Block Modeling in the Vertical Dimension Constrained by Three-Component GPS Measurements

Bill Hammond, G. Blewitt, C. Kreemer, H.P. Plag
University of Nevada, Reno, Reno, NV 89557
whammond@unr.edu

Introduction

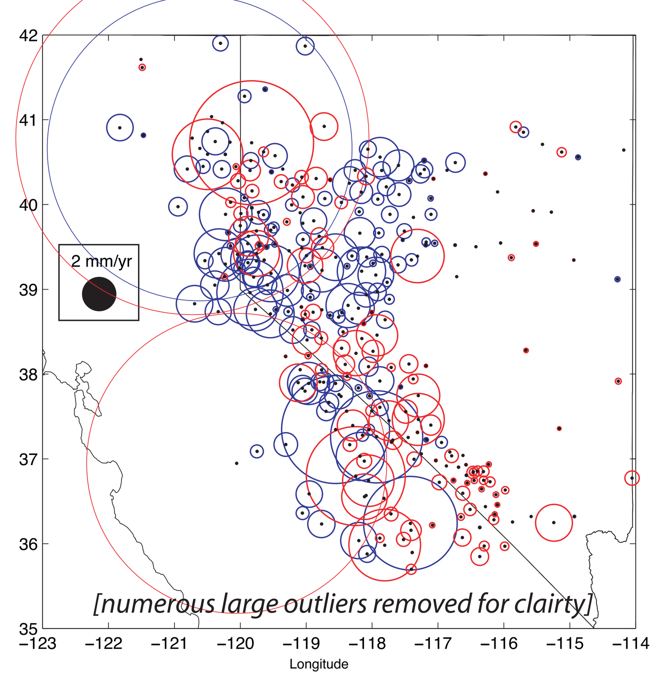
We are developing an analytical procedure for solving for crustal block motions in complex fault zones using all three components of GPS velocity constraints. Traditional block modeling assumes that the Earth's lithosphere is divided into elastic spherical caps that come into contact and are locked (not slipping) at the surface, but slip continually below seismogenic depths during the interseismic time. In areas of tectonic extension or contraction, however, where the blocks have a component of motion normal to the faults, these models predict variations in the vertical interseismic velocity. Thus vertical component GPS should be sensitive to the tectonic signals if the slip rates are large enough.

Using the vertical component data could be helpful for constraining the dips on faults, the long-term rate of uplift of mountain ranges, and subsidence of valley bottoms. We will explore the use of vertical component GPS measurements to constrain such a model. These models may also be useful for identifying where additional sites could be deployed to best measure interseismic vertical motions.

