# Using Virtual Quake for GNSS Tsunami Early Warning: Coupling Earthquakes, Tsunamis, and Ionosphere Physics

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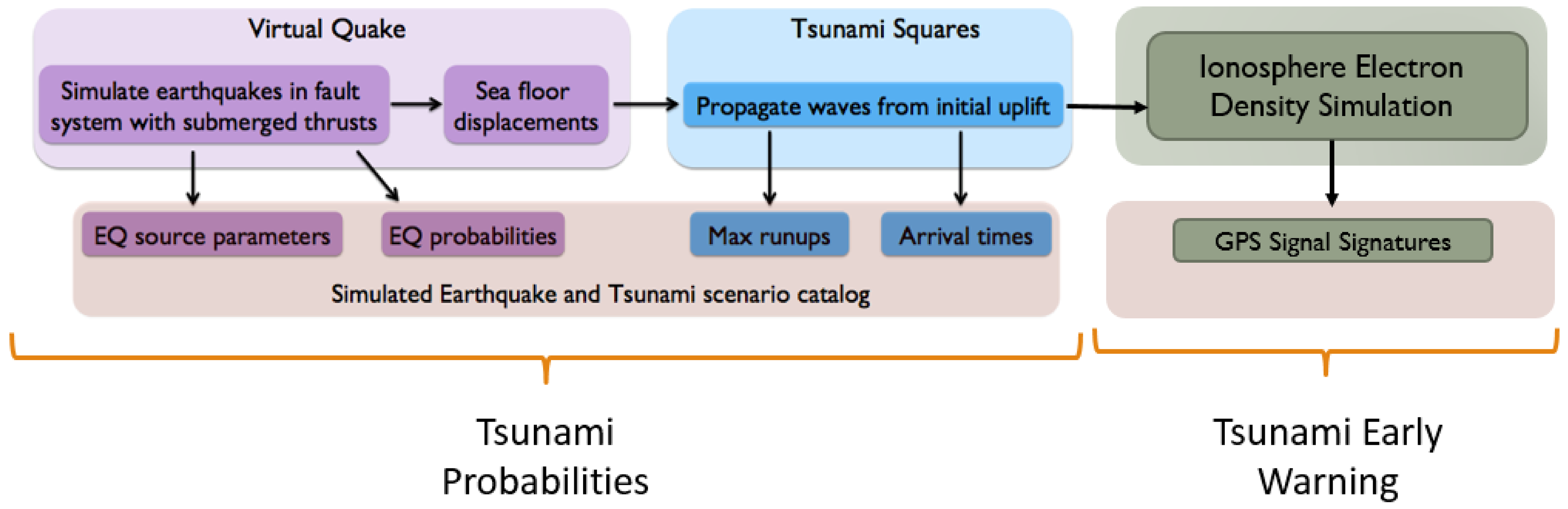
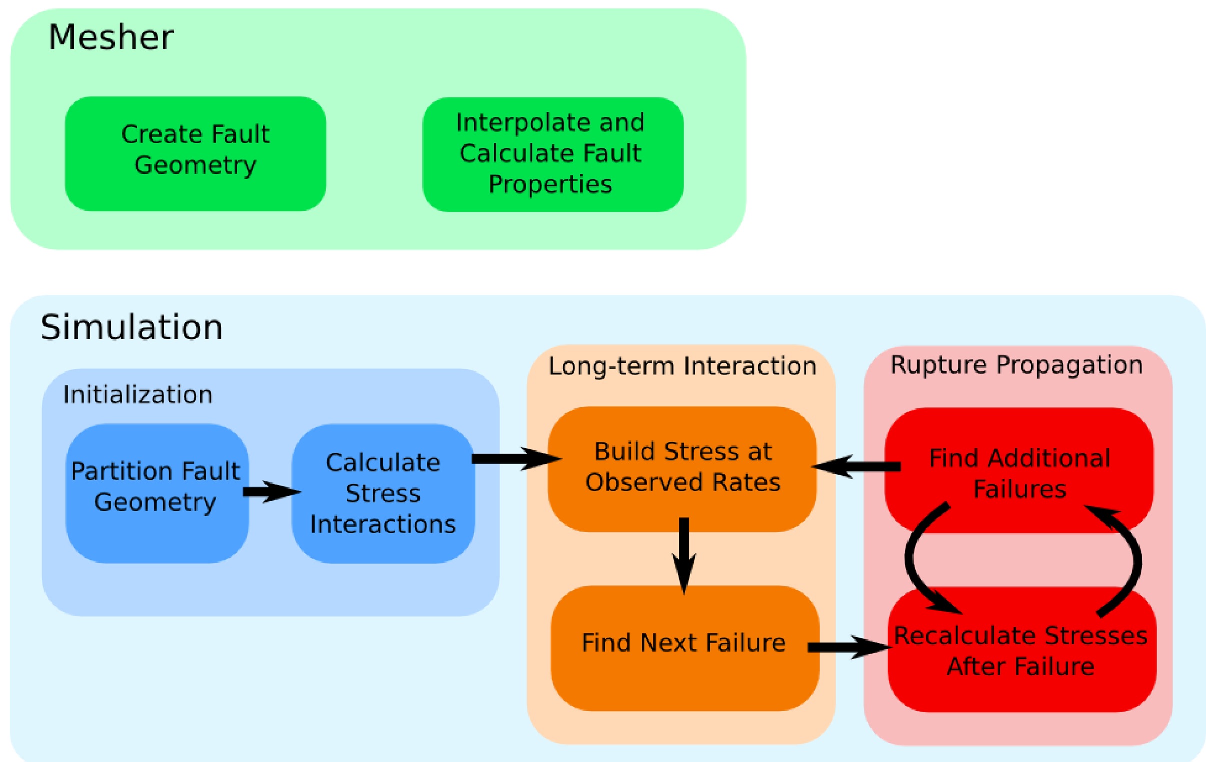
In light of growing demand for fast Global Navigational Satellite System tsunami early warning in the Pacific Rim, computer simulations are being developed to play key roles at all stages. Virtual Quake is an earthquake simulator that can rapidly produce long histories of earthquakes for complex fault systems, including tsunamigenic regions, as well as expected seafloor uplift from such earthquakes. When paired with the Tsunami Squares simulator, large catalogs of tsunami scenarios can be generated. To translate potential tsunamis to potential observables, we plan on coupling our tsunami generation pipeline to a simulation of total electron content (TEC) fluctuations in the ionosphere caused by tsunamis. These TEC signatures can be detected by GPS receivers, allowing fast comparison of ionospheric perturbations to precomputed catalogs of tsunami scenarios for rapid hazard assessment.

