Advanced Technologies in Earth Sciences

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Jochen Zschau *Editors*

Early Warning for Geological Disasters

Scientific Methods and Current Practice

GEOTECHNOLOGIEN

Springer

Chapter 3
CISN ShakeAlert: An Earthquake Early Warning Demonstration System for California

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Abstract To demonstrate the feasibility of earthquake early warning (EEW) in California, we have developed and implemented the CISN ShakeAlert demonstration system. A Decision Module combines estimates and uncertainties determined by three algorithms implemented in parallel, $\tau_c - P_d$ Onsite, Virtual Seismologist, and ElarmS, to calculate and report at a given time the most probable earthquake magnitude and location, as well as the likelihood of correct alarm. A User Display receives the alert messages in real-time, calculates the expected local shaking intensity, and displays the information on a map. Currently, CISN ShakeAlert is being tested by ~70 individuals and test users from industries and emergency response organizations in California. During the next 3 years we plan to expand this demonstration warning system to the entire US West Coast.

3.1 Introduction

Scientists and engineers at the California Institute of Technology (Caltech), UC Berkeley, the Swiss Federal Institute of Technology (ETH), and the University of Southern California (USC) started in 2007 to develop and implement an earthquake

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F. Wenzel and J. Zschau (eds.), *Early Warning for Geological Disasters*, Advanced Technologies in Earth Sciences, DOI: 10.1007/978-3-642-12233-0_3,

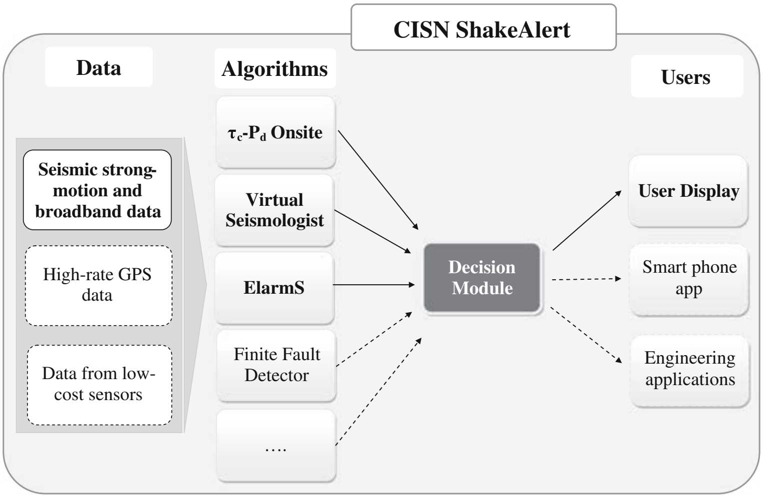

Fig. 3.1 The current CISN ShakeAlert system receives real-time estimates of earthquake source and ground-motion parameters determined by three algorithms, $\tau_c - P_d$ Onsite, Virtual Seismologist, and ElarmS, that run in parallel in California. The Decision Module combines these estimates and provides a unified 'ShakeAlert' view of the earthquake in progress. The ShakeAlert information includes rapid estimates of magnitudes, locations, expected seismic intensities, and probabilities of correct alarm (called 'likelihood' parameter). A User Display that runs on a user's computer receives and displays the alert messages in real-time. Dashed lines show components under development, including, for instance, the usage of high-rate GPS-data and a finite fault detector for the rapid detection of large earthquakes

early warning (EEW) demonstration system for California, called CISN ShakeAlert. The project is funded by the US Geological Survey (USGS), as well as participating partners. The USGS has the formal responsibility of issuing earthquake alerts in California. ShakeAlert makes use of the existing infrastructure of the California Integrated Seismic Network (CISN), including real-time waveform data streams from ∼380 broadband and strong-motion stations throughout California.

The USGS/ANSS/ARRA program provided Government Furnished Equipment and funding to upgrade the CISN during the past 2 years. ARRA funds were used to upgrade around 210 CISN stations with faster Q330 s dataloggers, upgrade telemetry hubs, and build a state-of-the-art microwave telemetry backbone (Romanowicz et al. 2011; Thomas et al. 2011). These improvements have reduced data latencies in the CISN data acquisition systems. Waveform data thus arrive within seconds at the three processing facilities at Caltech/USGS Pasadena, UC Berkeley, and USGS Menlo Park, providing the basis for EEW in California.

CISN ShakeAlert is a distributed system, which enables the independent development of individual system components (Fig. 3.1). An associator, called Decision Module, combines the outputs from three EEW algorithms implemented in parallel, $\tau_c - P_d$ Onsite (Böse et al. 2009a, b; Kanamori 2005; Wu et al. 2007), Virtual Seismologist (Cua et al. 2009; Cua and Heaton 2007), and ElarmS (Allen 2007; Allen et al. 2009; Allen and Kanamori 2003). Each algorithm is capable of detecting and characterizing earthquakes within seconds from event initiation. The Decision Module uses estimates of source parameters and uncertainties determined by the three algorithms to calculate, update, and report the most probable solutions at a given time. The earthquake alert information includes rapid estimates of magnitudes, locations, expected seismic intensities, and probabilities of correct alarm (called 'likelihood' parameter). A User Display that runs on a user's computer receives and displays the alert messages in real-time (Fig. 3.1).

3.2 Early Warning Algorithms

The following subsections give a brief description of the three EEW algorithms used in CISN ShakeAlert.

3.2.1 $\tau_c - P_d$ *Onsite Algorithm*

The $\tau_c - P_d$ Onsite algorithm belongs to the group of single-sensor approaches to EEW (Kanamori 2005). In principle, this type of warning approach can be quicker at detecting and processing of earthquakes, but is expected to be less reliable compared to regional warning algorithms that are based on observations at multiple seismic sensors.

The $\tau_c - P_d$ Onsite algorithm—developed by Kanamori (2005) as an extension of earlier methods proposed by Nakamura (1988) and Allen and Kanamori (2003)—uses the period τ_c and amplitude P_d of initial shaking to estimate the size and forthcoming shaking in an earthquake. The period parameter τ_c is defined as $\tau_c = 2\pi/\sqrt{r}$, with

$$r = \left[\int_0^{\tau_o} \dot{u}^2(t)dt\right] / \left[\int_0^{\tau_o} u^2(t)dt\right], \tag{3.1}$$

where u(t) and u̇(t) are the ground-motion displacement and velocity time series, and τ_0 is the duration of the time window used. Usually, τ_0 is set to 3.0 [s]. Wu et al. (2007) systematically studied the archived records from earthquakes in southern California to determine a $\log_{10}(\tau_c)$-Mw scaling relationship for EEW. The second parameter, P_d, which is the maximum amplitude of the high-pass filtered (>0.075 Hz) vertical displacement during the initial 3.0 [s] of the P wave, is used to estimate the peak ground velocity (PGV) at the recording site (Wu et al. 2007).

