Consensus InSAR Time Series and Velocity Model for Southern California

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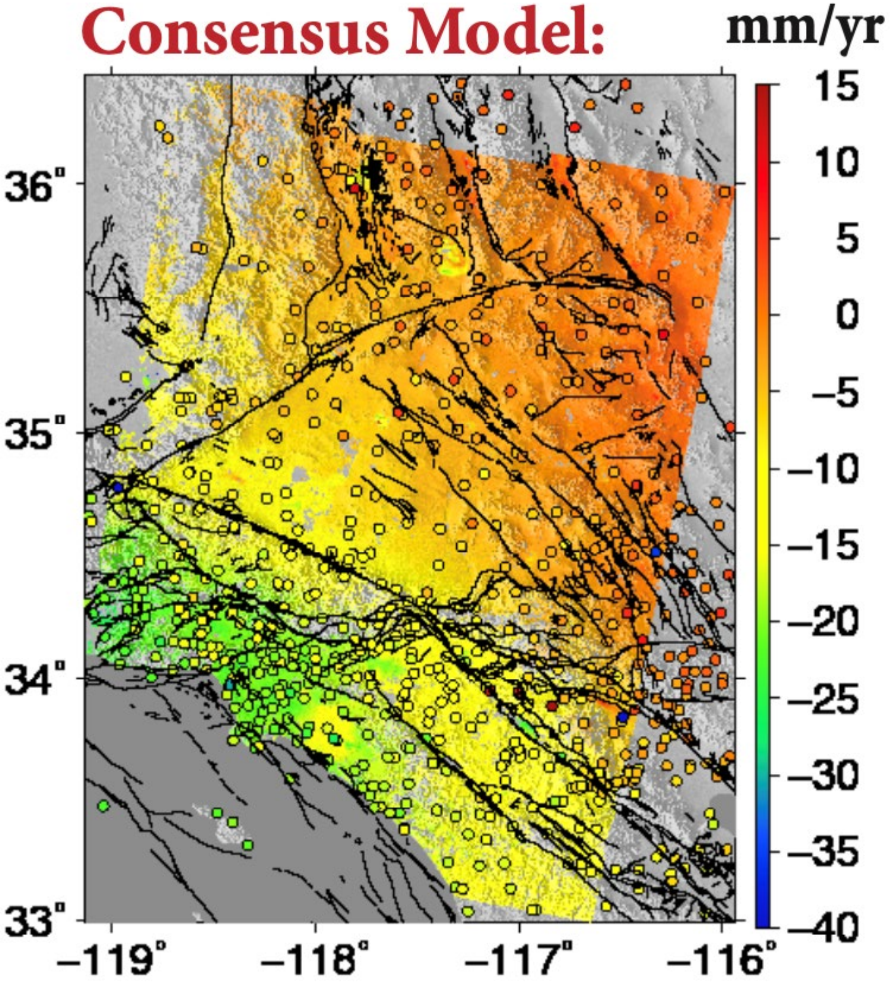
Introduction and Motivation

