

# Integrating NASA Space Geodetic Observations with Numerical Simulations of a Changing Earth

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## Abstract

**We describe results from numerical simulations of earthquake fault systems that allow us to better understand the physics of the San Andreas fault system and to model and interpret current and proposed NASA observational efforts in the area of space geodesy and crustal deformation. Numerical simulations are particularly useful for investigating the relationship between observable multi-scale space-time patterns in data and the fundamentally unobservable, underlying multi-scale dynamics that produce them. In addition, our simulations are also designed to provide physical understanding of fault system processes and their influence on factors such as: 1) Seismic activity through time; 2) Surface displacements observable by GPS, strainmeters and InSAR; 3) Relative importance of fault network topology and frictional processes in determining dynamical behavior; and 4) Partitioning of slip and seismic activity among active strike slip faults in California. One outcome of our research is a new mapping function, which we call a “Local Ginzburg Criterion”, that can be used to reveal information about the underlying dynamics using surface strain observations on faults systems.**

## Introduction

The last five years has seen unprecedented growth in the amount and quality of space geodetic data collected to characterize geodynamical crustal deformation in earthquake prone areas such as California and Japan. The Southern California Integrated Geodetic Network (SCIGN), the Bay Area Regional Deformation (BARD) network, and the ERS and JERS Interferometric Synthetic Aperture Radar satellites are important examples. NASA also plans to participate in the recently proposed Earthscope NSF/GEO/EAR/MRE initiative both through contributions to the Plate Boundary Observatory (PBO), as well as

taking a leading role in the development of an InSAR satellite such as LightSAR or ECHO (Earth Change and Hazard Observatory).

Earthquakes are one of the most important contributors to time- and space-dependent changes in the earth's surface observed by NASA space geodetic satellites and systems. Observation of phenomena associated with these sudden and extreme events, together with analysis via modeling and numerical simulations, are critical if we are to find answers to the two fundamental questions:

1. What are the motions of the Earth and the Earth's interior, and what information can be inferred about the Earth's internal processes?
2. How is the Earth's surface being transformed, and how can such information be used to predict future changes?

In this work, we focus particularly on the development and use of numerical simulations of stress-evolution in earthquake fault systems, together with NASA space geodetic datasets, with an eventual goal of developing the capability to forecast the largest earthquakes in fault systems such as those in California.

## Earthquake Physics: Unobservable Dynamics, Multi-Scale Physics

There are two serious drawbacks to a purely observational approach to the problems of understanding earthquake physics and earthquake forecasting: 1) Unobservable dynamics; and 2) A vast range of space and time scales. We argue that because of these fundamental problems, an approach integrating numerical simulations with data is the only possible approach that will lead to significant future progress in this field. We also argue that the *lack* of a modern simulation-based approach, allowing rapid prototyping of candidate models, has severely retarded research.

### Unobservable Dynamics

Earthquake faults occur in topologically complex, multi-scale networks or systems that are driven to failure by external forces arising from plate tectonic motions [2]. The basic problem is that the true (force-displacement) dynamics is *unobservable*. In fault systems, these unobservable dynamics are usually encoded in the time evolution of the *Coulomb Failure Function* (CFF):

$$\text{CFF} \equiv \tau(\mathbf{x}, t) - \mu_s \sigma_N(\mathbf{x}, t) \quad (1)$$

where  $\tau(\mathbf{x}, t)$  is shear stress at point  $\mathbf{x}$  and time  $t$ ,  $\mu_s$  is coefficient of static friction, and  $\sigma_N(\mathbf{x}, t)$  is normal stress. However, the space time patterns associated with the time, location, and magnitude of the sudden events (earthquakes) *are observable*. Our scientific focus will thus be on understanding the *observable space-time earthquake patterns* that arise from fundamentally *unobservable dynamics*, using new data-mining, pattern recognition, and ensemble forecasting techniques appropriate for these multi-scale systems [2]. In view of the lack of observational data for the stress-strain dynamics, any new techniques that use space-time patterns of earthquakes to interpret underlying dynamics and forecast future activity must be developed via knowledge acquisition and knowledge

reasoning techniques derived from the integration of diverse and indirect observations, combined with a spectrum of increasingly detailed and realistic numerical simulations of candidate models.

## Range of Scales

The second problem, equally serious, is that the nonlinear earthquake dynamics is strongly coupled across a vast range of space and time scales that are much larger than “human” dimensions [2,3,4]. Examples of some of the important spatial scales are shown in the table below. Corresponding time scales are not easily shown, since this would require a third axis. Although all scales are important, we place more emphasis on the fault network and system scale, since this is the scale of most observational data networks.

