



**Jet Propulsion Laboratory**  
California Institute of Technology

# InSAR Timeseries Analysis: theory and overview

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Earthscope 2024  
Aug 24 2024

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## Acknowledgement

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Space Administration



With contributions from many colleagues:

Zhang Yunjun, Scott Staniewicz, Sara Mirzaee, Virginia Brancato, Yujie Zheng, Piyush Agram, Falk Amelung and other colleagues at JPL, Caltech and University of Miami

# Outline

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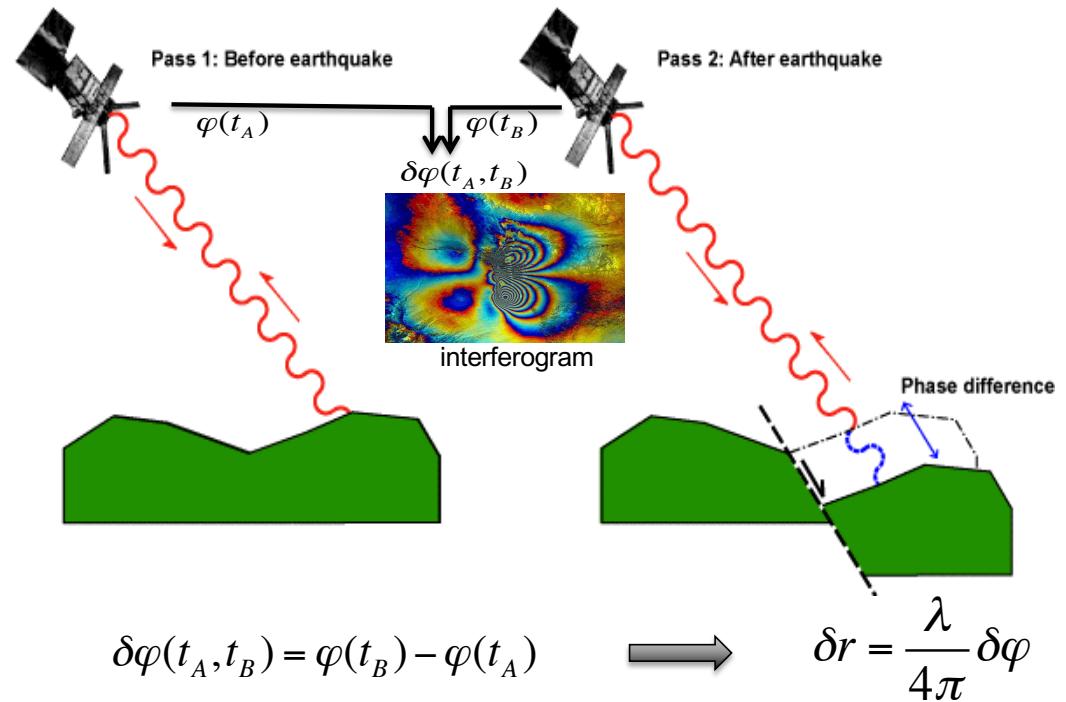
- ❑ InSAR
- ❑ Why InSAR time-series analysis
- ❑ InSAR time-series analysis techniques based on scatterers
  - PS time-series
  - DS time-series
    - ❖ DS analysis algorithms based on interferogram networks
      - Small Baseline algorithms (subsets of interferograms)
      - Full covariance-based algorithms
  - PS+DS time-series techniques
- ❑ Error analysis of InSAR displacement time-series
  - Propagation delay (Troposphere, Ionosphere)
  - Geometrical residuals
  - Phase unwrapping error
  - Phase scattering

# InSAR (Interferometric Synthetic Aperture Radar)

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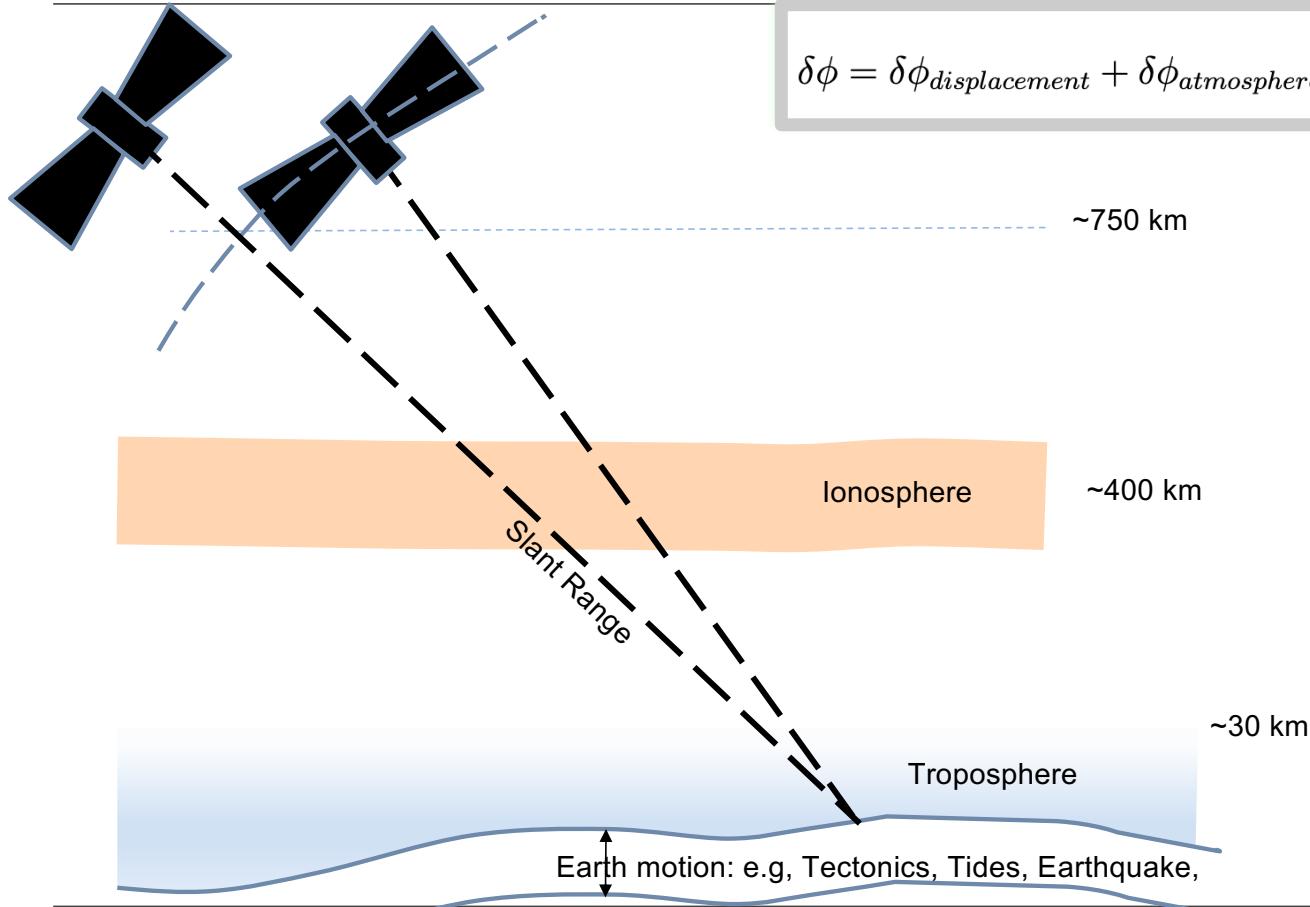


- InSAR measures phase difference between two SAR acquisitions
- The interferometric phase, between two SAR images acquired at different times over the same region from the similar viewing geometry, can represent ground movements
- The phase difference is equivalent to range change or distance change between radar and target



## InSAR phase components (repeat pass)

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$$\delta\phi = \delta\phi_{displacement} + \delta\phi_{atmosphere} + \delta\phi_{geometry} + \delta\phi_{scattering} + \delta\phi_{noise}$$

$\delta\phi$  Total interferometric phase

$\delta\phi_{displacement}$  Surface displacement

$\delta\phi_{atmosphere}$  Atmospheric delay

$\delta\phi_{geometry}$  Introduced by non-zero baseline

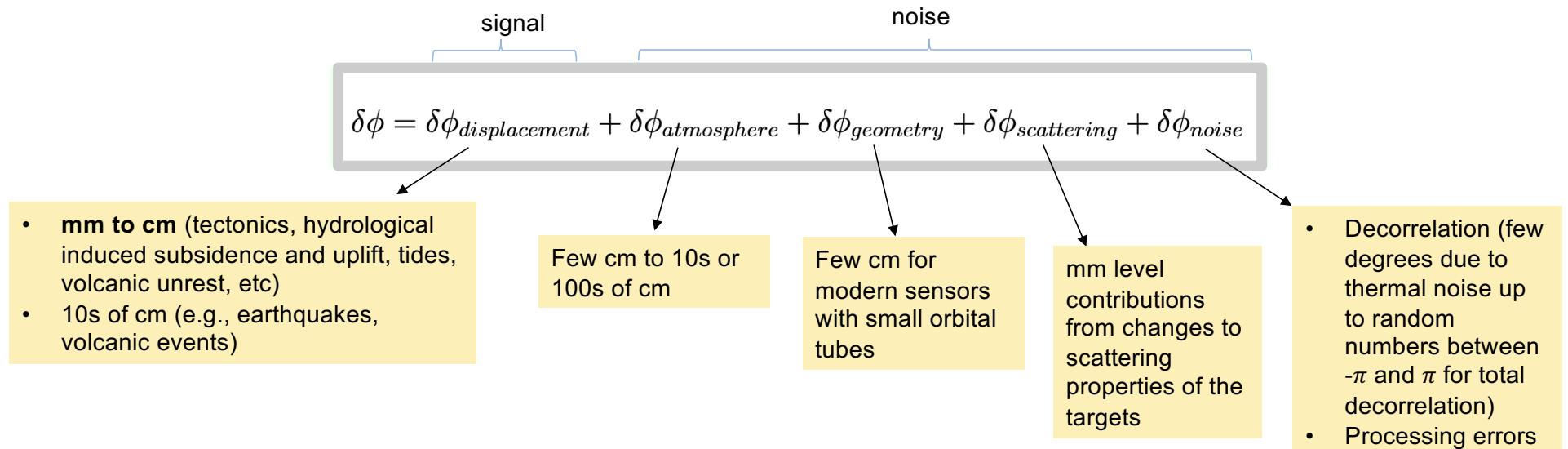
$\delta\phi_{scattering}$  Surface scattering components

$\delta\phi_{noise}$  Noise

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# Repeat pass InSAR phase components

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- When the goal is to estimate ground displacement, the displacement component is **signal** and the rest are **noise**
- Most InSAR noise components are spatially correlated but mostly random in time
- The goal of InSAR time-series analysis is to enhance the signal to noise ratio

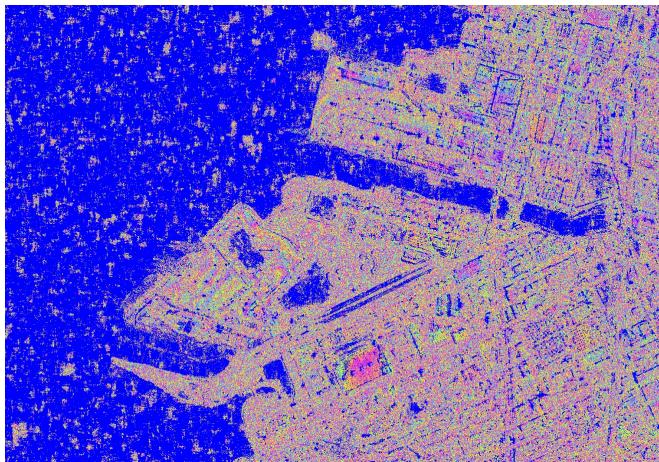
## Why InSAR Time-series analysis?