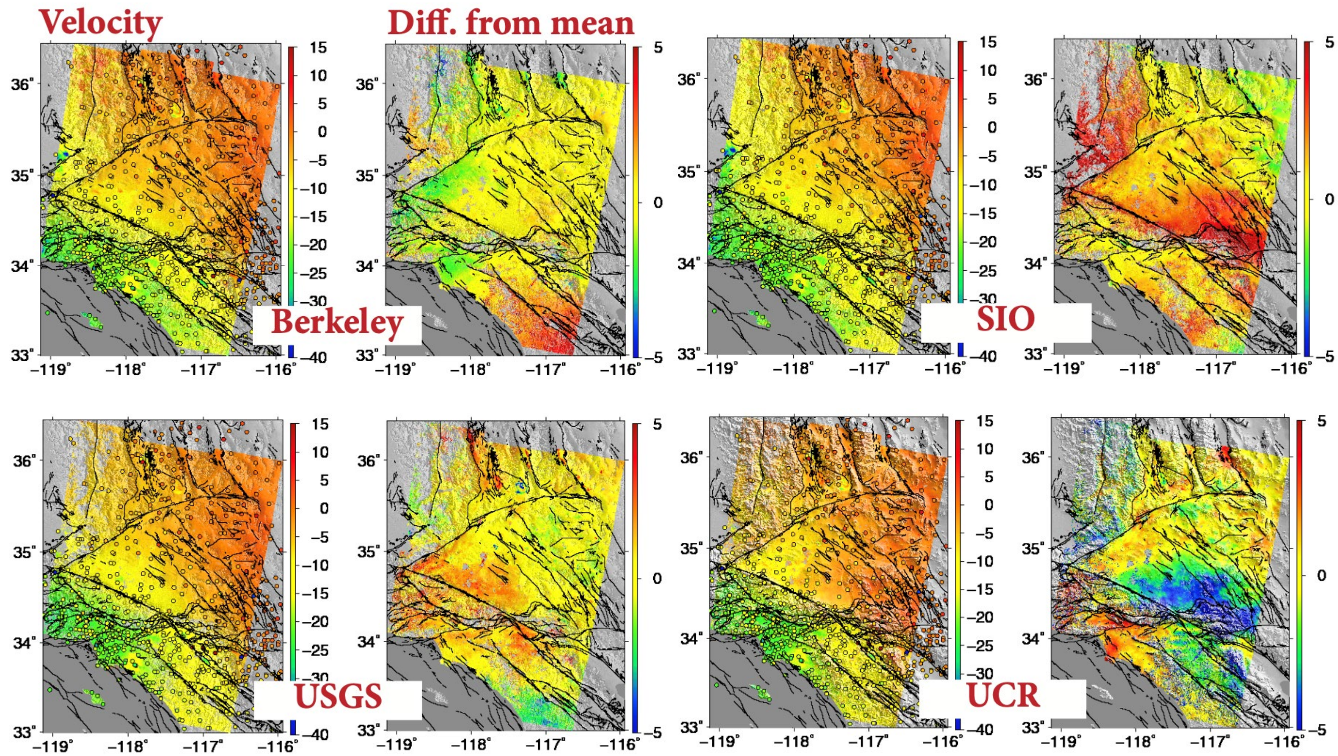
- Our goals:
  - To provide a set of **self-consistent and well documented products** (deformation time series and velocities) over *[Southern]* California.
  - To compare different existing methods of InSAR processing, post-processing, and error correction
  - To explore new approaches and best practices for InSAR processing and interpretation
- We began as part of SCEC Community Geodetic Model.
  - Preliminary result, on the right: one frame of the descending Sentinel-1 track 71 over Southern California, obtained from the combination of the results from 5 different research groups.

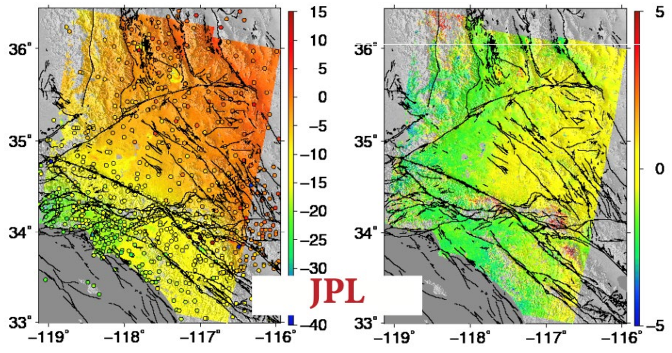
How it started…



Participating groups and methods

	BKLY	USGS	JPL1	SIOX	UCRV
Coregistered stack	●	●	●	●	●
GMTSAR	●	●		●	●
ISCE			●		
ESD correction			●		
DEM error correction			●	●	
Topo-correlated atm. removed			●	●	
Weather model removed (ERA5)	●				
CANDIS correction	●			●	
Coherence-based SBAS				●	
GPS correction				●	
Spatiotemporal smoothing		●	●	●	
Phase closure masking			●	●	●

