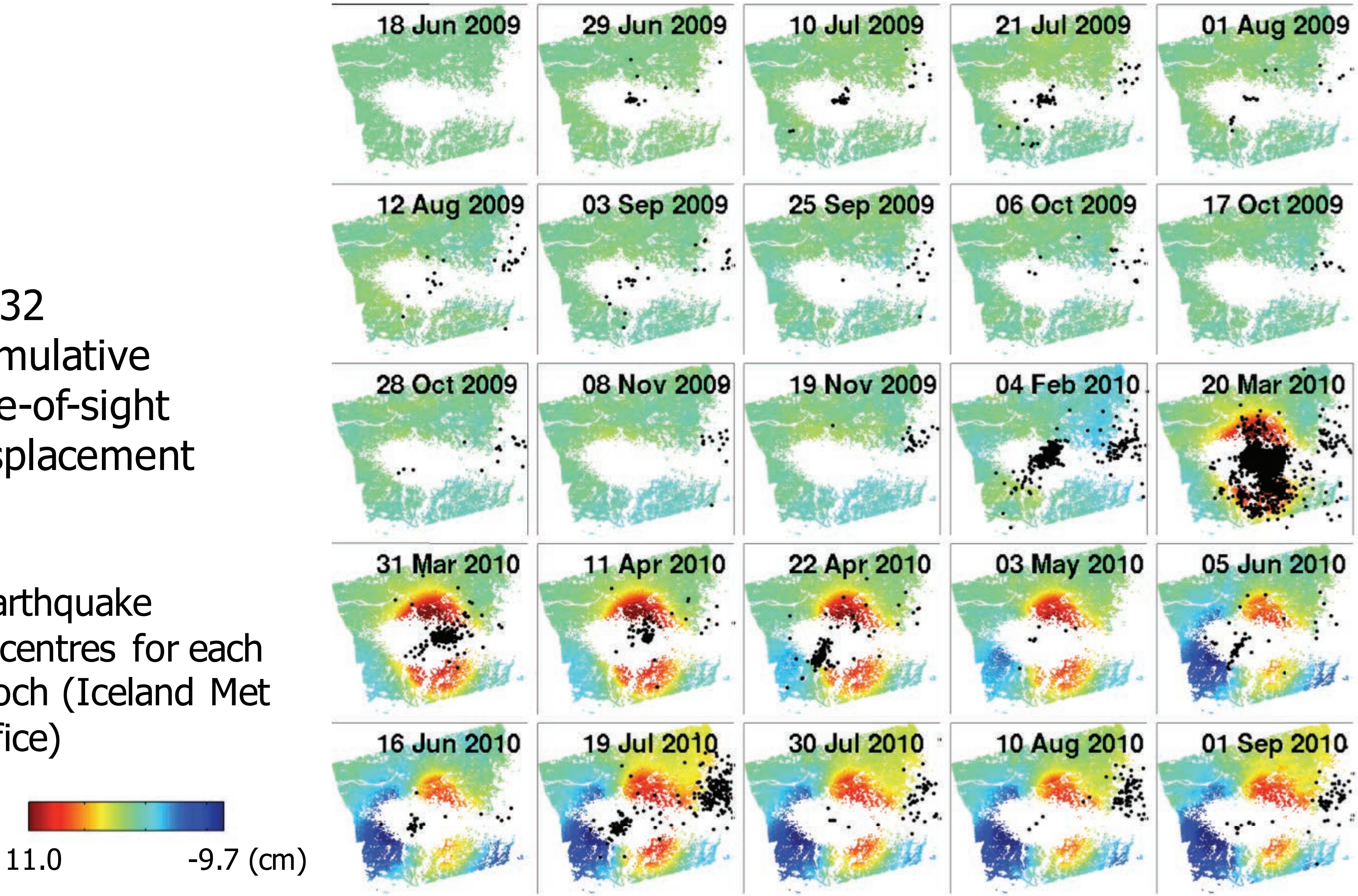


- PS show good agreement

Eyjafjallajökull PS time series

T132 cumulative line-of-sight displacement

•Earthquake epicentres for each epoch (Iceland Met Office)