Our real-time tests of the $\tau_c - P_d$ Onsite algorithm in California over the past 5 years (Böse et al. 2009b) have shown that some modifications are necessary to decrease the number of false triggers and thus to increase the robustness of the algorithm. In particular in real-time mode during small to moderate-sized earthquakes there may be too many false alarms, as well as too much scatter in the source parameter estimates. The main modifications, which we have implemented, are the $\tau_c - P_d$ Trigger—Criterion (Böse et al. 2009a) and the Two-Station-Method.

The $\tau_c - P_d$ Trigger—Criterion is based on τ_c-dependent and implicit magnitude-dependent P_d thresholds. For a local earthquake with period τ_c and rupture-to-site distance r, $r_{min} \leq r \leq r_{max}$, we expect $P_{d,min} \leq P_d \leq P_{d,max}$. Böse et al. (2009a) determined displacement amplitudes $P_{d,min}$ and $P_{d,max}$ from empirical attenuation relations for earthquakes in southern California with $r_{min} = 1$ km to $r_{max} = 100$ km. The application of the $\tau_c - P_d$ Trigger—Criterion removed 97 % of previous false triggers throughout California and led to a significant reduction of the scatter in magnitude estimates for small earthquakes (Böse et al. 2009a).

The second modification that we have implemented is the Two-Station-Method. A 'trigger' at a station, i.e. τ_c and P_d values that have passed the $\tau_c - P_d$ Trigger-Criterion, needs to be confirmed by one or more 'picks' of the seismic P-wave at neighbored stations, before being reported to the ShakeAlert system. Whenever one or more close-by stations detect the P-wave within a certain time window, the trigger is confirmed and reported. The earthquake location is updated, assuming that the epicenter is in between the two stations taking into account travel time differences.

If two or more reports are associated with each other, i.e. are expected to refer to the same earthquake, we start calculating and reporting the median values of the magnitude. On-line and off-lines tests with waveform data from California, Taiwan and Japan, have shown, that the magnitude errors are normally distributed with $\sigma_{M,\,single} \approx 0.55$, if estimated at single stations. As can be shown from Monte Carlo simulations, the errors should decrease with $\sigma_{M,\,multiple} = (\text{number of stations})^{-0.4}$, if magnitudes are estimated from median values from multiple stations. However, the errors observed for earthquakes in California are larger than these estimates suggest. A possible explanation is that the uncertainties at different stations (for the same event) are correlated with each other. Thus we need to consider inter- and intra-event errors caused by the variability from earthquake to earthquake (e.g. caused by different stress drops) and the variability from station to station (during the same event). In a preliminary error analysis, we find $\sigma_{M,\,inter} = 0.55$ and $\sigma_{M,\,intra} = 0.37$ (Barba et al. 2010), and obtain

$$\sigma_{M,\,multiple}(\sigma_{M,\,inter},\ \sigma_{M,\,intra}) \approx 0.4 + 0.3\exp(-\text{number of stations}/3.6). \quad (3.2)$$

The uncertainties in epicenter location for earthquakes within CISN are 0.14° (≈15 km), and for PGV $\sigma\sigma_{\log(PGV),\,single} = 0.326$ (Wu et al. 2007). For the current telemetry and processing delays in the CISN first reports from $\tau_c - P_d$ Onsite usually become available 5 s after event origin or later, depending on the distance between the earthquake and the reporting station, as well as station equipment.

To quantify the probability of correct alert, we calculate a preliminary likelihood parameter, which depends on the number of reporting stations and the time in between these reports. If the number of reporting stations does not increase with time as expected for a moderate or large earthquake, a 'Cancel' message is sent to the CISN ShakeAlert Decision Module and User Display for event deletion and user notification.

We are also developing new algorithms for more rapid and more robust onsite warning, such as PreSEIS Onsite, which is based on Artificial Neural Networks (Böse et al. 2012a). PreSEIS Onsite uses the acceleration, velocity and displacement waveforms from a single three-component broadband or strong-motion sensor to perform real-time earthquake/noise discrimination and near/far source classification. When a local earthquake is detected, the algorithm estimates the moment magnitude, epicentral distance Δ, and peak ground velocity (PGV) at the site of observation. Our training and test datasets consist of 2,431 records of 161 crustal earthquakes in California, Japan and Taiwan with $3.1 \leq M \leq 7.6$ at $\Delta \leq 115$ km. First estimates become available at 0.25 s after the P-pick and are regularly updated with progressing time. We find that the prediction errors of this new approach are around 60 % smaller compared to the $\tau_c - P_d$ Onsite algorithm (Böse et al. 2012a).

3.2.2 Virtual Seismologist Algorithm

The Virtual Seismologist (VS) method is a Bayesian approach to earthquake early warning (EEW) that estimates earthquake magnitude, location, and the distribution of peak ground motion using observed ground motion amplitudes, predefined prior information, and envelope attenuation relationships (Cua 2005; Cua et al. 2009; Cua and Heaton 2007). The application of Bayes' theorem in EEW (Cua 2005) states that the most probable source estimate at any given time is a combination of contributions from prior information (possibilities include network topology or station health status, regional hazard maps, earthquake forecasts, the Gutenberg-Richter magnitude-frequency relationship) and constraints from the available ground motion observations. VS is envisioned as an intelligent, automated system capable of mimicking how human seismologists can make quick, relatively accurate, "back-of-the-envelope" interpretations of real-time (and at times, incomplete) earthquake information, using a mix of experience and available data.

