The Community Geodetic Model

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SCEC
an NSF+USGS center

The Community Geodetic Model

Motivation:

Spatially and temporally dense time series of ongoing deformation provide unique input for addressing the fundamental problems of earthquake physics targeted by the SCEC community.

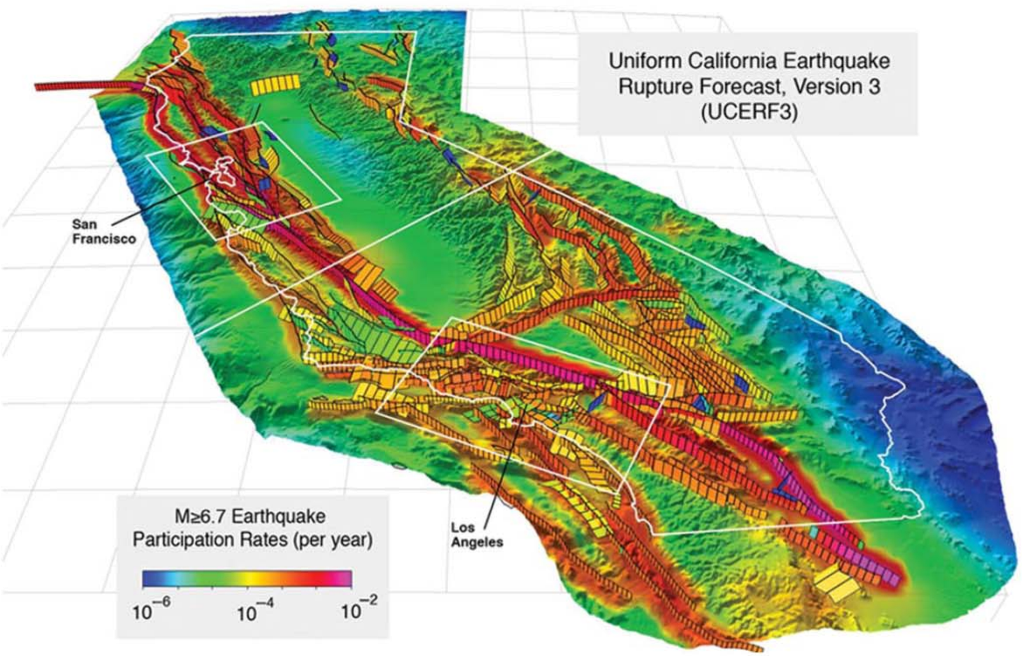
Expanded GPS coverage, new SAR missions, and maturing data analysis techniques that leverage the complimentary features of both data types now enable us to record deformation at unprecedented resolution.

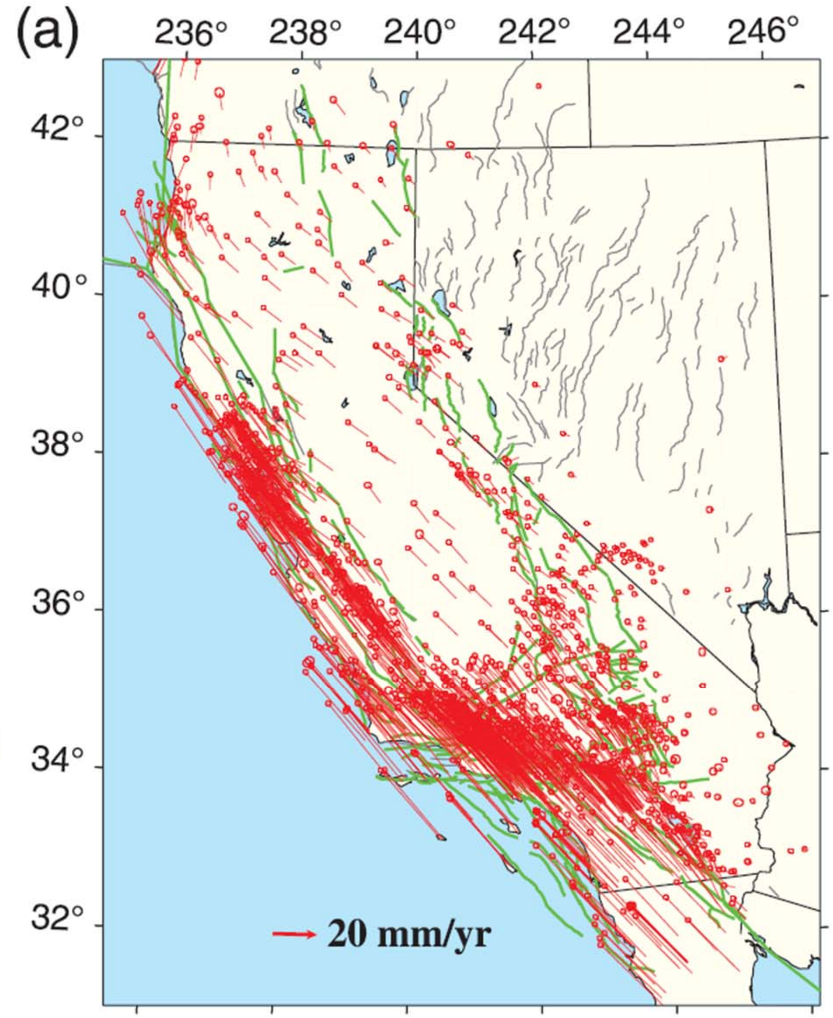
SCEC4 Fundamental Problems of Earthquake Physics:

Stress transfer from plate motion to crustal faults: long-term fault slip rates

- Geodetic data included as input for quantifying slip rates and strain rates in three of four UCERF3 deformation models

  → Requires well-constrained velocities and realistic uncertainties



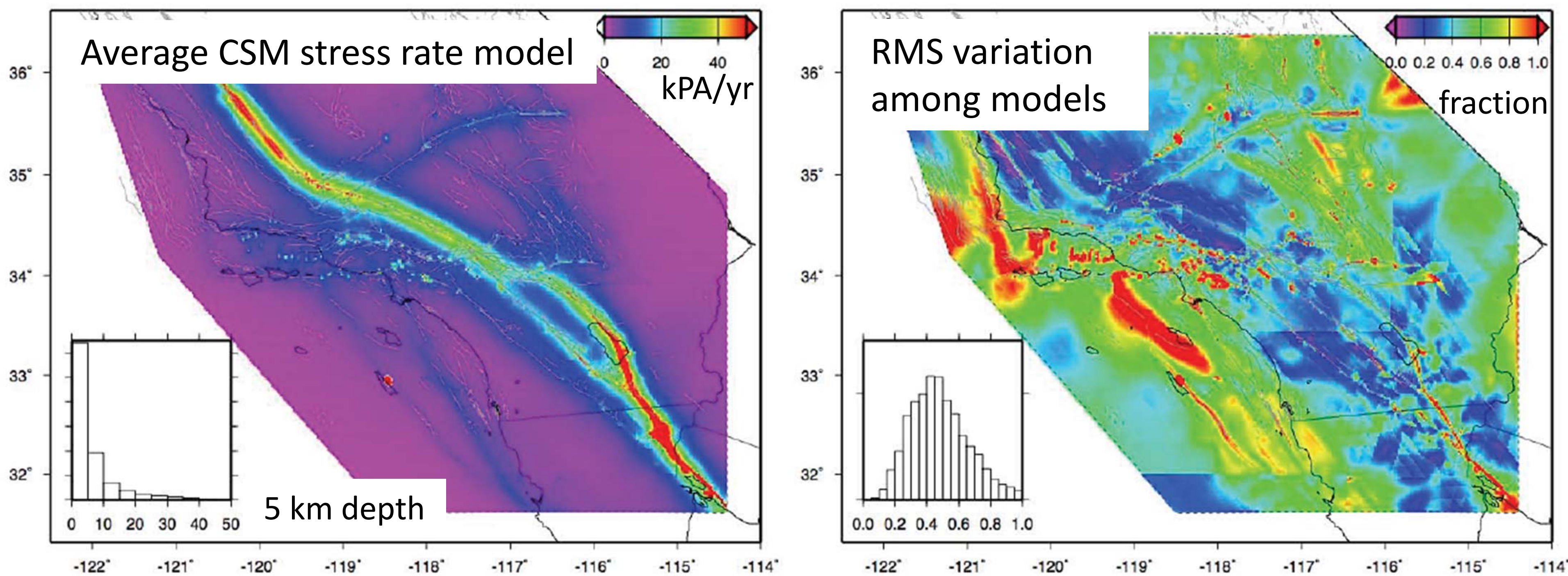


Field et al., BSSA, 2014

SCEC4 Fundamental Problems of Earthquake Physics:

Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms

- Geodetic crustal velocities constrain regional tectonic stressing rate models for the CSM
  - → Requires well-constrained velocities with broad regional coverage



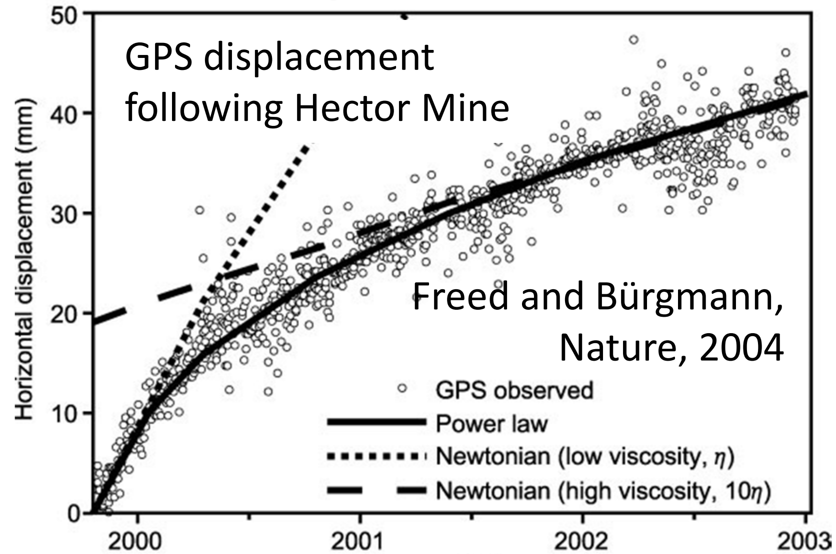
Models: Loveless & Meade, Smith-Konter & Sandwell, Strader & Jackson, Cooke & Marshall, UCERF3 ABM, UCERF3 NeoKinema, UCERF3 Zeng

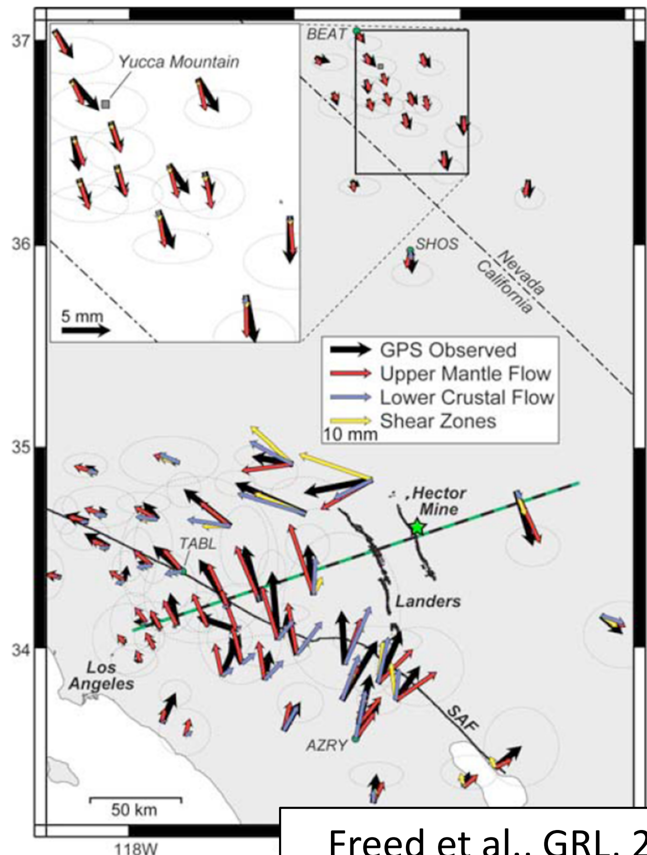
Figure courtesy Jeanne Hardebeck

SCEC4 Fundamental Problems of Earthquake Physics:

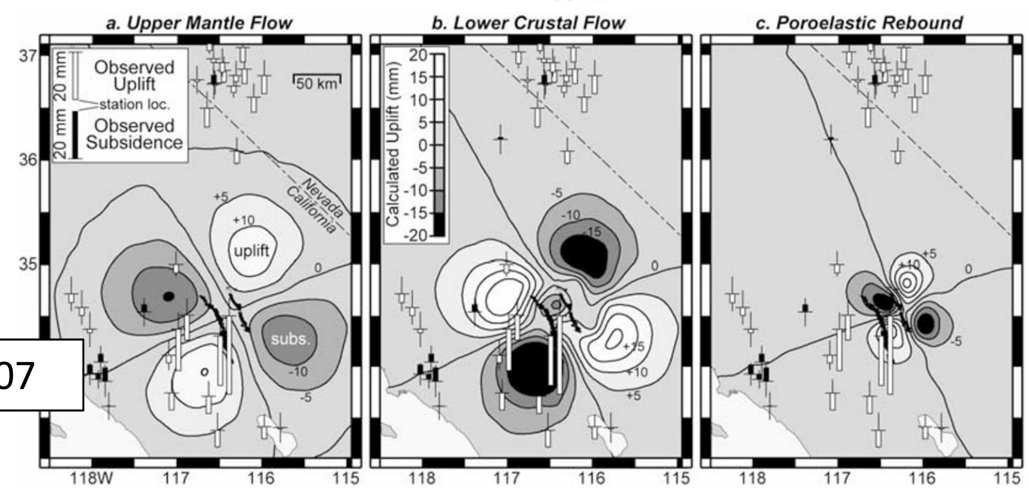
Stress transfer from plate motion to crustal faults: long-term fault slip rates

- Postseismic deformation illuminates causative physical processes, frictional properties, and rheology with implications for fault loading throughout the earthquake cycle
  - → Requires spatially and temporally dense **three-component** decadal time series over broad region





Freed et al., GRL, 2007

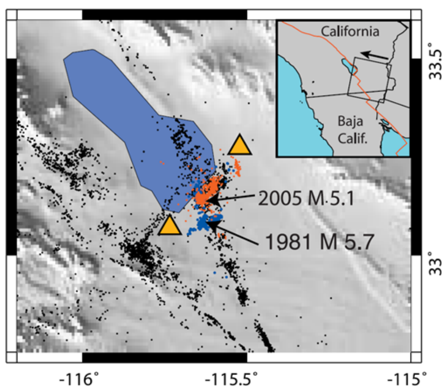


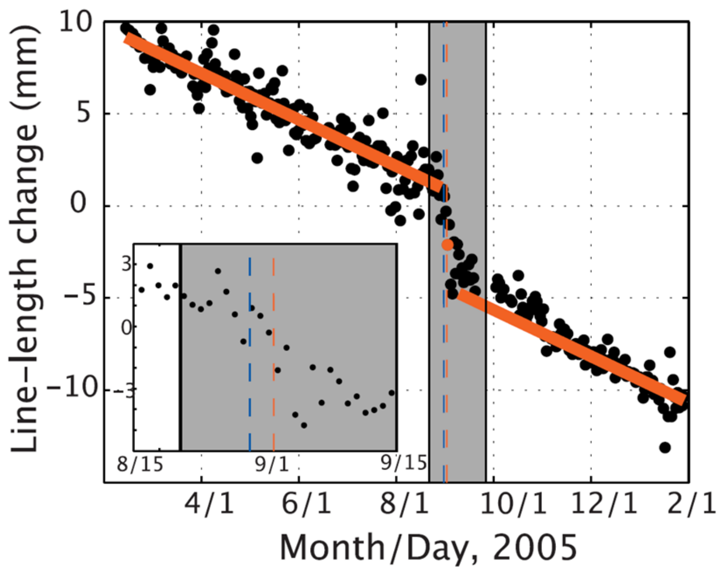
SCEC4 Fundamental Problems of Earthquake Physics:

Causes and effects of transient deformations: slow slip events and tectonic tremor

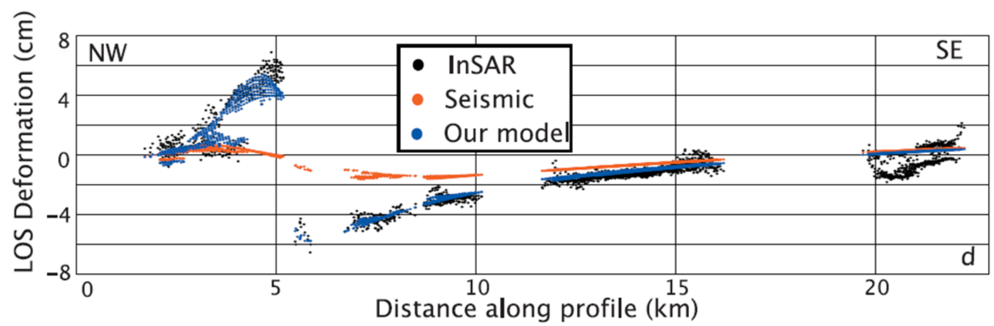
- Geodetic time series constrain location and evolution of aseismic transients for physical modeling of fault properties, driving mechanisms, and relation to seismicity

