Prototype Development of the new CISN Earthquake Alert System ("CISN ShakeAlert"): Collaborative Research with California Institute of Technology, University of California at Berkeley, University of Southern California, and Swiss Federal Institute of Technology, Zürich

Final Report: August 2009 – July 2012

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Executive Summary

Over the past three years (2009-2012) we migrated from three semi-parallel processing threads (Onsite, ElarmS, and Virtual Seismologist) with three outputs to a single integrated system, named CISN ShakeAlert. CISN ShakeAlert provides a continuum of earthquake alert information, including the predictions of source (origin time, magnitude, location) and ground-motion parameters (peak shaking, MMI intensity, warning times) and their uncertainties. Since late 2011 the alerts are being passed to a small group of collaborating beta test users from the business, utility and transportation sectors, as well as emergency management agencies in California, providing a complete end-to-end warning demonstration system (Böse, Allen *et al.*, 2012). CISN ShakeAlert demonstrates that building an earthquake early warning (EEW) system in California with the California Integrated Seismic Network (CISN) as a backbone is feasible, but additional investments are necessary.

Waveform Processing Library: To unify the waveform processing modules of the three Event Detectors, a new Waveform Processing Library (wplib) was developed and implemented. Wplib uses internal memory buffers and works in a single process multi-threaded environment. Among others, wplib supports the import of waveforms from the Multicast and Earthworm networks at all three datacenters (if available), creates waveform buffers, reads/writes waveforms to these buffers, and provides calls to the plug-in waveform processing modules. The integration of wplib in the three Event Detectors helped reducing processing delays in the order of several seconds.

Event Detector 1: Real-time tests of the τ_c-P_d Onsite algorithm in California over the past five years have shown that some modifications were necessary to increase the robustness of the algorithm in real-time mode. The main modifications that have been developed are (1) the τ_c-P_d Trigger–Criterion, which was implemented in the previous project phase, and (2) the Two-Station-Method, which we added in 2010. In addition, we developed a simple associator and localization procedure for Onsite. Since 2010, Onsite is also providing uncertainty estimates and likelihood parameters. For the current telemetry and processing delays in the CISN first reports from τ_c-P_d Onsite usually become available 5 seconds after

event origin or later, depending on the distance between the earthquake and the reporting station, as well as station equipment.

Event Detector 2: Over the last 3 years, the ElarmS algorithms have been completely reassessed and re-coded to solve technological and methodological challenges. The new version (ElarmS-2, or E2) is completely rewritten and is now production-grade code. The improved algorithm maximizes the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. ElarmS-2 is designed as modular code and consists of a new waveform processing module that provides data more rapidly to the event monitor. The new event monitor module has a significantly improved associator that allows for more rapid associating with fewer triggers, while also adding several new alert filters that check each event prior to release and minimize false alarms. The online performance over the last 5 months shows that on average, ElarmS currently issues an alert 6.79 ± 3.94 sec after the first P-wave detection, and 12.01 ± 5.92 sec after the origin time for all events across California. This time is reduced in regions with dense station instrumentation. Standard deviations of magnitude, origin time and median location errors are 0.32 magnitude units, 2.77 sec and 2.64 km, respectively. The latest version (E2.3.1), which we have tested by running the algorithm of the past 5 months of data, successfully detects 92% of earthquakes (M>3.5) across California without issuing any false alarms. This version is now the operational ElarmS contribution to ShakeAlert.

Event Detector 3: The Virtual Seismologist (VS) early warning approach was originally formulated as a Bayesian approach that combined various types of potential prior information (network topology, fault maps, previously observed seismicity, along with the processing and interpretation of real-time information (envelope amplitudes, picks) to provide the most probable earthquake point-source characterization at a given time. VS implementation efforts have thus far been focused on real-time processing of incoming picks and waveform data. Optimal use of prior information is part of on-going research at ETH. Enhancements to the VS codes over Phase II of the project include the development of the Virtual Seismologist Multiple Threshold Event Detection (VS-MTED) approach and the addition of Vs30-based correction factors. VS continues to run as 3 separate and independent installations at SCSN, BDSN, and Menlo Park.

Finite Fault Detector: To provide rapid estimates of fault rupture extent during large earthquakes, we have developed the Finite Fault Rupture Detector algorithm (*FinDer*) that is based on strong-motion data. *FinDer* uses image recognition techniques to detect automatically surface-projected fault ruptures in real-time (assuming a line source) by estimating their current centroid position, length L, and strike ϑ. The approach is based on a rapid high-frequency near/far-source classification of ground motion amplitudes in a dense seismic network (such as CISN), and comparison with a set of pre-calculated templates using Matching by Correlation. FinDer has not been added to the ShakeAlert system yet.

Decision Module: Each Event Detector independently examines raw waveform data, associates arrivals into events, computes magnitudes and sends the location, time, magnitude, and uncertainty values along with station ground motion observations and predictions to a central process, called the Decision Module (DM). The DM decides which incoming reports correspond to the same event, for which it calculates a set of combined event attributes and issues an alert message. This strategy results in a more robust system that profits from the different strengths of the independent detection methods while minimizing their different weaknesses.

UserDisplay: The UserDisplay (UD) has two purposes: (1) to translate alerts (origin time, location, magnitude) from the Decision Module to site-specific warnings (expected MMI intensity, remaining warning time), and (2) to display these values on a map to alert users. The User Display is written in Java and is thus platform-independent. A desktop version is available since 2010. A copy of the UserDisplay Operations Guide can be found in Appendix A of this report.

Performance Testing Center: SCEC and CISN ShakeAlert researchers have developed an operational testing system for the CISN ShakeAlert system that we call the CISN Testing Center (CTC). CTC ShakeAlert performance summaries are now posted on the CTC web site showing ShakeAlert performance summaries for the time period between September 2011 and the present. The CTC generates ShakeAlert performance summaries for each significant California event, and cumulative performance summaries over specific periods of time. Many of the CTC ShakeAlert performance summaries compare ShakeAlert forecast parameters, such as location and magnitude, against final observed parameters in the ANSS earthquake catalog. CTC ShakeAlert event summaries are generated for each M3.0 and larger ANSS catalog California earthquake. Event summaries show performance of the individual ShakeAlert algorithms, and the performance of the Decision Module that sends the public communications. CTC ShakeAlert Cumulative summaries show ShakeAlert performance for a given catalog.

Engagement of End Users and Outreach: We are working with a group of 15 selected Beta Test Users from institutions and industries throughout California that have potential uses for EEW information. ShakeAlert Beta Test Users are currently running the ShakeAlert UserDisplay. In return, they provide feedback which includes suggestions to improve the UserDisplay and other alert delivery mechanisms, as well as information on their potential uses of EEW. Beta Test User suggestions are incorporated into revisions of the UserDisplay and other elements of the ShakeAlert system, as appropriate. One of the test users has now progressed to the point of automated implementation of response to our early warnings. The BART system in the San Francisco Bay Area now automatically stops trains when an earthquake it detected. To form a knowledge base for EEW implementation into a public system, we also collect feedback detailing implementation costs and challenges within the Test User organizations, as well as anticipated benefits and savings. Thus, Beta Test Users are contributing to an operational Earthquake Early Warning system that will meet the needs of the public.

Complete Report

The following sections give a detailed description of the different components of CISN ShakeAlert. Parts that were already published in the literature were kept shorter and corresponding references are given. A copy of the UserDisplay Operations Guide can be found in Appendix A.

I. Waveform Processing Library (Caltech with TOT)

At the early stage of the project phase, the Technical Operations Team (TOT) analyzed the codes and delays caused by the waveform processing of each of the three Event Detectors, On-Site, Virtual Seismologist (VS) and ElarmS (Table 1). The TOT found that due to the complexities of the three codes the development of a single waveform processing module as was anticipated was an unrealistic goal with the current support. Instead, the TOT developed and implemented a new Waveform Processing Library (wplib) that is based on codes that were already available. To avoid the problem of slowed down read/write access to the waveforms and overall processing thread by storing waveforms in GCDAs (Generic Continuous Data Areas), wplib uses internal memory buffers and works in a single process multi-threaded environment (Böse, Solanki, *et al.*, 2009). Wplib provides the following:

- Import waveforms from Multicast Network or Earthworm
- Create waveform buffers
- Read/Write waveforms to the buffers
- Calls to plug-in waveform processing modules
- Start / Stop the processing

Table 1. Comparison of waveform processing of the three Event Detectors at the beginning of the project phase.