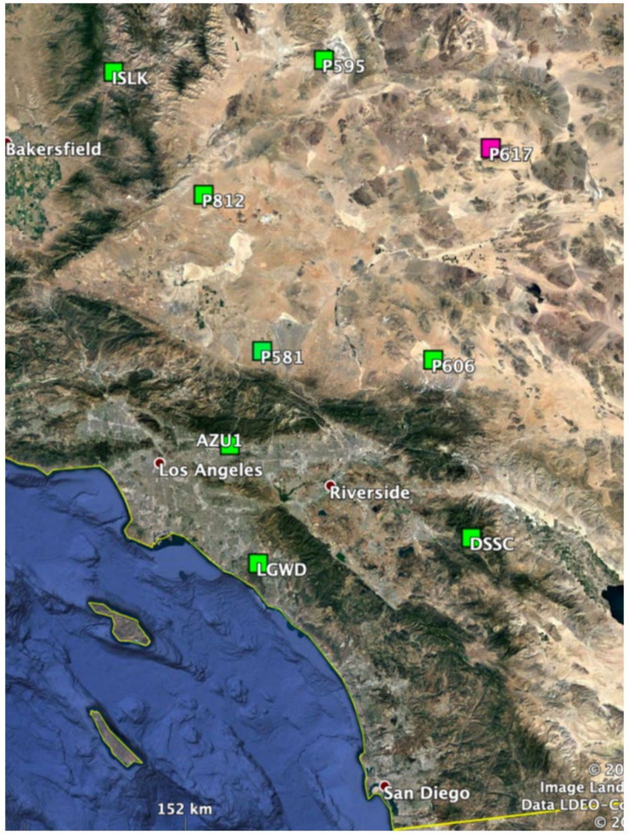




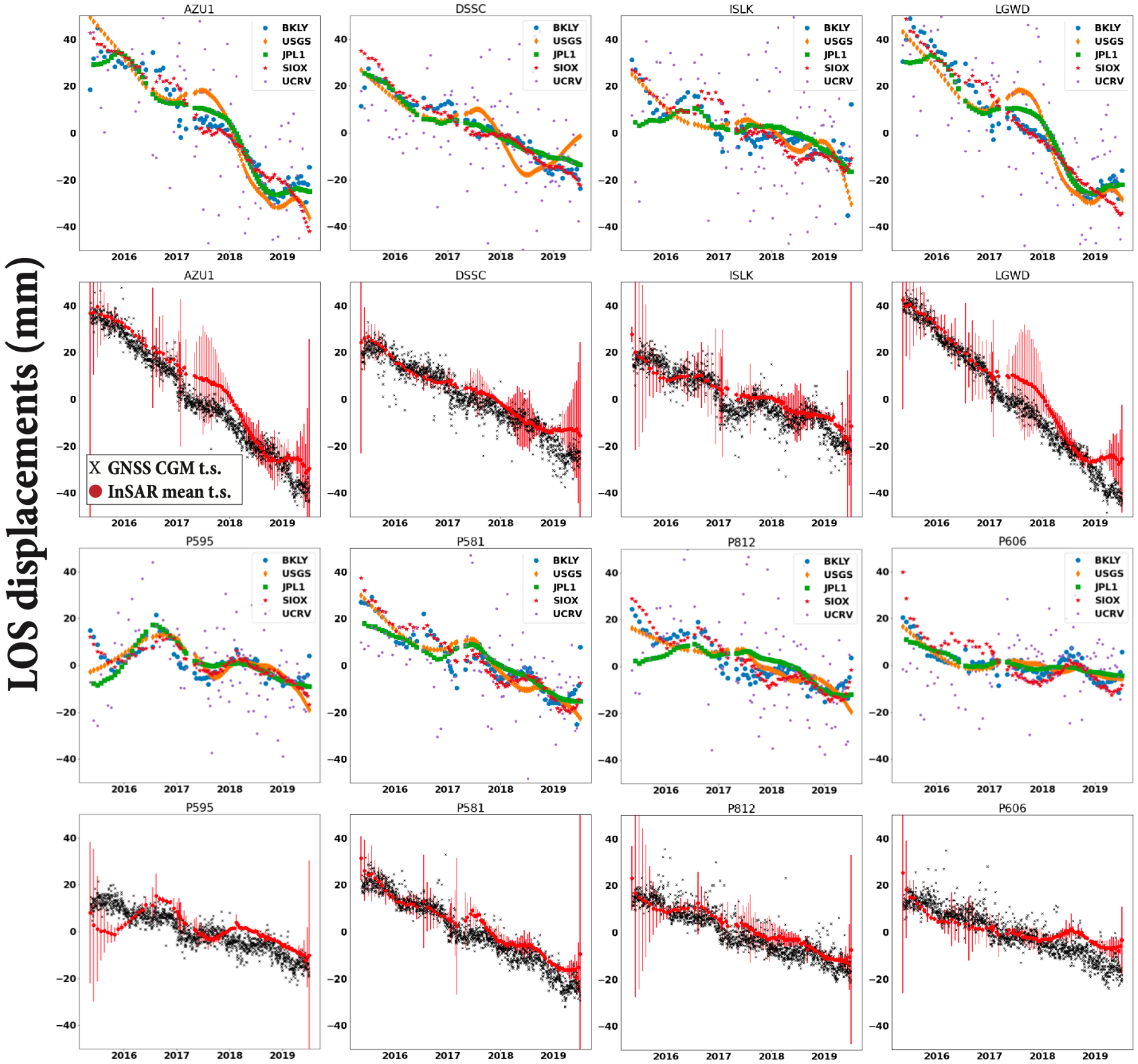
- **Topo-correlated atmosphere removal**
  pros: can remove time-correlated atmosphere
  cons: can sometimes remove deformation signals
- **Weather model corrections**
  pros: corrects for seasonal tropospheric contribution using auxiliary data
  cons: models may lack coverage or resolution
- **CANDIS correction**
  pros: reduces turbulent tropospheric contribution
  cons: may smooth some time-dependent signals.
- **GPS correction**
  pros: helps correct InSAR errors at long spatial wavelengths
  cons: solution is poorly constrained in areas of poor GNSS coverage and at image edges
- **Spatiotemporal filtering**
  pros: removes turbulent atmospheric noise
  cons: requires prior knowledge of noise characteristics

Validation against GNSS

Collation and averaging of InSAR solutions processed by the SCEC CGM (InSAR) Working Group help to reduce systematic biases, missing data or other inaccuracies due to any single strategy.

