NEXT GENERATION WORK

The next Track-1 system would allow us to extend our models higher into the ionosphere so that instead of projecting currents down to ~100 km in altitude, we could model the actual propagation and resulting physics of those currents. The FDTD models could be coupled to models of the magnetosphere to provide a more complete physics analysis of the effect of space weather on the earth.

PUBLICATIONS AND DATA SETS

Samimi, A., and J. J. Simpson, Parallelization of 3-D global FDTD Earth-ionosphere waveguide models at resolutions on the order of ~1 km and higher, *IEEE Antennas and Wireless Propagation Letters* (in press).

Samimi, A., M. Rodriguez, N. Dupree, R. Moore, and J. J. Simpson, The application of global 3-D FDTD Earth-ionosphere models to VLF propagation: Comparison with LWPC, *IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting*, Puerto Rico, June (2016).

PHYSICS-BASED STRONG GROUND MOTION SIMULATIONS

Allocation: NSF PRAC/6.60 Mnh
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EXECUTIVE SUMMARY

Earth scientists, engineers, and computer scientists working with the Southern California Earthquake Center (SCEC) use physics-based numerical simulations and high-performance computing (HPC) to improve the understanding of seismic hazards, and earthquake processes and their effects. This past year, SCEC teams used Blue Waters to perform deterministic earthquake ground motion simulations with frequencies up to 8 Hz, while introducing new physics required for more realistic ground motion simulations, including rough-fault geometrical complexity, frequency-dependent attenuation, material plasticity, small-scale material heterogeneities, and surface topography. Earthquake simulations using our improved numerical models were validated against records from past earthquakes. We also increased the computational performance of our research software through graphics processing unit (GPU) code and parallel I/O improvements, and through workflow optimizations.

INTRODUCTION

The SCEC performs fundamental research in earthquake system science and develops predictive models of earthquake processes. SCEC scientists develop and apply the best available geoscientific understanding of faulting and wave propagation processes, together with state-of-the-art computation techniques, to produce the next generation of physics-based seismic hazard models. SCEC's research program is a collaboration among several user communities with shared interests in reducing seismic risk and enhancing seismic resilience. SCEC's computational research activities help to educate a diverse STEM workforce from the undergraduate to the early-career levels, and cross-train scientists and engineers in challenging HPC environments.

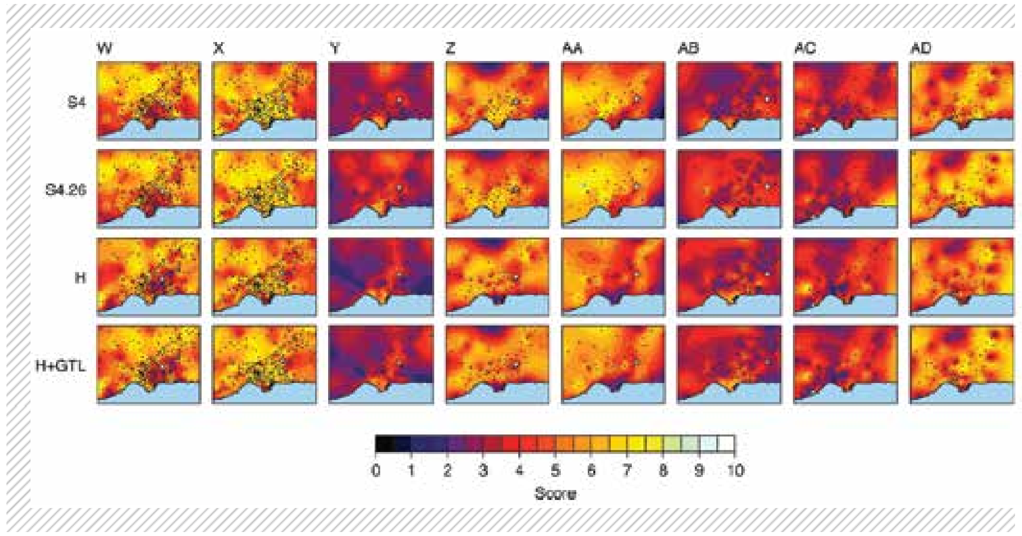

FIGURE 1: Goodness-of-fit (GOF) maps for all events with 53 or more stations used for validation. Contours indicate the score obtained by averaging the GOF values for all three components of motion (EW, NS and UD). Dots correspond to the location of stations and stars indicate the epicenters for each event. Event labels at the top of each set of four maps correspond to the results obtained using alternate velocity models (CVM-S4, CVM-S4.26, CVM-H and CVM-H+GTL), as indicated with labels on the left margin.