Algorithm	Code	Memory buffers	Import from	Delays
On-site algorithm	compact	internal	Multicast Network or Earthworm	**< 0.01 seconds**
Virtual Seismologist	compact	internal	Waveform Data Area (WDA)	**3-5 seconds**
ElarmS	4 modules + ElarmS program	shared	Waveform Data Area (WDA)	**3-5 seconds + delays caused by writing/ reading to shared memory buffers**

Wplib was implemented by Caltech and integrated into the VS and ElarmS codes by ETH Zurich and UC Berkeley in early 2010. A revised implementation of the Gain Correction and Baseline Removal filter is currently being evaluated.

From its early design, Onsite has been capable to import data from both the Multicast (MC) and Earthworm (EW) networks at Caltech by running two versions of the code on gneiss. The import of the faster 1 second uncompressed Q330 data packets was implemented as

qmaserv2->(mcast_packet)->q330_mcast_input_to_EEW ['*mcast2ew*']

In 2012, UC Berkeley developed and implemented an alternative import program for Q330 data packets:

qmaserv2->(mcast_packets)->qmcast2ew->(earthworm_tracebuf)->EW_input_to_EEW ['*qmcast2ew*']

qmcast2ew reads the MC packets from the network, transforms them to EW tracebuf2 packets, and inserts them into an EW ring; qmcast2ew is a modification of mcast2ew, which reads the multicast MiniSEED packets that are multicasted by cs2mcast. qmcast2ew allows running a single EEW multithreaded waveform processing program, i.e. does not require running separate versions of the Event Detector codes.

Installation of qmacast2ew on eew2 (Berkeley: Onsite, ElarmS, VS) was accomplished in May 2012, on dacite (Caltech: ElarmS) in September 2012. Caltech is currently installing qmacast2ew on cinnabar (Solaris SPARC machine) to provide faster datastreams also to VS.

II. Algorithm (Development and Implementation)

a. **Event Detector 1: Onsite** (Caltech)

Real-time tests of the τ_c-P_d Onsite algorithm in California over the past five years have shown that some modifications were necessary to increase the robustness of the algorithm (Böse, Hauksson *et al.*, 2009a; Böse, Allen *et al.*, 2012). The main modifications that have been developed are (1) the τ_c-P_d Trigger–Criterion (Böse, Hauksson *et al.*, 2009b), which was implemented in the previous project phase, and (2) the Two-Station-Method, which we added in 2010. In addition, we developed a simple associator and localization procedure for Onsite. Since 2010, Onsite is also providing uncertainty estimates and likelihood parameters. For the current telemetry and processing delays in the CISN first reports from τ_c-P_d Onsite usually become available 5 seconds after event origin or later, depending on the distance between the earthquake and the reporting station, as well as station equipment.

Two-Station-Method:

A 'trigger' at a station, i.e. τ_c and P_d values that have passed the τ_c -P_d-Trigger-Criterion (Böse, Hauksson *et al.*, 2009b), needs to be confirmed by one or more 'picks' of the P-wave at neighbored stations, before being reported to the ShakeAlert system (Böse, Allen *et al.*, 2012). The earthquake location is determined as the point in between the two stations taking the respective travel time delays into account.

Association and uncertainty estimates:

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 $\sigma_{M,\ single}$≈0.55, if estimated at a single station; if estimated from multiple stations (Barba, Böse *et al.*, 2010; Böse, Allen *et al.*, 2012), the errors decrease with $\sigma_{M,\ multiple}(\sigma_{M,\ inter}, \sigma_{M,\ intra})$≈0.4+0.3 exp(-number of stations/3.6). The uncertainties in epicenter location for earthquakes within CISN are 0.14^{O} (≈15 km), and for PGV $\sigma_{log(PGV),\ single}$= 0.326 (Wu, Kanamori *et al.*, 2007).

Likelihood parameter:

To quantify the probability of correct alert, we have started to calculate and report 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 (Böse, Allen *et al.*, 2012).

Research:

We have developed a new algorithm for rapid and robust onsite warning, which is based on Artificial Neural Networks (Böse, Heaton *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. First estimates become available at 0.25 seconds after the P-pick and are regularly updated with progressing time. The algorithm was developed and tested using 2,431 records of 161 crustal earthquakes in California, Japan and Taiwan with 3.1 ≤ M ≤ 7.6 at Δ ≤ 115 km. We found that the prediction errors of this new approach are around 60% smaller compared to the τ_c-P_d Onsite algorithm (Böse, Heaton *et al.*, 2012a). However, we currently do not plan to integrate *PreSEIS Onsite* into CISN ShakeAlert.

Outlook:

The following aspects of the Onsite Event Detector will need further attention:

- The associator and localization procedures need to be improved.
- The P/S-wave discrimination should be improved.
- The current uncertainty and likelihood estimates are preliminary; additional testing and validation are necessary.
- The algorithm tends to overestimate the magnitudes for earthquakes in particular regions, such as in the Imperial Valley (Hauksson *et al.*, in prep). We think that this trend could be caused by the low stress drops of these events (Böse, Hauksson *et al.*, 2009c). Further research is required.

Others:

Caltech has a new research website at www.eew.caltech.edu.

b. Event Detector 2: ElarmS (UC Berkeley)

Earthquake Alarm Systems (ElarmS) is a network based Earthquake Early Warning (EEW) system. It is one of the three algorithms participating in the California ShakeAlert project, a project of the California Integrated Seismic Network (CISN) funded by the USGS, to develop an EEW capability for the state. Over the last 3 years, the ElarmS algorithms have been completely reassessed and re-coded to solve technological and methodological challenges. The new version (ElarmS-2, or E2) is completely rewritten and is now production-grade code. The improved algorithm maximizes the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. ElarmS-2 is designed as modular code and consists of a new waveform processing module that provides data more rapidly to the event monitor. The new event monitor module has a significantly improved associator that allows for more rapid associating with fewer triggers, while also adding several new alert filters that check each event prior to release and minimize false alarms. We outline evolution of the methodology and summarize the performance of both the online real-time system, and the anticipated real-time performance of the latest version. The online performance over the last 5 months shows that on average, ElarmS currently issues an alert 6.79 ± 3.94 sec after the first P-wave detection, and 12.01 ± 5.92 sec after the origin time for all events across California. This time is reduced in regions with dense station instrumentation. Standard deviations of magnitude, origin time and median location errors are 0.32 magnitude units, 2.77 sec and 2.64 km, respectively. The latest version (E2.3.1), which we have tested by running the algorithm of the past 5 months of data, successfully detects 92% of earthquakes (M>3.5) across California without issuing any false alarms. This version is now the operational ElarmS contribution to ShakeAlert.

1. Introduction

Earthquake Early Warning (EEW) is the concept of recognizing earthquakes in progress and sending immediate alerts to surrounding population centers, ideally several seconds before damaging ground shaking begins. Network-based early warning algorithms use data from several seismic stations near the source to rapidly estimate event magnitude, location and origin time, typically from P-wave arrivals.

The California Integrated Seismic Network (CISN) embarked on a multiyear EEW project in California in 2006. The project, christened ShakeAlert, is implementing, testing, and integrating three distinct EEW systems into a single, end-to-end production-grade system to provide warnings to test users from industrial, governmental, and corporate groups, with a view to eventually providing warnings to the general public (Böse et al, in press). The system uses seismic data from about 400 seismic stations from the seismic networks across the state that contributes to the CISN (Fig. 1).

