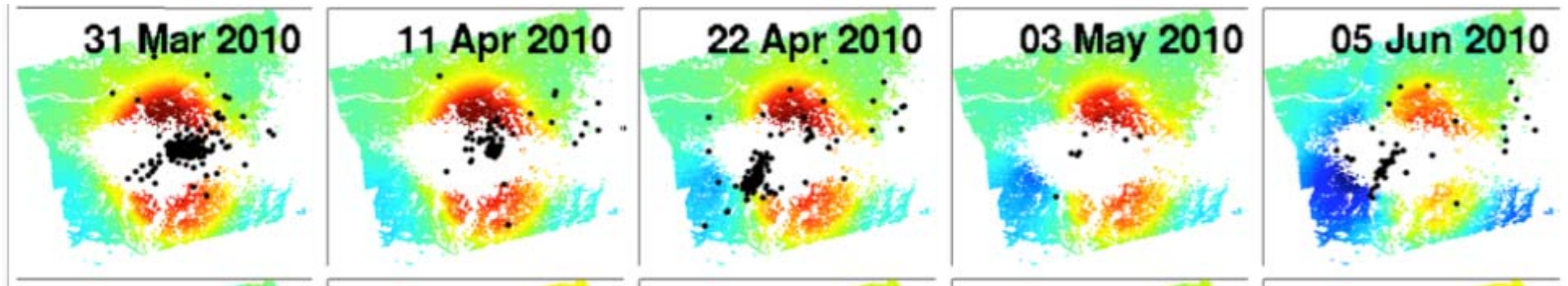


Terrain Motion and Persistent Scatterer InSAR



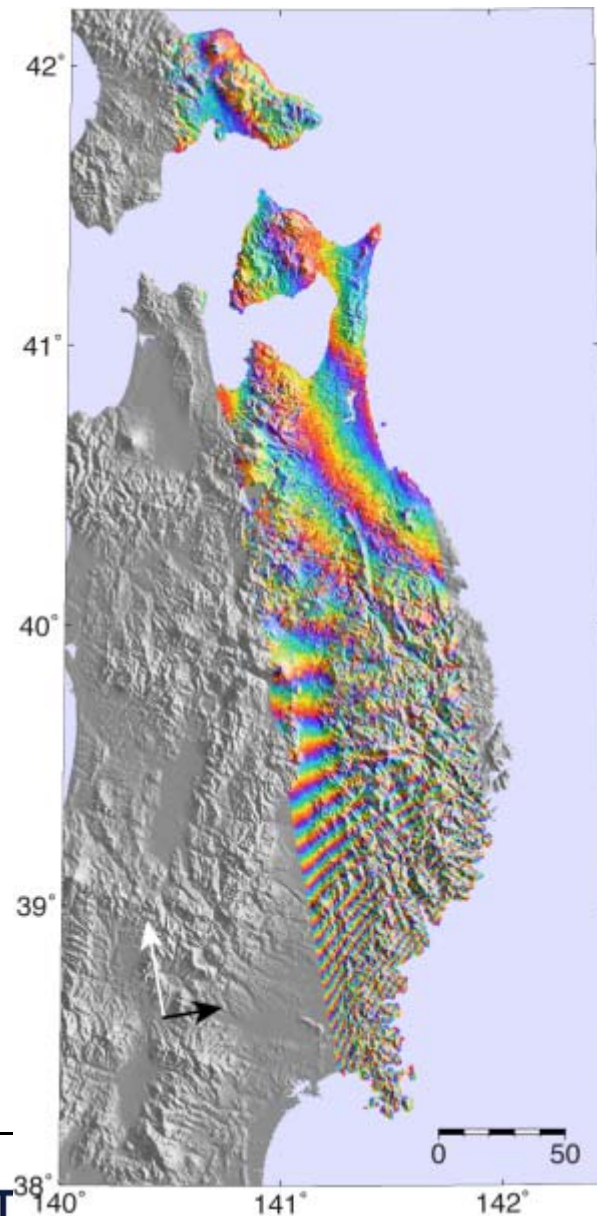
Andy Hooper
University of Leeds

**ESA Land Training Course,
Gödöllő, Hungary, 4-9th September, 2017**

Good Interferogram

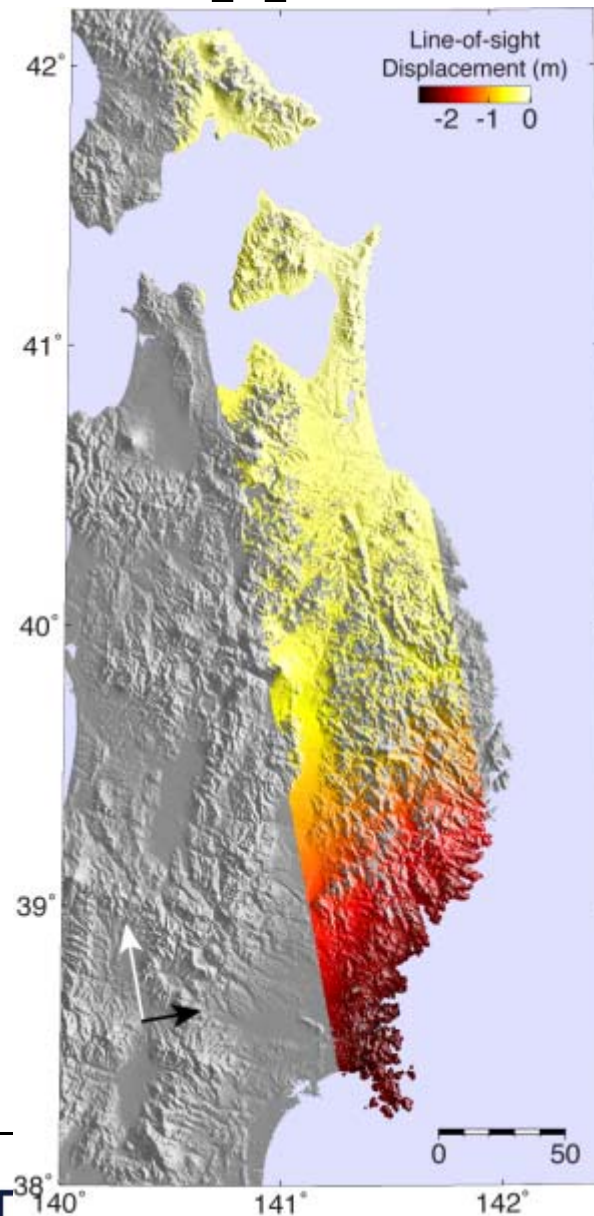
2011 Tohoku earthquake

- 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



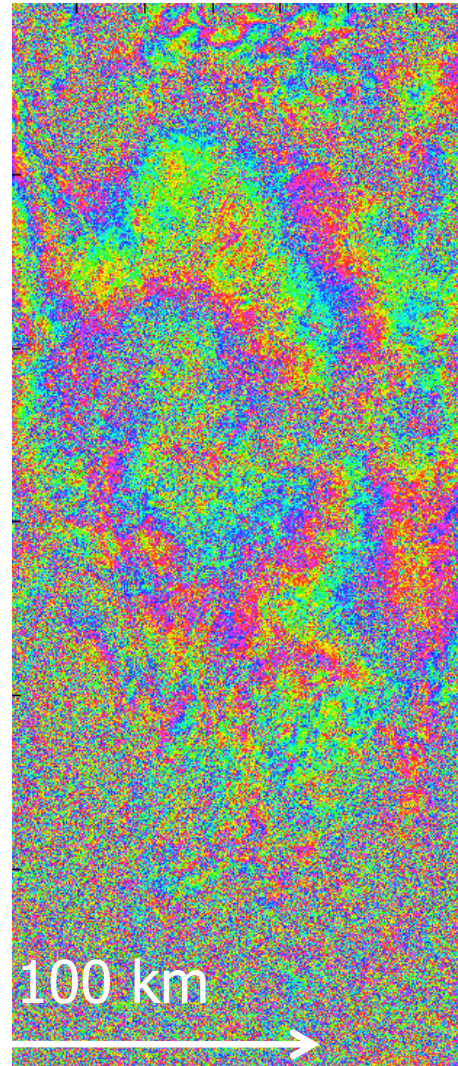
- Can be easily unwrapped
- Deformation dominates

Integrated phase cycles
giving 2.5 m relative
displacement

Typical interferograms

Signal dominated by
atmosphere, orbit and
DEM errors

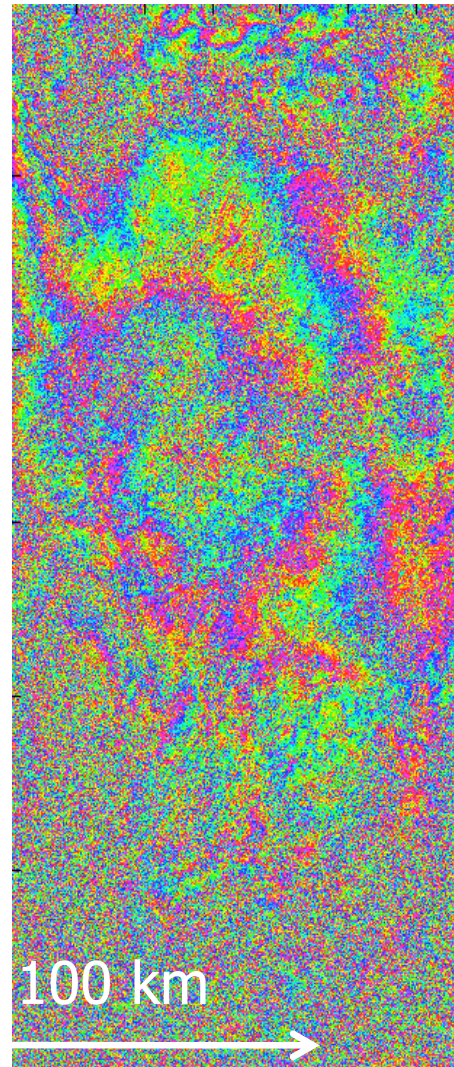
(larger than
deformation for low
strains and short
intervals)



Typical interferograms

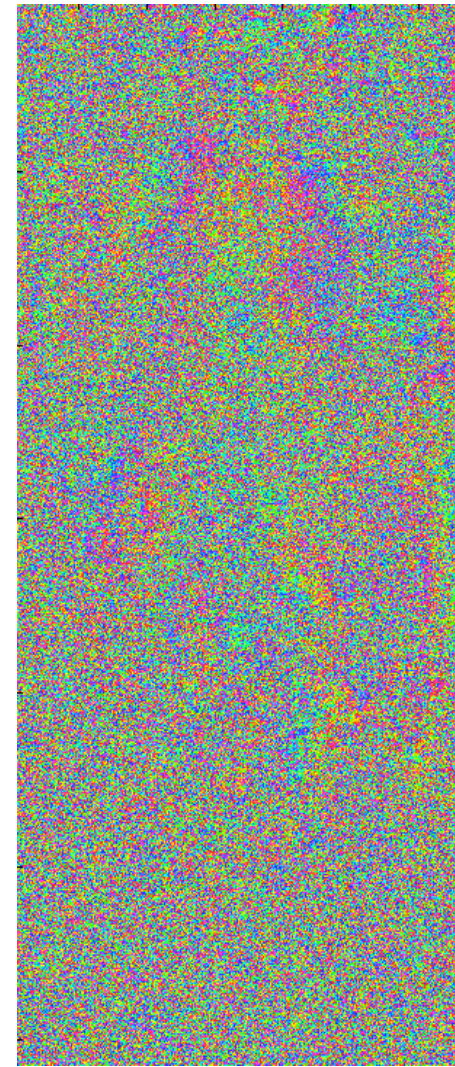
Signal dominated by
atmosphere, orbit and
DEM errors

(larger than
deformation for low
strains and short
intervals)



High
Decorrelation

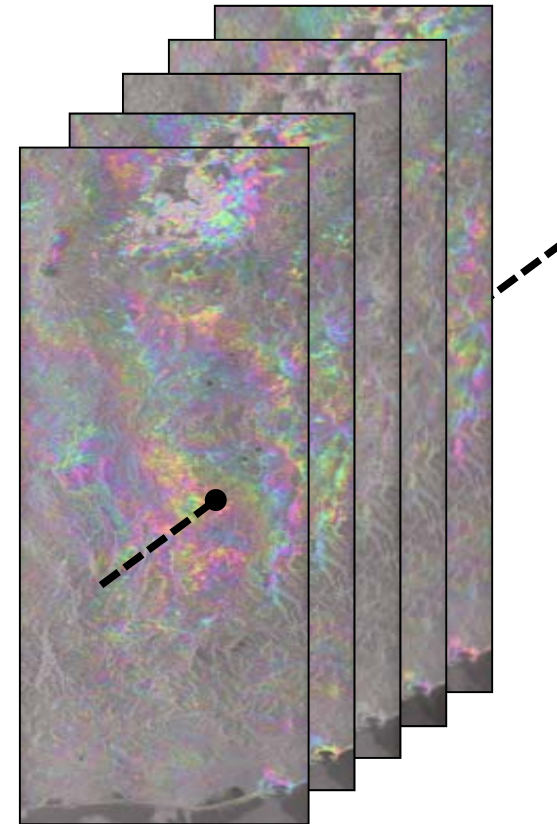
(especially for
long intervals)



Persistent Scatter (PS) InSAR

Motivation!

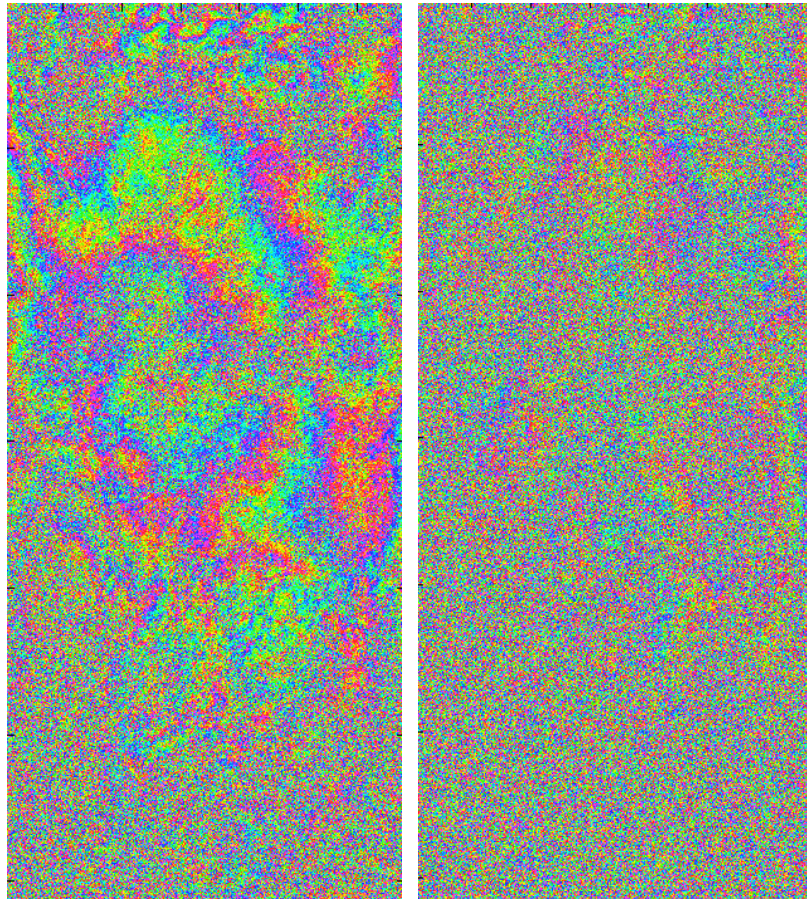
- Allows better selection of coherent pixels
- DEM error estimation possible
- More reliable phase unwrapping possible (3-D)
- Other errors can be reduced by filtering in space and time
- Sub-pixel resolution possible