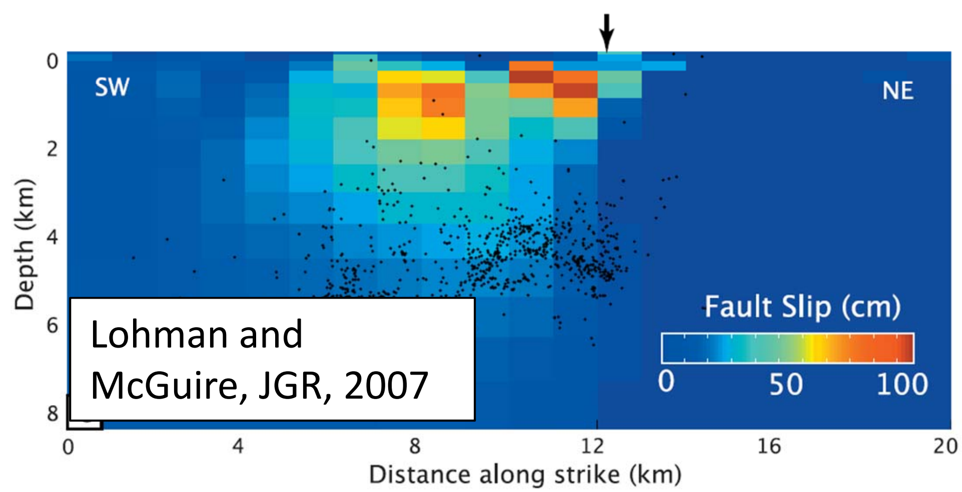
  → Requires spatially and temporally dense three-component time series, *perhaps filtered to remove trends, seasonal, or other signals*





__Example:__ Aseismic slip associated with Obsidian Buttes swarm constrained by a single pair of GPS sites and InSAR





Lohman and McGuire, JGR, 2007

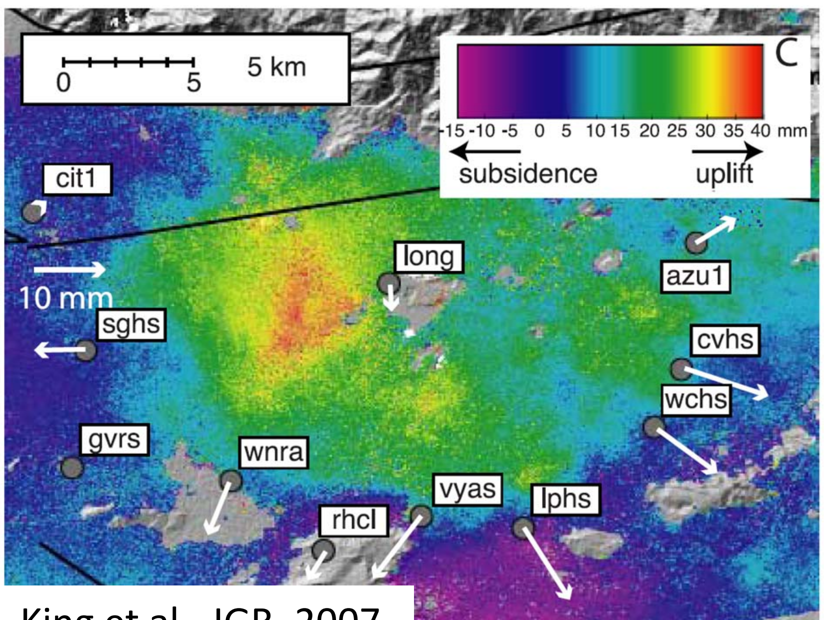
SCEC4 Fundamental Problems of Earthquake Physics:

Causes and effects of transient deformations: slow slip events and tectonic tremor

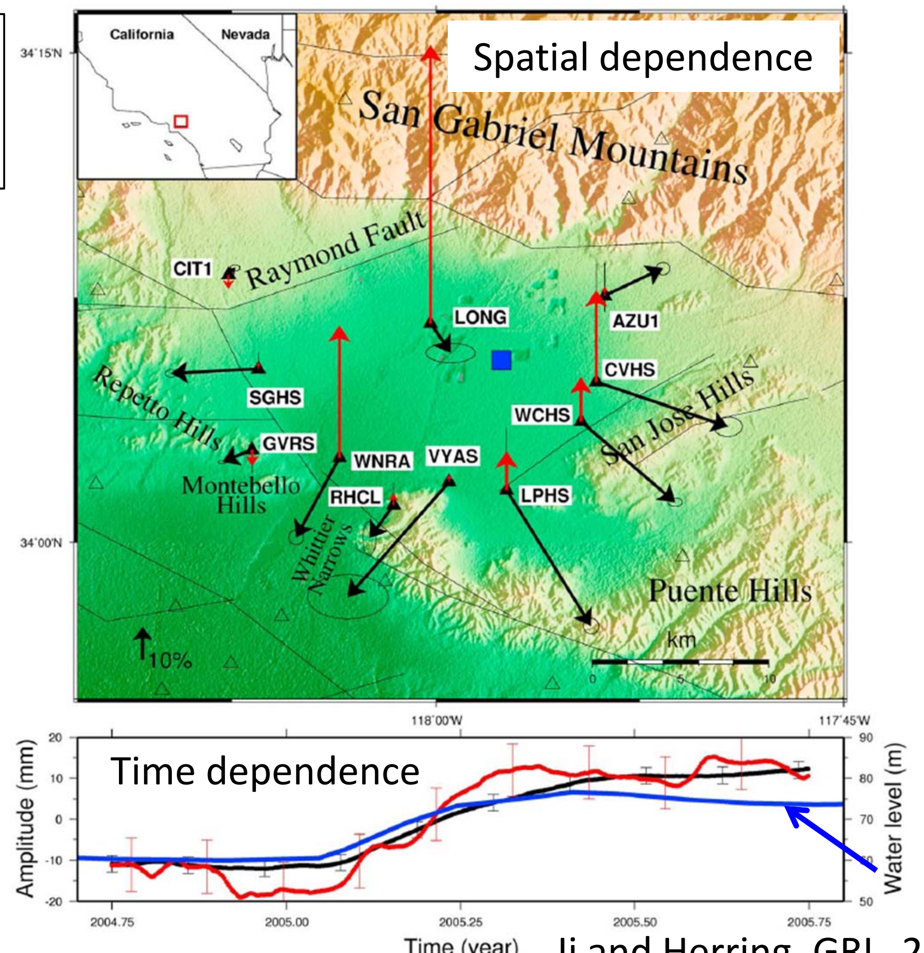
- Southern California GPS and InSAR data provide high spatial and temporal resolution observations for detecting and modeling hydrologic transients

  → Requires spatially and temporally dense three-component time series, *perhaps filtered to remove trends, seasonal, or other signals*

Example: *Transient deformation due to San Gabriel Valley aquifer recharge and signal detection using Principal Component Analysis.*



King et al., JGR, 2007



Ji and Herring, GRL, 2012

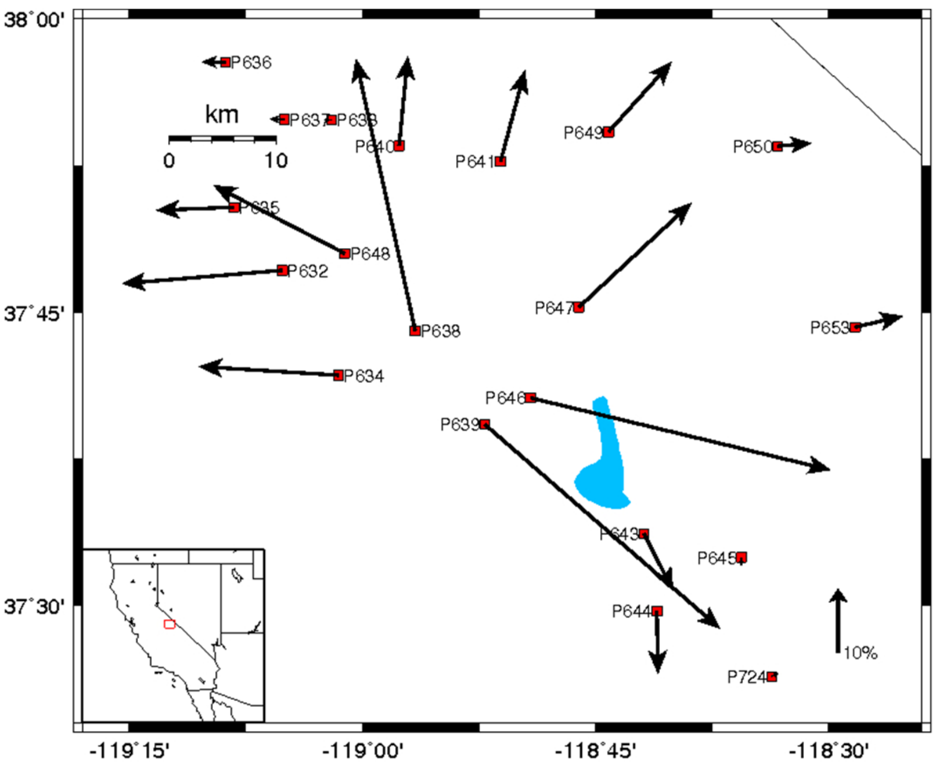
SCEC4 Fundamental Problems of Earthquake Physics:

Causes and effects of transient deformations: slow slip events and tectonic tremor

- Geodetic time series constrain location and evolution of aseismic transients for anomaly detection and possible future use in time-dependent forecasting

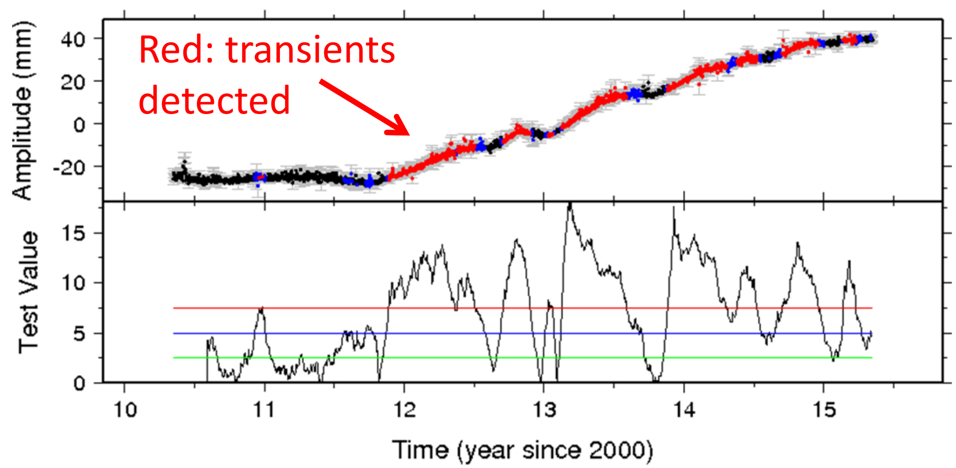
  → Requires spatially and temporally dense three-component time series, *perhaps filtered to remove trends, seasonal, or other signals*

Spatial template based on previously observed transient event



Example: Online transient detector applied to GPS time series flags repeated deformation events at Long Valley caldera.

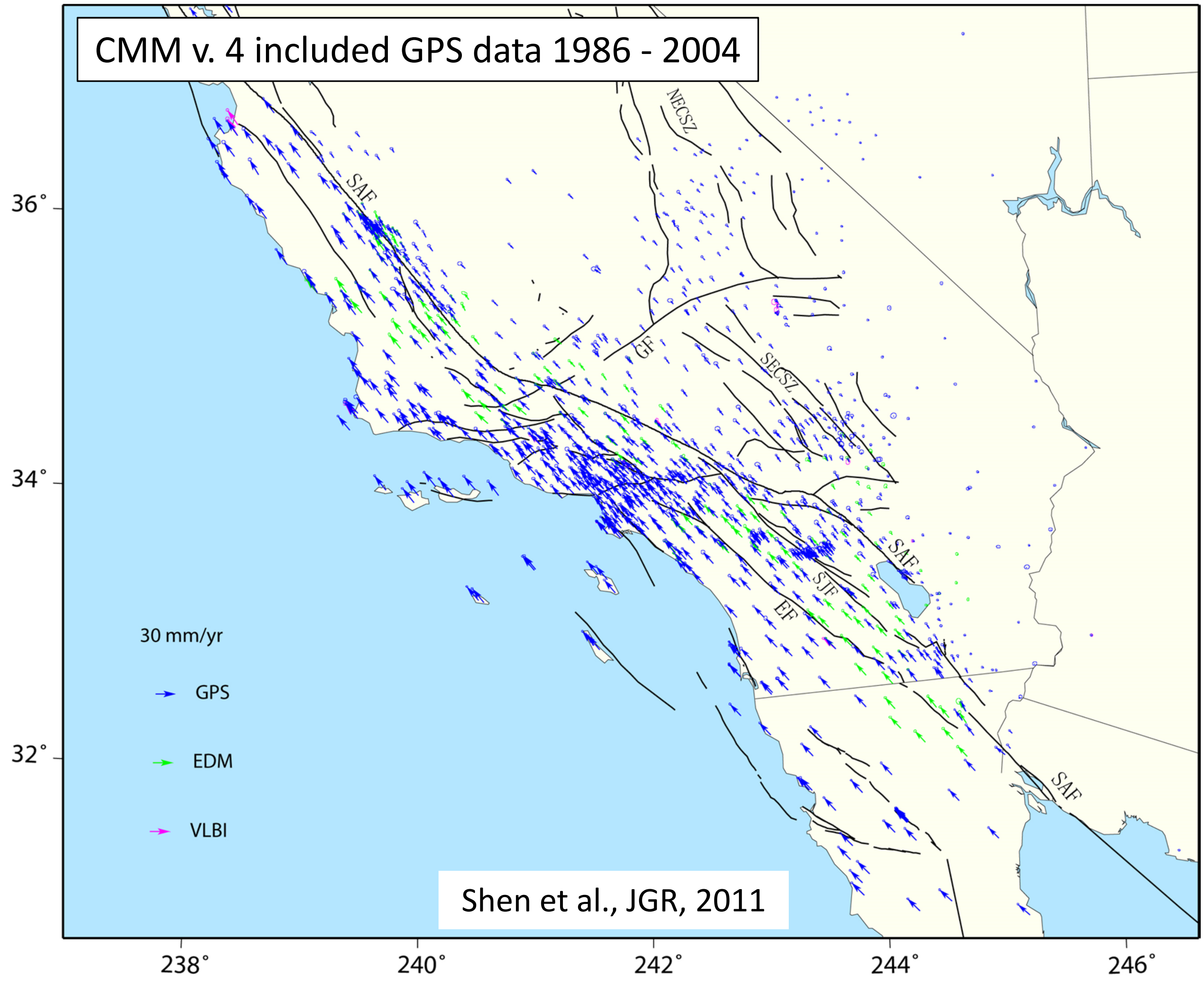
Detections based on how well spatial template fits data at a given epoch



Ji and Herring, GRL, 2013

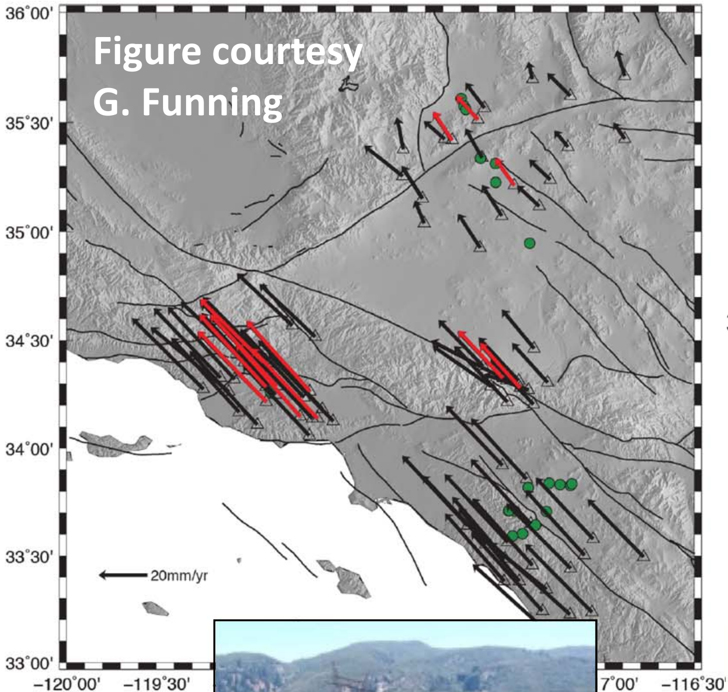
New geodetic data and analysis techniques:

Starting point: SCEC Crustal Motion Map (CMM) v.4



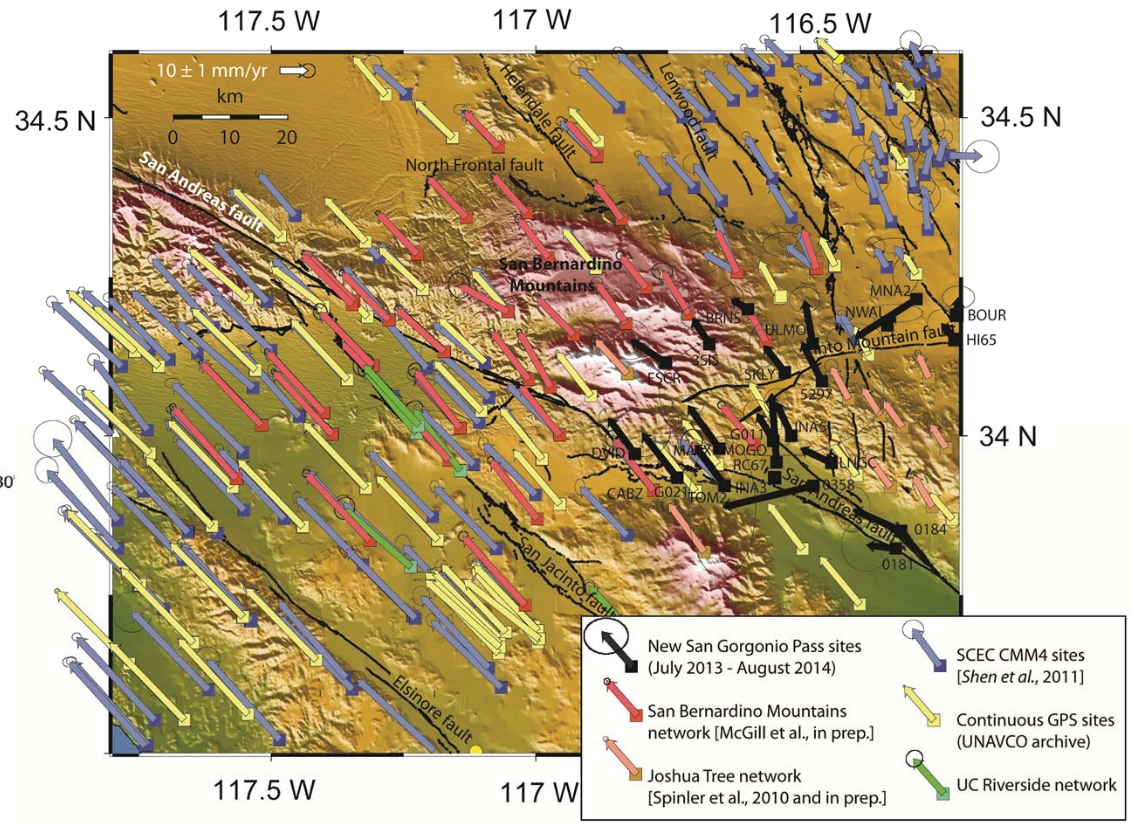
New geodetic data and analysis techniques:

GPS expansion since SCEC Crustal Motion Map (CMM) v.4



SCEC intern Lisa Jose

Recent SCEC-supported campaign GPS data collection has densified coverage in target areas.



