Simulating Gravity, Potential, and Sea Level Change with Topologically Realistic Earthquake Fault System Models

Kasey Schultz

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Abstract Following the success of the GRACE mission, NASA has shown interest in gravity field mapping satellites. The next decade will see many new earth-observing satellites including NI-SAR (formerly DESDynI). These satellites will beam huge data sets back to earth, containing information about the ever changing surface of our planet. The hope is that this data will facilitate advancements in earthquake monitoring and forecasting. Virtual California (VC) is a computer program that simulates the California fault system, and with a few refinements it will model the time evolution of the gravity field around a fault system. It may be possible to use VC in the modeling chain for computing earthquake scenarios for many different earth-observing satellites. For example, VC could compute pre- and co-seismic sea level change data for undersea subduction zones. These data sets can be analyzed by missions employing the GNSS (Global Navigation Satellite System), which is currently being discussed as a possible contributor to a tsunami early warning system. To make these advancements we must understand how the patterns in the data relate to seismic activity. I propose using Virtual California to determine the required sensitivity and resolution for satellite-based seismic gravity field monitoring, to reveal the connection between gravity change patterns and the onset of seismic activity, and to develop advanced forecasting techniques for California's fault system.

1 Introduction

Years	World fatalities
2003—2012	790,600
1993—2002	78,700
1983—1992	100,900
1973—1982	343,000

(a) Data from USGS [16]

Years	World economic damages
2003—2012	44.1 billion annually
2010	46.2 billion
2011	230.3 billion
2012	18.6 billion

(b) Data from CRED [2]

Table 1: (b) shows worldwide economic impact from geophysical disasters (in 2012 US dollars). Note: Geophysical loss is dominated by earthquakes, with small contributions from volcanoes.

During the past decade earthquakes have killed nearly 800,000 people worldwide, more than the previous 30 years combined, and caused $44 billion per year in damages. In just the past three years we have seen two of the most devastating natural disasters ever recorded. The 2010 Haiti earthquake damages amounted to 123% of the country's gross domestic product [2]. The March 2011 earthquake off the coast of Japan and subsequent tsunami caused more than $200 billion in damages, and crippled the country's energy production for years to come. In the United States, California is particularly vulnerable, having one of the most active fault systems in the world underneath one of the largest population densities. With such devastating impacts, the call for accurate earthquake forecasting has never been louder.

The complexity of fault systems and earthquakes makes directly monitoring the underlying dynamics across entire fault systems nearly impossible. Computer simulations can simultaneously probe all relevant spatial and temporal scales, potentially revealing patterns invisible to direct observation. I propose using Virtual California to study the relation between gravity changes and seismic activity, and to develop advanced forecasting techniques for California's fault system.

2 Virtual California Earthquake Simulator

Virtual California (VC) is a computer program that simulates topologically realistic driven earthquake fault systems in California [9, 10, 1, 12]. It is designed to quickly simulate many thousands of events over long periods of simulation time, producing a rich dataset to study the statistical properties of the fault system (described in detail in [12]).

Fault topology, long-term slip rates, and frictional parameters are derived from field observations to define the fault model. The fault model is broken down into multiple fault-segments, and a simulation begins when the quasi-static elastic interactions between segments are calculated using Okada's half-space greens functions [7]. "Backslip" is applied to the segments at geologically-observed rates to drive the fault system. This continues to build stress on the segments until the stress exceeds the frictional parameters, at which point the segment breaks and transfers stress to the surrounding segments via the previously calculated interactions. The transferred stress results in propagating ruptures through the system, a simulated earthquake.

Despite what the name implies, the only part of VC that is specific to California is the fault model. The fault model can be changed to any fault system and still work with the simulation physics to produce a simulated seismic history. The proviso is that local fault slip histories and geology are needed to define fault system parameters. General forecasting techniques developed through VC may then be extended to any fault system.

3 Minimal Tuning

Fault simulations must initially be tuned to correctly simulate actual earthquakes. The primary tuning parameters in Virtual California are the dynamic triggering factor and slip scaling. The dynamic triggering factor is used to encourage rupture propagation during a simulated earthquake. The slip scaling parameter is used to prevent small ruptures from slipping too much. These parameters act to tune the rupture and slipping properties of faults without requiring field measurements of each fault's physical properties, a result of VC's abstraction and generality.

