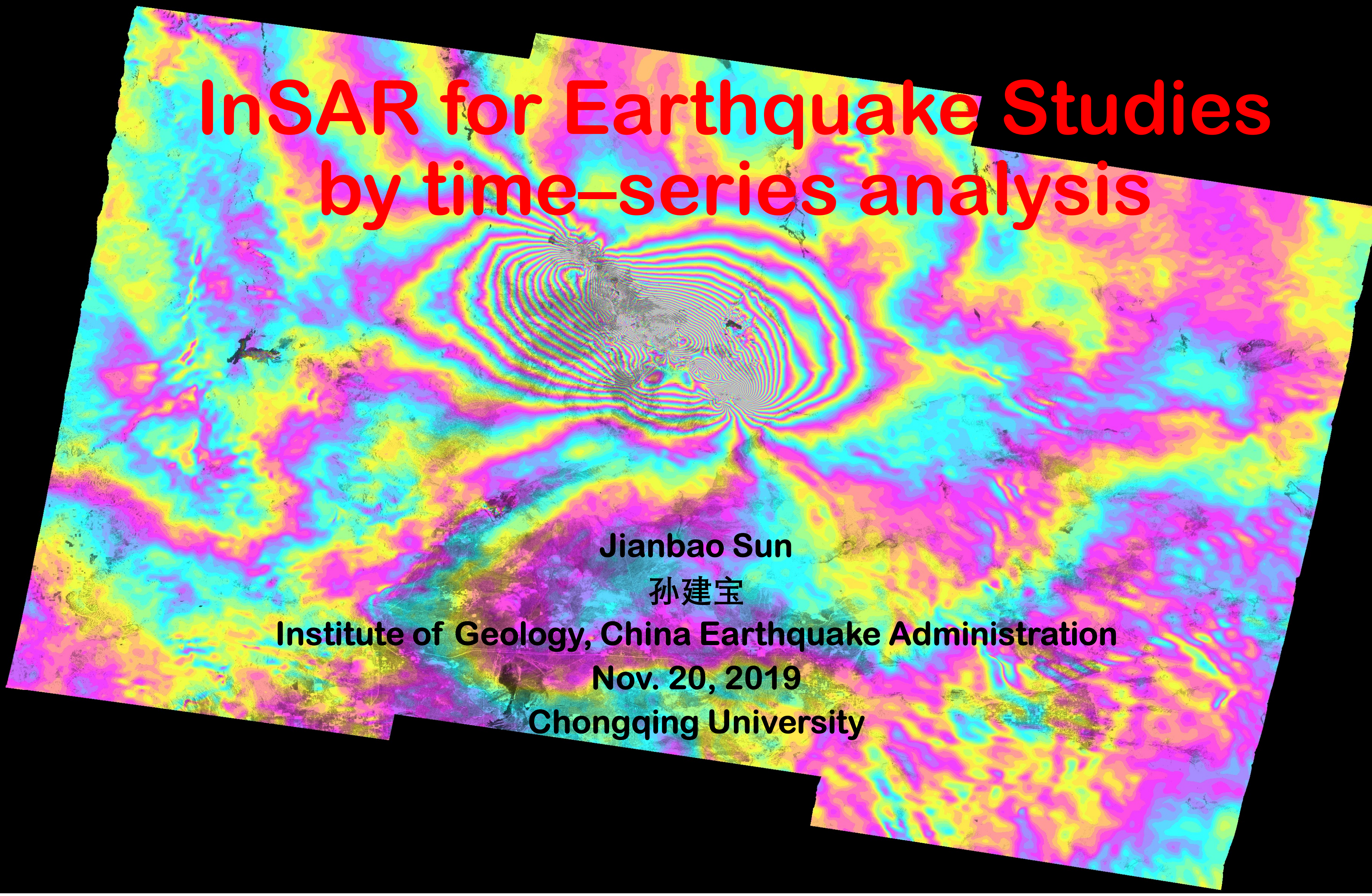
InSAR for Earthquake Studies by time-series analysis



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Content

1. InSAR on earthquake-related deformation detection, requirements and speciality

2. The public approaches on high-precision crustal deformation analysis

3. The Stanford Method for Persistent Scatterer analysis (StaMPS) and its usefulness on geophysical process detection from surface down to upper mantle.

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS, SBAS, Combination of the two)

5. What we do to further push forward the method in earthquake and geophysical studies

Materials for this class

1. Andy Hooper's PhD. Thesis, available from Prof. Howard Zebker's website at Stanford

2. Hooper et al., Persistent Scatterer InSAR for Crustal Deformation Analysis, with Application to Volcan Alcedo, Galapagos, JGR, 2007

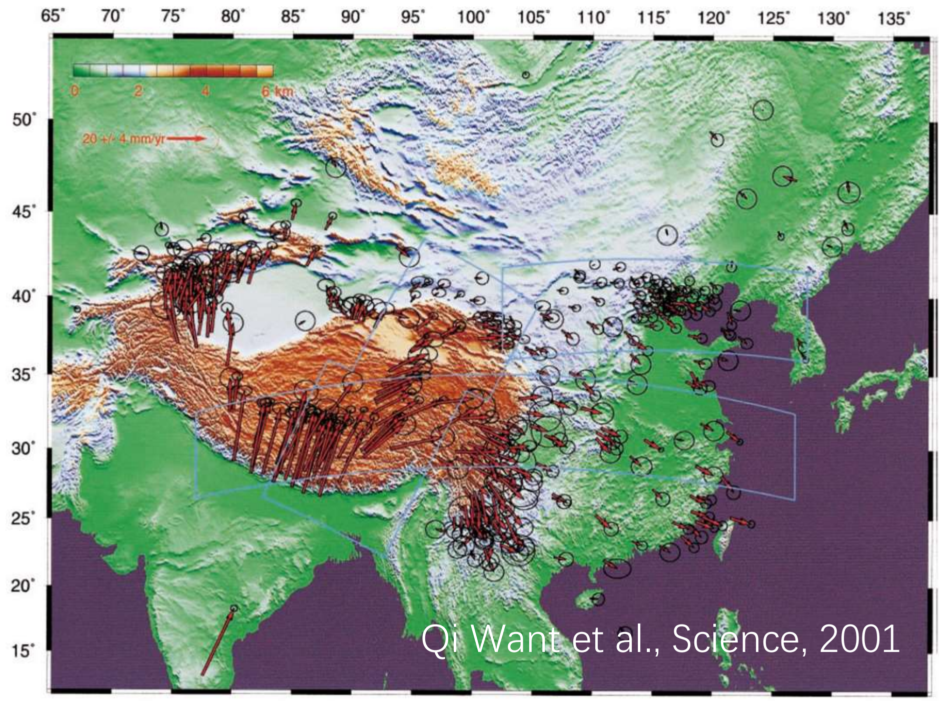
3. Hooper, A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, GRL, 2008

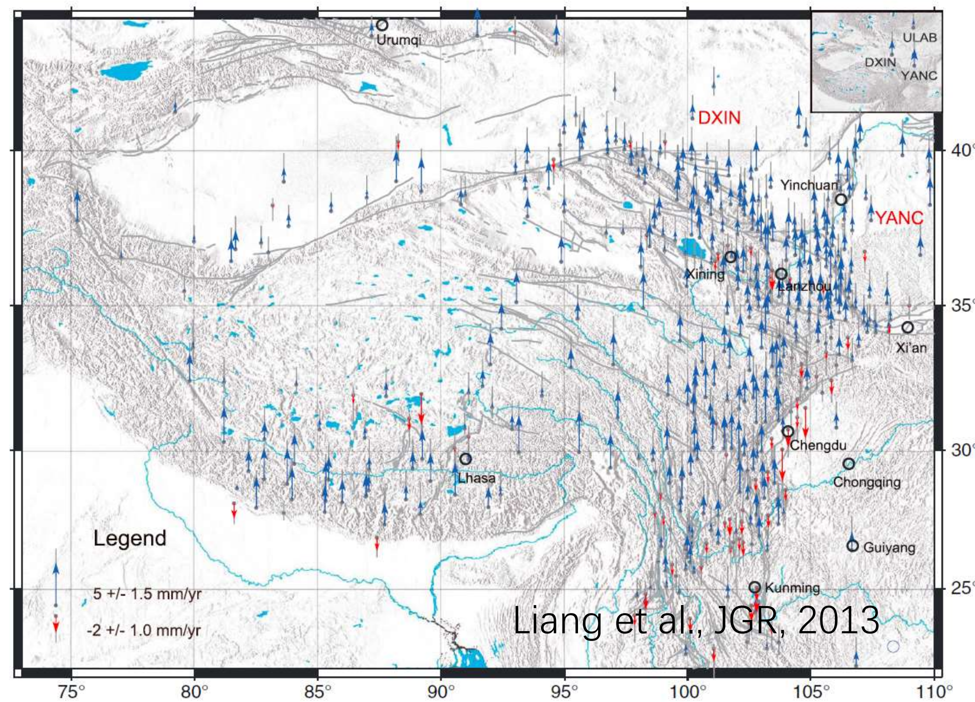
4. StaMPS and TRAIN software manual @github

5. Stamps_S1_PS_Exercise.pdf from Andy Hooper

(atmospheric delays TRAIN, PyAPS, GPS, GACAOS etc.)