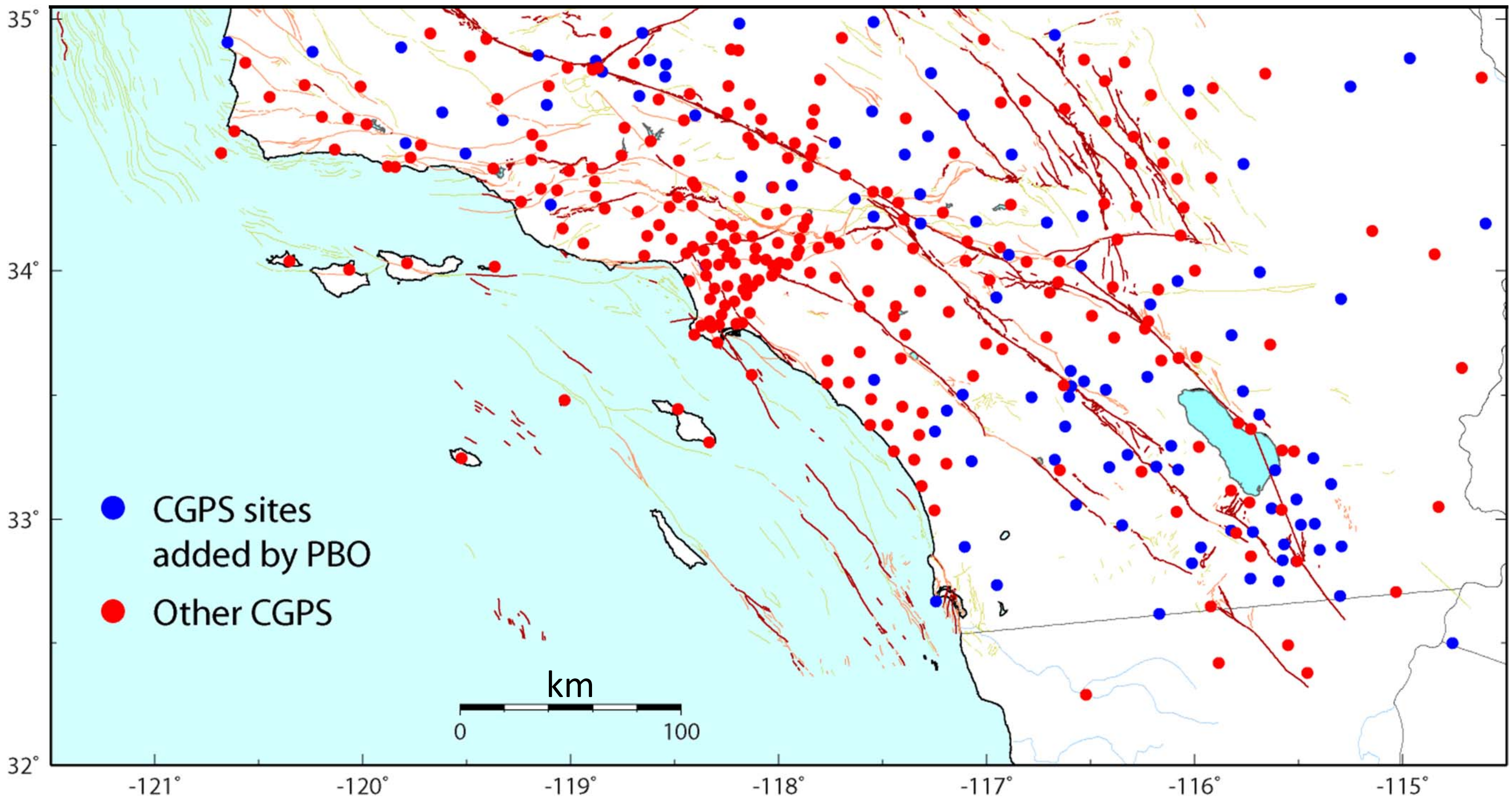
Spinler et al., JGR, 2010; McGill et al., JGR, 2015

Posters #305, 306

New geodetic data and analysis techniques:

GPS expansion since SCEC Crustal Motion Map (CMM) v.4

- EarthScope Plate Boundary Observatory substantially increased southern California continuous GPS (CGPS) coverage starting around 2006.
- CGPS sites provide better record of vertical deformation than campaign data

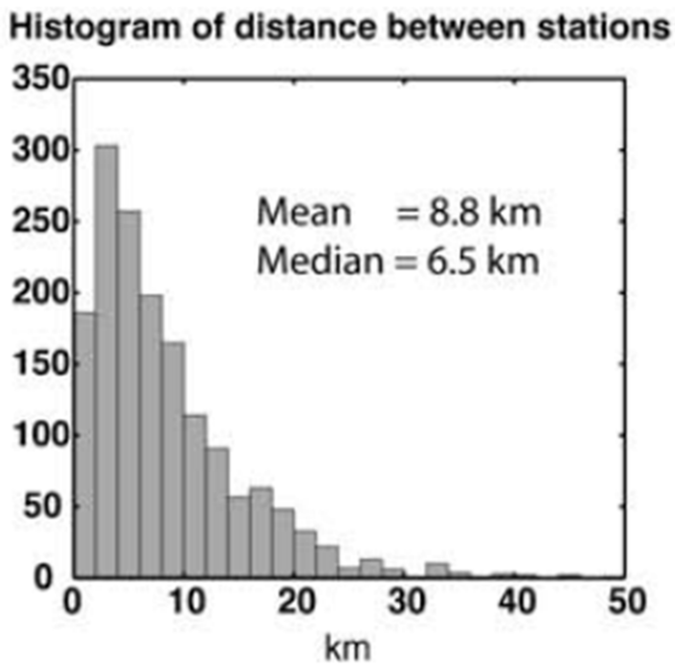


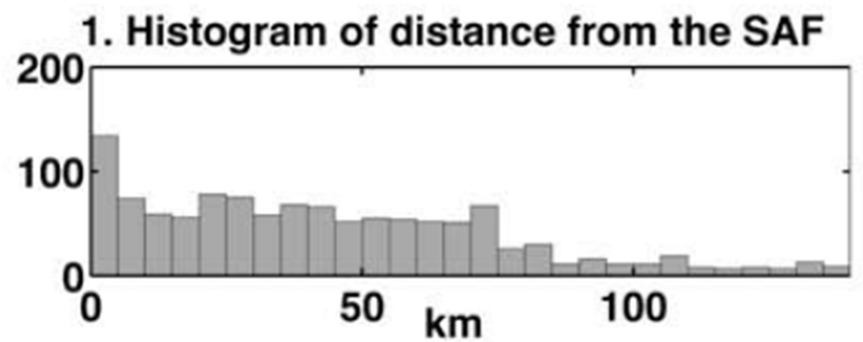
New geodetic data and analysis techniques:

However, station spacing is not uniform around all major faults

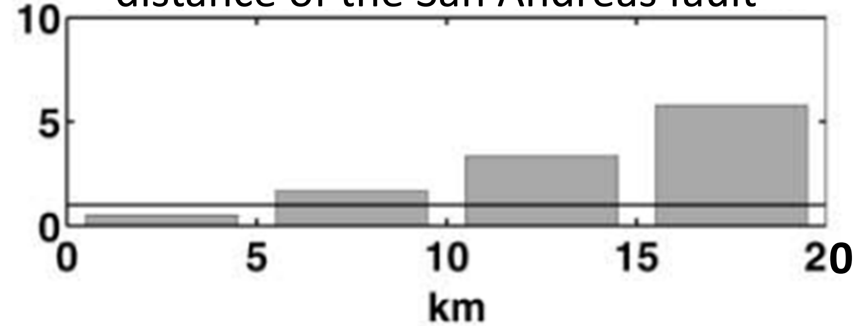
Wei et al. (2010) demonstrated that

- Minimum spatial wavelength of deformation observable with irregularly spaced sites is 3 – 4 times the station spacing.
- In southern California minimum wavelength is 15 – 40 km.





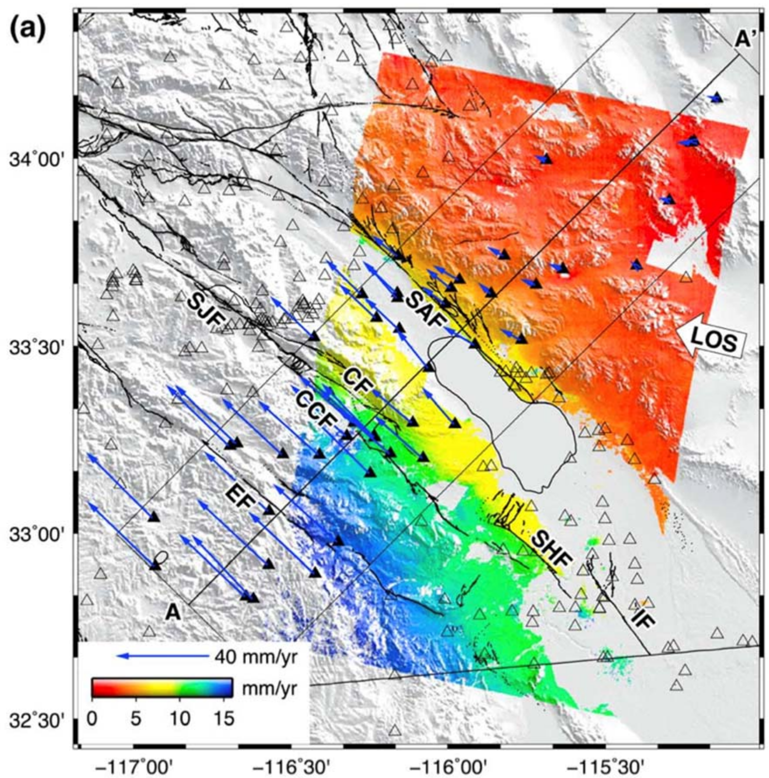
Number of stations within a given distance of the San Andreas fault



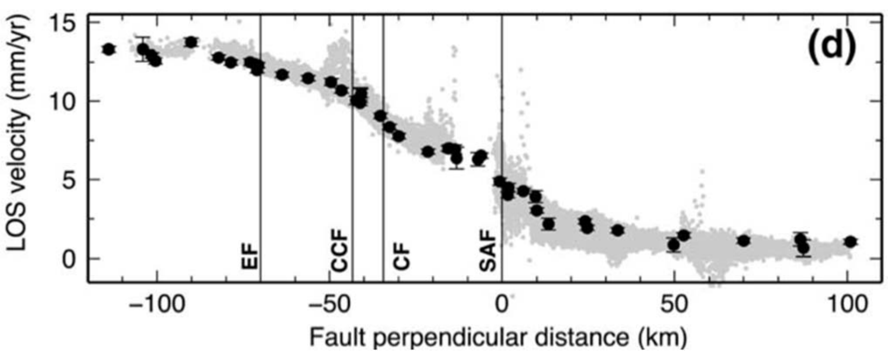
New geodetic data and analysis techniques:

We know that InSAR complements GPS, providing spatially dense line-of-sight measurements of interseismic deformation.

Example: Joint analysis of GPS and InSAR velocities shows that assumed fault dip influences San Andreas and San Jacinto fault slip rate estimates more than elastic heterogeneity does.



GPS and InSAR velocity profile, aligned at wavelengths >70 km



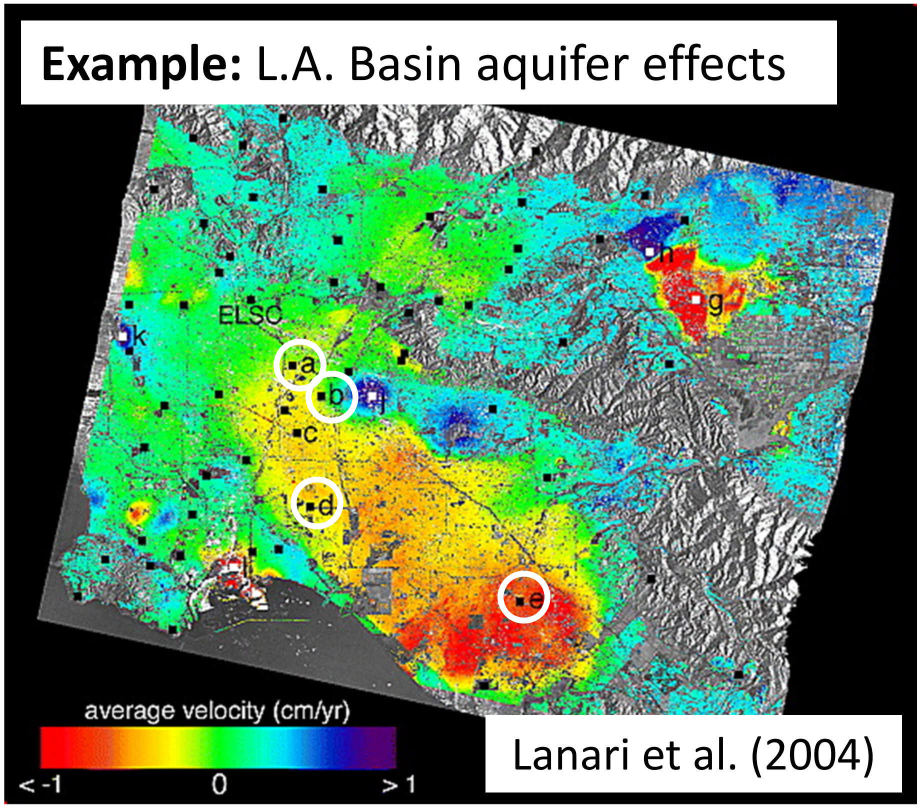
GPS: CMM4 and PBO velocities

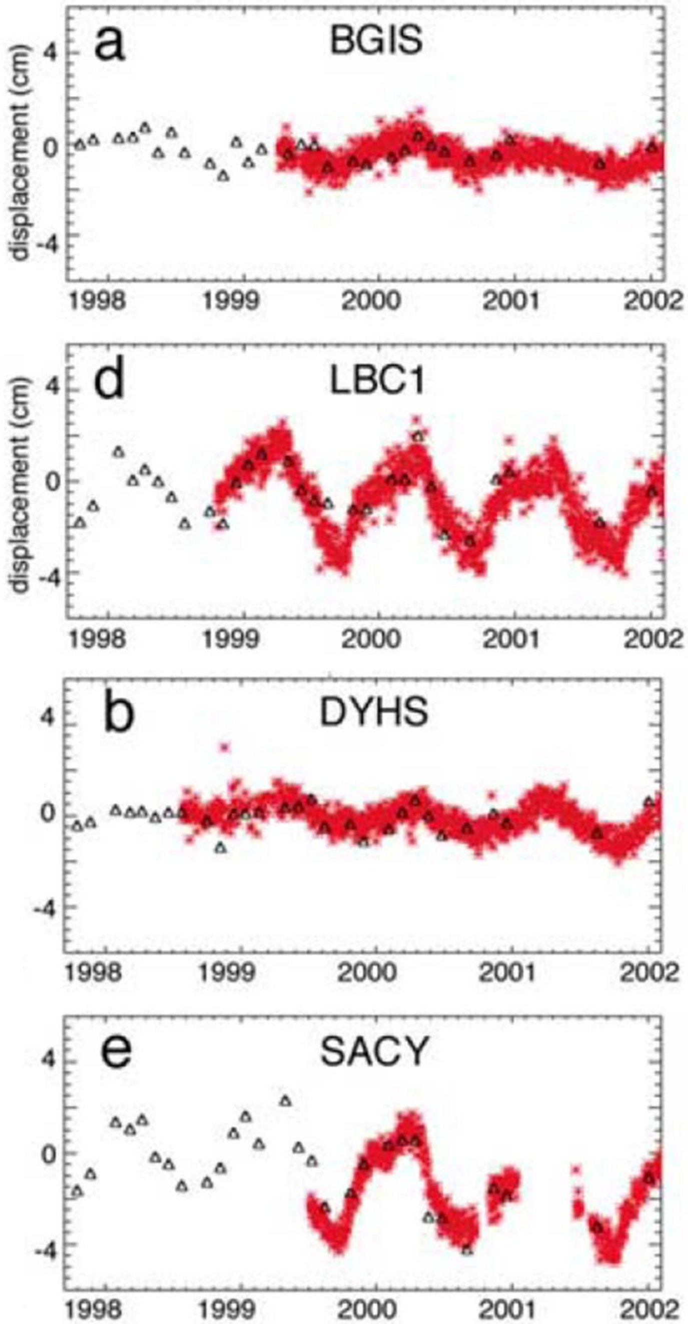
InSAR: ERS-1/2 1992 - 2007 (Manzo et al., 2011)