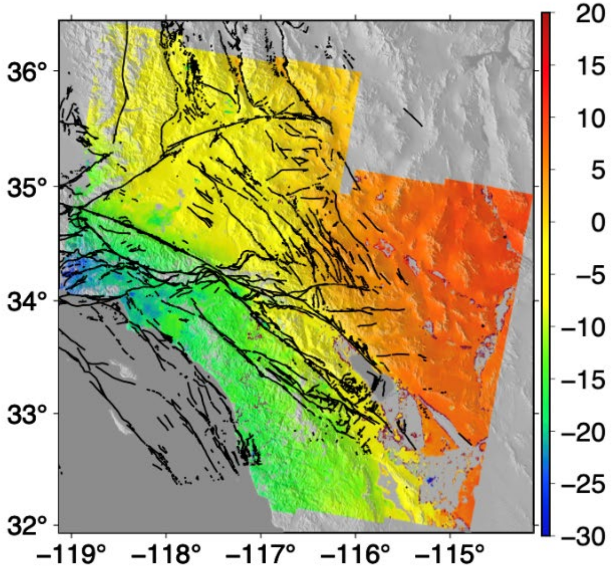


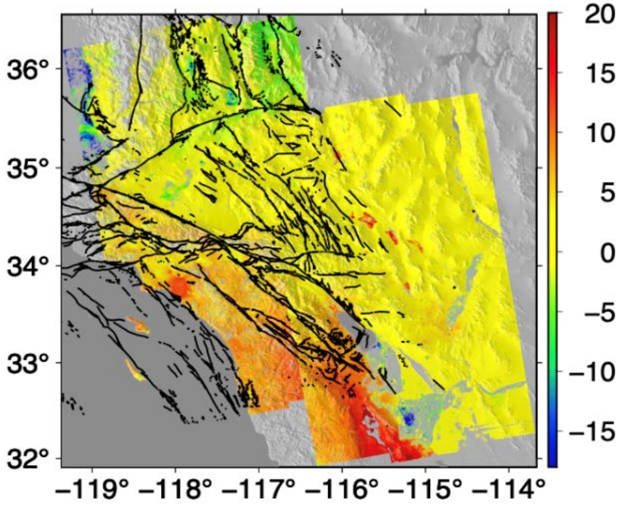
- 1st and 3rd row: comparison of the time series from individual groups to each other
- 2nd and 4th row: comparison of the combined model (red) against GNSS
- On the left: map of the study area with test GNSS stations marked in green and reference station in magenta