1. InSAR on earthquake-related deformation detection, requirements and speciality

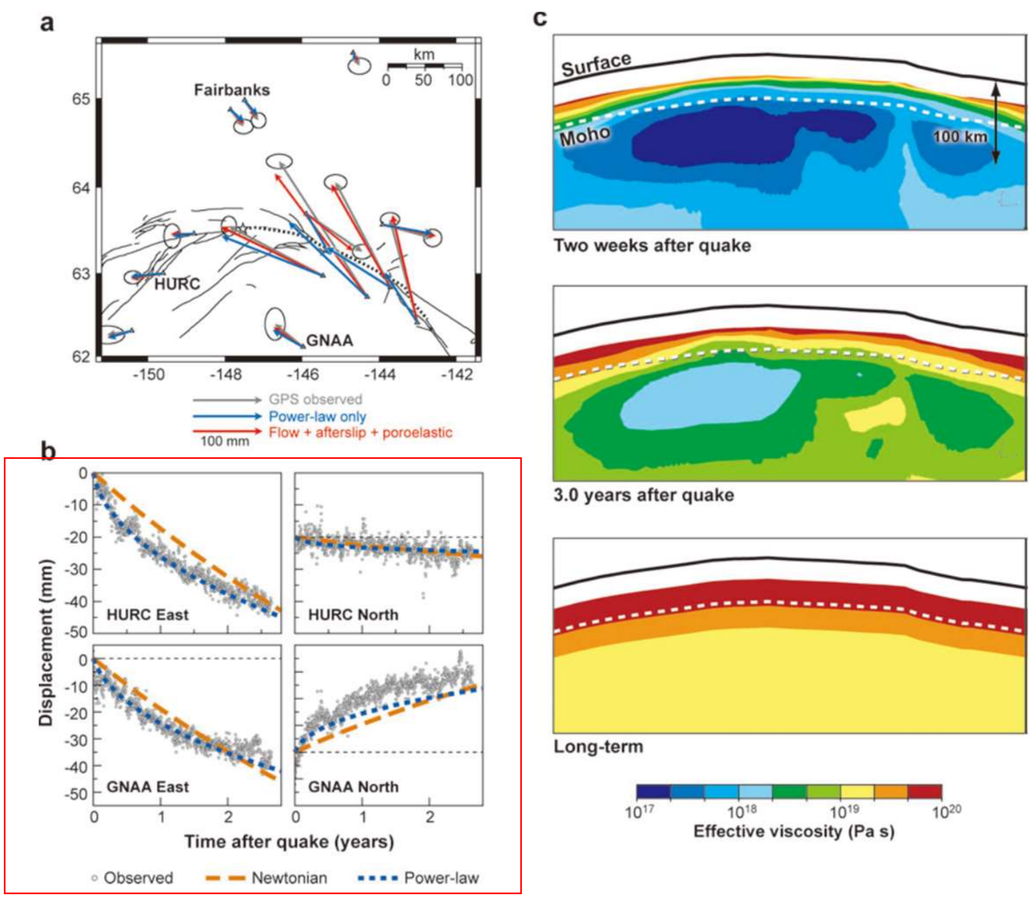




Deformation detection (horizontal and vertical) on continental scales by GPS.

InSAR can be used to detect subtle motion of fault zones or continental deformation, which could be as long as thousands of km crossing different tectonic regions or multiple countries, and we do not focus on man-made infrastructures, a city or a small mountain, such as that in geohazard fields, though we can deal with it with the same technology we used for crustal deformation detection. Due to small strains in the crust occurred as deep as tens-of-km, the subtle deformation at surface requires high precision method to detect.

1. InSAR on earthquake-related deformation detection, requirements and speciality

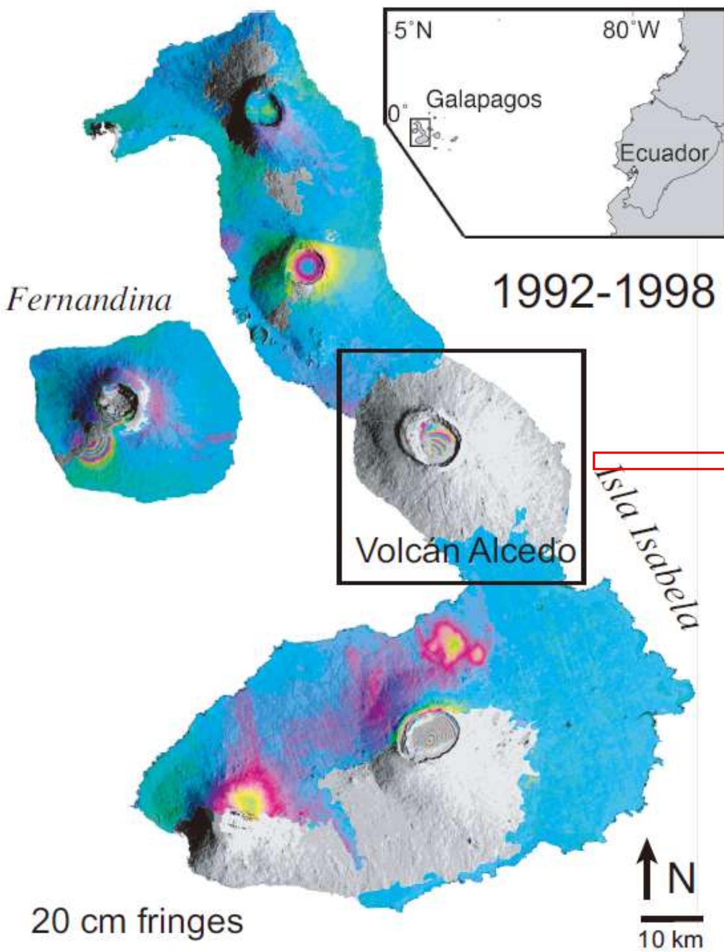


GPS data show that the postseismic deformation following large earthquakes are always nonlinear with time and heterogeneously distributed from crust to upper mantle. It is therefore inaccurate to use a prior formulation to describe the deformation process at the surface.

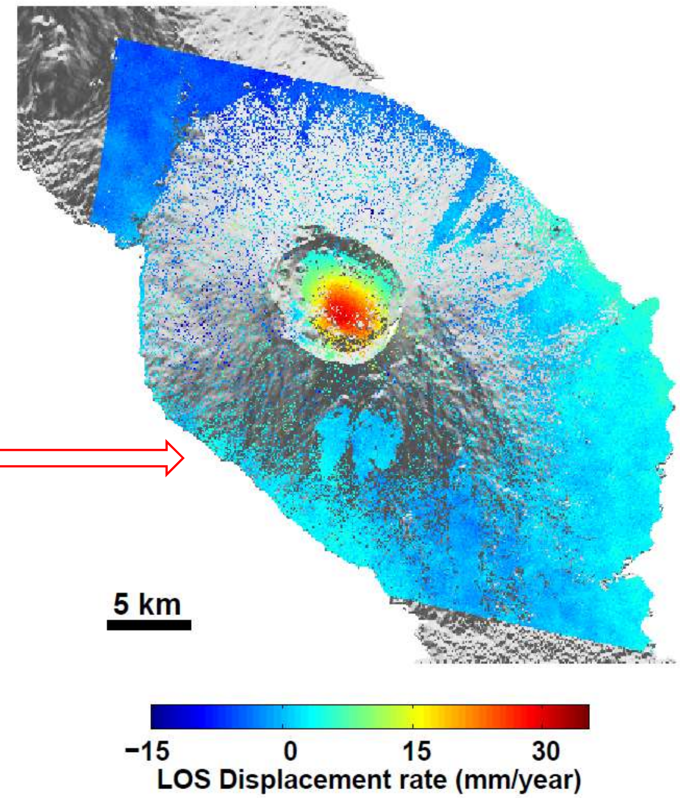
Observed and modeled cumulative surface displacements during 3 years following the 2002 Denali earthquake。

Burgmann & Dresen
Annu. Rev. Earth Planet. Sci. 2008.36:531-567.

1. InSAR on earthquake-related deformation detection, requirements and speciality



Amelung et al. ,2000



Hooper et al. ,2007

The deformation is difficulty to detect due to vegetation coverage and few man-made structures.