I am currently installing VC on the University of Texas' supercomputer Stampede, at the Texas Advanced Computing Center (TACC). Virtual California is fully parallelized so simulations can be scaled up to operate across many cores. I propose using the TACC supercomputing facility to run many simulations over a range of dynamic triggering and slip-scaling values. This allows VC to tune its two external parameters for each fault section in California, and will produce the most physically accurate data sets to date.

4 Gravity as a Forecasting Metric

Current methods for predicting seismic events rely on present day seismicity records, surface deformation from GPS instruments, and surface deformation from Synthetic Aperture Radar Interferometry (InSAR) mapping. Since these are all surface measurements, we must infer the processes and dynamics at depth based on their expression at the surface. However, changes in gravity at the surface are a measure of the stress and strain integrated over all depths of the underlying medium.

Over the last two decades, research has provided evidence supporting the use of gravity changes for forecasting. In 1992 Okubo showed that dilatational gravity change (due to compression) corresponds directly to subsurface density change from seismic activity [8]. In 2003 Song and Simons showed a correlation between the occurrence of large dip-slip earthquakes and a negative free air gravity change (due to vertical displacement) prior to rupture [13]. Moreover, in 2004 Sun and Okubo [14] showed that gravity changes from large dip-slip earthquakes are above the detection threshold of GRACE, a current NASA gravimetric satellite. More recently in 2012, Zhu and Zhan suggested that gravity changes can be used to generate medium-term (less than 3 years) earthquake forecasts [17]. They noticed that earthquakes typically occurred at the intersection of the zero gravity change contour line and the fault that is most likely to produce a major earthquake (determined from local seismic history) .

Gravity field measurements are distinct from InSAR measurements in that they can be measured over the oceans. The March 2011 Tohoku earthquake showed the destructive power of undersea megathrust earthquakes. The Cascadia subduction zone off the coasts of Northern California, Oregon and Washington can produce similar megathrust earthquakes, and is much closer to major metropolitan areas. The necessity of monitoring undersea fault zones is without question. In addition to total gravity changes, Okubo [8] introduced the Greens' functions for computing the change in gravitational potential due to seismic activity.

The change in gravitational potential, or the subsequent sea level change, is another ocean surface observable that corresponds directly to sub-seafloor stress loading. Virtual California can be easily modified to simulate the gravitational potential change and resulting sea level change patterns corresponding to pre-seismic activity in undersea thrust fault regions. These data sets can be fed into tsunami early detection systems—such as a tsunami early warning system that utilizes the GNSS—to help validate and optimize detection methods [5].

NASA has begun to acknowledge the scientific potential for space-based gravity field mapping following the success of the GRACE mission. In its 2010 Science Plan [6], NASA put forth four proposed missions employing space-based gravity field mapping: GRACE FO, GRACE II, Juno, and GRAIL. Given the current precision gravimetry, and since NASA has an established interest in space-based gravity field mapping in the near future, I propose using Virtual California to rigorously determine the required resolution and sensitivity for gravimetric satellites to monitor pre-seismic and co-seismic gravitational field anomalies, and to develop techniques for monitoring undersea fault zones.

5 Computing Gravity Changes with Virtual California

Following Hayes [4], I am currently extending Virtual California's capability by calculating gravity changes around faults. The gravity changes are computed via a custom implementation of Okubo's elastic half-space Greens' functions [8]. The total gravity changes (dilatation plus free air) are currently evaluated after an earthquake produces slip on the fault segments. These are computed for single ruptured fault elements in Figure 1 and for a simulated earthquake involving many elements in Figure 2. Strike-slip fault elements tend to have the lowest change in surface gravity ($\sim 50\mu gal$), with changes about an order of magnitude lower than those for normal and thrust ($\sim 500\mu gal$).