The formulation of the VS Bayesian methodology, the development of the underlying relationships describing the dependence of various channels of ground motion envelopes on magnitude and distance, and how these pieces come together for early warning estimation, was the result of the work of Cua and Heaton (2007) at Caltech. Implementation of the VS algorithm into real-time codes is an on-going effort of the Swiss Seismological Service at ETH Zürich, with support from ETH, the US Geological Survey, and from European projects SAFER (Seismic Early Warning for Europe), NERA (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation), and REAKT (Strategies and Tools for Real-Time Earthquake Risk Reduction). Since the contribution of prior information can be considered relatively static over the timescale of a given earthquake rupture, VS implementation efforts have thus far focused on real-time processing of incoming waveform data. The VS code implementation currently running in real-time

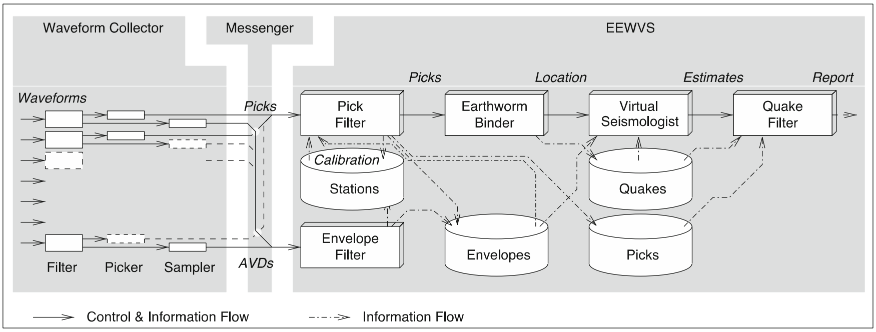

Fig. 3.2 System architecture of Virtual Seismologist codes (from Cua et al. 2009). What we refer to as the VS codes consists of 3 subsystems (collection of modules). The Waveform Collector subsystem performs basic waveform processing such as picking, gain correction, baseline removal, filtering, down-sampling, and the calculation of the ground motion envelopes used by VS. The Messenger subsystem sends information (picks and ground motion envelopes) to the EEWVS (Earthquake Early Warning Virtual Seismologist) subsystem. The EEWVS subsystem includes the Binder module for providing location estimates, which is then passed to the magnitude estimation module. The QuakeFilter module (within the EEWVS subsystem) compares the consistency of the candidate location and magnitude estimate with the available pick and envelope data

in California and Europe was designed and developed by Dr. Michael Fischer during his term at the Swiss Seismological Service at ETH Zürich.

Conceptually, VS maps incoming phase arrival and ground motion envelope amplitude information into continuously updated estimates of earthquake magnitude, location, depth, origin time, and likelihood. Within the context of the ShakeAlert effort, the likelihood parameter expresses a degree of belief that the incoming data come from a real earthquake (as opposed to noise). The higher the likelihood value, the more consistent the incoming data are with a regional earthquake. Figure 3.2 (Cua et al. 2009) shows the system architecture of the VS codes. Phase picks from a short-term average/long-term average picker based on Allen (1978) are first sent to a Pick Filter. If the picks satisfy certain thresholds, they are sent to the Binder Earthworm phase associator module (Dietz 2002), which provides estimates of event origin time, latitude, longitude, and depth. The location estimate is passed to the Virtual Seismologist module in Fig. 3.2, which provides a magnitude estimate, given the Binder location estimate, and the available ground motion envelope values. The QuakeFilter module then takes the candidate event information (location estimate from the Binder module, magnitude estimate from Virtual Seismologist module), checks the consistency of these estimates with the observed phase picks and ground motion envelope values, and outputs a likelihood value. We refer the reader to (Cua et al. 2009), for a more detailed discussion of the VS system architecture and real-time processing.

The use of ShakeMap-style site corrections (Wald et al. 1999) using shear wave velocity in the upper 30 m (Vs30) and the Borcherdt (1994) approach is currently implemented in the real-time codes. Caprio et al. (2011) are comparing the effectiveness of empirical station corrections and Vs30-based corrections in improving VS magnitude estimation.

Within the CISN ShakeAlert system, the VS algorithm is configured to require a minimum of four stations to initiate an initial event declaration (origin time, latitude, longitude, depth, magnitude, likelihood). Estimates and their updates are sent to the Decision Module, which combines the VS estimates with available estimates from $\tau_c - P_d$ Onsite and ElarmS, to produce the ShakeAlert estimate. VS can also predict peak ground motions at specified locations. However, this particular feature is suppressed within the ShakeAlert system, since the prediction of peak motions at the user sites is done by the User Display.

VS is currently running as three separate installations at the three processing facilities at Caltech/USGS Pasadena, UC Berkeley, and USGS Menlo Park. From the last 5 years of real-time testing, we find that, in general, the quality of the location estimate drives the quality of the magnitude estimate. If the location estimate is correct (or reasonably close to the true location), the VS magnitude estimate is quite good. Figure 3.3 shows the magnitude error (VS magnitude estimate – catalogue magni-

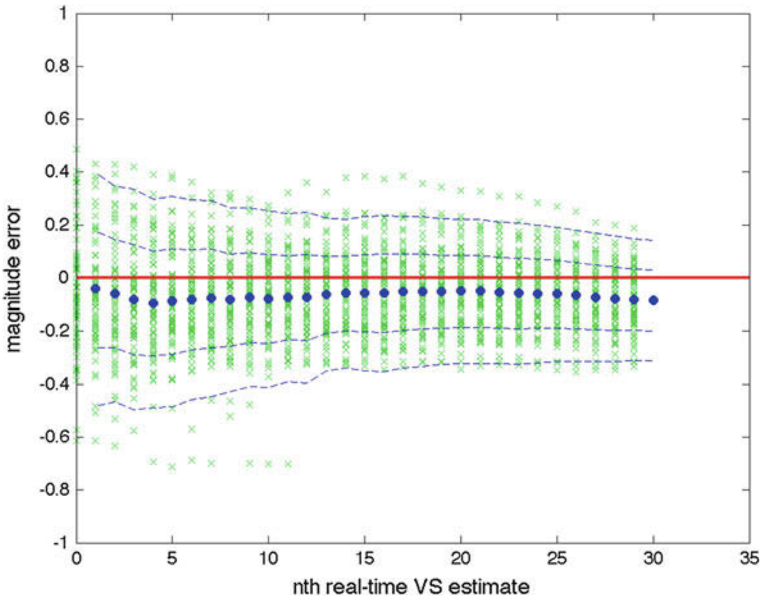

Fig. 3.3 VS magnitude error (VS magnitude – catalogue magnitude) for 80 southern California events from January through October 2011 with initial location estimates within 15 km of the catalogue location. The *green crosses* denote the temporal evolution of VS magnitude errors for individual events. The *blue dots* indicate the average VS magnitude error for 30 s following the initial VS estimate. The real-time envelope values are corrected to bedrock using the Borcherdt (1994) Vs30-based approach, similar to how the ShakeMap (Wald et al. 1999) codes correct for site amplification using Vs30, before the magnitude estimation step. This Vs30-based correction appears to over-correct for site amplification, as is indicated by the systematic offset of the average VS magnitude error by about 0.1 magnitude units

