# Numerical Seismicity Prediction with STAN Part II

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program element II
Fault Stress Interactions, Seismotectonics, Strain Measurements, Regional Modeling

## Non-technical summary (<100 words)

Under this grant I developed some flexible and objective models of seismic activity. I have used these models to compare theories of aftershock generation based upon static and dynamic stress transfer from dozens of mainshocks in southern California. I have found that peak dynamic stresses are a better predictor of aftershock locations than static stresses are. But the background stress state most consistent with dynamic triggering contradicts other observations. I have also found that aftershocks are an accelerated version of background activity, which implies that all earthquakes develop slowly, and that mainshocks mostly do not produce ”new” events.

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## Abstract

Studies with the Stress Transfer and Nucleation (STAN) model have progressed considerably this year, with an improved optimization technique, better statistical measures of fit quality, and more accurate dynamic stress transfer calculations. The new fast approximate dynamic stress transfer model can be used to compute remarkably accurate static stresses, in spite of its approximate treatment of the free surface. Preliminary results suggest that peak dynamic stresses computed using this model are a better predictor of aftershock locations than static stresses are, especially beyond a few source radii. Both static and dynamic stress transfer models display considerable skill when compared to a fit using randomized stress steps. An expanded set of mainshocks has been studied using some new classes of aftershock decay model, leading to relatively modest improvements in fit that invite farther study. Currently, the best fitting model is a variation on modified Omori that includes a slight dependence of p-value upon stress step. There are also some indications that the response to stress steps is nonlinear, saturating when stresses exceed a threshold. The development of STAN has opened up many topics worthy of future research.

# 1 Investigations

### Stress Transfer and Nucleation

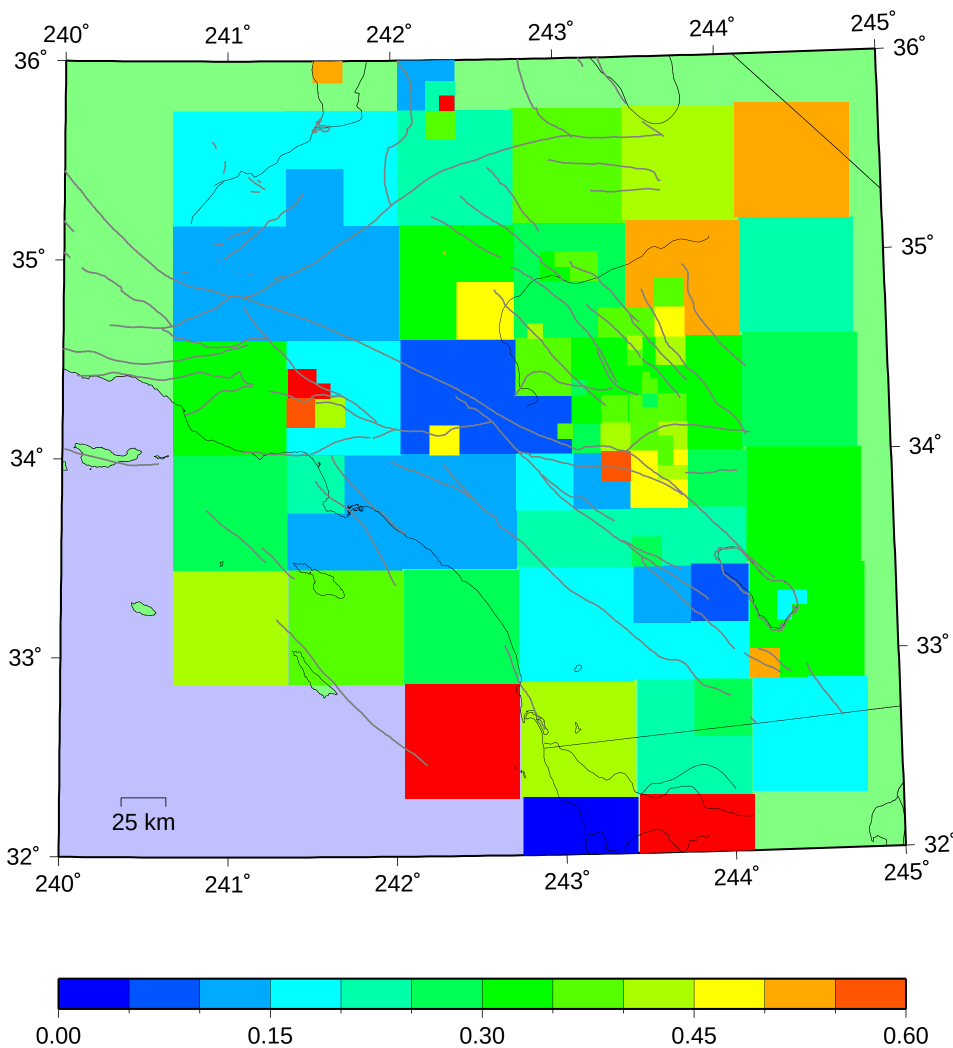
STAN is a new kind of seismicity model which incorporates both spatial and temporal variations in activity, and quantifies how well we understand the earthquake nucleation process. STAN can be used to make formal seismicity rate forecasts, fit models of stress transfer triggering, and invert for tectonic loading patterns given observed seismicity. Although STAN is by no means fully developed, it has already been productive. In implementing STAN, I had to decide what seismicity response was expected when a volume is repeatedly stressed, and developed a new approach to that problem. STAN is constructed with a minimum of free parameters, and it allocates these parameters in proportion to the data, with a clustering algorithm which breaks apart three dimensional space in proportion to the seismic activity. Although STAN can be constructed with any underlying set of assumptions, the current version does not assume that seismicity is concentrated on mapped faults. It instead assumes that the long term spatial seismicity distribution will persist, and be modified by stress transfer from observed mainshocks. The stress transfer generates aftershocks in each volume in proportion to the stress step multiplied by the activity level of that volume. It is assumed that each volume produces background seismicity in proportion to that same intrinsic activity level multiplied by a loading rate. The loading rate can be assumed constant or varied with location. Similarly, STAN can be constructed with a great variety of assumed temporal aftershock decay models.