ShakeAlert is based on three research EEW systems: ElarmS, developed and maintained at the University of California Berkeley (this manuscript); OnSite, developed and maintained at the California Institute of Technology (Böse et al, 2009); and Virtual Seismologist, developed and maintained at ETH Zurich (Cua et al, 2009). Each system has its own method of detecting triggers, associating them, estimating magnitude, and filtering out false alarms. By combining output from all three systems, ShakeAlert benefits from the strengths of each algorithm and minimizes the weaknesses. The ShakeAlert DecisionModule receives alerts from each algorithm, identifies when algorithms are describing the same event, and combines algorithm output into a single summary for each earthquake. The combined event information is then sent as a single sequence of updated alert messages across the internet. Test users who have signed up for the project can receive and use the alerts in a variety of ways. The most common use at this stage is to receive the alerts on computer desktops using the UserDisplay (UD) software provided by the project. When the UD receives an alert message for an event that meets the user's configured criteria, a popup message appears on the screen warning of impending shaking. The screen displays the estimated shaking intensity at the user's location and a countdown to the onset of shaking. An audible message also delivers this information. A summary of the ShakeAlert system is provided in Böse et al, (in press). One of the test users, the San Francisco Bay Area Rapid Transit (BART) train system has now implemented an automated response to earthquake alert information. Once triggered by ground motion, the BART automated train control system decelerates trains. This is the first automated earthquake response of a transit system in the US.

ElarmS is a network based EEW system. The original ElarmS code, most recently described in *Brown, et al., (*2011), has been running in realtime for the entire state of California (*Allen, et al*., 2009) using data from the CISN seismic networks since 2007. Theoretical foundations were first developed for southern California by Allen and Kanamori, 2003, and for northern California (Wurman et al., 2007). The system has also been tested offline with datasets of large earthquakes in Japan (*Brown, et al.,* 2009) and in Italy (Olivieri et al, 2008). Since 2009 events from the greater San Francisco Bay Area detected by ElarmS have been forwarded to the ShakeAlert DecisionModule. Finally, in 2010 and 2011 the research prototype system underwent a complete rewrite and rebuild. Existing processing elements were rewritten as a production code, and new algorithms have been developed to improve performance. The second generation ElarmS system replaced the first generation code as the authoritative version reporting to the ShakeAlert DecisionModule in early 2012. The new version detects and sends alert information for earthquakes throughout the state. In this manuscript we describe the significant methodology and code development that went into ElarmS version 2 (ElarmS-2 or E2) that is now operating in California, and outline E2 performance.

2. Elarms-2 Methodology

The second generation ElarmS code is designed specifically to maximize the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. E2 is written in C++ rather than FORTRAN. This improves processing speed and takes advantage of the power of the networking environment. In addition, the speed of data transmission has recently been increased. Many of the data loggers at the seismic stations of the CISN's networks have been replaced with funding through the recent American Recovery and Reinvestment Act (ARRA). These stations now send data in one-second packets to the waveform processing centers rather that in packets that could extend over several seconds. Since April 2012 (for the BK network), and August 2012 (for the CI network), these data are now processed directly, shaving up to 6 seconds off of alert times.

E2 consists of a new waveform processing module and a new event monitor module, plus several new alert filters that check each event just prior to forwarding alerts to the DecisionModule. We designed E2 as a modular code. This means it now is easy to upgrade individual elements of the algorithm (location, magnitude, etc.) at any time, without disrupting the processing stream (Fig. 2).

Moreover E2 has a replay capability, which means we are able to compare results from new algorithms or components with past performance and thereby optimize configuration changes. The replay capability is key to improve the system and we have updated E2 with several new versions (Table 1). Therefore, the overall performance of the real-time system over that last ~5 months is the result of several versions. The latest version E2.3.1 has been running since October, 2, 2012. Table 1 briefly shows the changes to each ElarmS module with each new version and are described in more detail below.

Waveform Processing (Elarms)

The new waveform processing (WP) module is operating at the three CISN network hubs, UC Berkeley, Caltech and the USGS Menlo Park. At each of these locations, WP processes individual data streams as they arrive from the seismic stations. The WP has been redesigned so that it can read and process smaller packets of waveform data and it can now send the resulting parameters more promptly to the event monitor, which runs at UC Berkeley (Fig 2). WP processes waveforms in one-second segments, starting on a second boundary. To allow monitoring of data quality for all stations and channels, the maximum values of displacement, velocity, and acceleration in each second are sent to E2. These ground motion parameters are bundled together into packets containing up to 50 channels. Event detection is based on a set of trigger parameters. When the trigger threshold is exceeded, the station information and trigger time are packaged into a trigger packet containing network, station, channel, location code, station latitude and longitude, and trigger time. This packet is immediately forwarded to Event Monitor. During the four seconds following the trigger time parameters providing information on the frequency content of the P-wave (τ_p^{max}), and the amplitude information (P_d and P_v) are computed every tenth of a second and also forwarded to the Event Monitor. More information on the determination of these parameters can be found in Brown et al. (2011).

The communication from the waveform processing centers to Event Monitor at Berkeley is handled by an Apache ActiveMQ server running at UC Berkeley. The waveform processing clients send compressed binary messages via the Java Message Service (JMS) API to the ActiveMQ message broker, which provides a publish-subscribe message environment for E2 and any other message-receiving clients. All waveform processing programs and E2 send heartbeat messages every five seconds to the message broker at UC Berkeley. These messages are logged in a file and received by a monitoring program that provides state-of-health information to clients such as the CISN ShakeAlert UserDisplay.

3.2. Event Monitor (Elarms)

The second component of E2 is the Event Monitor (EM, Fig. 2). Its main tasks are to associate triggers in order to identify earthquakes in progress, characterize the source, and to filter out false events. The EM consists of efficient C++ code, a revised trigger associator, and a new alert filter which verifies each event before sending an alert to the DecisionModule for release to users. Trigger and event pools are also two improvements. The EM can handle multiple events in the event pool at the same time. There is only one EM, which is running at UC Berkeley. It operates on data from the entire state which it receives as triggers and ground motion information from WP modules at each of the three data centers.

Before any association, the quality of each trigger is evaluated. Signal to Noise ratio (SNR) must be greater than 0.5. Two criteria must be satisfied: -5.5<log(P_d)<3.5 and -0.9 <τ_p^{max} < 1. The EM has a capability to associate just two triggers to declare an event, the trigger criteria are more strict in this case, 0.5 < log(P_d) <3 and 0.3 < log(τ_p^{max}) < 1. If a trigger from any channel fails to satisfy the criteria, it is sent back to the trigger pool. This process continues until the updated P_d and τ_p^{max} pass the quality checks.

The EM's associator then attempts to link qualified triggers with existing events from events pool. To be associated, the trigger time must fall within the time-space window shown in Fig 3. New triggers are permitted to contribute an event's location and origin time if they are within 1500 km of the epicenter. This improvement prevents E2 from creating separate (false) events using triggers from stations far from the epicenter, and allows it to better characterize events with long fault ruptures. If a qualified trigger cannot be associated with any of the existing events, the EM attempts to create a new event by associating it with other triggers from the trigger pool. A new event can only be created if the trigger satisfies the equation

$$|t_{new} - t_n| = \Delta d / v_p + 3 \quad (1)$$

where $|t_{new} - t_n|$ is the onset time difference between new trigger and existing triggers in the event. Δd is distance between stations and v_p is P-wave velocity. This criterion prevents the association of triggers that are inconsistent with a P-wave travelling between the station of the new trigger and other stations in the event.

The new E2 associator has additional levels of event creation. If a new trigger cannot be associated with an existing event, it is added to trigger pool, a hopper of unassociated triggers. When it is otherwise unoccupied, the system scans through the hopper, looking for any set of 3 or more triggers which can be associated together into an event based on space/time box shown in Fig 3 and Eq. 1. This multi-trigger event step is the most important as it generates most events in the regions of California where there is denser station coverage which is also where most of the population is located. In these regions, P-wave triggers occur at multiple stations in rapid succession. If the system cannot generate a multi-trigger event, it scans through the hopper again, looking for any two triggers which are less than 100 km apart and are separated by fewer than 16.5 seconds in time. A trigger which is not associated with an existing event, or used to generate a new event, remains in the trigger pool. Any individual trigger may never be associated. In that case it will continually be returned to the trigger pool until it expires and is deleted after 30 seconds.