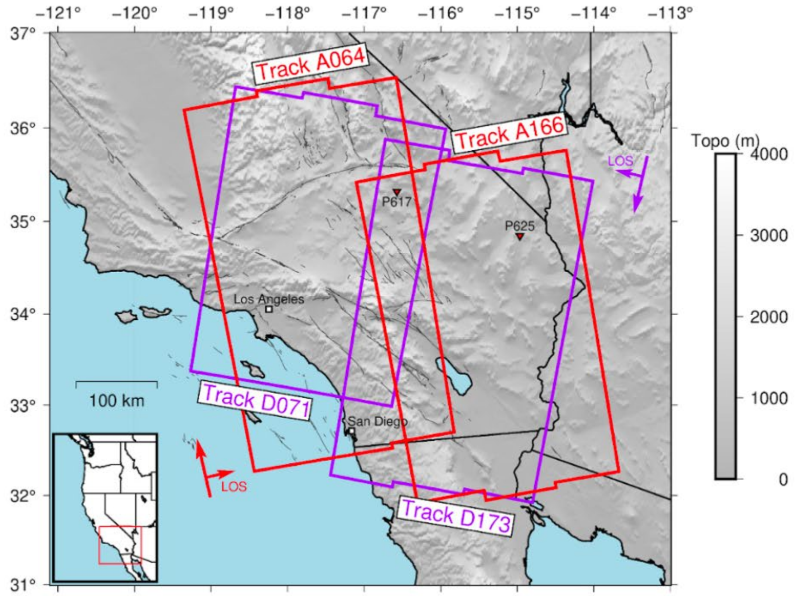


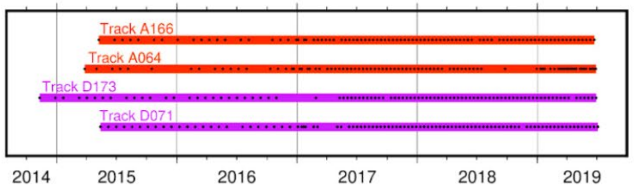
Current consensus model

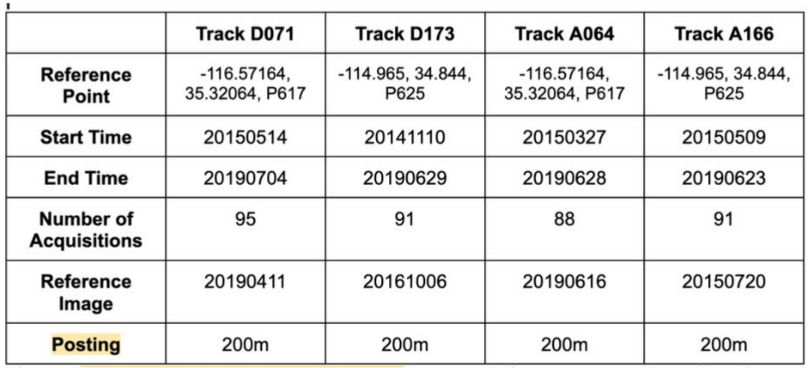
How it’s going:







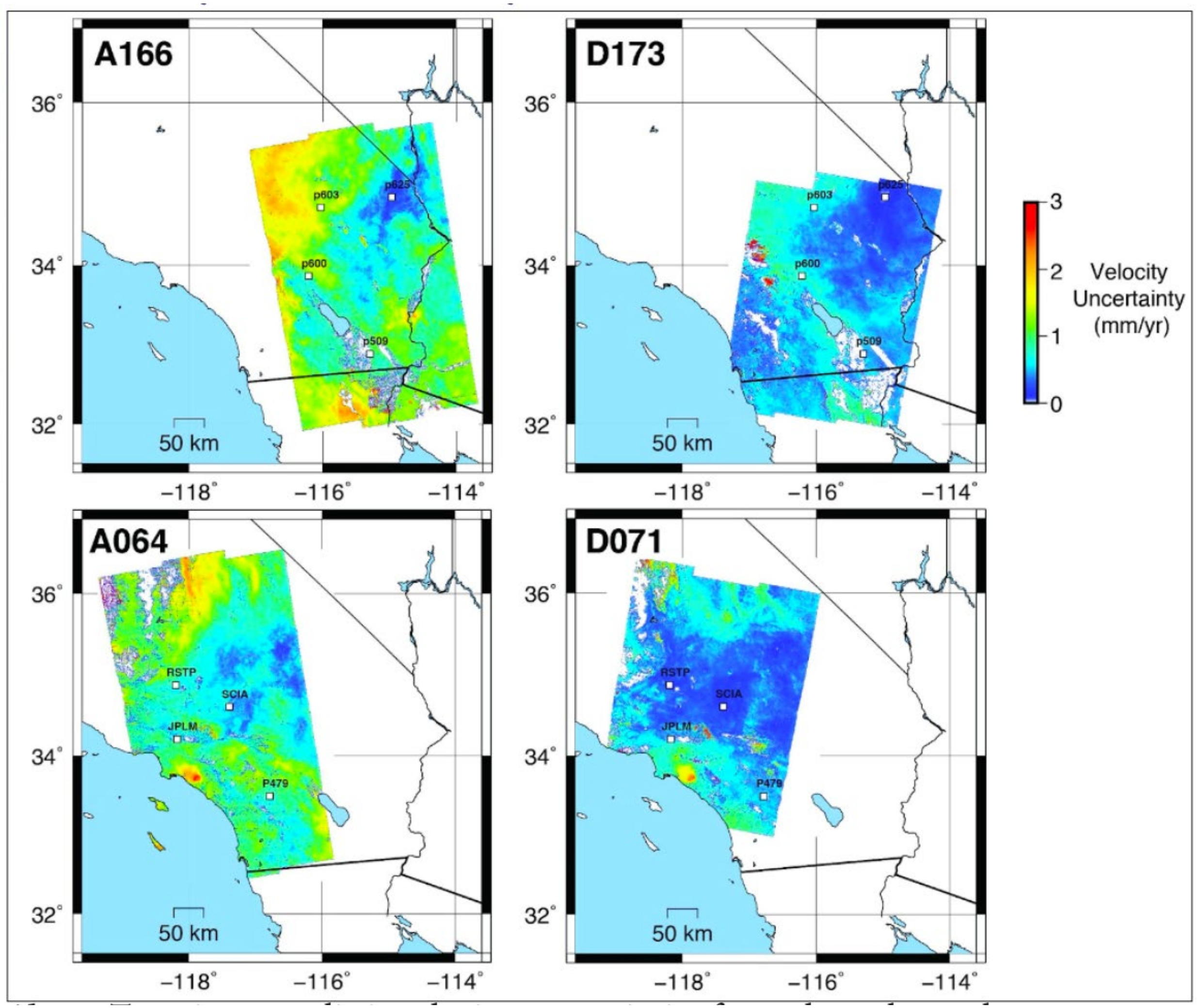




	Track D071	Track D173	Track A064	Track A166
Reference Point	-116.57164, 35.32064, P617	-114.965, 34.844, P625	-116.57164, 35.32064, P617	-114.965, 34.844, P625
Start Time	20150514	20141110	20150327	20150509
End Time	20190704	20190629	20190628	20190623
Number of Acquisitions	95	91	88	91
Reference Image	20190411	20161006	20190616	20150720
Posting	200m	200m	200m	200m