#### A Procedural Outline of STAN

1. Cluster events onto an adaptive grid.
2. Compute stress transfer from mainshock sources to each subset.
3. Apply aftershock generation and decay models to each stress subset to compute the ”activity” of that location given the observed event count.
4. Evaluate statistical measure of fit for each subset.
5. Optimize, adjusting generation and decay parameters to find best statistic.

A key element of every STAN model is the battery of statistical tests used to evaluate the fit. Since STAN defines an expected seismicity rate as a function of time and space, it is well suited to evaluation with maximum likelihood techniques. Non-parametric Komolgorov-Smirnov (K-S) statistics are also used, because they provide better information about the quality of the fit than likelihood fits do. STAN models can also be evaluated by the quality of their forecasts. Ideally, we would wish that the models have predictive skill, and expect that the best models would make the most successful predictions. After some goodness of fit measure such as the K-S statistic has been optimized, so that the misfit

KS statistic, Dynamic stress fits




These statistics are combined into a single log likelihood statistic using their probabilities of
Komolgorov-Smirnov statistics for a STAN subsets are shown, with the red representing poor fits.
significance.

is minimized, the fit can be re-evaluated for true skill by comparing it with predictions based upon a much simpler algorithm, such as persistence. Tests such as these provide an objective basis for evaluating a huge variety of seismicity models, from exceedingly simple to absurdly complex.

The adaptive grid is created very simply, and has 3 parameters that define it, the minimum and maximum grid size, and the minimum event count. It starts with a very fine grid covering the whole region of interest at a 1km resolution in three dimensions. Those cells that satisfy the minimum event count are kept, and the resolution of the grid is halved for all the others. Then the remaining events are compared with the new grid, and all cells meeting the minimum event count criteria are saved, and the resolution is halved again, until the maximum grid size is reached. Cells of the maximum size do not necessarily satisfy the minimum event count.

## 2 Results

There have been several new developments in STAN this year. There are new stress transfer models, more mainshocks, improvements to the fitting algorithm, and new statistical measures. New seismicity models are being developed. Space limitations prohibit a full discussion of all of these improvements, but the highlights are summarized below.

A fast approximate stress transfer model was developed during 2002, under a combination of NSF and USGS funding. This dynamic stress transfer model was developed to compliment the static stress transfer models which have been a part of STAN from the beginning. It uses point sources and the method of images to compute stress histories inside the medium very quickly and without the numerical instabilities that plague most models of the seismic waveform. It includes the near and intermediate field terms that are so important for this application, and it runs about 280 times as fast as a reflectivity model. Complex mainshock sources are represented with hundreds of source points whose moment, mechanism and timing are constrained by a variety of seismic and geodetic observations (Wald and Heaton 1994, Wald Heaton and Hudnut 1996, Ji et al 2000). The most important limitations the fast approximate dynamic stress transfer model has are its inability to model structure, and the approximate free surface. The point source dynamic model satisfies the stress free condition in a way that does not produce surface waves, and so it would not be appropriate for observations beyond regional distances. The approximation was evaluated by comparing the static stresses from this model with exact solutions computed using the Okada (1992) equations, and found to be much more accurate than a reflectivity model, especially for stresses inside the medium, where triggering must be evaluated. The fast approximate dynamic stress transfer model was presented at the 2002 fall AGU meeting.