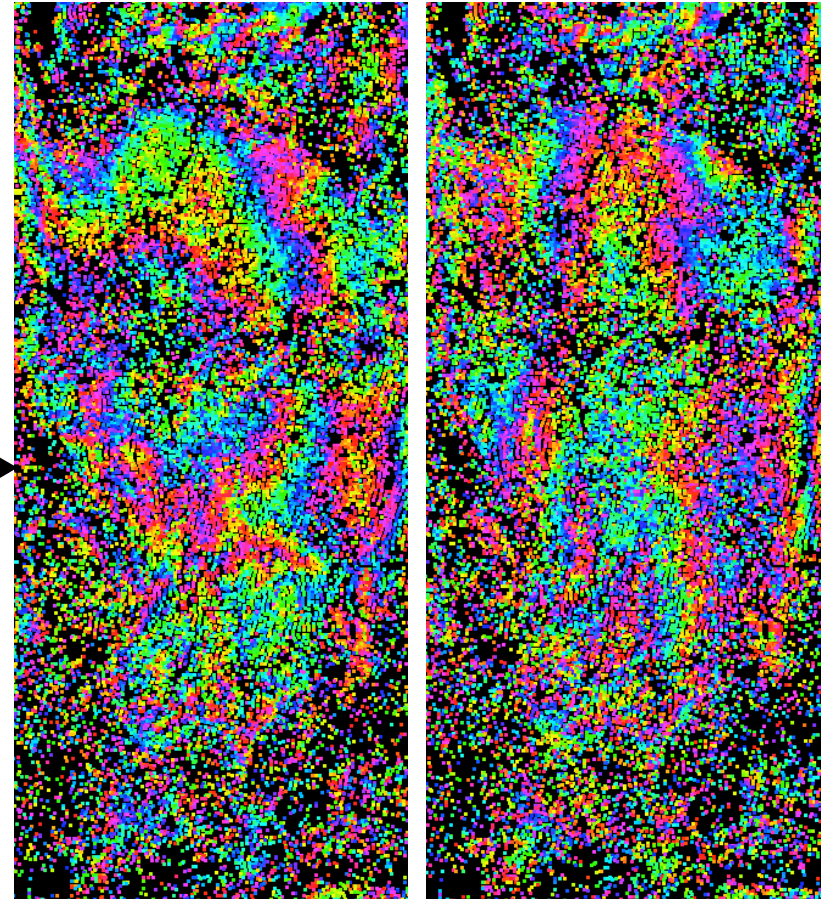
A time series analysis approach

Improvement of coherence

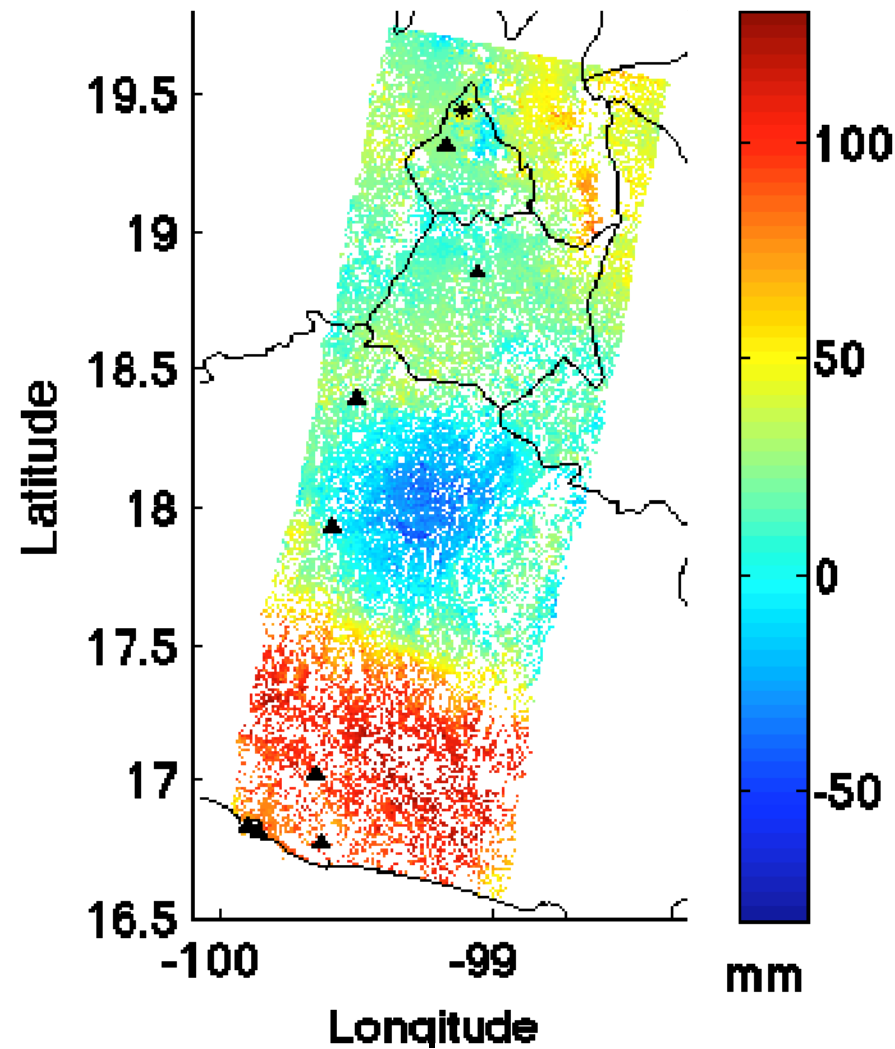
InSAR (80 looks)



Persistent Scatterer InSAR



After unwrapping and reduction of non-deformation signals



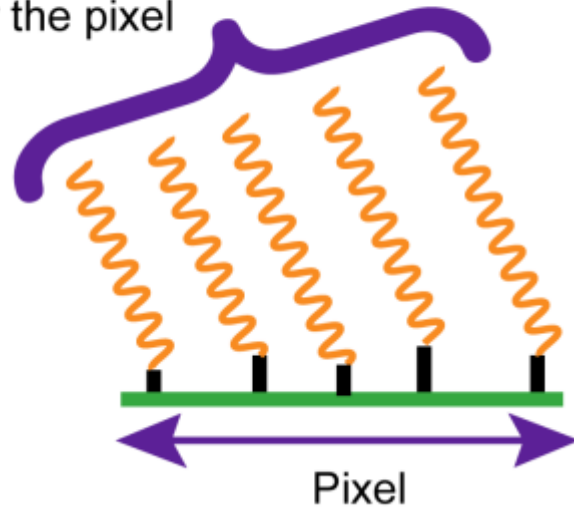
High resolution PS Processing



Barcelona Olympic Port (Institut de Geomatica)

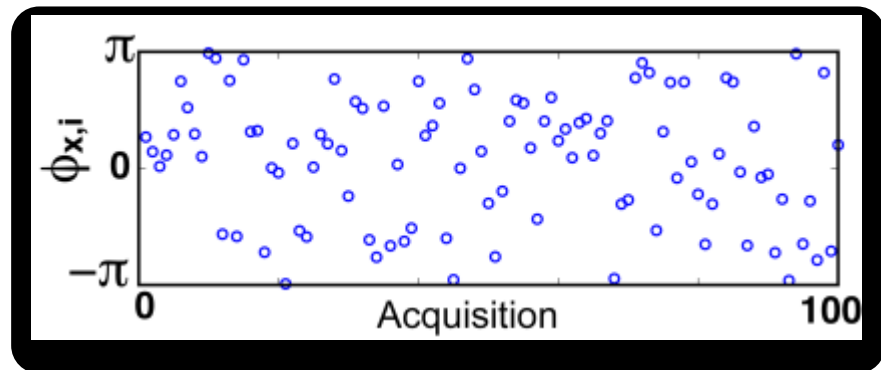
Cause of Decorrelation

The echos sum to give one phase value for the pixel



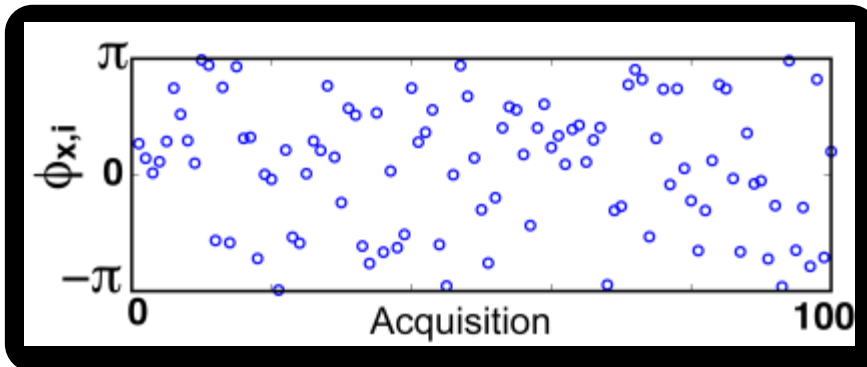
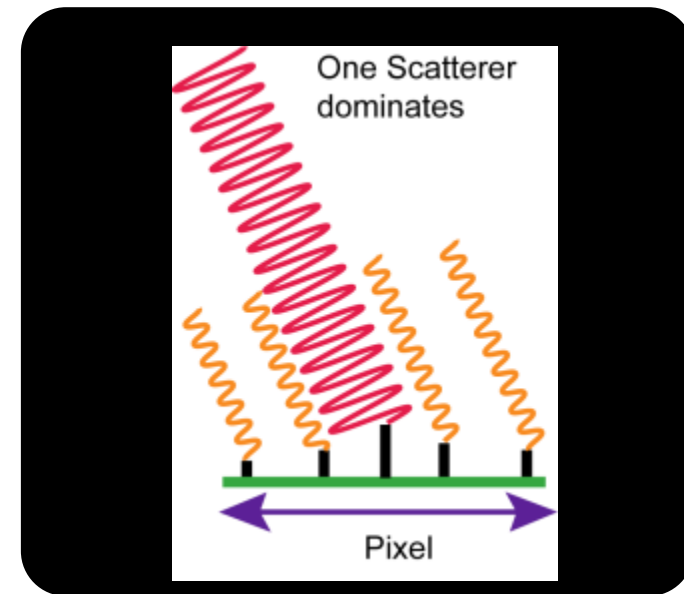
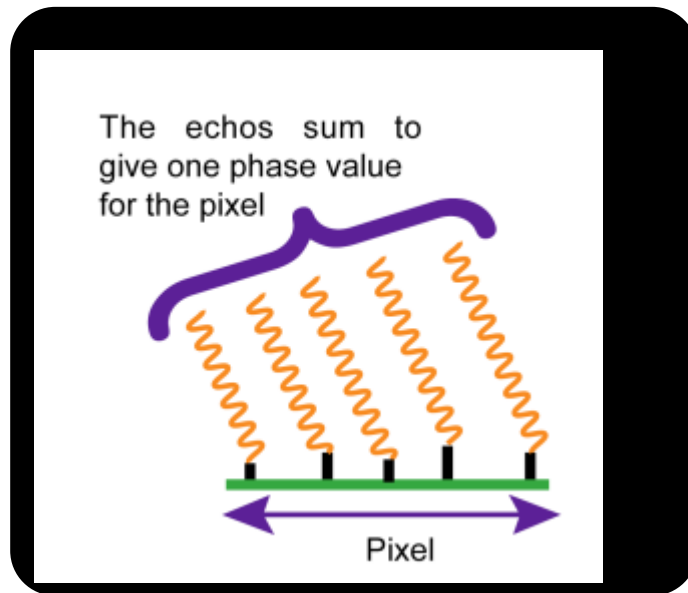
Distributed scatterer pixel

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

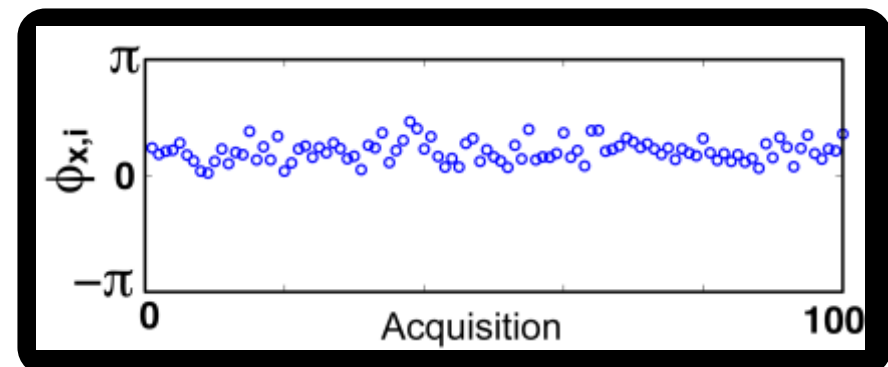


(similar effect if incidence angle changes)