Lindsey and Fialko, JGR, 2013

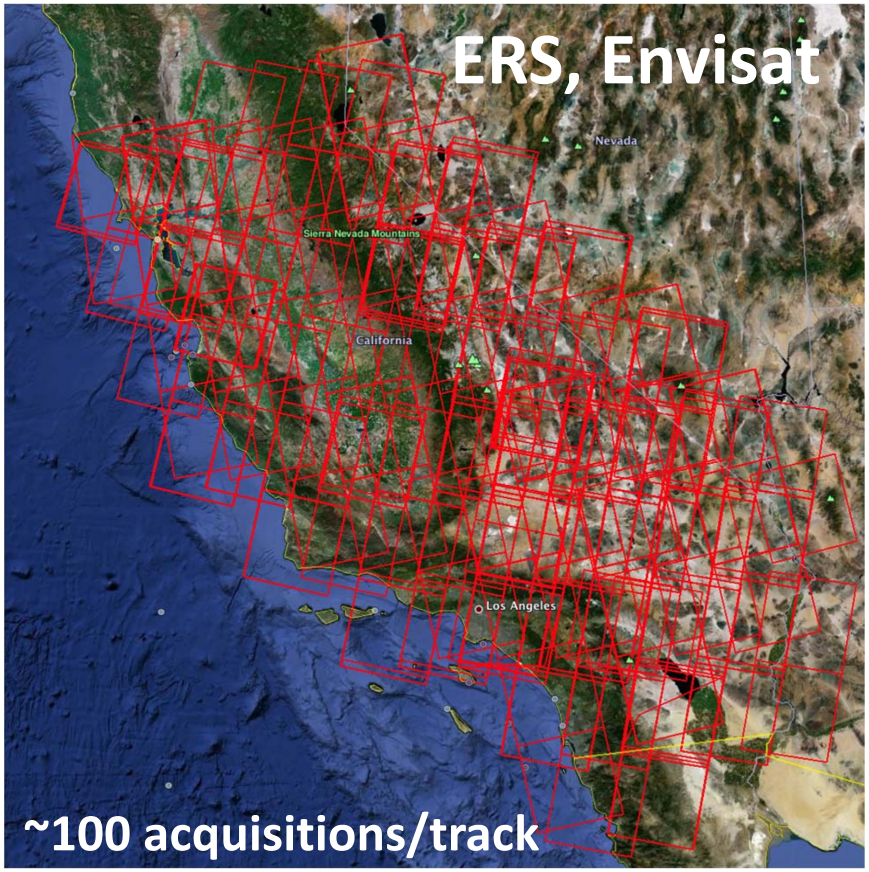
New geodetic data and analysis techniques:
We can extend dense near-field spatial coverage to track temporal changes.

- InSAR time series analysis techniques using small-baseline (SBAS) or persistent scatterer (PS) approaches exist.
- Recovered time-varying motion agrees well with GPS under certain assumptions (e.g., temporal/spatial smoothness).
- Accuracy: ~5-10 mm displacement, ~1-2 mm/yr rate

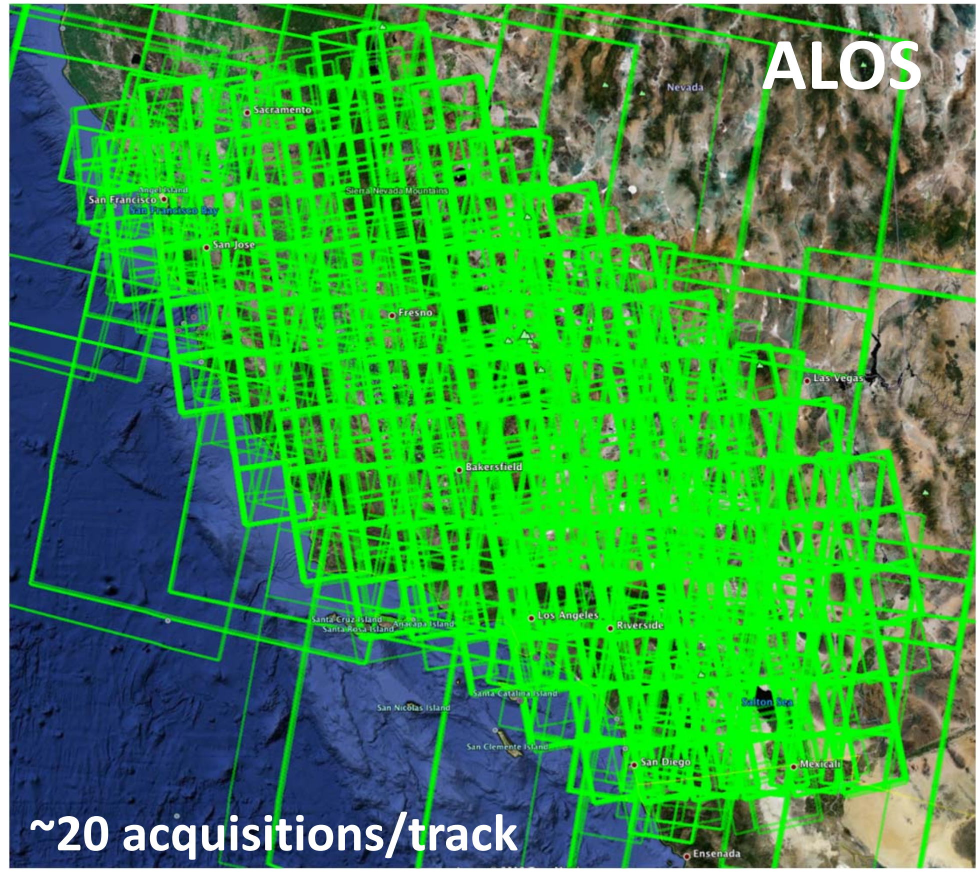




New geodetic data and analysis techniques:
Existing southern California SAR coverage is good, but temporal coverage and, in some cases, lack of two look directions limit the use of InSAR to its full potential.



1992-2000; 1995-2011
~11,000 So. Cal. scenes

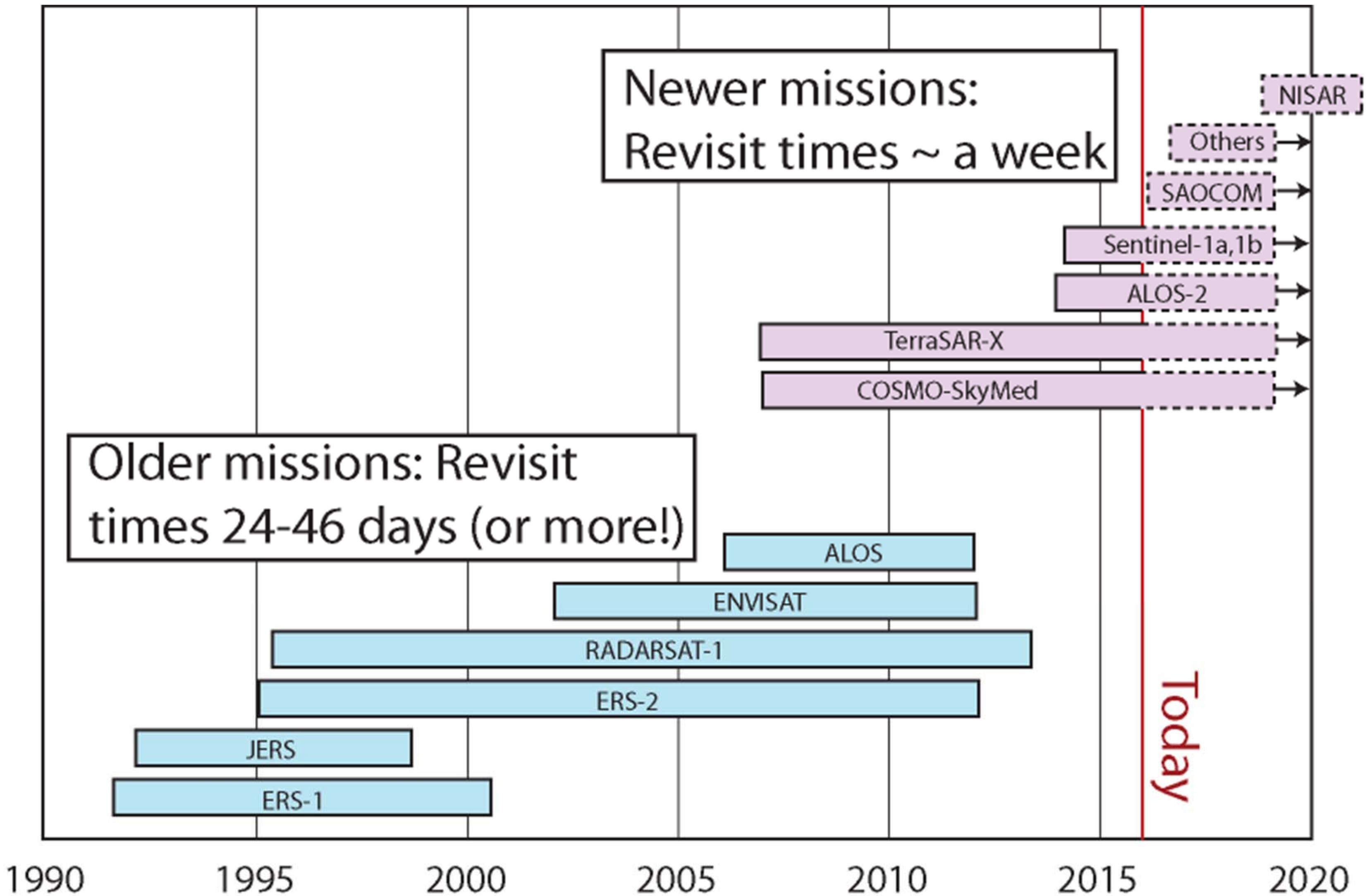


2006-2011
~4100 So. Cal. scenes

Figure courtesy S. Baker

New geodetic data and analysis techniques:

More frequent repeat passes, ascending and descending orbits, and better baseline control are on the horizon.



The Community Geodetic Model

Motivation:

Spatially and temporally dense time series of ongoing deformation provide unique input for addressing the fundamental problems of earthquake physics targeted by the SCEC community.

Expanded GPS coverage, new SAR missions, and maturing data analysis techniques that leverage the complimentary features of both data types now enable us to record deformation at unprecedented resolution.

The Community Geodetic Model

What will it look like?

A consensus set of models consisting of

- GPS time series that synthesize processed continuous and campaign positions (north, east, vertical) from multiple sources in a common reference frame
- GPS secular velocity field estimate(s) derived using one or more analysis strategies
- Characterization(s) of seasonal signals and earthquake-related displacements for optional GPS time series cleaning
- Line-of-sight (LOS) velocity map(s) estimated from stacked interferograms and consistent with far-field GPS rates
- One or more sets of LOS InSAR time series aligned with GPS
- Realistic uncertainty estimates for time series and rates

The Community Geodetic Model

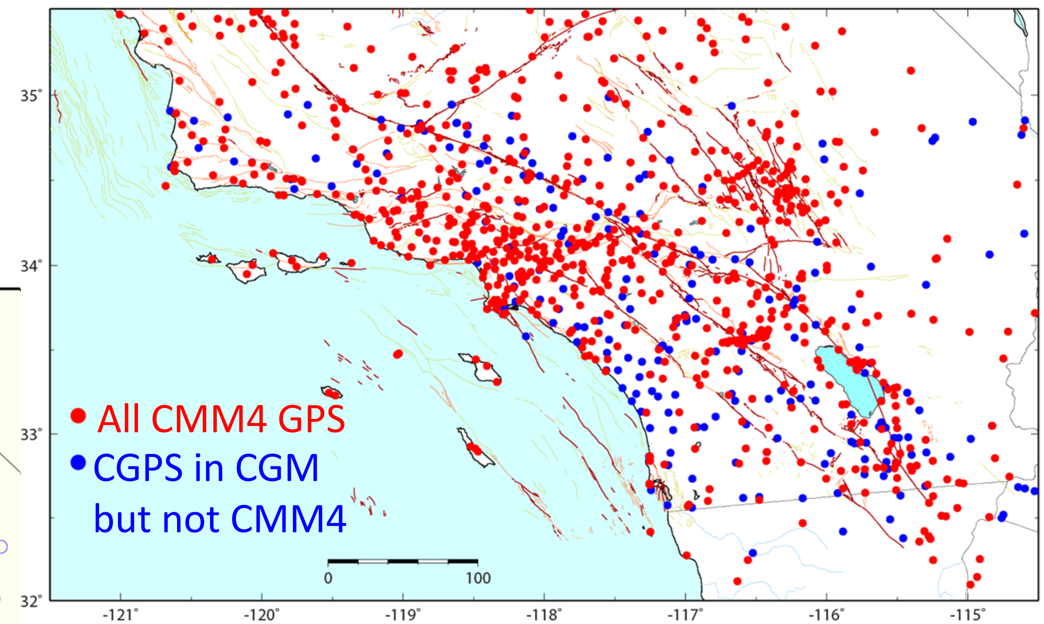
How will we do it?

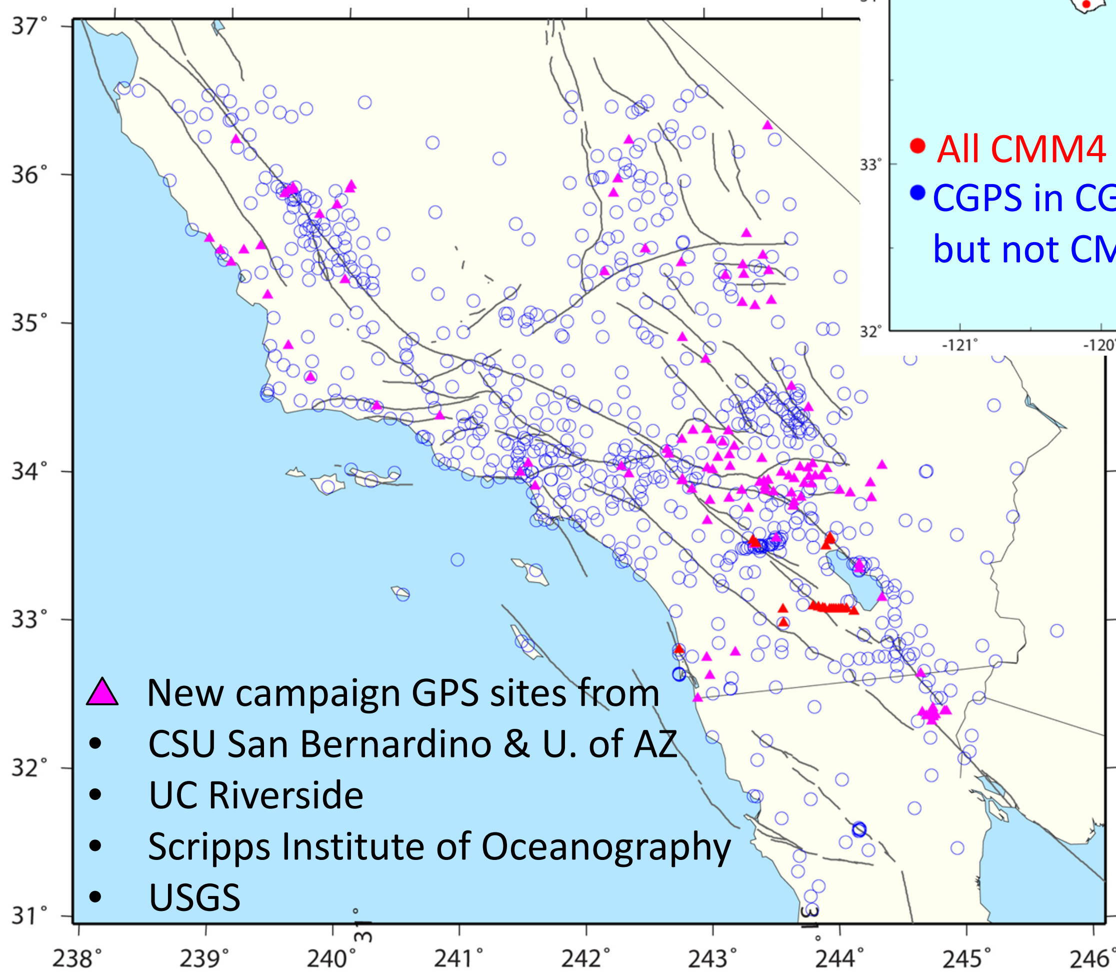
- Engage in a collaborative process to generate ideas, explore strategies, and vet results
- Maintain communication via virtual and in-person workshops
- Draw upon synergistic activities in the broader geoscience community
- Develop GPS and InSAR components in parallel