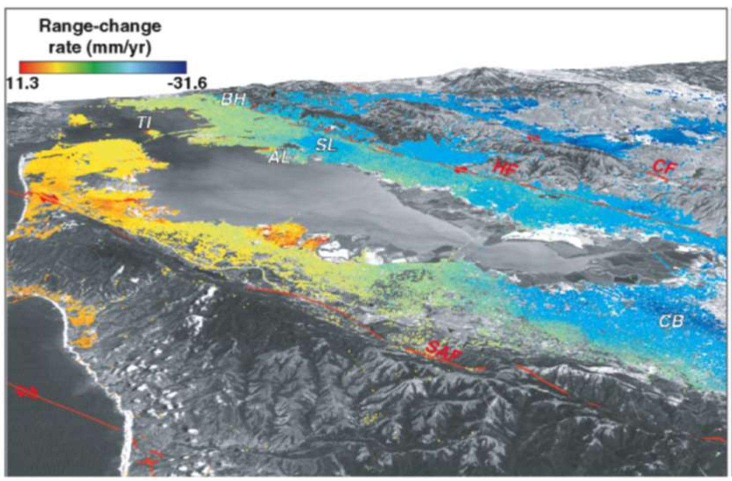
1. InSAR on earthquake-related deformation detection, requirements and speciality

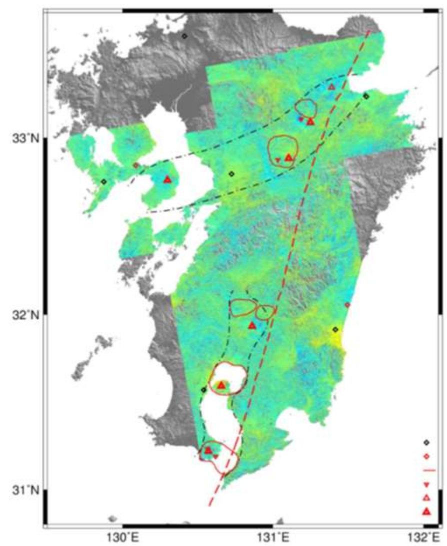
Summary:
For earthquake study, we want:

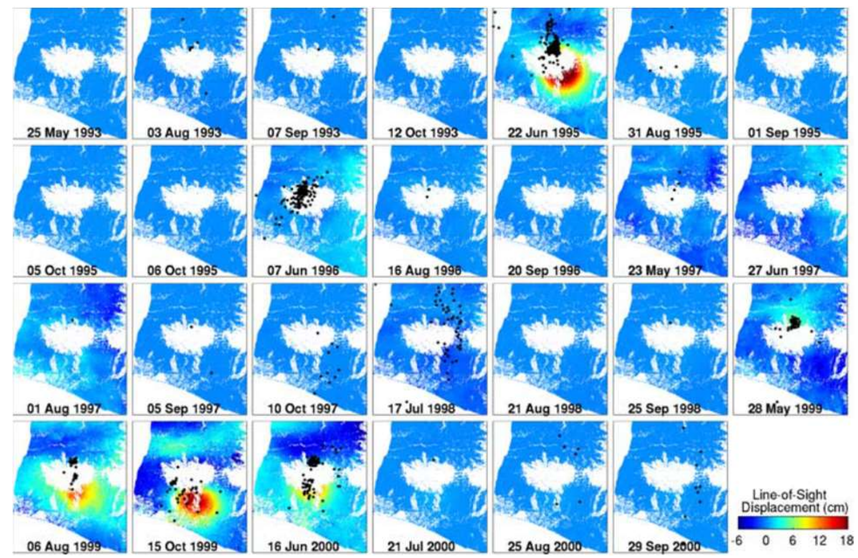
1) A method to detect deformation in a continental scale, because strain and stress accumulation is a long-term and subtle process, and it can distributed in a lager area across many fault zones, not only localized in one of them.
2) We need the method in high precision, so that we can detect possible motion in the lithosphere, especially the motion in the lower-crust or upper mantle. Moreover, we also want the method to analyze the non-steady motion, rather than only linear or simple nonlinear deformation close to the surface.
3) The method could be used to detect deformation in all kinds of environments, including big cities where many man-made structures exist, and also the rural regions with few man-made targets (such as Tibet), because earthquakes occur everywhere around the global, and it could have influences over both kinds of area even in one shock, such as the Wenchuan EQ in the Longmenshan area.
4) Finally, these requirements are special to earthquake and geophysical studies, which also covers normal applications, such as geohazard aspects. The only exception is that we do not need very high-resolution SAR data to detect very small targets, such as buildings or bridges. In addition, we don’t need meter level positioning in geocoding process as well.

2. The public approaches on high-precision crustal deformation analysis

1) Permanent Scatterer InSAR (PS-InSAR), optimized for isolated pixels
2) Small Baseline Subset InSAR (SBAS), optimized for distributed pixels
3) Combine PS+SBAS, or Distributed Scatterer InSAR, utilizing both point-like and distributed pixels





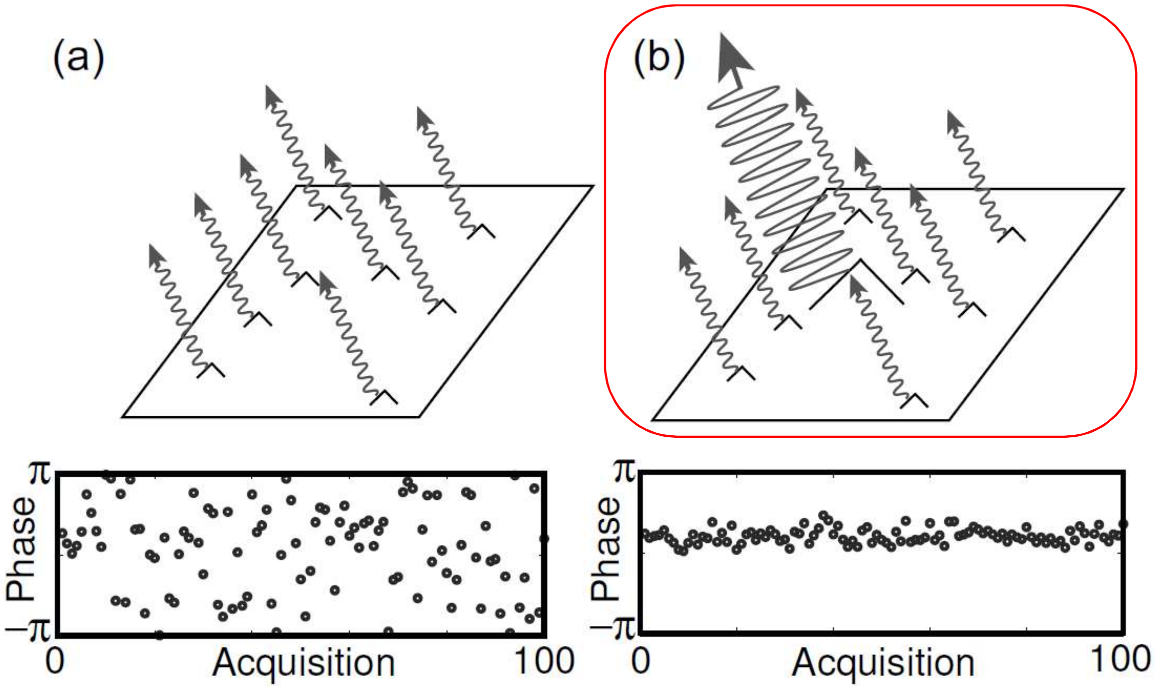


Ferretti et al, 2004

Zhang Yunjun et al, 2016

Hooper, 2008

2. The public approaches on high-precision crustal deformation analysis



Phase simulations for (a) a distributed scatterer pixel and (b) a persistent scatterer pixel

2. The public approaches on high-precision crustal deformation analysis

1) Methods (PS-InSAR) to identify and isolate these PS pixels in interferograms have been developed by several groups [*e.g., Ferretti et al., 2001; Crosetto et al., 2003; Lyons and Sandwell, 2003;Werner et al., 2003; Kampes, 2005*].

2) All of these methods use a functional model of how deformation varies with time to identify PS pixels. Once an initial set of amplitude stable pixels has been identified, each candidate pixel is tested for phase stability by examining its phase differences with nearby candidates. Only a pixel whose phase history is similar to the assumed model of deformation is deemed stable and not merely the result of random chance.

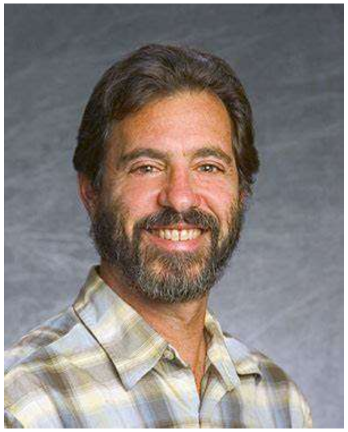
3) First, it can fail if the distance between neighboring PS pixels is too large, such that the contribution to the unmodeled phase from the difference in delay along the ray paths through the atmosphere exceeds the limit for reliable unwrapping. PS pixel density should exceed 3 to 4 per km^2.
It is not feasible for nature environment without many man-made structures.

4) The second limitation is that an approximate model for the temporal variation in deformation is needed to isolate the deformation signal from atmospheric, topographic and other phase errors.
Prior model is unknown for most of the geophysical problems.