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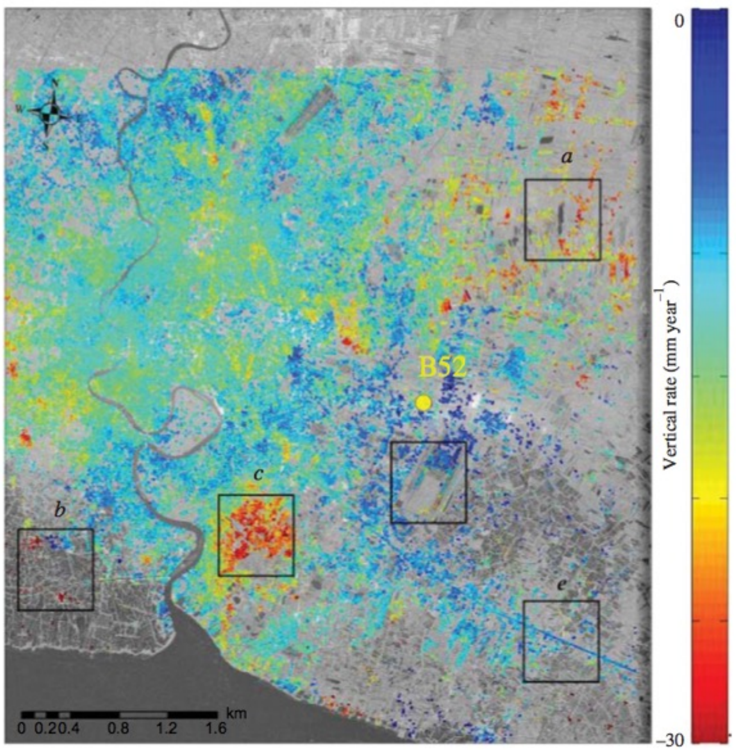
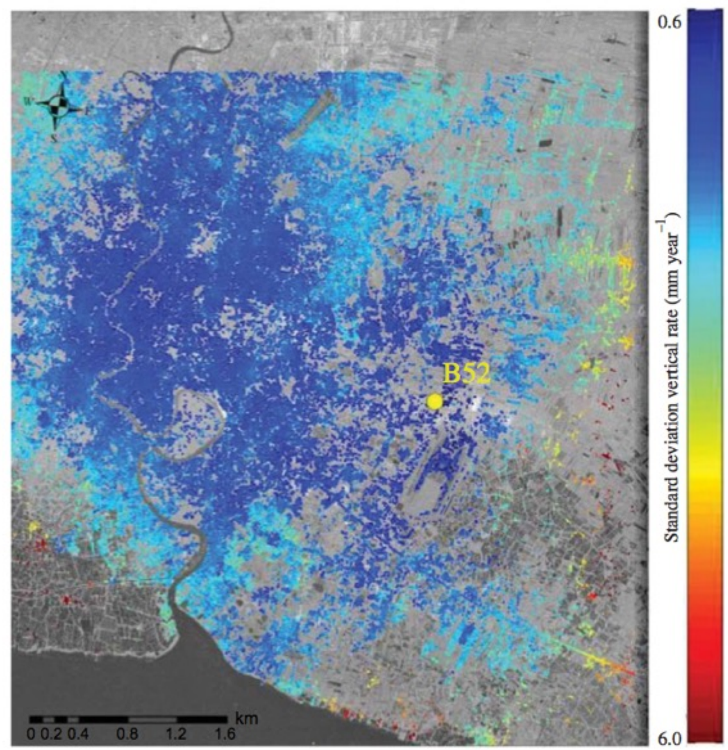
Error estimation

- Because no temporal model was assumed, probability density functions can be estimated by repeatedly fitting a temporal model using the percentile bootstrapping method.

