# Annual Report for Proposal 11124; Holt: Near Real Time Estimation of Velocity Gradient Tensor Fields for Continuous Monitoring in Southern California

## Summary

We have further tested and developed a geodetic network processing system designed to detect anomalous strain transients. The modeling procedure determines time-dependent velocity, displacement and velocity gradient tensor fields from continuous GPS time series [*Hernandez et al.*, 2005, 2006, 2007a,b,c]. The plan thus fulfills the SCEC Science Objective **A5** to **"***Develop a geodetic network processing system that will detect anomalous strain transients*". We tested retrospectively two cases from the SCEC IV test and the third case blind. All three tests resolved strain anomalies both spatially and temporally at a high level of accuracy. Work also began in the development of detection automation. More work is needed in this area to determine objective thresholds and methods for automated transient recognition. This plan for automation fulfills the recommendations under **Research Strategies** in **Tectonic Geodesy** for A5 to: (a) "*Adapt methods for detecting, assessing and interpreting transient deformation signals so that they can be run with minimal user intervention as part of an ongoing detection effort that ingests data at frequent (daily to weekly) time intervals*"; and (b) "*Refine capabilities of detection algorithms and assess their sensitivity thresholds through continued participation in the Transient Detection Blind Test Exercise*". The data product that we are developing falls under Science Objective C to "*Improve and develop community products (data or descriptions) that can be used in system-level models for the forecasting of seismic hazard*."

## 1.0 Method and Results to Date on SCEC IV Transient Detection Exercise

For the SCEC IV exercise the PI modified the methodology of [e.g., *Holt et al.*, 2000a, 2000b; *Beavan and Haines*, 2001] to interpolate displacements, rather than velocities, from CGPS data to determine a displacement gradient tensor field. A result of the research performed to date is that all transients in the synthetic test exercises are now being detected – at both short and longer time scales. Previous analysis detected only the long wavelength deformation and post-seismic characterestics in the real data similar to that described by *Freed and Bürgmann* [2004] and *Freed et al.* [2007]. However, the analysis missed several shorter duration transients. The move to modeling displacements, as opposed to time-dependent velocities from our earlier work, involved simpler processing steps and a more direct use of CGPS data. The purpose of this work is to automate this process and better develop metrics for transient recognition as they are occurring.

Regularization of the solution for Southern California consists of obtaining the sharpest estimate of strain tensor field possible that can be supported by the CGPS data. The smoothing of the strain solution is controlled through optimization of the following functional in a formal least-squares joint inversion of strain and displacement field:

$$\chi = \sum_{cells} \sum_{ij,kl} (\hat{e}_{ij} - e_{ij}^{obs})^T \mathbf{V}_{ij,kl}{}^{-1} (\hat{e}_{kl} - e_{kl}^{obs}) + \sum_{knots} \sum_{i,j} (\hat{u}_i - u_i{}^{obs})^T \mathbf{V}_{i,j}{}^{-1} (\hat{u}_j - u_j{}^{obs}), \qquad (1)$$

where $\mathbf{V}_{ij,kl}$ is the variance-covariance matrix of the strains, $\mathbf{V}_{i,j}$ is the variance-covariance of the displacements, $\hat{e}_{ij}$ and $e_{ij}^{obs}$ are the model and observed strains, and $\hat{u}_i$ and $u_i^{obs}$ are the model and observed displacements. The fitting algorithm that minimizes (1) is equivalent to a finite element method that satisfies force balance equations (spherical Earth). The methodology solves the Weak formulation of the linear problem, where the basis functions for the displacement rates at any time snap shot are higher order elements involving the Bessel form of bi-cubic spline interpolation on a generally curvilinear grid of quadrilateral sub-domains [*de Boor*, 1978; *Beavan and Haines*, 2001] (0.1°x0.1° grid). The final model predicts a continuous displacement and strain tensor field. Finer grid spacing can be used to adapt to problems supported by dense station spacing. We use a constant Poisson's ratio of 0.25 and displacement boundary conditions may or may not be imposed. Also, *a priori* constraints from fault location, strike and expected range of fault slip rates can be used to define anisotropic and inhomogeneous components of the variance-covariance matrix $\mathbf{V}_{ij,kl}$, which influences the model parameter estimates for interpolated displacements and strains. Thus, the fitting procedure has a physics-based link to force-balance on a sphere with additional constraints provided by knowledge of structural and geodetic information.