An animation showing the gravity changes throughout 100 years of simulated seismic history

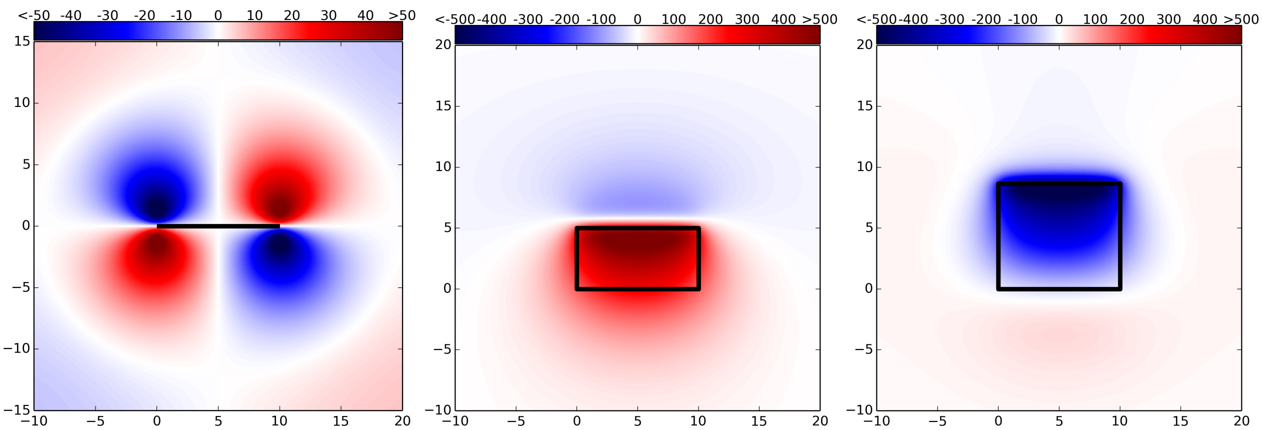

Figure 1: Total gravity changes (dilatational and free-air) around single fault elements, the color unit is μgal. Dark lines represent the projection of the fault. The x/y axes measure distance along/from the fault in km. The fault parameters are L=10km, W=10km, slip=5m, depth to top of fault is 1km, Poisson's ratio is 1, and density is $2670 kg/m^3$. Left: Vertical strike-slip faulting. Middle: Normal faulting, dip=60°. Right: Thrust faulting, dip=30°. **Note**: different colorbar limits.

can be found at https://www.dropbox.com/sh/7wj9zmq7lj2uurs/tdqCMJlte9. These preliminary calculations give the scale of gravity changes for a given fault model, but refinements must be made to proceed to evaluating the forecasting potential. This preliminary work is explained in greater detail in "K.W. Schultz, M.K. Sachs, J.B. Rundle, D.L. Turcotte, *Simulating Gravity Changes in Topologically Realistic Driven Earthquake Fault Systems*", currently in preparation.

6 Proposed Work

Modeling the time evolution of gravity changes over entire fault systems may reveal aspects of seismic susceptibility previously undetected. The following steps are my proposed approach to realizing this goal:

- Evaluate gravity changes as a function of simulation time.
- Following Hayes [3], I will calculate the steady state gravity change patterns associated with the measured geologic slip rates to define a background. After removing this background, any pre-seismic patterns that emerge can be used to create "pattern dynamics" operators. These operators relate the current state of the system to future states. This technique is called linear pattern dynamics, and is described in detail in [11].
- Determine the statistical relationships between gravity changes, surface deformations, and stress changes to identify pre-seismic patterns. One measure of statistical relation is the correlation operator , which can be measured between any pair of these quantities, denoted as $x(t)$ and $y(t)$ below, by computing

$$C_{xy} = \frac{1}{\sigma_x \sigma_y (t_2 - t_1)} \int_{t_1}^{t_2} x(t) y(t) dt \quad (1)$$

— where σ_x (σ_y) is the standard deviation of $x(t)$ ($y(t)$), and $t_1 - t_2$ defines a time interval.

- Calculate the eigenfunctions of the various correlation operators. These can be used to define the characteristic patterns of large earthquakes [11, 15]. These eigenpatterns can then be used with hidden Markov methods to define state transition probabilities.

It may furthermore be possible to compute observable gravity and sea level changes corresponding to slow/silent slip events that are sometimes seen in earthquake fault zones. These silent earthquakes dont generate seismic waves, but they have been discussed as possible precursors.

Virtual California, as part of Quakesim, has already been recognized for its scientific potential and real world impact, being selected as a co-winner of NASA's 2012 Software of the Year Award. By calculating the time evolution of gravity changes throughout the earthquake cycle, and developing statistical tools to further develop VC's role in earthquake forecasting, my project will improve an already invaluable scientific tool.