Persistent Scatterer (PS) Pixel



Distributed scatterer pixel

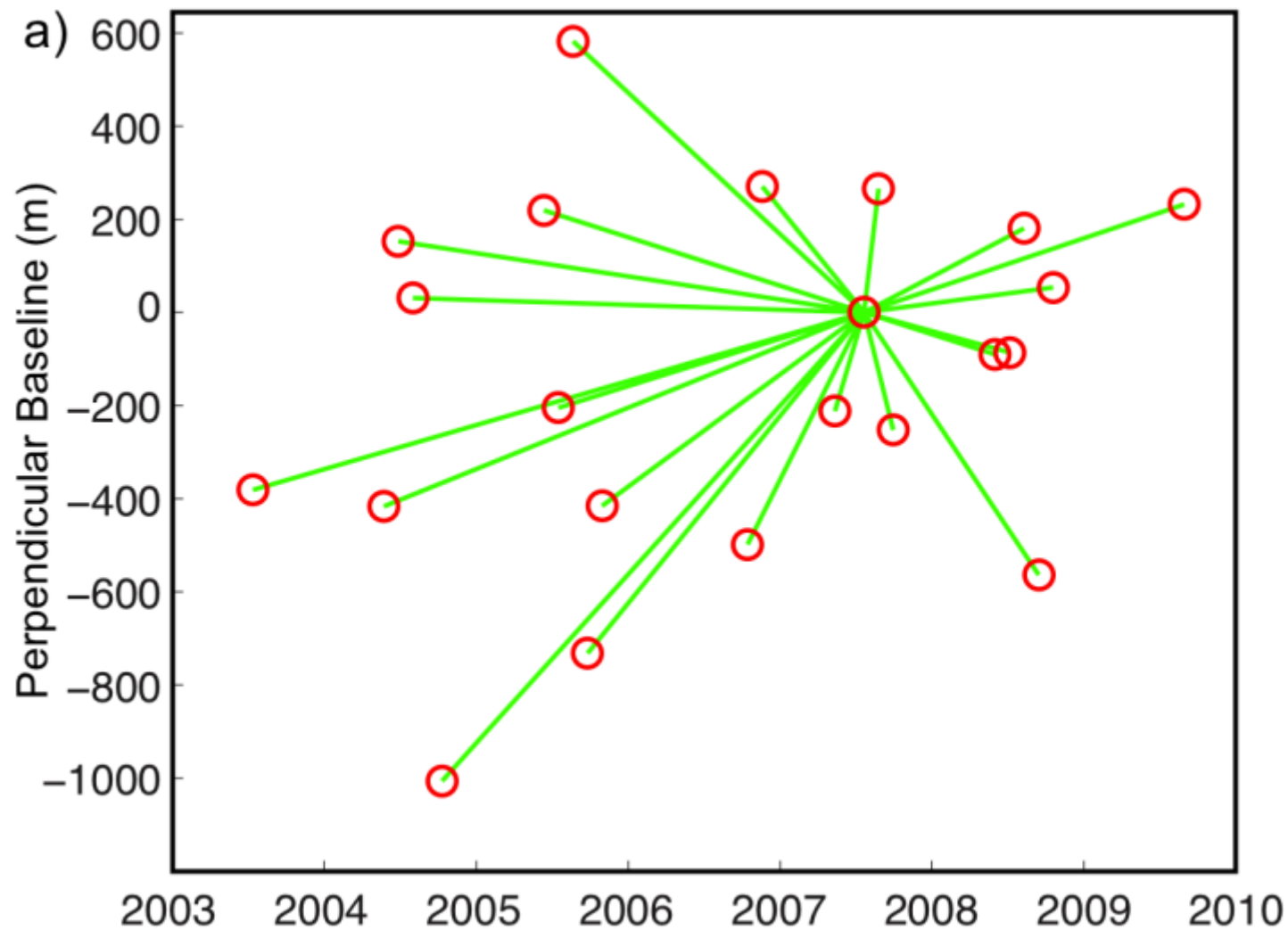


"Persistent scatterer" (PS) pixel

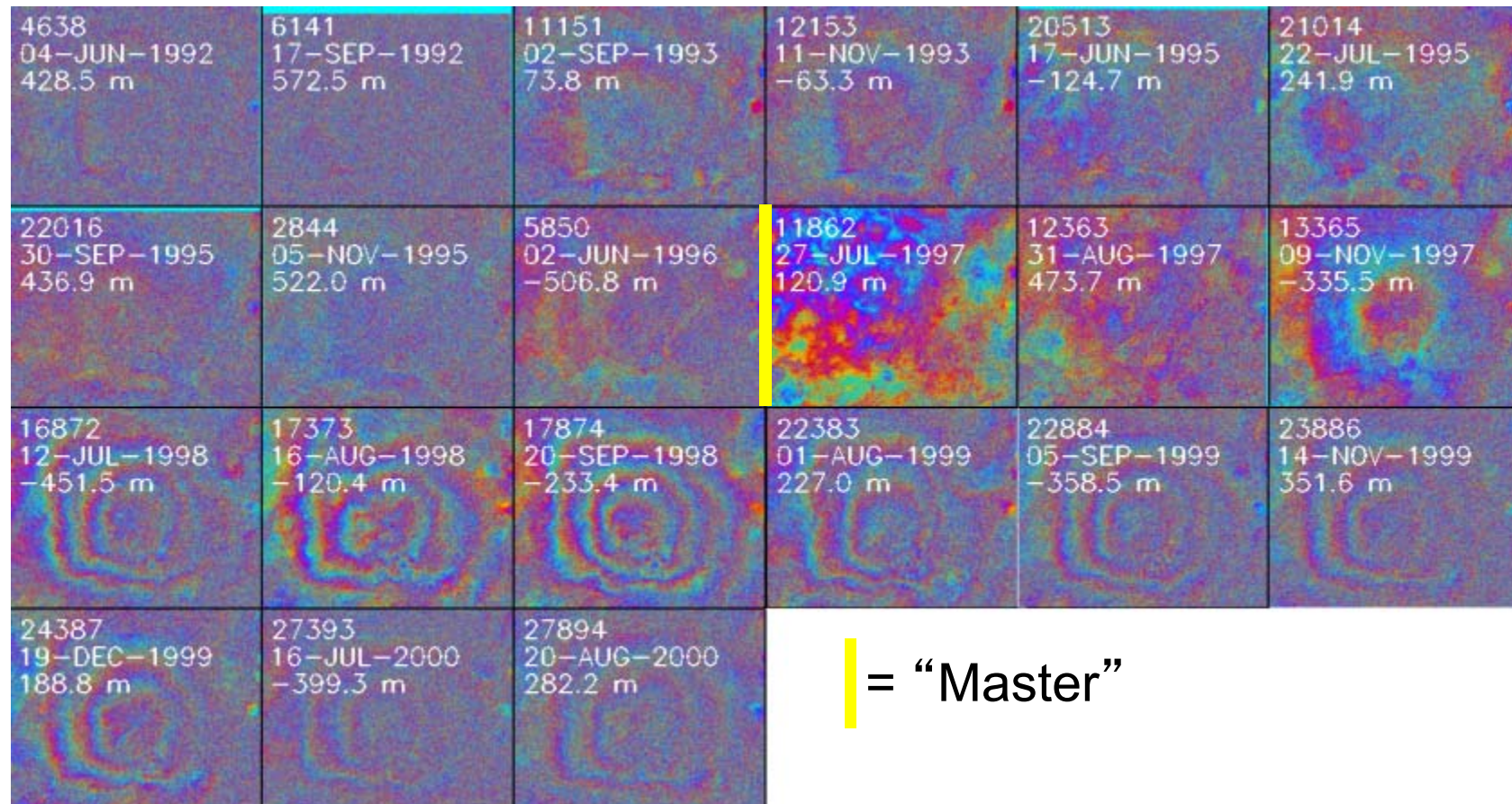
PS Interferogram Processing

- 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



Interferometric Phase

For each **pixel** in each **interferogram**:

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

Deformation in LOS

Atmospheric Delay

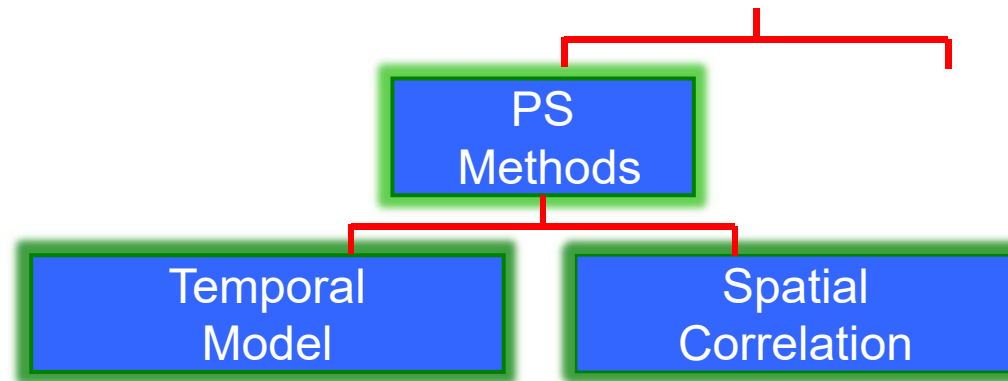
Orbit Error

DEM Error

“Noise”

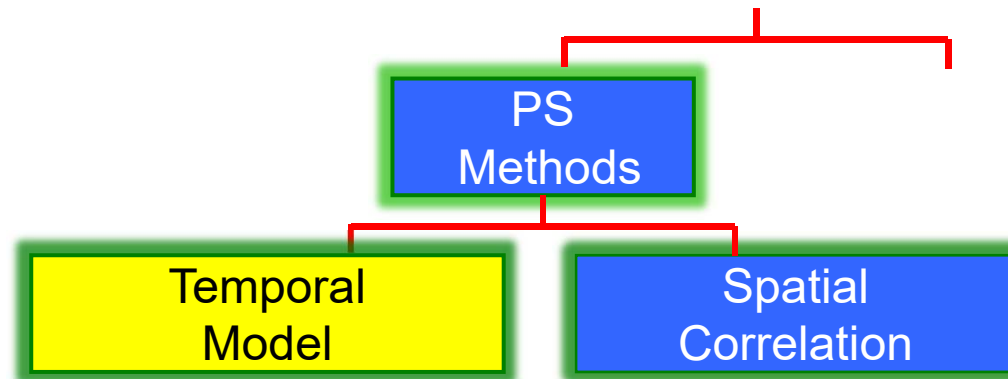
$W\{\bullet\}$ = wrapping operator

PS Processing Algorithms



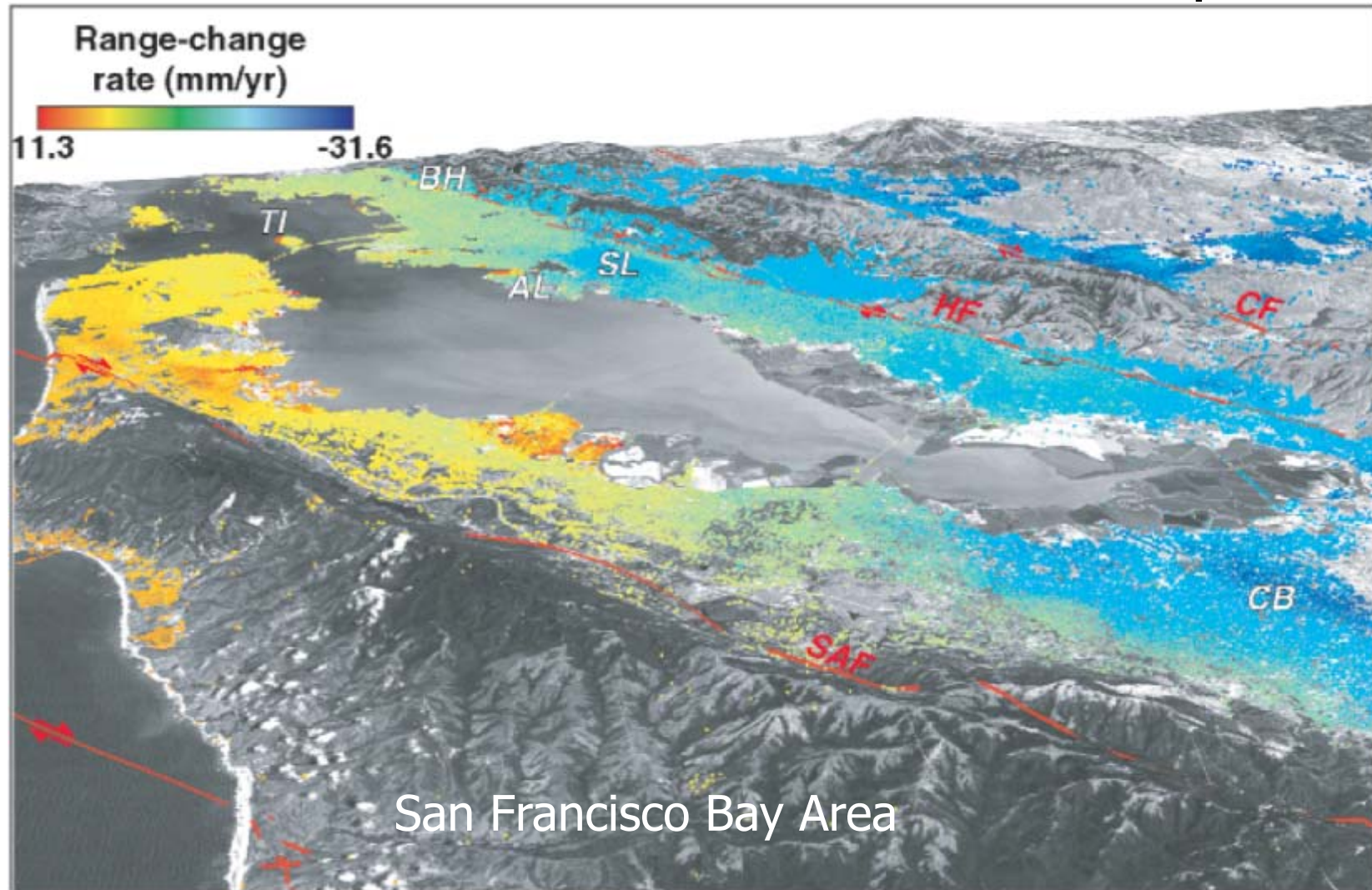
- Relying on model of deformation in time: e.g. “Permanent Scatterers” (Ferretti et al. 2001), Delft approach (Kampes et al., 2005)
- Relying on correlation in space: StaMPS (Hooper et al. 2004)

PS Processing Algorithms



- 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)

“Permanent Scatterer” Technique



Ferretti et al, 2004

Double-difference phase

For each **pair of pixels** in each **interferogram**:

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

Deformation in LOS

Atmospheric Delay

Orbit Error

DEM Error

“Noise”

Double-difference phase

If pixel pairs are **nearby**:

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

The diagram illustrates the components of the double-difference phase equation. The equation is shown as $\delta\phi_{\text{int}} = \delta\phi_{\text{defo}} + \delta\phi_{\text{atmos}} + \Delta\phi_{\text{orbit}} + \delta\Delta\phi_{\text{topo}} + \delta\phi_{\text{noise}}$. Below the equation, five boxes represent the sources of these terms: 'Deformation in LOS' for $\delta\phi_{\text{defo}}$, 'Atmospheric Delay' for $\delta\phi_{\text{atmos}}$, 'Orbit Error' for $\Delta\phi_{\text{orbit}}$, 'DEM Error' for $\delta\Delta\phi_{\text{topo}}$, and '"Noise"' for $\delta\phi_{\text{noise}}$. Blue arrows point from each box to its corresponding term in the equation. Red 'X' marks are placed over the $\delta\phi_{\text{atmos}}$ and $\Delta\phi_{\text{orbit}}$ terms and their respective boxes, indicating that these errors are cancelled out when the pixel pairs are nearby.

Double-difference phase

If pixel pairs are **nearby**:

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

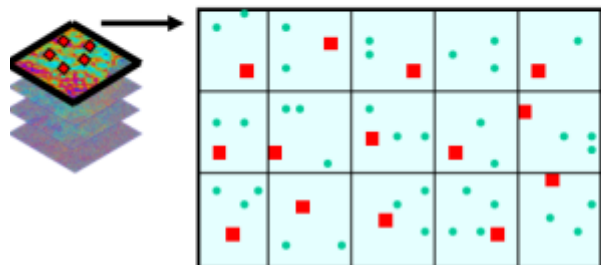
- model these two terms

Deformation
in LOS

DEM
Error

“Noise”

Preliminary Network

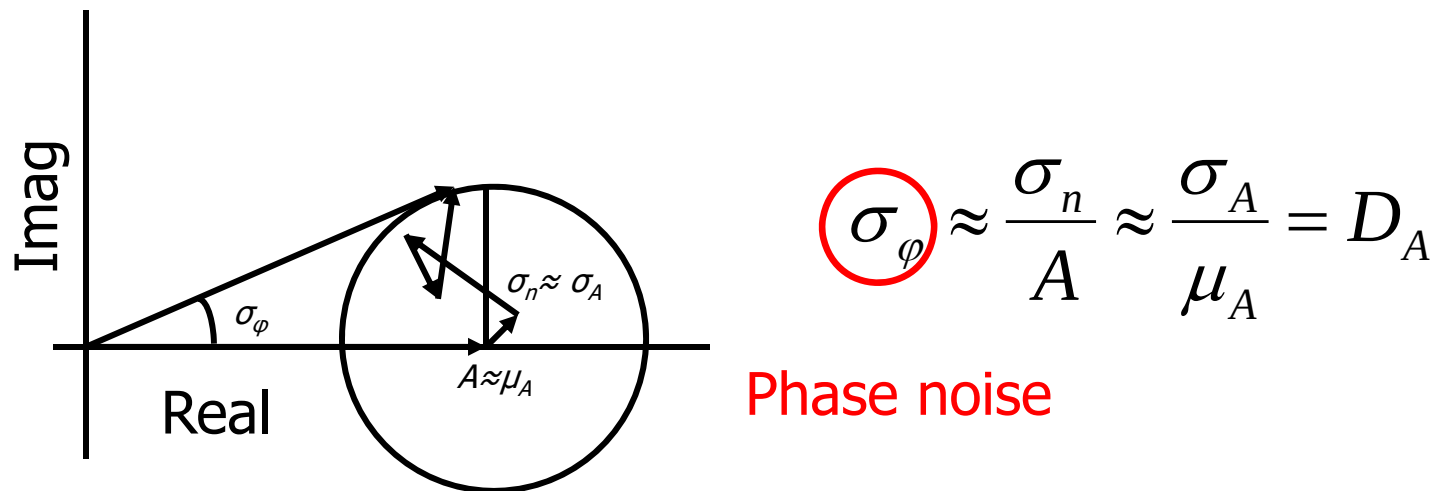


1: SELECTION

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

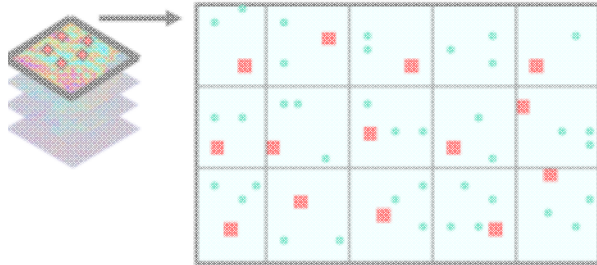
Initial selection

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



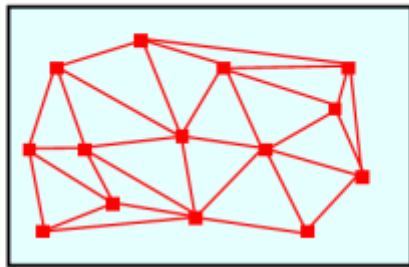
Reasonable proxy for small phase noise (<0.25 rad)