- a) to reduce the impact of decorrelation

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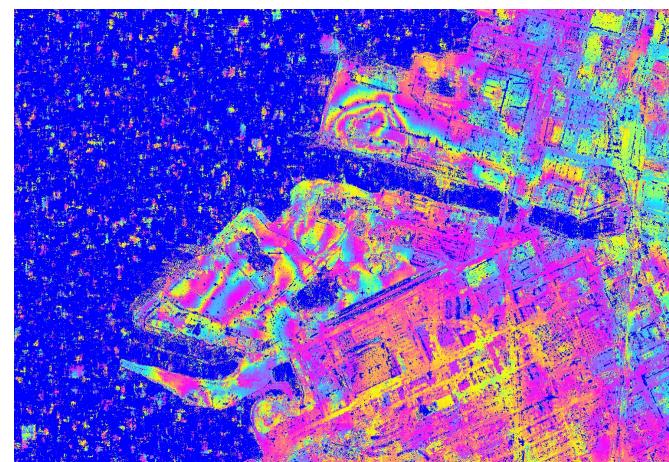


A regular interferogram over ~2.5 years



- $\pi$

Same interferogram from time-series analysis



$\pi$

Image from Fattah, et al (JPL)

An X-band interferogram is fully decorrelated over 2.5 years



(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) The same interferogram generated from timeseries analysis.

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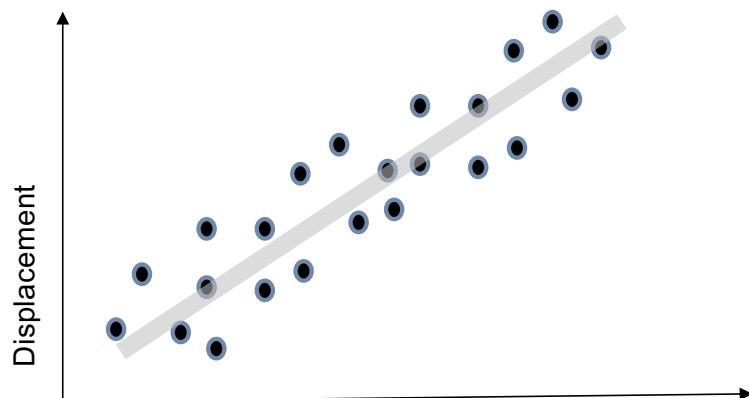
## Why InSAR Time-series analysis?

b) to improve the accuracy of estimated displacement

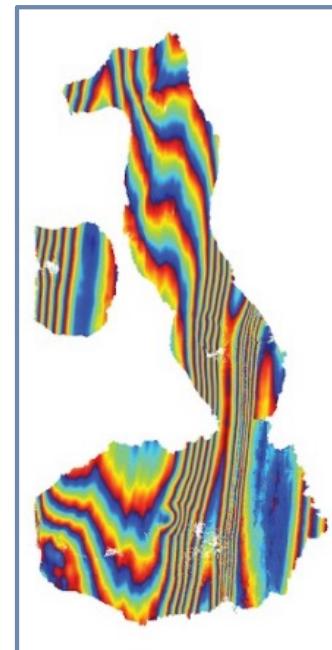
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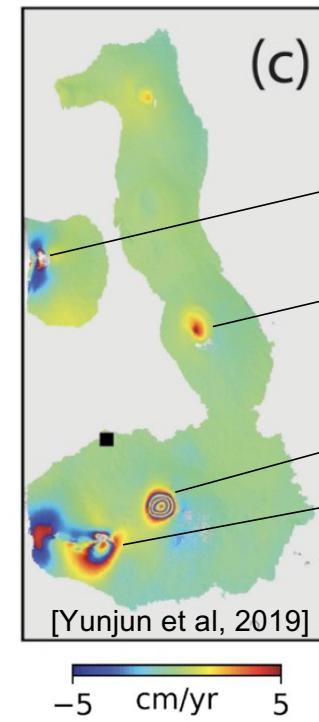
- Different sources of noise (such as tropospheric and ionospheric delay) are spatially coherent but mostly random in time
- Time-series analysis allows to reduce the impact of noise and improve accuracy of estimated displacement



One interferogram heavily dominated by atmosphere



A velocity map derived from time-series analysis



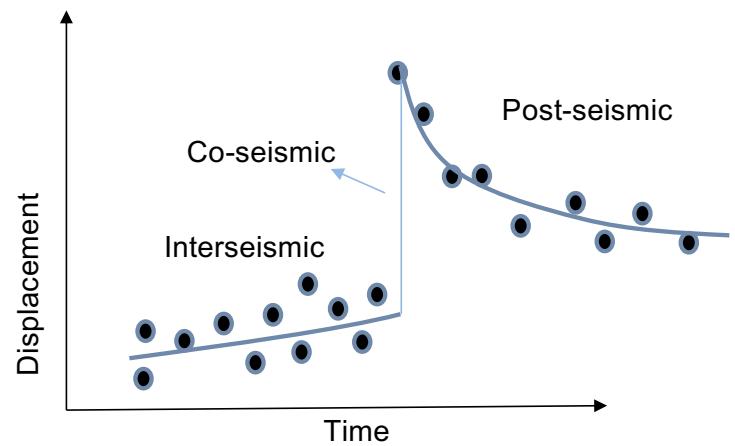
## Why InSAR Time-series analysis?

c) to understand the temporal evolution of the ground displacement

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- The displacement of the ground surface may evolve through time leading to non-linear change of the displacement time-series
- Examples of non-linear evolution of ground displacement:
  - Earthquake cycle (interseismic + coseismic + postseismic)
  - Volcanic unrest
  - Seasonal ground water change
- Understanding the temporal pattern of the ground displacement is crucial to better understand the driving mechanisms
- Measuring the displacement and its variation in time is only possible by time-series analysis





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# InSAR Time-series analysis techniques based on types of scatterers

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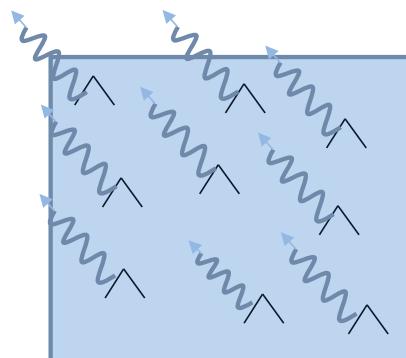
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## Types of scatterers

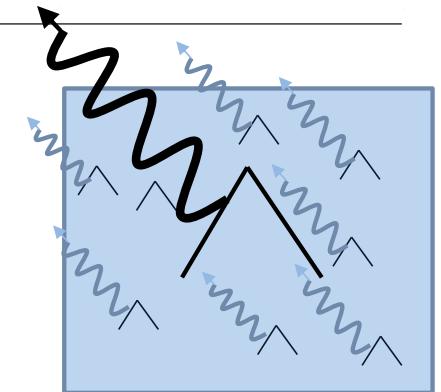
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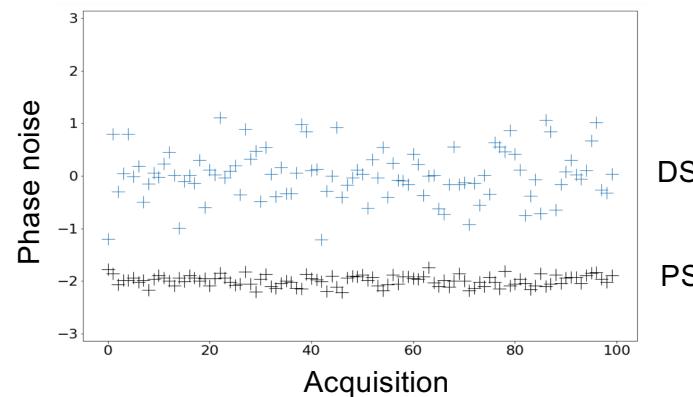
- One resolution cell (pixel) contains many scatterers
- A pixel may:
  - a) be largely dominated by a single point scatterer (**Persistent Scatterers (PS)**)
  - b) contain many scatterers contributing to the sum of the backscattered signal (**Distributed Scatterers (DS)**)
- The interferometric phase of PS pixels are precise over time
- The interferometric phase of DS pixels may be noisy. Therefore it is very common to reduce noise with multi-looking (averaging) many samples over a neighborhood to reduce noise



Distributed Scatterers



Permanent Scatterer  
dominates the resolution  
cell



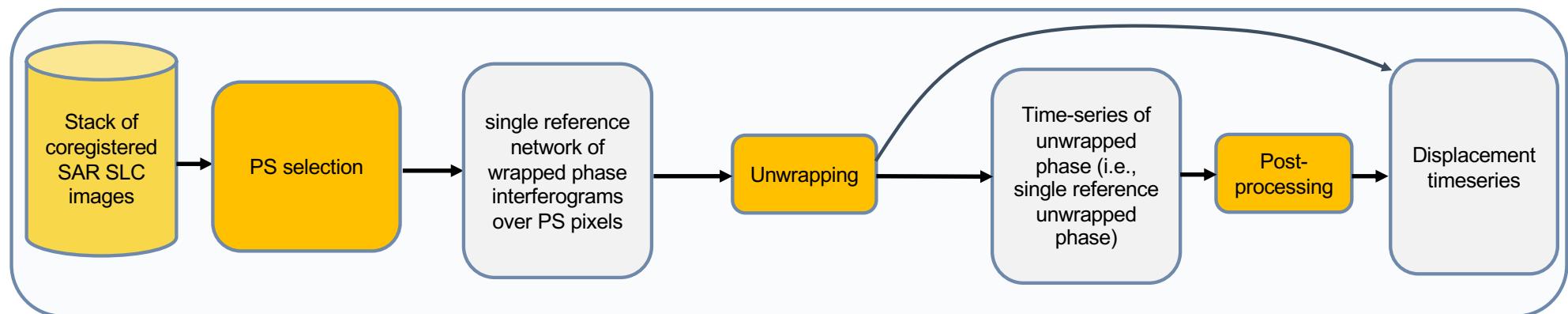
# Permanent scatterer time-series analysis

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PS InSAR time-series analysis involves [Ferretti et al, 2000, 2001]:

1. Coregister stack of SLC images
2. Identify PS pixels
3. Single-reference interferometric phase of PS pixels
4. Phase unwrapping



## Persistent scatterer time-series analysis, PS selection

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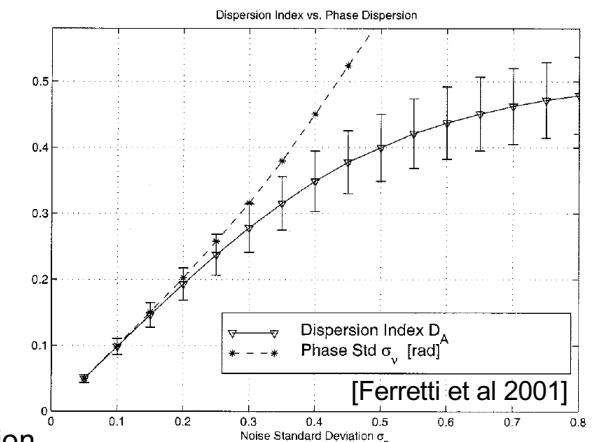


### 1- Amplitude based PS selection to detect stable natural and man made reflectors (e.g., building) [Ferretti et al 2001]

- The goal is to identify pixels with stable phase over time. The challenge is that the phase is dominated by contributions from atmospheric delay, displacement, geometrical phase and therefore estimating the phase noise is not trivial
- Amplitude is minimally affected by these environmental and geometrical contributors
- Ferretti et al, 2001 proposed amplitude dispersion index as a measure of phase stability

$$\sigma_v \simeq \frac{\sigma_A}{m_A} \triangleq D_A$$

Amplitude standard deviation  
Phase dispersion  
Amplitude mean  
Amplitude Dispersion index



Over high SNR pixels, amplitude dispersion seems to be a good measure of phase dispersion

## Persistent scatterer time-series analysis, PS selection

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### 2- Phase-based PS selection [Hooper et al, 2004]

- In order to identify PS pixels (stable phase over time) with low SNR, Hooper et al 2004 suggested to evaluate the phase noise to identify PS pixels
- As mentioned in previous slide, the phase is dominated by atmosphere, geometrical residuals and displacement and therefore can not be readily analyzed to identify low noise pixels
- Assuming a model for interferometric phase, Hooper et al suggest to filter out or estimate different phase components (atmosphere, orbit, DEM error, etc) to isolate noise which then can be evaluated to identify PS pixels

$$\phi_{x,i} = \phi_{def,x,i} + \phi_{\alpha,x,i} + \phi_{orb,x,i} + \phi_{\varepsilon,x,i} + n_{x,i}$$