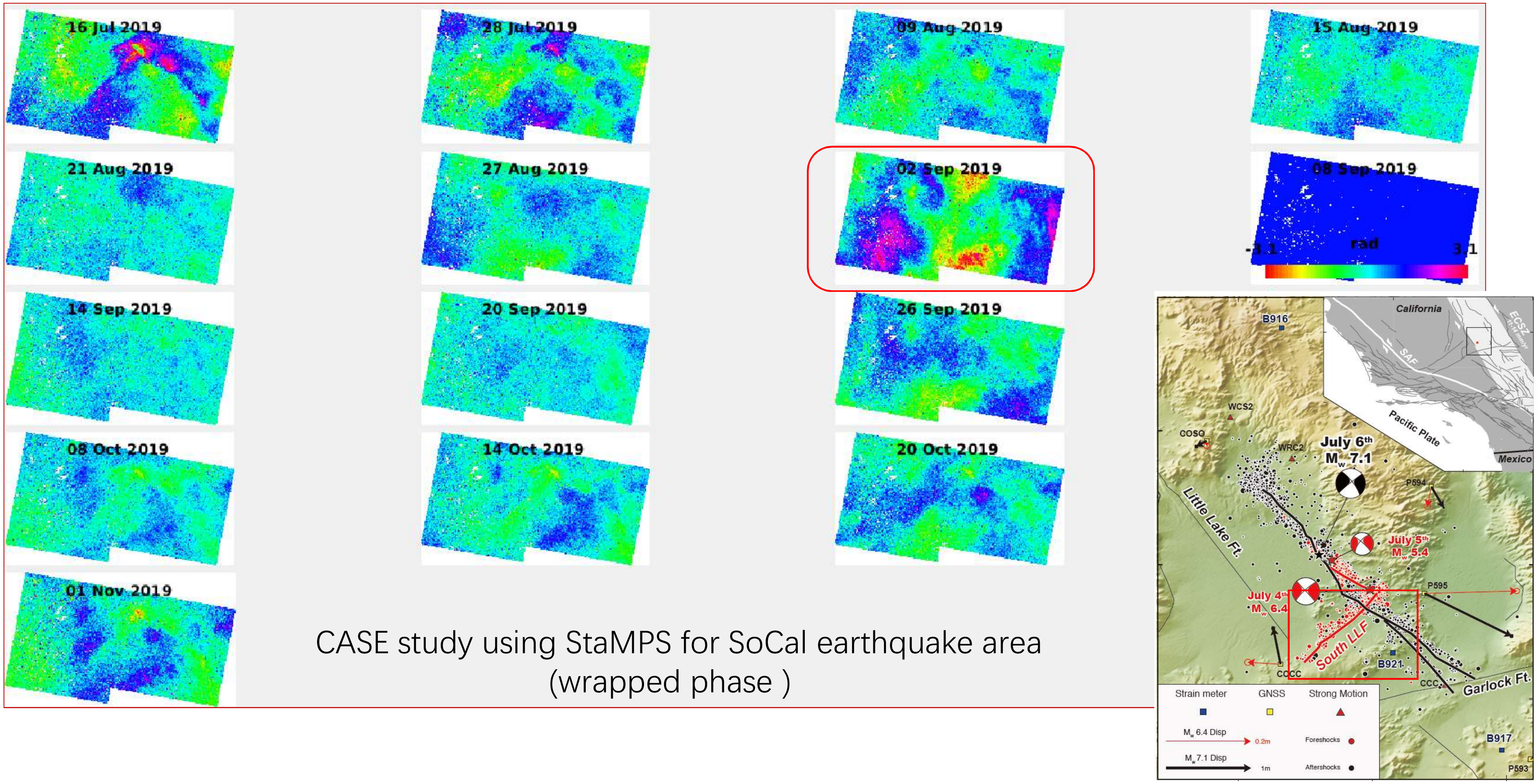
3. The Stanford Method for Persistent Scatterer analysis (StaMPS) and its usefulness on geophysical process detection from surface up to upper mantle.

1) StaMPS is developed by Hooper when he was at Stanford for PhD. with Prof. Howard Zebker (GRL, 2004). Then the method was updated in 2007 and 2008 (JGR and GRL papers). And now the software is in version 4.1 beta. It could be used for processing most of the free or commercial satellite data. Note that the conventional processing could be done with popular InSAR processors, such as SNAP, GMTSAR, ISCE, DORIS and GAMMA etc. StaMPS is based mainly on matlab scripts, and some c code for data conversion from conventional InSAR processing.

2) It overcomes main issues in previous PS-InSAR method by using spatial correlation for PS identification. Such as no prior deformation model is assumed. It can be used for rural regions for identifying many more PS points than previous methods. The 3D phase unwrapping is introduced for reliable deformation estimate. Therefore, it is better for geophysical studies than others.



3. The Stanford Method for Persistent Scatterer analysis (StaMPS) and its usefulness on geophysical process detection from surface down to upper mantle.



CASE study using StaMPS for SoCal earthquake area (wrapped phase)

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

The following staff is mainly from Hooper et al., 2007 JGR paper:

Four parts to StaMPS processing:

1. **Interferogram Formation**. There are aspects of interferogram formation for PS processing that differ to conventional interferogram Formation
2. **Phase Stability Estimation**. We make an initial selection of candidate pixels based on analysis of amplitude, and then use phase analysis to estimate the phase stability of these pixels in an iterative process.
3. **PS Selection**. We estimate for each pixel the probability it is a PS pixel based on a combination of amplitude and estimated phase stability. We then use the estimated probabilities to select PS pixels, rejecting those that appear to be persistent only in certain interferograms and those that appear to be dominated by scatterers in adjacent PS pixels.
4. **Displacement Estimation**. Once selected, we isolate the signal due to deformation in the PS pixels. This involves unwrapping the phase values and subtracting estimates of various nuisance terms.

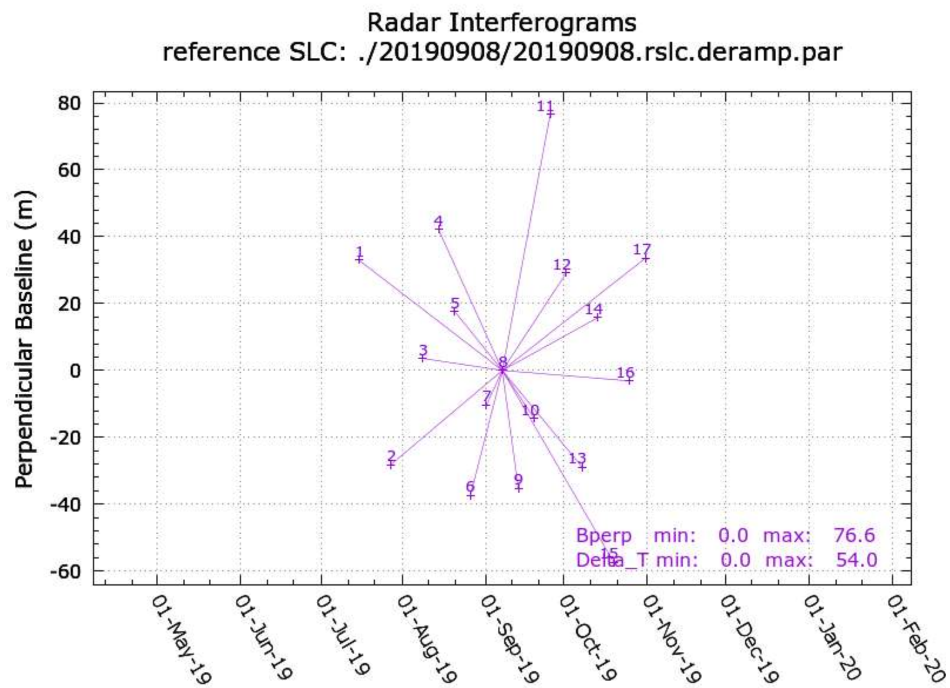
4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

Interferogram Formation:
using conventional InSAR processing software, but do not apply common spectral filtering in both range and azimuth directions, because the operations would coarsen the pixel resolution. Generally, the finer the resolution, the fewer scatterers will be contained within each resolution cell, and the greater the chance of the cell being dominated by one scatterer.

$$\begin{aligned}\rho_{total} &= \rho_{temporal} \cdot \rho_{spatial} \cdot \rho_{doppler} \cdot \rho_{thermal} \\ &\approx \left(1 - f\left(\frac{T}{T^c}\right)\right) \cdot \left(1 - f\left(\frac{B_\perp}{B_\perp^c}\right)\right) \\ &\quad \cdot \left(1 - f \cdot \left(\frac{F_{DC}}{F_{DC}^c}\right)\right) \cdot \rho_{thermal},\end{aligned}$$

where

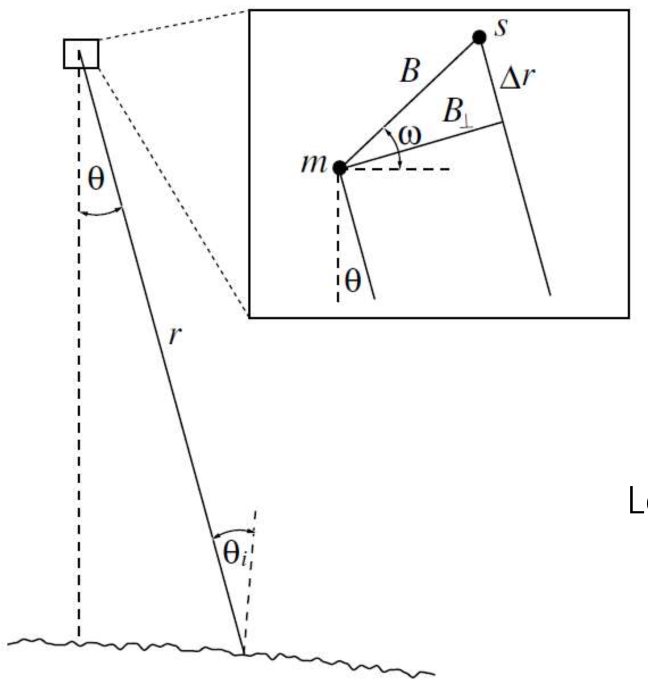
$$f(x) = \begin{cases} x, \text{for } x \le 1 \\ 1, \text{for } x > 1 \end{cases},$$