CGM development:

Include GPS data collected since CMM4

- PBO continuous GPS (CGPS) sites have been incorporated



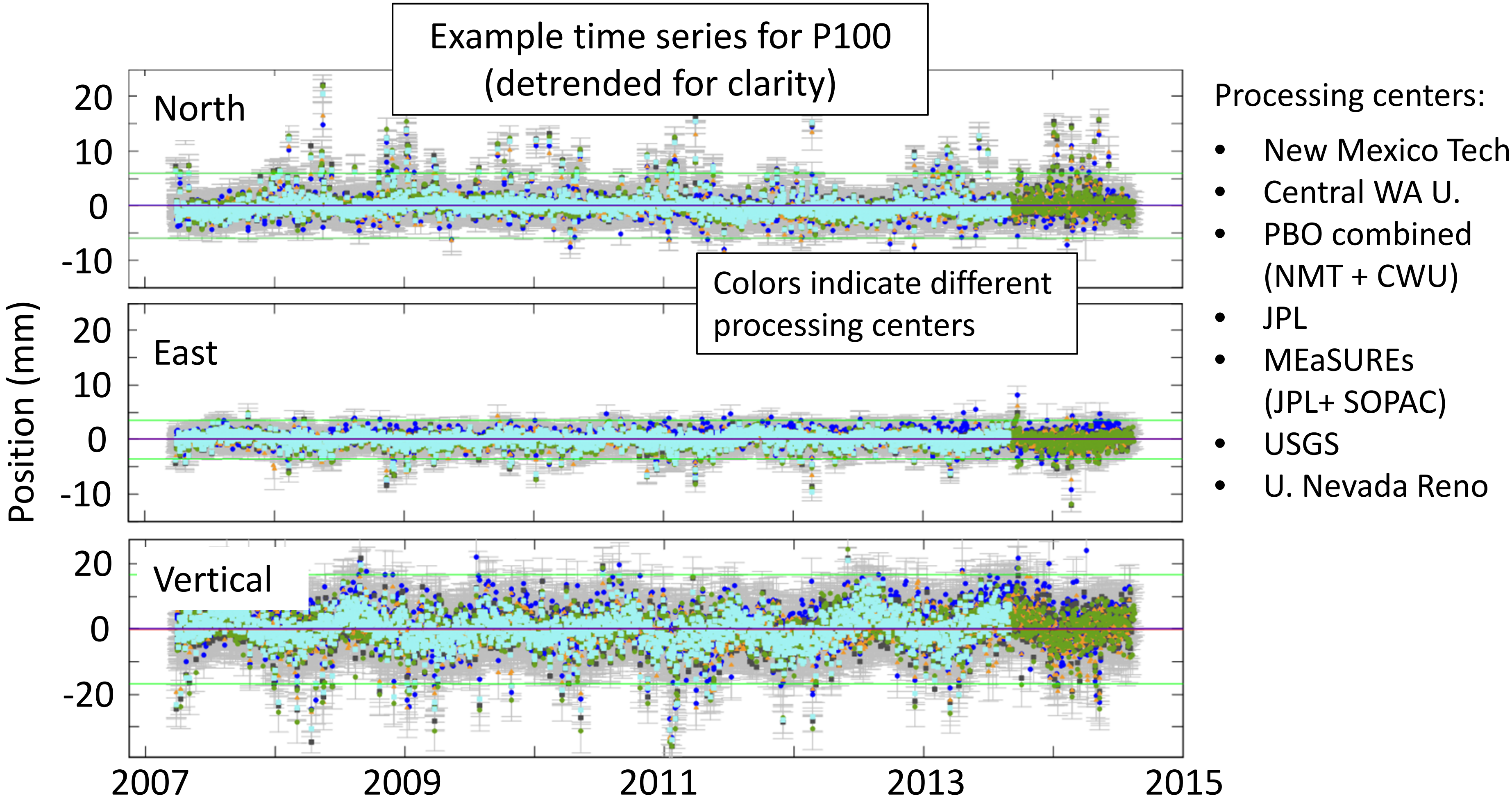


- SCEC-funded campaign GPS data being migrated to UNAVCO archive (M. Floyd, D. Agnew, Fran Boler)
- All campaign GPS data (1986 – 2014) and global tracking stations reprocessed in consistent manner using modern techniques (Z.-K. Shen, poster #198)

CGM development:

Synthesize position solutions from multiple processing centers to produce consensus time series

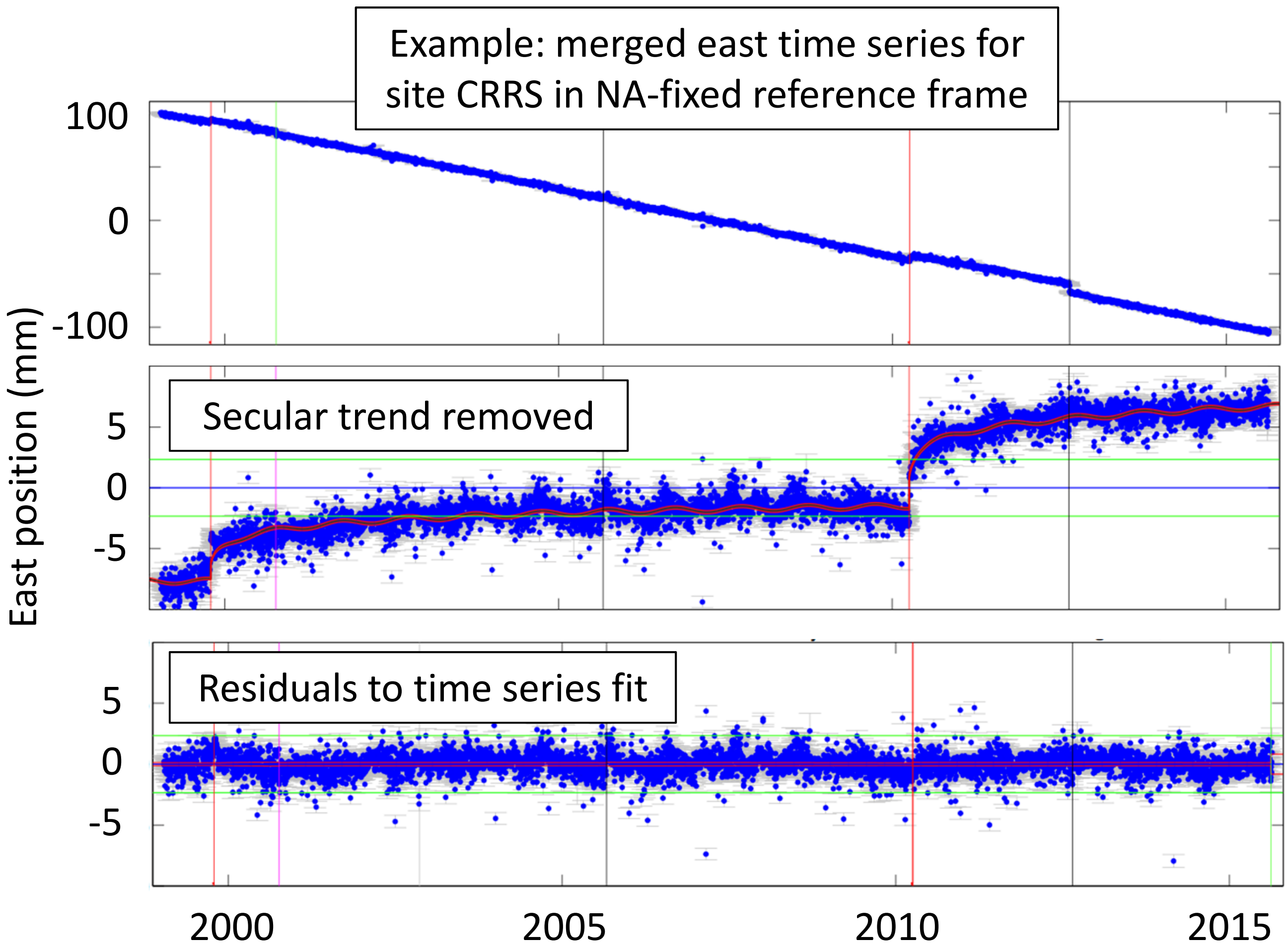
- Time series transformed into North America reference frame; uncertainties scaled according to fit of reference frame adjustment
- Epoch-by-epoch averaging of positions from each center to produce consensus time series



CGM development:

Comparison 1: Secular velocities

- All time series for each site are fit with same terms; temporally correlated noise model
- Inter-comparison of velocities (derived from individual and consensus time series) found weighted RMS differences of **< 0.1 mm/yr horizontal and < 0.6 mm/yr vertical**



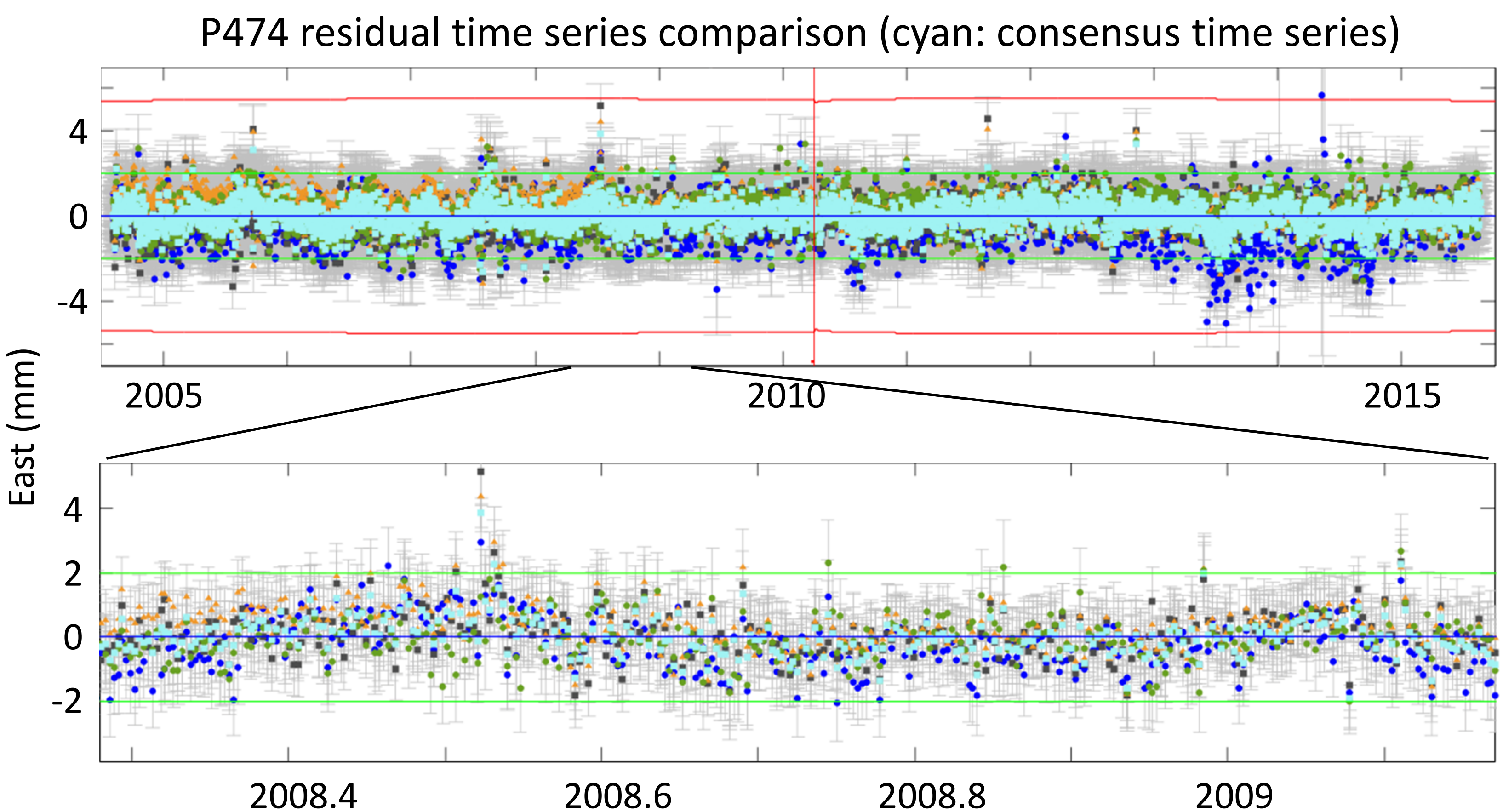
Time series parameterization

- constant (secular) velocity
- offsets
- postseismic (logarithmic)
- annual sinusoid

Note: all time series use same reference frame realization.

CGM development:
Comparison 2: Position time series (individual as well as consensus)

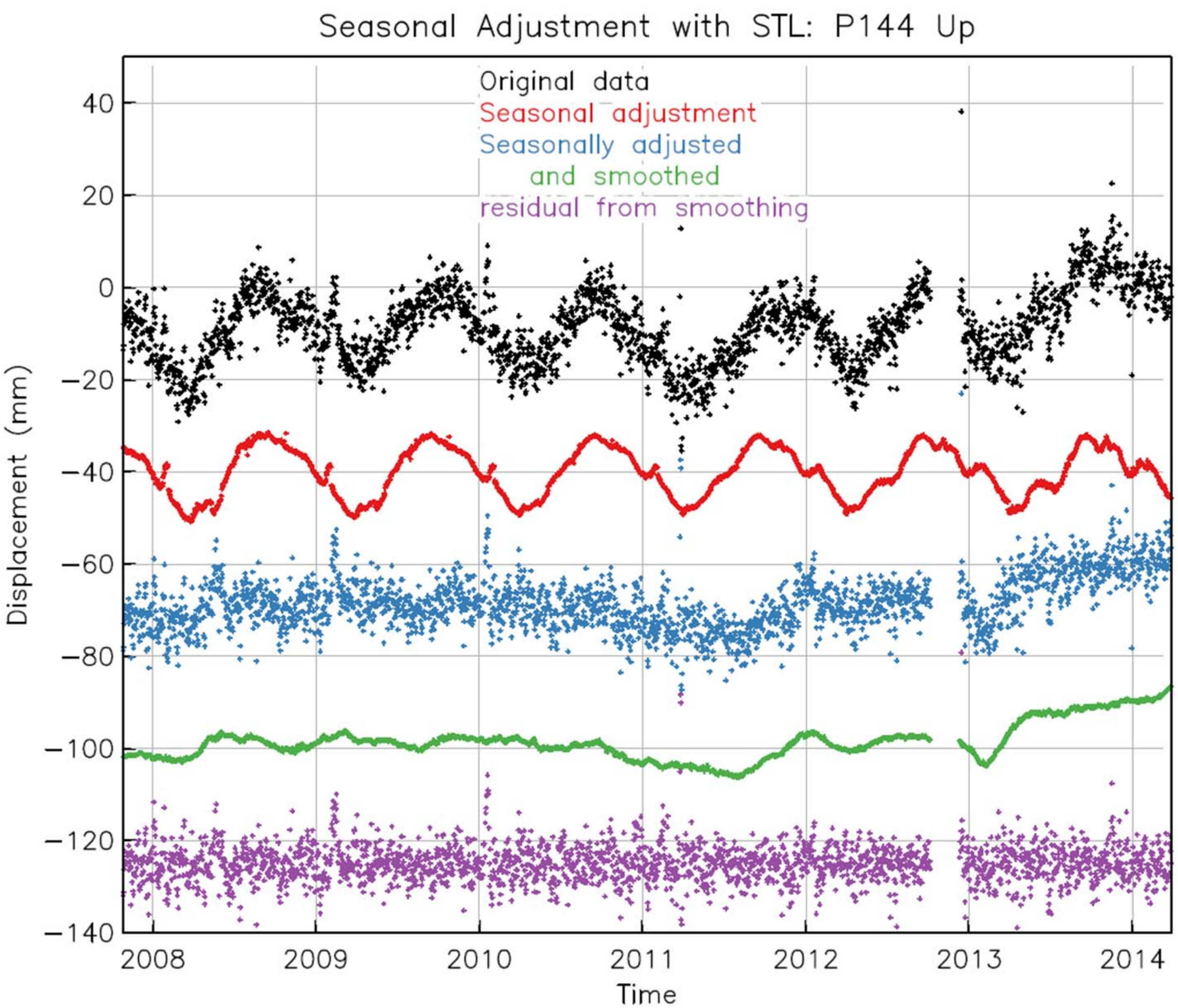
- Median WRMS scatter of residual time series ~1 mm horizontal, ~5 mm vertical
- Individual centers' daily position estimates differ from consensus time series with median WRMS of **< 0.7 mm horizontal and < 3.4 mm vertical**