If an event is created based on two triggers, the locator assigns the epicenter to be between them, but 1/3 closer to station that triggered first. If an event is made up of triggers from three or more stations, the locator estimates its position and origin time using a grid search algorithm. The algorithm assigns the center of a 400 by 400 km grid, with grid points every 5 km, to the middle of the stations. Each station is then assumed to be located on its nearest grid point, and an approximate epicenter is estimated. To obtain a higher resolution location, the search is repeated on a 40 by 40 km grid with a 2 km grid point spacing, based on the approximate epicenter from the first cycle. This accurate location is important, as accurate magnitude estimation relies on a good distance correction factor.

Rapid magnitude estimation is at the heart of ElarmS. This is accomplished using empirically derived scaling relationships between magnitude and the frequency (τ_p^{max}) and/or amplitude (P_d and P_v) content of the P-waves. An empirical scaling relationship between magnitude and τ_p^{max} was first determined from a calibration dataset of southern California earthquakes (Figure 4, *Allen and Kanamori*, 2003) and then updated by *Tsang, et al*., (2007). A second set of scaling relationships, between P-wave amplitude (P_d and P_v) and magnitude, was empirically determined, for northern California (*Wurman, et al*., 2007). E2 uses these same empirical relationships, as did ElarmS version 1. Until late August 2012, ElarmS used both the P_d and τ_p^{max} relationships for northern California and only the P_d relationship for southern California. Since then, we are only using the P_d-magnitude relationship in both parts of the state, as it is provides a more accurate estimate of magnitude with less variation in the absolute error. We only allow triggered stations within 100km of the epicenter to contribute to magnitude calculations for most of the state. However, this was a problem for the offshore events, particularily around the Mendocino Triple Junction region, where epicenters are often located more than 100 km away from coastline. Therefore, we released the 100km restriction for Mendocino Triple Junction region (Figure 1).

The original event monitor occasionally struggled with "split events", in which the system produces two separate, simultaneous events for a single real earthquake. This occurs when a small subset of triggers fall outside the initial association criteria, perhaps due to a poor initial location. We defined a "blackout window" around existing events. When the associator has a set of triggers prepared for generation of a new event, it checks all existing events. If any existing event epicenter is within 15 seconds and 90 kilometers of the proposed new event epicenter, the associator cancels the new event. Any triggers which were flagged for association with the new event are released back into the trigger pool. In offline reruns of past data, this simple procedure has prevented the creation of split events in most cases.

In the new E2, the EM has several filters that have been added at the end of processing, just before an alert message is sent to the DecisionModule for release. The purpose of these filters is to minimize the publication of false events. Firstly, the event magnitude must be greater than 2, and the estimated epicenter should not be on the edge of grid search area.

Secondly, an event must have triggers contributed from four stations. Although an event can be generated based on triggers from just two stations, we find that the false alarm rate is significantly reduced if we require 4 stations to be associated before an alert is issued and therefore we only issue alerts to the DecisionModule when four stations trigger at this time. We have also developed an Artificial Neural Network based approach to improve performance when only 2 or 3 triggers are available (Brown and Allen, in review). This is currently under consideration for inclusion in a future version of ElarmS. It is also requested that they be triggers at 4 stations rather than from four channels. This may seem like a minor technicality, but the seismic network in California has many stations are installed with more than one sensor, such as co-located accelerometers and broadband seismometers. The old requirement of triggers from four channels could potentially be satisfied by just two stations, which are not enough to accurately determine the epicenter.

Third, the percentage of triggered seismic stations must be greater than 40% of the number of stations within the range of the P-wave at a given point in time. This is estimated by first determining the most distant station from the epicenter that has triggered, counting the number of triggered stations and total number of stations within a circle of that radius around the epicenter, and then checking that the proportion is greater than 40%.

Fourth, we have developed a procedure to discriminate between local and teleseismic events based on τ_p^{max} and P_d values. Before implementing this filter, large magnitude teleseisms produced several false events. The initial displacements (P_d) of large local earthquakes generally have higher frequency content (τ_p^{max}), while the teleseismic events have still higher frequency with a much smaller displacement. A similar filter has been used in the Onsite algorithm (Böse et al. 2009). For ElarmS, we have observed a similar pattern based on the events' average τ_p^{max} and P_d (Figure 5). In this figure, red and blue triangles show the average τ_p^{max}, and P_d values of the calibration dataset of local events from northern and southern California, respectively. Teleseismic events are represented as black circles and local events plotted as green squares. We applied a linear boundary (black line) as a teleseismic filter to discriminate between local and teleseismic events. The discriminant is described by the equation 2

$$F = K + L * I^T \qquad \begin{cases} F < 0 & Teleseismic \\ else & Local \quad Earthqauke \end{cases} \tag{2}$$

where $K = 32.75$, $L = [-24.75 \quad 8.78]$ and $I = \log\left[\bar{\tau}_p^{\max} \quad \bar{P}_d\right]$

Filter correctly separates local events from teleseisms. Only three teleseisms are not excluded by the filter.

The alert filter continuously applies these criteria to events in the event pool. Once an event passes the criteria, it is released as an alert to the DecisionModule. After the initial alert, event information is updated as event parameters change due to additional data becoming available from stations that have already triggered or based on data from newly triggered stations. These updates are forwarded to the DecisionModule.

Defining the optimal alert criteria is a big challenge in earthquake early warning systems. Criteria which are too strict, such as requiring too many or a large percentage of stations to trigger, may not be met in a timely fashion or by a moderate size event. An alert message is then delayed or not sent at all. This would be considered a missed event. Criteria which are not strict enough may result in an alert message being sent when there is no real event, i.e. a false event. The replay capability has allowed us to explore the application of multiple filters with multiple thresholds. We find the performance of the current version to now be optimal and its performance is described in the next section.

4. Performance (Elarms)

Performance results presented here cover earthquakes for the state of California in the interval from April 12, 2012 to August 31, 2012. All the statistics are based on the first alert issued by E2. We choose the first alert as it is clearly the most important for early warning. We should also note that generally the errors for magnitude, location and origin time decrease with time after the first alert, i.e. the updates are more accurate than the first alerts. Performance is given in terms of "detected", "false" and "missed" events (Table 2) by comparison with California earthquakes in the merged catalog of the Advanced National Seismic System (ANSS, http://www.ncedc.org/anss/). An earthquake is considered to be "detected" if its E2 location and origin time match that of an earthquake in the ANSS catalog to within 100 km distance and within ±30 seconds of the origin time. A "false" alert meets the alert criteria for its region, but does not correspond to an earthquake in the ANSS catalog within the limits given above. A "missed" event is an earthquake with M≥3.5 that is listed in the ANSS catalog, but for which no E2 alert message was issued. ElarmS may not have detected the event, or it may have detected the event but not satisfied the criteria required to issue an alert. This is not a zero-sum process, as some E2 detections with $M_{E2} \geq 3.5$ may correspond to events in the ANSS catalog that have $M_{ANSS} \leq 3.5$ and thus legitimately be considered "detected".

We present two sets of performance statistics. The first is for "Online E2". This refers to the performance of the online real-time E2 system from April 12, 2012 to August 31, 2012. The version of E2 running during this interval was changing from E2.0 to E2.3, however, it provided a measure of actual real-time performance. The second set of performance statistics is for the "Version E2.3.1". This is the version that is now running in real-time but was not for the period of earthquake being assessed (April 12 to August 31, 2012). These performance statistics are therefore determined by relaying the events from this interval through the E2.3.1 version of the code.