4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

Interferogram Formation:
important error sources for conventional InSAR after co-registration of SAR image stacks:

1) Look Angle Error, include DEM error and PS phase center error.
2) Squint Angle Error, small, due to no azimuth filter applied, this is treated as noise.



$$\Delta\theta = \frac{\Delta h \, sin(\theta_i) + \xi \, cos(\theta_i)}{r},$$

$$\Delta\phi_\theta \approx \frac{4\pi}{\lambda} Bcos(\theta - \omega)\Delta\theta = \frac{4\pi}{\lambda} B_\perp(\theta)\Delta\theta,$$

Look Angle error could be **spatial correlated** or **spatial uncorrelated**.

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

Phase Stability Estimation: for temporal coherence estimate of pixels and looking for stable targets (PS)

1) Amplitude Analysis to reduce initial point numbers

The amplitude dispersion index: a high value of 0.4 for including most of the potential points.

Ratio of standard deviation and mean of amplitude value: $$D_{\mathcal{A}} \equiv \frac{\sigma_{\mathcal{A}}}{\mu_{\mathcal{A}}},$$

2) Phase Analysis: for the *x-th* pixel in *i-th* interferogram (ellipsoid flattened and topographic corrected):

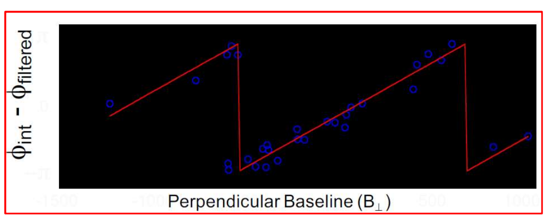
$$\psi_{x,i} = W\{\phi_{D,x,i} + \phi_{A,x,i} + \Delta\phi_{S,x,i} + \Delta\phi_{\theta,x,i} + \phi_{N,x,i}\}, (10)$$

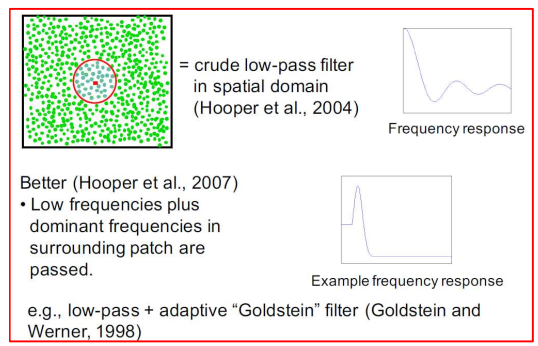
wrapped = disp. + atmospheric + residual orbit + look angle error + ***noise***

We seek stable points where the noise phase is small enough and does not obscure signals we extract.

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

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





4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

Phase Stability Estimation:
For those initial points selected using amplitude dispersion index, we have temporal coherence estimate using the following formula Gamma-x:

$$W\{\psi_{x,i} - \widetilde{\psi}_{x,i} - \Delta\widehat{\phi}^{u}_{\theta,x,i}\} = W\{\phi^{u}_{N,x,i} + \delta'_{x,i}\}, \quad (19)$$

where $\delta'_{x,i} = \delta_{x,i} + \Delta\phi^{u}_{\theta,x,i} - \Delta\widehat{\phi}^{u}_{\theta,x,i}$.
We define a measure of the variation of this residual phase for a pixel as

$$\gamma_x = \frac{1}{N}\left|\sum_{i=1}^{N} \exp\{\sqrt{-1}(\psi_{x,i} - \widetilde{\psi}_{x,i} - \Delta\widehat{\phi}^{u}_{\theta,x,i})\}\right|, \quad (20)$$

PS Selection: now we select PS in probabilistic way considering both amplitude and phase stability (see appendix B and C in Hooper et al., 2007 JGR paper)

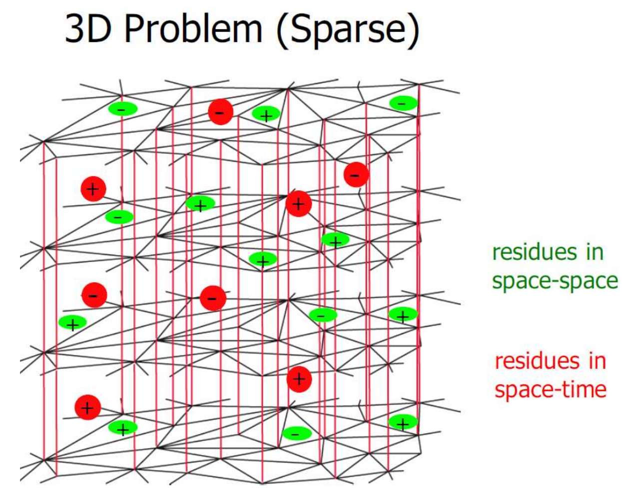
$$P(x \in A) = 1 - \frac{(1-\alpha)p_B(\gamma_x)}{p(\gamma_x)}.$$

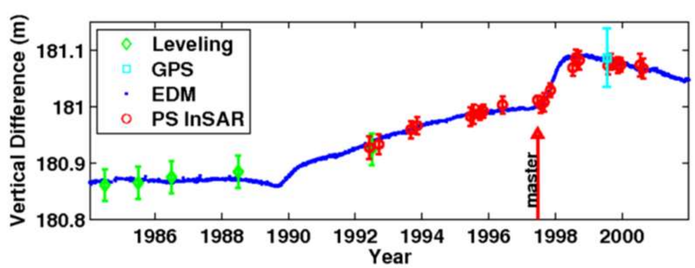
4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

Displacement Estimation:
3D phase unwrapping and spatial correlated nuisance terms removal:

1) 3D phase unwr apping works on time-series data, similar to snaphu in 2D. It is in automatic way, but need to carefully check phase jumps yourself in the processing.

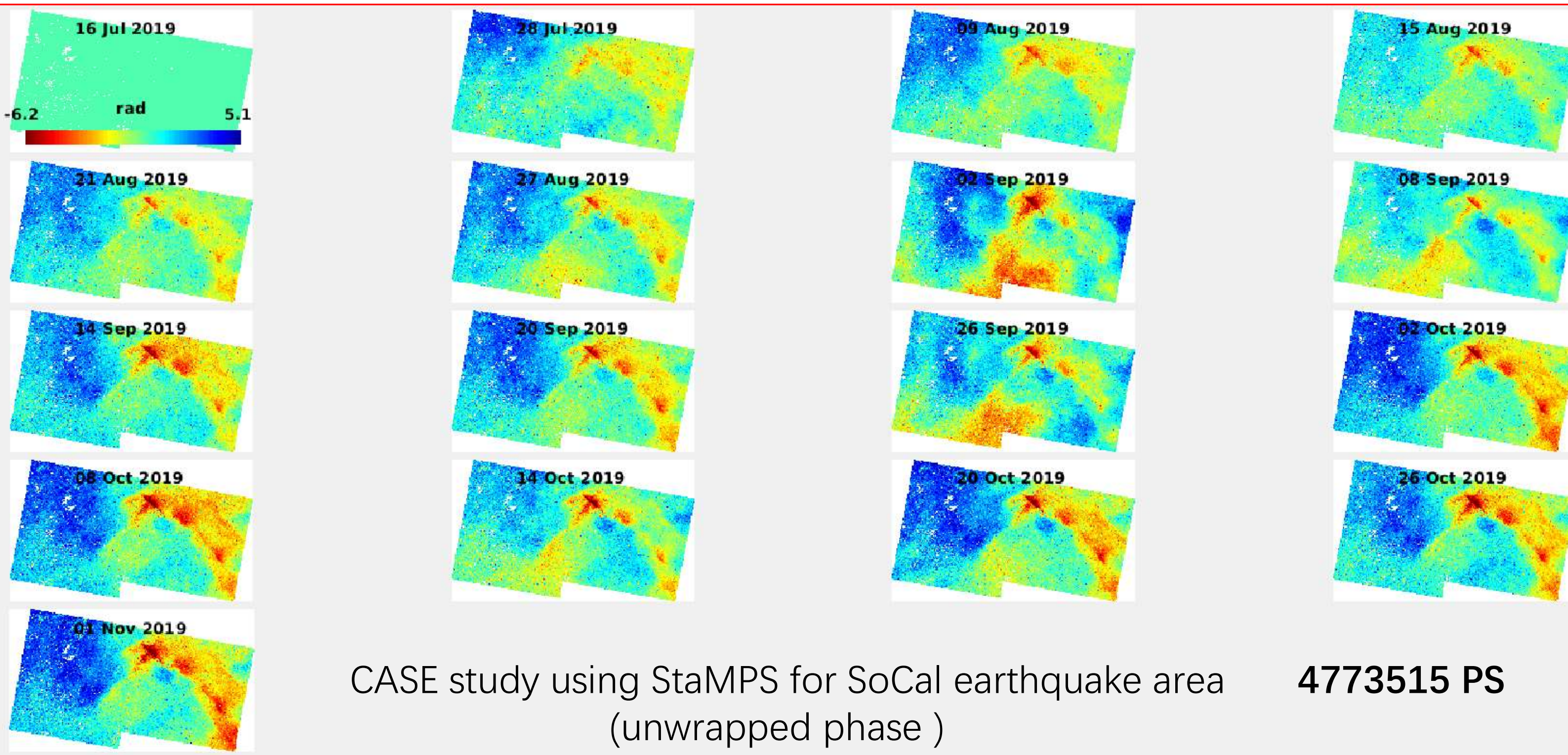
2) Filtering in time and space, and estimate of atmospheric and orbit errors subtracted, leaving deformation estimate (**not necessarily linear**).
A number of ways to deal with the atmospheric delays, typically we use ECMWF ERA5 models (weather forecast model in Europe).