CGM development:

Issues to consider: seasonal signals

- Time-varying amplitude
- (Unintended) removal with reference frame scale adjustment

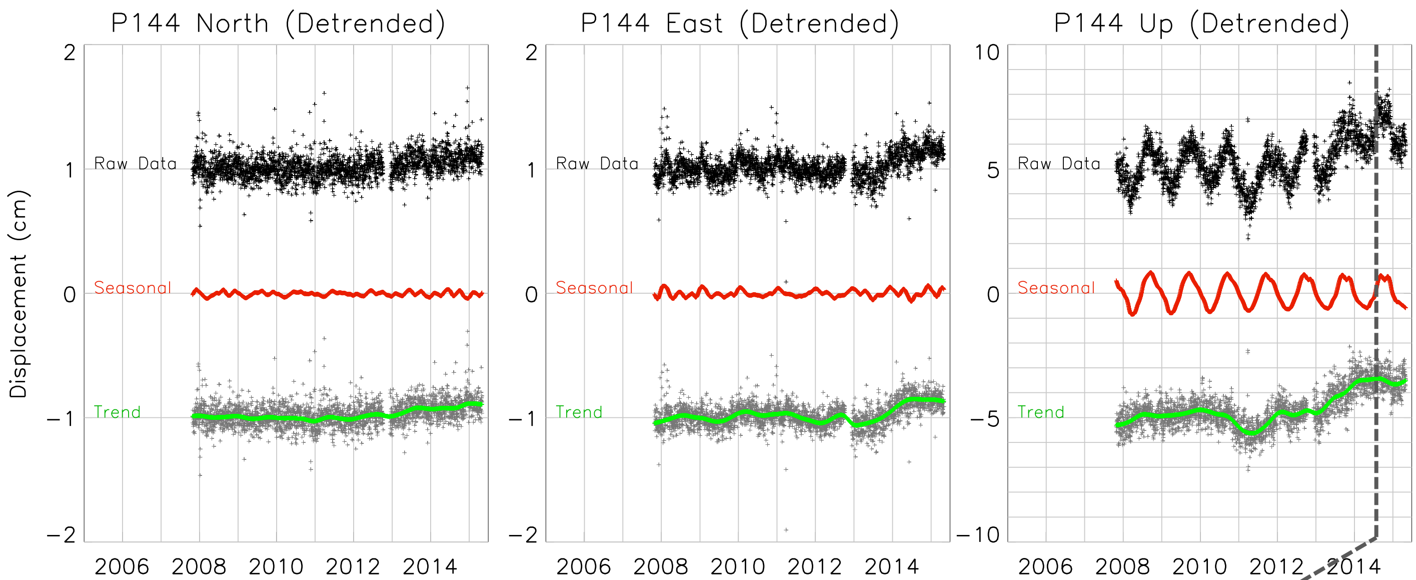


Non-sinusoidal, time-varying amplitude seasonal adjustment

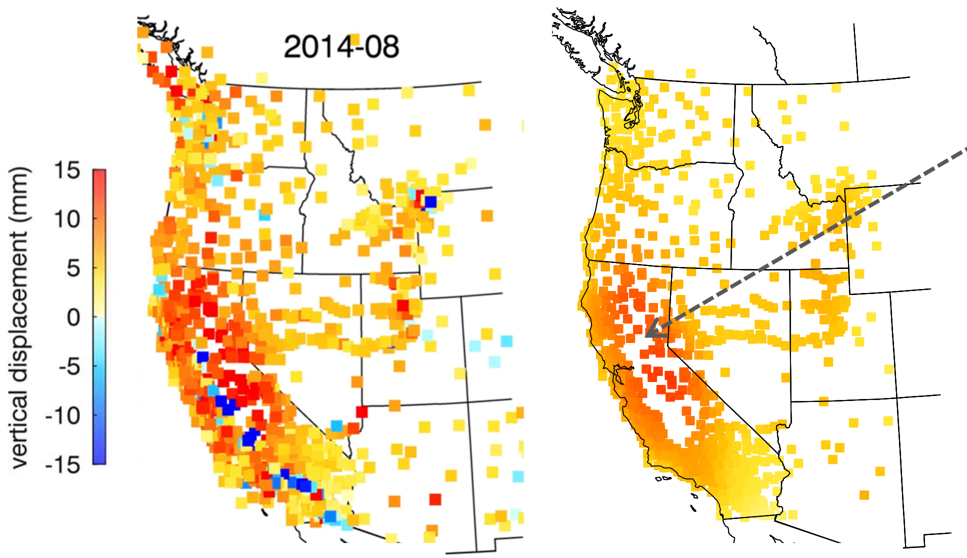
Borsa et al., Science, 2014

CGM development:

Issues to consider: large-scale hydrologic loading effect on vertical velocity estimates



- vertical velocity SNR << horizontal
- hydrological loading signals: 1mm ~ 1cm
- drought (unloading) leads to uplift since 2013



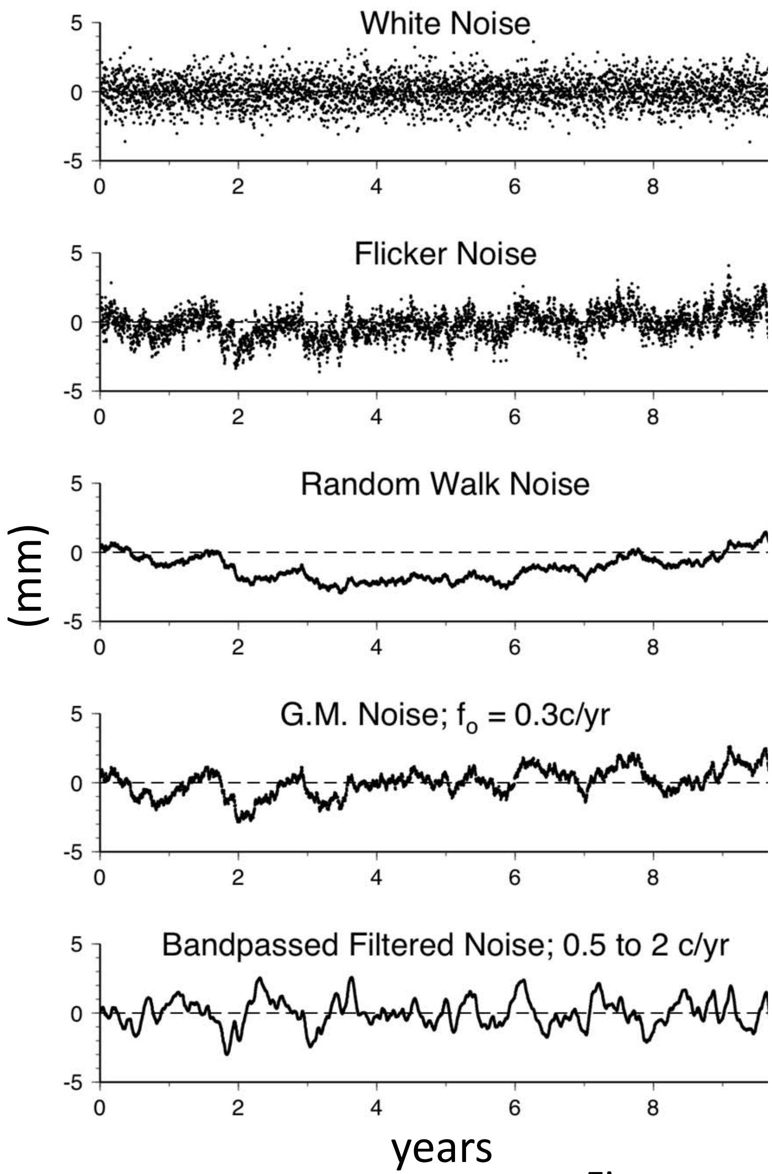
Observed Modeled

One can correct vertical positions with a best-fitting hydrological loading model, offering possible path to improved vertical velocity estimates. See poster #35 (Borsa et al.)

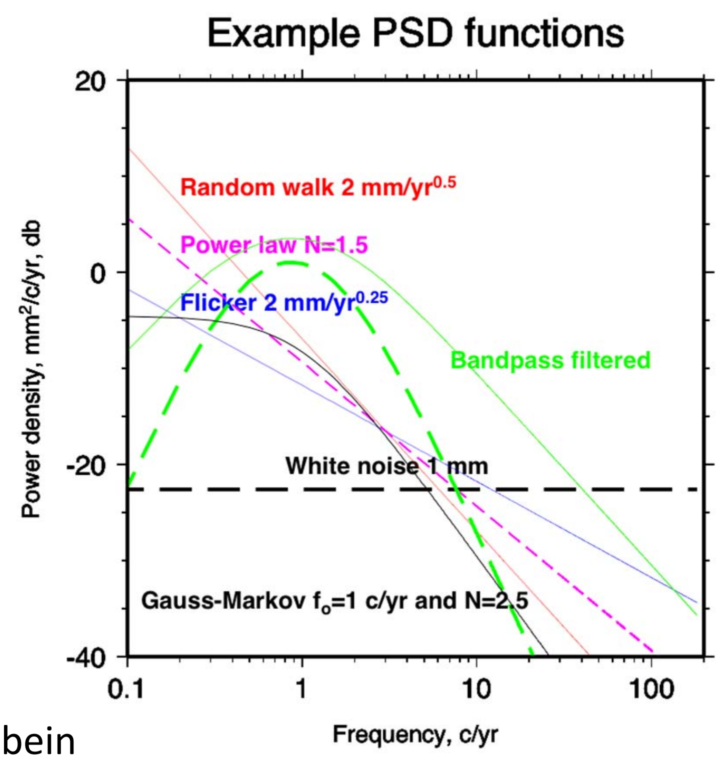
Figures courtesy A. Borsa

CGM development:

Issues to consider: temporally correlated noise



- Temporally correlated noise substantially increases velocity uncertainty, but is often underestimated without decadal or longer time series. (Langbein, J. Geod, 2012; Dmitrieva et al., J. Geod., 2015)
- Time-varying amplitude of seasonal trends can map into colored noise estimates, biasing velocity standard errors. (Davis et al. JGR, 2012)



Figures courtesy J. Langbein

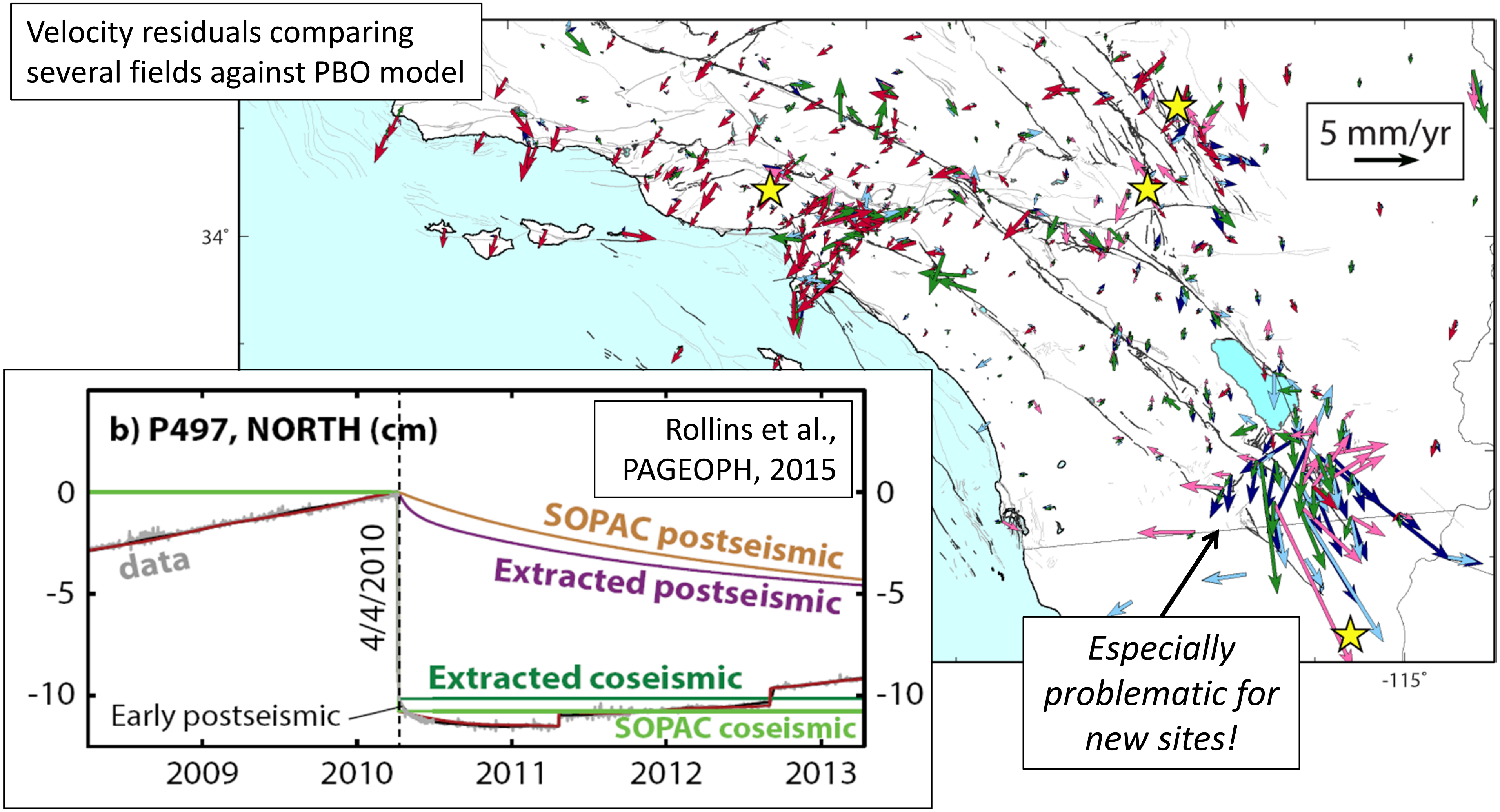
CGM development:

Issues to consider: model-dependent postseismic contamination of velocity estimates

Mitigation strategies include

- Use of multiple postseismic functions with different time constants (e.g., Rollins et al., 2015)
- Median-based trend estimators (e.g., Blewitt et al., AGU FM2014)
- Simultaneous estimate of velocities and source slip models (e.g., McCaffrey, poster #197)

Velocity residuals comparing several fields against PBO model



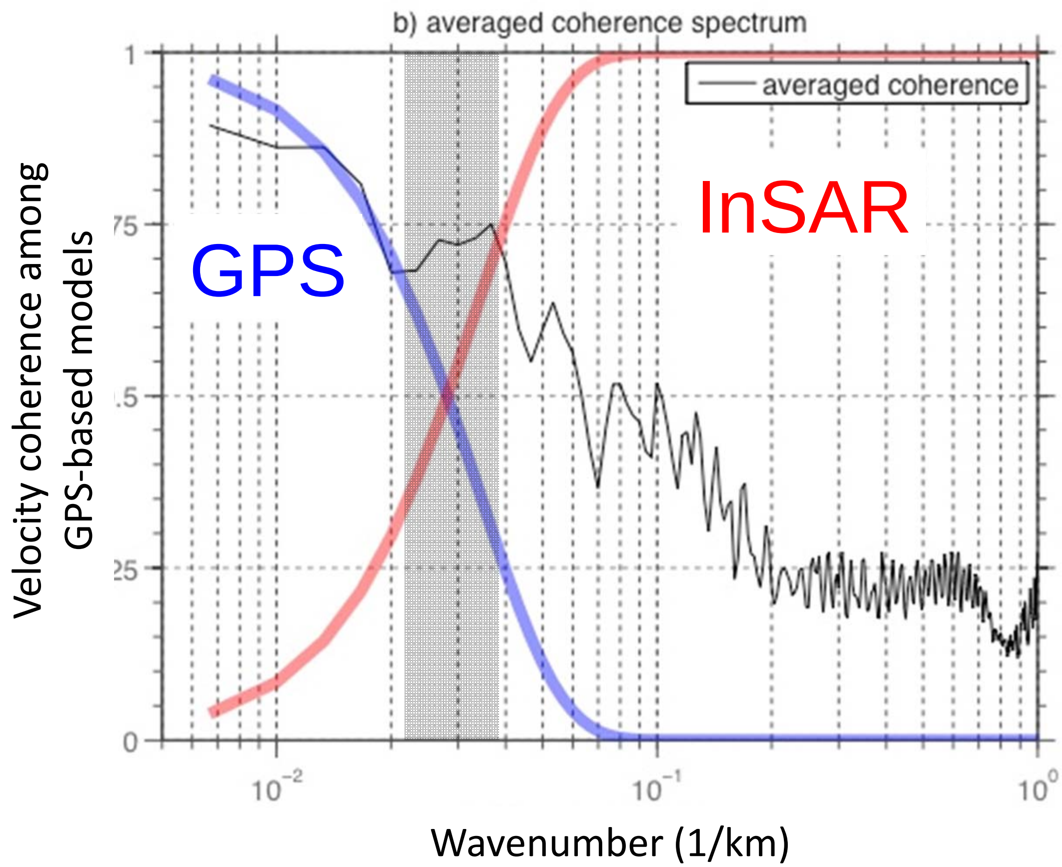
Especially problematic for new sites!

CGM development:
Integrating InSAR and GPS

- GPS provides high accuracy 3D vector data.
- GPS cannot measure small spatial scales (e.g., fault creep) due to sparse station spacing (median SoCal spacing 8 km).