- Line-of-sight time series and velocities from 4 overlapping ascending and descending Sentinel tracks, from ~2015 until 2019, just before the Ridgecrest earthquake sequence
- The overall processing parameters for each track, common for each processing center, are shown in the table on the left.
- For all five solutions, interferograms were produced with either GMTSAR (Sandwell et al., 2011) or ISCE software (Rosen et al., 2012), or with ARIA standard products (Bekaert et al., 2019). The choice of software for producing interferograms has been shown to have little impact on the results

Challenges and best practices: Calculating uncertainties



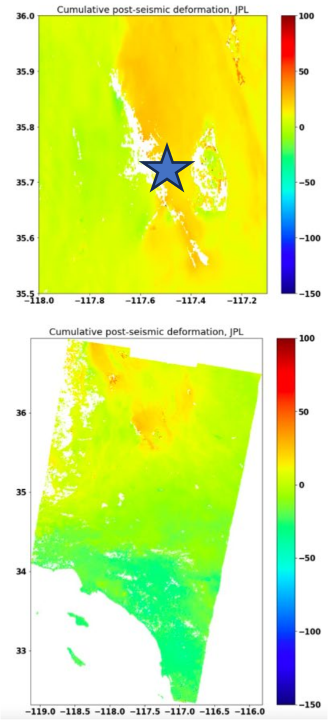
- To calculate the velocity uncertainties of the combined model for each track, we borrow the formulation from GNSS, incorporating power law effects
    - Noise is best represented by a white noise + flicker noise model.
    - We use the formulation of Zhang et al. (1997) Appendix B, to calculate the flicker noise covariance matrix.
    - We incorporate the noise covariance matrix with scaled white and flicker terms into a weighted LSQ inversion, representing time series as sum of secular and seasonal terms.

- To calculate velocities for time series, we use a simple epistemic estimate: we calculate the variance between the different input models.

Moving forward: after Ridgecrest

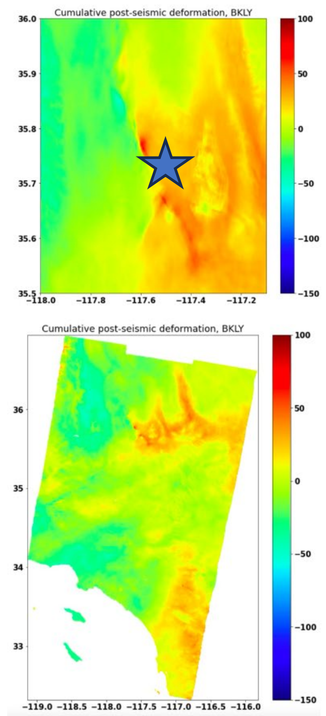
Cumulative post-seismic deformation:

JPL1



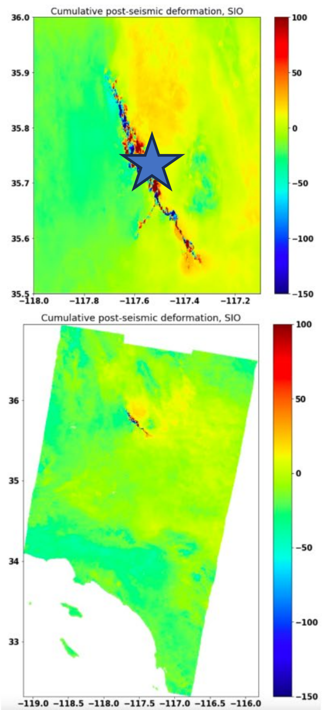
For time series analysis, a Small BAseline Subset approach was used, incorporating the estiation of a coseismic offset, DEM error correction, topo-correlated atmospheric noise correction, and temporal filtering. No spatial filtering is applied to avoid the smearing across the fault rupture. The coseismic offsets are estimated during the time series inversion without assuming explicit temporal function. A coherence threshold of 0.2 was used for pixel selection.

Berkeley



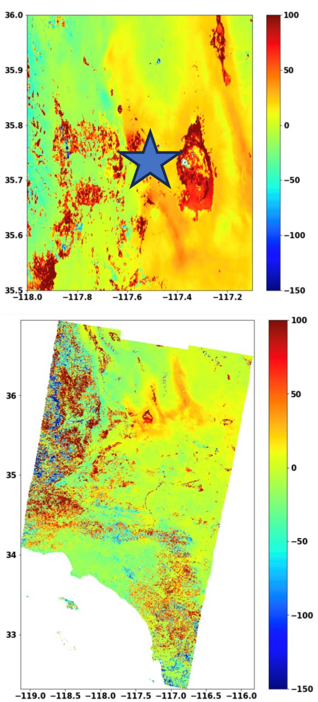
All interferograms are corrected for tropospheric delays by applying ERA-5 weather model using a modified version of the software package TRAIN (Bekaert et al., 2015). Further corrections are made using CANDIS (Tymofyeyeva et al., 2015) with a 90-day symmetric stencil. SBAS is performed for any pixel with a sufficient number of coherent interferograms above a threshold. Only post-seismic deformation was calculated for this exercise.