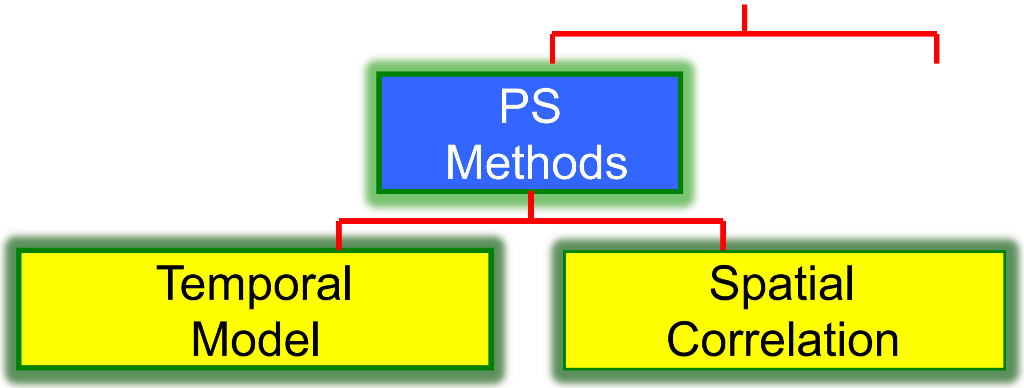


Subsidence rates in Bangkok



Standard deviations of rates

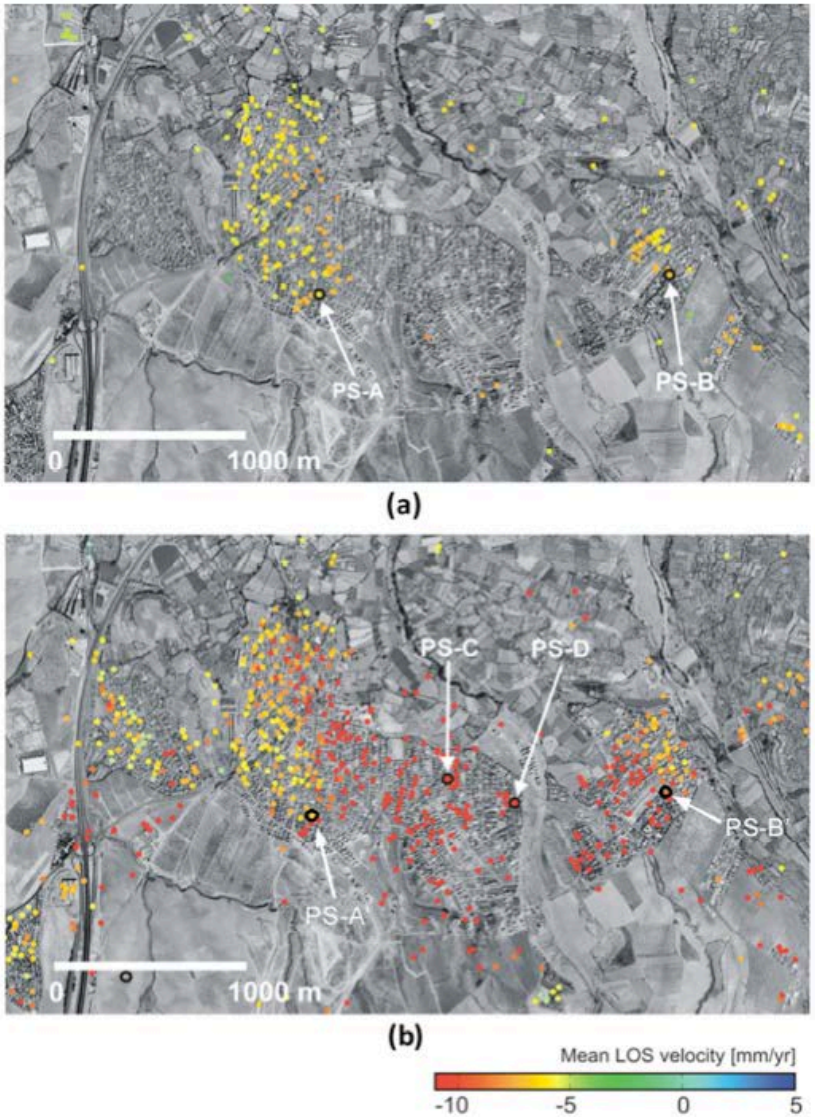
Comparison PS Algorithms



- Spatial correlation algorithm works in more general case, but may miss PS with non-spatially correlated deformation
- Temporal model algorithm more rigorous in terms of PS reliability evaluation, but may not work in rural areas, or where deformation is irregular in time.

Comparison PS Algorithms

(Sousa et al, 2010)



Temporal model approach
(DePSI, Ketelaar thesis, 2008)

Spatial coherence approach
(StaMPS, Hooper et al, JGR 2007)

Housing development near Granada, Spain

Persistent Scatterer (PS) InSAR

Summary

- Relies on pixels that exhibit low decorrelation with time and baseline
- Non-deformation signals are reduced by modelling and filtering
- PS techniques work best in urban environments, but can also be applied in rural environments

Interpretation of PS observations

Consider what is actually moving