METHODS & RESULTS

SCEC researchers used Blue Waters to perform simulations of earthquake faulting and wave propagation at frequencies of interest to civil engineers. A significant focus of our Blue Waters computational research this year involved validating simulations against data, with much of this effort led by engineering seismologists and engineers, who recognize the potential of SCEC's efforts in physics-based ground-motion prediction.

SCEC approaches seismic hazard analysis as an earthquake system science problem that requires integration of several interrelated computational models, including accurate 3D earth structural models, friction-based fault rupture models, and anelastic wave propagation (AWP) models. SCEC's approach iteratively improves these models, re-validates them against observed ground motions, and then re-combines the models, producing an improvement in broad-impact seismic hazard computational methods.

A team led by Ricardo Taborda at University of Memphis used Blue Waters to evaluate four existing southern California velocity models by assessing how well each predicted ground motion in the greater Los Angeles region when used as inputs to deterministic wave propagation simulations. These evaluations were performed by running multiple earthquake simulations and then using quantitative comparisons between simulated motions and a collection event data. The team used Blue Waters to simulate earthquakes within a domain with a surface area of 180 km x 135 km. Each earthquake was modeled as a point source with rupture parameters scaled according to magnitude. Hercules—finite-element software developed by SCEC-affiliated scientists—was used to simulate the ground motions for each earthquake and velocity model combination. Hercules has shown to be a reliable tool for 3D earthquake ground motion simulation [1,2]. The group simulated 30 moderate-magnitude earthquakes (3.5 to 5.5) and compared synthetics with data recorded by seismic networks on over 800 stations. Each of the 120 simulations (30 earthquakes, four velocity models) was run with a maximum frequency of 1 Hz and a minimum shear wave velocity of 200 m/s. The comparisons between data and synthetics were ranked quantitatively using standard seismological goodness-of-fit (GOF) criteria. The regional distribution of the GOF results for all events and models were analyzed and ranked according to the performance of each velocity model (Fig.1). The group identified one of the southern

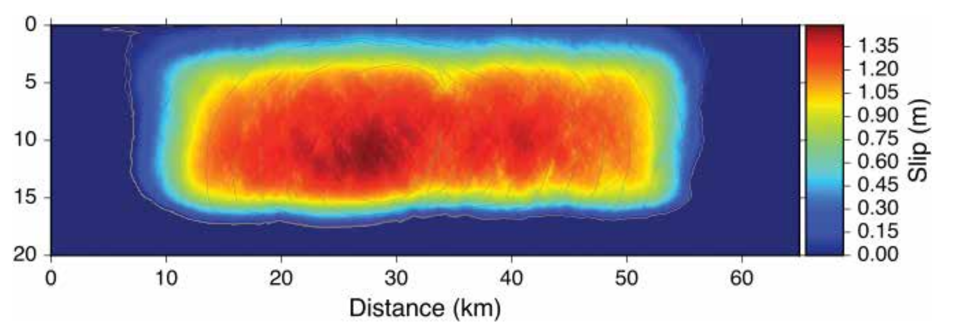

FIGURE 2: Sample final slip on fault for a moment magnitude 6.9 earthquake showing 1s (1 Hz) rupture contours in gray. The variation in the final slip is correlated with the topographic complexities on the fault surface.

California velocity models that yields consistently better results.

A team lead by Kim Olsen at San Diego State University used Blue Waters to generate a database of dynamic rupture sources on topographically complex faults (Fig. 2). Each dynamic source computation used 8,192 CPU cores for approximately 5.5 hours using the SORD code [3,4]. The ruptures were verified against ground motion prediction equations (GMPEs) used in engineering practice by running wave propagation simulations for a region approximately 40 km from all sides of the fault. The wave propagation simulations were completed using AWP-ODC—finite-difference software developed by SCEC-affiliated scientists—on 22,272 cores for approximately two hours. Each simulation produced 52.5 seconds of 0–7.5 Hz wave propagation. This group found that the dynamic rupture-based source models produce realistic ground motions at high frequencies, indicating that their database of ruptures contains suitable high-frequency source models for statistical analysis.

