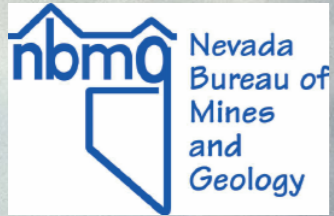


Uplift Across the Western Transverse Ranges from Integrated Analysis of GPS, InSAR, Leveling and Tide Gauge Data

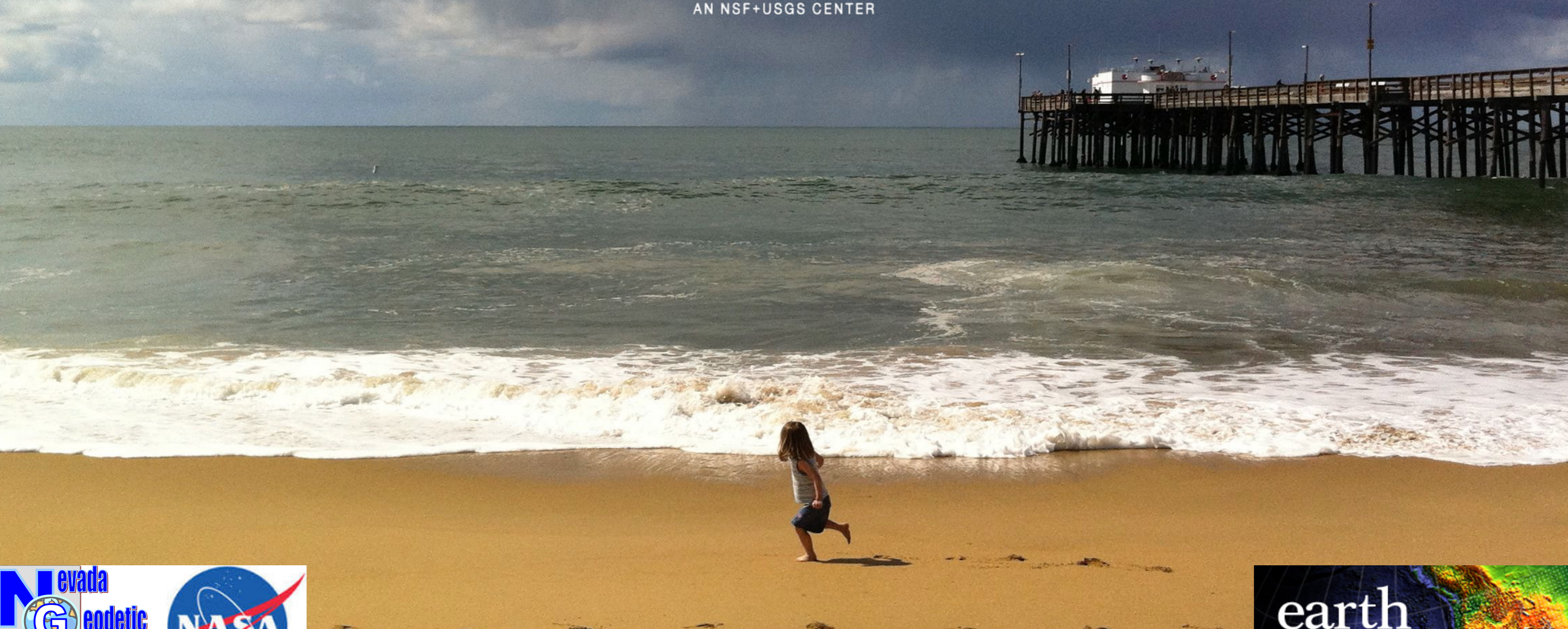


Bill Hammond, Reed Burgette,
Kaj Johnson, Geoff Blewitt

whammond@unr.edu



SC/EC
AN NSF+USGS CENTER



SCEC Ventura Special Fault Study Area Workshop, Palm Springs CA, Sept. 10, 2016



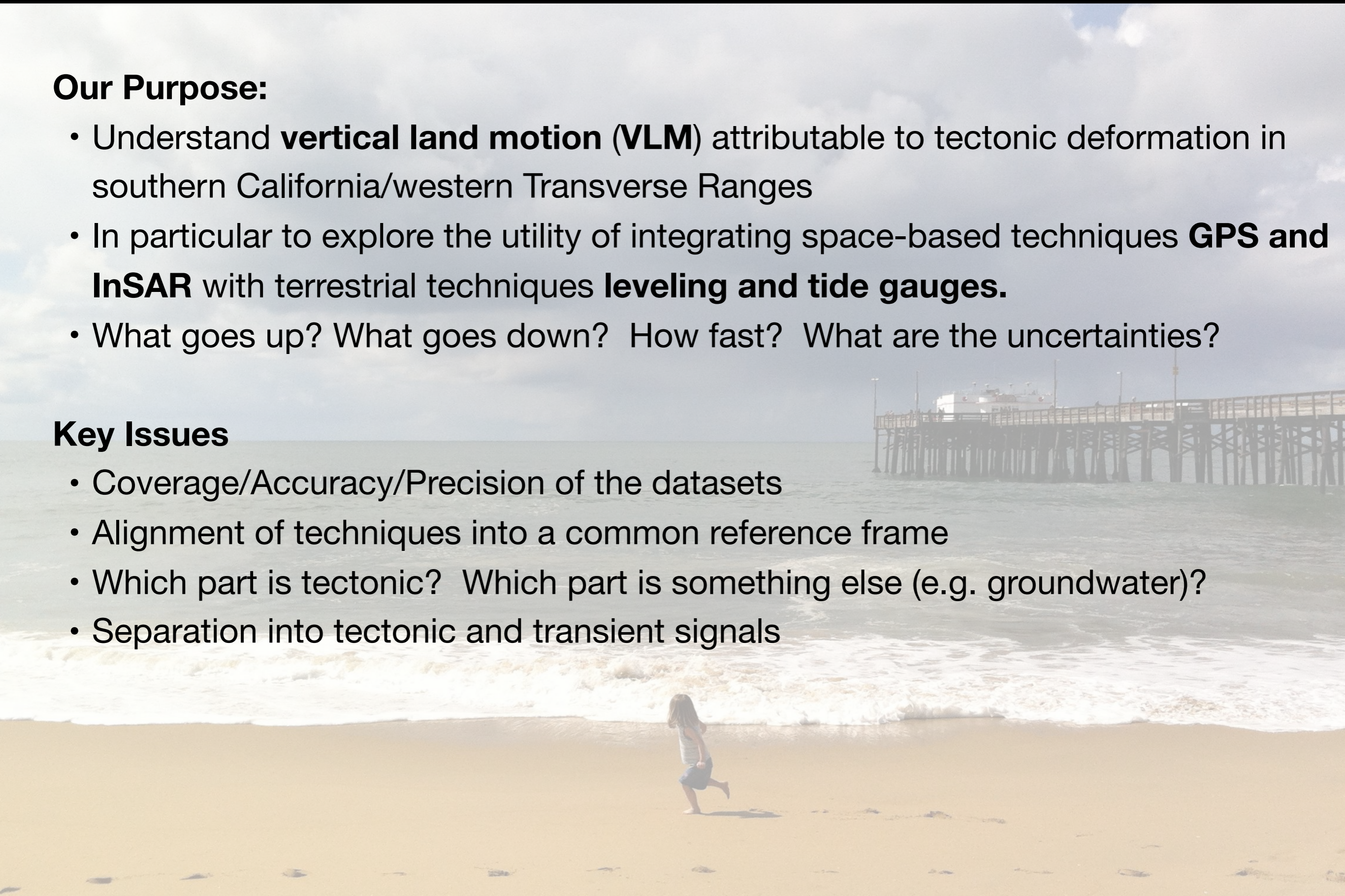
Vertical Land Motion

Our Purpose:

- Understand **vertical land motion (VLM)** attributable to tectonic deformation in southern California/western Transverse Ranges
- In particular to explore the utility of integrating space-based techniques **GPS and InSAR** with terrestrial techniques **leveling and tide gauges**.
- What goes up? What goes down? How fast? What are the uncertainties?