- It is assumed that deformation, atmosphere and orbital errors are spatially correlated, over a certain spatial length and therefore can be estimated (e.g, averaging or low pass filtering)
- The DEM error is baseline dependent and can be estimated
- Starting with initial PS pixels (with relaxed threshold of amplitude dispersion), the temporal coherence is iteratively computed and thresholded to identify PS pixels (i.e., pixels with high temporal coherence or small phase residual which is assumed to represent noise)

$$\gamma_x = (1/N) \left| \sum_{i=1}^N \exp \{j(\phi_{x,i} - \bar{\phi}_{x,i} - \hat{\phi}_{\varepsilon,x,i})\} \right|$$

## Persistent scatterer time-series analysis, PS selection

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### 3- Phase based PS selection [Agram and Zebker, 2007]

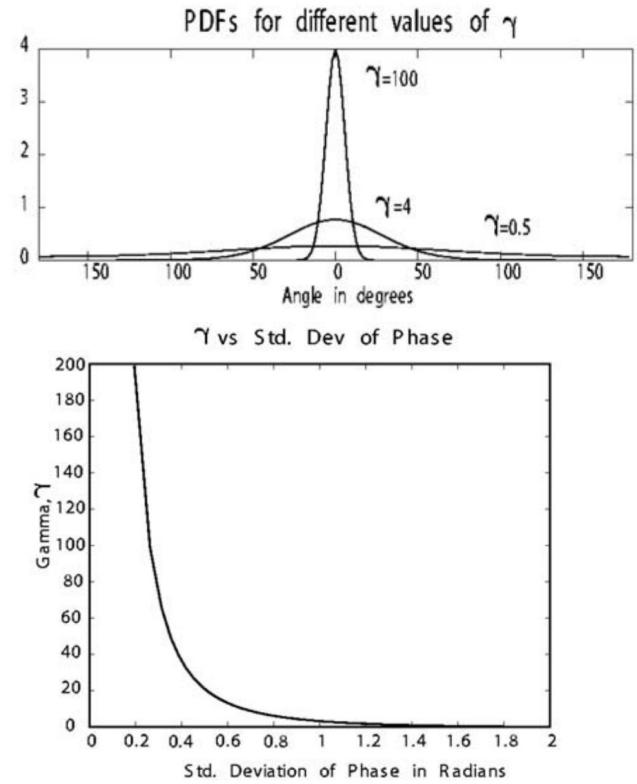
Determine the theoretical phase variation for a pixel as a function of  $\gamma$ , and compare it with the observed interferometric phase (corrected for atmosphere, topography, deformation and other correlated errors) to obtain the maximum likelihood estimate of  $\gamma$ , which is then thresholded to select PS pixels.

$$P(\phi) = \frac{1 - |\rho|^2}{2\pi} \cdot \frac{1}{1 - \beta_\phi^2} \cdot \left\{ 1 + \frac{\beta_\phi \cdot \arccos(-\beta_\phi)}{\sqrt{1 - \beta_\phi^2}} \right\}$$

where  $\beta_\phi = |\rho| \cos \phi$  and the interferometric correlation  $\rho$  depends on  $\gamma$  through

$$|\rho| = \frac{1}{1 + \gamma^{-1}}$$

Agram and Zebker 2007 use the same signal model of Hooper et al 2004 to isolate phase noise.



[Agram & Zebker 2007]

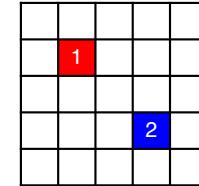
## Permanent scatterer time-series analysis, PS selection

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### 4- Phase similarity [Wang and Chen, 2022]

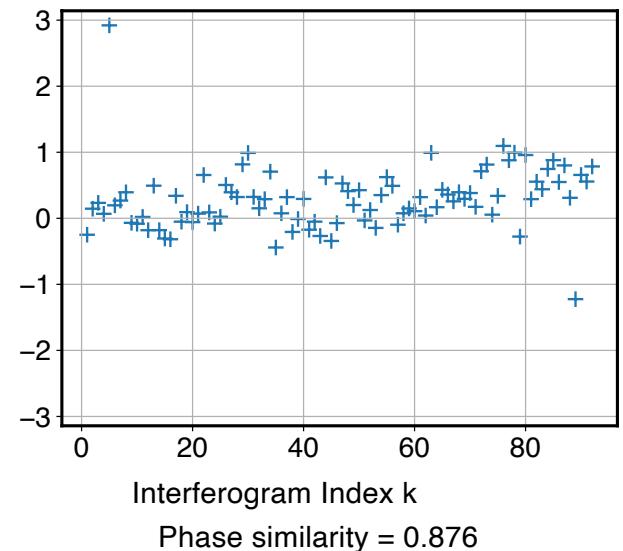
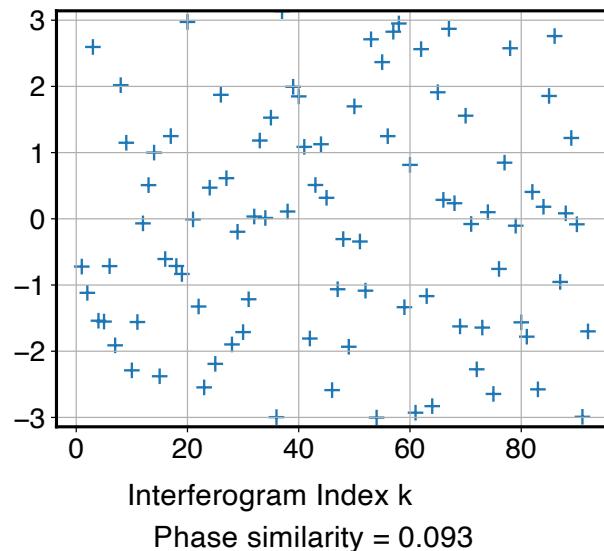
$$s_{1,2} = \frac{1}{K-1} \sum_{k=1}^{K-1} \cos(\varphi_k^{(1)} - \varphi_k^{(2)})$$



Pixel1 or Pixel2 is non-PS

Pixel1 and Pixel2 are PS

After initial selection of the PS pixels using MLE approach, Wang and Chen evaluate the cosine similarity between the possible PS candidates and through multiple iterations they converge to final identified PS pixels



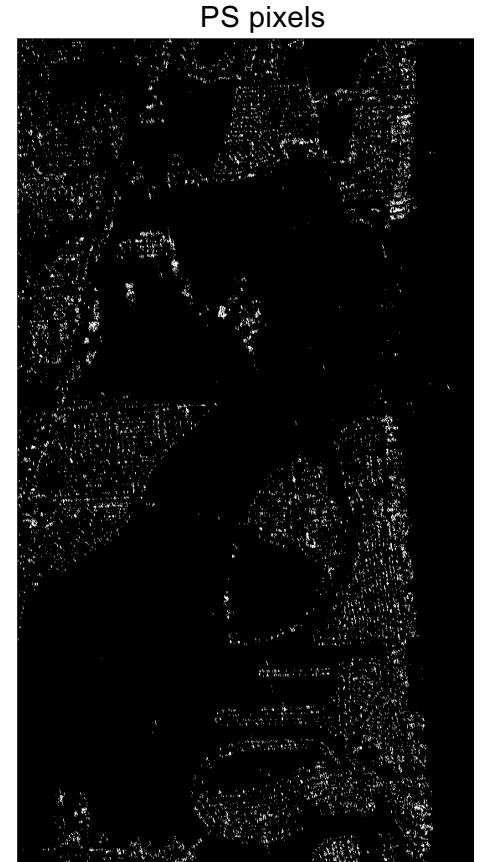
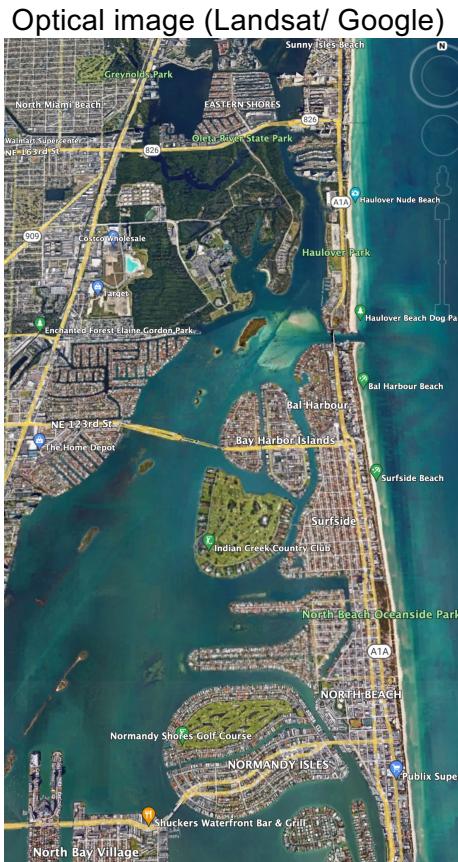
[Wang & Chen 2022]

# Persistent scatterer time-series analysis

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- Amplitude dispersion computed from a stack of 161 SLCs from Sep 2015 to May 2022 over north Miami beach
- Dark pixels in the amplitude dispersion are PS candidates
- PS pixels identified by thresholding the amp dispersion



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# Permanent scatterer time-series analysis

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No PS pixels identified over the Golf course, because the grass land does not contain strong scatterers and



Clear subsidence signal in Miami beach [Mirzaee et al, 2023]

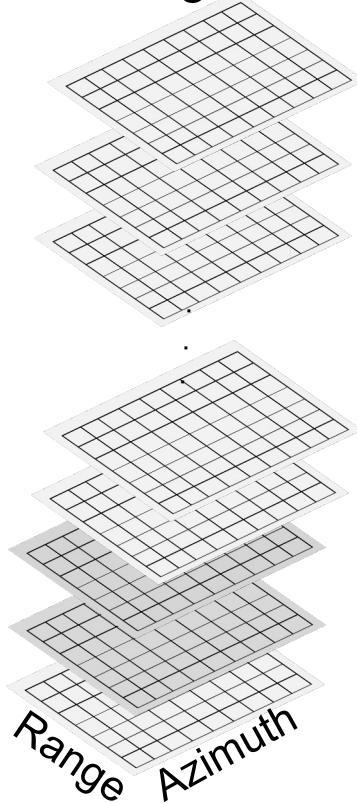
Most PS pixels are identified over buildings

## Distributed Scatterer (DS) time-series analysis

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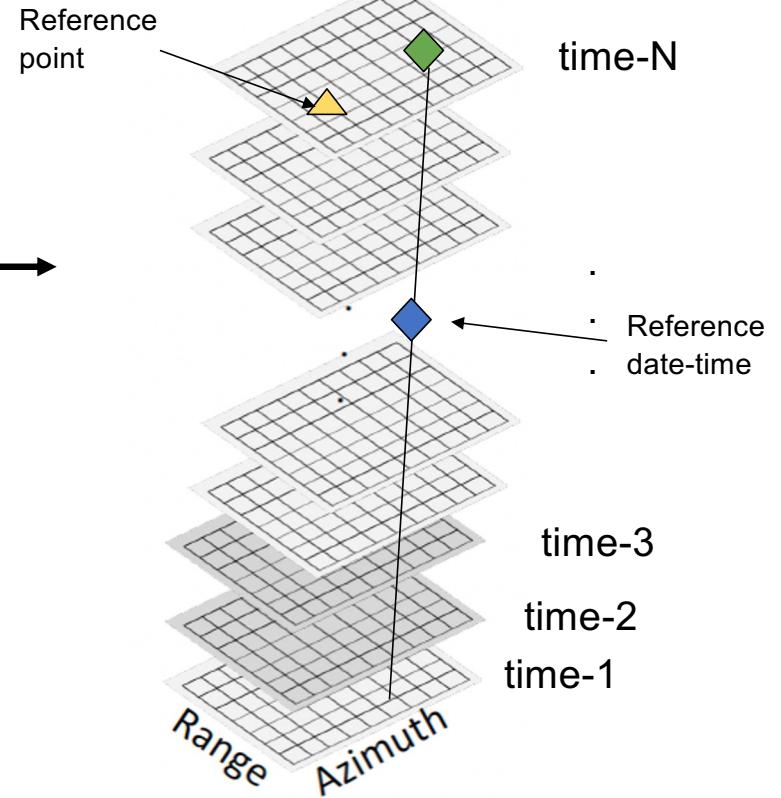
N Coregistered SLCs



DS time-series  
analysis from a  
network of  
interferograms

The estimated  
displacement time-series is  
relative to a reference time  
and relative to a reference  
point