We use a reference strain field to define $e_{ij}^{obs}$ values within regions of Southern California. That reference strain field is obtained from SCEC4.0 GPS in the case where time dependent displacements from real CGPS data are being fitted. For previous SCEC transient exercises, and for Phases 4a, b, and c, the reference strain rate field was obtained from the time-averaged solutions from all synthetic data (from *Fakenet* code) from period 2007.0 – 2009.0. It is important to have accurate estimates of the variance-covariance matrix, $\mathbf{V}_{i,j}$, of the time-dependent displacements. In the presence of transients, the model solution will be forced to misfit the reference strain field in the joint inversion in order to match the time-dependent displacements. We use an adjustable isotropic component of strain variance, embedded in $\mathbf{V}_{ij,kl}$, as a measure of the *a priori* expected departure of strain from the reference field - due to potential transients. If the isotropic component of variance is small, then the solution will be forced to match the reference strain field, and potentially misfit the time-dependent displacements. Any transients embedded in the time-dependent displacements will thus be greatly smoothed or damped. If the isotropic component of variance is increased, the solution is more flexible to match the time dependent displacements closely because the penalty for misfitting the reference strains is diminished. This isotropic component of variance is adjusted until the reduced Chi-Squared misfit to the time dependent displacements is optimal (around 1.0). This single adjustable parameter is isotropic, and constant everywhere, because there is no *a priori* expectation on the style or distribution of potential strain rate transients. We have found that correlated, long-wavelength, noise in displacements can be minimized by solving for the frame of reference in the inversion process [e.g., *Holt et al.*, 2000a].

## 1.1 Method for Obtaining Time-Dependent Velocity Estimates from CGPS Observations

We have used general polynomial functions to interpolate continuous displacement GPS time series and generate time dependent model displacements and velocities for all CGPS stations in the SCIGN network [*Hernandez et al.*, 2005, 2006]. A forth order representation is:

$$d(t) = \frac{1}{24}(a)t^4 + \frac{1}{6}(b)t^3 + \frac{1}{2}(c)t^2 + (d)t + e + f\sin(\tfrac{2\pi t}{T}) + g\cos(\tfrac{2\pi t}{T}) + h\sin(\tfrac{4\pi t}{T}) + i\cos(\tfrac{4\pi t}{T}). \quad (2)$$

A weighted least-squares inversion of each displacement time series, d(t), from the CGPS observations, provides estimates of the coefficients. This function fits generally long-wavelength non-linear trends. Once the fit to the time series is obtained, the annual and semi-annual signals are then removed from all of the GPS time series. We next fit a two-week moving average filter to the cleaned time series and these filtered estimates of displacement are then used in the remainder of the analysis.

Displacements from all of the cleaned time series are output in two week duration epochs and then modeled using the treatment described above. The reference field is subtracted from each epoch solution to infer anomalous displacements and strain.

## 1.2 Results to Date from the SCEC IV Transient Exercise with Implications for Future Work

The time series from SCEC IV A, B, and C were analyzed using the method described in section 1.1 above. Time series for A and B were analyzed retrospectively, whereas the time series for C was analyzed "blind", without knowledge as to the location or duration of the slow event. Anomalous strains and displacements, corresponding to the true solution, were well resolved both temporally and spatially for all three sets of time series (compare solution with true displacements in Figures 1-3).

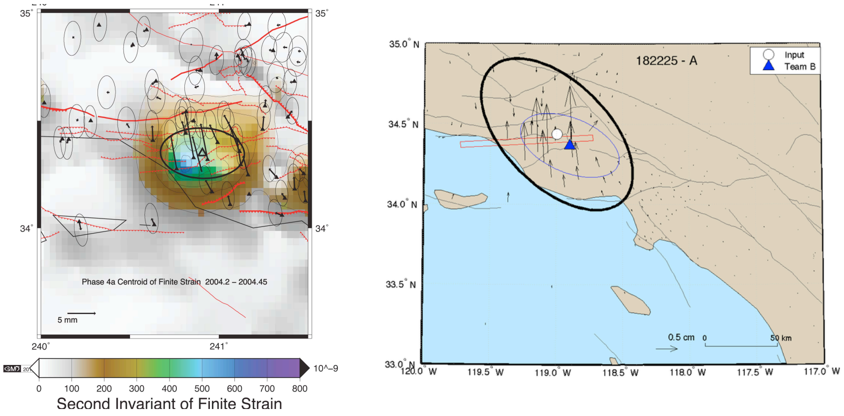

**Figure 1. Left**: Finite strain (contoured dilatations – negative = contraction, pos. = extension) with principal axes of finite strain (bold = compressional and open = extensional) for IV-a. **Right**: True solution input embedded in time series for IV-a. The algorithm recovered the finite anomalous displacements and anomalous strain for this event (thrust).