Preliminary Network



1: SELECTION

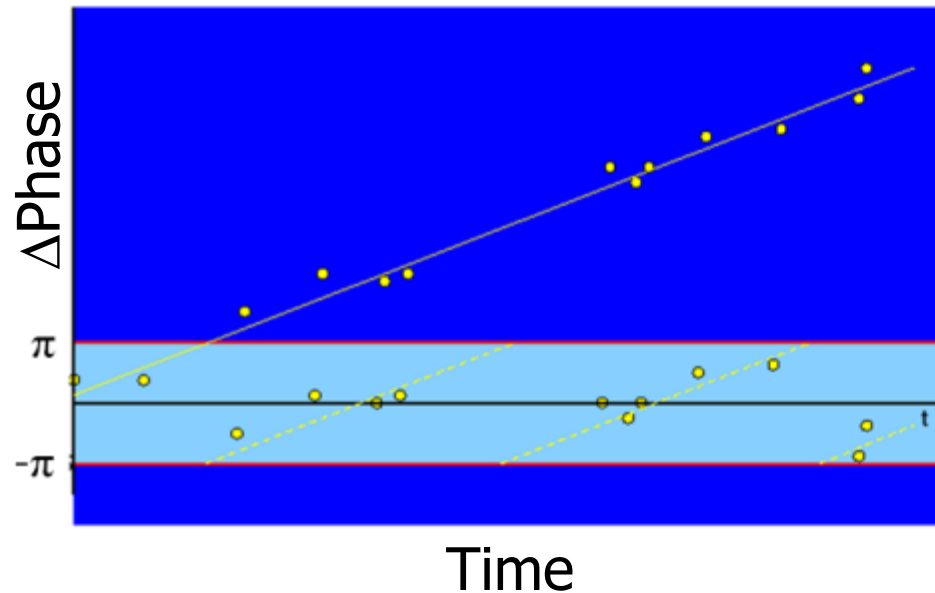
Only consider point (-like) scatterers.
Select the **best points** (■) in each grid cell
(ca. 250x250 m).



2: ESTIMATION

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

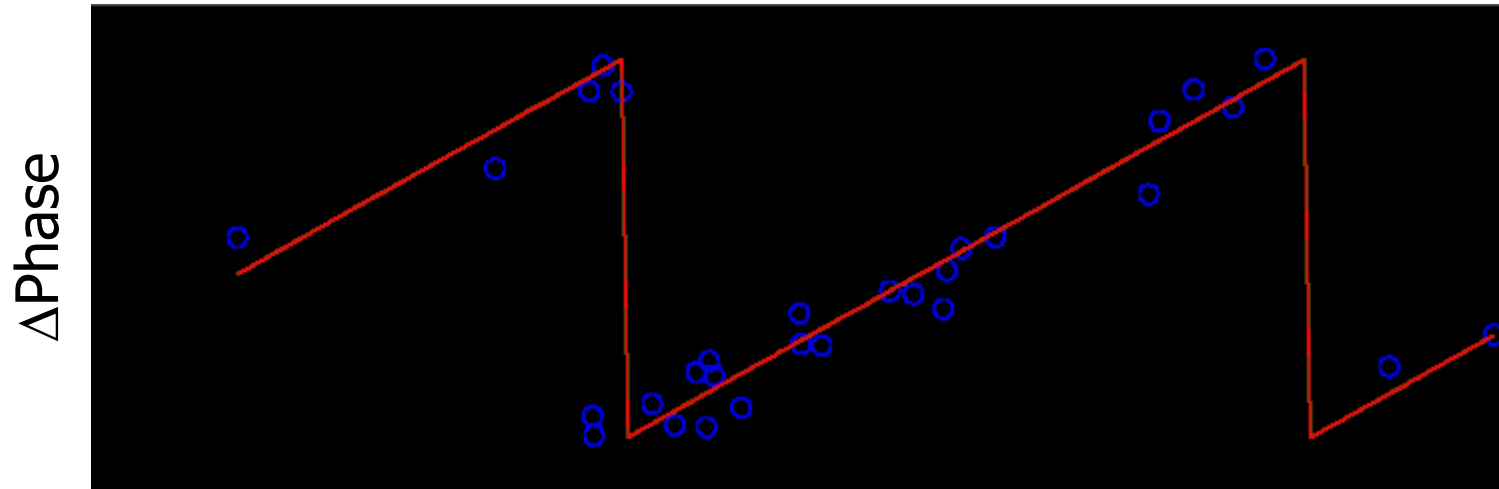
Estimation in Time



(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



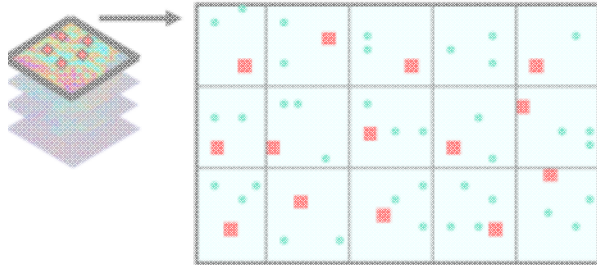
Perpendicular Baseline ($B_{\perp}$)

Constant for each
interferogram

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

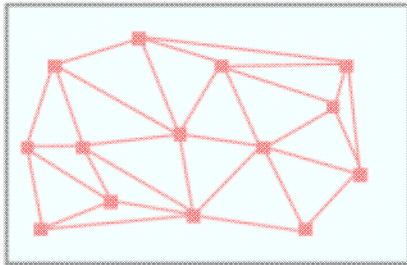
θ is incidence angle, Δh is DEM error,

Preliminary Network



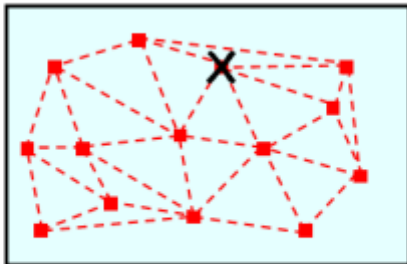
1: SELECTION

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2: ESTIMATION

Construct a "network" to estimate
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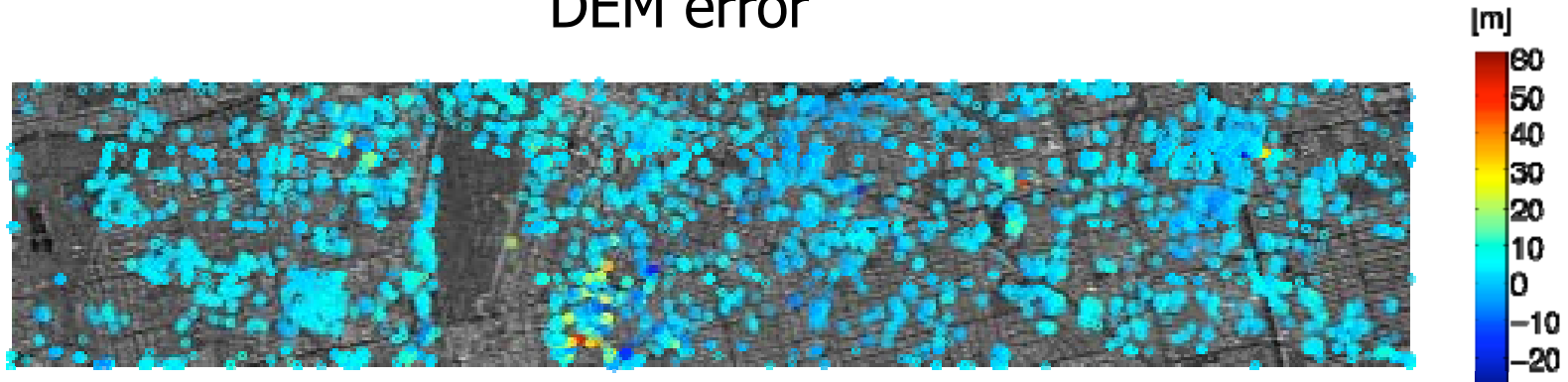


3: INTEGRATION

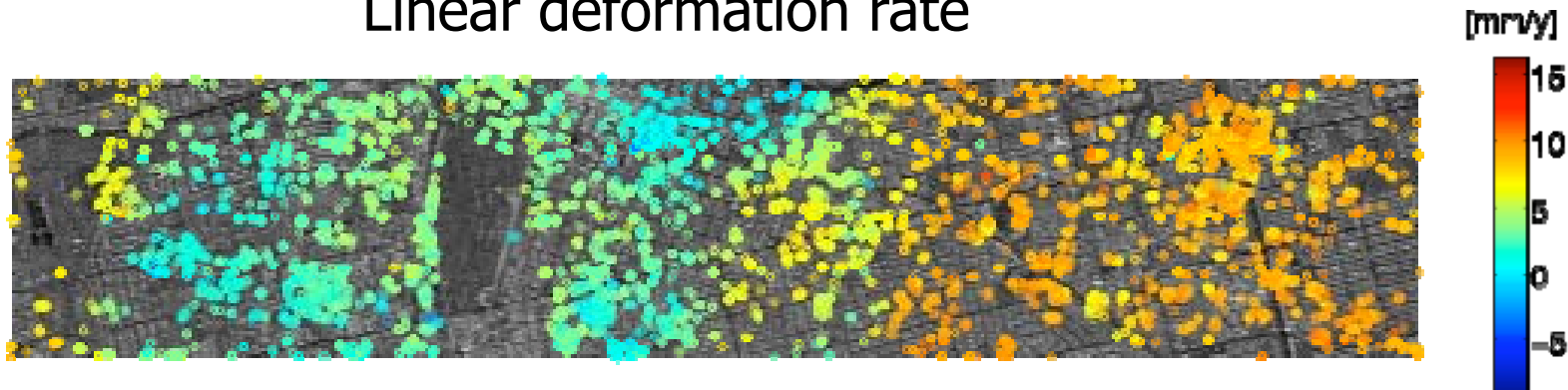
Obtain the **parameters at the points** by LS
integration w.r.t. a reference point (X).
Identify incorrect estimates and/or incoherent
points using alternative hypothesis tests.

Integrated results (Las Vegas)

DEM error



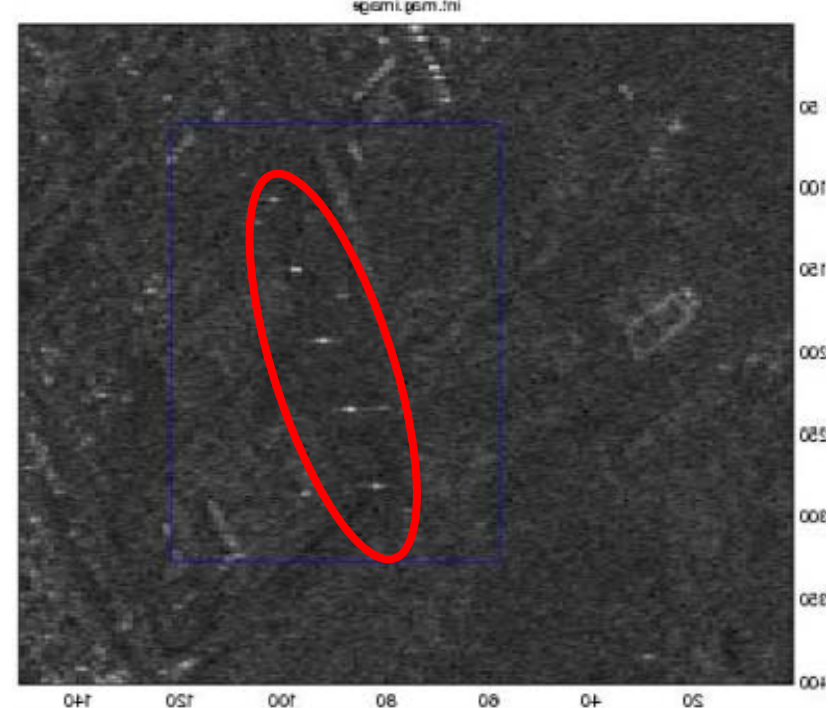
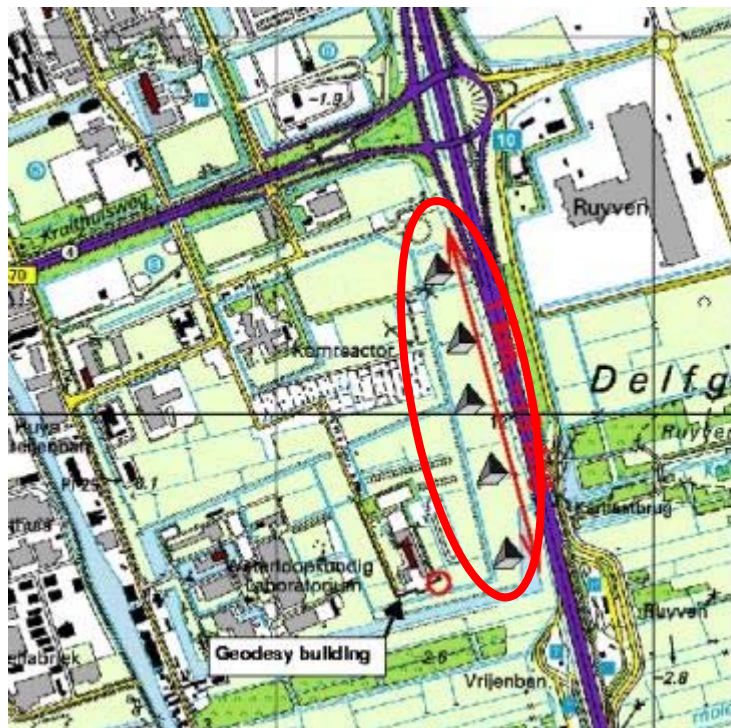
Linear deformation rate