N displacement epochs

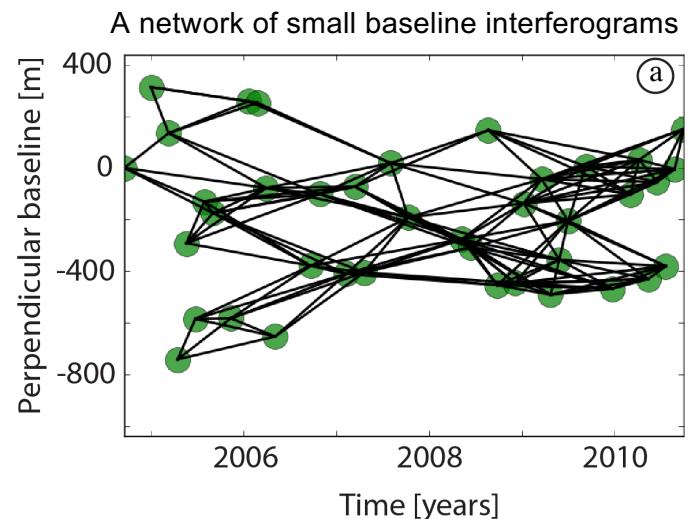


## Distributed Scatterer (DS) time-series analysis algorithms

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- The interferometric phase of Distributed Scatterers (DS pixels) are noisier than PS pixels and therefore the DS analysis algorithms generally involve multi-looking/averaging to reduce noise
- In theory one could create a single reference network of DS interferograms (similar to PS algorithm), unwrap and estimate displacement time-series
- In practice, DS pixels decorrelate rapidly in time and therefore a redundant network of interferograms are used to invert for a single reference interferometric phase time-series
- Depending on the network of interferograms we have two main category of DS analysis algorithms
  - **Small Baseline algorithms (SBAS)**
  - **Full covariance based algorithms**



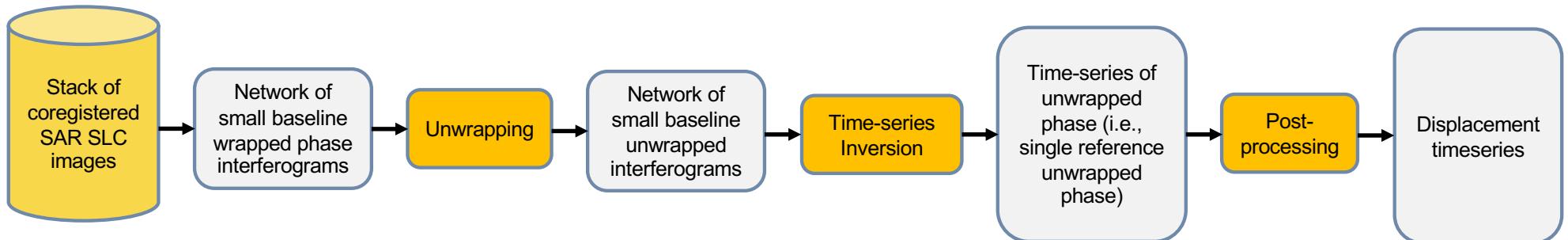
- Each green circle in this plot represents one SAR image
- Each line represents one interferogram
- Generally interferograms made with short temporal and short perpendicular baselines are more coherent

## DS time-series analysis algorithms- Small Baseline algorithms

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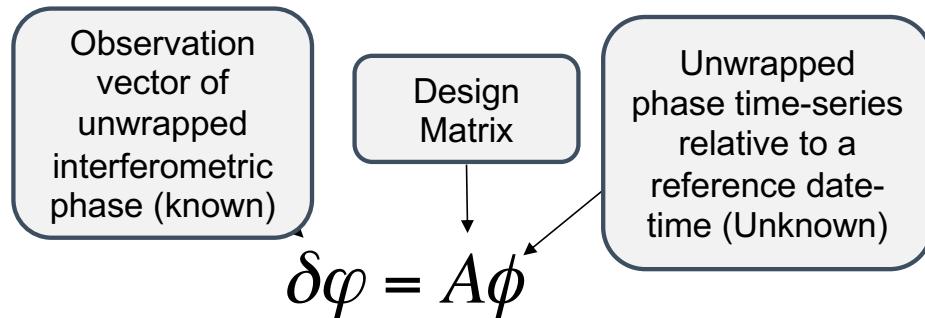


- Taking a coherent network of small baseline interferograms, the Small Baseline Subset (SBAS) algorithms attempt to improve signal to noise ratio in individual interferograms [Berardino et al, 2002]
- More coherent interferograms are easier to unwrapping
- The redundant network of unwrapped interferograms are inverted to estimate a single-reference network of unwrapped interferograms (i.e., the unwrapped phase timeseries)
- The estimated unwrapped phase time-series can be converted to range-change time-series (range-change = phase \*wavelength/4/PI)
- The estimated range change time-series can be post processed to correct for different contributions such as tropospheric delay, DEM errors etc to isolate the displacement time-series signal [Yunjun et al, 2019; Fattah & Amelung 2013]



## DS time-series analysis algorithms- Small Baseline algorithms

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$$\delta\hat{\varphi}_{ij} = \hat{\phi}(t_j) - \hat{\phi}(t_i)$$

$$\gamma = \left| \frac{1}{M} \sum_{i=1}^M \exp[j(\delta\varphi_i - \delta\hat{\varphi}_i)] \right|$$

$$0 \leq \gamma \leq 1$$

Temporal  
coherence

The unwrapped phase time-series can be obtained by minimizing the L1 or L2 norm of the residual vector

In case of L2 norm minimization, the estimated unwrapped phase is obtained with least squares estimator

Given the weight of observation vector, a weighted least squares can be used to estimate the time-series

Temporal coherence derived from the residual vector represents the quality of inversion

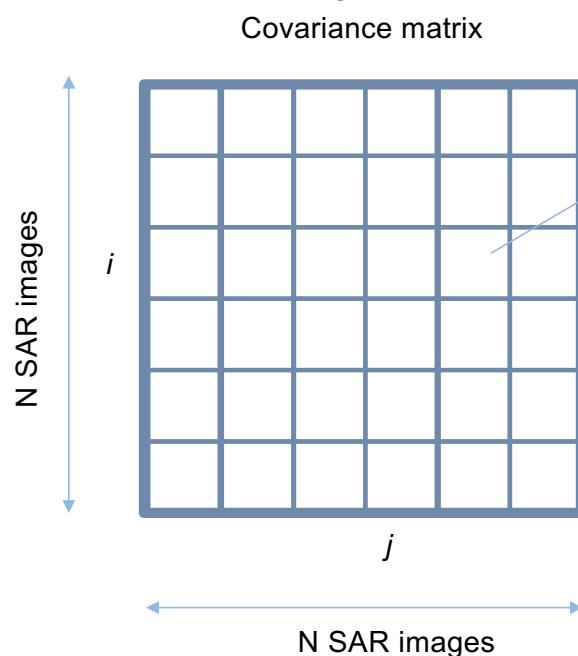
## DS time-series analysis - Full covariance algorithms

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Covariance-based approach, extracts information from all possible interferometric phases [Guarnieri & Tebaldini, 2007 and 2008]

Assuming N co-registered SAR images, a NxN covariance matrix can be formed whose elements are multi-looked interferograms



$$\hat{C}_{ij} = \frac{1}{M} \sum_{x \in \Omega} d_x^i d_x^{j^H}$$

$d_x^i$  A vector of complex SLCs at pixel x at time i

H Hermitian conjugate operation

$\Omega$  A neighborhood to multi-look interferometric phases

M

Coherence matrix is the magnitude of covariance normalized by amplitude.  
Coherence is between 0 and 1

$$|\Gamma_{ij}| = |\hat{C}_{ij}| / \sqrt{\sum_{x \in M} |A_x^i|^2 \sum_{x \in M} |A_x^j|^2}$$

# DS time-series analysis - Full covariance algorithms

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## 1) Maximum Likelihood Estimator (MLE) [Guarnieri and Tebaldini]:

[Ferretti et al, 2011] in the SqueeSAR algorithm, propose PTA algorithm to maximizing the probability distribution function of the data using repetitive optimization algorithms

$$\boldsymbol{\Theta} = \arg \max_{\boldsymbol{\Theta}} \{ \boldsymbol{\Theta}^H (|\hat{\Gamma}|^{-1} \circ \hat{\Gamma}) \boldsymbol{\Theta} \}$$

## 2) Classic Eigenvalue Decomposition (CED) [Fornaro et al 2015]

Also known as EVD or CEASAR, the CED estimator suggest that the phase of the eigenvector corresponding to the largest eigenvalue of the complex covariance matrix represents the wrapped phase time-series

$$\hat{\Gamma} \hat{\boldsymbol{\nu}} = \lambda_m \hat{\boldsymbol{\nu}}$$

## 3) Eigenvalue Based Maximum Likelihood Estimator (EMI)

Instead of using PTA for estimating the MLE of the wrapped phase time-series, [Ansari et al, 2018] suggest to simply take the eigenvector corresponding to the minimum eigenvalue of  $|\hat{\Gamma}|^{-1} \circ \hat{\Gamma}$

$$(|\hat{\Gamma}|^{-1} \circ \hat{\Gamma}) \hat{\boldsymbol{\nu}} = \lambda_m \hat{\boldsymbol{\nu}}$$

## DS time-series analysis - Full covariance algorithms

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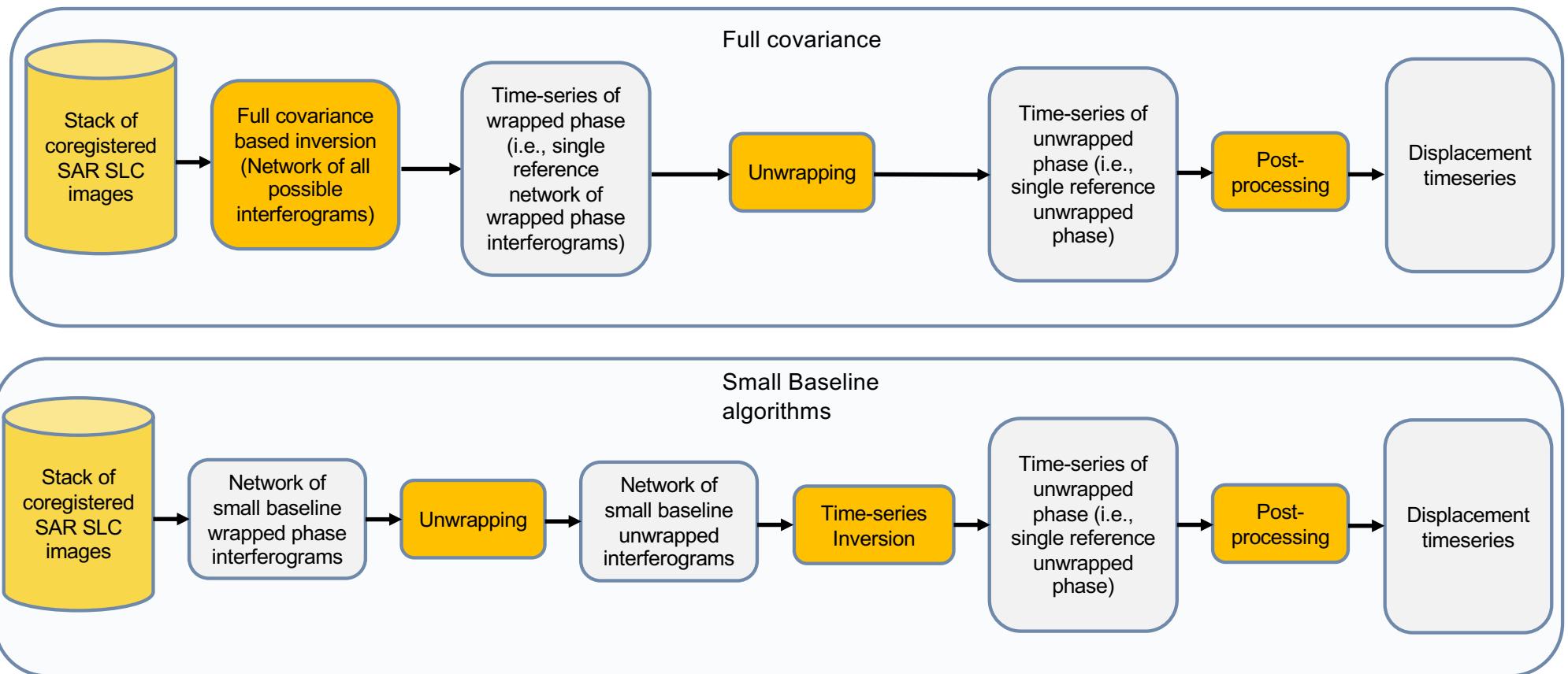
- Simulations show that MLE estimates of wrapped phase time-series are more precise than the CED estimates
- However, MLE estimators require computing the inverse of the Coherence matrix. Computing the inverse requires the coherence matrix to be positive-definite
- Ignoring an estimate when coherence is not positive definite will lead to loosing an estimate for many coherent pixels