tude) for real-time VS detections with initial epicentral location estimates within 15 km of the catalogue epicenter for 80 M >= 3.0 southern California events from January through October 2011. On average, if the location is reasonable (i.e., within 15 km of the true location), the VS magnitude estimate is within 0.1 magnitude units of the catalogue magnitude. (The systematic 0.1 magnitude unit underestimation is due to an over-correction of site amplification effects.) This indicates that, if provided a reasonable location estimate, the underlying ground motion envelope relationships from Cua and Heaton (2007) coupled with the Vs30-based correction provides reasonable magnitude estimates. However, the Binder earthworm module was not designed as an EEW associator, and, when operating on 4 picks, simply supplies a hypocenter that fits the arrival times, without being able to recognize whether a particular pick is erroneous or not. Thus, whether the early location estimates are reasonable or not, is determined by how effective the Pick Filter module is at distinguishing between earthquake- or non-earthquake-related picks.

The minimum requirement of 4 picks for an initial event declaration corresponds to initial VS estimates becoming available, on average, around 20 s after the earthquake origin time (the expected initial VS estimate time is a function of station density in a given region), corresponding to an average blind zone of about 70 km. While VS can calculate a magnitude estimate with as little as 2 s of P-wave information from a single station, using less than 4 stations for a location estimate results in too many false detections. An experimental version of VS, called VS-MTED (Virtual Seismologist Multiple Threshold Event Detection) was developed by Fischer et al. (2009) to enable single-station event declarations when amplitudes are high enough, potentially allowing for larger warning times for large events, while requiring a larger number of stations for picks with low amplitudes to minimize false alerts from small earthquakes. Meier et al. (2011) are exploring ways of using the concept of not-yet-arrived data (Horiuchi et al. 2005; Satriano et al. 2007) to improve the discrimination of earthquake and non-earthquake signals with sparse observations. Faster, more robust discrimination between earthquake and noise signals would allow VS (or any other network-based EEW approach, for that matter) to provide faster, more reliable EEW estimates.

3.2.3 ElarmS Algorithm

ElarmS is a network-based early warning algorithm. P-wave detections and subsequent parameters (frequency, amplitude) are combined from several proximal stations to collectively characterize an event (Allen 2007; Allen et al. 2009; Allen and Kanamori 2003; Brown et al. 2010a, b). Network-based algorithms are generally more accurate than single-station algorithms, but are not as fast.

ElarmS consists of two processing modules. The Waveform Processing module, or WP, runs in parallel at three locations (UC Berkeley, USGS Menlo Park, Caltech/USGS Pasadena) and receives the constantly streaming waveforms from seismic sensors throughout California. The WP scans the waveforms looking for

P-wave arrivals, detected by a short-term/long-term average method (Allen 1978). When a P-wave is detected the WP records peak amplitudes (displacement, velocity and acceleration), maximum predominant period, and signal to noise ratios every tenth of a second for 4 s following the P-wave pick. Every second it sends these parameters, along with the original P-wave arrival time, to the ElarmS Event Monitor module.

The Event Monitor module, or EVM, runs in a single installation at UC Berkeley. It receives the P-wave detections and parameters from the three WP modules, and identifies earthquakes in progress, by associating triggers (P-wave detections), estimating event location and estimating event magnitude. Finally the EVM sends an alert message to the ShakeAlert Decision Module if appropriate.

ElarmS associates triggers together using a space/time window based on expected travel times. If P-wave detections occur near each other in space and time, ElarmS will associate those triggers together into a single event. Later triggers are added to the event using the space/time window and the estimated event epicenter.

The event hypocenter is estimated using a grid search. The grid extends 50 km in each horizontal direction from the mean trigger location, at a fixed depth of 8 km, and with 1 km resolution. Imagining that an earthquake begins at each grid point, ElarmS predicts the P-wave arrival time at each triggered station. The predicted travel times are compared to the actual observed arrival times, and the grid point with the lowest residuals is used as the event hypocenter.

ElarmS calculates magnitude twice, using two separate scaling relations, and then averages the two magnitudes into a single event magnitude. The first scaling relations are based on the maximum predominant period, τ_p^{max}, of the first 4 s of P-wave. The vertical waveforms are integrated to velocity if necessary (for accelerometer data) and low-pass filtered at 3 Hz. Then τ_p is defined by the iterative equation:

$$\tau_{p,i} = 2\pi (X_i/D_i)^{1/2} \tag{3.3}$$

where $X_i = \alpha X_{i-1} + x_i^2$, x_i is the ground velocity of the previous sample, $D_i = \alpha D_{i-1} + (dx/dt)_i^2$, and α is a smoothing constant (Wurman et al. 2007). τ_p^{max} is the maximum observed τ_p, and the period-based magnitude for each triggered station is then:

$$M_{\tau p} = 5.22 + 6.66 \log_{10}(\tau_p^{max}) \tag{3.4}$$

The $M_{\tau p}$values from all triggered stations are averaged together to get a single $M_{\tau p}$for the event.

For the amplitude-based scaling relations, ElarmS uses the peak displacement, P_d, observed at velocity instruments and the peak velocity, P_v, observed at accelerometers. Again, the waveforms are low-pass filtered at 3 Hz and only vertical instruments are used. The amplitude-based magnitude is:

$$M_p = 1.04 \log_{10}(P_d) + 1.27 \log_{10}(R) + 5.16 \quad \text{[HHZ channels]} \tag{3.5}$$

$$M_p = 1.37 \log_{10}(P_v) + 1.57 \log_{10}(R) + 4.25 \quad \text{[HHZ channels]} \tag{3.6}$$

$$M_p = 1.63 \log_{10}(P_v) + 1.65 \log_{10}(R) + 4.40 \quad \text{[HHZ channels]} \tag{3.7}$$

where R is the distance (in kilometers) to the estimated event epicenter (Wurman et al. 2007). The M_p values from all triggered stations are averaged together to get a single M_p value for the event. Finally, the M_p and $M_{\tau p}$ are averaged together into a single event magnitude, M, which is sent in any alert messages to the Decision Module.