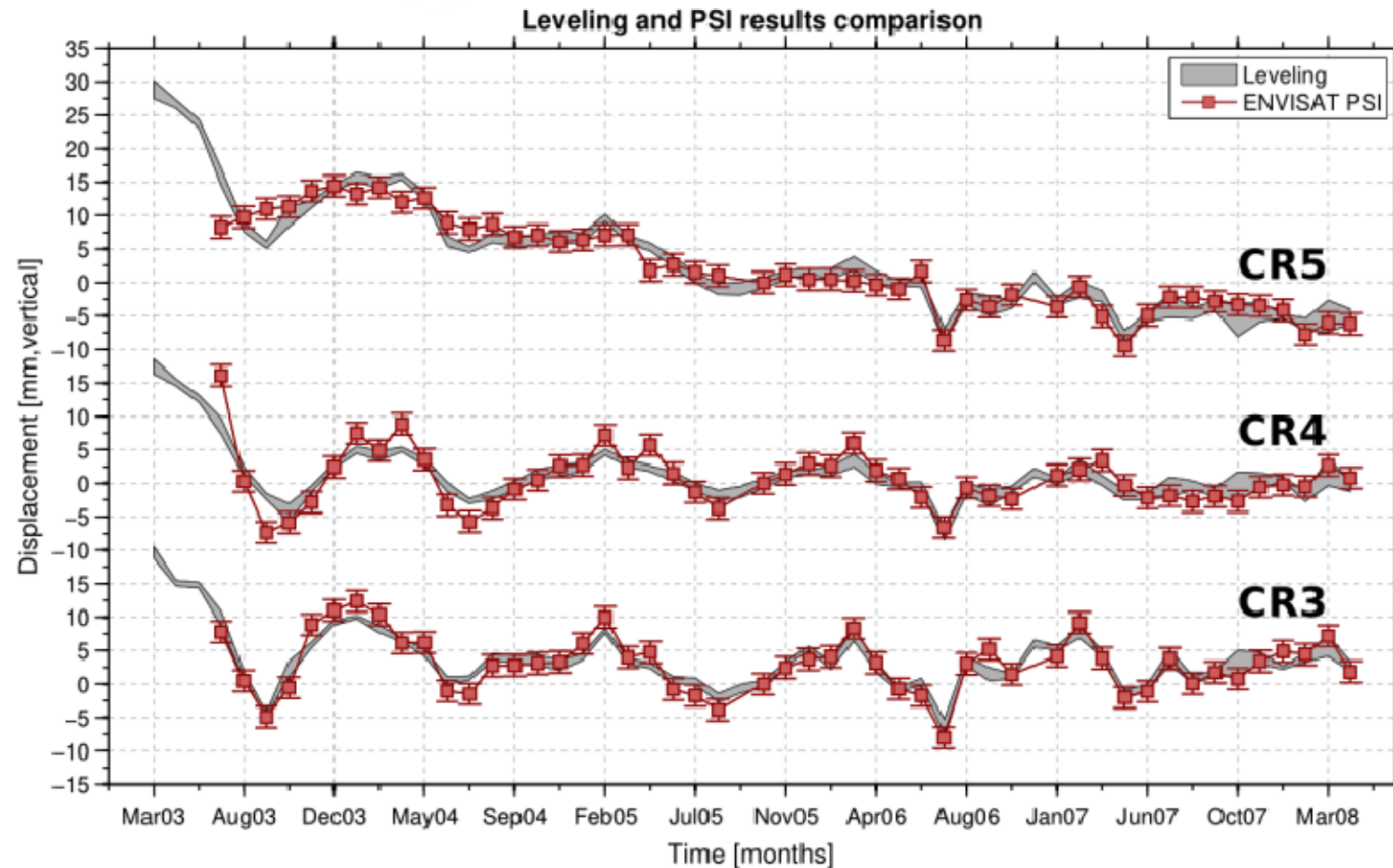
Next steps...

- 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

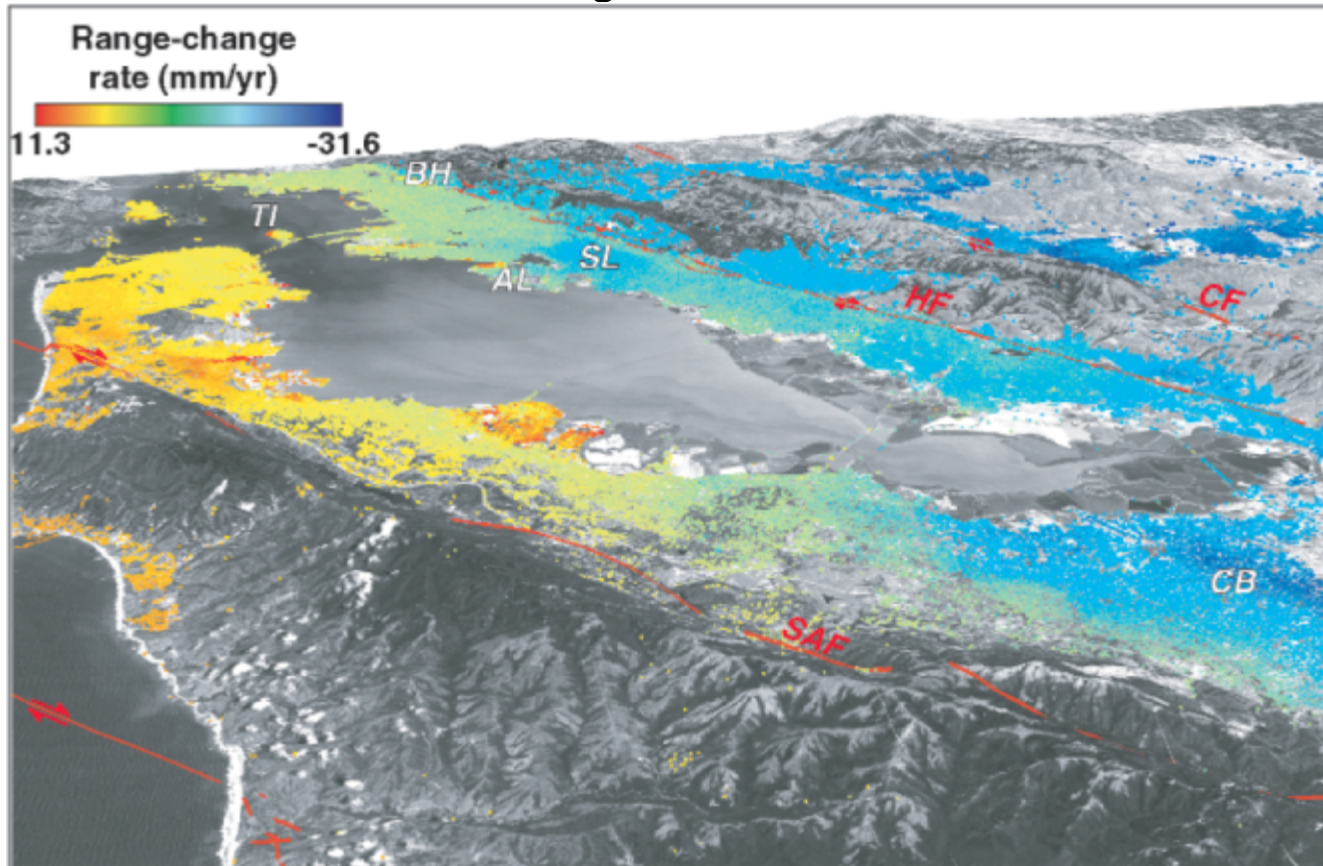


Corner Reflector InSAR vs Leveling



Marinkovic et al, CEOS SAR workshop, 2004

Results: Bay Area, California



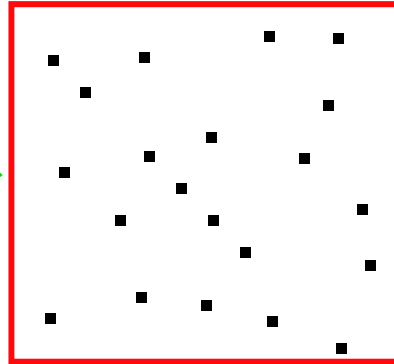
San Francisco Bay Area (Ferretti et al., 2004)

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

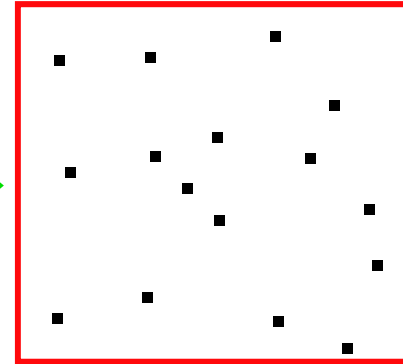
Initial Selection



All pixels



Best candidates
picked
e.g. Amplitude

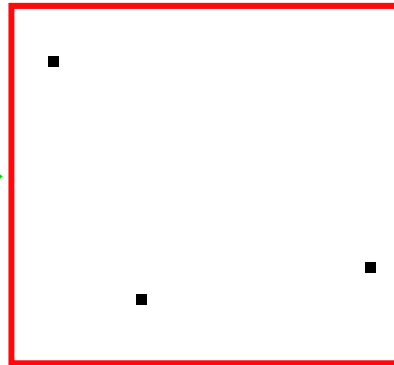


Bad candidates
rejected using
phase model
for pixel pairs

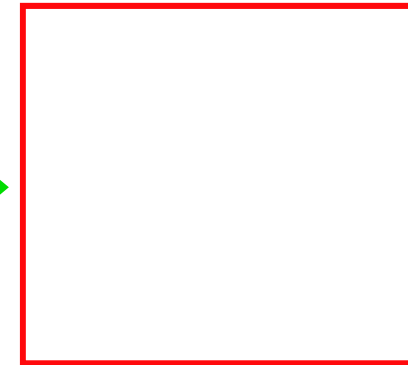
Why few pixels picked in rural areas



All pixels



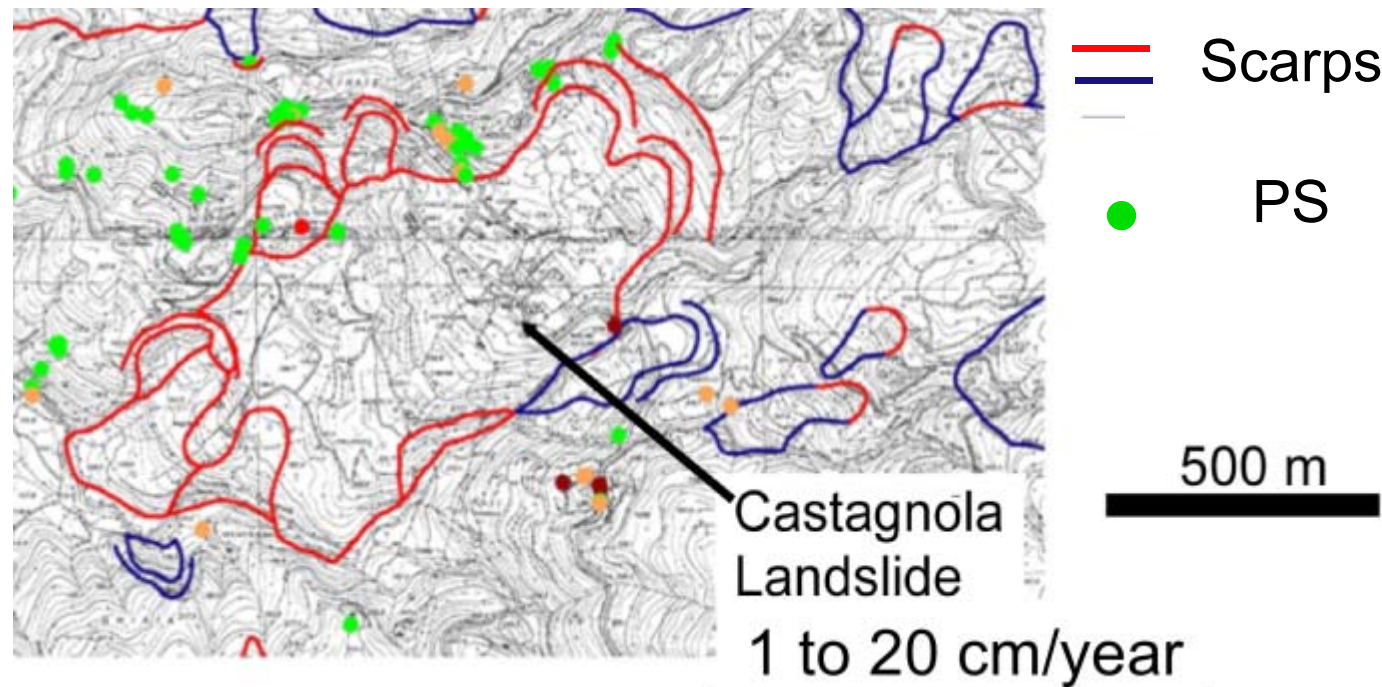
Too few “best”
candidates



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.

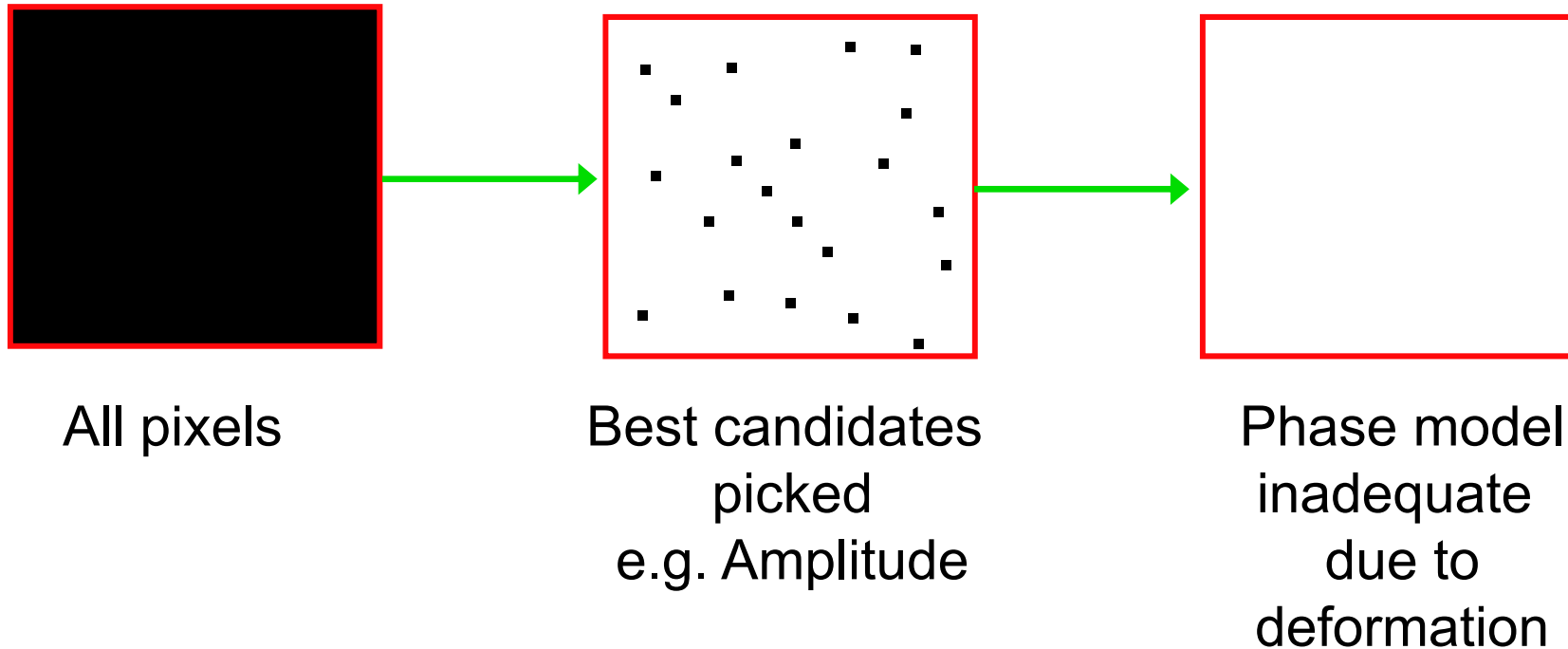
Results for Castagnola, Italy



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

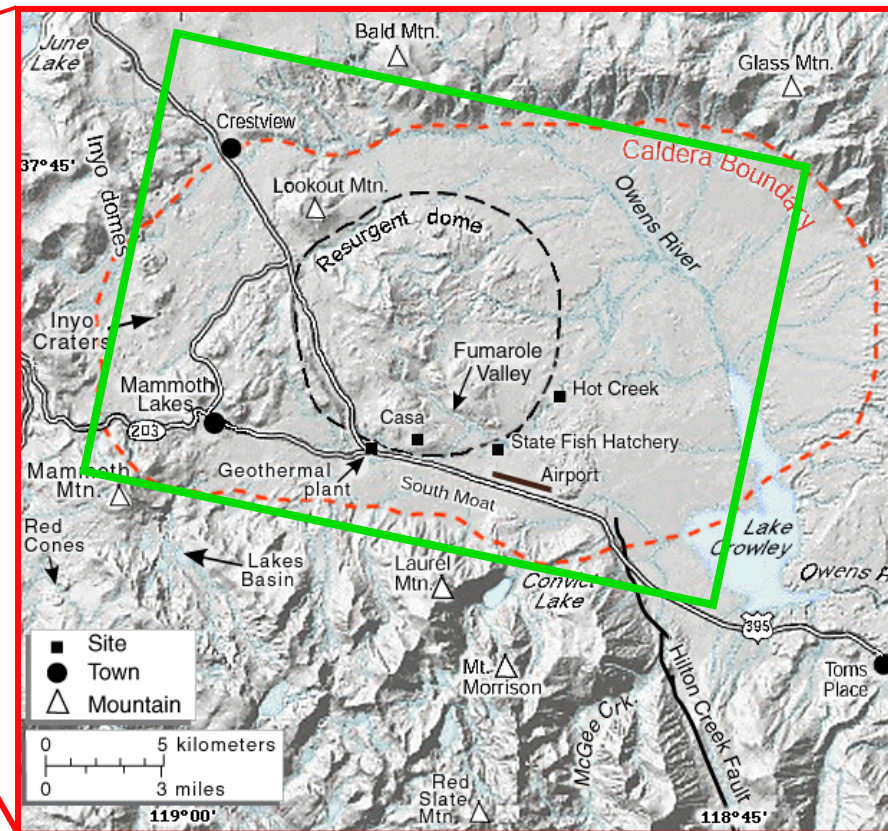
Why few pixels picked when deformation rate is irregular