## Space-Time Patterns

Spatial Scale	Physics	Input from Lower Scale	Output to Upper Scale	Comp. Methods	Research Status
Atomic: $10^{-10}\text{m} - 1\ \mu\text{m}$	Quantum Disordered system	Fundamental atomic constants	Cohesive potentials	Quantum DFT, MC	Computational chemistry, Not proposed here
Grain size $1\ \mu\text{m} - 1\ \text{cm}$	Contact interactions, planar fault elastic walls	Cohesive potential across grains	Effective viscosity, LG effective constants	MD	Not proposed, but we use input from ACES partner research on this topic
Fault zone $1\ \text{cm} - 100\text{m}$	Fluidized viscous gouge, elastic walls & interactions, strong correlations	Effective viscosity, LG effective constants	Effective friction laws, e.g., rate & state, stick-slip, leaky stress, elastic constants $\mu, \lambda$ , effective LG constants	FD, FEM, CA, BEM, Inertial solvers	Not proposed, but we use effective parameters ( $\mu, \lambda, \alpha$ ) from literature, ACES, and our other funded research.
Fault system $100\text{m} - 10\ \text{km}$	Coarse-grained planar faults, effective friction, strong correlations	Effective friction laws, e.g., rate & state, stick-slip, leaky stress, effective elastic constants $\mu, \lambda, \alpha$ , effective LG constants	Effective elastic moduli $\mu, \lambda$ , effective coefficients of friction & stress leakage ( $\mu_s, \mu_K, \alpha$ ), effective LG constants	CA, BEM, FEM, Quasistatic solvers	Basis of our statistical mechanics approach. We use results from literature and our other separately funded research
Fault networks $10\ \text{km} - 1000\ \text{km}$	Geometric fault complexity, Deep viscoelastic relaxation, Static-kinetic friction, strong correlations	Effective elastic moduli $\mu, \lambda$ , effective coefficients of friction & stress leakage ( $\mu_s, \mu_K, \alpha$ ), effective LG constants	Effective viscosity spectrum, Effective viscoelastic modulus spectrum	CA, BEM, GeoFEM	Work proposed here is primarily on this scale.
Tectonic Plate Boundary	Viscoelastic flow on very long time scales, kinematics of plate motion at fault velocities $V$	Effective viscosity spectrum, Effective viscoelastic modulus spectrum	No larger scale of interest	GeoFEM	Models on this scale give us fault loading velocities $V$

**Table Key:** FEM - Finite Element Method; GeoFEM - Japanese Geo FEM software; MC - Monte Carlo; DFT - Density Functional Theory; FD - Finite Difference; MD - Molecular Dynamics; PD - Particle Dynamics; LG - Landau Ginzburg; CA - Cellular Automata; BEM - Boundary Element Method

As a result of the unobservable dynamics and multi-scale physics, observations of earthquakes have focused on the observable data of time, location and magnitude of earthquakes, and whether these events may organize themselves according to space-time patterns [1-5]. The idea that earthquakes demonstrate space-time patterns has been suggested for many years. Examples include Mogi donuts, precursory quiescence and activation, Parkfield periodic behavior, Bufe-Varnes time-to-failure power laws, and so forth. The Gutenberg-Richter and Omori scaling (power) laws indicate that earthquakes are self-similar over many scales of space and time. Analysis of observations, theory, and the numerical simulations that connect the observable space-time patterns to the dynamics is needed to determine whether these patterns are demonstrated at all scales in space and time, over a limited range of scales, or at only a few distinct scales. It may be that certain characteristic patterns indicate that a given event is a candidate foreshock of a future, larger event. Understanding these issues will have important implications for our ability to understand the details of the underlying stress-strain dynamics that may in fact be responsible for the observable patterns.

### Simulation Methods and Local Ginzburg Criterion

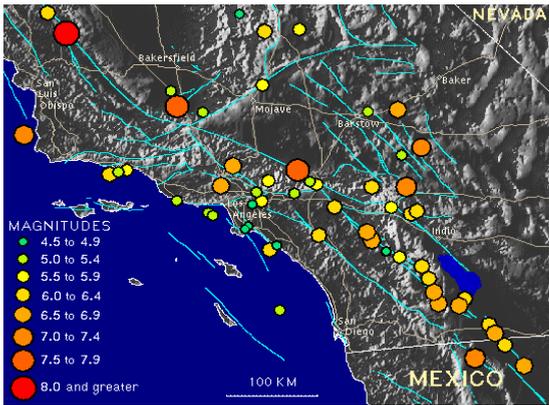


Figure 1

As an example, we consider the interpretation of crustal deformation data as measured, for example, by either GPS networks or InSAR images. In figure 1 [7] we show a map of southern California, with the fault system and major historic earthquakes superposed. Figure 2 [6] shows a model of the three dimensional network of major strike slip faults, at a spatial scale of resolution of approximately 10 km.