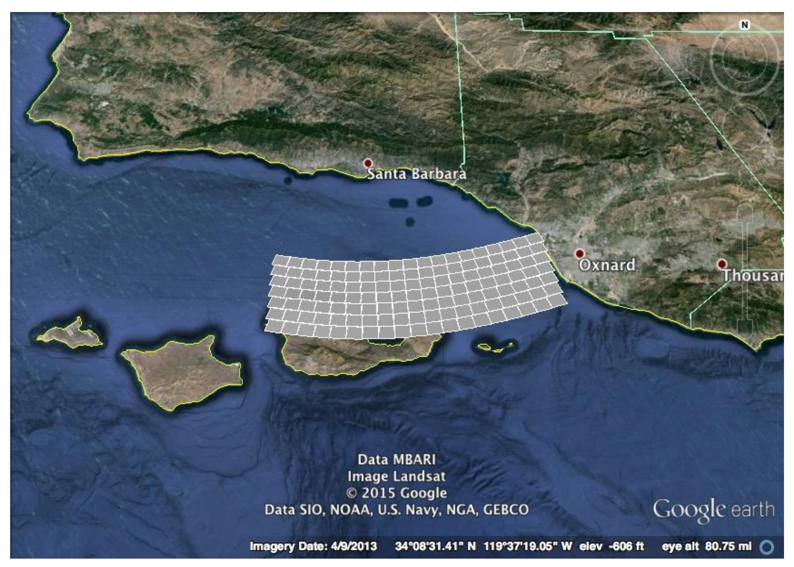



**Virtual Quake** uses field observations to define fault locations, tectonic slip rates, and frictional parameters. These values are combined into a meshed fault model embedded in an elastic medium composed of small rectangular fault patches, or elements. Each element is then allowed to slip at its defined rate. Stress accumulates on elements until frictional values are exceeded, causing an element to fail, and initiating an earthquake. A failed element transfers stress to all other elements in the model, pushing some past their failure threshold and causing the earthquake rupture to grow. When this chain reaction is finished, the earthquake is recorded and all elements of the model resume slipping at their defined rates [1].