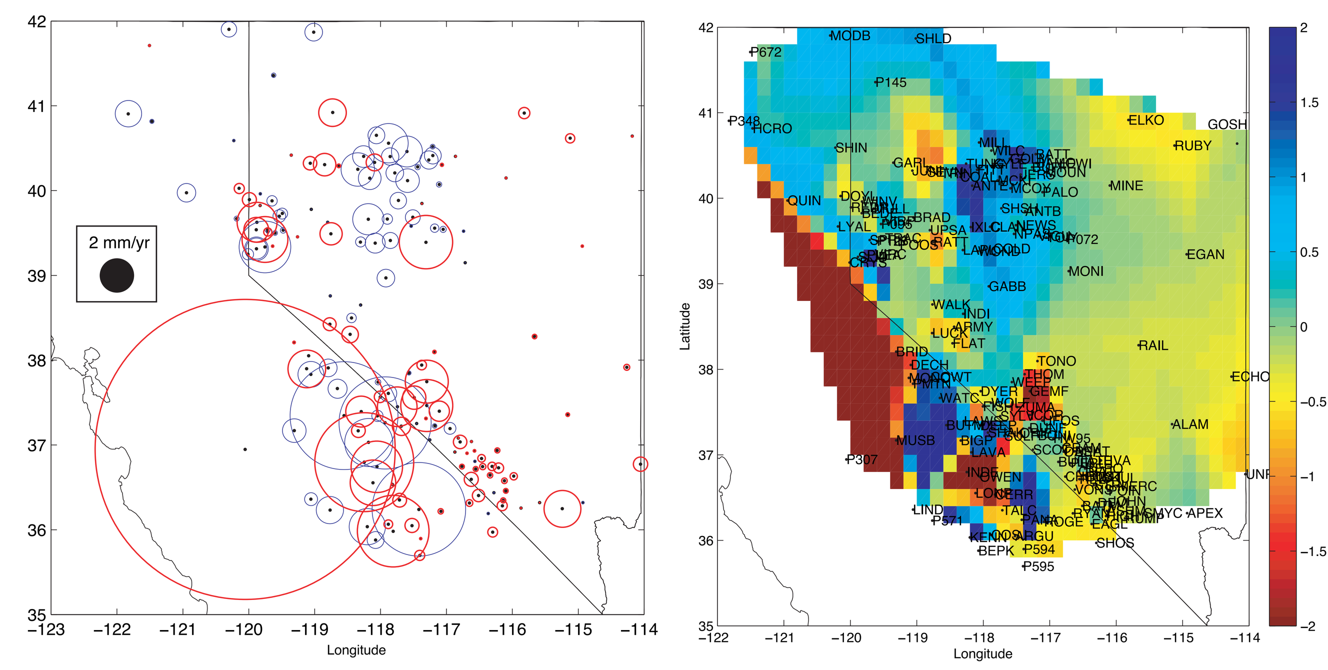
We here present the analytical formulation for block modeling that uses the vertical component as a constraint, plus observations of vertical GPS in eastern California and Nevada. Much of the vertical signal is attributable to viscoelastic relaxation following large historic earthquakes in cetnral Nevada. The total vertical signal is expected to have contributions from postseismic and strain accumulation on faults. Separating these signals requires modeling both components and comparing these models to the observations.