### 4- Combined phase-linking algorithm [Mirzaee, Amelung, Fattah, 2023]:

- 1- Compute Covariance and Coherence matrices
- 2- Check if Coherence is positive
- 3- If Coherence is positive-definite, Estimate MLE  
else:
  - Regularize Coherence
  - if regularized coherence positive-definite, estimate MLE
  - else estimate CED

# DS time-series analysis - Full covariance algorithms

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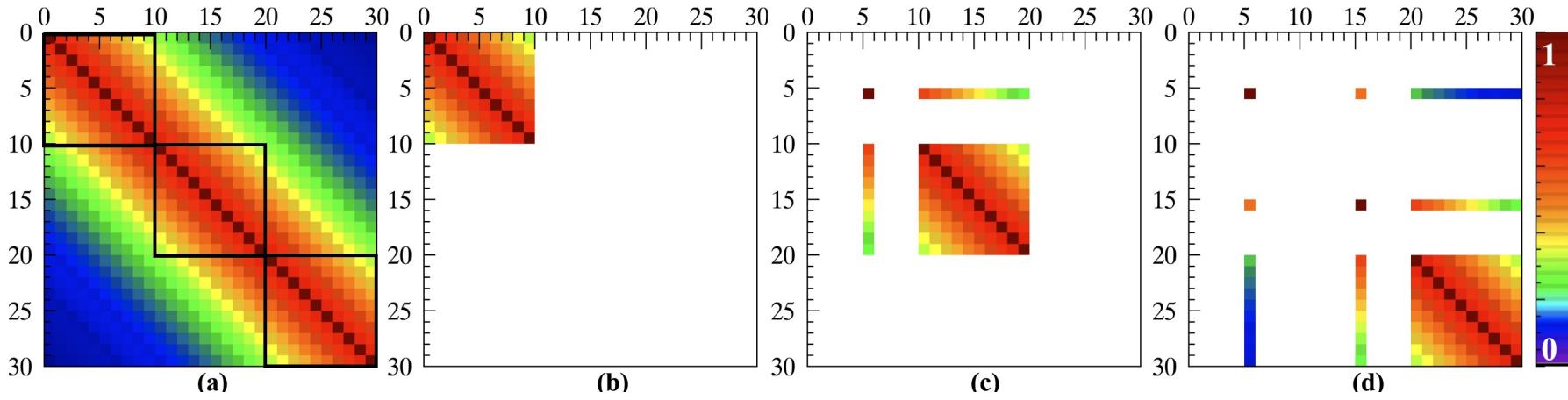
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## DS time-series analysis - Full covariance algorithms for Big data

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- Regardless of the choice of the estimator, the wrapped phase time-series from a full covariance matrix formed from a large stack of SLCs is an expensive operation.
- With new acquisitions added to the existing stacks, there is a need for time-series update in opposite to reprocessing the entire stack with every new acquisition.
- Ansari et al, 2017 proposed Sequential Estimator algorithm which processes a covariance matrix in batch and allows to update an existing time-series without processing the full covariance matrix.



[Ansari et al, 2017]

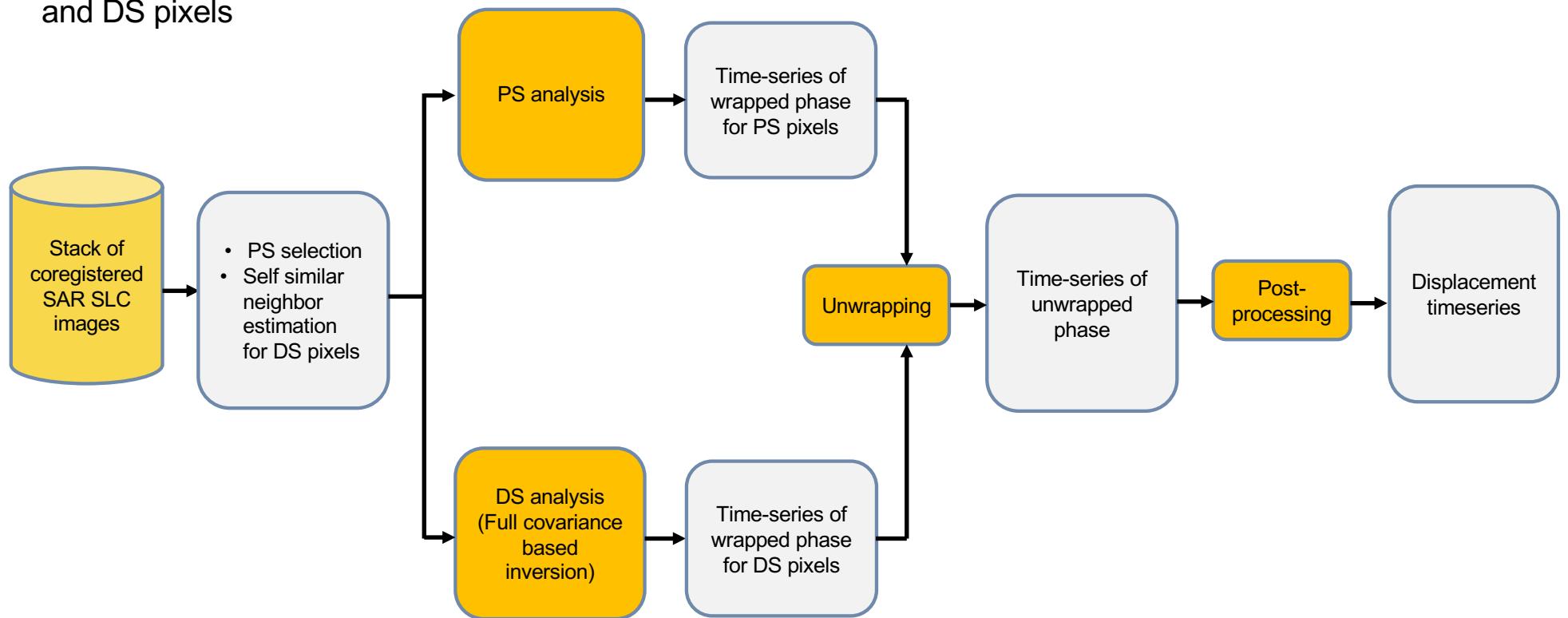
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## PS+DS time-series analysis

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The combined PS+DS time-series analysis algorithms provide estimated time-series for both PS and DS pixels



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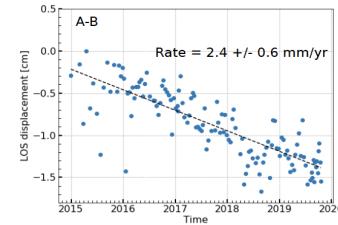
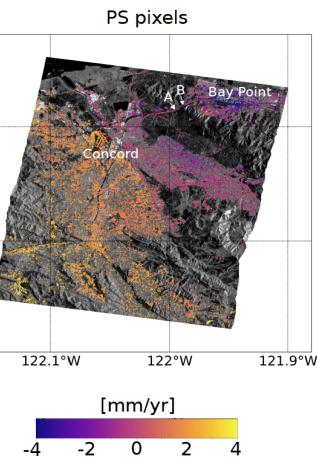
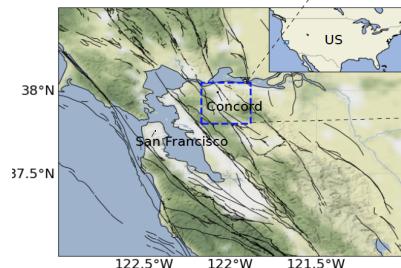
# PS+DS time-series analysis- Examples

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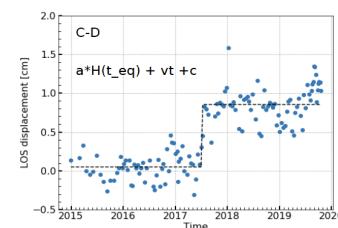
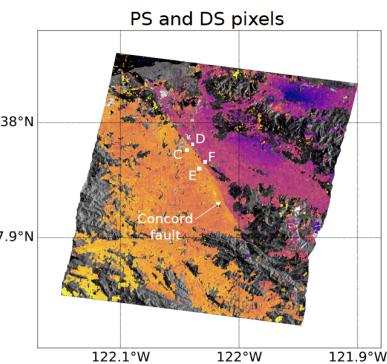


## Example 1: Concord Fault

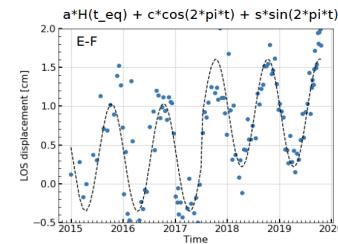
Concord fault, a strike-slip fault running through Concord city, California in the east of San Francisco bay area is under a high stress level and therefore may be capable of producing earthquakes larger than 2014 South Napa earthquake (USGS). At shallow depths, the fault may release part of the strain aseismically with episodic events.



Strong subsidence signal



A creep event



Seasonal displacement superimposed on the creep event

138 SAR acquisitions acquired by Sentinel-1 were coregistered using ISCE. We estimated the neighborhood map using KS2 test and the estimated the wrapped phase time-series of DS pixels using the Sequential approach with mini-stacks of 15 acquisitions and with the eigen-decomposition as the solver. We used an amplitude dispersion of 0.4 for choosing PS pixels and then unwrapped the phase series of PS and DS pixels together. We use 2D unwrappers to simultaneously unwrap the PS and DS pixels. The DS and PS rate maps generally agree.

Strong seasonal deformations are clearly visible in the time series. The series can be best explained with a combination of a linear trend and a seasonal component. The latter represents the creep event superimposed on the seasonal deformation.

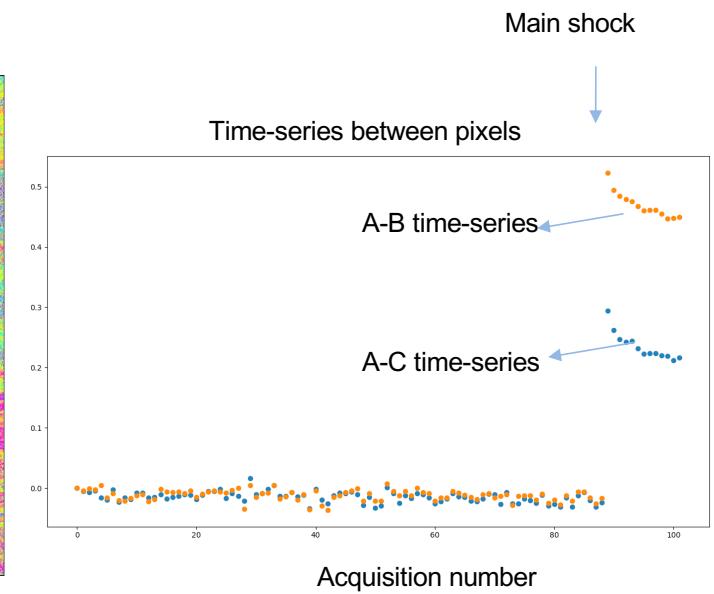
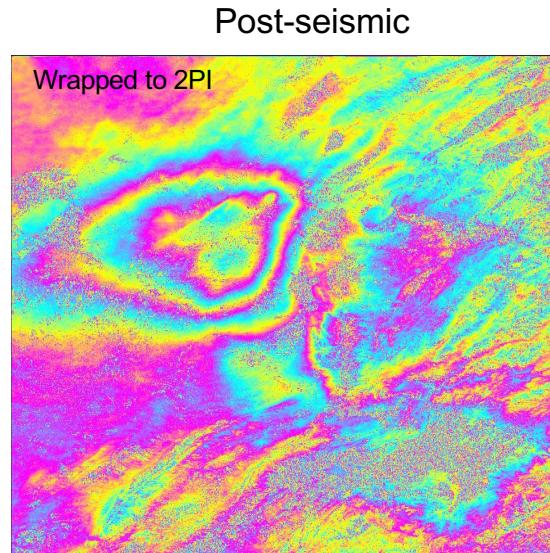
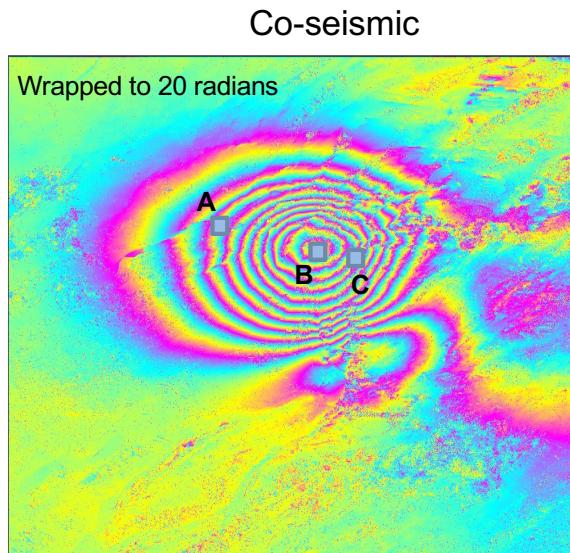
[Fattah et al, 2019]

