# Detection and Analysis of Time-Dependent Earthquake and Volcanic Processes using Space Geodesy

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## Contents

# 1 Abstract

# 2 Technical Plan

In the past decade there has been a tremendous increase in the number and density of geodetic networks for the study of crustal deformation. Large-scale permanent GPS arrays have been developed in Southern California (SCIGN) [*need reference*], in Japan (GEONET) [*Miyazaki et al.,* 20XX], the Basin and Range (BARGEN) [*Werneke et al.,* 20XX], the Pacific Northwest (PANGA) [*need reference*], the the San Francisco Bay region (BARD) [*King et al.,* 1995], and elsewhere. Plans for the Plate Boundary Observatory (PBO) call for 1,000 ? permanent GPS sites in addition to 175 borehole strainmeters. These GPS networks yield daily estimates of site positions with a precision of a few millimeters in the horizontal and XX mm in the vertical over regional distances [*need reference*]. These networks are, for the first time, providing deformation data that is dense in both space and time.

The last decade has also witnessed an explosive growth in the use of interferometric SAR (InSAR) for the measurement of crustal deformation [*need references*]. INSAR maps of ground deformation have now been obtained for earthquakes [ e.g., *Massonnet et al.,* 1993; *Zebker et al.,* 1994; *Murakami et al.*, 1996], post-seismic deformation [ e.g., *Peltzer et al.,* 1996] and volcanic deflation [*Massonnet et al.,* 1995]. [*Need to update references*]. Recent results have been obtained showing the interseismic pattern of deformation across the San Andreas [*Peltzer et al.,* 20??] and North Anatolian Faults [*Parsons et al.,* 20??]. While existing spacecraft provide only limited temporal resolution the potential for a repeat pass interferometry mission (such as ECHO), promise even greater spatial and termporal data densities.

Until rather recently much of the communitities research effort has focused on obtaining accurate interseismic velocities from GPS networks, and analyzing coseismic displacement fields obtained by both GPS and InSAR. More recently, transient deformation events have been discovered that point to entirely new processes such as silent earthquakes. Because these events are invisible to seismic instrumentation, silent deformations are an important and challenging target for space geodesy. Silent earthquakes have now been discovered by permanent GPS networks in southwest Japan [*Hirose et al.,200?*; *Ozawa et al.,2001?*], the Cascadia subduction zone [*Draegert et al., 2001?*], and beneath Kilauea volcano in Hawaii [*Cervelli et al., 2002*]. The moment magnitudes of these events range from $M_W 5.5$ (check) beneath Kilauea to nearly $M_W 7$ in the case of the two subduction zone events. The durations of these events vary considerably. The Bungo Channel event in southwest Japan lasted roughly one year, the Cascadia silent earthquake approximately two weeks, while the Kilauea silent slip event had a duration of roughly two days. Previously, evidence for slow earthquakes had been seen on strain and creep meters [*Linde et al., 19XX*]. Transient post-seismic deformation is also well established, with characteristic time scales ranging from 25 years (post 1906) [*Thatcher , 1975*], to *need other references to Landers, Loma Prieta, Northeast Japan, etc.*

Of course, deformation in volcanic regions is well known to be episodic [ e.g., need lots of references]. Transient deformation preceeds some, if not all, volcanic eruptions, although relatively few are well monitored. The time scales of the pre-eruptive deformation, however, can be quite variable. Permanent GPS stations on Kilauea volcano recorded 8 hours of extension prior to a rift eruption in 1997 [*Owen et al., 2000*]. On the other hand, a network of borehole strainmeters showed transient motion only 30 minutes prior to a basaltic eruption of ?? in Iceland [*Linde et al., 2000*]. Long-term inflation is also seen prior to eruption of many shield volcanos. Recent evidence from InSAR shows signs of inflation episodes on numerous Aleution volcanos. Say something about Long Valley?

While past results are certainly not promising, it is not inconceivable that deformation transients might precede earthquakes. Given the tremendous investment in building permanent GPS networks and collecting INSAR data, it is imperative that we explore these data fully to reveal the underling fault-slip process. In particular, given data from frequently sampled, dense geodetic networks, it is now possible to address questions such as: " Does the pattern of aseismic slip-rate change before large earthquakes?" "What is the space-time evolution of silent earthquakes; ie what are characteristic rupture velocities and rise times, and what does this reveal about fault zone processes and constitutive properties?"