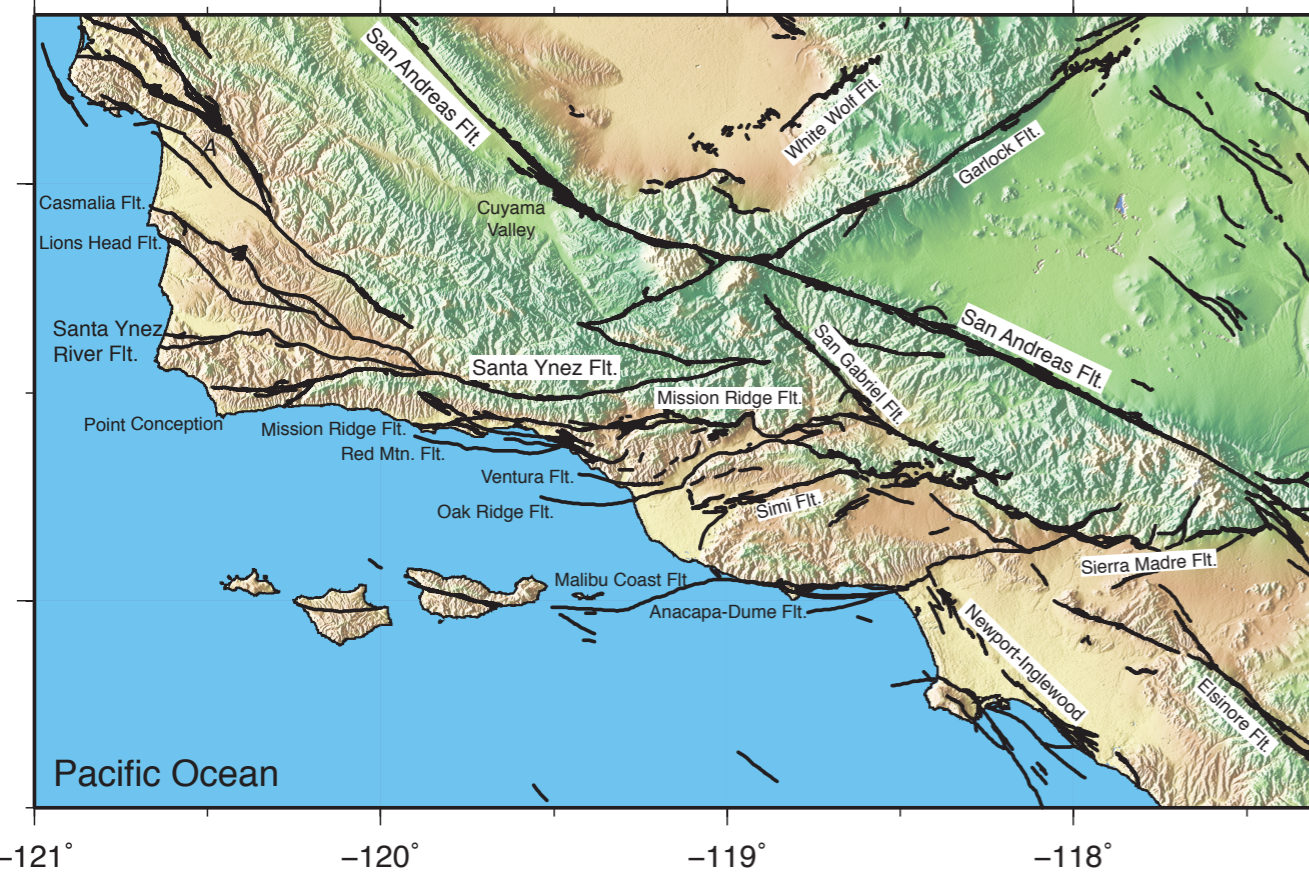
Key Issues

- Coverage/Accuracy/Precision of the datasets
- Alignment of techniques into a common reference frame
- Which part is tectonic? Which part is something else (e.g. groundwater)?
- Separation into tectonic and transient signals

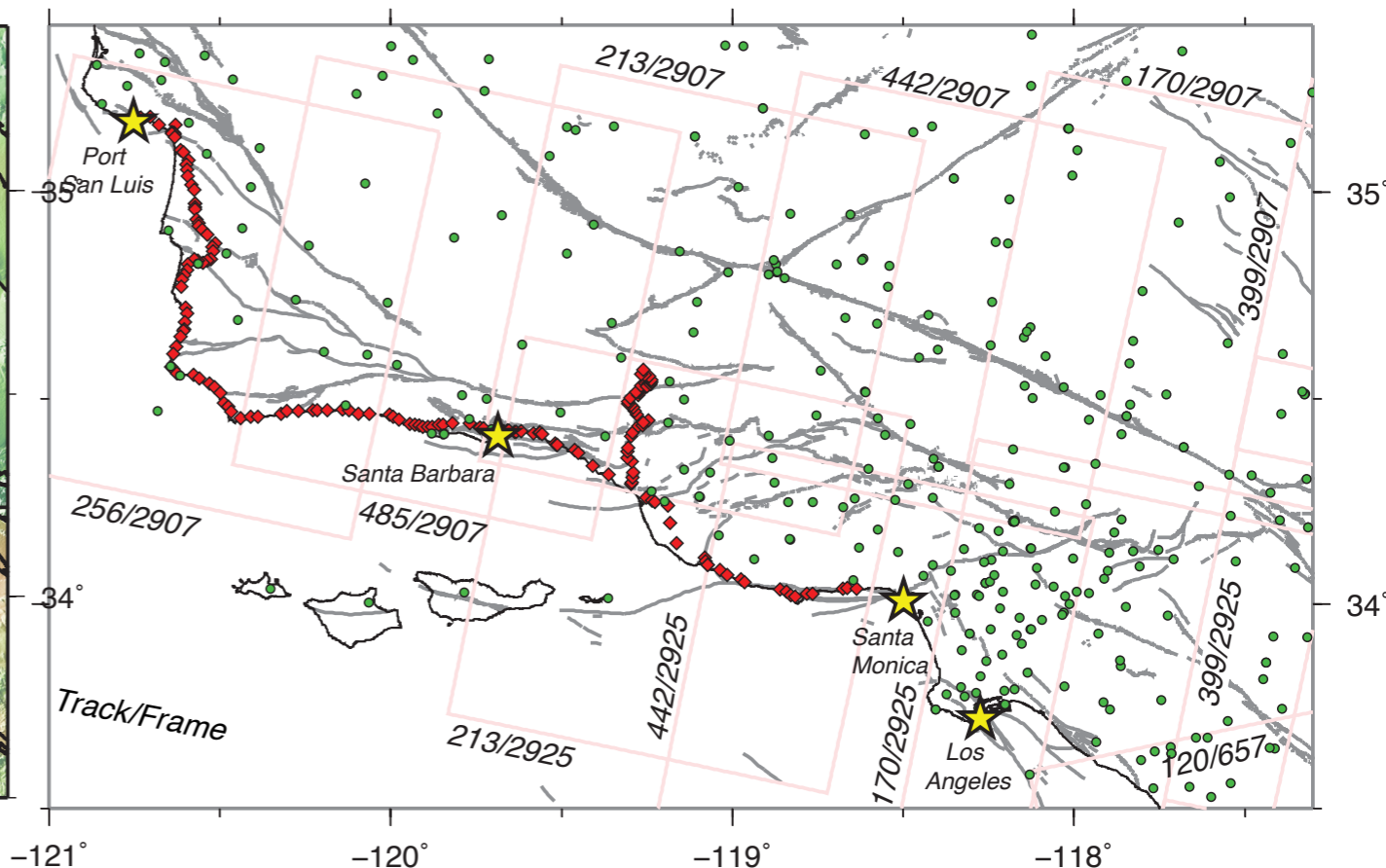


Data Resources

Western Transverse Ranges



GPS, Leveling, Tide Gauges, InSAR



Some details

InSAR - ERS+ENVISAT data from WinSAR archive. Gamma software processing. 20 track/frame sets, all but one descending. VLOS using SBAS. Aligned to strain rate map (Kreemer et al., 2012) projected to LOS to remove horizontal signal. Un-project to vertical, quadratic wrap to mosaic of vertical rates.

GPS - Processed at NGL with GIPSY using JPL products. Data between 1996.0 to present. NA12 reference frame. Use stations in domain with >5 years of data. 204 stations meet criteria. Uncertainty in rate wrt Earth center near 0.5 mm/yr.

Leveling - 16 first-order repeated leveling lines obtained from NOAA. Decades of data along dense coastal and inland lines, processing linked to tide gauges. Uncertainty in relative rates near 0.3 - 1.7 mm/yr.

Tide Gauges - Vertical rates of ocean wrt land determined including colored noise (Burgette et al. 2009, 2013). Flip sign and shift to align into GPS reference frame. Uncertainty in rate near 0.2 mm/yr.