## PS+DS time-series analysis- Examples

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Kurdistan Earthquake, 2017



- A stack of 120 coregistered SLCs were processed with full covariance algorithm (using FRInGE) to estimate the wrapped phase time-series.
- The wrapped phase time-series were unwrapped.
- The co-seismic and post-seismics are the result of a fit to the estimated unwrapped time-series

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## PS+DS time-series analysis- Examples

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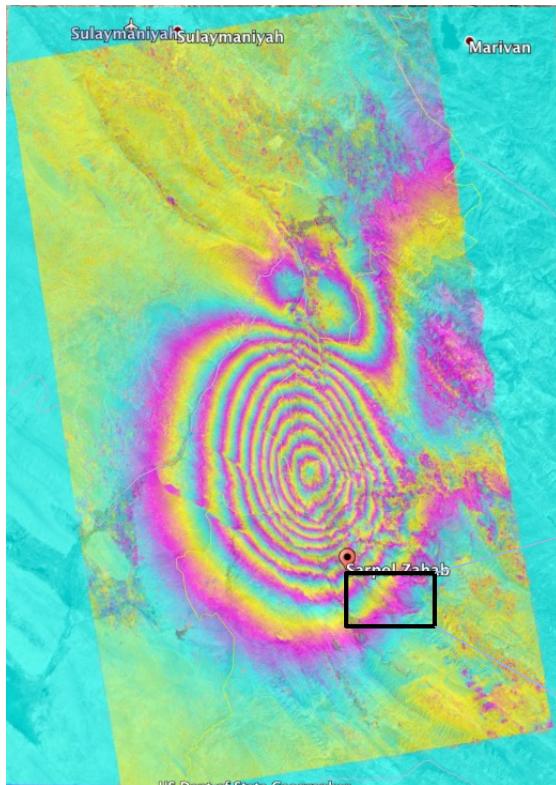


Magnitude of the normalized full covariance matrix, represents the coherence matrix

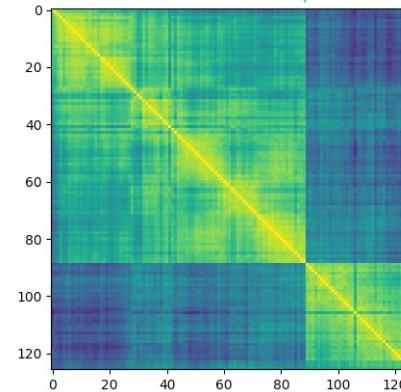
Changes in the scattering properties of the scene can impact coherence

Changes can be potentially detected by coherence time-series

Co-seismic



A change in the coherence magnitude history most likely caused by the damages caused by the Earthquake



A change in the coherence matrix after the earthquake, demonstrates the potential of full coherence matrix for change detection and damage proxy mapping.



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# Error analysis of the InSAR timeseries

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This document has been reviewed and determined not to contain export controlled technical data

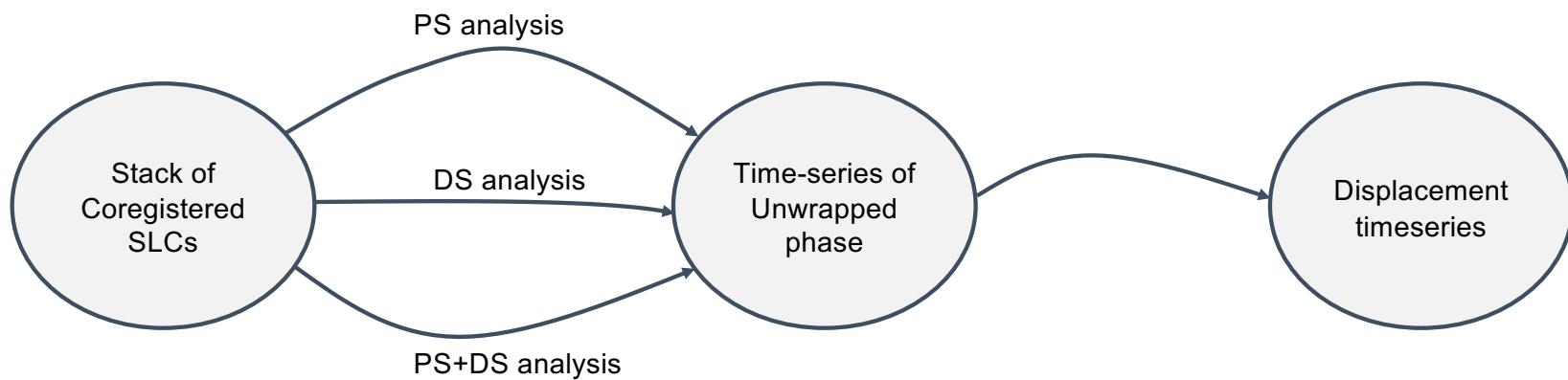
## Error analysis of InSAR time-series

National Aeronautics and  
Space Administration



The uncertainty of the estimated displacement time-series is a function of:

1. the quality of the stack of coregistered SLC
2. the quality of the time-series of unwrapped phase
3. accuracy in isolating the ground displacement from other interferometric phase contributions (tropospheric delay, ionospheric delay, interferometric phase components driven by the dielectric changes, etc)

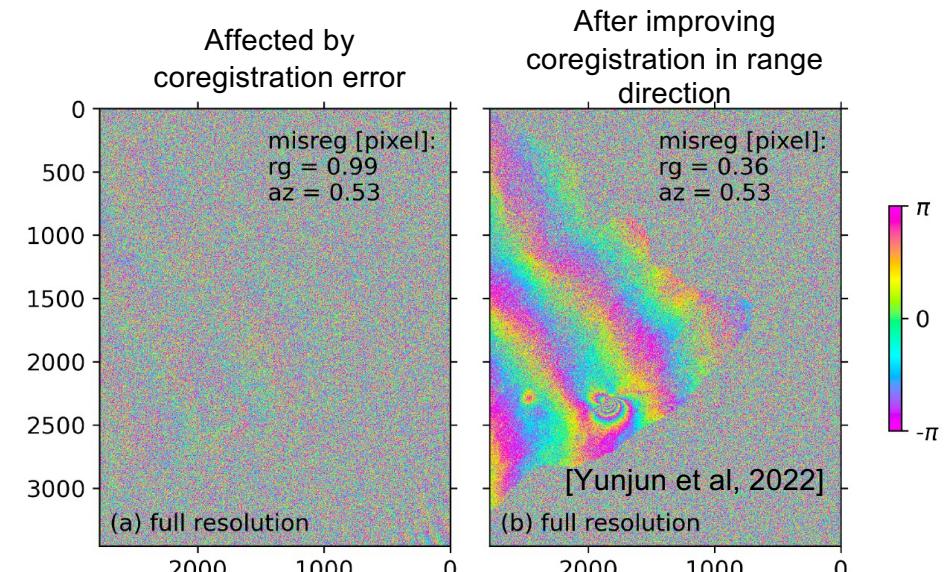
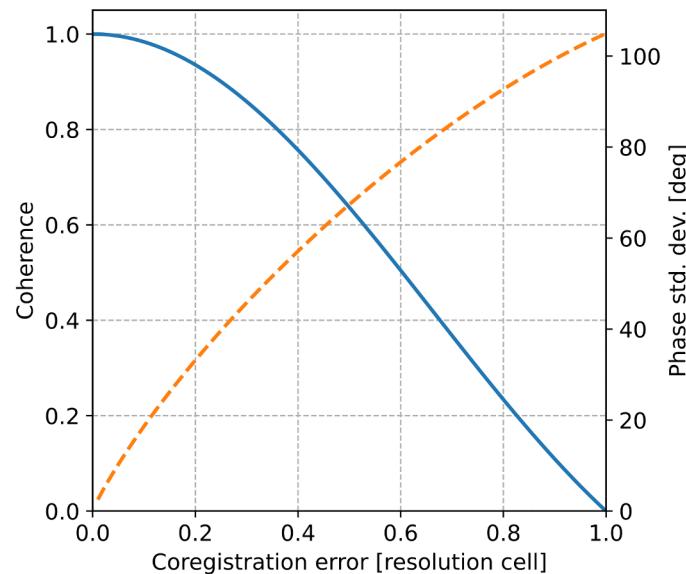


## Coregistration error

National Aeronautics and  
Space Administration



- The input stack of SLC images for InSAR time-series analysis should be aligned (coregistered) with accuracies of  $\sim 1/10^{\text{th}}$  of the SLC resolution cell or better
- Coregistration errors (or misregistration) of the stack of SLC images leads to increased interferometric phase noise, i.e., worsens the accuracy of interferometric phase and subsequent time-series products

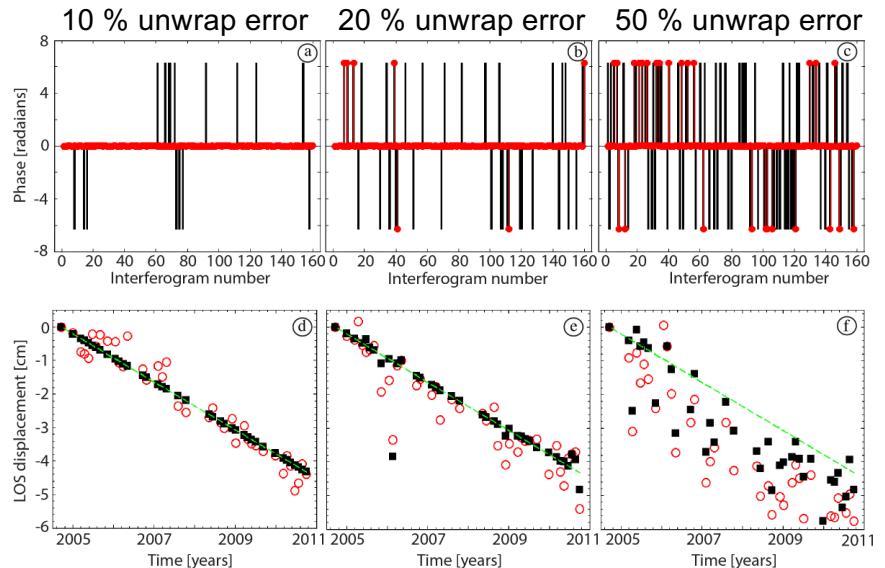


## Unwrapping errors

National Aeronautics and Space Administration



- ❑ Phase unwrapping is the process of reconstructing the phase field by adding integer number of phase cycle to the wrapped interferometric phase
- ❑ Unwrapping error: wrong integer cycle (wrong  $2\pi$ ) added to the wrapped phase
- ❑ Unwrapping errors can lead to non-closing triplets of the Integer cycles
- ❑ Evaluating the closure phases of the dense stacks of interferograms helps to identify areas affected by unwrapping errors and potentially correct them



**Figure 4.4** Effect of the unwrapping error correction on the interferometric phases and on the estimated displacement history. (a-c): The unwrapping errors in the simulated interferograms before (black bars) and after (red bars) unwrapping error correction for the three simulations with a) 10%, b) 20% and c) 50% of the simulated unwrapping errors. (d-f): The estimated displacement history before (red circles) and after (black squares) unwrapping error correction compared with the simulated displacement (green dashed line) for the three simulations with d) 10%, e) 20% and f) 50% of the unwrapping errors.