We propose to complete development of time-dependent inversion methods for space geodetic data. These inversions provide full space time history (essentially 'movies') of slip-rate on faults. We will also develop automated procedures for detecting changes in deformation without specifying the details of the causative structure. That automated methods are required is obvious when one considers that a 1000 station array generates $9 \times 10^5$ three-dimensional position determinations per year.

## Existing GPS Data

Figure 1 illustrates trasnient deformation data from the Japanese GEONET. Time series are shown for two stations in the southern end of the study area, near the source region of the two Hyuganada earthquakes, and two stations near the Bungo Channel at the northern end of the study area. The data have been filtered to remove coseismic offsets caused by the two M 6.7 earthquakes, as well as rigid body translations and rotations resulting from inaccurate realization of a fixed reference frame. Note that the two southern stations exhibit coherent motions begining in XX indicative of post-seismic deformation following the two Hyuganada earthquakes. The two stations near the Bungo Channel also show coherent motion begining at a somewhat later time. It is these data that provide the evidence for the silent earthquake.

*Need to flesh this out and include some SCIGN data*

## Inversion Methods

There are major challenges in developing time dependent inverse methods for transient changes in slip-rate. First, we do not know *a priori* the nature of the time variations that we are trying to detect. Secondly, space geodetic measurements contain spatially and temporally correlated

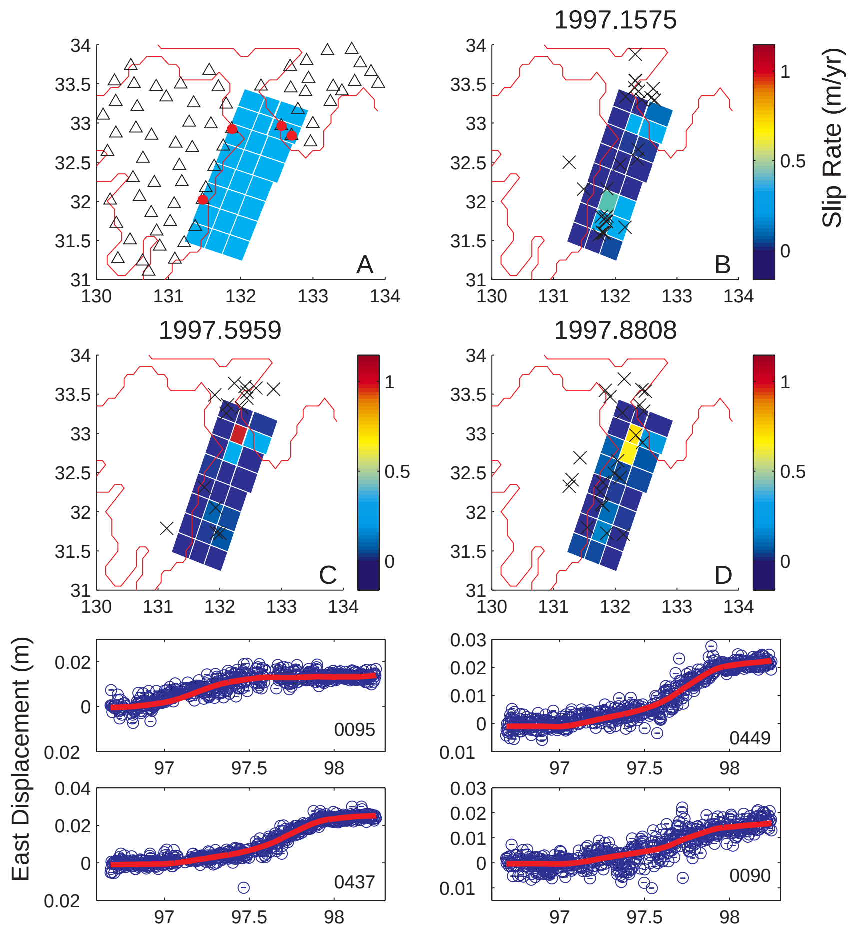


Figure 1:

errors, due to atmospheric path delays, and in the case of GPS multipath and random benchmark motions [ e.g., *Wyatt*, 1989]. Thus any viable estimation procedure must allow for general, non-parametric estimation of the temporal variations in fault slip, and account for correlated errors in the observations. Secondly, due to imperfect resolution of the data, any inversion procedure will involve some spatial and temporal smoothing. It is very desireable that the amount of smoothing be determined by some rigorous procedure, not simply the analysts prejudice about what the slilp-distribution should look like.