- GPS
- ◆ Leveling
- ★ Tide Gauges
- InSAR

GPS Velocities: MIDAS

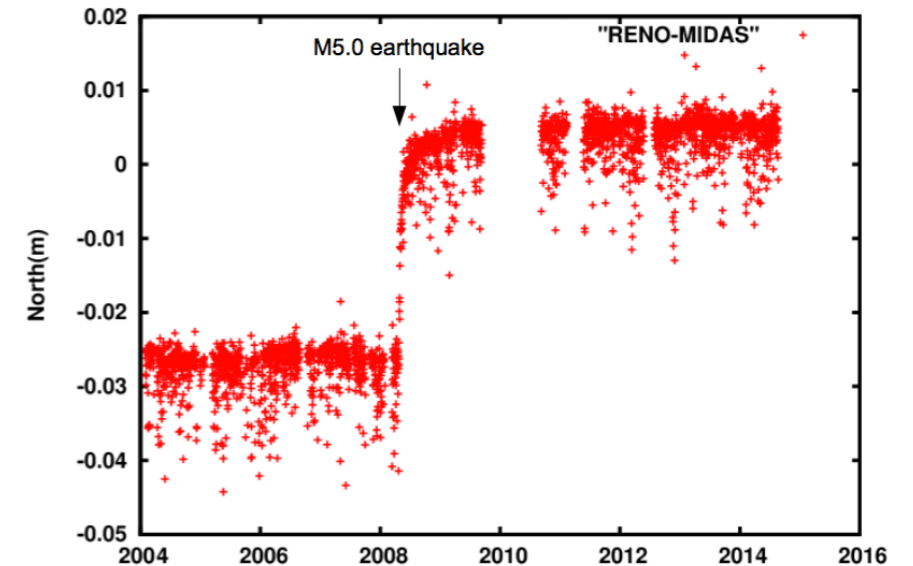
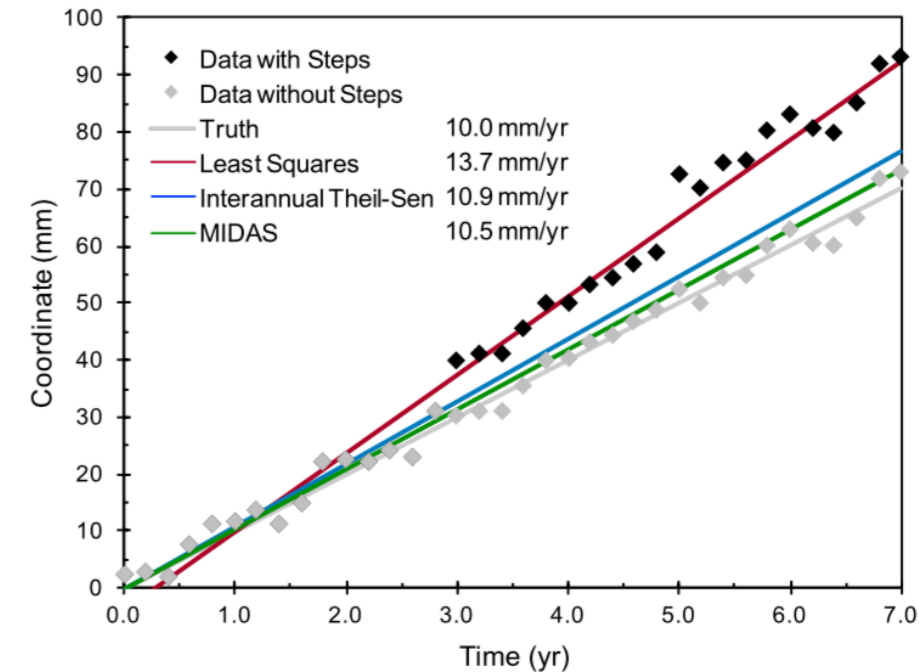
New technique helps isolate the 'long-term' trend in time series data

- Non-parametric time series trend estimator based on Theil-Sen
- Not least squares: Robust median-based estimate of station velocity
- Median trend estimator
- Insensitive to steps, outliers, seasonal terms and heteroscedasticity in noise structure
- Tolerant at up to 29% outliers and steps
- Similar results to least squares in "normal cases"
- More stability in odd cases without detailed parameterization
- Fast algorithm, simple form, suitable for automated large N analyses
- Most accurate method in DOGEx exercise
- All MIDAS rates (3 components) online at <http://geodesy.unr.edu>
- Works for other kinds of time series data too (e.g. tide gauges)

$$\hat{v} = \text{median}_i (x_{i+365} - x_i)$$

$$\sigma = 1.4826 \text{ median}_i |x_{i+365} - x_i - \hat{v}|$$

$$\sigma_v = 1.2533 \frac{\sigma}{\sqrt{N/4}}$$



Example: Station RENO

- Detrended using MIDAS rate,
- Accurately estimates pre-seismic trend

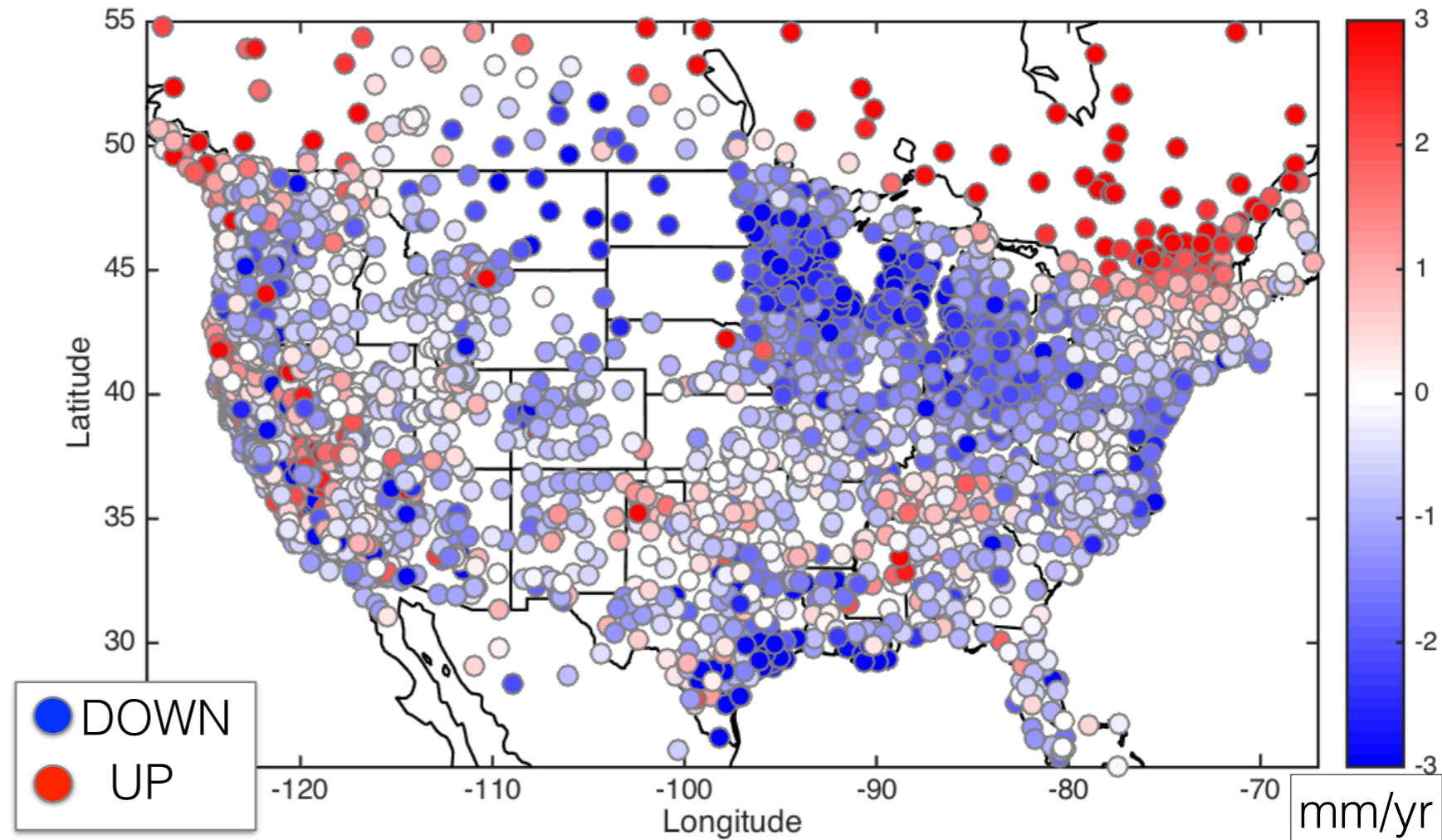
Blewitt, G, C. Kreemer, W.C. Hammond, J. Gazeaux, 2016, MIDAS robust trend estimator for accurate GPS station velocities without step detection, *J. Geophys Res.-Solid Earth*, 121, doi:10.1002/2015JB012552 [open access]

GPS Imaging of Vertical GPS Velocity

This method helps isolate the signals from large scale processes such as tectonics and GIA
Deemphasizes signals present only at single stations

- MIDAS addresses robustness in the temporal part
- GPS Imaging tackles the spatial part
- Weighted median-based geographic spatial filtering (despeckling) applied
- Insensitive to outliers
- Preserves edges in field
- Suitable for focusing on signals that are consistent at multiple stations
- Emphasizes signals with wavelength greater than the station spacing
- Efficient: Helps cope with data from 1000s of stations

