Measuring uncertainty in surface strain rates in Southern California using multiple methods and elastic models

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Problem

Geodetic data can be used to infer surface strain rates, which are correlated with seismic hazard (e.g. Savage & Simpson, 1997; Bird, 2015). However, there are two challenges with this approach: 1) geodetic strain rates may include both elastic and inelastic ("off-fault") contributions (e.g. Johnson, 2013), and 2) it remains challenging to quantify uncertainties arising from data errors and spatial interpolation uncertainty. Here we explore a geostatistical approach to quantify uncertainty in surface strain rates in southern California. We generate conditional realizations of the velocity field and compute strain rates for each to estimate the mean and uncertainty in the total strain rate field, and the implied total moment deficit rate, for southern California. Future work will focus on using elastic fault models to remove an estimate of the elastic component of the strain rate field and quantifying the remaining off-fault component to determine whether the off-fault component is statistically significant given the uncertainties.

Variogram Analysis of GNSS Velocities

We use a geostatistical approach (e.g. Chiles and Delfiner, 2001) to interpolate GNSS velocities in southern California. This involves first estimating a spatial structure function using a variogram, then populating a covariance matrix using the structure function.

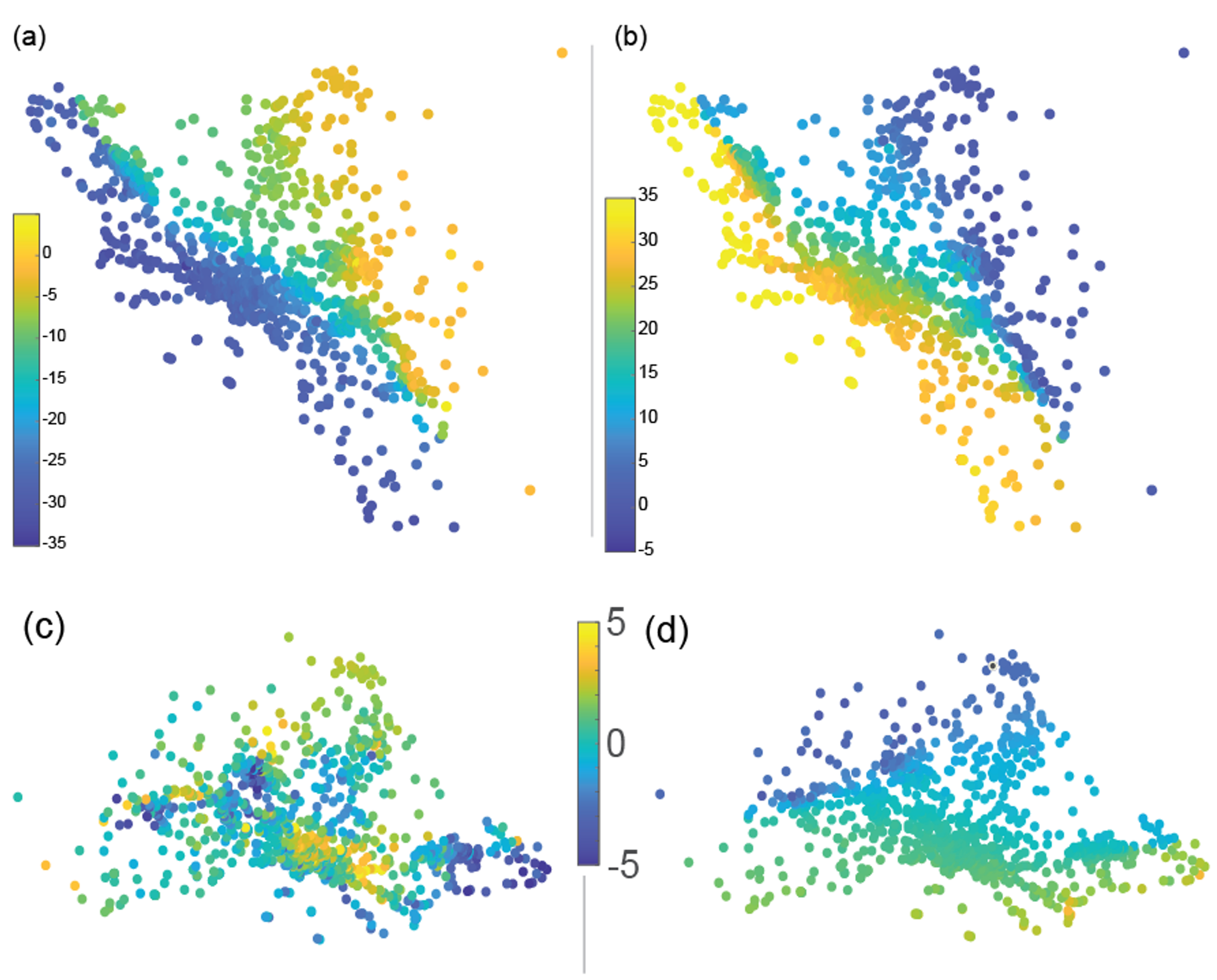
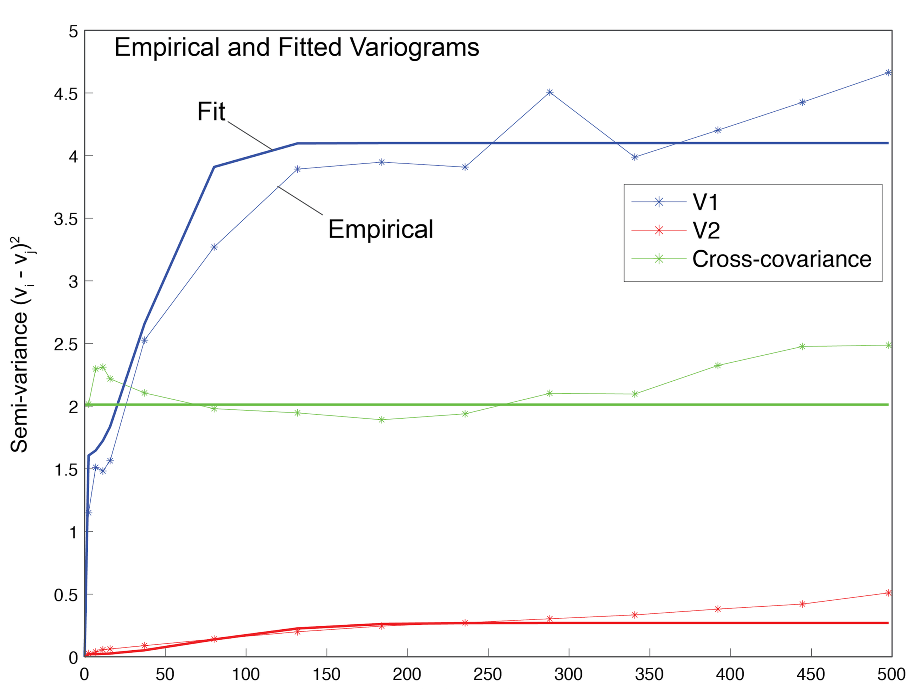


Figure 1: We first transform the data (a - Easting, b - Northing) into a coordinate system that is parallel/perpendicular to the overall San Andreas fault strike (c-d) and transform the fault-parallel velocities to remove non-linear trends (d)

Figure 2:
The ***empirical variogram*** is the mean semivariance The ***semi-variance*** (one-half the squared difference between two stations) within a given distance bin. We fit a Gaussian structure function to the empirical variogram (solid lines); other models such as exponential can also be used.



Interpolating Velocities using Kriging

Kriging matches the GNSS observations quite well and ignores outliers in the velocity field. We also generate ***stochastic realizations of the velocity field, conditioned on the data***, that account for the uncertainty in the observed velocities and the data spacing. The structure function assumes that the velocity is continuous and differentiable, so some areas with creeping faults may be over-smoothed.