The Vertical GPS Signal - Nevada and Eastern California

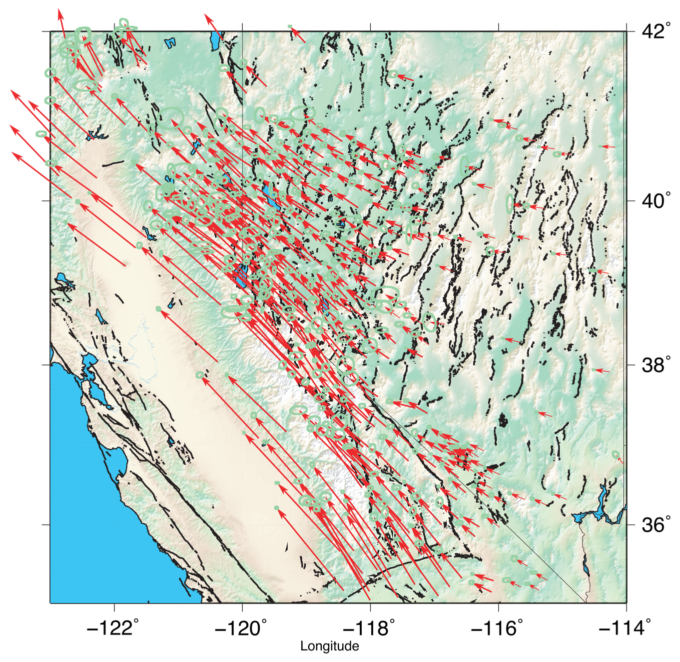
3 Years Minimum
Red is Down, Blue is Up



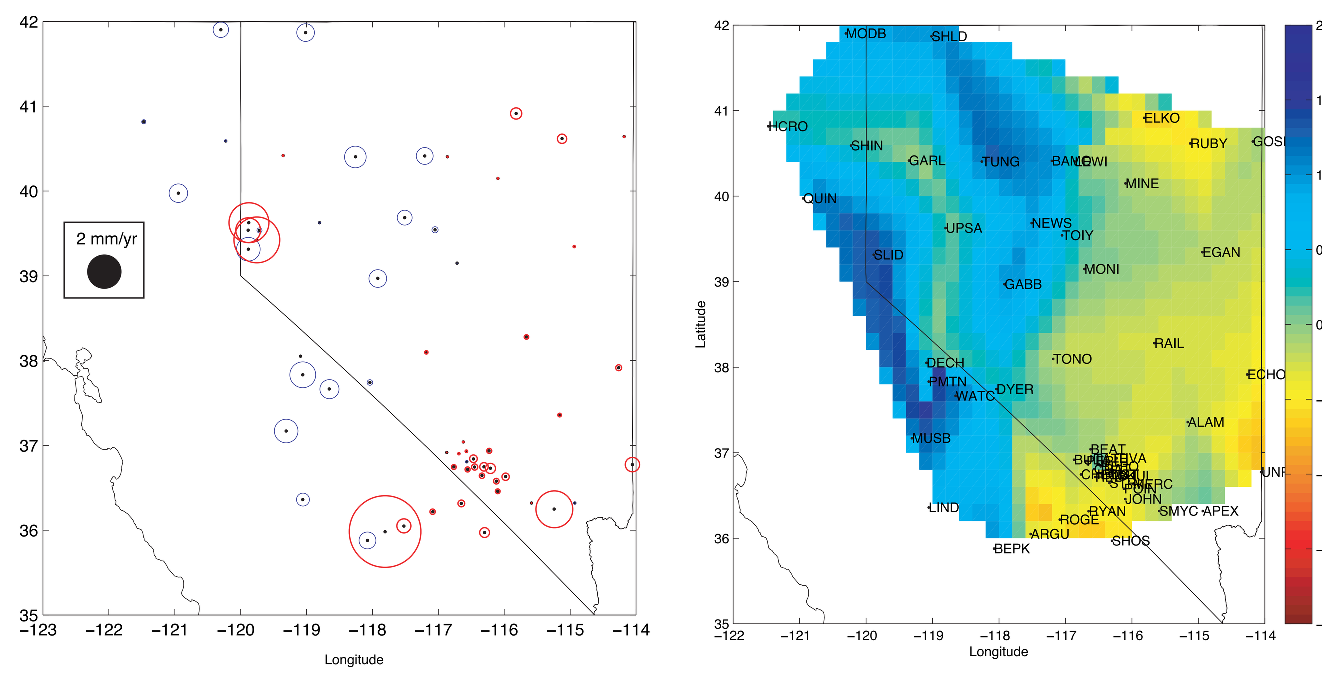
4 Years Minimum
Red is Down, Blue is Up



Horizontal GPS Velocities
North America Reference Frame



6 Years Minimum



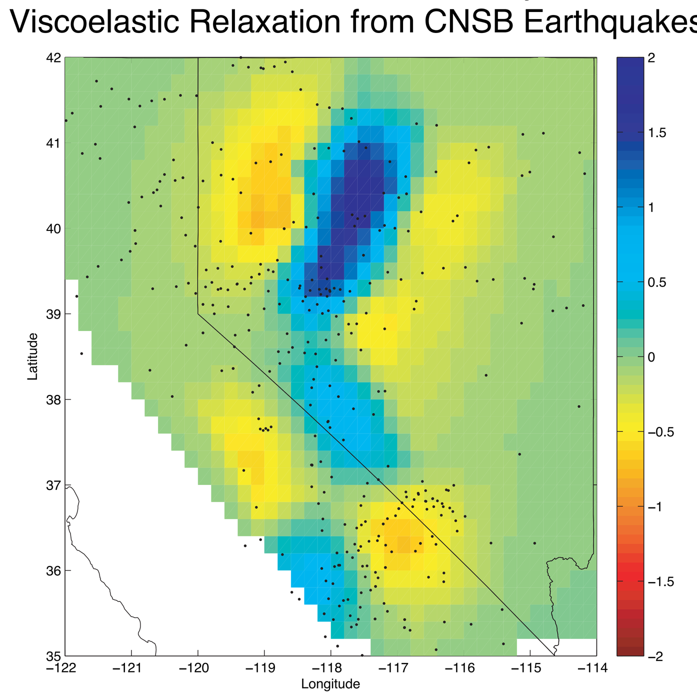
left) The vertical GPS velocity field at sites (far left) and interpolated (near left) for various choices for the minimum time series length observed. A 4 year minimum provides more spatial coverage compared to 6 years, but large outliers appear that reflect the larger uncertainties of vertical rates compared to horizontal rates. Once time series are over 5 years long, there are fewer outliers and a more stable picture of the vertical rate field emerges. Only sites from PBO, MAGNET and BARGEN have been included in this figure. For this analysis regional filtering has been applied using stations on that geographically cover the Great Basin.