ElarmS has been sending alert messages to the Decision Module since March 2011 for Northern California events. Between March 18, 2011 and December 6, 2011, there were 138 real events $M \geq 3.0$ in this region (according to the ANSS catalog). ElarmS successfully sent alert messages for 106 of the events, corresponding to a 77 % success rate. For events $M \geq 3.5$, ElarmS sent alerts for 37 out of 45 events, for an 82 % success rate. ElarmS also had a 25 % false alert rate. False alerts are alerts for which there is no corresponding event in the ANSS catalog.

In 2011 we developed a second generation ElarmS code. ElarmS-2 consists of an upgraded Waveform Processing module for faster performance, and a redesigned Event Monitor module for improved accuracy. The new WP module processes smaller packets of waveform data and sends the resulting parameters more promptly. Changes to the EVM module include a more modern coding language (C++), a revised trigger associator, and a new alert filter which verifies each event before sending an alert to the Decision Module. ElarmS-2 is in the final stages of testing and will replace ElarmS-1 in early 2012.

3.3 Decision Module

The Decision Module (DM) of CISN ShakeAlert (Fig. 3.1) combines earthquake information feeds from the three algorithms ($\tau_c - P_d$ Onsite, Virtual Seismologist, and ElarmS) to provide a unified 'ShakeAlert' view of earthquakes in progress. The DM publishes this information in an xml-formatted message for use by any number of users, including the User Display application. The DM has been operational since February 2011 (Neuhauser et al. 2010).

ShakeAlert uses the Java-based publish/subscribe ActiveMQ Messaging Broker with C++ Messaging Service extension for all communication between the ShakeAlert modules, and all messages are in XML format. The Decision Module subscribes to the earthquake message topics that are published by the $\tau_c - P_d$ Onsite, Virtual Seismologist and ElarmS algorithms. When the DM receives a message of a possible earthquake, it tries to associate the event message with any current event messages that it has stored using a location and time metric (Fig. 3.4). If DM cannot associate the message, it assumes that the newly received message is describing a new earthquake in progress and publishes the earthquake in XML format. If DM does

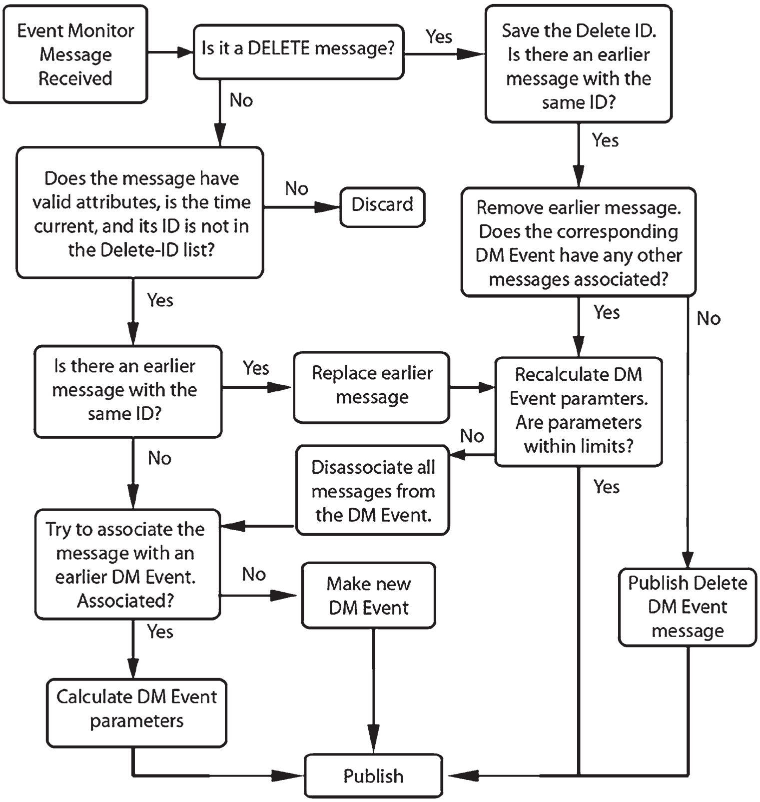

Fig. 3.4 Flow chart for DM logic

manage to associate the message with another earthquake in its memory, it updates the earthquake parameters and republishes the earthquake message (Neuhauser et al. 2010).

Earthquake source parameters from different algorithms are currently combined using a weighted average based on parameter uncertainties. In the future it is intended to include other types of information including prior information using a Bayesian scheme (Neuhauser et al. 2010). When provided by the algorithms, the DM will also output combined uncertainty information for earthquake location and magnitude, and likelihood estimates in its output message to allow end user applications to customize their actions based on these values. In addition, the DM can include both observed and predicted ground motions provided by the algorithms.

The DM receives periodic heartbeat messages from the algorithms, and forwards these messages in addition to its own heartbeat message to the ActiveMQ broker. A separate Health Aggregator module receives these heartbeat messages, determines the overall state of the ShakeAlert modules, and publishes a summary State-of-Health message through ActiveMQ to the User Display and any other user applications interested in monitoring the status of the ShakeAlert system.

3.4 User Display

The User Display (UD) receives XML messages from the Decision Module (DM) and displays their content in a simple and easily understandable way (Böse et al. 2010; Solanki et al. 2011). The app is written in Java and is thus platform-independent. The current version 2.3 has the following features:

- calculation and display of remaining warning time for a given user
- calculation and display of expected MMI intensity at this site (the user can specify a Vs30 value for site characterization if desired)
- description of expected MMI intensity at user site (e.g., "Moderate Shaking expected")
- display of estimated magnitude
- display of the probability of correct alarm ('likelihood' parameter)
- calculation and display of P/S-wavefronts
- display of user site
- display of a 30-km radius blind-zone around the user for education purpose
- siren and audio announcement

The User Display pops up automatically whenever a DM message is received (Fig. 3.5). The user can set thresholds for intensities, magnitudes and probability