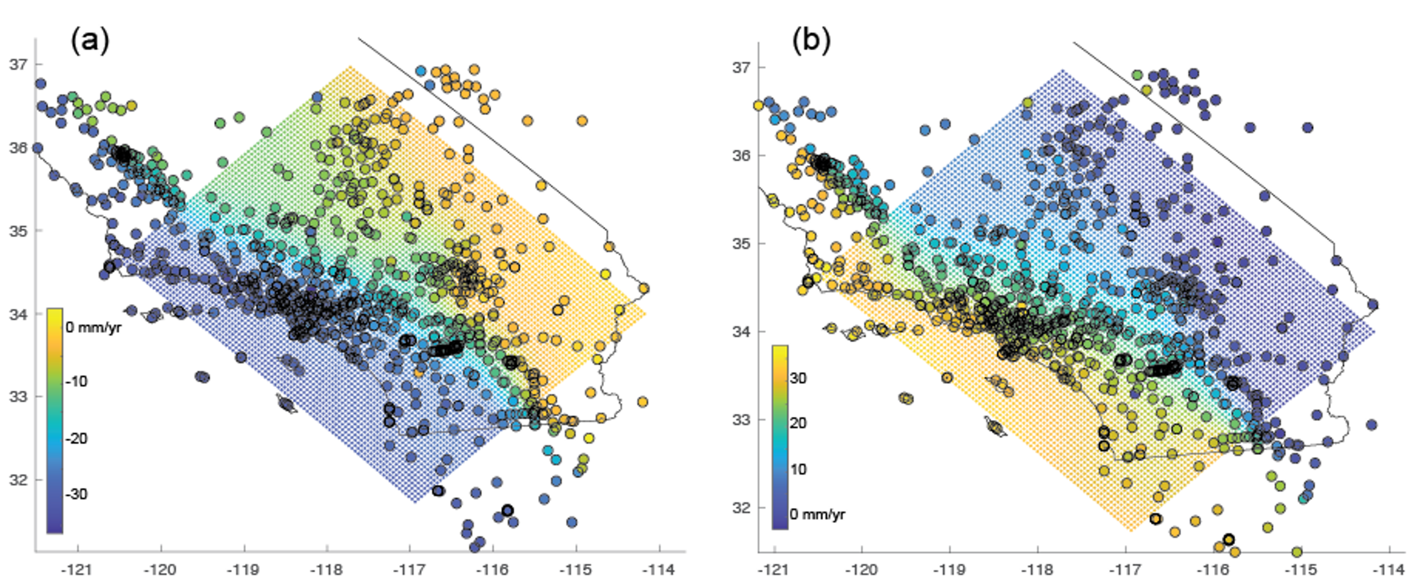


Figure 3: Observed (circles) and interpolated (dots) velocity fields for Easting (a) and Northing (b) velocities. The Easting, Northing, and Up components of the GNSS velocity field are interpolated separately.