Figure 6a shows Online E2 performance for all $M_{ANSS} \geq 3.5$ including detected, false, and missed alerts. Figure 6b shows the same results but for Version E2.3.1. In the two maps, epicenters of earthquakes with $M_{ANSS} \geq 3.5$ from the ANSS catalog are shown as blue stars. Successfully detected E2 epicenters are white stars; where their locations do not exactly coincide, the two stars are connected by a line. Green circles denote missed events and red squares are false events. In the entire state, Online E2 detected 48 of the 53 ANSS earthquakes, while the Version E2.3.1 found 49 events (Table 2). We also show the performance in the most populated, and the most instrumented regions of the state, the Bay Area and Los Angeles regions (Fig 1). In the Bay Area region, the Version E2.3.1 detected one more event than the Online E2, while both versions exhibit the same detection capabilities in Los Angeles region (Table 2). Although both versions of E2 successfully detect most earthquakes outside the network, including offshore of Cape Mendocino and south of the California/Mexico border, we note that estimates for epicenter locations have larger errors than is true for detections within the network.

Online E2 sent 6 alert messages for false events (Table 2). One of these is in the Los Angeles box; there are no false alerts in the Bay Area region. Version E2.3.1 sends no false alerts. Several of false events emitted by the old version of E2 were due to teleseismic events, and they have been excluded by the teleseismic filter implemented in the new E2.3.1.

In the entire state, Online E2 missed 5 events with M_{ANSS} ≥ 3.5 (Fig. 6). Although one of the missed events is in northern Bay Area (the Geysers region), most are missed due to poor accuracy of P-wave trigger time in regions where station density is low. One event near Point Arena, for example, was considered missed because the epicentral error is more than 100 km. The associator works well where there is dense station coverage so we miss no events in the Bay Area and Los Angeles regions, where inter-station spacing is generally less than 20 km, with Version E2.3.1. Performance can, however, be compromised by seismicity swarms or aftershock sequences. For example, E2.3.1 missed earthquakes in the Brawley swarm of August 26-29, 2012. There were 21 events with M_{ANSS} ≥ 3.5 and E2.3.1 reported 18 of them. The three missed earthquakes occurred within 2 minutes of a larger event, a problem also noted in the Japanese system during the aftershocks of the Great Tohoku-oki earthquakes. We are developing improvements to the associator scheme specifically to take such cases into account. Overall, the E2.3.1 performs better than the older versions, in that it detects one additional event in the state, issues no false events and misses fewer earthquakes.

In the latest version of E2 (Version E2.3.1), all performance statistics are improved over past versions, due to recently implemented improvements in the Event Monitor. Details of the performance, in terms of errors in estimates of the earthquake parameters magnitude, origin time and location, are shown in Figure 7 for Online E2 and Versions E2.3.1. The light and dark gray histograms show errors for all events with M_{ANSS} ≥ 3.0 and M_{ANSS} ≥ 3.5, respectively. For the Online E2, median magnitude error for events with M_{ANSS} ≥ 3.0 is -0.15±0.41 magnitude units (Table 3). For the larger events (M_{ANSS} ≥ 3.5), mean magnitude error -0.14±0.46. The negative mean error means that on average, ElarmS underestimates the magnitude by 0.14 magnitude units. The magnitude errors of Version E2.3.1 has dropped to -0.1±0.35 and -0.04±0.32 for the datasets including the smaller and larger events respectively.

Origin time and location errors are both strongly influenced by the location algorithm. Origin time errors are distributed about zero for both versions of E2, and for both events sets. Standard deviations of the origin time errors are 4-5 sec for Online E2 and drop to 2-3 s for the Version E2.3.1. The median error in the epicentral location (i.e. distance between true and estimated epicenters) of Online E2 is 2.93 km. Although median error of location decreased to 2.64 km with version E2.3.1, main success achieved by decreasing number of events with higher location error (Figure 7).

4.1 System Latency (Elarms)

System latency is the time between the origin of an earthquake and ElarmS publication of the first alert for the event. The total delay is due to the time it takes for P-wave energy to travel to the first few seismic stations, the delay in packetizing the data, telemetering the data to one of the three WP processing hubs, WP processing, sending the parameter data to the EM at UC Berkeley, and EM processing up to the point that the alert criteria is satisfies and an alert is published. At each stage that data is passed from one piece of hardware or processing software to another a delay is introduced.

Here we evaluate four measures of latency. First, we look at the “telemetry latency” which is the delay in sending waveform data packets from a seismic station to the network WP processing hub. Second, we consider the “WP processing delay” which is the delay in processing the waveforms by the WP module to generate parameters. Third, we evaluate “P-wave latency” which is the time between when a P-wave arrives at a seismic site and when that trigger is detected by one of the WP modules. Finally, “alert latency” is the time between the origin time of an earthquake and the first published alert from ElarmS.

Telemetry latency is the actual transit time of data from the station to its network processing hub where the WP module is applied to the data (UC Berkeley for BK, USGS Menlo Park for NC and some NP, Caltech for CI, AZ and some NP). It is independent of data packet size, since it is calculated as the time difference between a data packet's arrival at a waveform processing hub and the time of the last sample in the packet. To evaluate telemetry delay, we collected all packets from all channels/stations and networks for the hour from 16:00:00 - 17:00:00 on May 30, 2012. Figure 8 shows the resulting telemetry latencies for each seismic network. The y-axis is normalized so that each network is represented by the same area in the histogram allowing comparison of the delays for different networks. As the networks are different sizes, the histogram does not correctly represent the average telemetry delay seen by E2. On average, pure telemetry latency is 1.14 sec (Table 4). BK has the lowest latency with a median of 0.36 sec. The rest of the northern California network (NC) has a median of 1.19 sec. The southern California networks (CI and AZ) are ~1 sec slower transmission than the BK stations on average.

We also investigated both the WP queue time, that is the interval a waveform packet waits at a processing center before being processed; and the waveform processing time, that is the time needed for WP to process a waveform packet. These two times are determined from the difference between time a packet is sent to the EM module and the time the packet is received at the waveform processing hub from the station. Both these times have median values that are less than 0.001 s. Thus, they are negligible compared to other delays in the E2 system.

Next we consider the P-wave latency, which is the time between when a P-wave arrives at a seismic site and when that trigger is detected by one of the WP modules. This measure combines a series of delays. Firstly, it includes the data packetization by data loggers at the stations. A data logger will not send its data to the data center where waveform processing takes place until the data packet is full. In the past, data loggers at the BK, CI and AZ network stations (which provide the bulk of the data for the EEW system) forwarded data in packets holding 4-6 s of data, delaying processing of the earliest data in the packet by that amount. Thanks to recent hardware upgrades supported by funding from the American Recovery and Reinvestment Act (ARRA), most of these data loggers have been replaced with more modern units which send data in 1 s packets. Finally, it included the telemetry latencies and the WP processing latencies described above.

Figure 9 shows P-wave latencies for each seismic network. As with Figure 8, the y-axis is normalized so that each network is represented by the same area in the histogram allowing comparison of the delays for different networks. Median latencies for each network are shown in Table 5. For the two months since the CI network update, the median latency for all data, thus all networks is 2.07 ± 3.35 s. There is a significant tail to the distribution that extends out to several hundred seconds for a very small percentage of the data. The tail indicates that data from some stations are drastically delayed, due to poor telemetry, temporary telemetry failure or some other station disruption.

With 1.97 ± 2.29 sec median data latency, BK has dropped considerably, from 3.83 sec before the ARRA upgrade of data loggers at BK stations and the implementation of processing code to take advantage of the upgrades. The equipment operated by the CI network is very similar to that at BK, and the median latency is 1.92 ± 1.79 sec. Latencies for the NC network follow a more Gaussian-shaped distribution with a median of 7.09 ± 3.30 sec. The median latency for NP stations is 2.29 ± 3.62 sec. There are a significant number of stations with large latencies resulting in a larger standard deviation. AZ has the highest median latency, 8.84 sec. This is due to an extra telemetry step as the data is forwarded from the Scripps Institute of Oceanography to the regional processing center at Caltech.