- InSAR has superb spatial coverage for LOS motion.
- InSAR has large spatial scale errors due to troposphere, ionosphere, and orbital errors.
- Current temporal coverage aliases some signals.

We **need both GPS and InSAR** to provide multi-component deformation measurements that span length scales of 30 m to 2000 km with good spatial and temporal coverage.



GPS constrains signals with wavelength >=~40 km

Tong et al., JGR, 2013

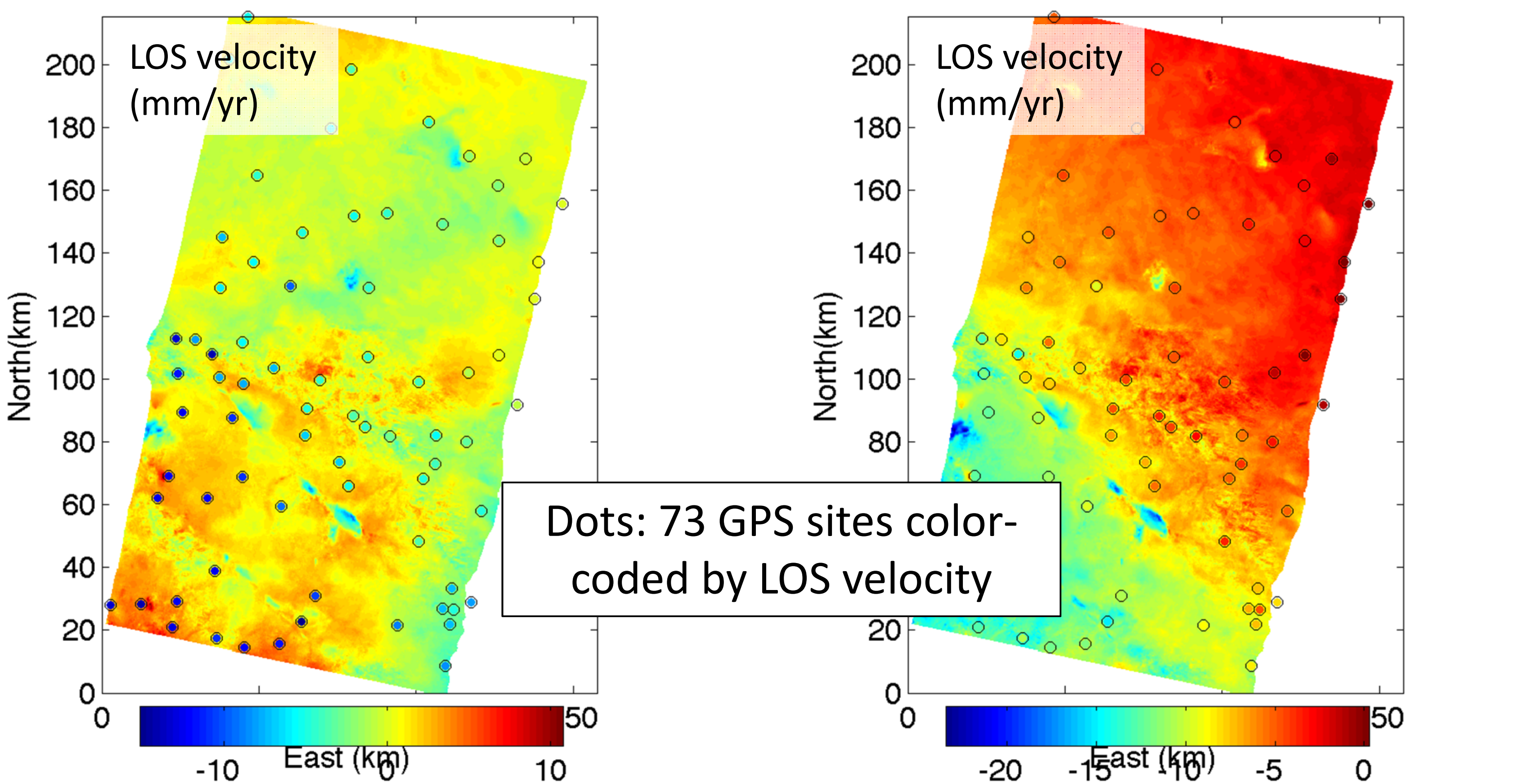
CGM development:

Comparison of InSAR time series analysis approaches for estimating LOS velocities

Comparison of LOS velocities obtained using different time series analysis techniques applied to same dataset

Filtered to remove orbital errors and atmospheric noise at long wavelengths

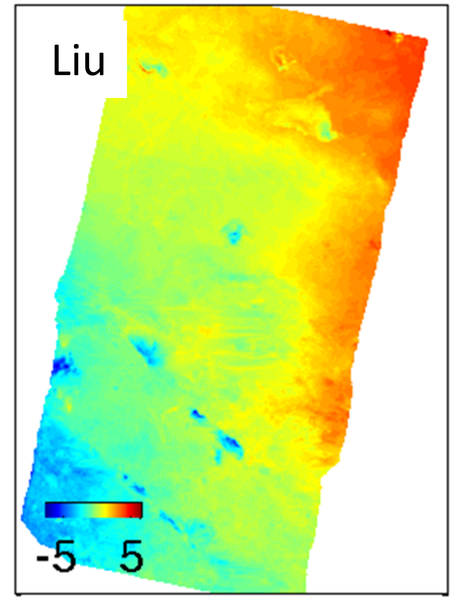
Orbital errors and atmospheric noise mitigated by using GPS velocity field as long wavelength constraint

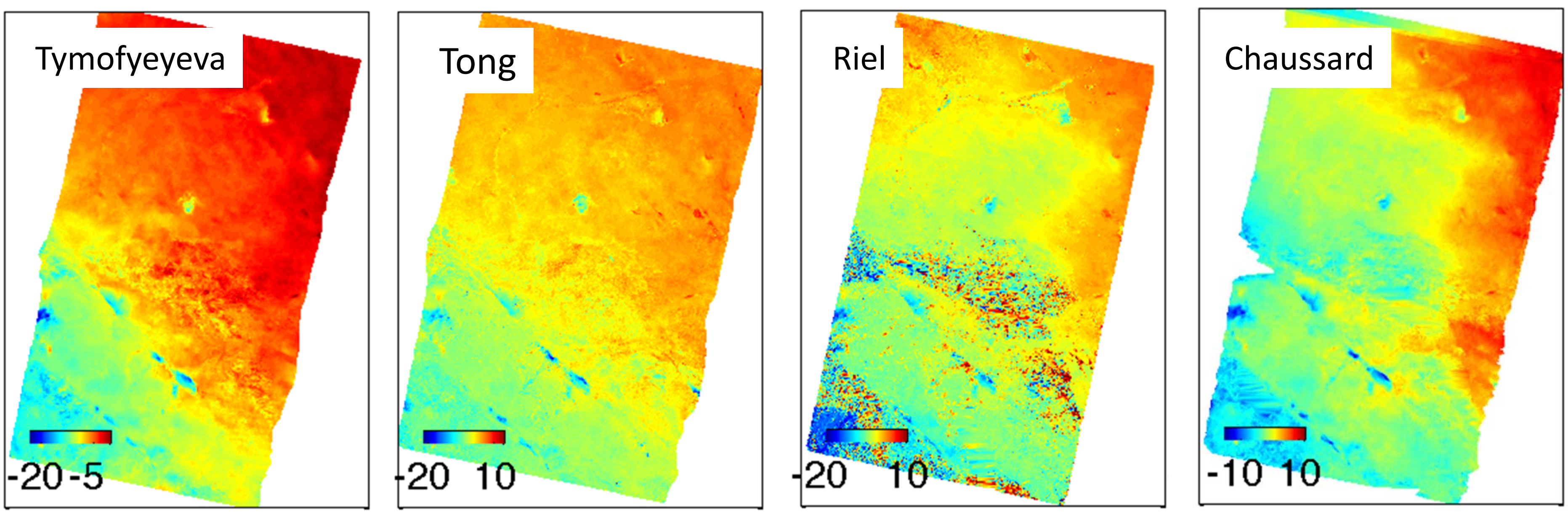


CGM development:

Comparison of InSAR time series analysis approaches for estimating LOS velocities

- Comparison of models which (except Liu)use GPS to constrain far-field rates
- Good agreement among models at short (<40 km) spatial scales
- Liu results show potential for InSAR-only velocity field over intermediate length scales (e.g., 100 km)

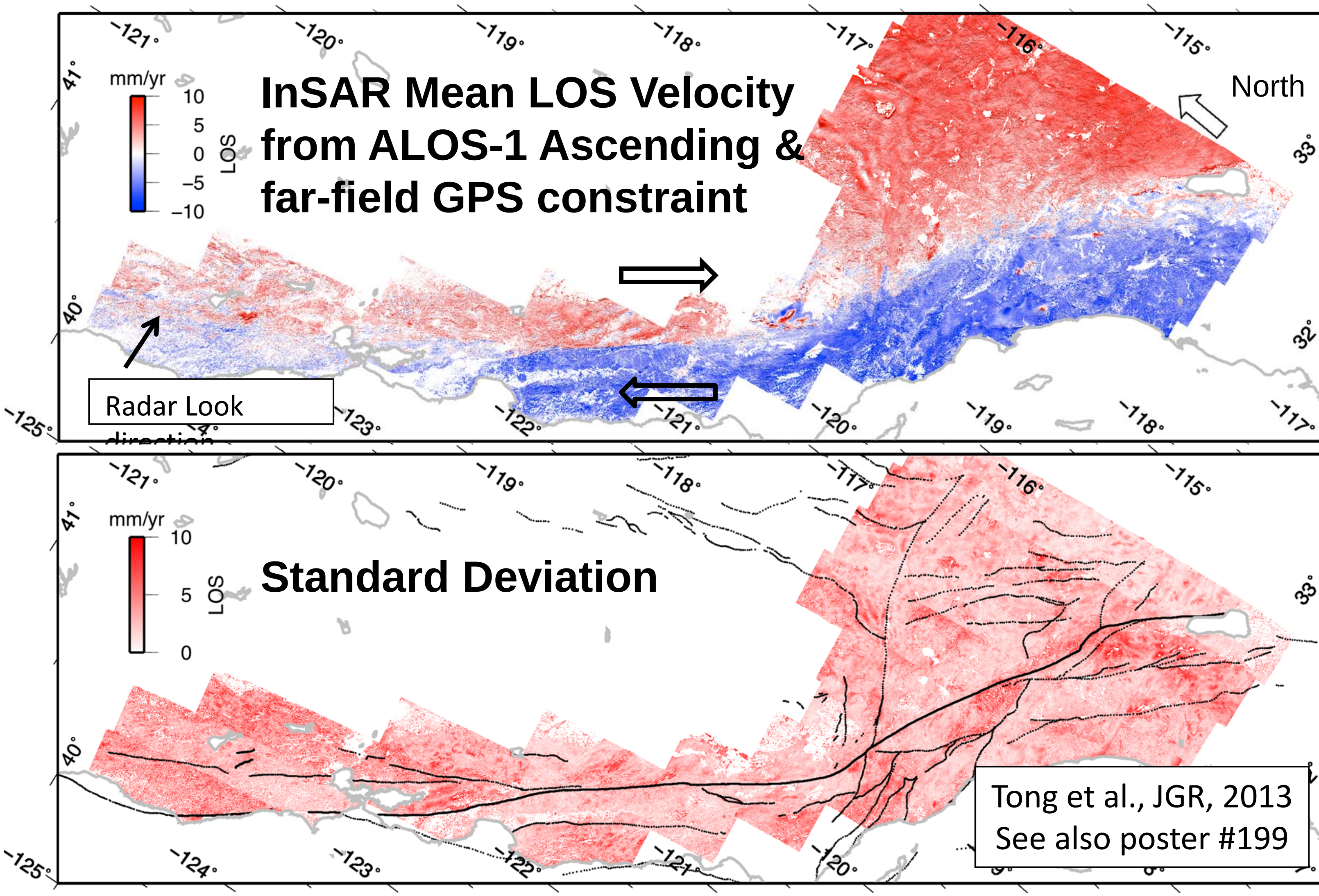




CGM development:

Initial InSAR-GPS LOS velocity field and standard deviation

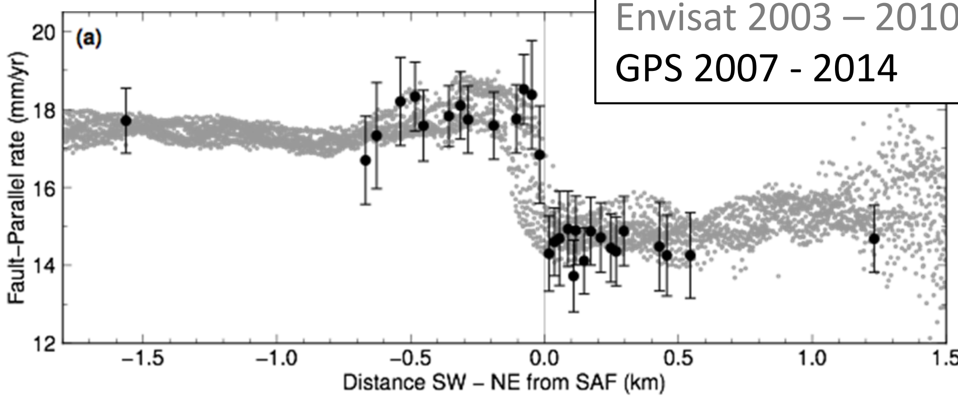
- Provides high spatial resolution creep observations, but with ambiguity between horizontal and vertical



CGM development:

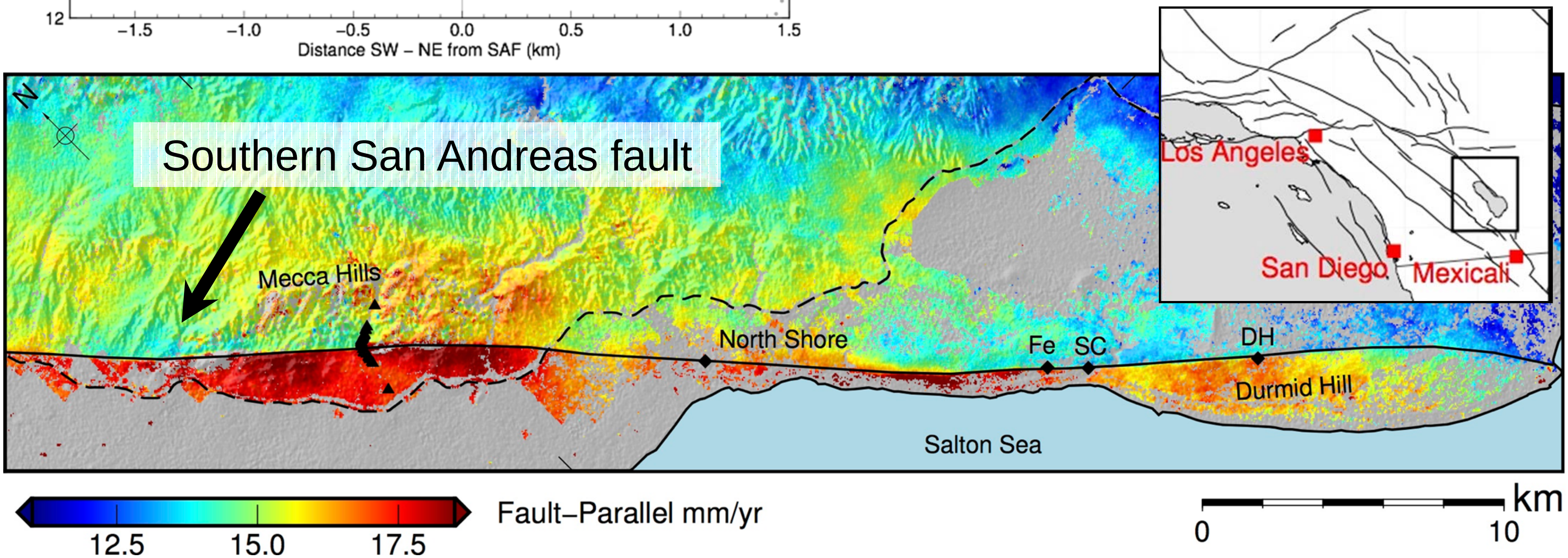
InSAR-GPS velocities with two look-directions

- Envisat data provide two independent Line-of-Sight observations
- GPS records direction of horizontal motion
- Jointly, InSAR and GPS constrain **Vertical** and **Fault-Parallel** motion



Envisat 2003 – 2010
GPS 2007 - 2014

Lindsey et al. (JGR, 2014)
See also poster #209



The Community Geodetic Model

Looking ahead…

InSAR time series analysis with ERS, ENVISAT, and ALOS-1 data is difficult:

- The cadence of acquisitions is irregular and frequency too low.
- The baselines are not well controlled, limiting ability to make redundant interferograms for atmospheric/ionospheric correction.
- Seasonal signals are aliased due to poor temporal sampling.
- Agricultural/vegetated areas suffer temporal decorrelation.
- Infrequent acquisitions limit usefulness for tracking transient motion.