Example of rural area with irregular deformation



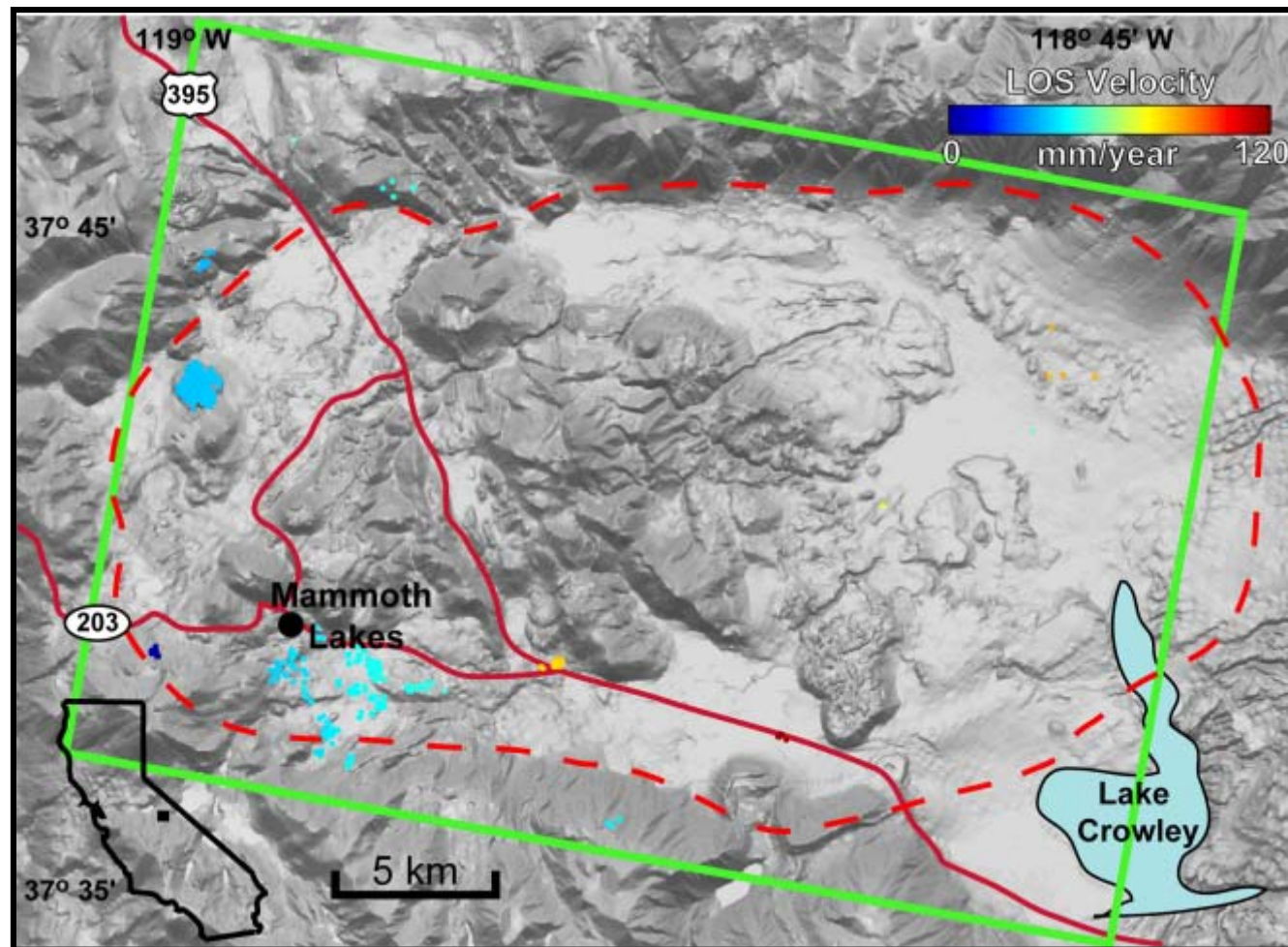
Long Valley Volcanic
Caldera



5km



Using Temporal Model Algorithm



- 300 high-amplitude persistent scatterers

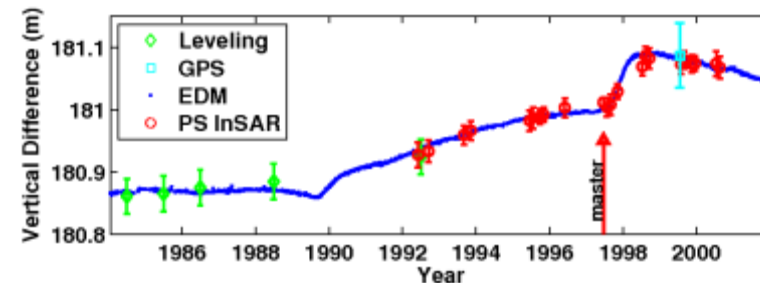
StaMPS PS Approach

Developed for more general applications, to work:

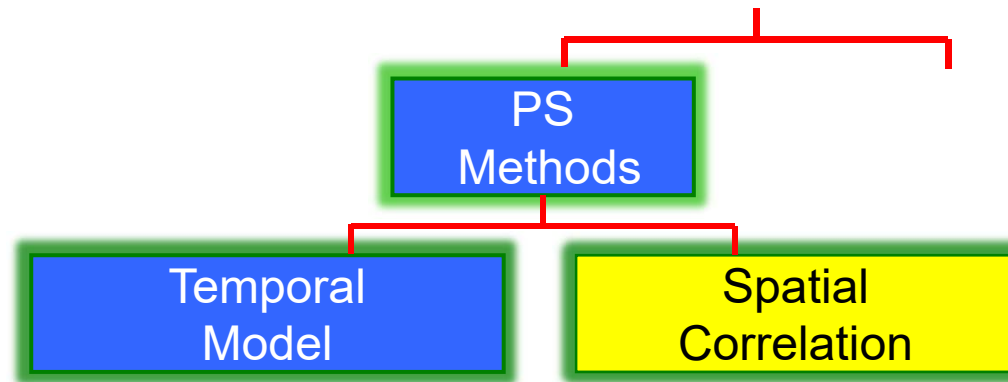
a) in rural areas without buildings (low amplitude)



b) when the deformation rate is very irregular



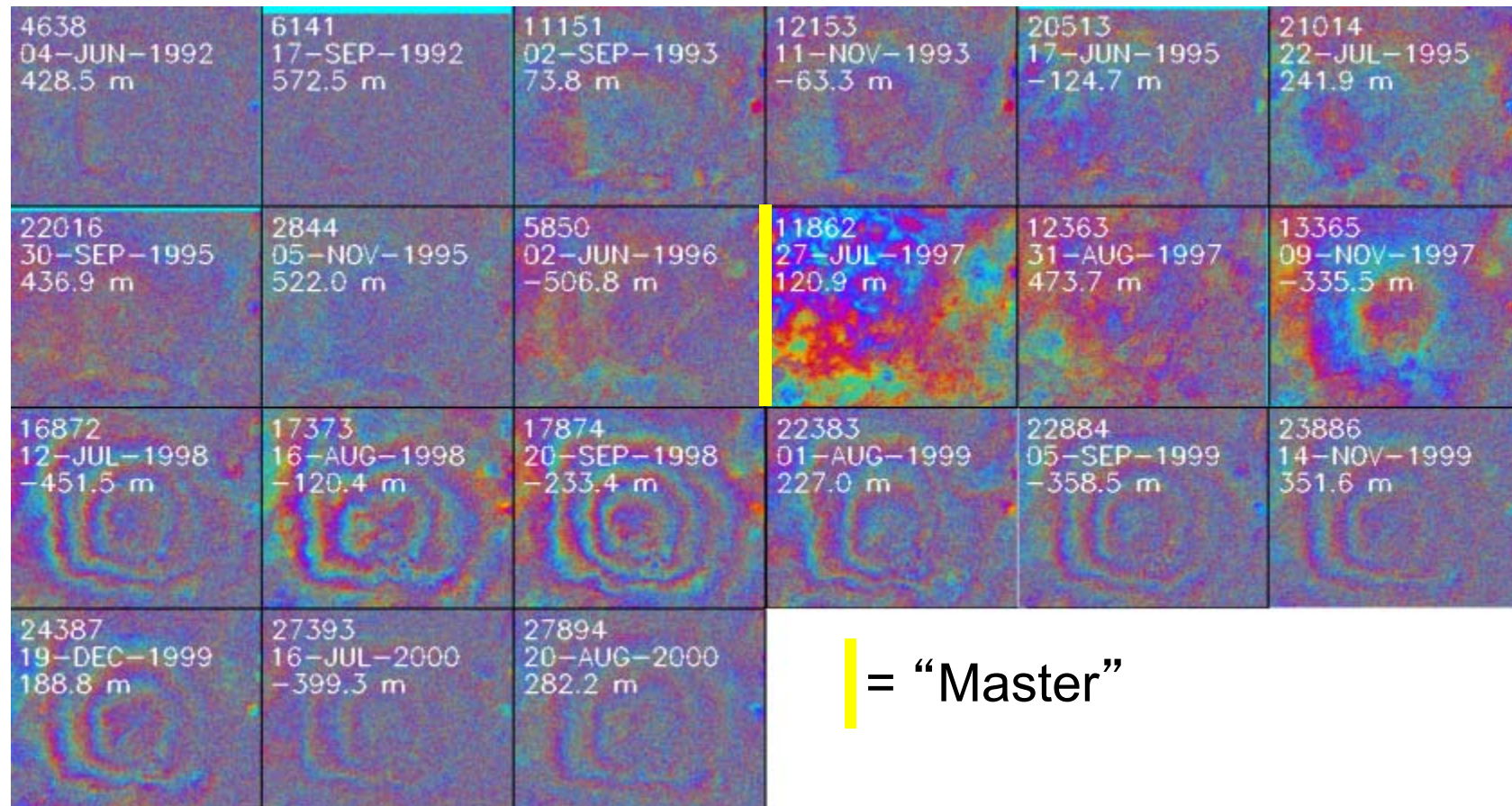
PS Processing Algorithms



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

Series of single-master interferograms

- Pre-Processing as for Temporal Model Algorithm



Spatial Correlation PS Algorithm

Exploits spatial correlation of the deformation signal.

Interferometric phase terms as before:

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

Deformation in LOS

Atmospheric Delay

Orbit Error

DEM Error

"Noise"

Spatial Correlation PS Algorithm

Exploits spatial correlation of the deformation signal.

Interferometric phase terms as before:

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

Spatial Correlation PS Algorithm

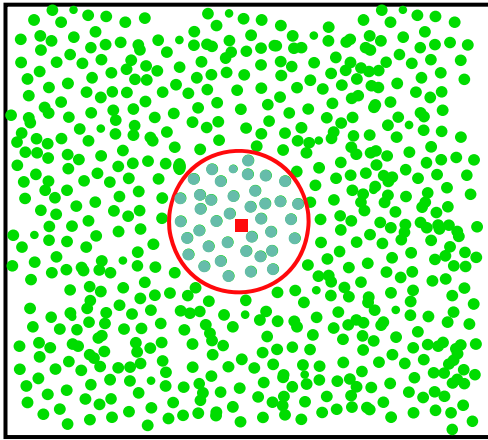
Exploits spatial correlation of the deformation signal.