[Fattah, 2015]

## Unwrapping errors – impact of interferogram network

National Aeronautics and Space Administration

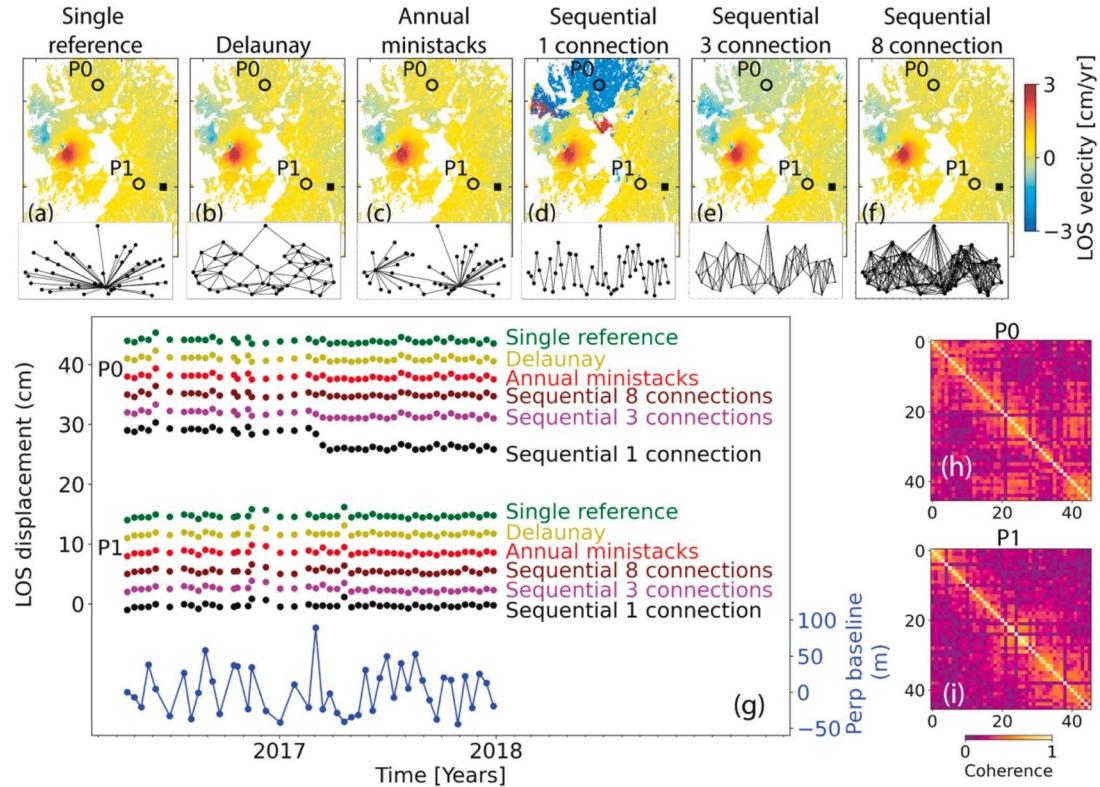


Phase unwrapping error in individual interferograms propagate to time-series depending on the interferogram network

Single reference and Delaunay are most robust networks

(i) For cases with long-term coherent interferograms → use a single-reference network: because the unwrap errors don't propagate and because it requires the least memory.

(ii) For cases with strong seasonal decorrelation and cases where correlation is lost rapidly → a Delaunay network may be preferred if overhead extra computation can be afforded



[Mirzaee et al, 2023]

## DEM error

National Aeronautics and Space Administration

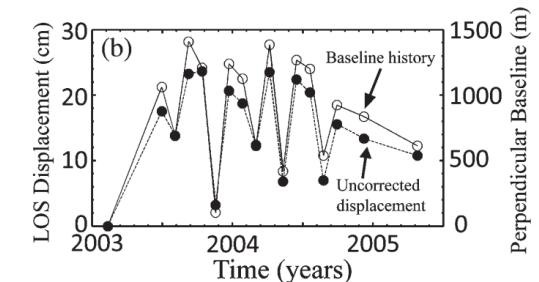
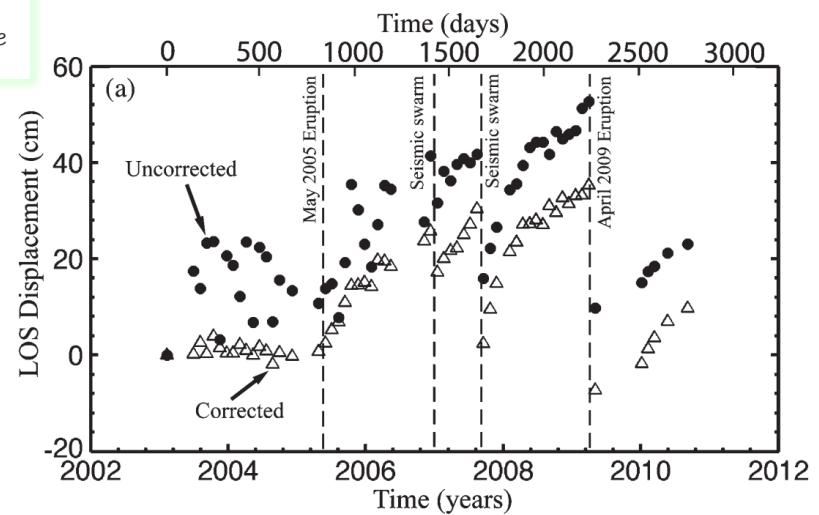


$$\delta\phi = \delta\phi_{displacement} + \delta\phi_{atmosphere} + \delta\phi_{geometry} + \delta\phi_{scattering} + \delta\phi_{noise}$$

- We use an existing Digital Elevation Model (DEM) to remove topographic component from the interferometric phase.
- Any error in DEM will lead to residual topographic effects in the estimated time-series
- The contribution of DEM error in the estimated time-series is a function of the perpendicular baseline time-series. This dependency allows to estimate DEM error from InSAR time-series data when the baseline diversity increases the sensitivity to DEM errors

$$\phi_{topo}^{\varepsilon}(t_i) = \frac{4\pi}{\lambda} \frac{B_{\perp}(t_i)}{r \sin(\theta)} z^{\varepsilon}$$

- Sentinel-1 and NISAR have small baseline variation (< few hundred m) and therefore are less sensitive to DEM errors
- Missions with large baseline diversity (e.g, CSK Envisat, ERS, ALOS-1) with few km baseline separation, are most affected by DEM error.



[Fattah & Amelung, 2013]

# Tropospheric delay

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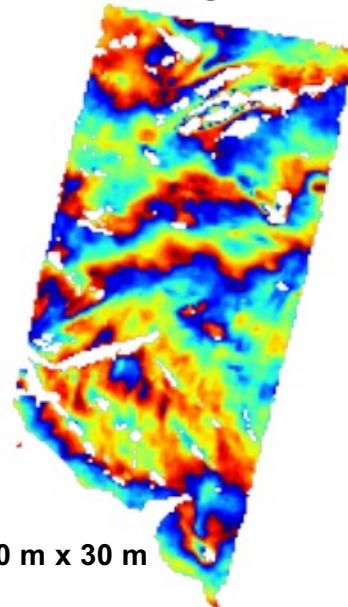


$$\delta\phi = \delta\phi_{displacement} + \delta\phi_{atmosphere} + \delta\phi_{geometry} + \delta\phi_{scattering} + \delta\phi_{noise}$$

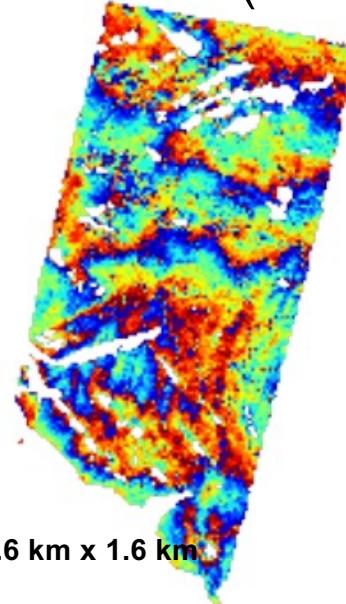
- Microwave signals experience a delay while propagating through atmosphere.
- The two main components of the delay comes from **troposphere** and **ionosphere** layers of the atmosphere

In this example  
independent observation  
from optical sensor  
(MERIS) acquired at the  
same time as the SAR  
acquisition predicts the  
impact of tropospheric  
delay on InSAR data

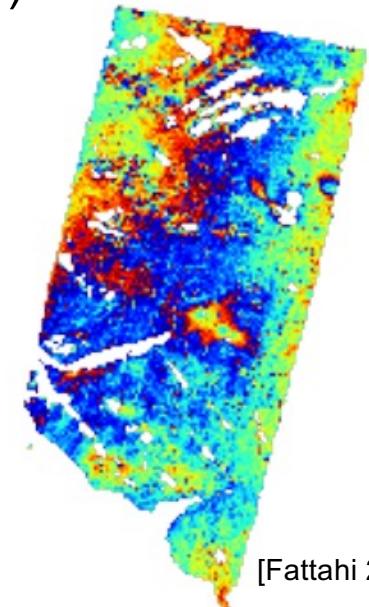
InSAR



MERIS (wet delay)



corrected InSAR



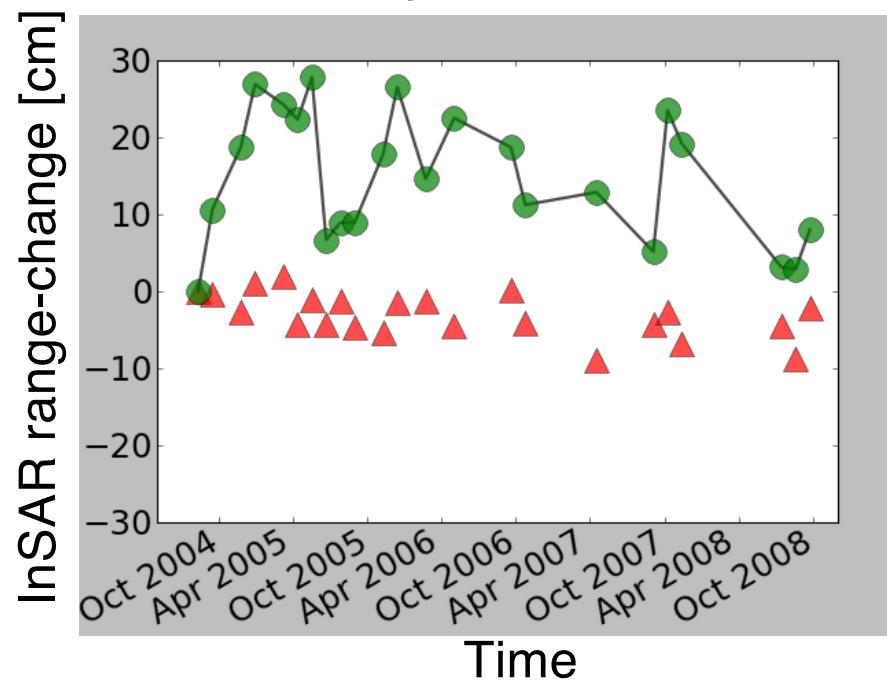
## Tropospheric delay

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Space Administration



- The time-series between two pixels ~200 km away in western Indian plate boundary, significantly improves after tropospheric delay correction.
- The tropospheric delay correction using atmospheric models depends on the spatial resolution of the model, their temporal sampling and accuracy of the model parameters
- The tropospheric delay correction using atmospheric models usually can NOT correct the turbulent component of the delay