MIDAS Vertical Rates



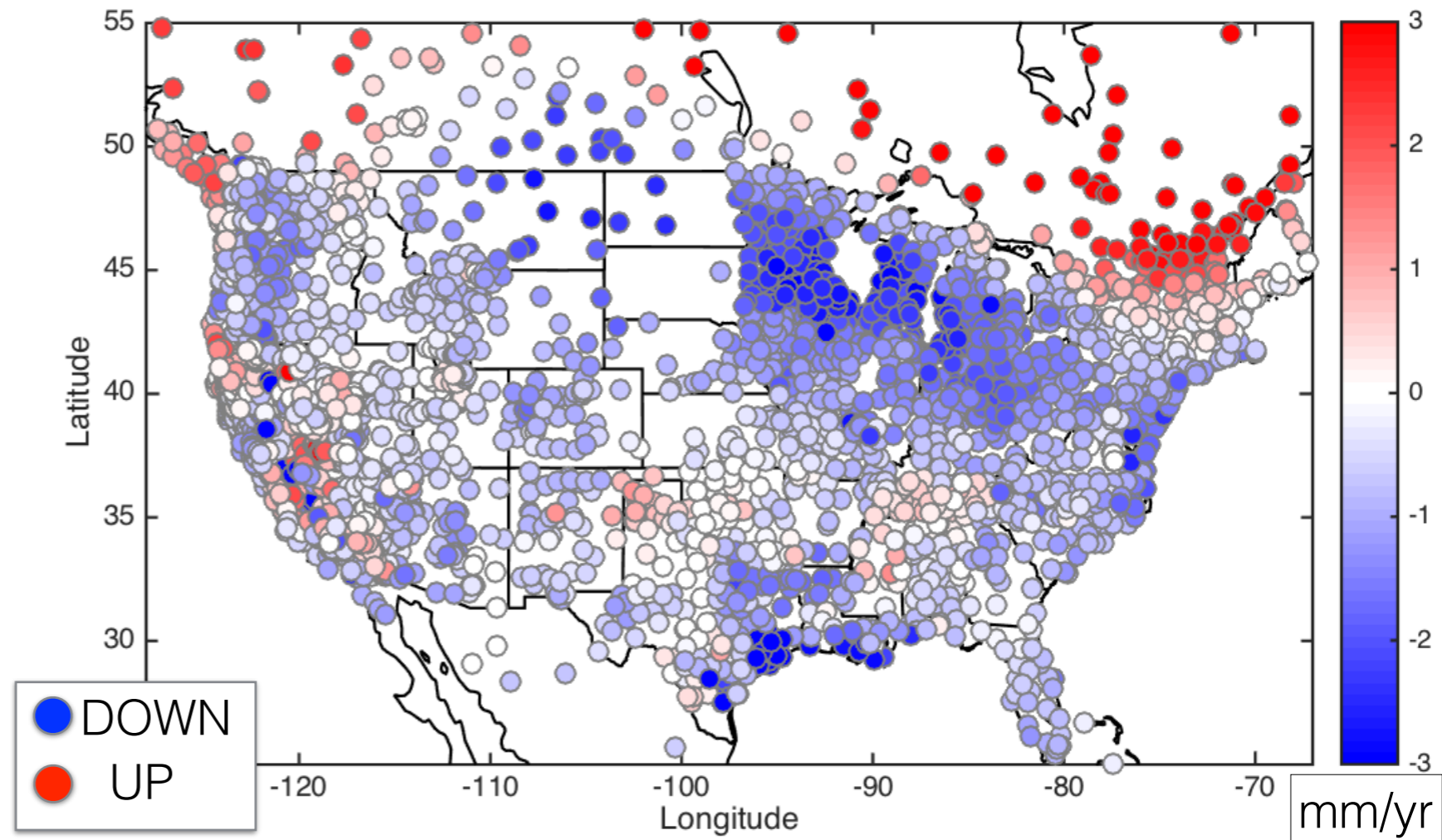
- Uses 5 year time minimum duration for time series
- IGS08 Reference frame

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MIDAS Rates Despeckled Weighted-Median Spatial Filtered



example benefit of median spatial filtering
an photograph with lots of speckle noise

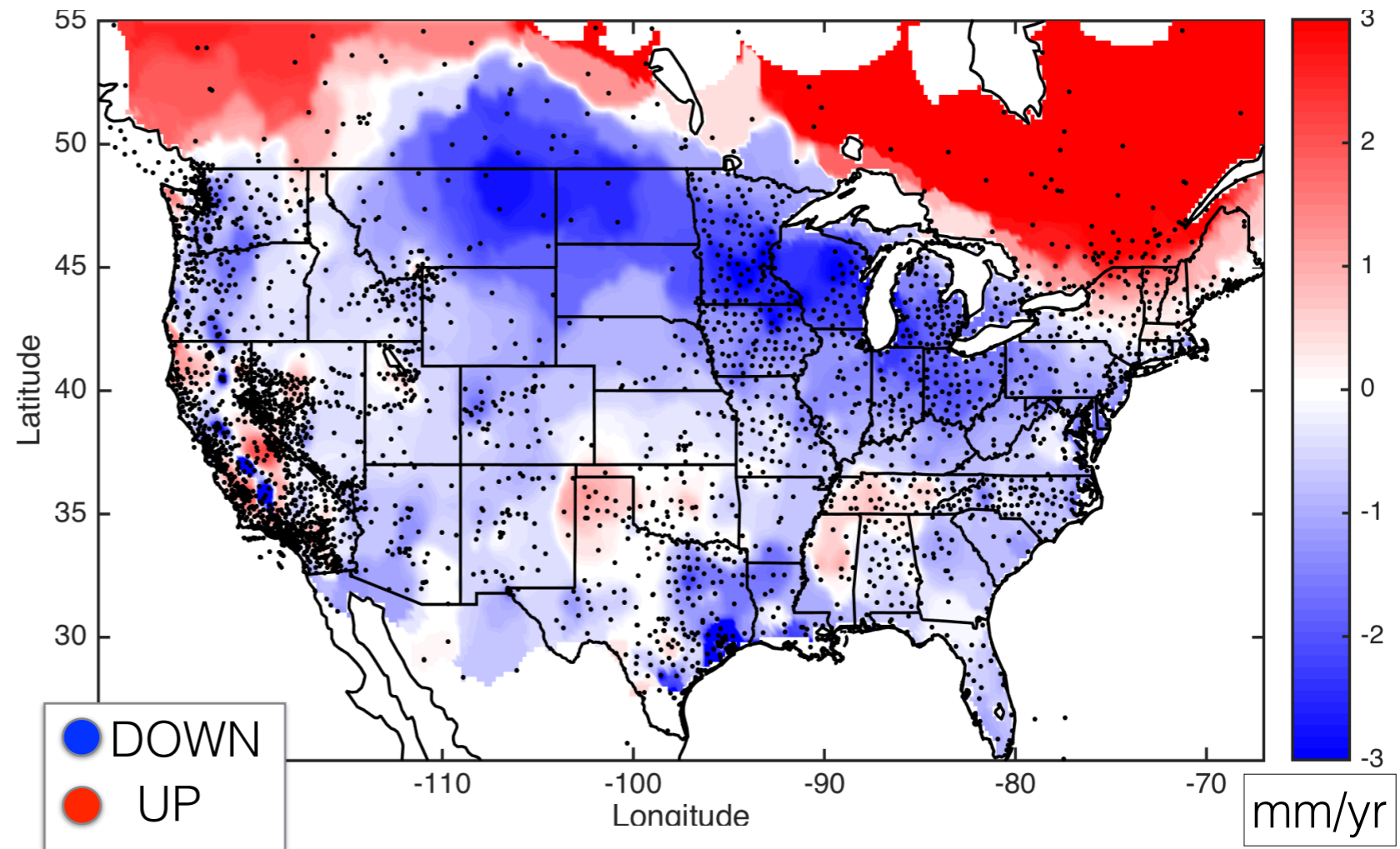


GPS Imaging of Vertical GPS Velocity: North America

Seeing, for example:

- GIA very well
- Location of hinge between uplift and subsidence
- Forebulge collapse south of hinge driving subsidence along east coast 1-2 mm/yr
- Gulf coast subsidence, a combination of pumping and sediment loading
- Technique enhances signals with geographic coherence that are detected in many stations
- GPS Imaging of surface manifestation of mantle flow