Our approach is based on previous work of *Segall and Matthews* [1997] and is referred to as a Network Inversion Filter (NIF). The NIF marries linear time domain filtering with spatial inverse methods. *Segall et al.* [2000] showed how to separate spatial and temporal smoothing by implementing the spatial smoothing through pseudo-observations. This method has been applied to the postseismic deformation following the 1989 Loma Prieta Earthquake [*Segall et al.*, 2000], the

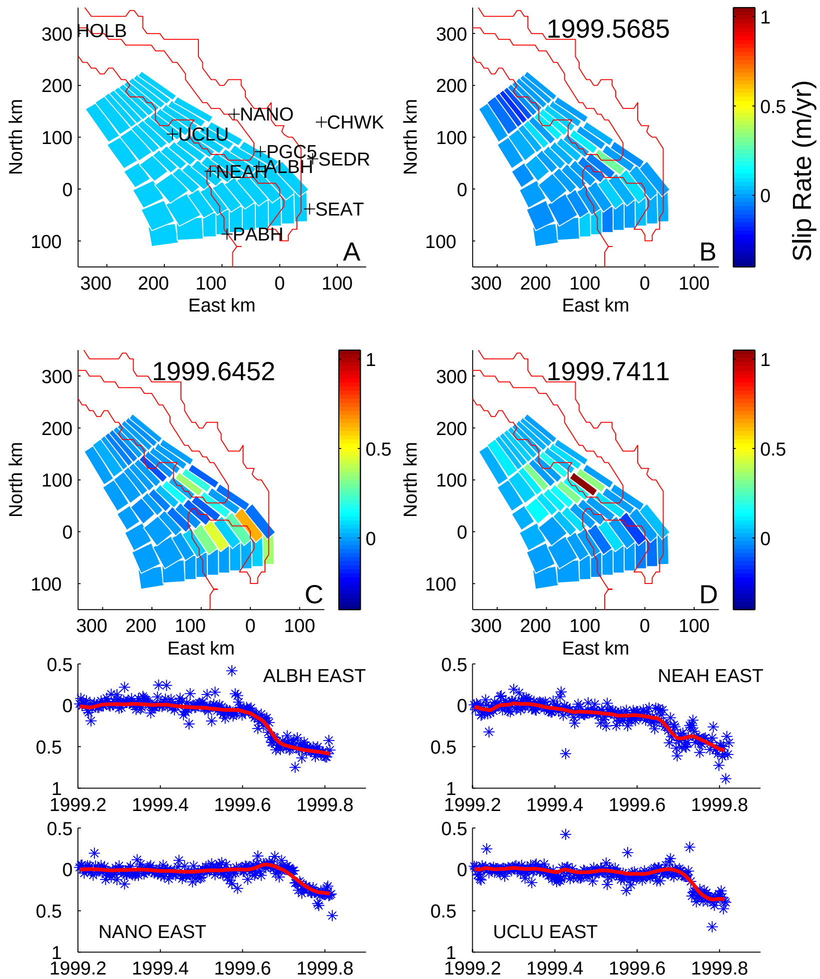


Figure 2:

1999 Izmit earthquake [*Burgmann et al.*, 2001], and volcanic deformation following the 1997 dyke intrusion beneath the Izu peninsula in Japan [*Aoki et al.*, 1999]. Recently [*Miyazaki et al.*, 2002] account for reference frame errors in the GPS data in the observation equations.

To be specific, we GPS station positions relative to an *a priori* estimate $\mathbf{X}(t)$, as a function of time $t$, as follows

$$\mathbf{X}(t) = \sum_k H(t - t_{eq(k)})\mathbf{X}^{cos(k)} + \int_A s_p(\boldsymbol{\xi}, t - t_0) G^r_{pq}(\mathbf{x}, \boldsymbol{\xi}) \mathbf{n}_q(\boldsymbol{\xi}) dA(\boldsymbol{\xi}) + F\mathbf{f}(t) + L(\mathbf{x}, t - t_0) + \boldsymbol{\epsilon} \quad (1)$$

where the first term on right hand side represents coseismic displacements. $\mathbf{X}^{cos(k)}$ are coseismic offsets at times $t_{eq(k)}$, and $H(t)$ is a Heavyside function. The second term on the right hand side represents deformation due to transient aseismic slip. We relate the time dependent site motions to slip on faults in an elastic medium as a function of position $\boldsymbol{\xi}$ and time, $s_p(\boldsymbol{\xi}, t - t_0)$ through Green's functions $G^r_{pq}(\mathbf{x}, \boldsymbol{\xi})$. To date, Green's functions relating slip to surface displacement have been computed using analytical expressions for dislocations in uniform half-spaces, although there is no empidement to computing Green's functions in heterogeneous or layered media. In (1) $p, q, r$ = 1,2,3, and summation on repeated indices is implied, $\mathbf{n}_q(\boldsymbol{\xi})$ is the unit normal to the fault surface $A(\boldsymbol{\xi})$.