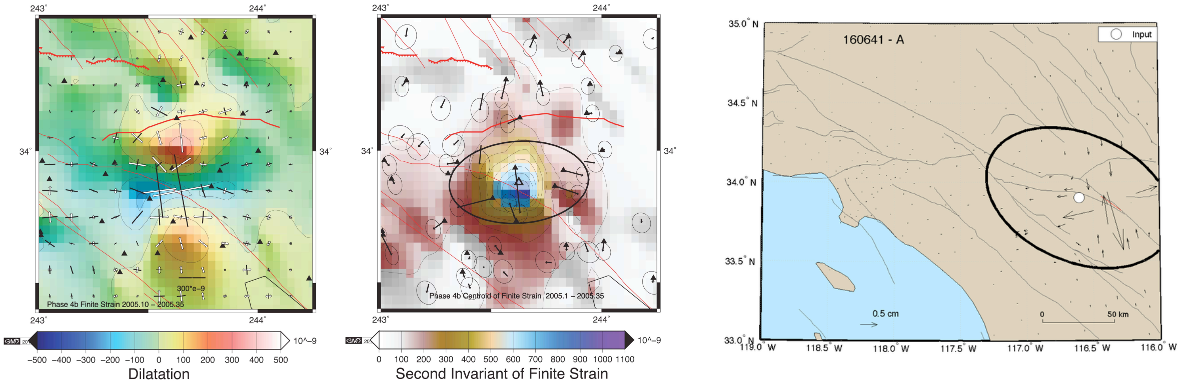

**Figure 2. Left**: Finite strain (contoured dilatations) with principal axes of finite strain (bold = compressional and open = extensional) for IV-b. **Center**: Second invariant of finite strain with 1-sigma confidence ellipse for location of transient. **Right**: True solution input embedded in time series for IV-b. The algorithm recovered the finite anomalous displacements and anomalous strain for this event (strike-slip on southern San Andreas).

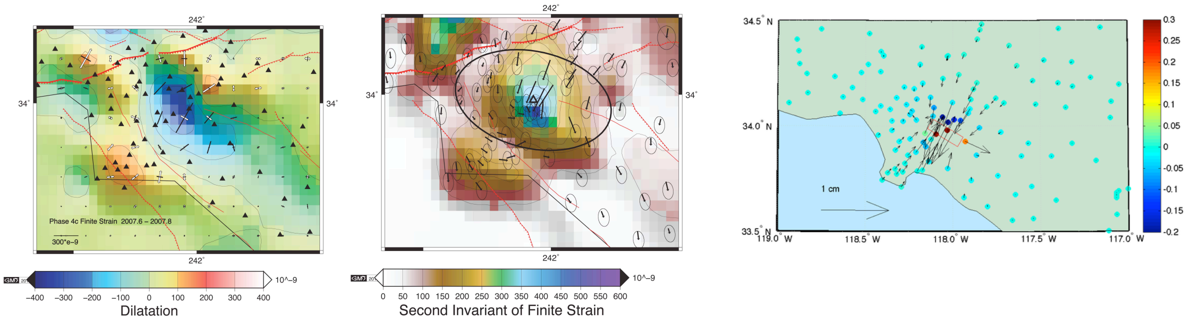

**Figure 3. Left**: Finite strain (contoured dilatations) with principal axes of finite strain (bold = compressional and open = extensional) for IV-c. **Center**: Second invariant of finite strain with 1-sigma confidence ellipse for location of transient. **Right**: True solution input embedded in time series for IV-c. The algorithm recovered the finite anomalous displacements and anomalous strain for this event (thrust).

Results from the transient analysis indicate that we can accurately resolve anomalous displacements and strain associated with total anomalous slip of less than 1 cm. No errors were provided for the time series, but we assumed standard errors of ± 3 mm for the CGPS displacements.

The procedure is nearly ready for automation, applied to real data. However, a number of additional steps and tests need to be conducted in order to refine a fully automated near-real-time detection algorithm. We are developing algorithms that analyze finite anomalous strain (1) as it is occurring in near-real-time and (2) retrospectively, with regular solution confidence level updates. This code development will provide Maria Liukis with appropriate and fully tested data products for use at the Collaboratory for the Study of Earthquake Predictability (CSEP).

## Intellectual Merit

The intellectual merit is that we have developed a modeling procedure that quantifies time-dependent velocity, displacement and velocity gradient tensor fields from continuous GPS time series in southern California. The code is currently under development for automated detection of anomalous strain events within southern California. The plan fulfills the SCEC Science Objective **A5** to **"***Develop a geodetic network processing system that will detect anomalous strain transients*". The work on automation fulfills the recommendations under **Research Strategies** in **Tectonic Geodesy** for A5 to: (a) "*Adapt methods for detecting, assessing and interpreting transient deformation signals so that they can be run with minimal user intervention as part of an ongoing detection effort that ingests data at frequent (daily to weekly) time intervals*"; and (b) "*Refine capabilities of detection algorithms and assess their sensitivity thresholds through continued participation in the Transient Detection Blind Test Exercise*". The data product that we are developing falls under Science Objective C to "*Improve and develop community products (data or descriptions) that can be used in system-level models for the forecasting of seismic hazard.*"

### Broader Impact

The Broader Impact of this work involves the training of a graduate student, Gina Shcherbenko, and two undergraduates, Eric Caruso and Patrick Abejar. The development of a data product enabling automated detection of anomalous strain from CGPS data also constitutes a broader impact.

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