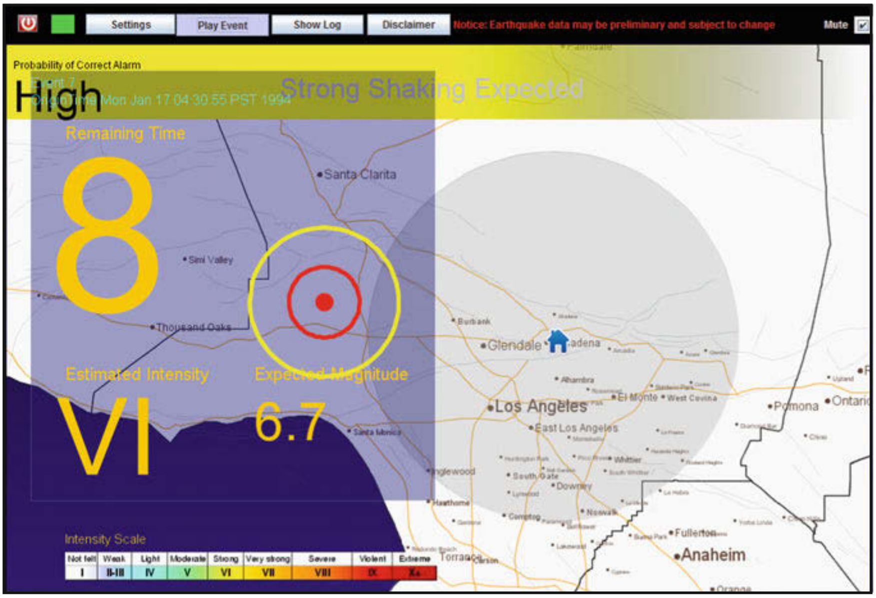

Fig. 3.5 Simulated performance of the User Display for the 1994 M6.7 Northridge earthquake in southern California with a user at Caltech (*blue house*). *Yellow* and *red circles* show P- and S-wavefronts. The *shaded area* around the user gives an approximation of the current blindzone of CISN ShakeAlert

values to reduce the number of reports. Like the 'CISN Display' (www.cisn.org) UD uses Openmap. Multiple map layers showing, e.g., fault lines or infrastructure can be added. XML messages received by the UD are stored locally in a history folder and can be replayed. A log-file summarizes the key information for each received DM report. Network Time Protocol (NTP) is used for time synchronization. Further features include password-protection, encrypted communication with the DM, and the capability to receive and display heartbeats from the three algorithms and DM to ensure robust communication.

3.5 Performance of CISN ShakeAlert

The CISN Testing Center (CTC) is a standalone computational system that runs routine evaluations of the CISN ShakeAlert system by comparing ShakeAlert earthquake forecast parameters, including magnitude and location, against observed earthquake parameters from the ANSS catalog. The intended users of CTC performance evaluations include the scientists and engineers developing the ShakeAlert system, and scientists working to improve earthquake early warning algorithms. The CTC is designed to provide reliable ShakeAlert system forecast evaluations and to provide open performance evaluations that can easily be repeated. To support tracking of ShakeAlert performance over time, the CTC is designed to be inexpensive to build and operate. These testing goals were used to establish the design and operation of the CISN Testing Center.

We have implemented the CTC at the Southern California Earthquake Center (SCEC) headquarters using computer resources that are separate from CISN ShakeAlert computer systems. The CTC software running at SCEC is based on the Collaboratory for the Study of Earthquake Predictability (CSEP) automated testing framework (Zechar et al. 2010) developed for the CSEP Project at SCEC (Jordan 2006). The CSEP software (CSEP 2012) is designed to perform validation testing of short-term earthquake forecasts and it is currently in use in earthquake forecast testing centers in the US (Jordan 2006), Switzerland (Marzocchi et al. 2010), Japan (Nanjo et al. 2011), and New Zealand (Gerstenberger and Rhoades 2010). The CSEP software provides utility programs that can retrieve observational earthquake catalogs from ANSS and other seismological data centers, and other programs that support evaluation of seismic forecasts. SCEC developers have written specialized evaluation modules to evaluate operational performance of the ShakeAlert EEW system (Maechling et al. 2011).

CTC testing is one part of a larger ShakeAlert system testing approach that includes software unit tests, system regression tests, and performance evaluation testing. CTC evaluations focus on ShakeAlert end-to-end system performance and ShakeAlert earthquake parameter forecast validation. An overview of the CISN ShakeAlert System and the CTC components are shown in Fig. 3.6.

The CTC automates ShakeAlert evaluations and provides routine feedback on system performance to ShakeAlert developers. Each night, or on request, the CTC

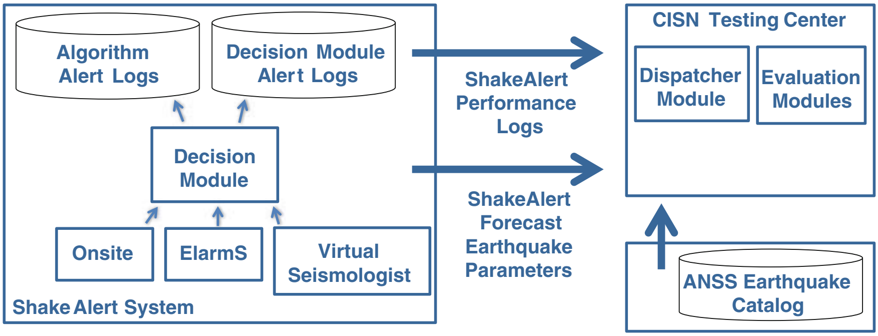

Fig. 3.6 The CISN Testing Center (CTC) (*right*) collects earthquake early warnings from ShakeAlert algorithms and from the ShakeAlert Decision Module (*left*) and evaluates ShakeAlert performance by comparing ShakeAlert forecast parameters against observed parameters in the ANSS earthquake catalog (*bottom right*)

server at SCEC initiates retrieval of ShakeAlert forecast logs and retrieval of the current ANSS catalog. Then, using both the forecast and observational information, the CTC software runs performance metrics and posts the evaluation results online for review by scientists and engineers. Example forecast evaluation summaries from the operational ShakeAlert system are shown in Fig. 3.7.

The CTC performance metrics (Maechling et al. 2009) developed by the scientific and engineering groups during ShakeAlert development can be put into three general categories; speed of operation, event performance, and cumulative event performance.

The CTC speed of operation summary measures how long it took the ShakeAlert system to produce the first alert for an earthquake. We measure this as time in seconds between an event origin time and the time the ShakeAlert Decision Modules publishes the first alert for the event. This measurement varies depending on the location of the earthquake, performance of the CISN real-time seismic network, and performance of the ShakeAlert algorithms and Decision Module.