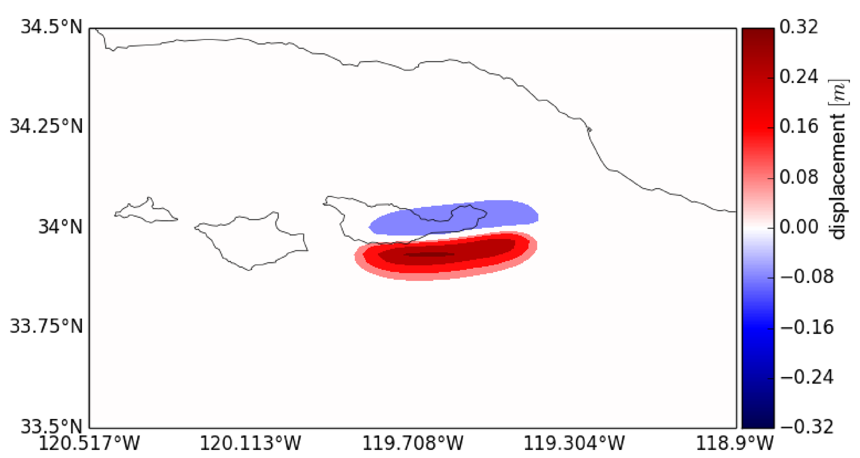



Because Virtual Quake uses a static fault geometry, all stress interactions between fault elements can be computed once at the beginning of the simulation. Transmission of stresses during simulated earthquakes occur very quickly, enabling many thousands of years of simulated events to be generated over relatively short time scales.

Using Okada's elastic halfspace deformation functions [2], the seafloor uplift resulting from displacements on underwater thrust faults can be determined. These uplifts become the initial conditions for tsunami models, in this case Tsunami Squares.