Hooper et al., 2004

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

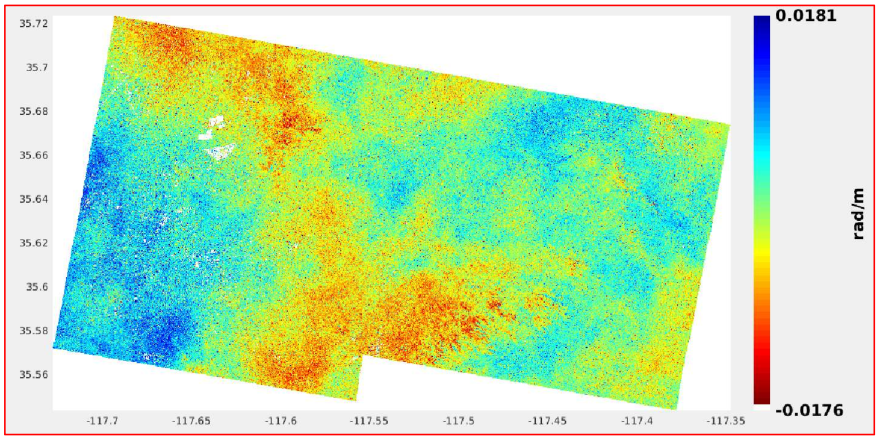


CASE study using StaMPS for SoCal earthquake area (unwrapped phase)

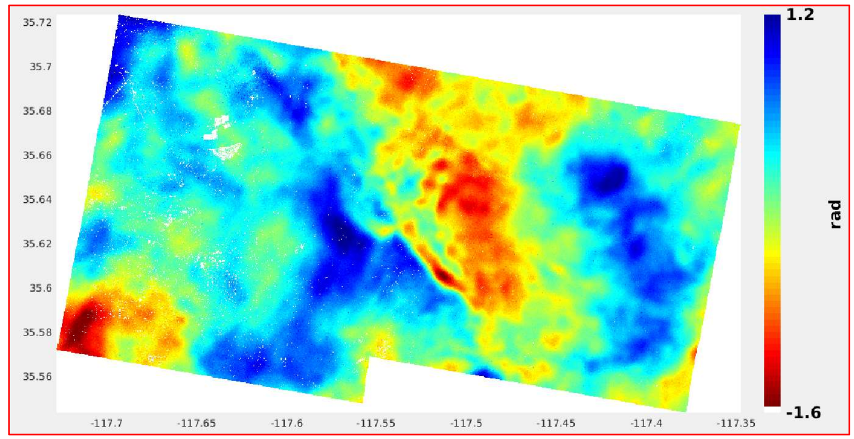
4773515 PS

Using ps_plot('u',1,[],1[])

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

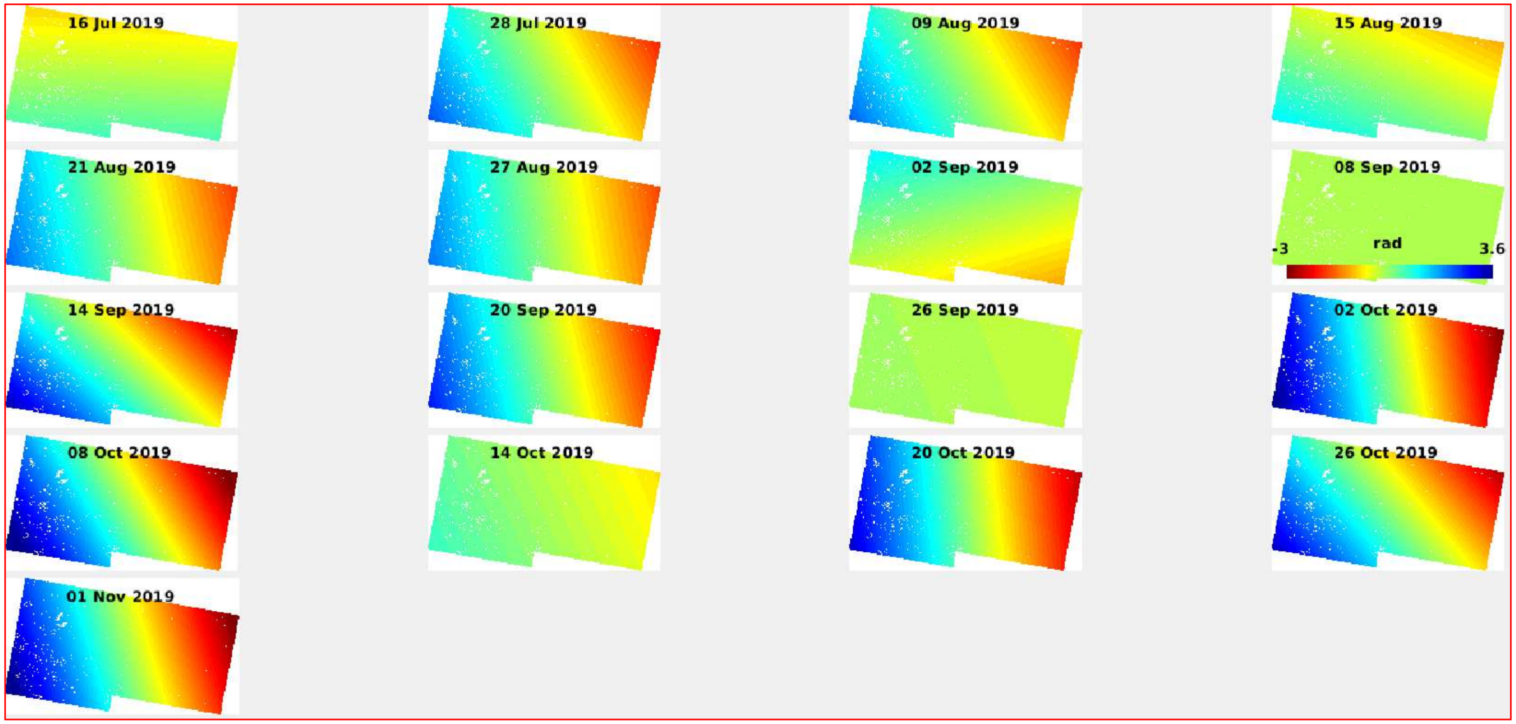


Using ps_plot('d')



Using ps_plot('m')

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)