The CTC event summaries show the earthquake forecast parameters produced by the real-time ShakeAlert algorithms and Decision Module as a time series showing how the forecast parameters change with time. To generate event summaries, the ShakeAlert system logs the performance of the seismological algorithms within ShakeAlert, as well as the processing of the Decision Module, which sends alerts to ShakeAlert end-users.

The CTC cumulative event summaries show performance measures for the ShakeAlert system for a given catalog of earthquakes. Cumulative performance summaries are useful in detecting systematic bias in performance such as consistent over-, or under-prediction of final magnitudes. CTC cumulative plots show performance of first report, and final report, showing how ShakeAlert forecast parameter estimates change during course of an alert.

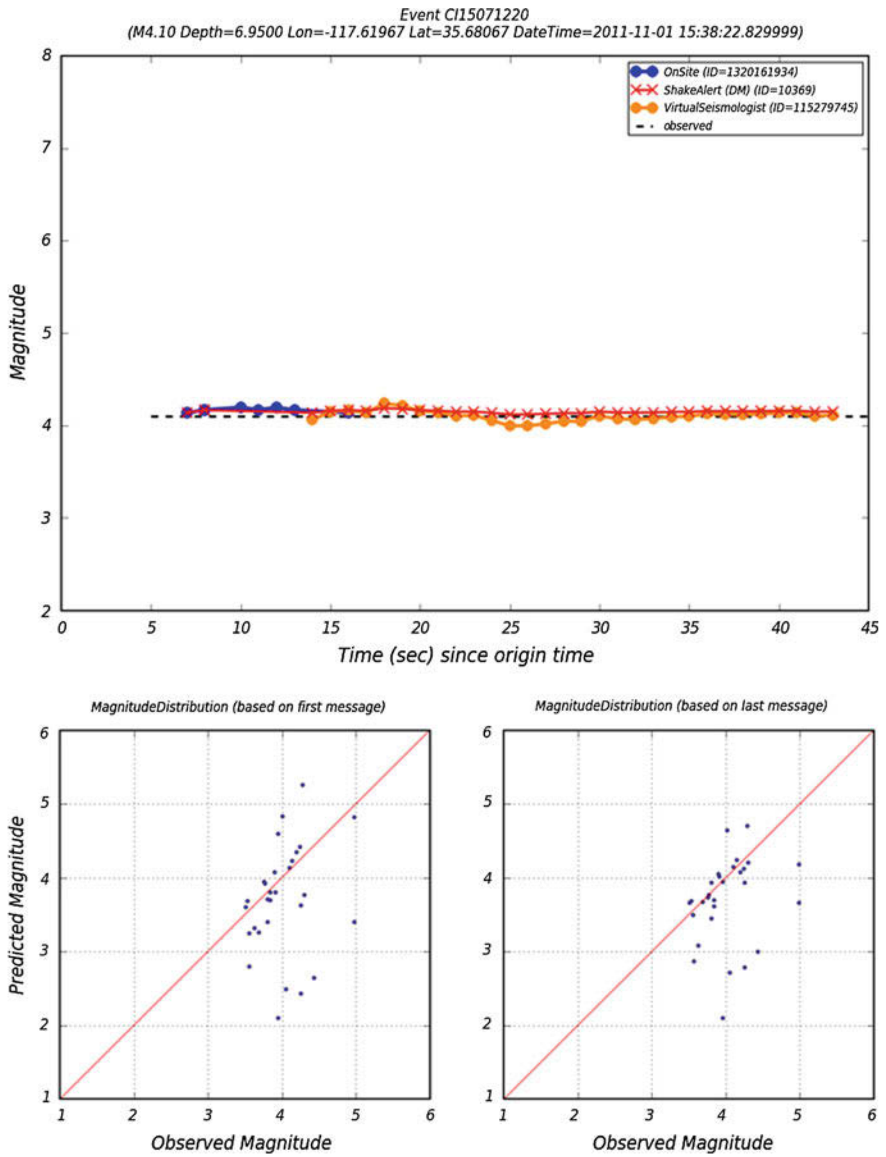

Fig. 3.7 Preliminary CISN testing results from ShakeAlert system show (*top*) time series of magnitude forecasts produced by the $\tau_c - P_d$ OnSite algorithm (*blue*), Virtual Seismologist algorithm (*orange*), and ShakeAlert Decision Module (*red*) for a central California M4.1 earthquake, with time scale showing seconds after origin time that ShakeAlert information is produced. The two graphs (*bottom*) compare ANSS final magnitude values to ShakeAlert Decision Module forecasts for approximately 4 months of M3.5+ California earthquakes based on ShakeAlert first report (*bottom left*), and ShakeAlert final report (*bottom right*)

We believe that the automated testing capability of the CTC software will provide consistent and inexpensive evaluations of ShakeAlert system performance over time. The CISN Testing Center measurements establish ShakeAlert system performance baseline against which we can measure future system performance as EEW algorithms and ShakeAlert Decision Modules software are updated and the CISN network is changed.

We have also developed software to replay the waveform records of historic and simulated earthquakes as simulated real-time data streams. The streams are processed by the same codes as used in the real-time ShakeAlert system. This way we can study the possible performance of the system and assess uncertainties for a much larger dataset of possible earthquake scenarios.

3.6 Outreach

Warnings of imminent shaking are of little use if the recipients are not prepared to act on them. In principle, two classes of use are possible, those based on automated procedures and those based on individual actions. For both cases, preparatory work is necessary to make use of rapidly received alerts. The latter case must be based on broad-based education of the recipients, which is well beyond the scope of our project. In Japan, for example, the public issuance of earthquake early warnings was preceded by a broad information campaign. We are focusing our outreach efforts on prospective users of early warning information who may be able to implement automatic responses that will save lives and property, and improve the possibility and speed of recovery from damaging earthquakes.

Currently, about 70 scientists and engineers receive ShakeAlert information through the User Display. In spring 2012, we have started to add new users to test the ShakeAlert output, which were chosen from industries and institutions throughout California. These users provide critical services to the State of California or its agencies, or operate critical infrastructure. Two examples are the California Emergency Management Agency (CalEMA) which is the state-wide coordinator of emergency response activities, and the Bay Area Rapid Transit District (BART) which provides transportation services in the San Francisco Bay Area.