The remaining terms are related to measurement and reference frame errors. The term $F\mathbf{f}(t)$ represent reference frame errors, where $F$ is a linearized Helmert transformation [e.g. *Hofmann-Wellenhof et al.*, 1997] and $\mathbf{f}(t)$ is a vector of rigid body translation, rotation, and scale factor. The fourth term on the right hand side of (1), $L(\mathbf{x}, t - t_0)$, represents random benchmark wobble, which we model as a Brownian random walk with scale parameter $\tau$ (units length/time$^{1/2}$) [*Wyatt*, 1982; 1989]. While some studies have advocated a flicker noise model for benchmark motion [*Mao et al.*, 1999; *Zhang, et al.,* 1997 ], *Langbein and Johnson* [1997] using over 10 years of data show that a random walk fits the data quite well. Without a long time series it is very difficult to distinguish between flicker noise (with a $1/f$ spectral decay) and random walk (with a $1/f^2$ spectral decay). A key feature of the Network Inversion Filter is that it can distinguish spatially correlated transient signal from site specific colored noise. The reason for this is that elastic deformation causes a spatially coherent signal, whereas the local benchmark motions are, by definition, assumed to be spatially incoherent. The fact that the local benchmark motions are spatially incoherent may be more important than the precise form of the spectral decay in the time domain.

The final term $\boldsymbol{\epsilon}$ represents observation error, which we take to be normally distributed with zero mean and covariance $\sigma^2 \Sigma_{\mathbf{x}}$, where $\Sigma_{\mathbf{x}}$ is the covariance matrix of the GPS positions, and $\sigma^2$ is a scale factor to account for unmodeled errors such as mulitpath, or azimuthally varying path delays.

The previous inversions using the NIF (cited above) suffered from two problems. First, the linear Kalman Filter approach did not allow for non-negativity constraints. It is well established in time independent inversions that the addition of non-negativity constraints ( e.g., prohibiting left-lateral slip on the San Andreas Fault) substantially improves spatial resolution. Secondly, the spatial and temporal smoothing parameters were determined by Maximum Likelihood. Using a prediction error decomposition, *Segall and Matthews* [1997] showed that the likelihood could be computed using a recursive filter that inverted the state-covariance matrix at each epoch. While relatively fast, compared to inverting the full data covariance matrix, this approach proved to be computationally burdensome – the full data set needed to be run through a forward filter for every choice of smoothing (hyper) parameters.

Recent work, detailed in *McGuire and Segall* [in prep] has substantially improved on previous methods. Firstly, we have implemented an non-linear, extended Kalman Filter, that allows non-negativity constraints to be applied. We have found that this substantially improves the spatial resolution of the inversions as expected. Secondly, we include the hyper parameters in that state vector and estimate them directly in the filter. This avoids the computationally costly maximum likelihood procedure. Synthetic tests indicate that this procedure leads to nearly optimal choices of the smoothing parameters.

Details of the inversion procedure are omitted here for brevity. Rather we show results of time dependent inversions using data from southwest Japan and the Cascade subduction zone. *Need to describe the results here.*

## Proposed Work

**ENIF.**

Any work needed on the ENIF? Possibilities include: (1) Explore effects of spatially variable random walk variance, and alternate stochastic models for local benchmark motion. (2) Explore possibility of incorporating InSAR results with GPS data.

Otherwise the main task here will be to come up with a version of the code that can be distributed.

**Anomaly Detector.**

Time domain filtering methods are not only able to estimate past fault-slip histories, they also lead rather naturally to anomaly detectors. As discussed previously, it can be difficult to synthesize data from an array of stations by eye to infer changes in the underling fault-slip process, particularly when networks contain hundreds to thousands of stations. It is clear that automated procedures are needed to assess whether changes in the style of crustal deformation have taken place. Time domain filtering is ideal for this because the filter is continually predicting the next state, conditioned on all past data, and then comparing with the next set of observations. When the new data differs significantly from the prediction this is a natural indicator of a change in the underlying process.