Using ps_plot('o')   ax+by+c=0

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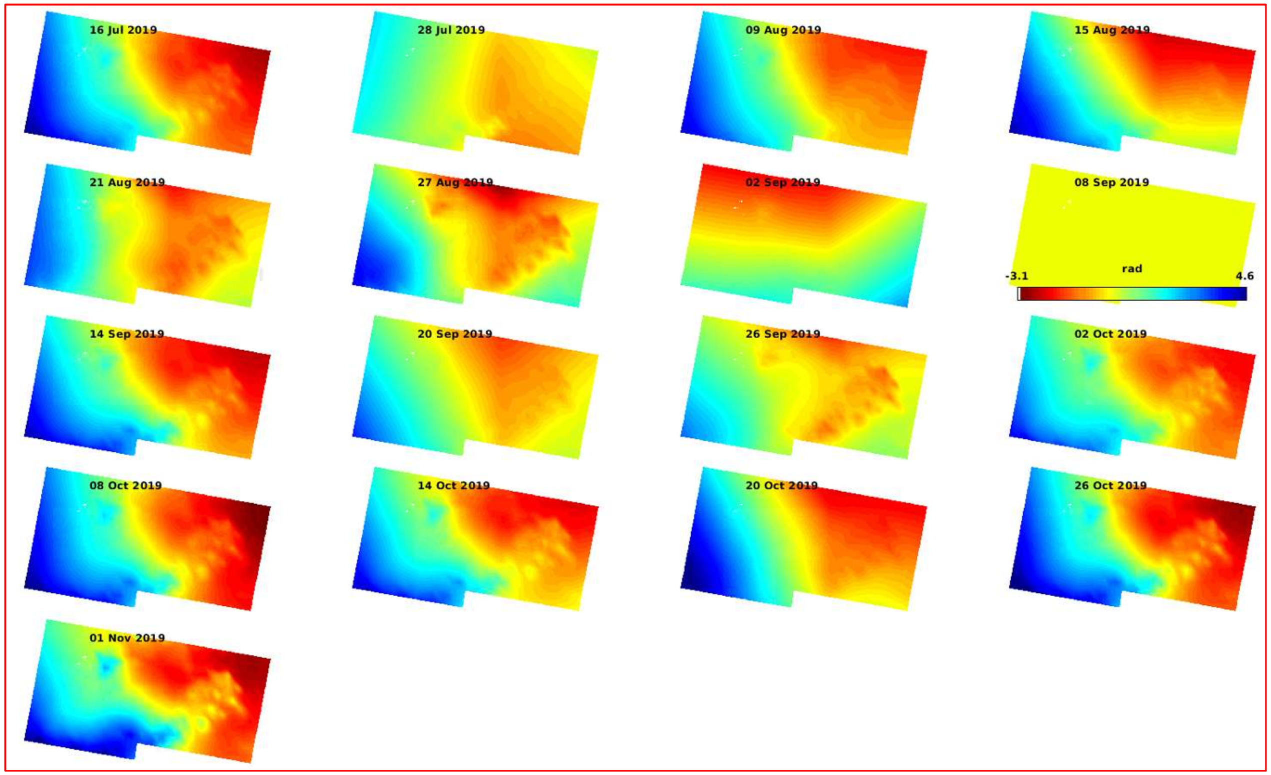
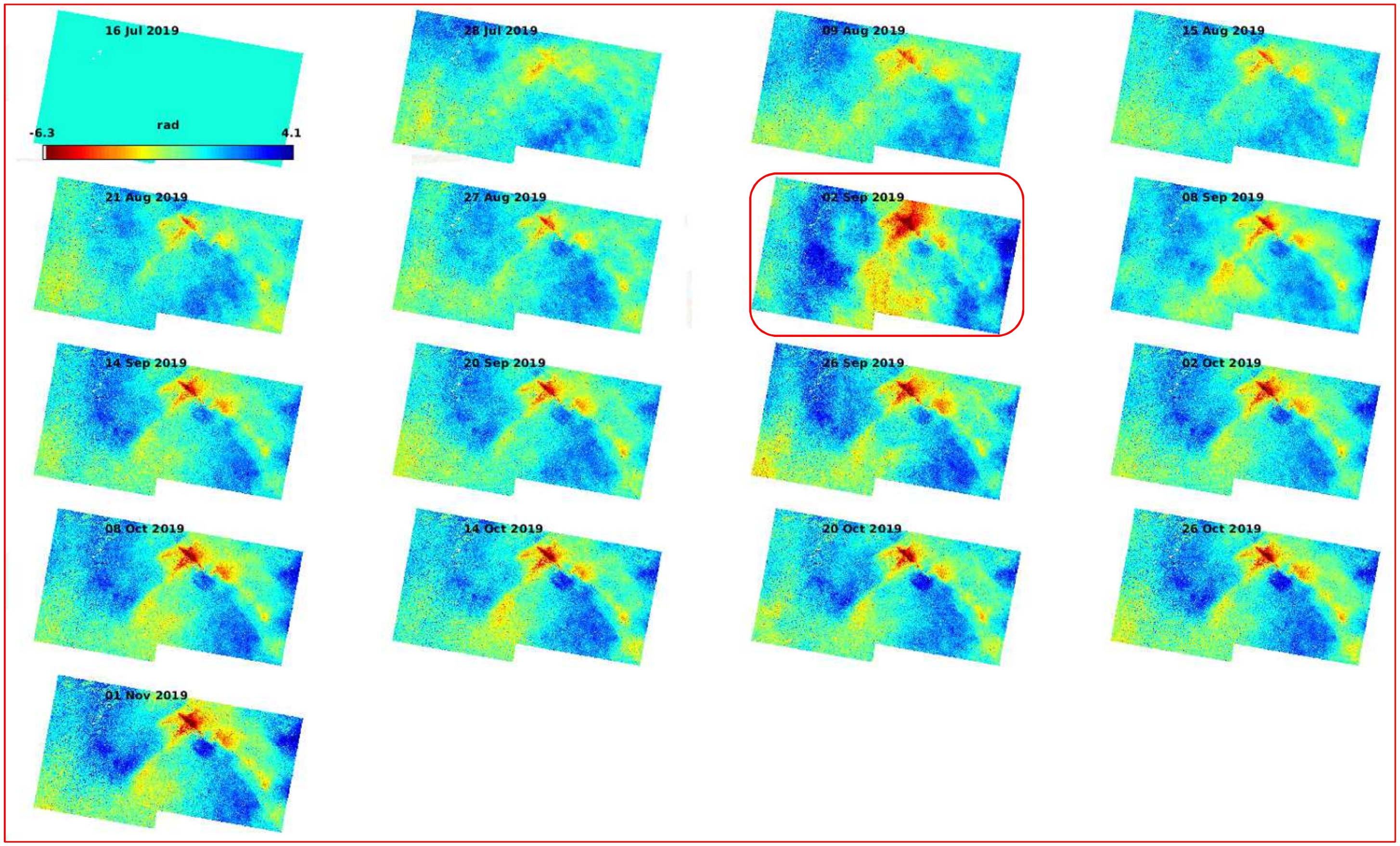


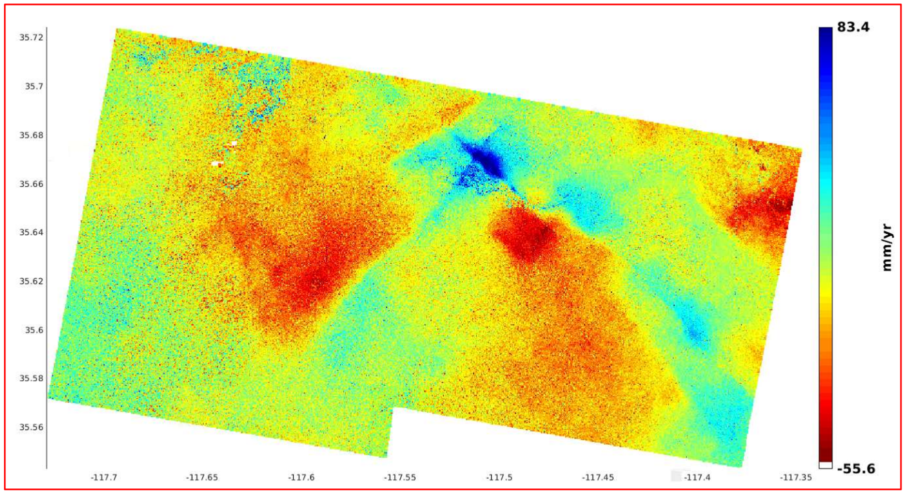
Using ps_plot('a','a_era5')

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

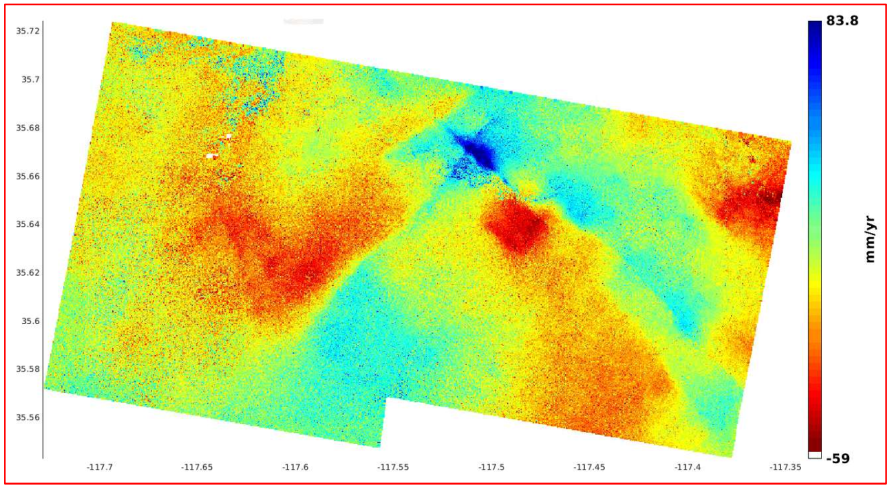


Using ps_plot('u-dao','a_era5', 1,[], 1,[])

4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)