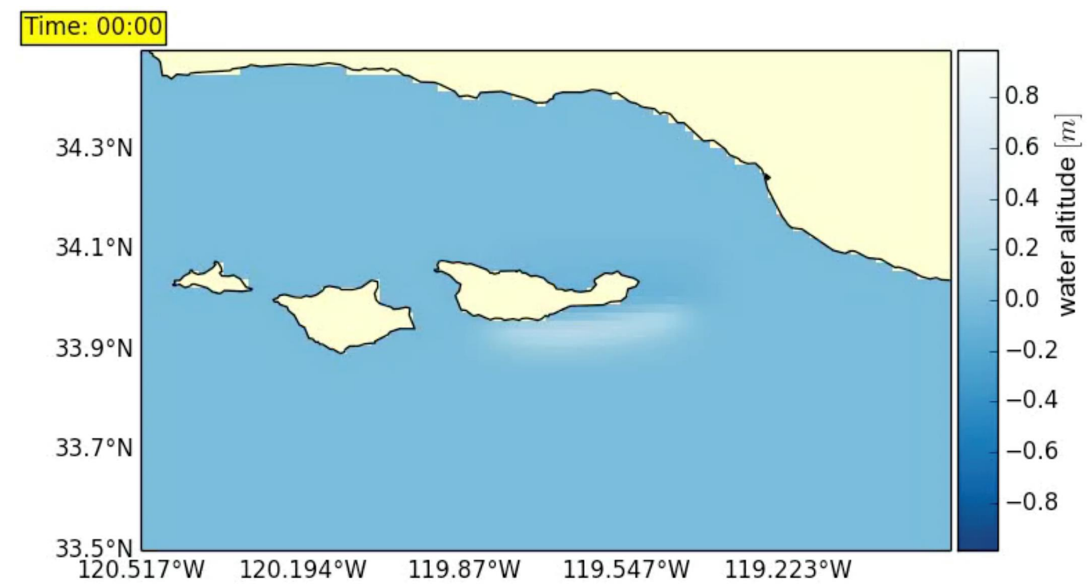



Channel Islands thrust fault off California coast

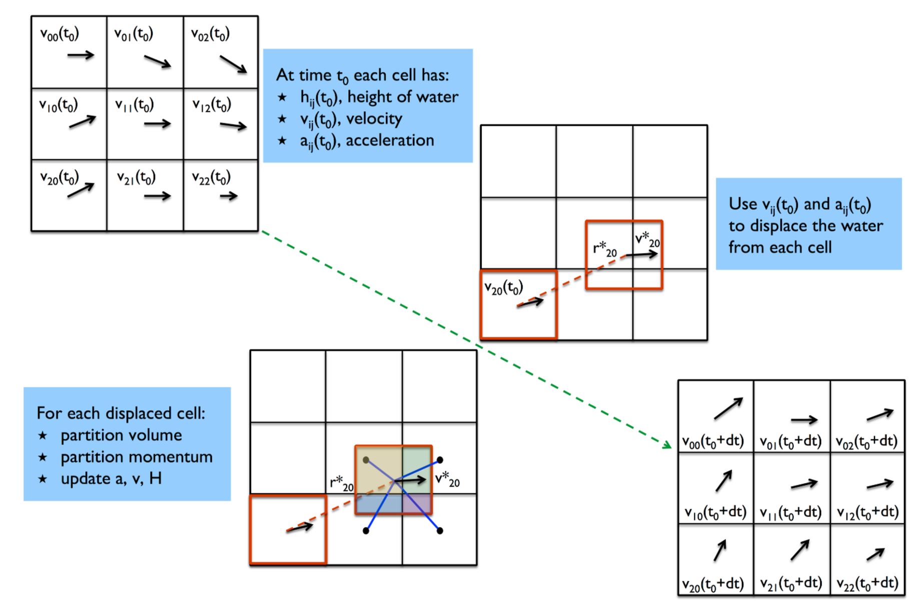



Surface height displacement after earthquake

Virtual Quake is open source, and available for download at
`geodynamics.org/cig/software/vq/`




Initial water uplift for thrust fault earthquake



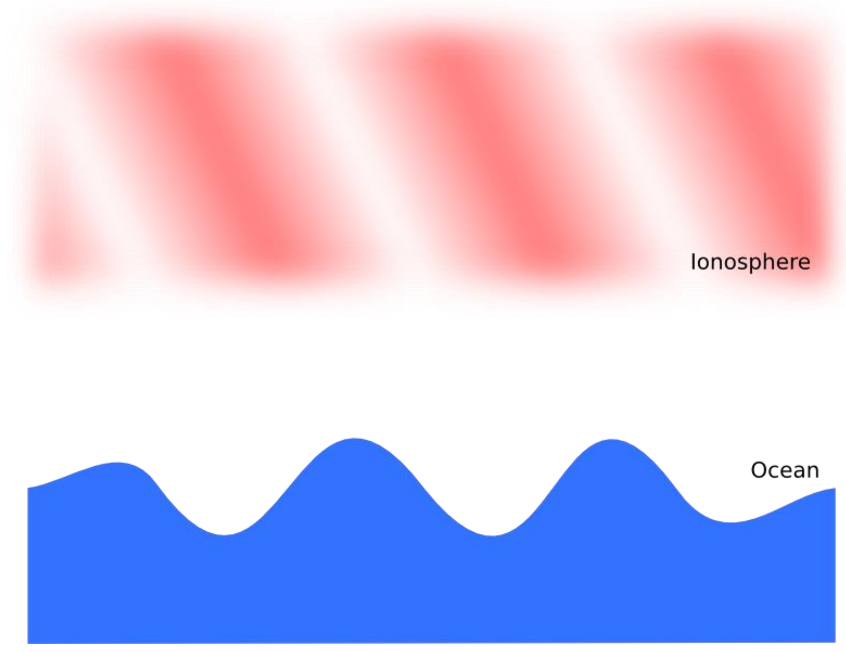
One time step of the Tsunami Squares simulation

**Tsunami Squares** is a two-dimensional numerical simulator of fluid flows. While typical simulators solve systems of nonlinear continuity and momentum equations, Tsunami Squares uses an efficient approach to solve equivalent equations for a fixed grid of uniform squares [3].

In the case of ocean tsunamis, the water is divided into a grid of squares, and each square's water is assigned a height, velocity, and acceleration. Initially, the bathymetry is given an uplift according to a chosen source earthquake. At each time step, each square's water is displaced to a new location according to it's velocity and acceleration, distributing it's water and momentum to up to four squares in the new location. New accelerations for each square are determined from the slope of the surrounding water heights. By these methods, mass and momentum are conserved, and tsunami propagation is determined quickly. The speed of this method is suitable for the large number of simulations required for producing tsunami early warning scenario catalogs.

Perturbations in the **Ionospheric Total Electron Content** (TEC) are known to follow large disturbances in the earth's surface, such as tsunamis and seafloor displacements. These TEC fluctuations modify the speed at which radio signals, such as those from GPS satellites, propagate through the ionosphere. By observing the phase delays in such signals, the TEC state can be determined [4].

Models coupling the TEC to earth surface height changes allow for the simulation of expected TEC fluctuations from given events such as tsunamis and large thrust earthquakes [5]. Fast comparison of observed TEC changes to a precomputed catalog of simulated TEC signals associated with tsunami scenarios could allow for fast tsunami hazard assessment.




TEC perturbations corresponding to changes in ocean surface height.

**References:**

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