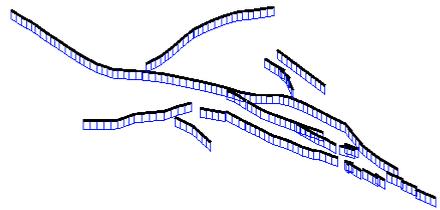


Figure 2

We have emphasized in the prior discussion that the Coulomb Failure Stress (CFF) is inherently *unobservable*, whereas the surface data are *observable*. The question we would

like to ask is whether there is some way to process surface data through a mathematical mapping so that the resulting processed data would resemble the CFF on each fault? Figure 3 shows that such mappings can be constructed, at least in theory. Here we call this mapping the “Local Ginzburg Criterion” (LGC) after a somewhat similar method of analysis in the theory of critical phenomena [8], but basically the method consists of defining a normalized, squared, time-dependent strain rate for each fault so that all locations can be treated as having the same strain rate statistics. In the theory of critical phenomena in complex, interacting, nonlinear systems, sudden changes in the dynamical state of the system are usually preceded by large fluctuations in the *order parameter* [8]. For earthquake fault systems, the order parameter is the slip deficit on a fault, fluctuations in which correspond to fluctuations in strain rate along the fault. The Ginzburg Criterion (GC) is defined to be the variance in the order parameter divided by the square of the mean. When this parameter becomes large, of the order of 10% or more, sudden changes in the order parameter of the system are imminent. Changes of this type include nucleation events, first order phase transitions, which in our case are large earthquakes.

We wish to define a similar quantity, a *fluctuation metric*, for each earthquake fault segment as a function of time. We therefore define our Local Ginzburg Criterion:

$$\text{LGC} \equiv \{ \text{surface shear strain rate at time } t \text{ and position } \mathbf{x} / \text{divided by} / \text{time average of surface shear strain rate at } \mathbf{x} \text{ over the interval } [0, t] \}^2.$$

Since the LGC and the CFF can vary over several orders of magnitude, we display in figure 3 values of the *unobservable* quantity  $\Phi \equiv \text{Log}_{10}[1 - \text{CFF}]$  on the left, and of the

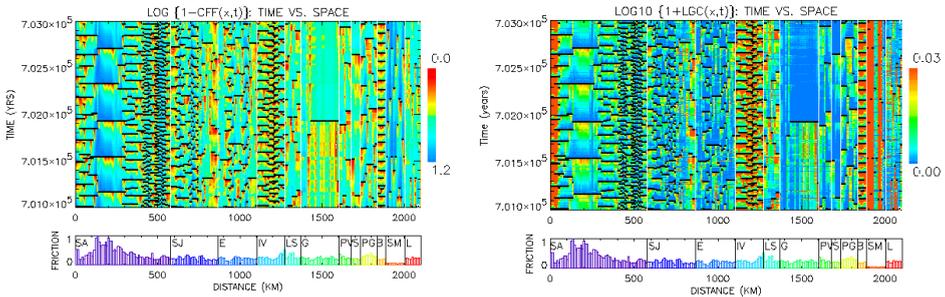


Figure 3

*observable* quantity  $\Psi \equiv \text{Log}_{10}[1 + \text{LGC}]$  on the right. We find that the histogram of  $\Psi$  resembles an exponential distribution with a long tail, having a standard deviation  $\sigma$ . We therefore assign the color “blue” to the value  $\Psi = 0$ , and the color “red” to all values of  $\Psi > .5 \sigma$ , with other spectral colors between.

The result is shown in figure 3, where the *observable* LGC is seen to be a close representation of the *unobservable* CFF. Using simulations, it may be possible to define other such mappings. Figure 3 represents two time (abscissa) - space (ordinate) plots of dynamical quantities, the CFF on the left, and the LGC on the right. The space axis has been constructed by concatenating all of the fault segments. From left to right, these faults are indicated by: SA, San Andreas; SJ, San Jose; E, Elsinore; IV, Imperial Valley; LS, Laguna Salada; G, Garlock; PV, Palos Verdes; S, Santa Cruz Island; PG, Pisgah; B, Brawley; SM, Santa Monica; and L, Landers.

The image of the CFF at the left of figure 3 is essentially a synoptic picture of the system dynamics over a large time-space region, where horizontal lines represent earthquakes, hot colors represent CFF near 0, and cool colors represent small CFF stress. The “earthquake cycle”, or “elastic rebound cycle” can be seen as cool colors turning hotter through time as a result of plate tectonic forcing, culminating in an earthquake (horizontal line), followed by a return to cool colors corresponding to low CFF. Note that in nature, both the friction strength (right middle), as well as the CFF values in space and time are inherently *unobservable*. The observable LGC, which is derived from surface strain data measured along the faults, was constructed to mimic these dynamics.

## Future Work

Numerical simulations provide a means for rapidly testing a range of hypotheses, so that 1) Scientific questions can be framed in the context of the proposed observations; and 2) Diverse observations can be analyzed, interpreted, and integrated into a self-consistent model. In future work, we will use modern data assimilation methods to determine model parameters that optimize agreement between data and simulations. New data can also be used in a process of model steering that allows continuous improvement in model parameters. We will also seek to define new mappings between the unobservable dynamics and the observable surface deformation measurable by space-geodetic techniques. The result will be an important and critical step on the path to an earthquake forecast capability using ensemble forecasting methods.

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