This year the STAN inversion technique has been overhauled to make it more adaptive and robust. It is still a nested grid search, carried out in multi-dimensions, but the grid size now adjusts to the location of the best fitting parameters. If the current best fit lies at the edge of the grid, the grid is only moved, not reduced in size. This makes the algorithm somewhat similar to a downhill simplex, but with a far greater number of field points. With downhill simplex, the global minimum is not always reached, because the objective function has fairly sparse sampling, and so it is often a good idea to re-run the optimization several times. STAN's fitting algorithm is more reliable than downhill simplex, although it is still relatively slow and best suited to low dimensional inversions. After implementing the new algorithm, I no longer observe advantages of simpler models over more complex ones, except in predictive mode.

log likelihood statistics of STAN fits

| | Omori | MOM | Dieterich |
|---|---|---|---|
| Static | -3730 | -3723 | -4986 |
| Dynamic | -3624 | -3549 | -5001 |
| Random | -5615 | -5424 | -5311 |

The table above is similar to the one that was presented at the EGS/AGU meeting in France during April 2003. It shows that the best models are the dynamic ones with the traditional modified Omori (MOM) temporal decay. Both static and dynamic stress transfer models show considerable skill when compared to a fit made with randomized stresses. If this model were ”just a fitting exercise” the randomized stresses would fit the observations as well as the static and dynamic stresses do. The log likelihood statistical measure pools the probabilities of the observed earthquake times being drawn from the theoretical distributions as evaluated for each STAN subset. This new approach to pooling the KS statistics which quantify the fits of the subsets is much more statistically correct than the previous weighted sum approach. The least negative log likelihoods fit the best. Although these fits correspond to very low probabilities, that is due to the large number (39640) of events being fit, and not an indication of a poor fit.

Recently 49 mainshocks were added to the STAN models. Formerly, I included just 3 large mainshocks (1992 Landers, 1994 Northridge and 1999 Hector Mine), using detailed source models. These smaller mainshocks will necessarily be much simpler. Initially, I have represented them with simple point sources having an isotropically distributed stress step that decays with the cube of distance. Even this crude representation of smaller mainshocks improves the models, but not dramatically. I am planning to explore more accurate approximations to both the static and dynamic stresses for smaller mainshocks, and take into account their focal mechanisms.

STAN is ideally suited for the study of aftershock decay models that depend upon both space and time, in an inseparable way. Currently the best fitting model is modified Omori, which is represented with a seismicity rate function $\Lambda$ that can be separated,

$$\Lambda(x, t) = X(x) \times T(t)$$

being simply a multiple of some function $X$ that depends only on location, with a function $T$ dependent only on time. Such separable functions can be studied without employing a model like STAN.

The temporal aspects can be ignored when one studies the spatial aspects, and vice versa. By contrast, the Dieterich seismicity theory isn't separable. It involves stresses in its temporal decay, and is best studied with models that include both temporal and spatial aspects. Unfortunately the Dieterich models are not very well supported by the observations, as you can see in the table of statistics. But there is a whole universe of possible seismicity theories/aftershock models which have variations in decay with stress step and should be evaluated. Currently just a few of these possibilities have been explored. Motivated by some interesting variations in decay properties that can be seen in plots of the decay of subsets of the Landers aftershocks defined using stress step, I've introduced a variation on the modified Omori model, which includes a logarithmic dependence of p-value on stress step. Preliminary tests of this model have shown that it is a modest improvement over all previous models. Farther study is needed in order to determine if the improvement in fit is statistically significant.

Another potentially significant question is just beginning to be studied with STAN is the potential nonlinearity of the seismicity response to stress. A few models in which the seismicity is predicted to saturate, producing the same amplification factor to all stress steps exceeding 20MPa have been constructed. These models provide slightly improved fits to the seismicity than the linear models do. I plan to investigate variations in the threshold and hopefully a variety of nonlinearities with the hope that they will help all of us decide on the physical mechanisms behind the seismicity triggering phenomenon.

## 3 Non-technical summary ($<$100 words)

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## 4 Reports published

Gross, S. J., Failure Time Remapping in Compound Aftershock Sequences, *Bull. Seism. Soc. Am.*, **93**, in press, August 2003.

Gross, S. J., A model of tectonic stress state and rate using Northridge aftershocks, *Bull. Seism. Soc. Am.*, **91**, 263-275, 2001.

## 5 Availability of data

The research did not involve the collection of any new data, only the construction of models, so this topic does not apply. Colleagues interested in conducting research with these models should contact Susanna Gross at (303) 492-1039 or sjg@colorado.edu,

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Gross, S. J., Failure Time Remapping in Compound Aftershock Sequences, *accepted by Bull. Seism. Soc. Am.*, **93**, to appear in August 2003.

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