MIDAS Rates with GPS Imaging



- Uses 5 year time minimum duration for time series
- IGS08 Reference frame

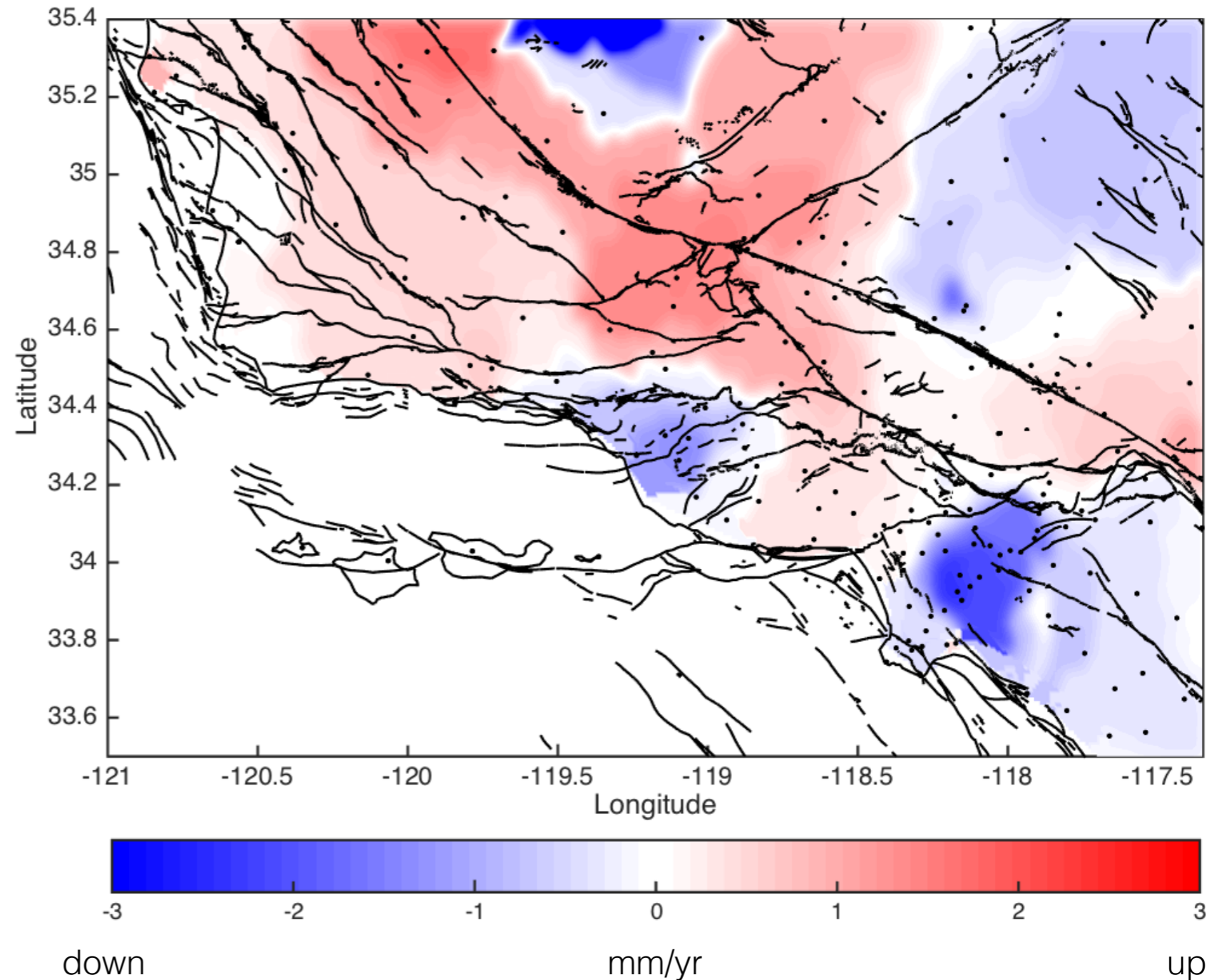
Hammond, W.C., G. Blewitt, C. Kreemer, 2016, GPS Imaging of vertical land motion in California and Nevada: Implications for Sierra Nevada uplift, *J. Geophys Res.-Solid Earth*, in review

GPS Imaging of Vertical GPS Velocity: West Coast

GPS-Only Imaging

Signals:

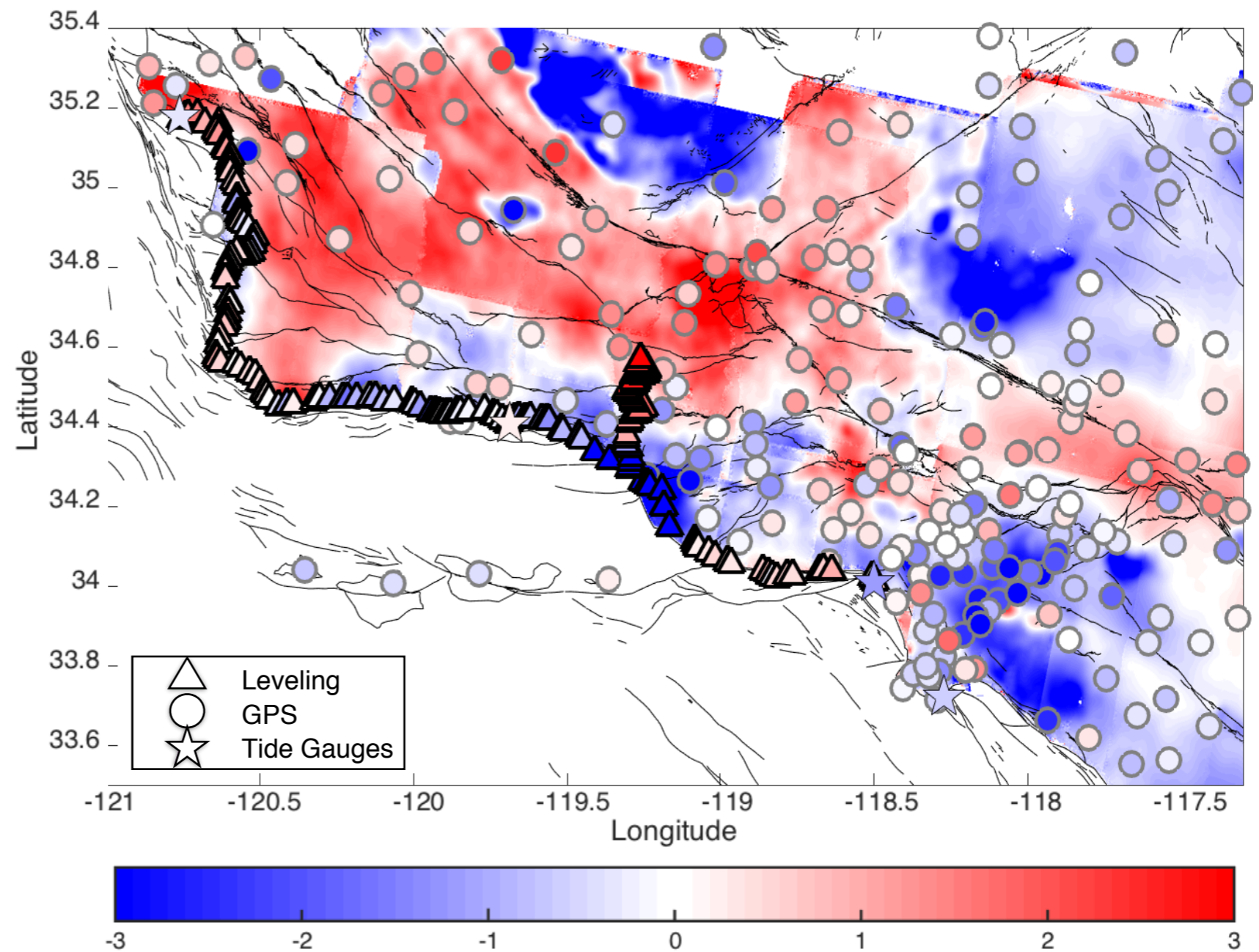
- Central Valley subsidence
- Peripheral elastic unloading from groundwater extraction
- Western Transverse Ranges uplift
- San Andreas/San Gabriel Uplift
- Subsidence in Ventura/LA Basins
- Landers/Hector Mine Postseismic uplift to the east



GPS+ Imaging of Vertical GPS Velocity: West Coast

GPS+InSAR+Tide Gauges+Leveling Imaging

- All techniques aligned to common GPS ref. frame
- Replace GPS Imaging with InSAR
- Nice spots of agreement on aquifers, across ranges
- Better control on San Gabriel uplift
- Sees groundwater and tectonic signals
- Works well where GPS networks are dense + other techniques present
- Seams between InSAR scenes



Alignment Technique:

