SCEC M8 Simulation:
Scalable Earthquake Simulation on Petascale Supercomputers

Petascale simulations are needed to understand the rupture and wave dynamics of the largest earthquakes at shaking frequencies required to engineer safe structures (> 1 Hz). Toward this goal, we have developed a highly scalable, parallel earthquake wave propagation code called AWP-ODC that has achieved “M8”: a full dynamical simulation of a magnitude-8 earthquake on the southern San Andreas fault up to 2 Hz. M8 was calculated using a uniform mesh of 435 billion 40 meter cubes that represents the three-dimensional crustal structure of Southern California in a 810 km by 405 km x 85 km simulation volume. The M8 production run on NCCS Jaguar produced 368 seconds of wave propagation data with sustained performance of 220 Tflop/s for 24 hours using 223,074 cores. As the largest-ever earthquake simulation, M8 opens new territory for earthquake science and engineering—the physics-based modeling of the largest seismic hazards with the goal of reducing their potential for loss of life and property.

The SCEC M8 simulation produced a realistic dynamic earthquake source description and detailed physics-based anelastic ground motions data at frequencies used in earthquake engineering building designs.

SCEC’s AWP-ODC scientific software is an integral part of the SCEC Community Modeling Environment (SCEC/CME) and is used to support SCEC earthquake modeling using large NSF and DOE computer allocations. Previous AWP-ODC ground-breaking science results include SAF scenarios TeraShake (revealing order-of-magnitude LA wave-guide amplification), multiple ShakeOut simulations (used as the basis for a Southern California earthquake drill that involved more than 6 million people), and a Pacific Northwest mega-thrust scenario (forecasting up to 5 minutes of shaking in Seattle for such an event).

Recent M8 work has produced further AWP-ODC performance improvement, and additional M8 simulations, include a 160 Tbyte, IO-intensive run analyzed by state-of-the-art 4D visualization and simulations using alternative rupture directions and velocity models. M8 ground motion results will also be used to analyze building response to strong ground motions.

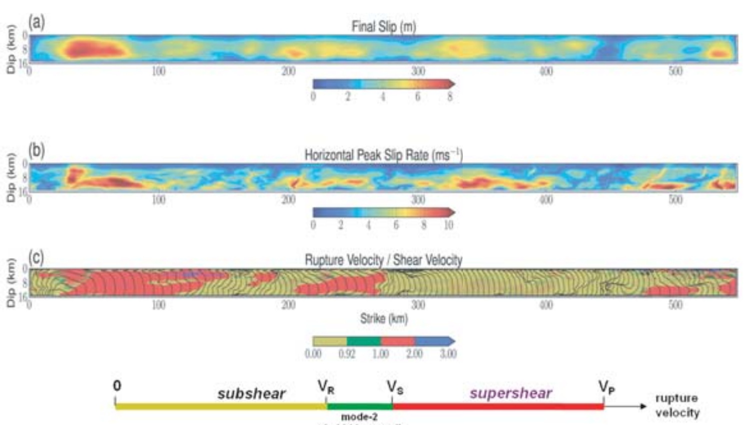
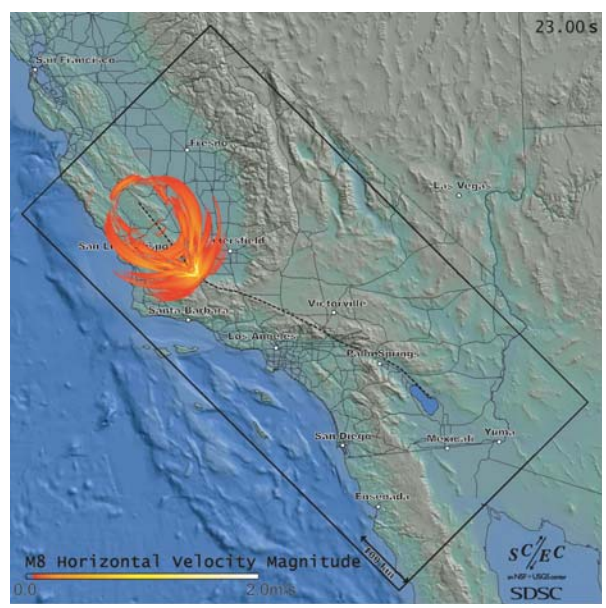


Figure 1 (above) shows the M8 dynamic rupture final slip (top), horizonal peak slip (middle), and rupture velocity (bottom) along 545 km on the southern San Andreas Fault. Figure 2 (right) shows instaneous peak velocity as the M8 rupture propagates south on the San Andreas Fault at super-shear velocities.