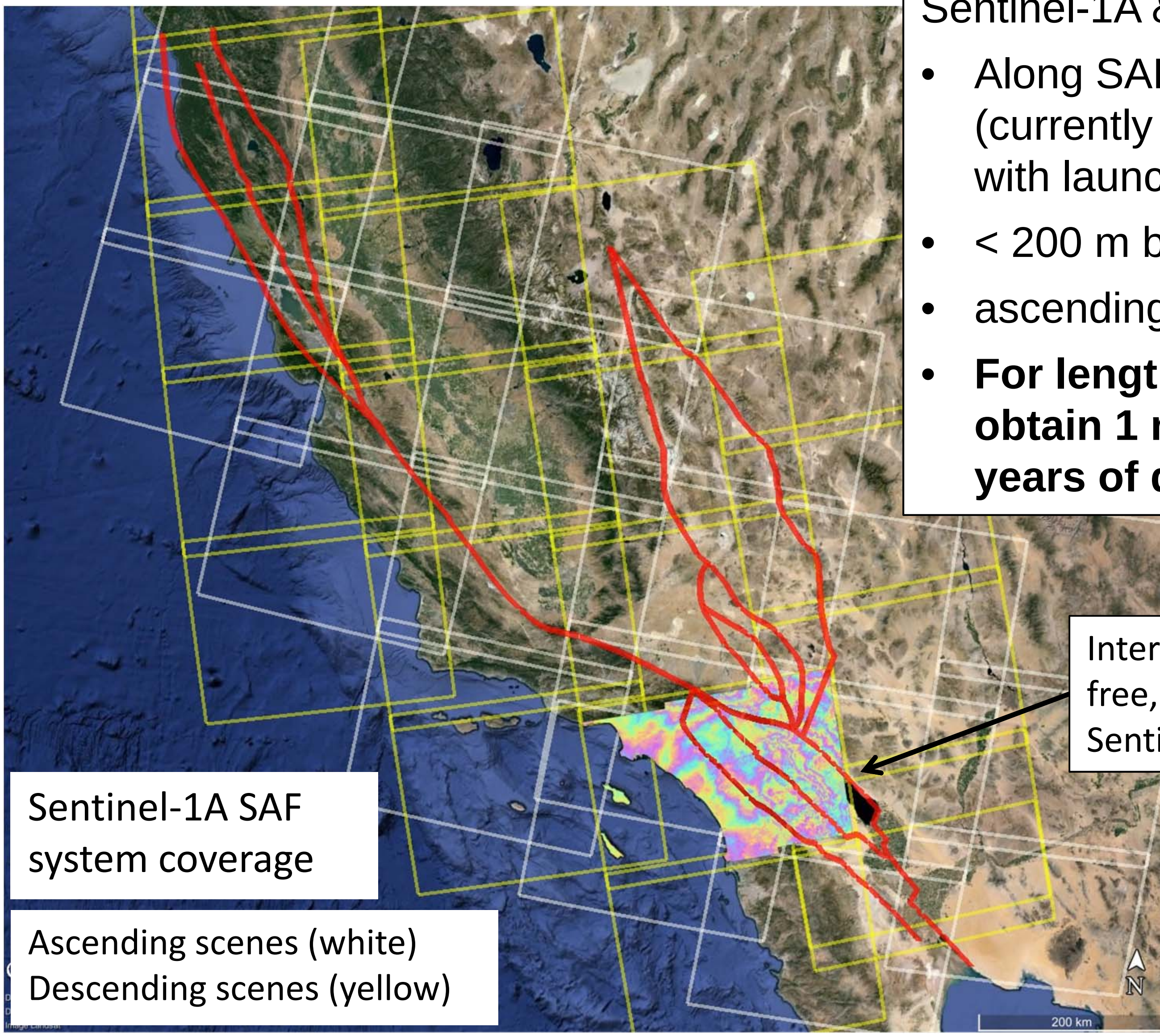
→ **New SAR missions address these issues**

Looking ahead:

New SAR missions will be much better suited for time series analysis

Sentinel-1A & 1B (ESA)

- Along SAF 12-day repeat possible (currently 24-day; can be 6-day with launch of Sentinel-1B in 2016)
- < 200 m baseline control
- ascending and descending
- **For length scales <20 km, can obtain 1 mm/yr precision with 3 years of data**



Sentinel-1A SAF system coverage

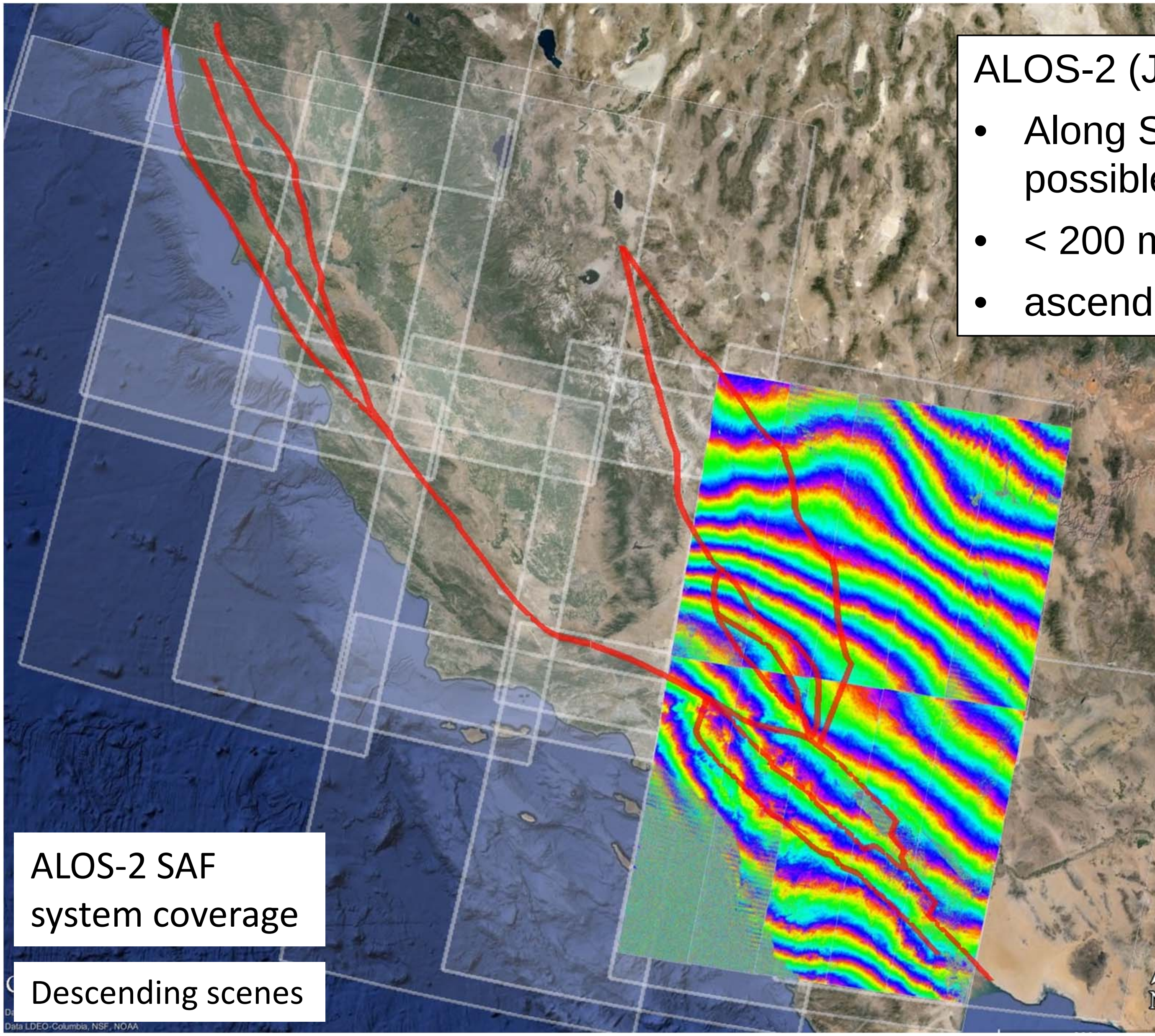
Ascending scenes (white)
Descending scenes (yellow)

Interferogram constructed using free, open source software from Sentinel-1 Toolbox

See poster #194

Looking ahead:

New SAR missions will be much better suited for time series analysis



ALOS-2 (JAXA)

- Along SAF: 14-day repeat possible (42-day currently)
- < 200 m baseline control
- ascending and descending

See poster #194

The Community Geodetic Model

Looking ahead…

Techniques for estimating vertical velocities from GPS, and through joint use of multiple data types, are advancing to new levels with recent, targeted research.

Looking ahead:
New approaches for quantifying vertical motion

UNR MIDAS algorithm

- Median-based velocity estimate insensitive to steps, outliers, seasonal, transients
- Weighted median-based geographic spatial filtering
- Results highlights trends with wavelength > station spacing

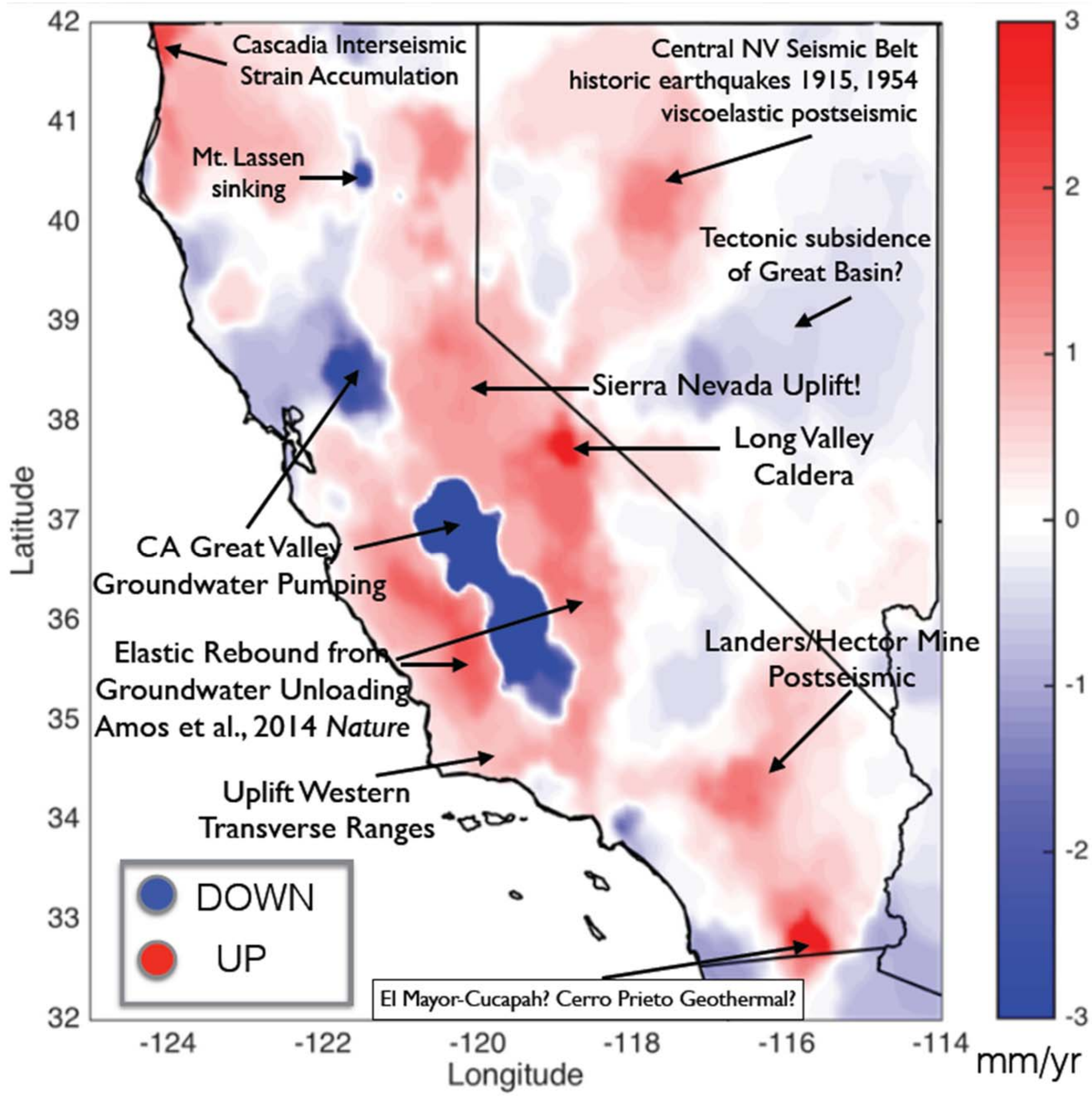
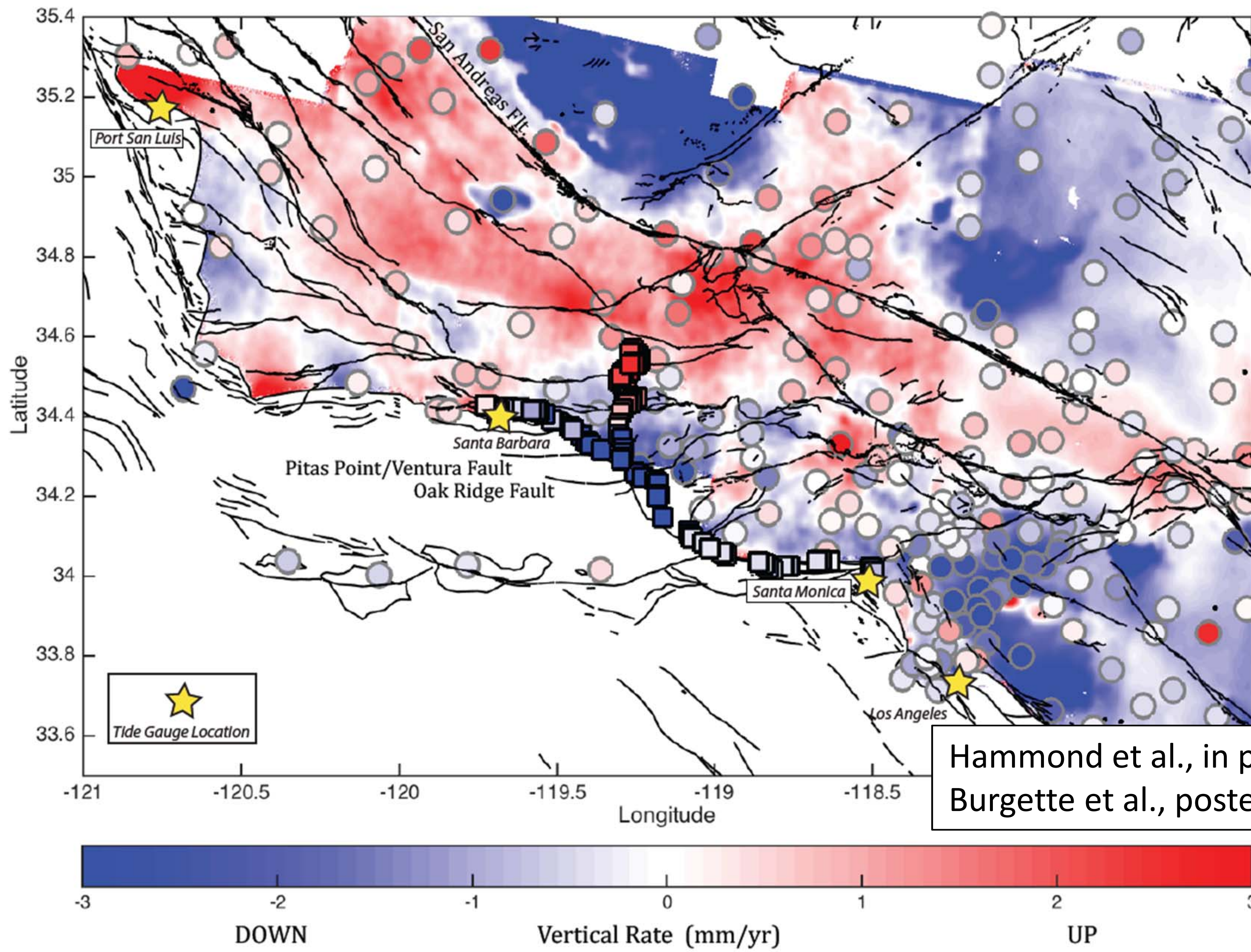


Figure courtesy W. Hammond

Looking ahead:

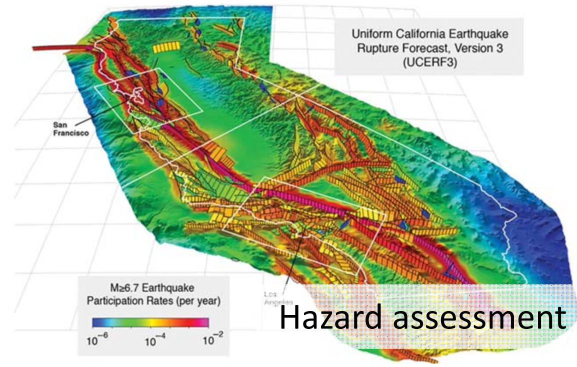
New approaches for quantifying vertical motion

Merging GPS, InSAR, tide gauge, and leveling data to derive vertical rate map that best fits the four data-types.



Hammond et al., in prep.
Burgette et al., poster #201

The Community Geodetic Model



Some final thoughts

- Community models bring together broad expertise and diverse perspectives.
- Requires a suite of models using different approaches.
    - Allows users to choose models based on their applications.
    - Reveals the effect of modeling choices on results.
    - Aids in evaluating the scope of epistemic uncertainty.
- SCEC IT infrastructure and broader community resources facilitate this.
- ***Several models have been contributed – how about yours?***