The goal of the test with prospective users of EEW is twofold. First, as the producers of the early warning information and alerts, we need information from the users. Exactly what types of information are useful to the users? We also need to evaluate delivery mechanisms, procedures, and possible user products (Hellweg et al. 2010; Hellweg and Vinci 2011; Vinci et al. 2009). Secondly, we want the alert recipients to evaluate the effectiveness of possible uses within their organization, as well as the benefits of having alert information available to themselves and to society. To support both these aspects of our project, interaction with and education of the users is very important. A detailed introduction to the CISN ShakeAlert system is an integral part of our interaction with the users, as are regular opportunities for feedback and support. We will support their efforts to determine and implement appropriate responses. In future workshops, users will be surveyed to document how EEW was used in their organizations as well as how it is expected improve their earthquake response, as well as documenting the expected savings in terms of lives, damage, and improved resilience.

3.7 Research on Finite Fault Ruptures

Seismic ground motions can be underestimated when predicted from epicentral rather than rupture-to-site distances. This can result in warnings not being issued because shaking intensities do not exceed pre-defined thresholds. A prominent example is from the recent 2011 M9.0 Tohoku-Oki earthquake in Japan: while ground motion predictions by the Japanese Meteorological Agency (JMA) were fairly accurate in the Sendai area, close to the point of rupture nucleation, a warning was not transmitted to people and users in the Kanto district around Tokyo. Shaking in this region was strong, but underrated by the JMA EEW system that relies on point source approximations of earthquakes.

As part of the ongoing methodological development, we have been investigating the use of real-time GPS displacement data streams for rapid earthquake detection and source parameter estimation for large earthquakes (Allen and Ziv 2011). Using the example of the 2010, Mw7.2 El Mayor-Cucapah earthquake in Baja California, we have developed a simple algorithm to extract the permanent displacement at GPS sites starting one oscillation after triggering on the dynamic long-period signal. The estimate is continually improved with time. These permanent displacements can then be inverted for source characteristics given an approximate estimate of the fault plane. Estimates of fault plane parameters are available from existing fault catalogs and the appropriate region of fault rupture could be selected based on the seismic epicenter (Allen and Ziv 2011).

To take into account source finiteness for large earthquakes, we have also developed the Finite Fault Rupture Detector, FinDer (Böse et al. 2012b). FinDer uses image recognition techniques to automatically detect and map finite faults in real-time. The approach is based on a rapid (high-frequency) near/far-source classification of ground motion amplitudes in a dense seismic network (<50 km), and comparison with a set of pre-calculated templates using ‘Matching by Correlation’. The knowledge on source dimensions as provided by FinDer will make predicted shaking intensities more accurate and thus more useful for EEW, ShakeMaps, and related real-time products in the future, because it will allow the usage of rupture-to-site distances in empirical ground-motion prediction equations.

Predicting the shaking from large earthquakes requires some estimate of the likelihood of the future evolution of an ongoing rupture. It seems reasonable to assume that large slip amplitudes increase the probability for evolving into a large earthquake. From simulated sets of 1-D rupture series from stochastic models of spatially heterogeneous slip, we found that while large slip amplitudes increase the probability for the continuation of a rupture and the possible evolution into a large earthquake, the recognition that rupture is occurring on a spatially smooth fault, such as the San Andreas Fault, has an even stronger effect (Böse and Heaton 2010). We conclude that an EEW system for large earthquakes will benefit from a rapid recognition of the causative fault and consideration of its smoothness. FinDer is suited for such rapid fault association (Böse et al. 2012b). If the predicted location and azimuth of the rupture agrees well with the parameters of a known fault, the probability that rupture is occurring along this fault is high. If rupture is occurring along a smooth (mature) fault, a warning should be issued immediately, because the probability for a large earthquake is high.

3.8 Conclusions and Outlook

Around 145 years after Dr. Cooper (1868) proposed the implementation of earthquake early warning (EEW) for San Francisco, and 25 years after Heaton (1985) envisioned a seismic computerized alert network for California, scientists and engineers from several institutions in- and outside of California have developed an EEW demonstration system. This system is based on the infrastructure of the California Integrated Seismic Network (CISN). CISN ShakeAlert combines the outputs of three independently running algorithms for EEW ($\tau_c - P_d$ Onsite, Virtual Seismologist, and ElarmS) to calculate and report a unified view of the ongoing earthquake. The ShakeAlert structure is open and flexible to allow the integration of additional algorithms and tools in the future (Fig. 3.1).

Within the next 3 years, we plan to expand the coverage of the current ShakeAlert system to the entire Pacific Westcoast, including the Cascadia subduction-zone, where great earthquakes with high tsunami-potential can occur. We also plan to integrate ShakeAlert into the daily routine operations of CISN (AQMS system). Our future research and development will mainly focus on the rapid detection and processing of ground motions from large earthquakes, possibly with the integration of real-time GPS data streams and development of new algorithms for finite-fault rupture detection (Allen and Ziv 2011; Böse and Heaton 2010; Böse et al. 2012b).

We are also working on methodologies that will make it possible to automatically detect and process complex fore-, main- and aftershocks sequences. One approach will be to predict the envelope of seismic ground motions for a proposed foreshock magnitude and location (Karakus and Heaton 2011). If there is significant disagreement between the predicted and observed amplitudes as recorded and calculated for a nearby station, it is likely that the waveforms from two or more earthquakes overlap in time.

In collaboration with the Computer Science Department at Caltech, we have started to implement the User Display and additional apps on the Android smart phone (Faulkner et al. 2011). In addition, an automated decision-making system framework for EEW applications is being developed to perform real-time cost-benefit analyses of actions controlled by EEW (Wu and Beck 2011).

CISN ShakeAlert is an EEW demonstration system. It is not robust enough to provide reliable and timely EEW throughout California. To design and build an EEW system that was robust enough to support the economy of California, much more resources would be needed than what is available today.

Acknowledgments This work is funded through contracts G09AC00258, G09AC00259, G09AC00255, and G09AC00256 from USGS/ANSS to the California Institute of Technology (Caltech), UC Berkeley, USC/SCEC, and ETH. It is also funded by grants from the Gordon and Betty Moore Foundation to Caltech and UC Berkeley. USC/SCEC received additional funding through SCEC3 (NSF Cooperative Agreement EAR-0529922 and USGS Cooperative Agreement 07HQAG0008). This is SCEC contribution #1641 and contribution #10072 of the Seismological Laboratory, Geological and Planetary Sciences at Caltech.

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