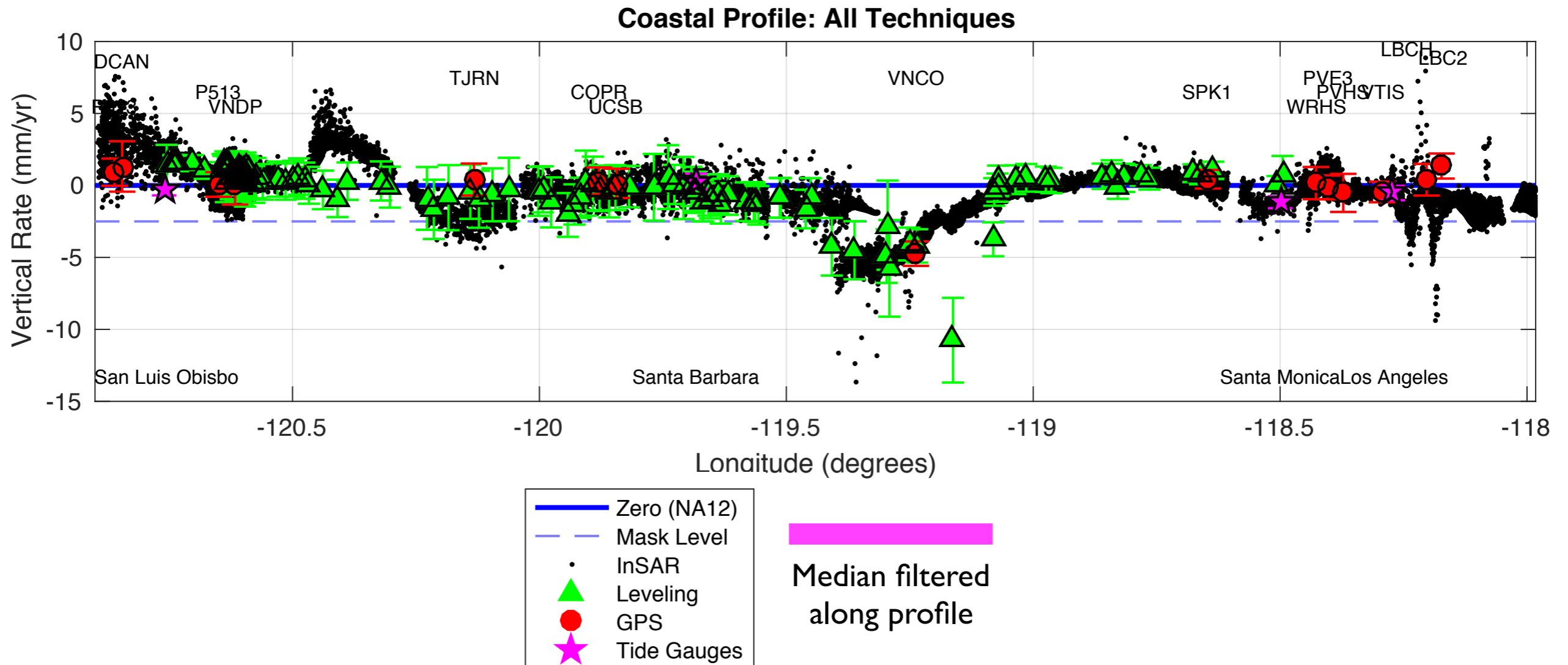
Shift & flip tide gauges

Leveling tied to tide gauges

Align to GPS

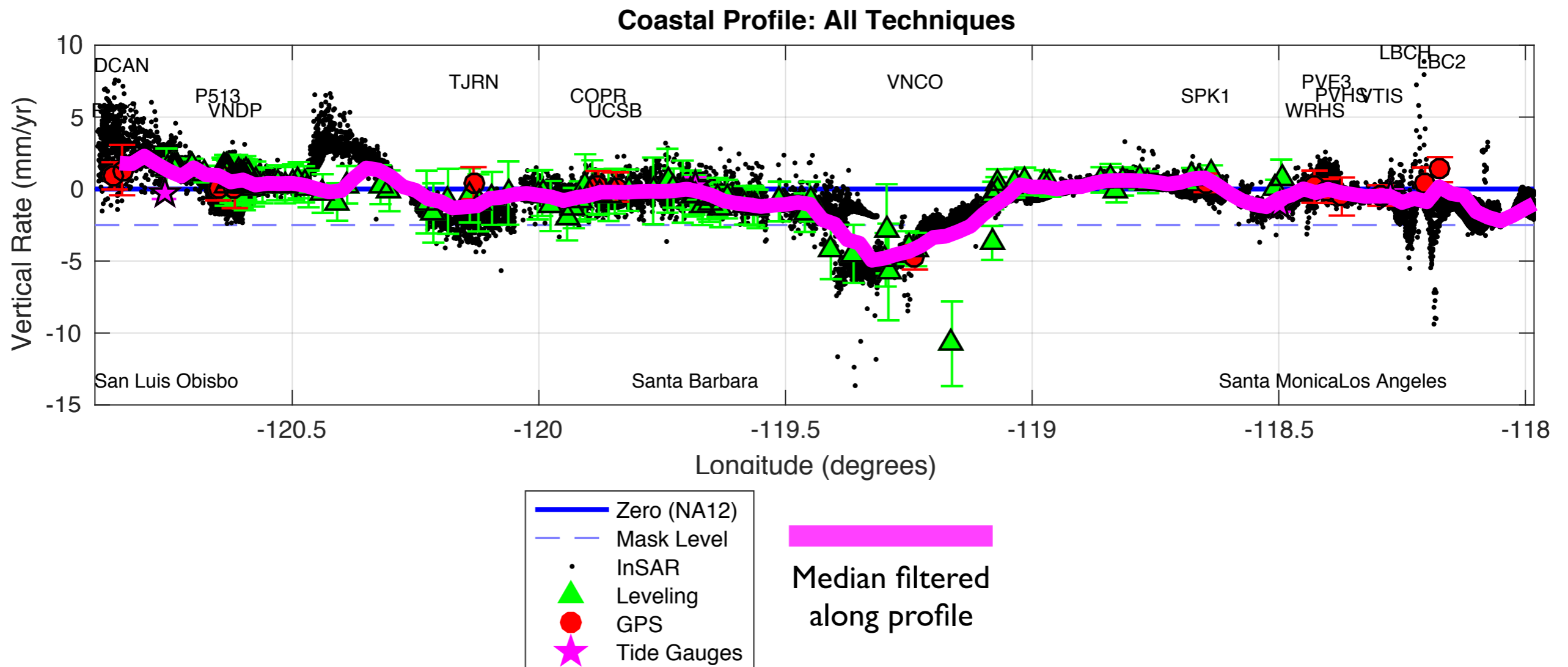
Wrap InSAR to GPS+Leveling+Tide Gauges (quadratic ramp)

Profiles



- Vertical rates along coastal profile (San Luis Obispo to Los Angeles)
- Alignments show internal agreement to ~ 1 mm/yr RMS
- InSAR a little unstable in a few places where GPS coverage sub-optimal
- Median filtered (robust) profile insensitive to outliers
- Best explanation of the data along coast of S. California
- Tide gauges aligned to IGS08 implies 0.99 ± 0.31 mm/yr regional geocentric sea level rise San Luis Obispo to Los Angeles

Profiles

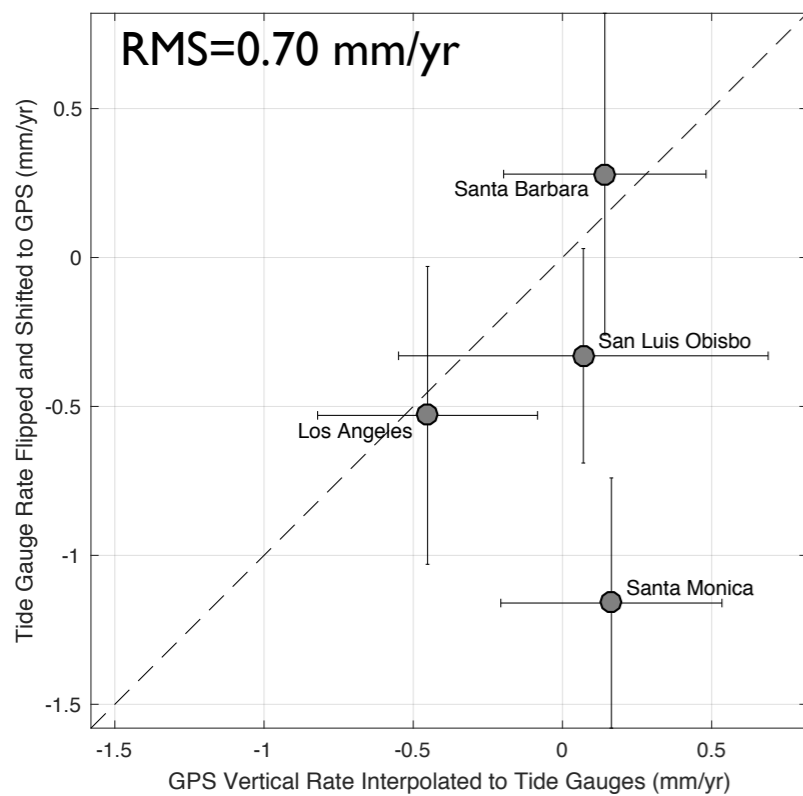


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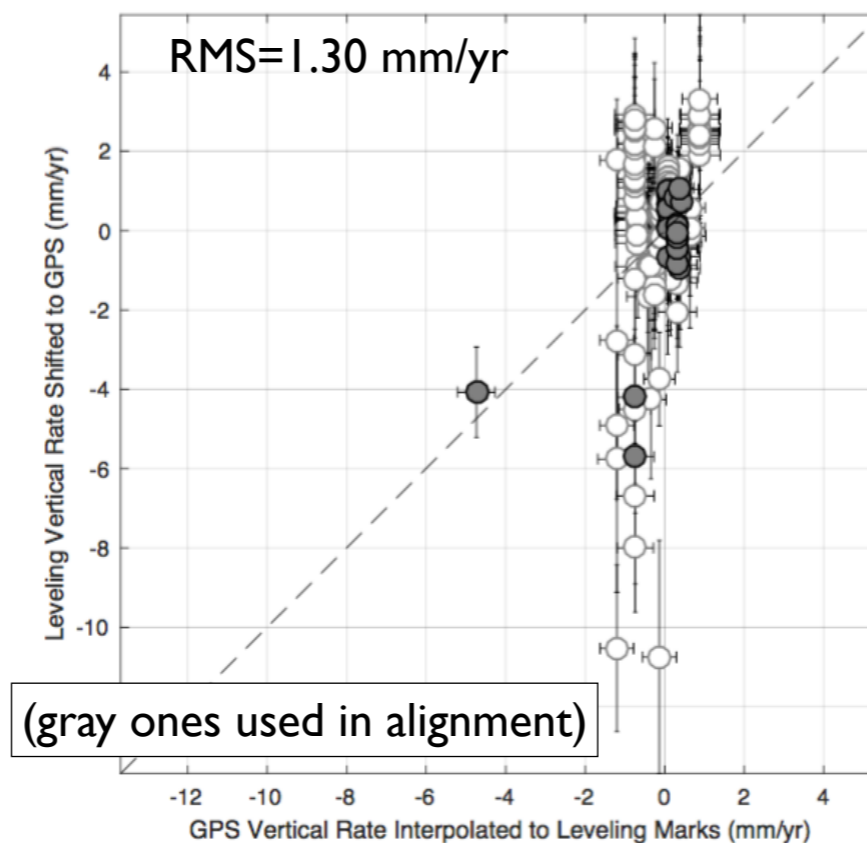
GPS Imaging of Vertical GPS Velocity: West Coast