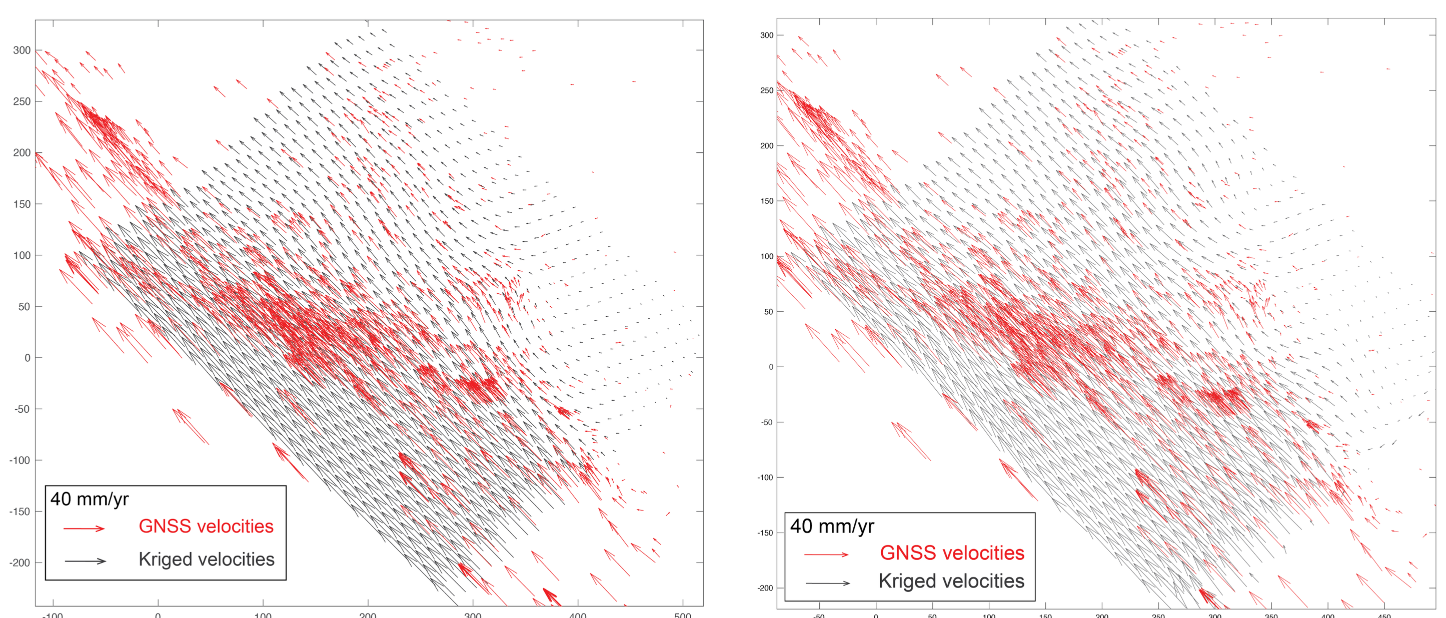
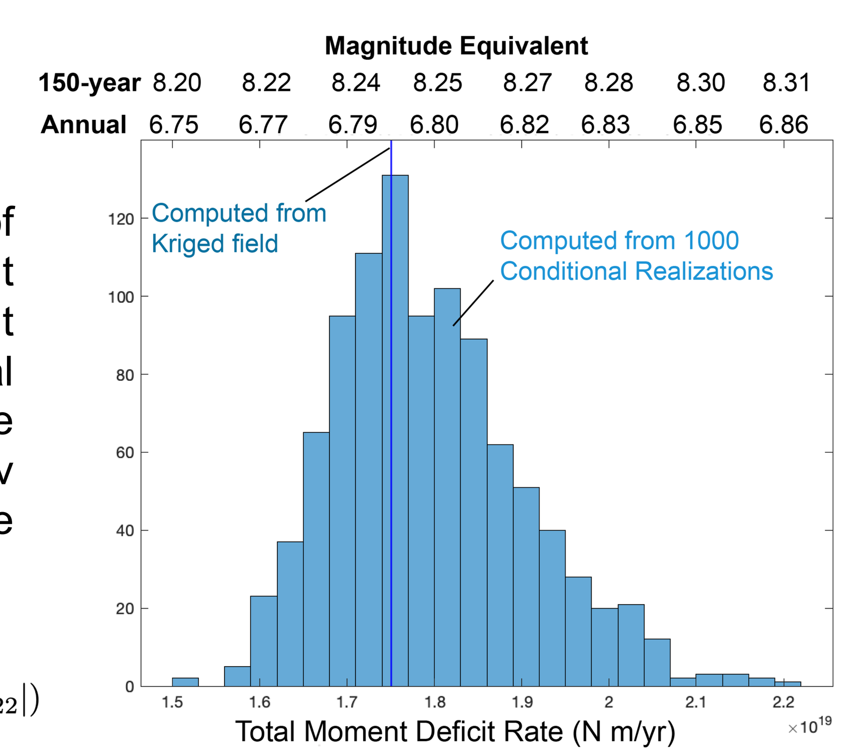


Figure 4: (left) kriged velocity field in vector form. (right) A conditional realization of the velocity field, accounting for random variability in the velocity field consistent with the estimated data noise.