The long running, high-quality continuous stations in eastern Nevada are extremely stable, with vertical GPS rates for MINE, EGAN, MONI, RAIL, ECHO, ALAM, that are within 0.2 mm/yr of one another.

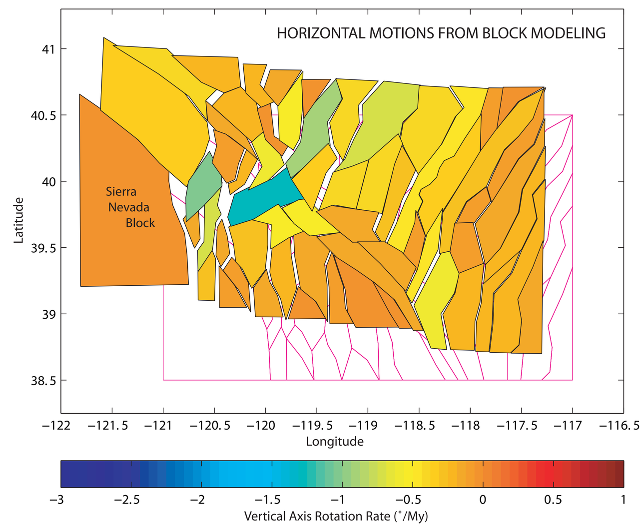
The promiment upward moving area in central Nevada is likely attributable to ongoing viscous relaxation following the historic earthquakes in central Nevada seismic belt (CNSB earthquakes include the 1954 Dixie Valley, 1954 Fairview Peak, 1915 Pleasant Valley, 1872 Owens Valley, 1932 Cedar Mtn.)

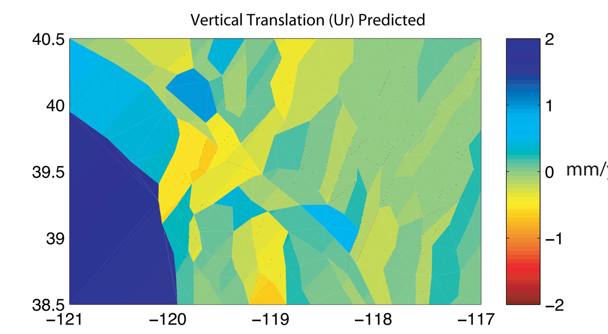
below) A model of the visoelastic relaxation process does a good job explaining this part of the vertical velocity field.

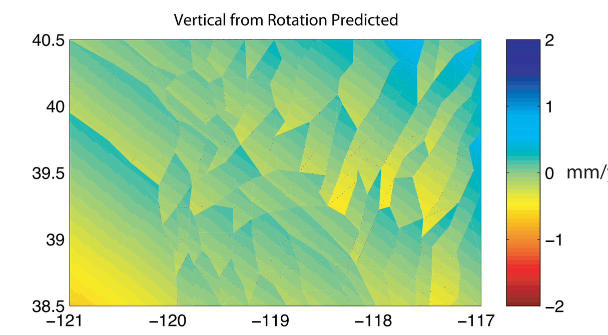
Vertical Rate Predicted by
Viscoelastic Relaxation from CNSB Earthquakes



The Northern Walker Lane







Above) Using the methodology outlined below, we use a block model of the northern Walker Lane to predict vertical motions. The total vertical motion will be the sum of the viscoelastic postseismic relaxation (left) and the interseismic tectonic signal.