- Level of agreement between techniques (after alignment) is a measure of overall uncertainty
- RMS misfits are near ~ 1 mm/yr

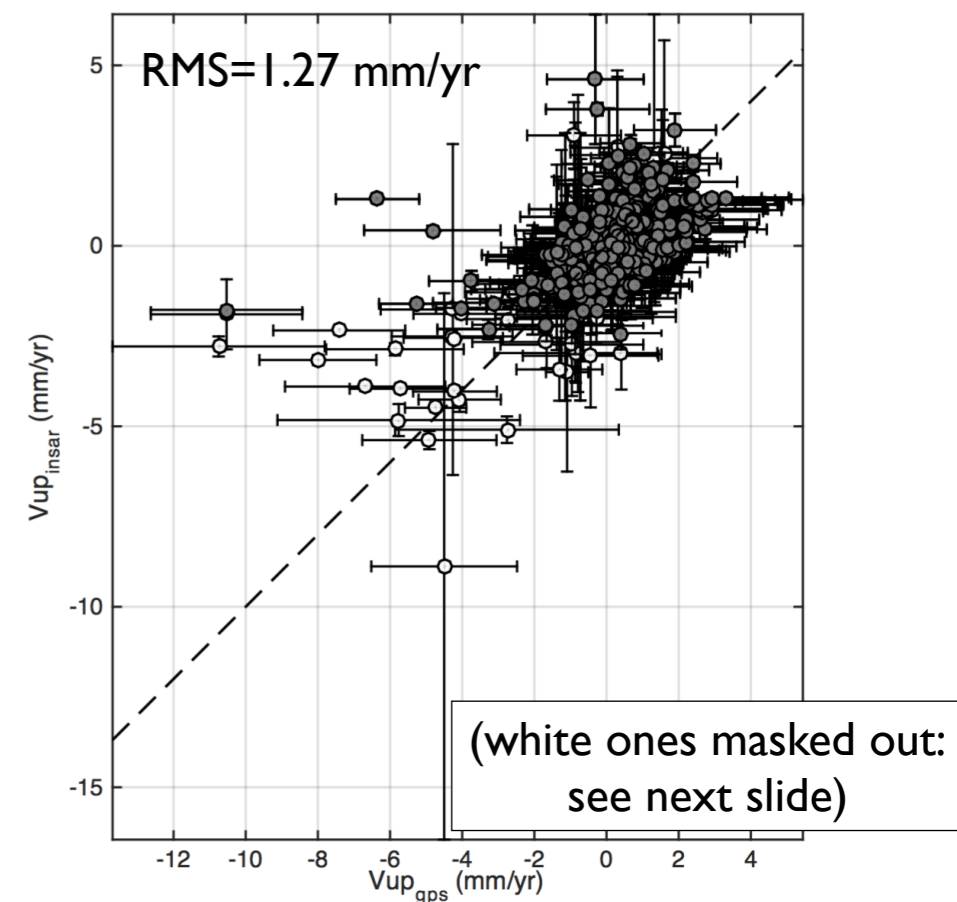
GPS vs. Tide Gauges



GPS vs. Leveling



GPS vs. InSAR



- VLM explains much of the difference in tide gauge rates
- Not necessarily error in tide gauge or GPS rate.
- Measure of GPS network's ability to estimate vertical rate at tide gauge
- **Santa Monica tide gauge:** Nearest GPS station is 8 km away

Mask Out Non-Tectonic Motion

An attempt based on characteristics of the data

Histograms of Vertical Rates

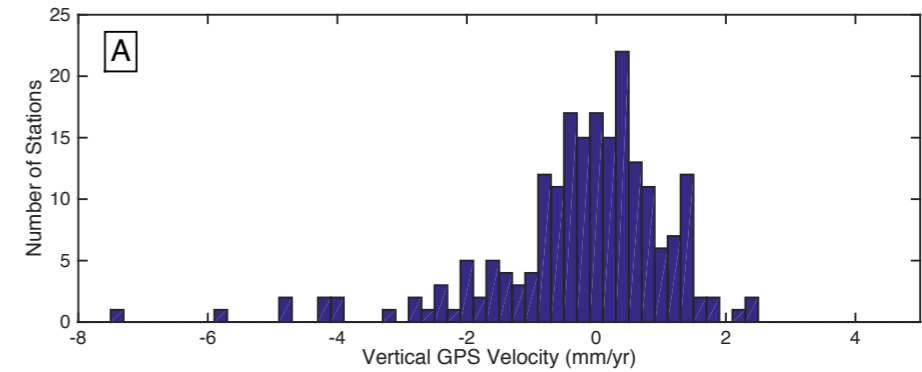
- Nice similarity
- Long tail on left
- Characteristic of non-tectonic motion

Select areas that:

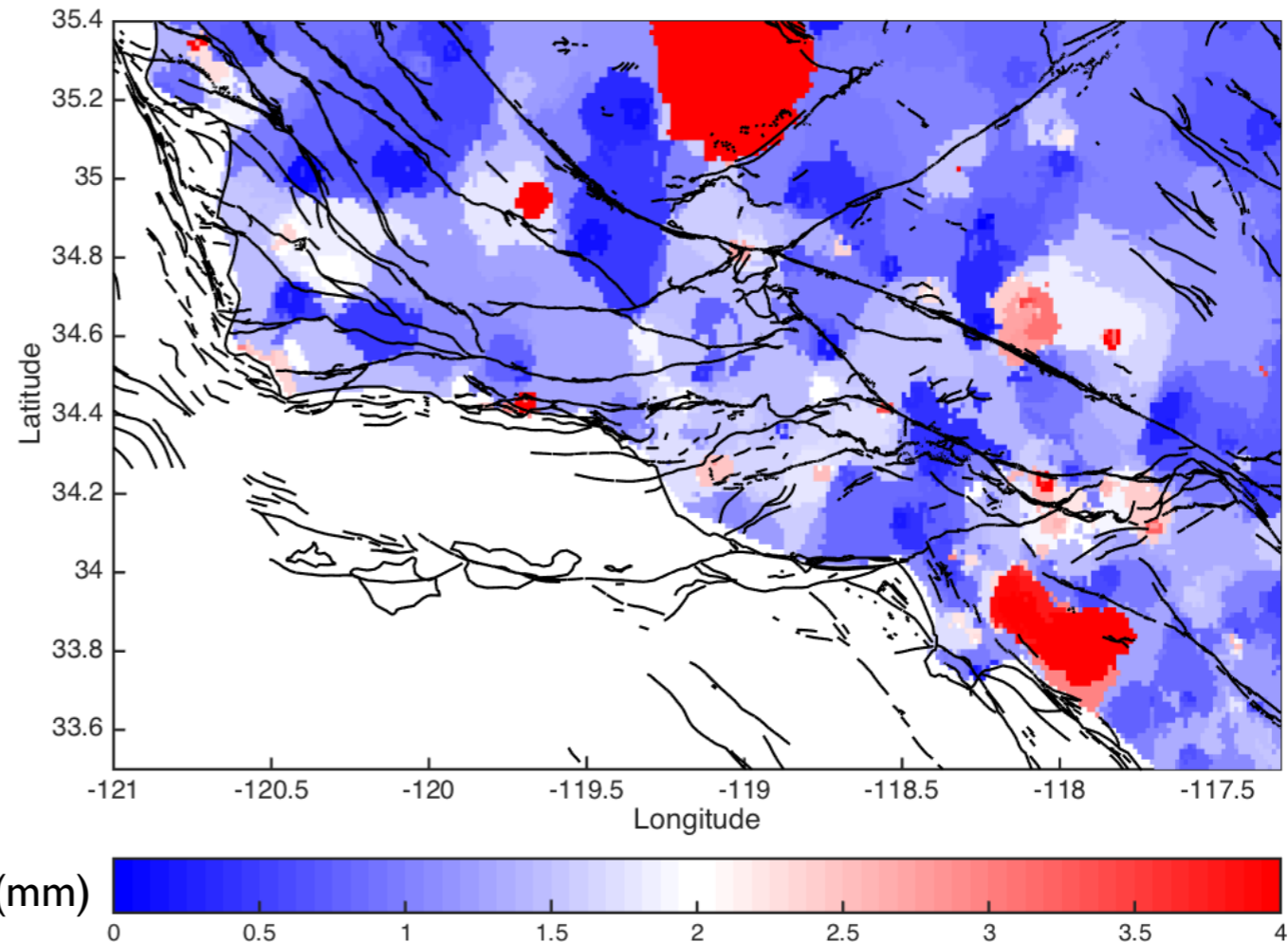
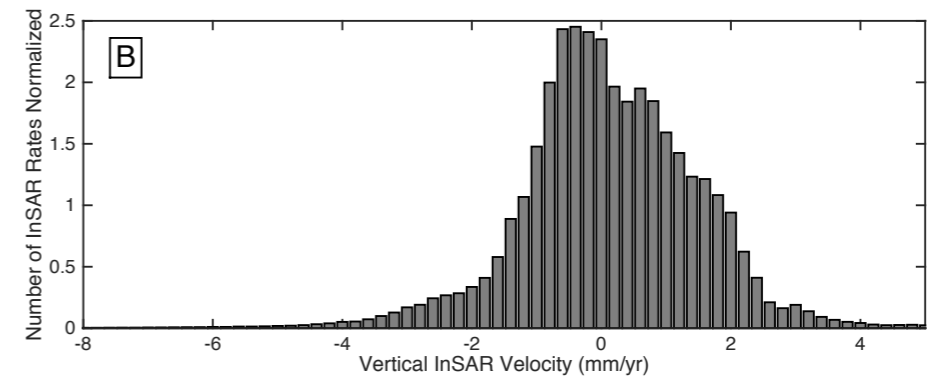
- Subside more quickly than -2.5 mm/yr
- Seasonal terms from InSAR SBAS analysis > 2.0 mm
- Interpolation (using GPS Imaging) of GPS annual terms > 2.0 mm