**Effect of stratified tropospheric delay correction**



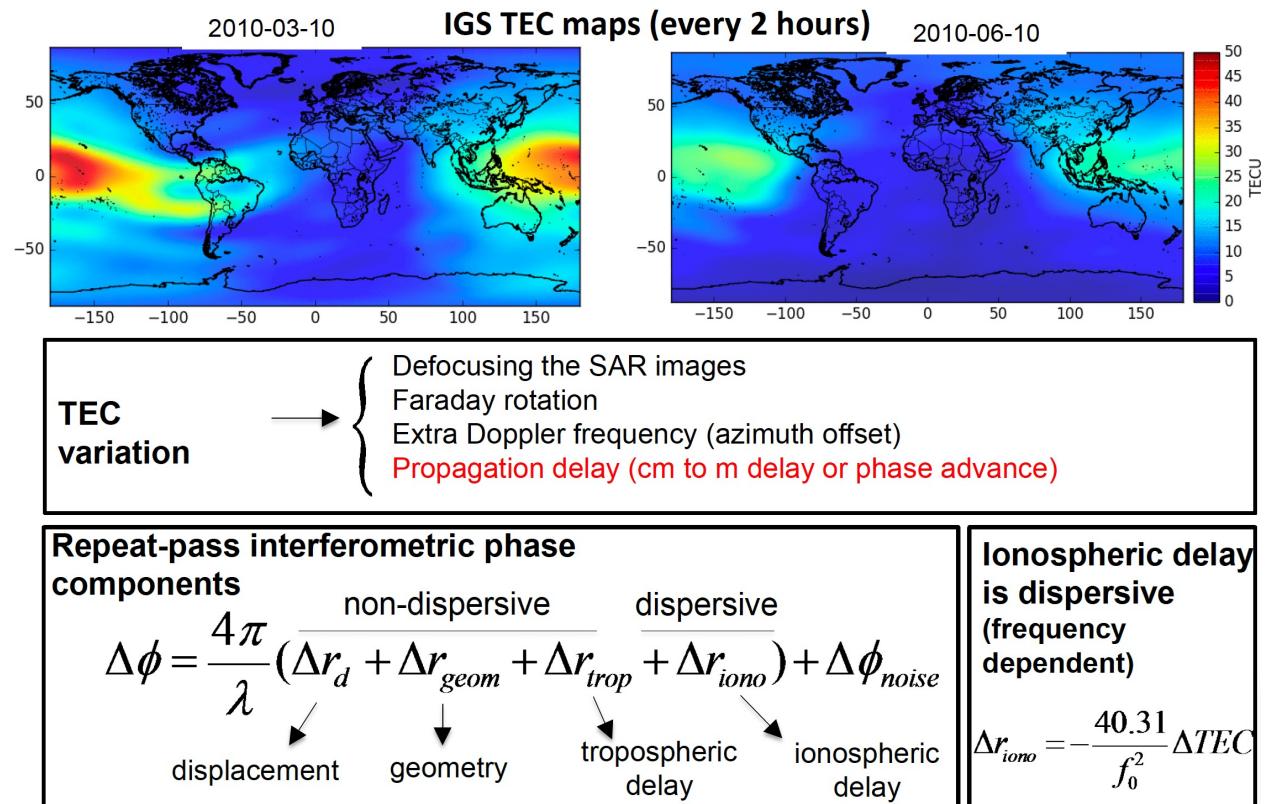
The dramatic improvement of the displacement time-series is due to very long distance and large height variation between the two pixels

# Ionospheric delay

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Space Administration



- Ionosphere is a dispersive media with respect to microwave signal
- Ionosphere impacts SAR data in all different frequencies. However the effect is larger in low frequencies (e.g., P and L bands compared to high frequencies such as X and C bands)
- The dispersive nature of ionosphere provides an opportunity to estimate the ionospheric delay from SAR data

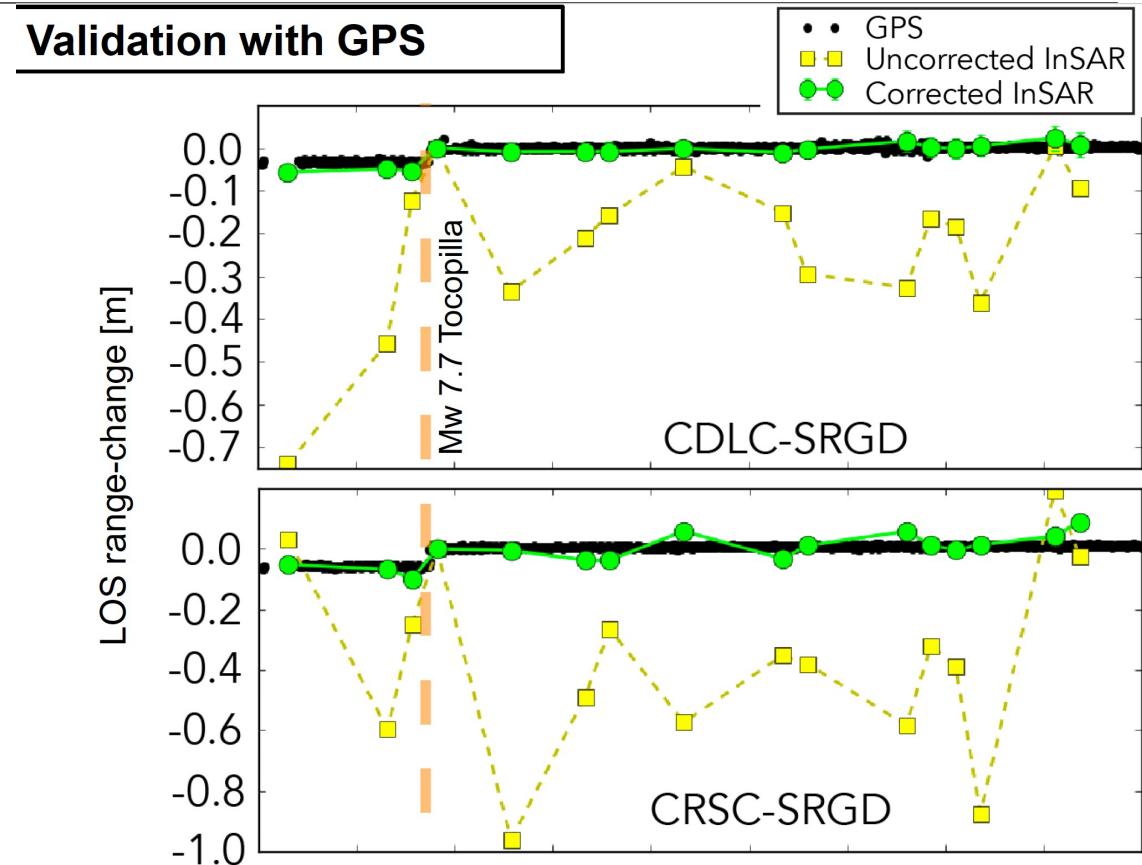


## Ionospheric delay

National Aeronautics and Space Administration



- The InSAR time-series before and after ionosphere correction compared with GNSS time-series demonstrates the impact of ionospheric phase on InSAR time-series in L-band.
- The impact of ionosphere is smaller in higher frequency radar data, however several studies have demonstrated that the ionosphere contribution is not negligible in C-band data.



## Closure phase

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Space Administration



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Phase triplet is the sum of three interferometric phases formed from three SAR acquisitions at times i, j and k

$$\Delta\phi_{ijk} = \Delta\phi_{ij} + \Delta\phi_{jk} + \Delta\phi_{ki}$$

Zero closure phase is the intrinsic assumption of all InSAR time-series analysis algorithms

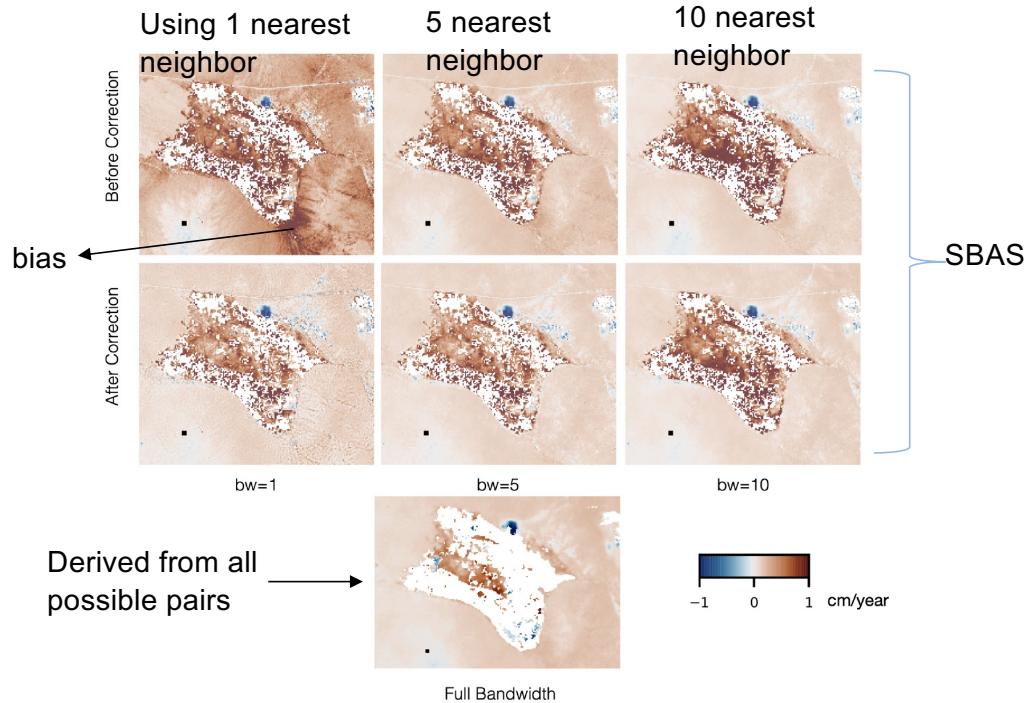
For single look interferograms  $\Delta\phi_{ijk} \equiv 0$ , for multi-looked interferograms  $\Delta\phi_{ijk} \neq 0$

Multi-looking gives rise to non-closing triplets

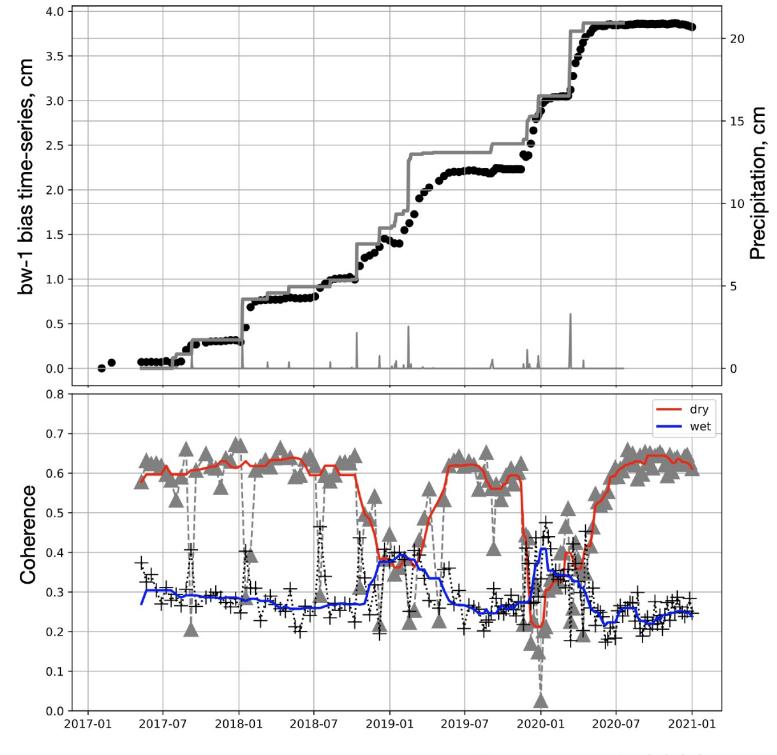
Zheng et al, suggest **spatial and temporal inhomogeneity** as the source of non-closing triplet

# Closure phase

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Space Administration



Estimated bias from cumulative closure phase is correlated with cumulative precipitation



**How to treat the displacement bias in short temporal baseline time-series:**

- 1- Use cumulative closure phase to estimate the bias
- 2- Use **all possible interferometric pairs** to minimize the bias

## References

National Aeronautics and  
Space Administration



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<https://ieeexplore.ieee.org/abstract/document/9130052>

# Open source tools

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ISCE2

<https://github.com/isce-framework/isce2>

ISCE3

<https://github.com/isce-framework/isce3>

Mintpy

<https://github.com/insarlab/MintPy>

FRInGE

<https://github.com/isce-framework/fringe>

MiaplPy

<https://github.com/insarlab/MiaplPy>



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Thank you!