Interferometric phase terms as before:

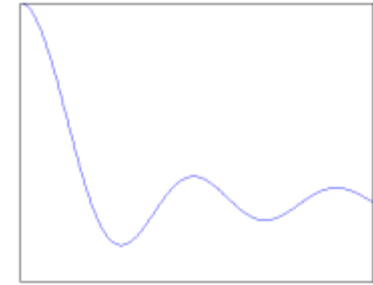
$$\phi_{\text{int}} = \phi_{\text{defo}} + \phi_{\text{atmos}} + \Delta\phi_{\text{orbit}} + \Delta\phi_{\text{topo}}^{\text{uncorr}} + \Delta\phi_{\text{topo}}^{\text{corr}} + \phi_{\text{noise}}$$

- Correlated spatially - estimate by iterative spatial bandpass filtering

Estimation of Spatially Correlated Terms



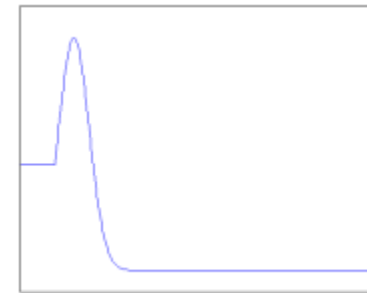
= crude low-pass filter
in spatial domain
(Hooper et al., 2004)



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

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

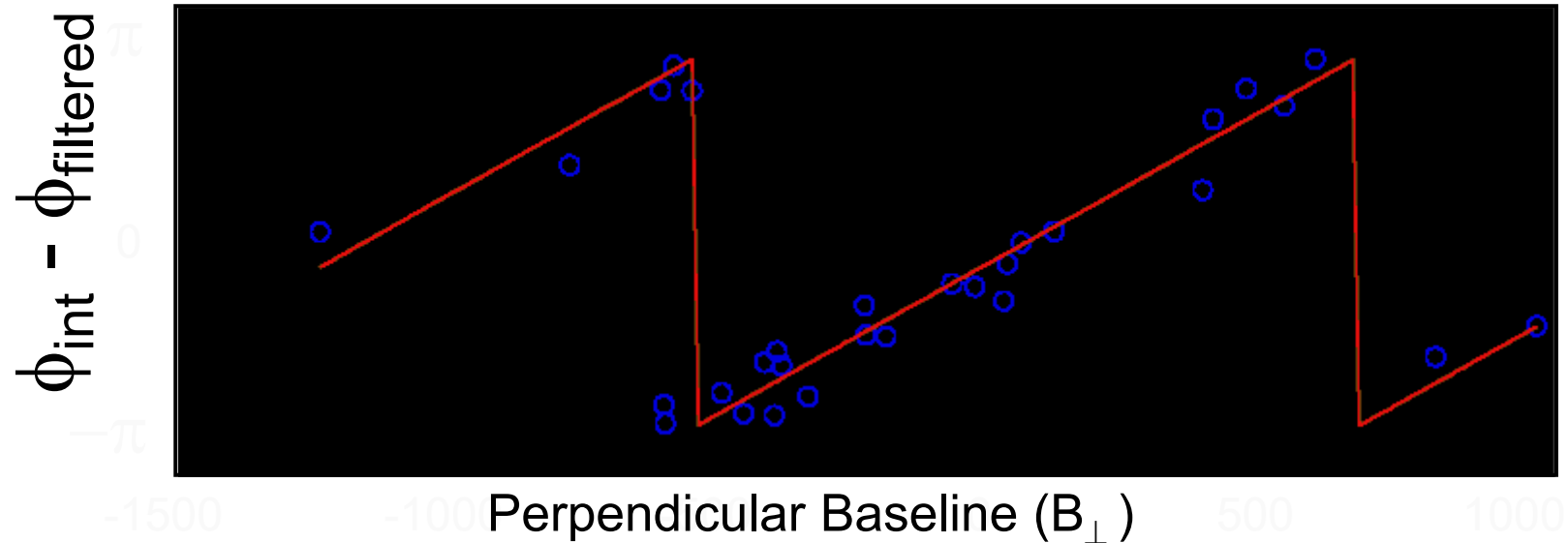
- Correlated spatially - estimate by iterative spatial bandpass filtering

Spatial Correlation PS Algorithm

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

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

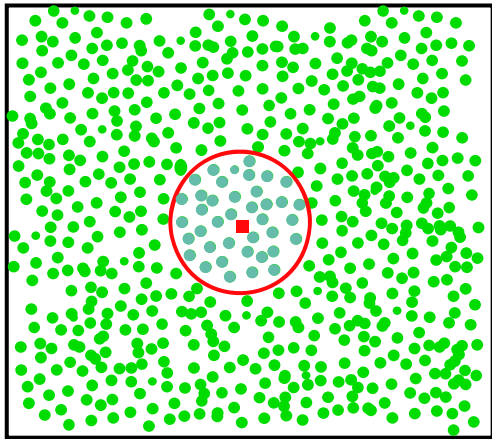
Spatial Correlation PS Algorithm



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

Temporal coherence is then estimated from residuals

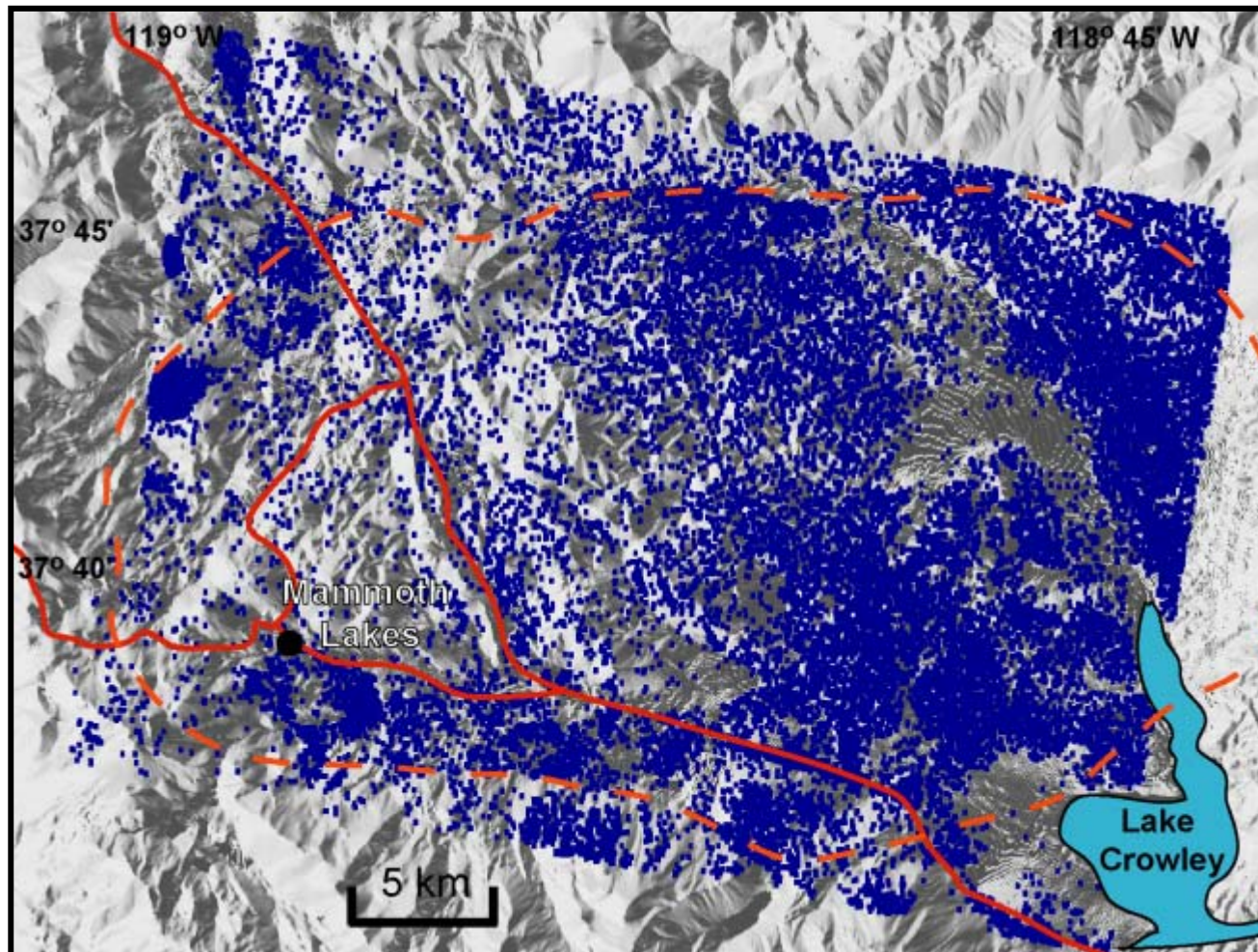
Re-estimation of Spatially Correlated Terms



Contribution of each pixel weighted based on its estimated temporal coherence

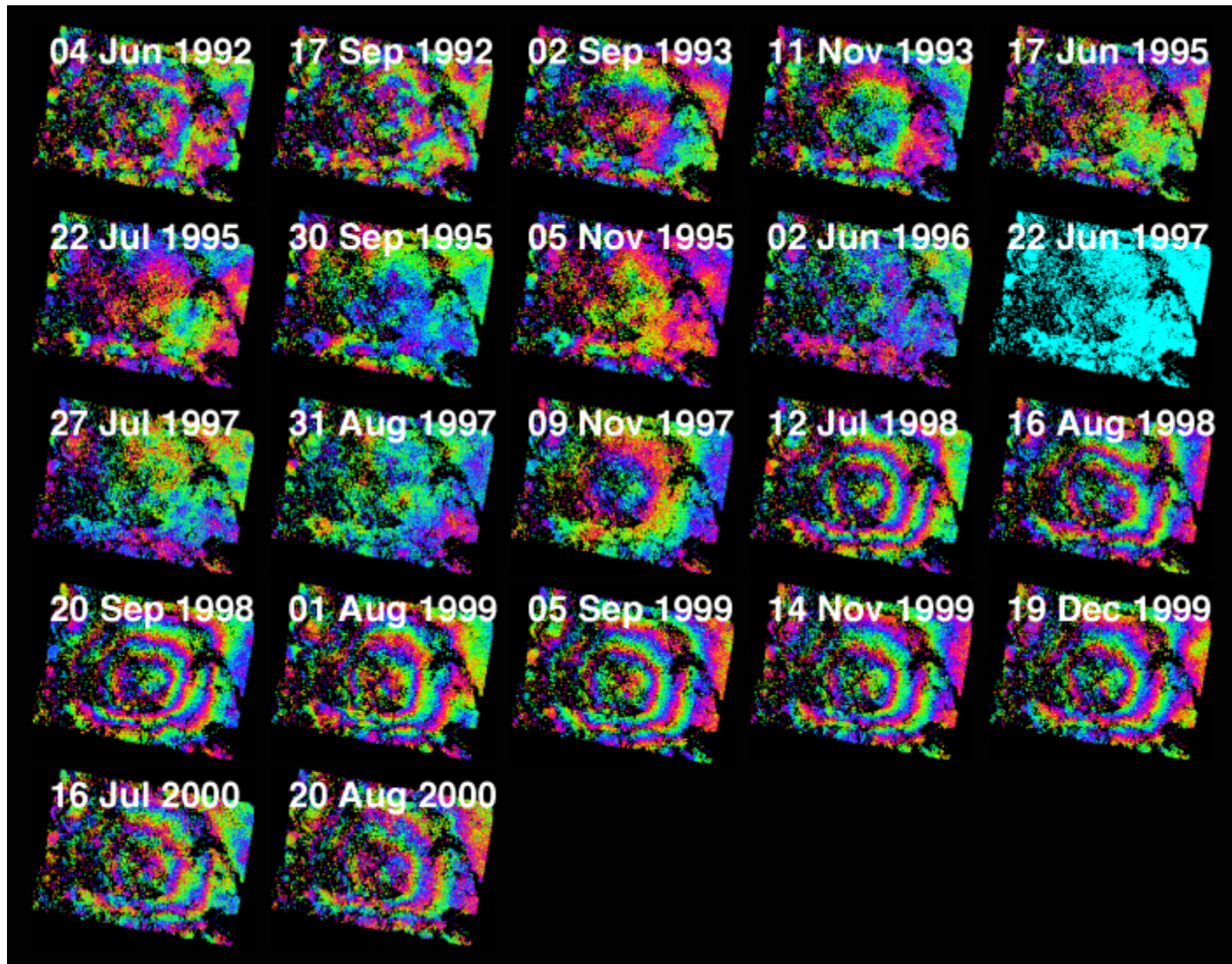
- Followed by reestimation of DEM error and temporal coherence
- Iterated several times

Results in Long Valley



- 29,000 persistent scatterers

Wrapped PS Phase



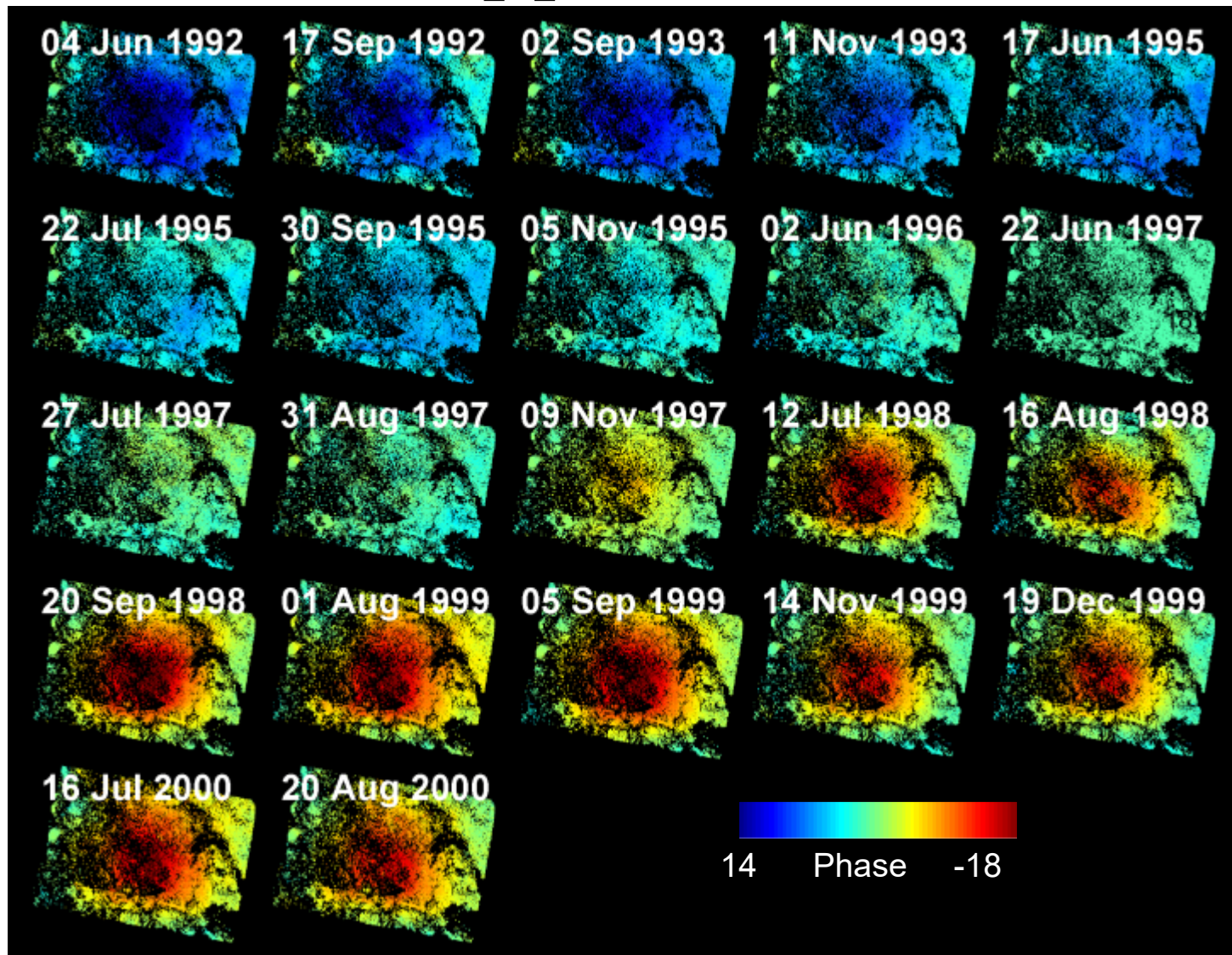
➤ Interferogram phase, corrected for topographic error



Phase unwrapping

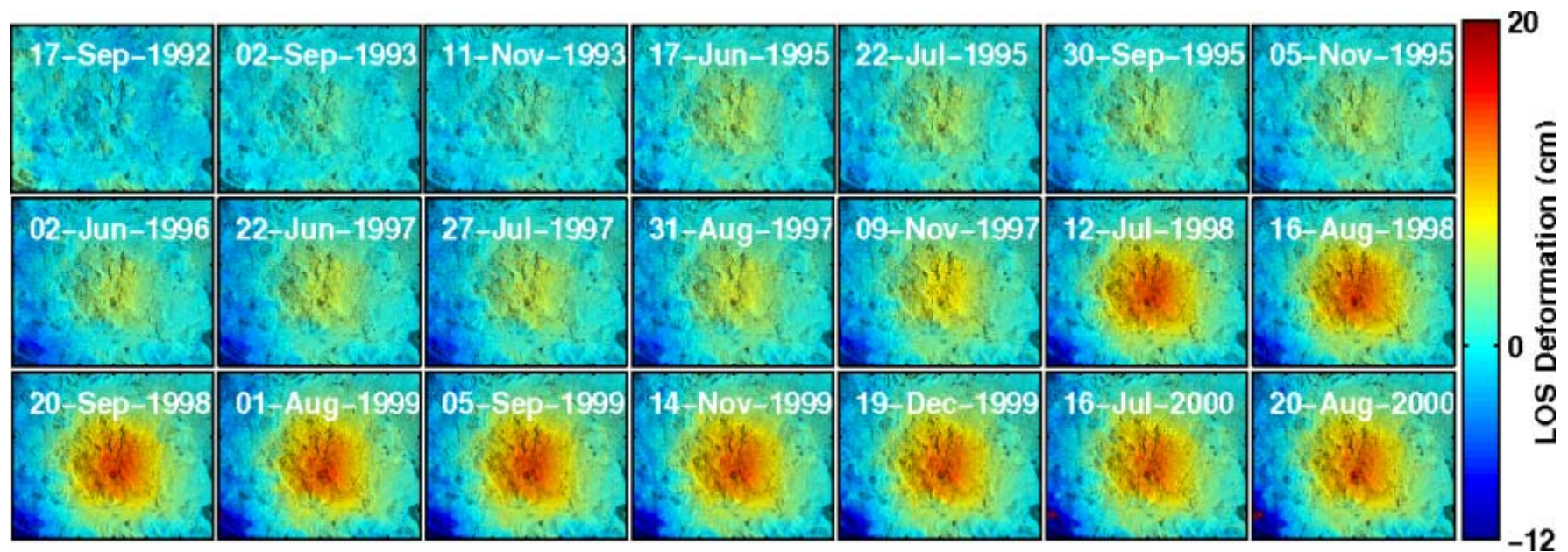
- With temporal model, phase is unwrapped by finding model parameters that minimise the wrapped residuals between double difference phase and the model
- If we do not want to assume a temporal model of phase evolution we need another strategy