Method: Blocks in Three-Dimensions

The long term motion is the sum of the interseismic rates and coseismic rates [*Savage*, 1983]

$$\vec{v}_{Long\ Term} = \vec{v}_{Interseismic} + \vec{v}_{coseismic} \; .$$

Since we use GPS data collected between the time of large earthquakes to constrain block motions, we must rearranging the terms to give us the basic relationship between our data and our model. We assume that any transient motions not associated with interseismic deformation have been removed.

$$\vec{v}_{Interseismic} = \vec{v}_{Long\ Term} - \vec{v}_{coseismic}$$

$$\vec{v}_{GPS} = \begin{bmatrix} 1 & -\cos\theta_0\Delta\phi & -\sin\theta_0\Delta\phi & r_0\sin\theta_0\Delta\phi & r_0\Delta\theta & 0 & r_0\Delta\theta & 0 & 0 \\ \cos\theta_0\Delta\phi & 1 & -\Delta\theta & 0 & r_0\sin\theta_0\Delta\phi & r_0\Delta\theta & -r_0\sin\theta_0\Delta\phi & 0 & 0 \\ \sin\theta_0\Delta\phi & \Delta\theta & 1 & 0 & 0 & 0 & 0 & r_0\Delta\theta & r_0\sin\theta_0\Delta\phi \end{bmatrix} \begin{bmatrix} U_\phi \\ U_\theta \\ U_r \\ \varepsilon_{\phi\phi} \\ \varepsilon_{\theta\phi} \\ \varepsilon_{\theta\theta} \\ \omega_r \\ \omega_\phi \\ \omega_\theta \end{bmatrix}$$

$$-\sum_{k=1}^{L} \left(a_k \vec{G}_{ss,ki} + b_k \vec{G}_{N,ki} \right)$$

$$\vec{v}_{GPS} = \boldsymbol{A}\boldsymbol{m}_{lt} - \sum_{k=1}^{L} \left(a_k \vec{G}_{ss,ki} + b_k \vec{G}_{N,ki} \right)$$

This arranges the equations for the three-dimensional translations and rotations of a block constrained by three component GPS vectors [*Savage et al.,* 2001] into matrix $\boldsymbol{A}$ and model parameters into vector $\boldsymbol{m}_{lt}$ for simplicity of programming, etc. Each block is allowed to translate (U_ϕ, U_θ, U_r) and rotate ($\omega_r, \omega_\phi, \omega_\theta$) in space, and deform according to a constant horizontal strain rates $\varepsilon_{\phi\phi}, \varepsilon_{\theta\phi}, \varepsilon_{\theta\theta}$. These nine parameters represent the potential "long-term" motion of the block possible in three-dimensions. The interseismic deformation is the long-term minus the cumulative effect of coseismic displacements, so the second term is the adjustment. It includes terms for the strike slip and normal slip rates a_k, b_k which are mapped into surface displacements using functions based on Okada's formulation for each component G_{SS} and G_N. These free parameters are ordered in model vector $\boldsymbol{m}_{slip}$ Since multiple fault segments may effect the strain accumulation at each GPS site, we sum over the nearest L fault segments. Usually 3 to 5 are enough, but this depends on the complexity of the fault system.

Since there are 9 parameters per block and 2 parameters per fault segment, there are rarely enough data on each block to fully constrain the problem. Thus the model must be regularized, with constraints placed upon it by a combination of the data and other constraints that we will discuss next.

1) Slip rate consistency with block motions. We assume that where blocks come into contact at faults, the difference in long term rate between adjacent blocks j_1 and j_2 is the same as the slip rate across the fault:

$$\boldsymbol{A}\boldsymbol{m}_{lt}(j_1) - \boldsymbol{A}\boldsymbol{m}_{lt}(j_2) - \left(a_k \vec{G}_{ss,k} + b_k \vec{G}_{N,k} \right) = 0$$