Moment Rate from Kostrov Summation

We use the ***Kostrov method*** (Savage and Simpson, 1994; Kostrov, 1954) to compute the total moment rate for each simulated strain rate field and show that the total moment rate estimated for southern California estimated using the Kostrov method may exceed that estimated using elastic models by 30% or more (Johnson, 2013; Maurer et al., 2018), consistent with previous results (Johnson, 2013).

Figure 7: Histogram of estimated total moment deficit rate and magnitude equivalent from the conditional realizations of strain rate computed with the Kostrov method compared to the kriged estimate.



$$M_0^{\min} = 2GAH \max\left(|\epsilon_{11}|, |\epsilon_{22}|, |\epsilon_{11} + \epsilon_{22}|\right)$$

Strain Rate with Uncertainty

We compute numerical gradients of the interpolated velocity field, including both the kriged version as well as the conditional realizations, and use the gradients to compute ***surface strain rates***.

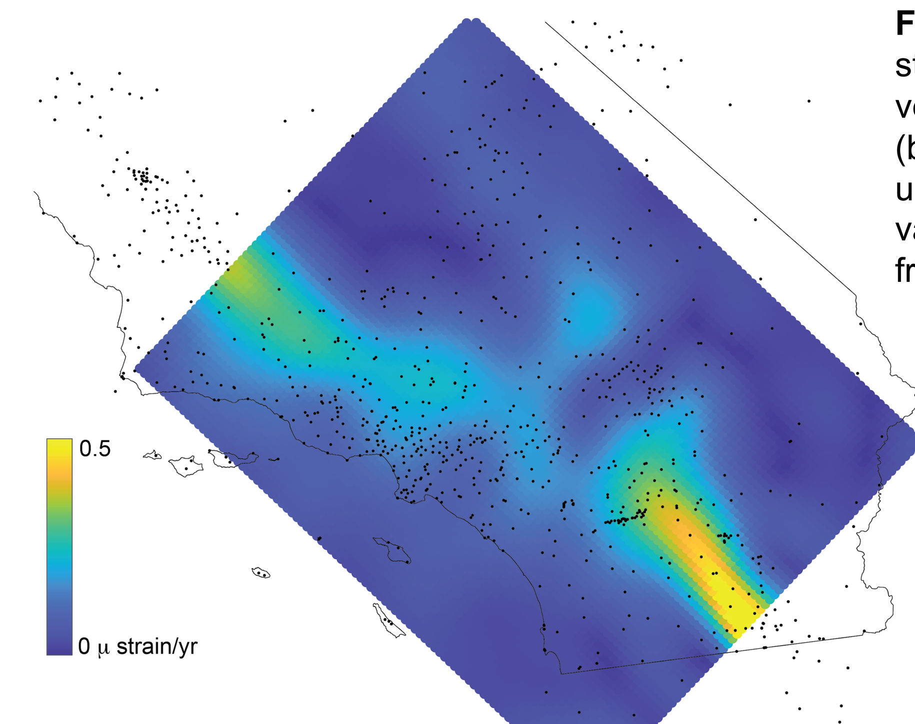


Figure 5: (left) Maximum shear strain rate based on the kriged velocity field in microstrain per year. (below) Max shear strain rate uncertainty based on the empirical variance of the strain rate computed from all the conditional realizations.