SCEC an NSF+USGS center | NSF | USGS science for a changing world | SDSC San Diego Supercomputer Center | National Center for Computational Sciences

M8 Simulation Specifications:

- Simulation Name: SCEC M8 Simulation April/November 2010
- Primary science goals: Regional scale wave propagation simulation using a realistic 3D earth model, dynamic earthquake source, simulating ground motions at frequencies of interest to building engineers
- Primary computational goals: Develop a highly-efficent software system capable of performing physics-based seismic hazard simulations at sustained petaflop/s performance.
- Parallel software used: SCEC Anelastic Wave Propagation - Olsen, Day, Cui (AWP-ODC)
- Type of solver: SCEC's dynamic rupture and anelastic wave propagation modeling software (AWP-ODC) solves 3D velocity stress wave equations with explicit staggered-grid split-node finite difference scheme fourth-order accurate in space and second-order accurate in time with three scalar-valued equations for velocity vector components and six scalar-valued equations for stress tensor components

M8 Simulation Configuration:

- Geographical volume:810 km x 405 km x 85 km
- Cartesian cell dimension: 40 meters
- Outer scale (810,000m) to inner scale (40m) ratio: $10^{4.3}$
- Simulation volume dimensions: 20250 x 10125 x 2125
- No. of grid points: 436 billion grid points with 3918 billion degrees of freedom
- Simulation time steps: 160,000
- Simulated ground motion real time: 368 seconds
- Simulation time step size: 0.0023 seconds
- Maximum simulated frequency (5 mesh points per wavelength): 2.0 Hz
- Minimum mesh velocity (Min Vs in input 3D earth velocity mesh): 400 m/s
- Free surface boundary condition: Zero-stress boundary condition to simulate the (flat) free surface of the Earth
- Absorbing boundary condition: Multi-axial Perfectly Matched Layer with a width of 10 grid points that applies damping separately for wavefields propagating parallel and perpendicular to the boundary.
- Finite Difference Stability: Mesh size, material properties, and time step size meet Courant-Friedrichs-Lewy (CFL) stability criterion

M8 Simulation Inputs:

- Inputs needed for initialization: 4.5 TB velocity mesh and 2.1 TB earthquake source description (6.9 TB Total)
- Input Velocity Mesh: 436 billion mesh points with 3 material (Vp, Vs, density) properties per point
- Input Earthquake Source: 2.1 TB dyanic rupture-based moment source with 881,475 subfaults and 108,00 timesteps.
- Earth structure material properties used: SCEC Community Velocity Model 4.0 (CVM 4.0)

M8 Parallel Computation:

- Simultaneous cores used: 223,074 on NCCS Jaguar out of 224,256 max
- Simultaneous nodes used: 18,589 out of 18,700 max
- Simulation run-time: 24 hours
- Memory used per core: 7 GB out of 8 GB max
- Communications pattern: Nearest neighbor in six directions
- Total simulation memory used: 123 TB out of 300 TB max

M8 Sustained Performance:

- Simulation CPU Hours: 5,353,776 CPU hours on Jaguar
- Sustained Performance: 220 TFlop/s out of 2.332 PFlop/s theoretical max full system
- Percentage of Theoretical Peak Performance: 10.9 % of all cores used

M8 Simulation Outputs:

SCEC
an NSF+USGS center

- Output forecast parameters: Free surface velocity in 3 components as time series.
- Output surface mesh dimensions: 10125 x 5075
- Output time step size: 0.046 seconds (every twentieth simulation timesteps)
- Number of output timesteps: 8000
- Output forecast parameter data: 4.5 TB (out of 10.0 PB Max)
- Aggregated disk I/O rate: 20 GB/s (during initialization) (out of 240 GB/s max)
- Required output storage total outputs: ~500 TB (including checkpoints, log files, volume outputs, and animations)
- Estimated energy required: 24 hours on 6950.6 kW Jaguar. Based on the national average for KWH (currently $0.10120 per hour) and Jaguar total power, estimated cost of energy to run M8 is 6950.6 kW x 24 x $0.101 = $16,846