Unwrapped PS Phase



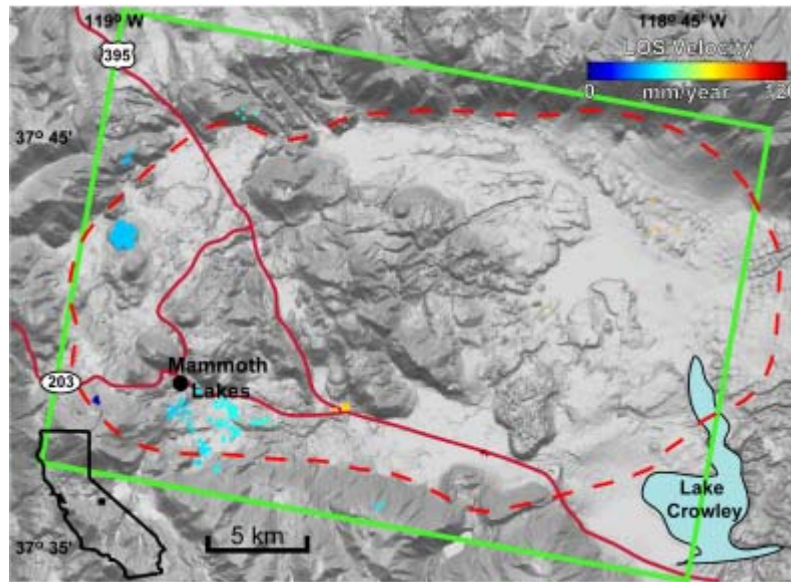
Estimation of Atmospheric Signal And Orbit Errors

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

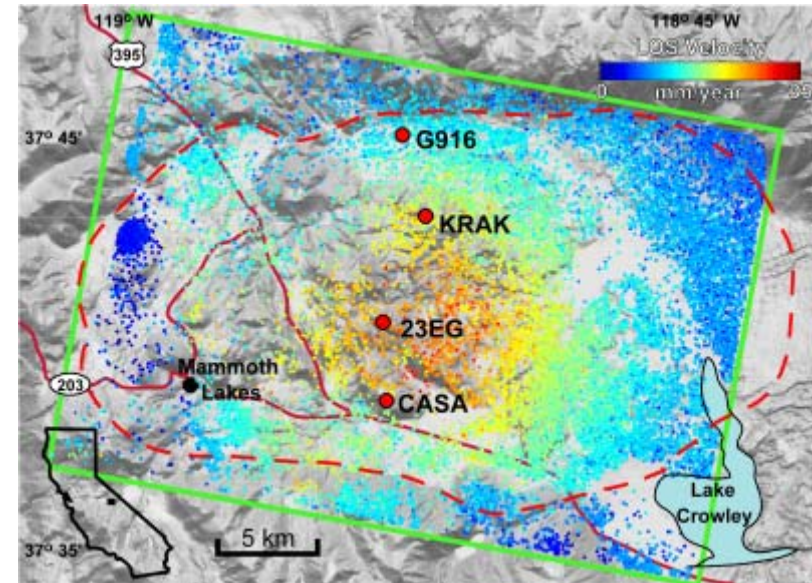


Estimate of atmospheric and orbit errors subtracted, leaving deformation estimate (not necessarily linear).

Comparison of approaches



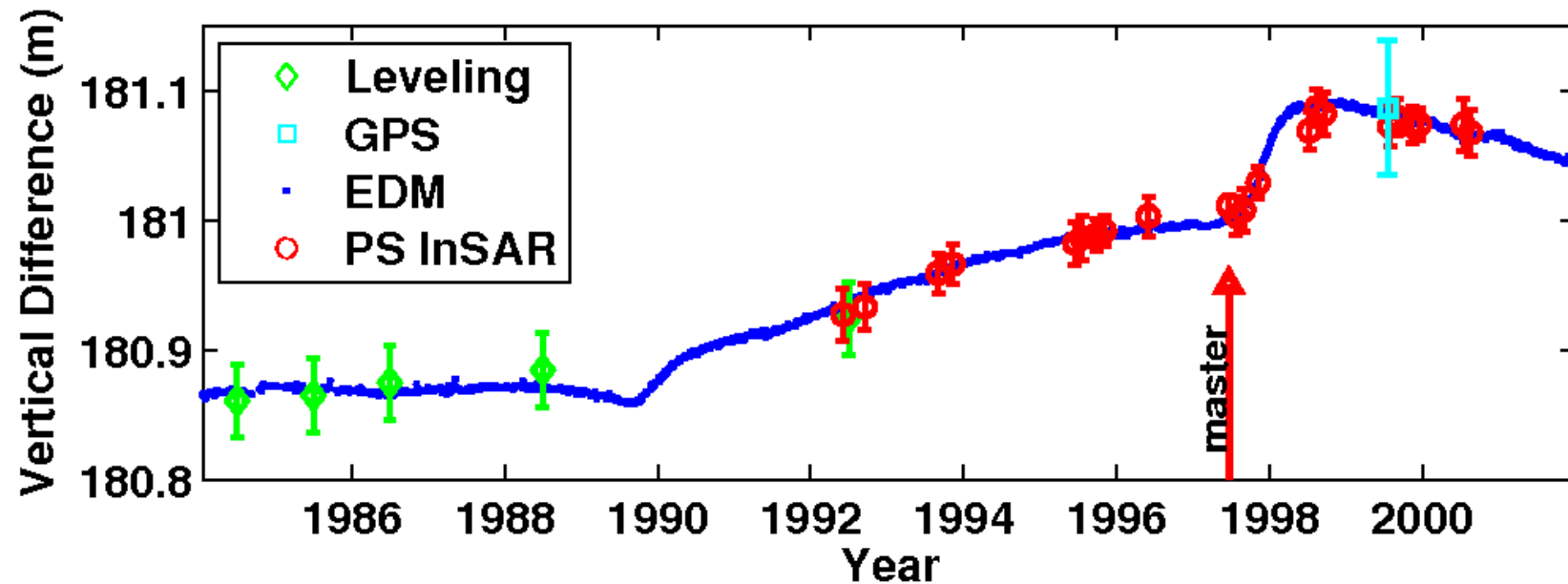
Temporal model approach



Spatial correlation approach

Long valley caldera

Validation with Ground Truth

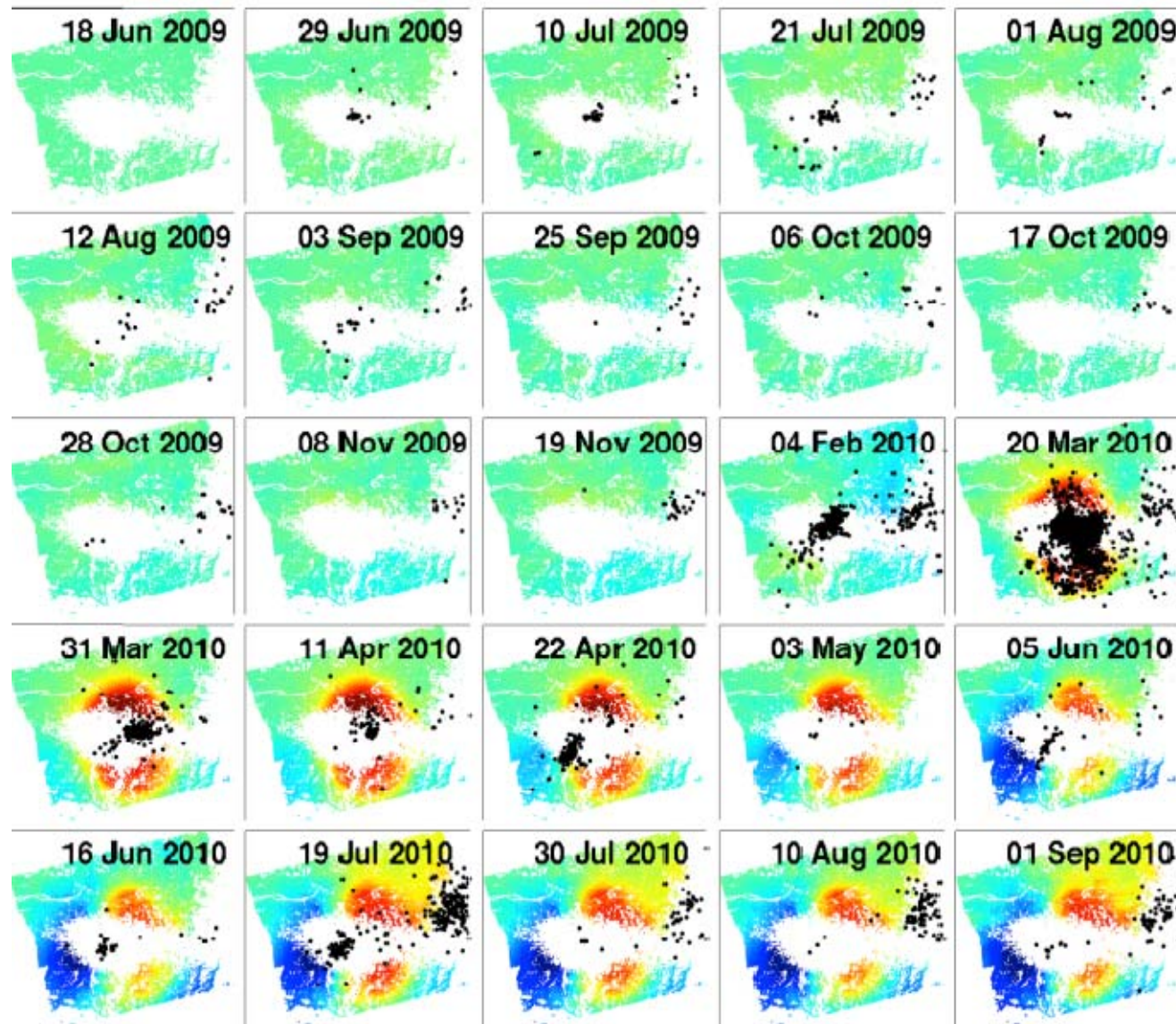
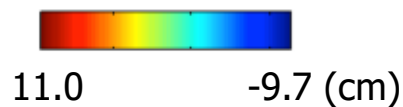


➤ PS show good agreement

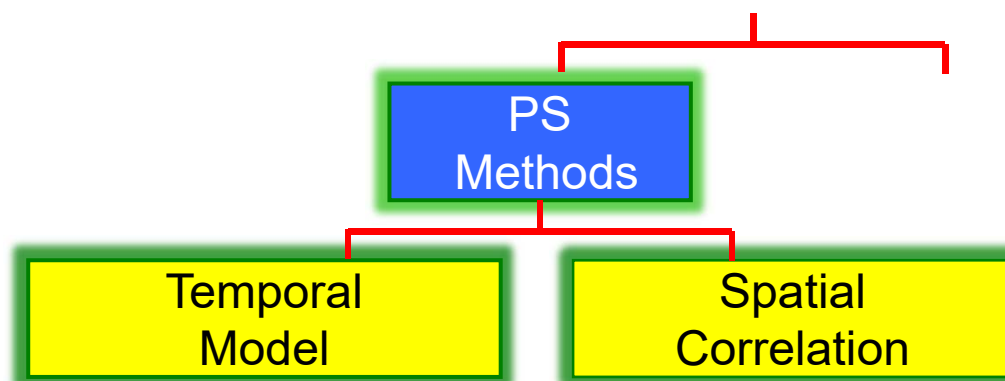
Eyjafjallajökull PS time series

T132
cumulative
line-of-sight
displacement

- Earthquake
epicentres for each
epoch (Iceland Met
Office)



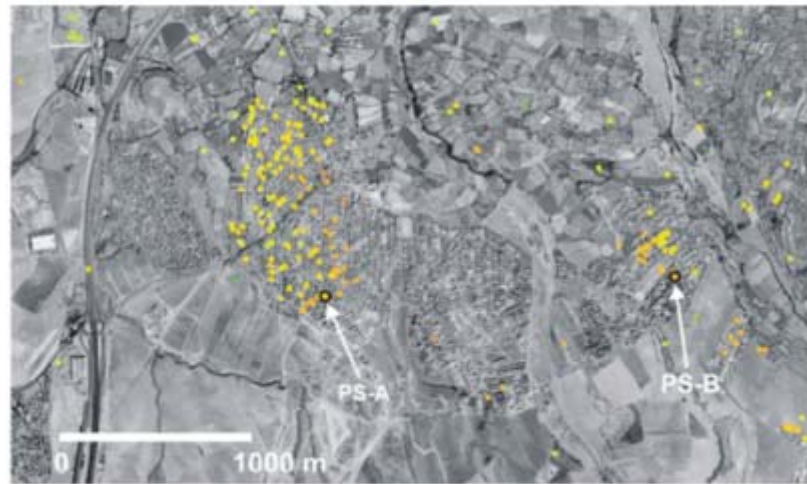
Comparison PS Algorithms



- 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.

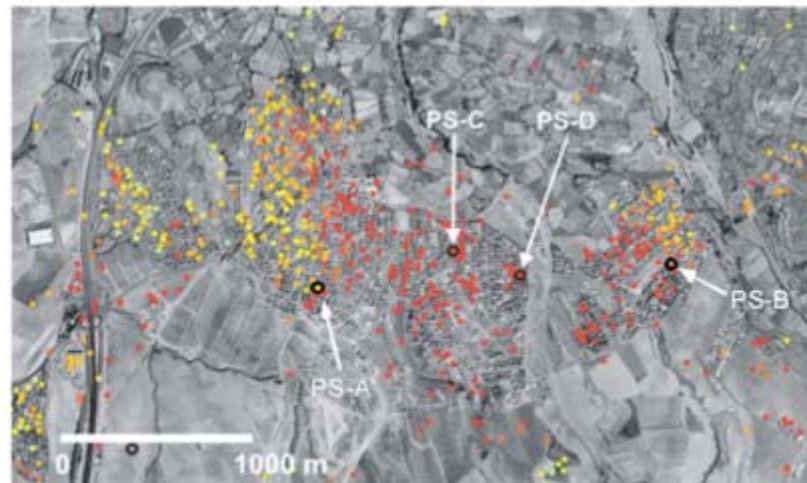
Comparison PS Algorithms

(Sousa et al, 2010)



(a)

Temporal model approach
(DePSI, Ketelaar thesis, 2008)



(b)



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

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