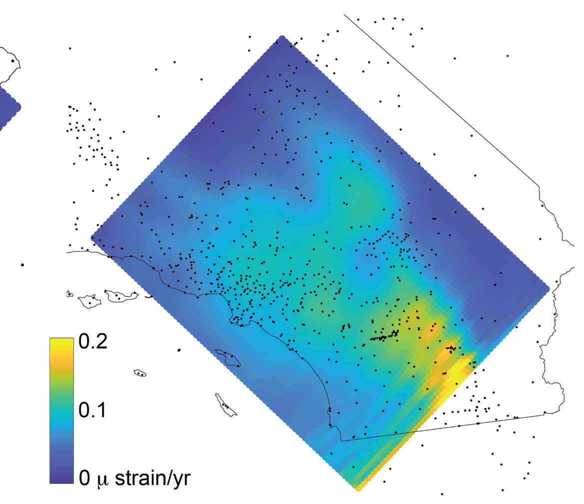
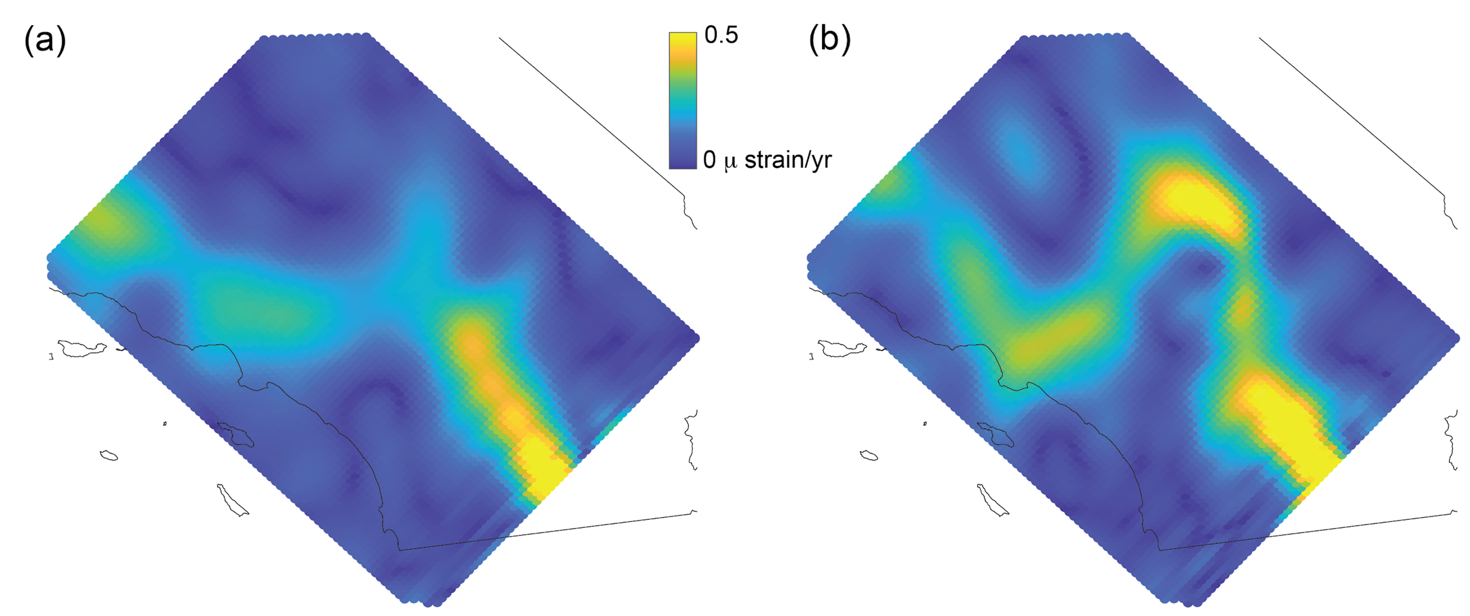


Figure 6: Maximum shear strain rate for the (a) minimum- and (b) maximum-moment models.These extremal models demonstrate the variability in strain rate relating to data and interpolation uncertainties.



Conclusions and Future Directions

Geostatistics provides a means to estimate the spatial structure of the data directly from the data itself (through variogram analysis), an optimal interpolator based on the estimated structure function (kriging), and a means for generating conditional realizations of the velocity field to derive uncertainty estimates for strain rates.

We will use the distribution of surface strain rates to estimate backslip on faults in southern California and remove the modeled component of the strain rate field to quantify the "off-fault" strain rates. We will compare these to the uncertainties in the total strain rate field to determine where off-fault strain is statistically significant given the uncertainties estimated through the geostatistical analysis.

References

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