Finally, we investigated the alert times for events that are detected by ElarmS to find out how many seconds the entire system requires, on average, to publish an alert for an event. This alert latency is determined for the Online E2 dataset and represents the entire delay including the time for P-wave to reach stations, for data packets to be filled, for the telemetry to the hubs, for WP processing, telemetry of parameters to EM at UC Berkeley, and for EM processing. It is the difference between the time an alert is first published and the origin time for the earthquake in the ANSS catalog. Figure 10a shows alert latencies for the 543 events that Online E2 detected between April 12, 2012 and August 31, 2012. On average, ElarmS needs 12.01 ± 5.92 sec to submit an alert to users. The tail of the distribution in the histogram is mainly due to events that occurred either offshore of Cape Mendocino or in poorly instrumented areas such as the north and northeastern regions of California. Alerts for offshore events and those that occur south of the California/Mexico border are typically more than 20 sec after the origin time. For events in the San Francisco Bay Area and Los Angeles the alerts are generated 11.22 ± 4.10 and 10.25 ± 3.98 sec after the origin time. For other onshore events in California the alert time is 12.27 ± 5.75 sec (Table 6).

We further separate out the time for the P-wave to reach the first seismic station and the time from the first P-wave trigger to the alert. We take the first P-wave trigger time and subtract the ANSS origin time to determine how long it takes for the first information about an earthquake to reach a network station. The distribution is shown in Figure 10b, and has a median of 5.97 ± 4.60 sec. We see some events that more than 10 seconds is needed for the P-wave to arrive at the first station. In more densely instrumented regions, such as the San Francisco Bay and Los Angeles areas, this time is about 3-4 seconds.

We also separate the E2 total processing latency, which is alert time minus the time of the first P-wave trigger onset, is determined. A median time of 6.79 ± 3.94 sec elapses between the first P-wave detection and when the alert is first published (Figure 10c, Table 6). Currently E2 processing latency is smallest in Los Angeles Area with a median of 5.56 ±3.10 sec. Despite the dense station coverage, the latency is larger that average in the Bay Area (7.81 ± 4.03 sec). This is due to the large P-wave latencies of the NC network. These latencies can likely be reduced by moving the EM processing to different (and possibly multiple) locations to better balance the performance of the various networks. For example running the EM at USGS Menlo Park rather than UC Berkeley will remove one additional telemetry hop for the slower NC data. We can only determine these statistics for the Online E2 dataset as the replay capability does not allow us to assess the real-time speed of the system. However, several of the improvements implemented in Version E2.3.1 are expected to further reduce the delay in issuing an alert.

5. Conclusions (Elarms)

We are now operating a completely new version of the ElarmS algorithms on the CISN real-time systems in California. ElarmS-2 (E2) was rewritten and rebuilt from what was a research prototype system to production-quality code for faster operation and easier maintenance and modification. At the same time, improvements to the algorithms were developed and implemented. New code maximizes the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. ElarmS-2 is designed as modular code and consists of a new waveform processing module that provides data more rapidly to the event monitor. The new event monitor module has a significantly improved associator that allows for more rapid association with fewer triggers, while also adding several new alert filters that check each event prior to release and minimize false alarms.

E2 detects and sends alert information for earthquakes throughout the state faster than earlier versions. The online version of E2 detected 91% of events in California with $M_{ANSS} > 3.5$, missing 5 and issuing 6 false alerts. The average alert time was 6.79 ± 3.94 sec after the first P-wave trigger, and 12.01 ± 5.92 sec after the origin time. The latest version of E2 (version E2.3.1), which is now running at the real-time system, but was tested with our replay capability, detects 92% of events over the same period with 4 missed events and no false alerts. None of the 4 missed events are in the San Francisco Bay Area or Los Angeles areas, but are instead in the more remote parts of California where station density is low. Standard deviations of magnitude, origin time and median location errors are 0.32 magnitude units, 2.77 sec and 2.64 km, respectively.

The ElarmS algorithm and system performance continues to be assessed on a weekly basis and further improvements are planned. Both the current "point source" approach to characterizing the earthquake source will continue to be improved and we also plan to integrate a "finite source" capability.

References (Elarms)

Allen R. M. (2004). Rapid magnitude determination for earthquake early warning. In: Manfredi G, editor. The Many Facets of Seismic Risk. Naples, Italy: University of Degli Studi di Napoli ''Federico II'';. p. 15–24.

Allen R. M. (2006). Probabilistic warning times for earthquake ground shaking in the San Francisco Bay Area, Seismol. Res Lett;77(3):371–6.

Allen R. M. (2007). The ElarmS earthquake early warning methodology and application across California. In: Gasparini P, editor. Earthquake Early Warning. Milan, Italy: Springer Ital.,;. p. 21–44.

Allen R. M., Kanamori H. (2003)., The potential for earthquake early warning in southern California, Science;300:786–9.

Allen R. M., Brown H., Hellweg M., Khainovski O., Lombard P., Neuhauser D. (2009). Realtime Earthquake detection and hazard assessment by ElarmS across California, Geophys Res Lett ;36:L00B08.

Böse, M., Allen, R., Brown, H., Cua, G., Fischer, M., Hauksson, E., Heaton, T., Hellweg, M., Liukis, M., Neuhauser, D., Maechling, P. & CISN EEW Group, 2012. CISN ShakeAlert – An earthquake early warning demonstration system for California, in: 'Early Warning for Geological Disasters - Scientific concepts and current practice', eds. Wenzel, F. & Zschau, J., Springer (in press)

Böse, M., Hauksson E., Solanki K., Kanamori H., Wu Y.-M., and Heaton T.H., (2009). A New Trigger Criterion for Improved Real-time Performance of On-site Earthquake Early Warning in Southern California, Bull. Seism. Soc. Am., 99, 2A, pp. 897-905, doi: 10.1785/0120080034.

Brown H.M., Allen R.M., Hellweg M., Khainovski O., Neuhauser D., Souf A., (2011). Development of the ElarmS methodology for earthquake early warning: Realtime application in California and offline testing in Japan, Soil Dyn. Earthquake Eng. 31 188-200, doi:10.1016/j.soildyn.2010.03.008

Brown H.M., Allen R.M., Grasso V.F., (2009). Testing ElarmS in Japan,. Seismol Res Lett;80(5):727–39.

Cua G., Fischer M., Heaton T., Wiemer S. (2009). Real-time performance of the Virtual Seismologist earthquake early warning algorithm in southern California. Seismol Res Lett ;80(5):740–7.

Olivieri, M., Allen R.M. and Wurman G., (2008). The potential for Earthquake Early Warning in Italy using ElarmS, Bull. seism. Soc. Am. 98, p495-503, doi: 10.1785/0120070054

Olson E.L., and Allen RM. (2005). The deterministic nature of earthquake rupture, Nature;438(7065):212–5.

Tsang L., Allen R. M., Wurman G., (2007). Magnitude scaling relations from P-waves in southern California, Geophys Res Lett;34:L19304.

Wald D.J., Quitoriano V., Heaton T.H., Kanamori H., Scrivner C.W., Worden B.C., (1999). TriNet ShakeMaps: rapid generation of instrumental ground motion and intensity maps for earthquakes in Southern California, Earthquake Spectra;15(3):537–56.

Wurman G., Allen R.M., Lombard P., (2007). Toward earthquake early warning in northern California,. J Geophys Res;112:B08311.