SIO



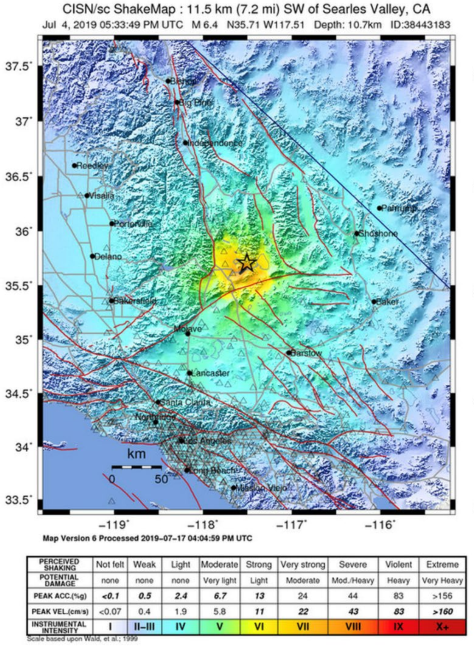
We first calculate time series using coherence-based SBAS, with no additional smoothing or corrections. We then solve for a coseismic offset in each pixel's time series (in addition to a velocity, annual and semi-annual seasonal parameters, and, where necessary, a postseismic deformation term). We remove the coseismic estimate from the unwrapped interferograms that observed the earthquake. We then calculate our time series in SBAS again, but with the addition of the CANDIS (Common-scene-stacking) atmospheric correction and a small smoothing term. We add back in the estimated coseismic offset for a complete displacement time series.

JPL2



Interseismic LOS time series are generated using Small Baseline Subset processing through the open-source MintPy software. We compute the interseismic displacement rates by fitting a long-term trend to the derived time-series. A step function fit was added to account for the displacement field produced by the Ridgecrest earthquake sequence.

Foreshock, July 4, 2019
Magnitude 6.4



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Main shock, July 5, 2019
Magnitude 7.1