There are two approaches that could be taken. In areas where the fault geometries are well known, and existing data permit inversions with the NIF, it is possible to use the NIF to create anomaly detectors. *There are however some questions about statistical significance that need to be addressed.*

On the other hand, there are many places where space geodetic networks are so broad that it will be difficult to model all the structures that might be contributing to the contemporary deformation field. In these situations it is desireable to have a filter that doesn not demand one know the full fault geometry. Such a method should be able to detect time varying strain at a range of spatial scales. Once detected, one could compute Green's functions for the NIF assuming the active structures in the vicinity of the anomalous deformation are reasonably well known.

An alternate approach, which we refer to as a Network Strain Filter (NSF !!), is to model the spatially coherent part of the deformation field in terms of a spatially and temporally variable deformation field. Ignoring for the moment rigid body motions, reference frame errors, random benchmark motion, etc, we can relate the position changes to the deformation gradient tensor $D(\mathbf{x}, t)$

$$\mathbf{X}(t) = \mathbf{X}(t_0) + D(\mathbf{x}, t) \cdot \Delta\mathbf{X} \quad (2)$$

where $D_{ij} = \epsilon_{ij} + \omega_{ij}$ is the sum of the symmetric strain tensor and the anti-symmetric rotation tensor. $\Delta\mathbf{X}$ is the vector from the network center of mass to the station at $\mathbf{X}$. Expanding $D(\mathbf{x}, t)$ in terms of spatial basis functions $B_n(\mathbf{x})$ we have

$$D(\mathbf{x}, t) = \sum_{n}^{N} B_n(\mathbf{x}) c_n(t) \tag{3}$$

Thus the new observation equation becomes

$$\mathbf{X}(t) = \sum_k H(t - t_{eq(k)})\mathbf{X}^{cos(k)} + (\sum_{n}^{N} B_n(\mathbf{x}) c_n(t)) \cdot \Delta\mathbf{X} + F\mathbf{f}(t) + L(\mathbf{x}, t - t_0) + \boldsymbol{\epsilon} \tag{4}$$

As in the case of (1), (4) can be solved using Kalman Filtering methods. The state vectro containts the coseiesmic offsets, the strain coefficients $c_n(t)$, the reference frame terms, and the random walk incerments.

The only real work we need to do is to determine the appropriate choice of basis functions and come up with a procedure for determining how many terms to include in the expansion $N$.

**Application to SCIGN**

*Need some words here.*

**Application to GEONET**

The second area we will study is the Tokai seismic gap region in Japan. For this component of the study, we will collaborate with Dr. Teruyuki Kato and Dr. Shinichi Miyazaki of the Earthquake Research Institute, University of Japan, and Dr. Takeshi Sagiya and Dr. Hatanaka of the Geographical Survey Institute of Japan

The Tokai area is thought to represent a significant seismic gap [*Ishibashi,1980*]. In Suruga Bay the Phillipine Sea plate subducts beneath the Eurasian plate. To the south on the Nankai Trough, major earthquakes occurred in 1944 (Tonakai, M7.9) and 1946 (Nankai, M8.0), however a major earthquake has not occurred in Suruga Bay since the 1854 Ansei-Tokai earthquake. The demonstrated capability of a major earthquake, the 140 year quiesence, and the proximity to metropolitan Tokyo have made the Tokai gap the focus of earthquake prediction efforts in Japan.

*Jeff, need to add something about the Tokai anomaly. Can you put in some plots of time series? Is it too early for a preliminary result?*

**Synergy with ongoing work**

We have ongoing work on Kilauea volcano. The volcano is rapidly deforming and experiences frequent episodes of transient deformation. Kilauea also presents significant volcanic, seismic, and tsunami hazards. An extensive GPS network already exists.

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## 4 Management Plan

This is an ambitious effort, ...... To accomplish these goals we have developed a cost-effective management plan, taking advantage of existing funding....and significant contributions from independently funded Japanese collaborators. Perhaps say something about postdoc doing PBO modeling studies.

P. Segall will serve as P.I. for the project and is responsible for its organization and overall progress. He will ... Co-I. McGuire will... Co-I. Hurst will ....

We have developed collaborative relations with Japanese scientists working on GPS and SAR. These collaborators add tremendous breadth to our efforts at no cost. In addition, they bring access to important GPS and other data. Dr. Shinichi Miyazaki (E.R.I, U. Tokyo) will be spending two years at Stanford, begining in 2003. Prof. T. Kato (E.R.I, U. Tokyo) and Drs. T. Sagiya (G.S.I.) and Y. Hatanaka have agreed to collaborate on the study of the Tokai GPS data.

This project will make use of existing GPS (and SAR?) data, making it particularly cost effective.

## 5 Cost Plan

## 6 Current and Pending Research

## 7 Resumes