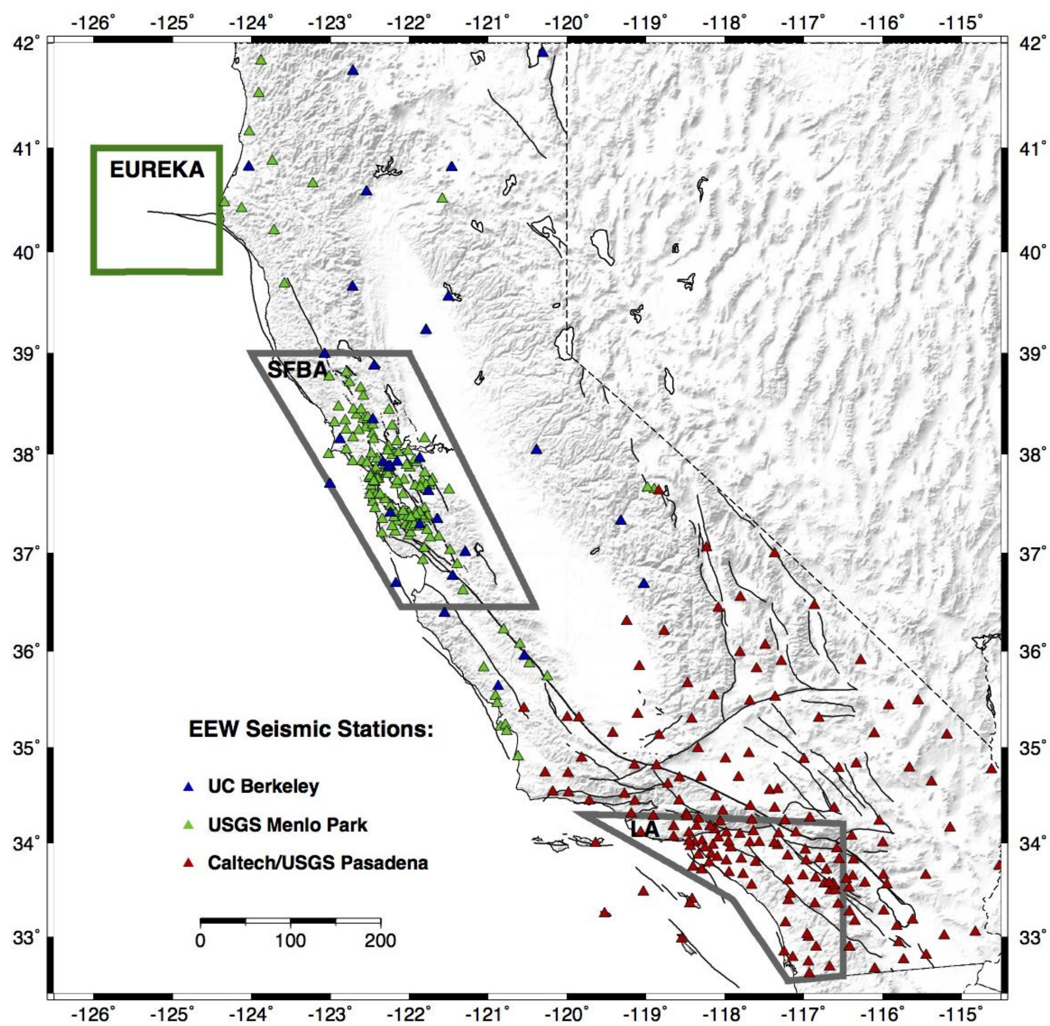

Figure 1. Map of CISN seismic stations that contribute to E2 processing. The two gray boxes indicate the San Francisco Bay Area and Los Angeles regions used in evaluating the performance of E2. These alert regions include areas with high densities of both population and seismic stations. The green box indicates the region where we release the requirement that a station must be within 100km of an epicenter in order to contribute to the magnitude estimate. This is necessary for the offshore earthquakes in the Mendocino Triple Junction and Gorda plate regions.

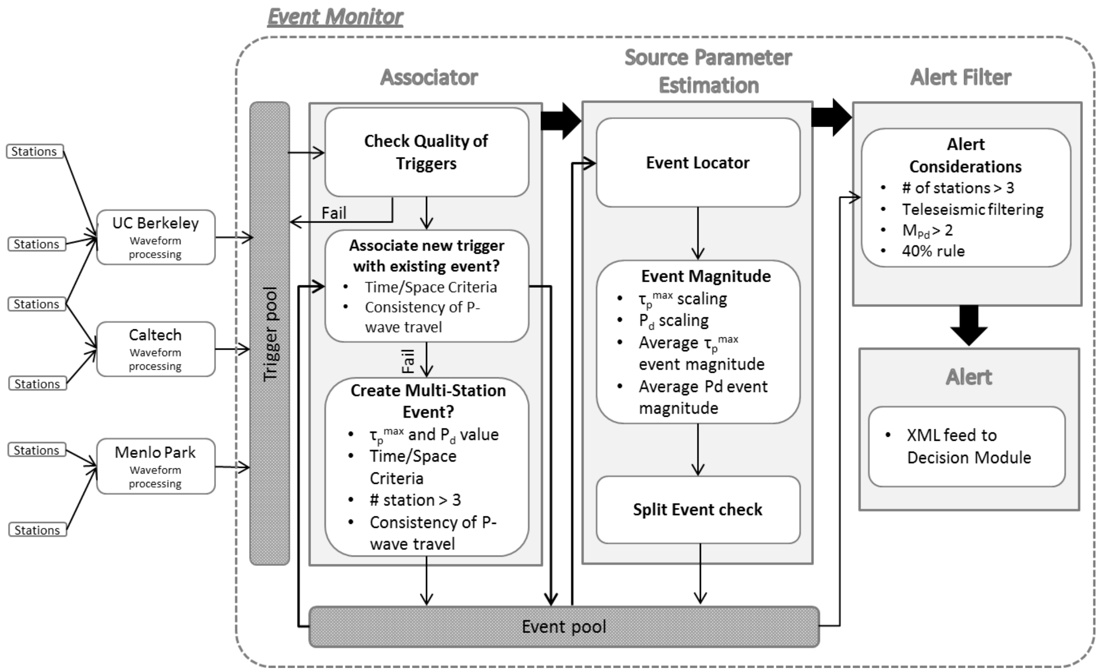

Figure 2. Processing flow for E2. Station waveform feeds are processed at the three CISN network hubs, UC Berkeley, Caltech and Menlo Park. P-wave triggers, amplitudes, frequencies and other parameters are generated at the three processing centers and forwarded to a single, state-wide trigger pool and event monitor running at UC Berkeley. After a quality check of new triggers, association is first attempted with existing events based on the trigger time falling within a defined space-time window. If new triggers cannot be associated with existing events, the associator then attempts to create a new event based on the space-time proximity of unassociated triggers. If three or more triggers are close in space and time, a new event is created. New or modified events are then located using the arrival times and a simple grid search algorithm (see text), and magnitude is estimated. A split event filter checks that the triggers from a single event have not been split into two events i.e. two or more events within a small space-time window, in which case one is deleted and the triggers are returned to the trigger pool. Finally, an alert filter continuously checks the event pool to identify any events that pass another set of criteria and can be published to the DecisionModule. Currently, event alerts are only published to test users.

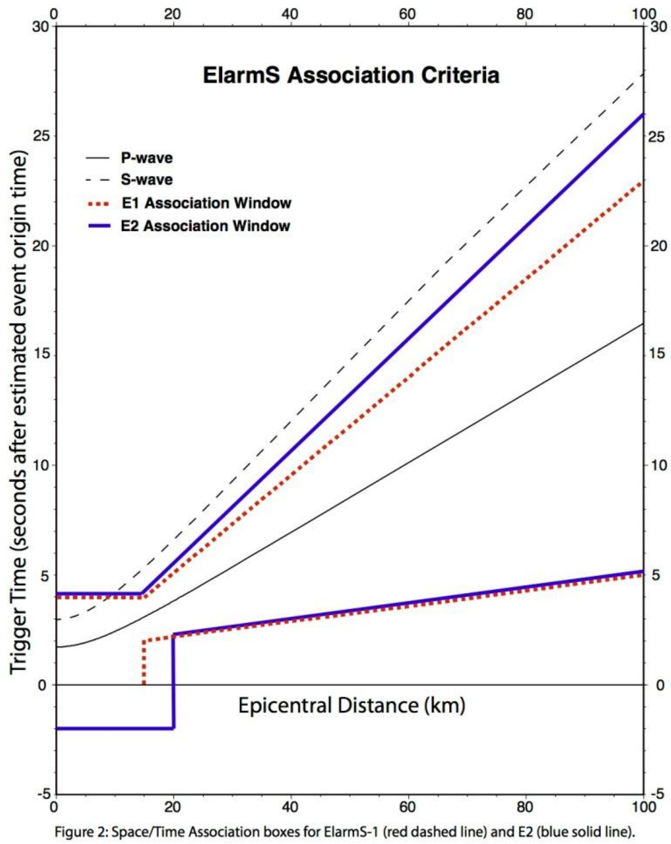

Figure 3. Time/Space association criteria for ElarmS. If a new trigger falls within this time and space window relative to an existing event, then it is associated with the event and its parameter information contributes to the event location, origin time and magnitude. Blue lines represent new E2 association criteria, while red lines show the ElarmS-1 association time/space box (Brown et al 2011). P- and S-wave velocities are shown as solid and dashed gray lines.