2) Since the problem is often underdetermined, we employ stochastic damping to regularize the inversion

$$\boldsymbol{m}_{lt} = 0$$

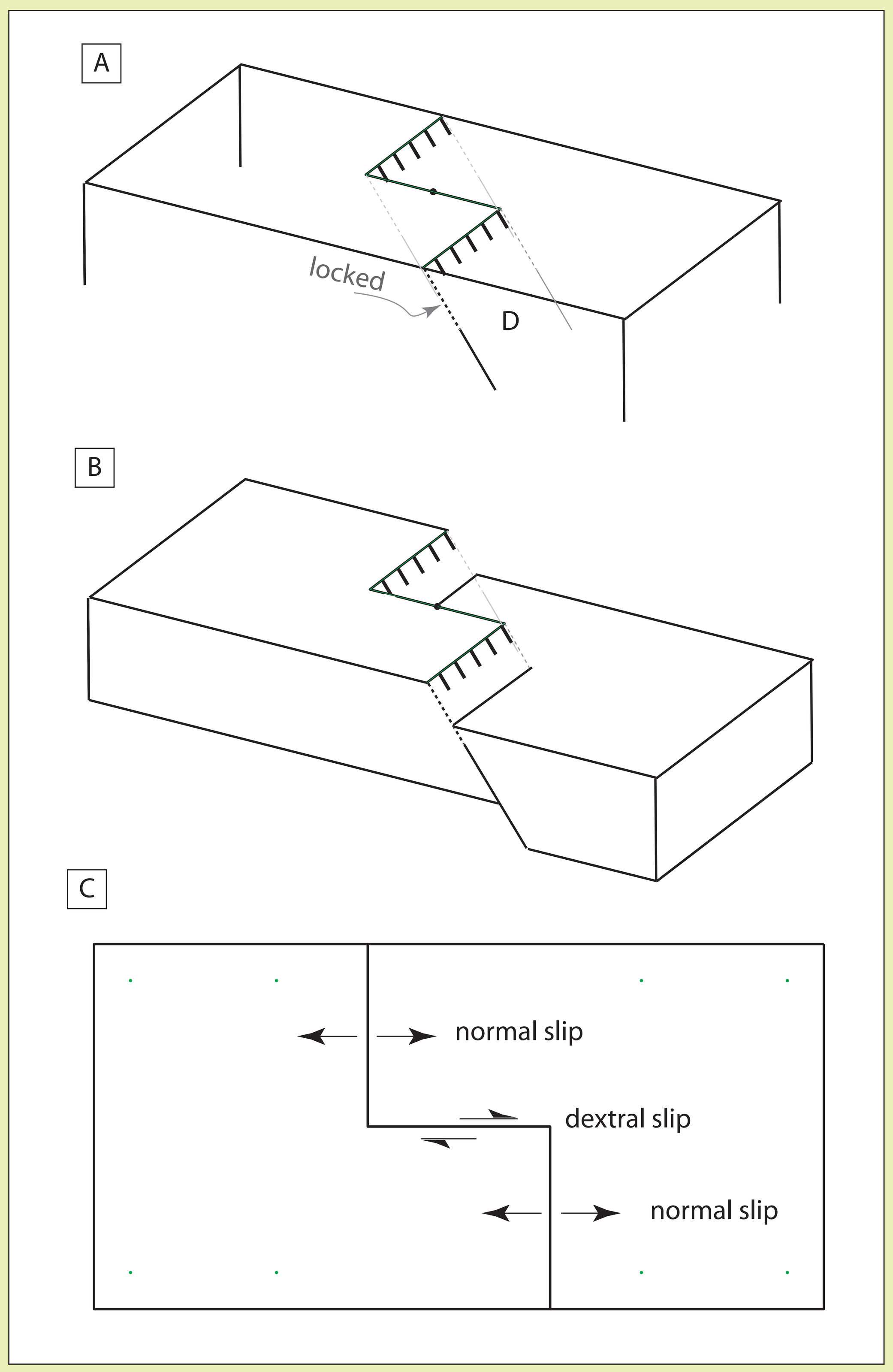
$$\boldsymbol{m}_{slip} = 0$$

and employ a weighted inversion using covariance weighting matrix

$$\boldsymbol{W}_i = \frac{1}{\sigma_i^2}$$

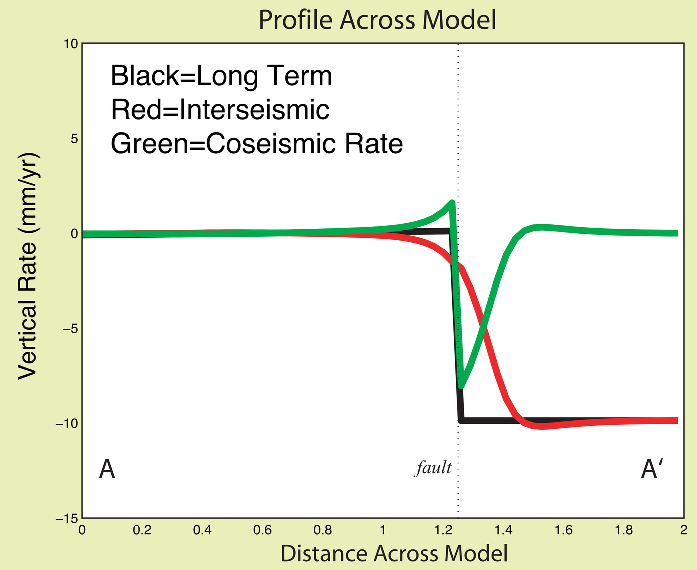
where the variances σ_i^2 are the data uncertainties for the data equations and *a priori* variances of model parameters are selected by the analyst to guide the solution. In practice we use separate a priori model variances for the vertical and horizontal axis rotations, horizontal and vertical translations, and strain rates.

