Numerical Simulations For Active Tectonic Processes: Increasing Interoperability And Performance

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Introduction

Under this project we will develop a solid earth system science framework for creating an understanding of active tectonic and earthquake processes. Earthquakes in urban centers are capable of causing enormous damage. The recent January 16, 1995 Kobe, Japan earthquake was only a magnitude 6.9 event and yet produced an estimated $200 billion loss. Despite an active earthquake prediction program in Japan, this event was a complete surprise. The 1989 Loma Prieta and 1994 Northridge earthquakes were also unexpected and caused billions of dollars of damage as well as loss of lives. Future similar scenarios are possible in Los Angeles, San Francisco, Seattle, and other urban centers around the Pacific plate boundary.

Due to the development of space-based techniques it is now possible to measure the quiet motions associated with plate tectonics and the earthquake cycle. These measurements are providing an unprecedented look at the earthquake cycle and are revolutionizing our understanding of earthquake processes and fault interactions. Comprehensive, real-time datasets collected using NASA-developed space systems will demand new technologies for storage, handling, transmission, visualization and analysis. These include surface geodetic data, primarily space-based GPS and InSAR data augmented by more traditional land-based datasets. We will develop tools to manage the increasing quantities of data that are becoming available.

We will construct a fully interoperable system for studying active tectonics and earthquakes, and we will develop simulation and analysis tools to study the physics of earthquakes using state-of-the-art modeling, data manipulation, and pattern recognition technologies. We will develop clearly defined accessible data formats and code protocols as inputs to the simulations. These codes must be adapted to high-performance computers because the solid earth system is extremely complex and nonlinear resulting in computationally intensive problems with millions of unknowns. Without these tools it will be impossible to construct the more complex models and simulations necessary to develop hazard assessment systems critical for reducing future losses from major earthquakes.

Objectives

During the last decade the field of solid earth geophysics and more specifically the study of crustal deformation and earthquakes has undergone a transformation due to the availability of space-derived crustal deformation data. GPS networks deployed globally and in particular the NASA sponsored Southern California Integrated GPS Network (SCIGN) are providing precise time-dependent information on how the earth's crust responds to earthquakes and plate tectonic processes. InSAR data are revealing spatially dense information on how the earth's crust deforms and how faults interact with each other. Deformation of the earth's crust and the interaction between earthquake faults is an extremely complex three-dimensional process requiring sophisticated models that make use of high-performance computers making this truly a Grand Challenge Problem. The infusion of these new data and our current limited understanding of earthquake processes make it an ideal time to develop a high-performance, fully interoperable system for studying active tectonics and earthquake processes. Our objective is to develop a system with the following specific components.

- A database system for handling both real and simulated data.
- Fully three-dimensional finite element code with adaptive mesh generator capable of running on workstations and supercomputers for carrying out earthquake simulations.
- Inversion algorithms and assimilation codes for constraining the models and simulations with data.
- A collaborative portal (object broker) for allowing for seamless communication between codes, reference models, and data.
- Visualization codes for interpretation of data and models.
- Pattern recognizers capable of running on workstations and supercomputers for analyzing data and simulations.

Realistic modeling of the evolution of the Earth's fault systems requires very large-scale computing and data intensive scientific simulations that far exceed the computing and memory storage capacities of the most advanced desktop computers or even small computer clusters. Effective use of scalable parallel computing systems and related technologies is the only option for geophysicists to achieve a better understanding of the complex evolving behavior of the Earth dynamics.

Scientific Rational

NASA has recently committed a great deal of effort and funding to develop the means to observe and characterize the movements of the earth's crust that arise from plate tectonics and which lead to catastrophic earthquakes. Recent research indicates that the phenomena associated with earthquakes occur over many scales of space and time. Understanding the dynamic processes responsible for these events will require not only a national commitment to develop the necessary observational datasets, but also the technology required to use these data in the development of sophisticated, state-of-the-art numerical simulations and models. The models can then be used to develop an analytical and predictive understanding of these large and damaging events, thus moving beyond the current, more descriptive approaches now routinely employed. Approaches emphasizing the development of predictive models and simulations for earthquakes will be similar to methods now used to understand global climate change, the onset of the El Niño-Southern Oscillation events, and the evolution of the polar ozone depletion zones.

One of the six major questions in NASA's strategic outlook asks how we can *develop predictive natural disaster models* and the Earth Science Enterprise strategic plan places a high priority on *developing predictive capabilities and on characterizing disasters*. High-performance computers integrating multiple datasets and models are required to accomplish these objectives. The modeling, simulation, data mining, data assimilation, and pattern recognition software to be developed in this project will be necessary for creating an understanding of earthquake systems and will be directly applicable to the development of early warning systems. By integrating these concepts within an object-oriented framework based on open standards, we can provide a blueprint for the design of fully autonomous, continuous monitoring systems of heterogeneous assets that will underpin much of NASA's solid earth science needs in the future. With this in mind, we note that should the U.S. choose to launch a major InSAR or similar mission to study solid earth processes, such a system will have the additional advantage of being already in place to handle the large-scale data analysis needs of such a venture.

The system that we will develop will serve the broad community of earth scientists studying processes of crustal deformation. These processes include, but are not limited to tectonics, earthquakes and volcanoes. We anticipate that in the future, additional codes will be added to this framework. For example, a mantle convection code that produces tractions at the base of the crust (top of the mantle) can be added to the system for studying how mantle processes influence surface deformation. We will disseminate our tools through work with individual investigators as well as through classes and workshops.

Simulations are essential for creating an understanding of the physics behind the observations of surface displacement and strain. This is particularly important for understanding data related to earthquakes and active tectonics because earthquake cycles occur on timescales of thousands of years and our observations sample only a small part of that system. In this second example the observed network of real faults in southern California, together with their nonlinear dynamics, is modeled as a driven system. The simulations include physical processes that are known to be important in the dynamics of the earthquake generation process. A computational limitation of these simulations arises because the stress transfer computation is order N^2 in the number of simulated fault segments, and thus computationally intensive for detailed simulations. In this work, we intend to reduce this to an order N or N log N problem at worst by the use of a fast multipole algorithm of the kind that has been used successfully in astrophysical N-body problems and computational fluid dynamics models.