The SCEC PAID Project team, led by Yifeng Cui at the San Diego Supercomputer Center, worked with the GPU IME team led by Wen-mei Hwu to optimize the nonlinear AWP-ODC GPU code for scalability and efficiency on Blue Waters XK7 nodes. The team integrated several improvements into the AWP numerical models, including support for plasticity yielding and frequency-dependent attenuation. They also optimized code performance through yield factor interpolation, memory tuning to increase occupancy, communication overlap using multi-streaming, and parallel I/O to support concurrent source inputs. Simulation of non-linear material behavior requires the addition of 17 new variables compared to linear computations, posing challenges regarding solution time and memory management. The improved nonlinear code has proven to be highly scalable and efficient and has achieved better performance than the linear code despite the additional variables and processing. The team then used the improved software on Blue Waters to perform 0–4 Hz nonlinear ShakeOut scenario earthquake simulations (Fig. 3). These results represent an advance in our ability to perform earthquake simulations at frequencies up to 4 Hz because our codes now include the advanced physics, including the small-scale complexity of the source, nonlinear effects, and frequency-dependent inelastic attenuation that are needed to accurately simulate these higher frequency ground motions.

WHY BLUE WATERS

Earthquake simulations at the spatiotemporal scales required for probabilistic seismic hazard analysis present demanding computational challenges. SCEC researchers use Blue Waters to addressing scientific problems that limit the accuracy and scale in current numerical representations of earthquake processes. Blue Waters provides the computational scale, data management capabilities, and variety of computing capabilities needed to perform our research.

NEXT GENERATION WORK

SCEC's earthquake system science computational requirements will continue to increase as new physical properties and principles are included in the simulations. Higher frequency calculations are important to engineering end-users, and they are much more computationally intensive. Once individual earthquake simulations are validated, ensembles of simulations are needed to make

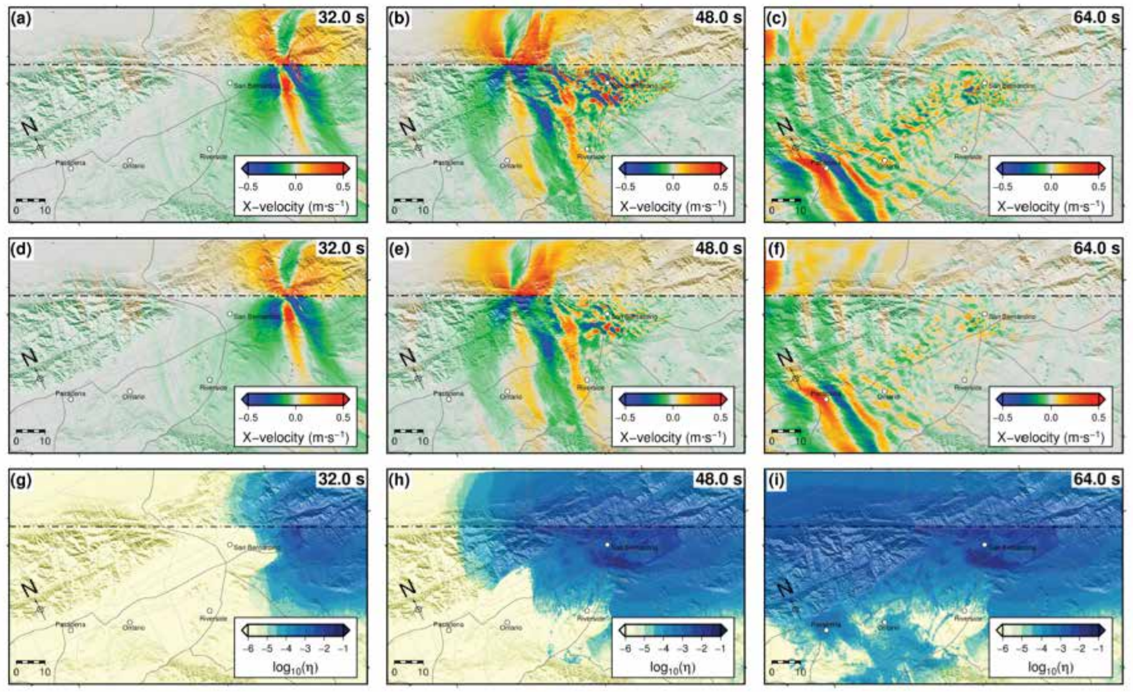

FIGURE 3: Snapshots from a 4 Hz San Andreas simulation inside the blue rectangle and the dashed line shows the fault trace. Maps a, b, and, c show fault-parallel velocity for the linear cases, and Maps d, e, and f for the nonlinear cases. Maps g, h, and i depict the evolution of permanent plastic strain at the surface obtained from the nonlinear simulation.

probabilistic calculations. Our computational requirements will grow dramatically as computational-intensive seismic hazard techniques are applied to more regions.

PUBLICATIONS AND DATA SETS

Taborda, R., S. Azizzadeh-Roodpish, N. Khoshnevis, and K. Cheng, Evaluation of the southern California seismic velocity models through simulation of recorded events, *Geophys. J. Int.*, 205:3 (2016), pp. 1342–1364, doi: 10.1093/gji/ggw085

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