Method: A Simple Model

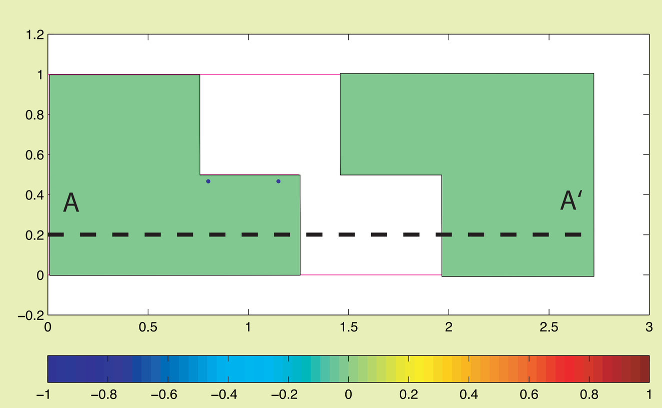


Method: A Simple Solution

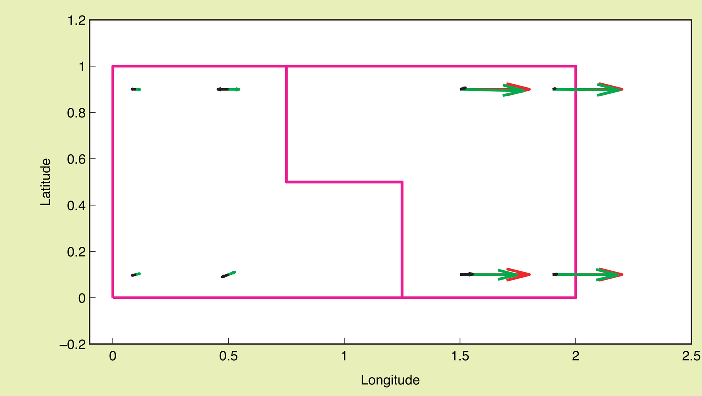
Profile Across Model

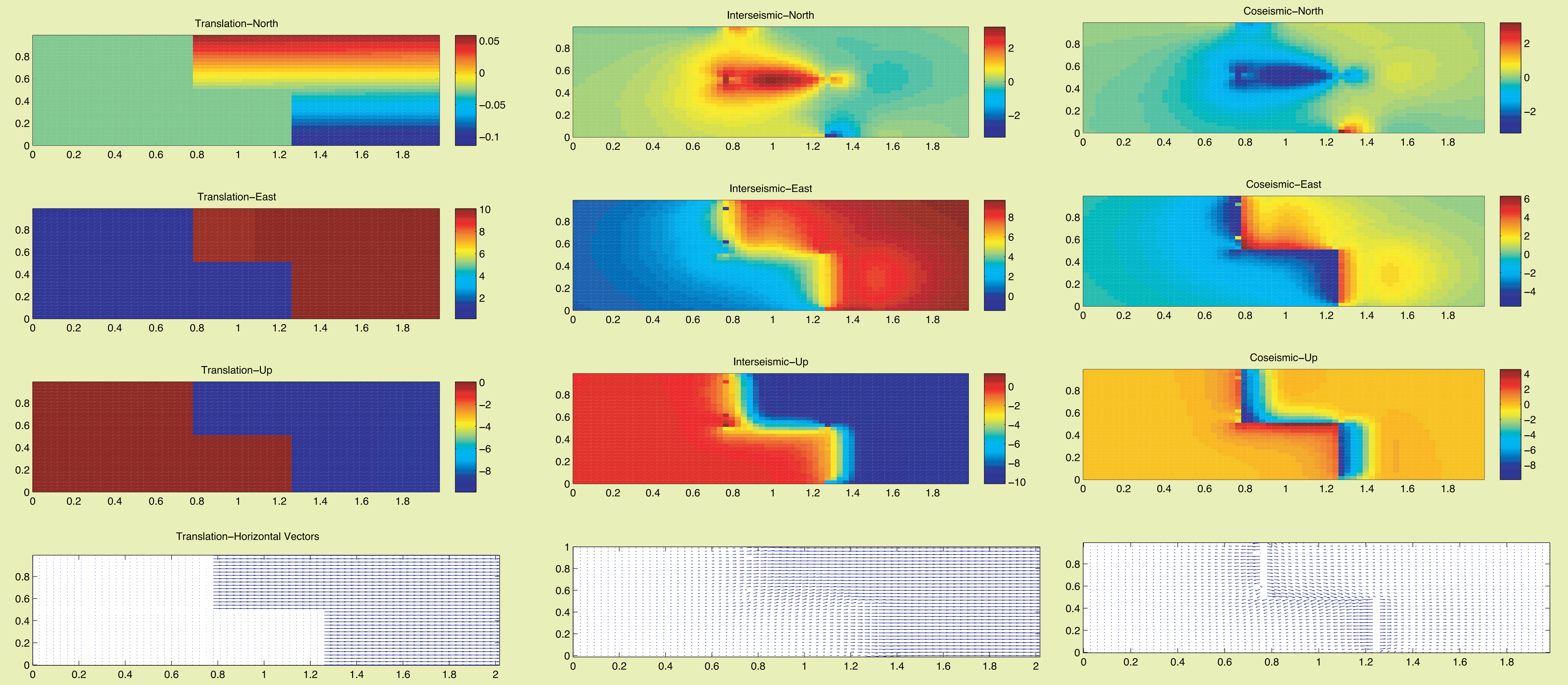


Map View
Long Term Motion



Red=Input Synthetic Data
Green=Model Prediction
Black=Residual





References

Okada, Y. (1985), Surface deformation due to shear and tensile faults in a half-space, Bulletin of the Seismological Society of America, 75, 1135-1154.

Savage, J. C. (1983), A dislocation model of strain accumulation and release at a subduction zone., Journal of Geophysical Research, 88, 4984-4996.

Savage, J. C., W. Gan, and J. L. Svarc (2001), Strain accumulation and rotation in the eastern California shear zone, Journal of Geophysical Research, 106, B10, 21,995-922,007.

Acknowledgements

Work on this project has been made possible by funding through the National Science Foundation's EarthScope Program via project 0844389 "Revealing the Nature of Contemporary Uplift and Collapse in the Sierra Nevada - Great Basin System" and from the NASA EarthScope Geodetic Imaging Component via project "Geodetic Imaging of Earth's Surface Deformation Using Integrated InSAR and GPS Observations".