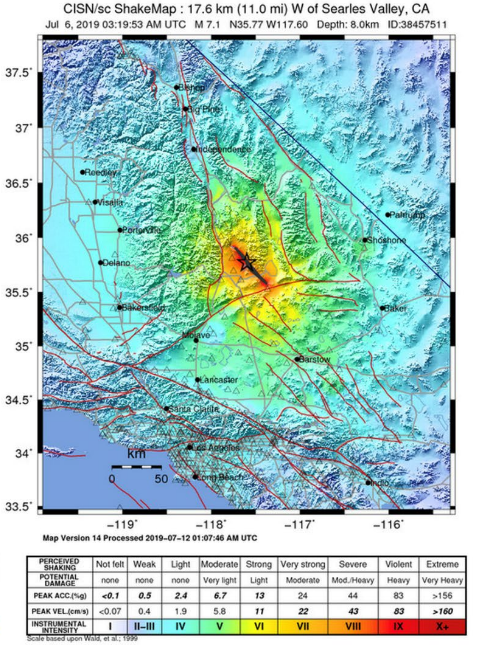


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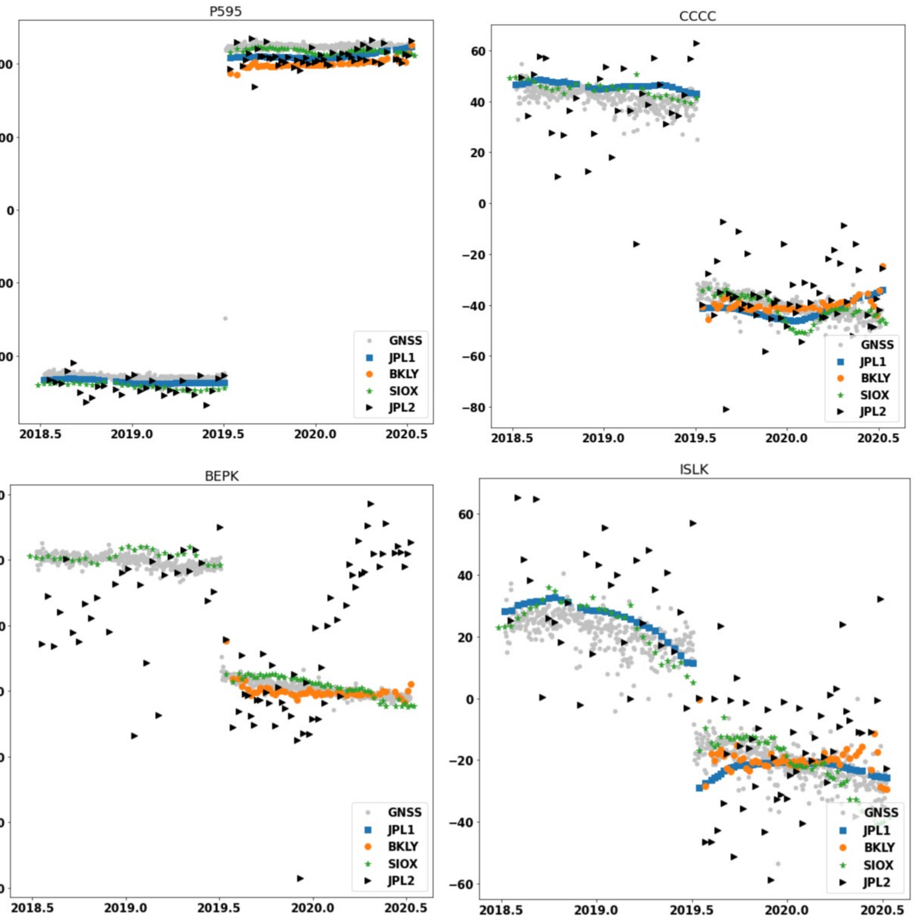
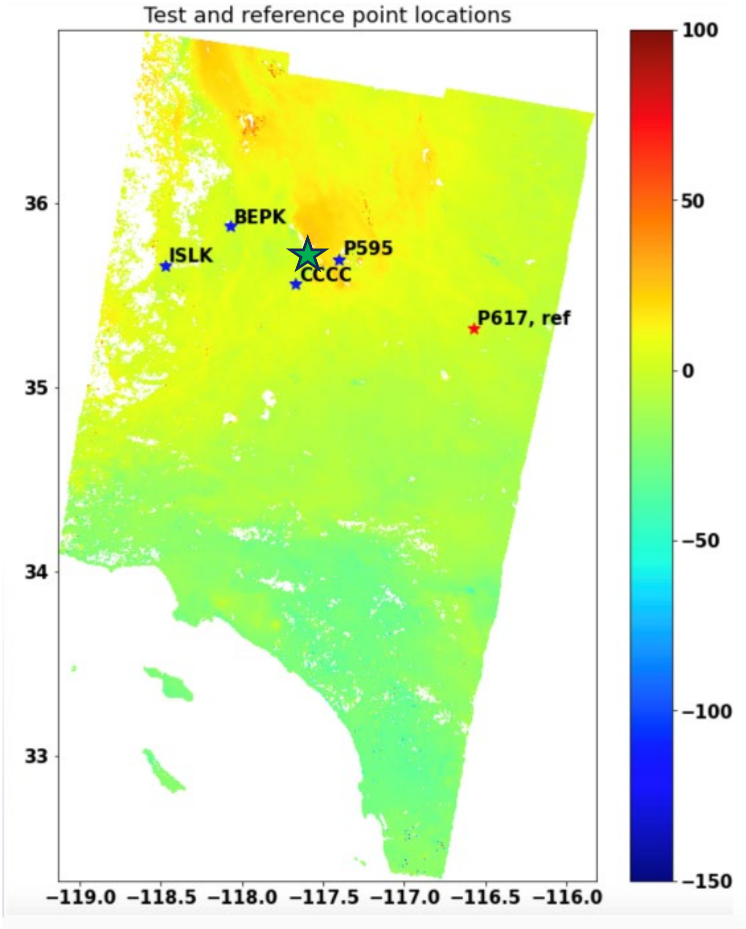
Figure credit: USGS, SCEC

Moving forward: after Ridgecrest

Time series comparison with GNSS:





Our goals:

- Compare methods used to compute time series spanning an earthquake
- Understand differences in the results that are produced using the different methods
- Develop best practices if possible
- Determine a way to combine multiple results into a consensus model
- Extend our time series past Ridgecrest and provide the community with an updated time series and velocity product

Moving forward: future plans

What's Next?: Statewide and beyond!

- Integration of **legacy and specialty datasets** (e.g. ERS/ENVISAT, ALOS 1/2, campaign GNSS) and InSAR datasets from **new and upcoming missions** (e.g. NISAR, and ESA missions) to extend integrated time series and velocities covering all of California (and beyond?) up to the present day.
- Continuing work toward providing **time-dependent 3D deformation** from a combination of GNSS and InSAR
- Calculation of strain and strain rates in Southern California and beyond
- Continued research to implement best practices for geodetic deformation measurements.
- Transition to automation and cloud computing for basic InSAR processing.
- Workshops to elicit community engagement and feedback.