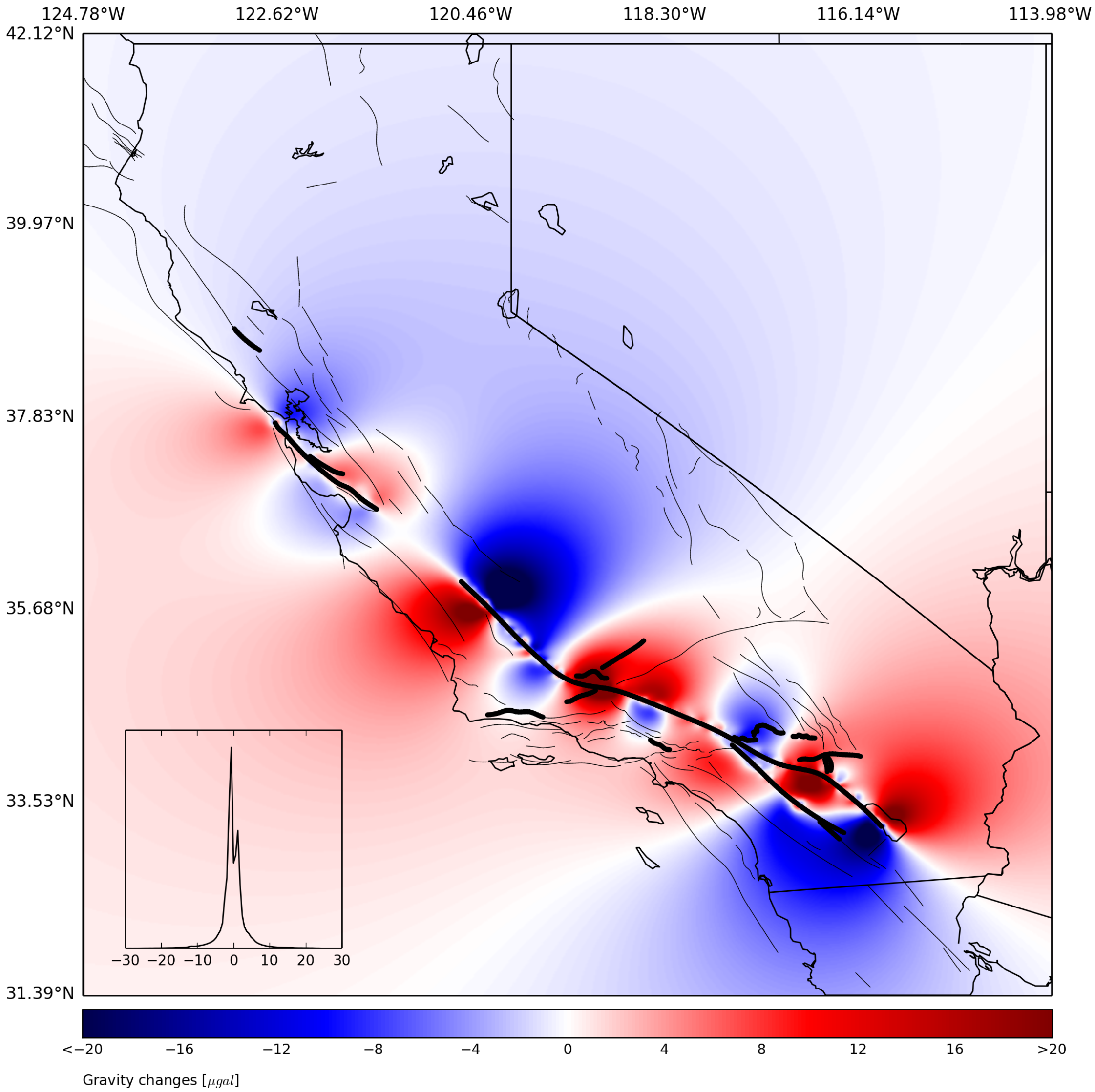

Figure 2: Co-seismic total gravity changes from a very large simulated earthquake (magnitude 8.0) involving multiple sections of the San Andreas fault. The dark black lines are the fault segments involved in this event, and the inset plot is a histogram of the event's gravity changes.

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