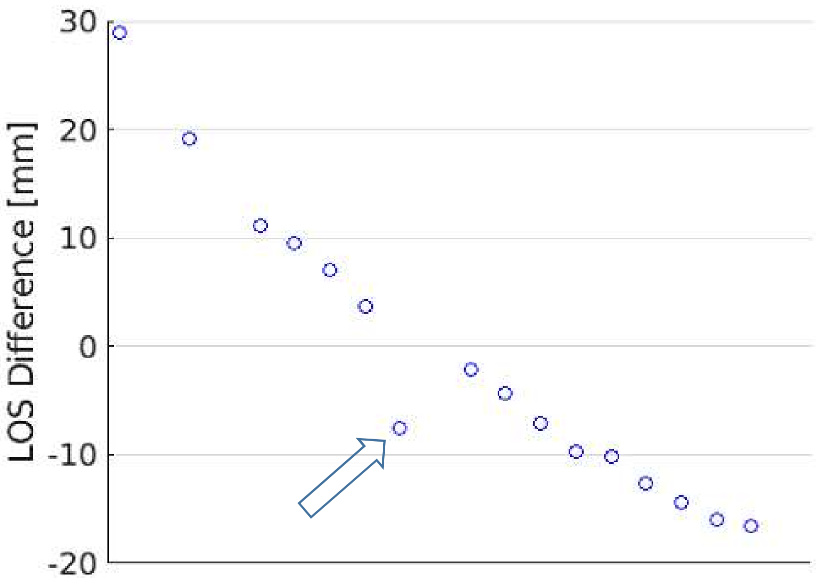


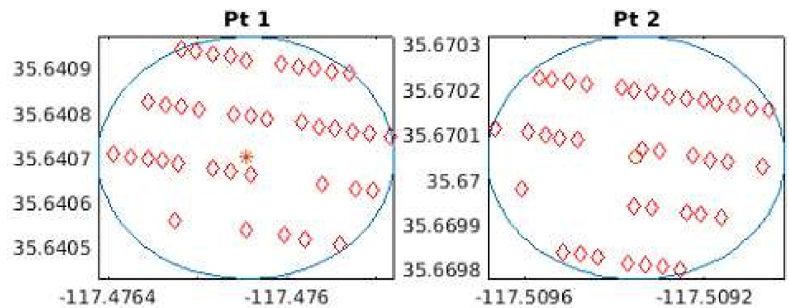
Using ps_plot('v-do')



Using ps_plot('v-dao','a_era5')

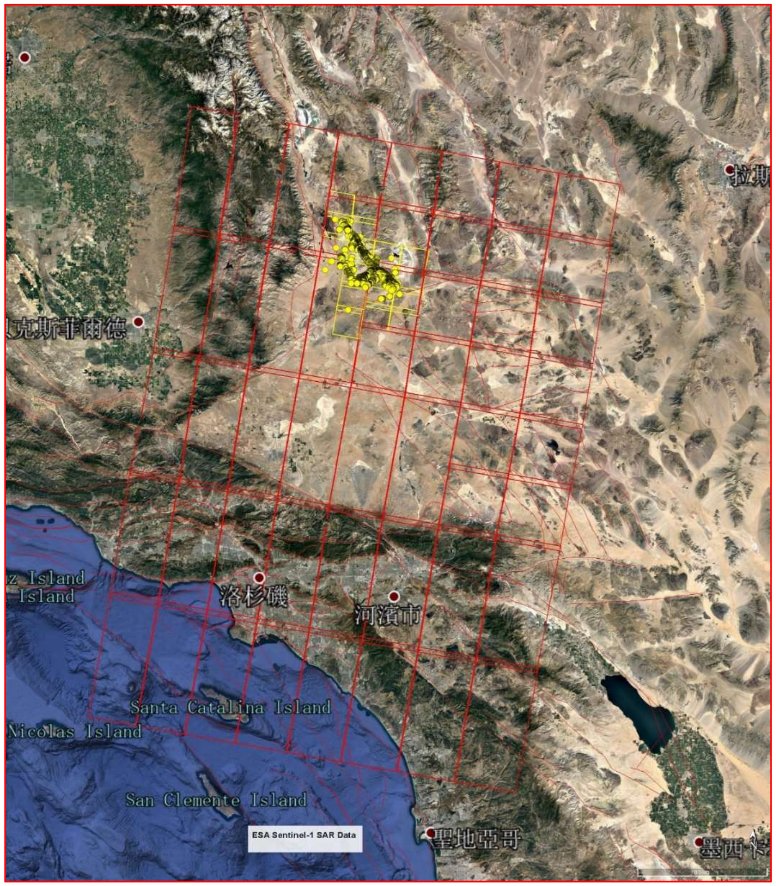
4. The underlay algorithms/equations to derive geophysical signals from InSAR time-series data, and what we will address today (PS)





ps_plot('v-dao','a_era5','ts')

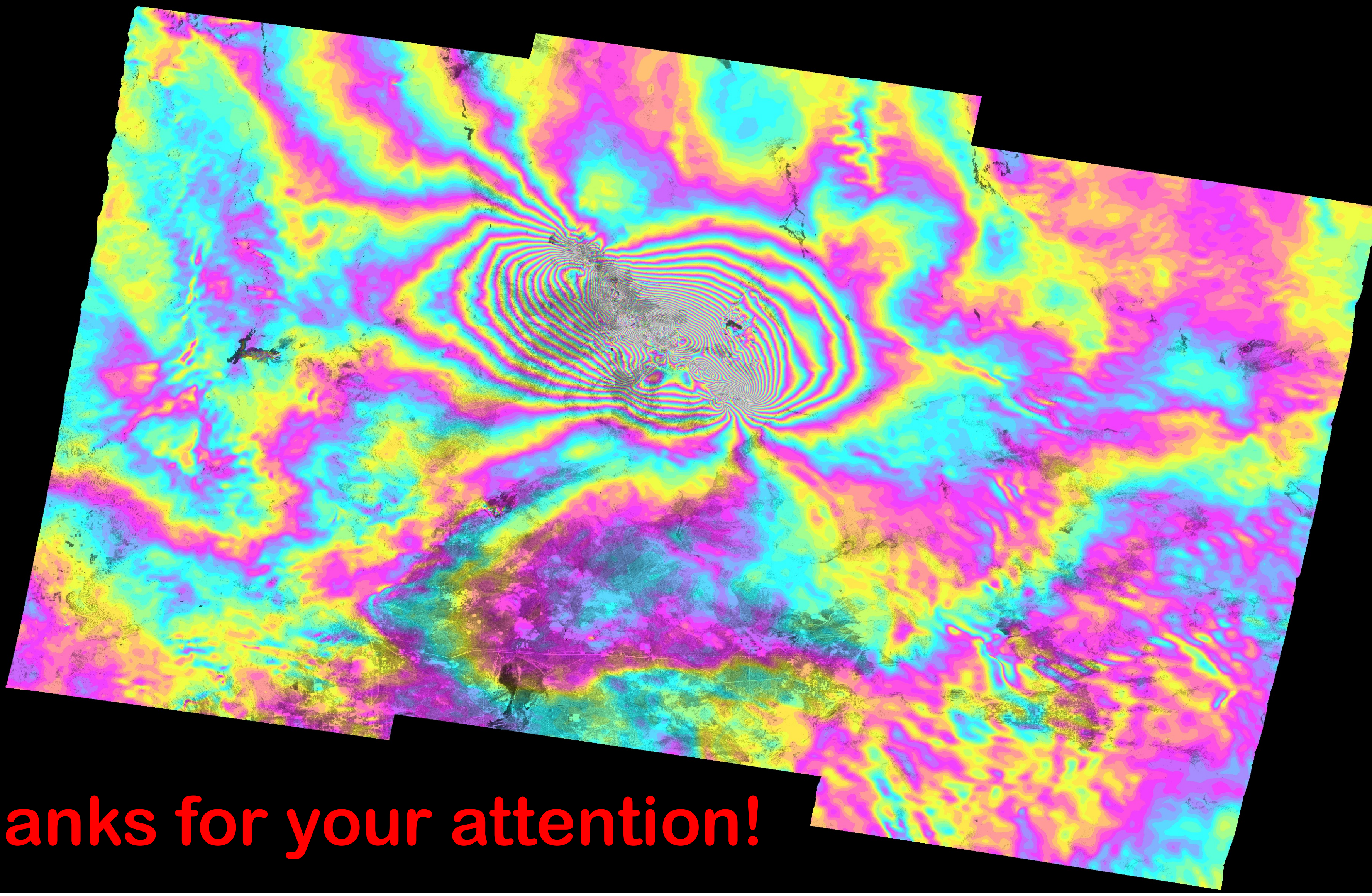
5. What we do to further push forward the method in earthquake and geophysical studies



1) With the huge amount of SAR data acquired by Sentinel-1 and other satellites in the future, such as Chinese missions, US NISAR mission, the data processing requires a large scale storage and computation capabilities. We developed parallel systems for InSAR time-series data processing based on Taihu Sunway Light system. The basic idea is to use a flexible patching scheme and do the processing using StaMPS on multiple nodes and multiple CPU cores.

2) We also do the conventional processing on a similar system, and mainly on SAR data co-registration in parallel.

3) We now use the ECMWF ERA5 model to estimate and mitigate the atmosphere noise in the InSAR time-series data, and also working on a processing strategy using split-spectrum method for L-band data ionosphere corrections.



Thanks for your attention!