Then pass the results to Kaj....

GPS



InSAR



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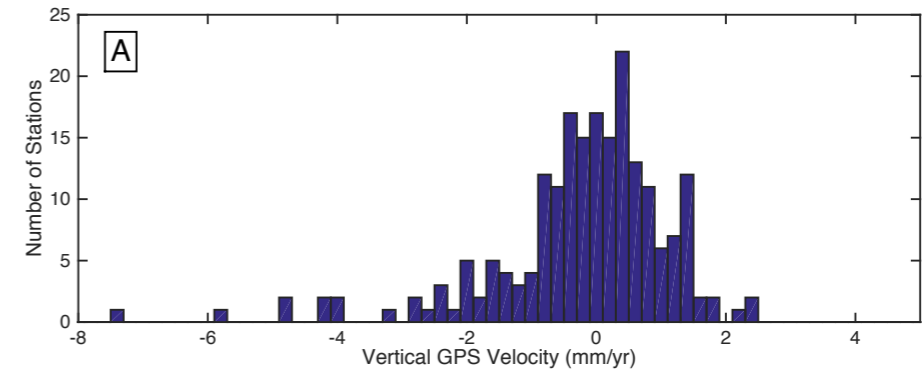
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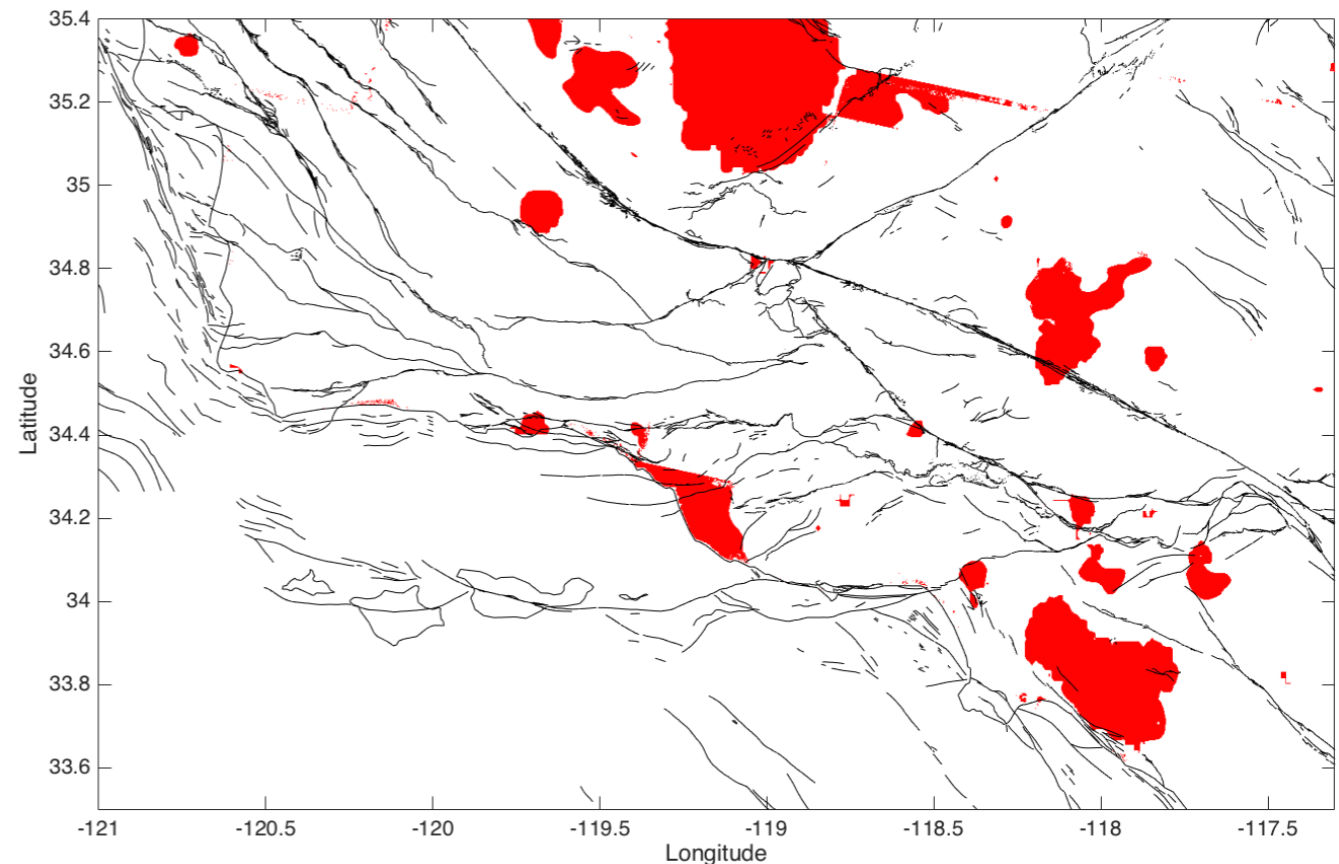
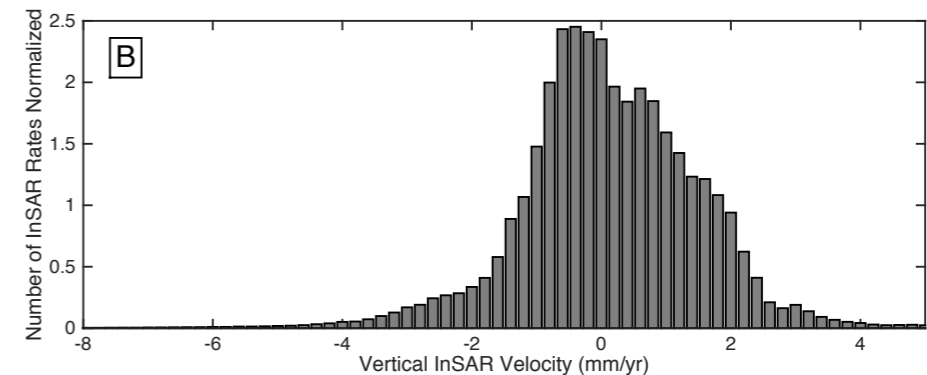
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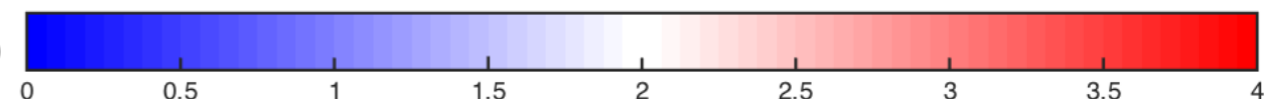
GPS



InSAR



annual term amplitude (mm)



Conclusions

- GPS Imaging sees through noise, enhances signals of VLM in the Ventura/Western Transverse Ranges special fault study area.
- Integration of 4 geodetic techniques enhances strengths and mitigates weaknesses of the individual techniques.
- Mosaic of vertical rates has uncertainty near ~ 1 mm/yr.
- Non-tectonic and tectonic signals can be separated based on characteristics of signal itself.
- Western Transverse Ranges uplift ~ 2 mm/yr.
- San Gabriel Mountains uplift highly asymmetric wrt San Andreas Fault, ~ 2 mm/yr.