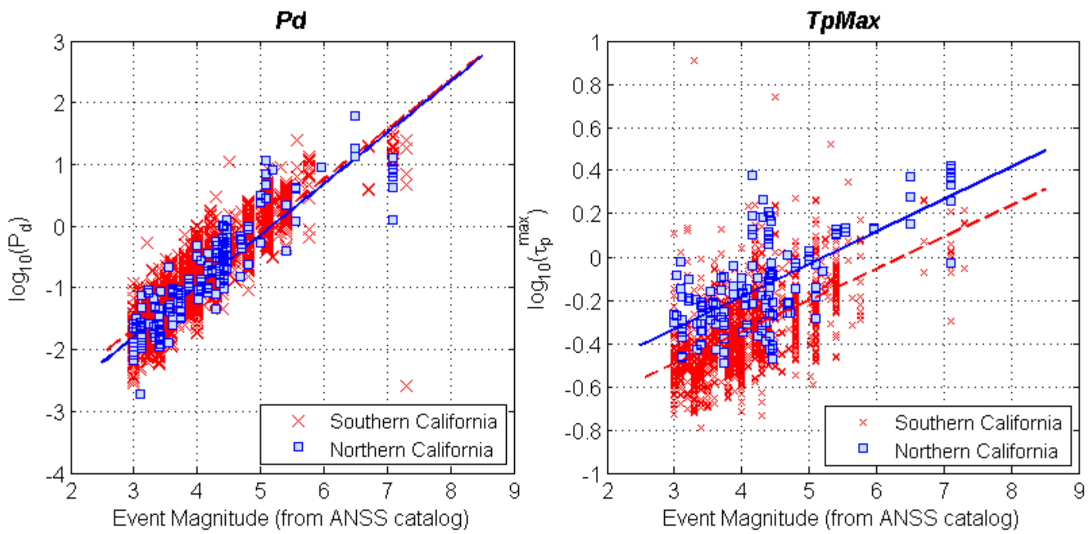

Figure 4. Scaling relationships for P-wave parameters. Red crosses and blue squares represent τ_p^{max} or P_d values from the calibration datasets in southern and northern California, respectively (modified from Brown et al, 2011). Diagonal red and blue lines are the resulting magnitude scaling relations used by ElarmS to estimate event magnitudes.

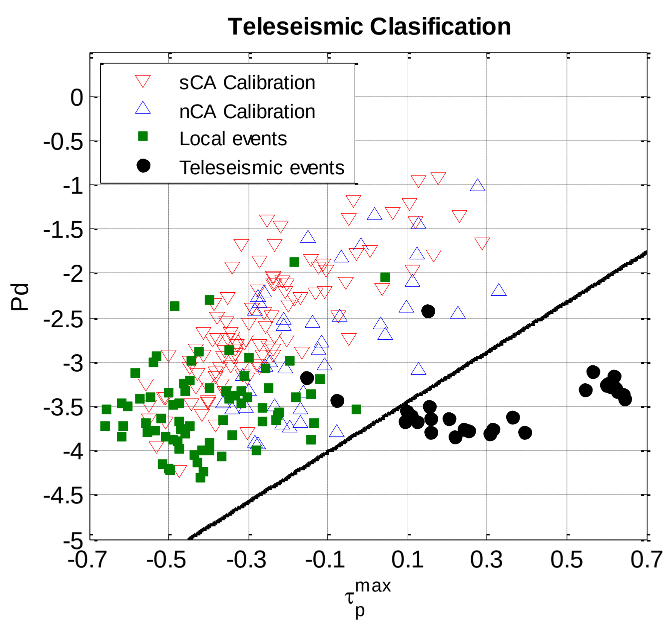

Figure 5. Linear teleseismic filter to discriminate teleseismic events from local earthquakes. Triangles are the average τ_p^{max} and P_d for the events of the calibration dataset. Green squares are average values from local events recorded by the real-time system. Average τ_p^{max} and P_d for ElarmS "events" determined to have been caused by teleseismic events are shown as black circles. The black line is the linear discriminant function which divides most local and teleseismic events. Teleseismic events P-waves have small displacements with longer periods. The discriminant is not perfect, as three teleseismic events are found on the wrong side of the line.

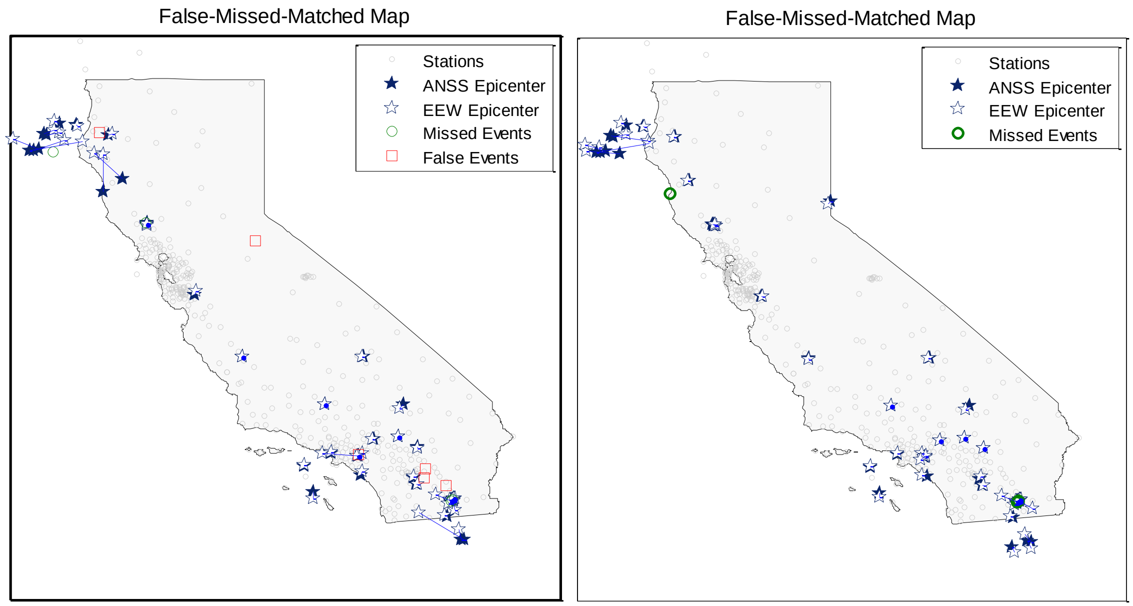

Figure 6. All detected, false, and missed earthquakes with M_{ANSS}≥3.5 that occurred in California between April 12, 2012 and August 31, 2012. Online E2 results (left panel) and version E2.3.1 results (right panel). For definitions of detected, false and missed events, see text. In the figure, ANSS epicenters are represented by blue stars and the corresponding E2 epicenters by white stars. If their separation is not close to 0 km, they are connected by a line. Green circles and red squares mark missed and false events, respectively. Although E2 successfully detected most earthquakes, we note that errors in source parameters are greater offshore of Cape Mendocino and south of the California-Mexico boarder.

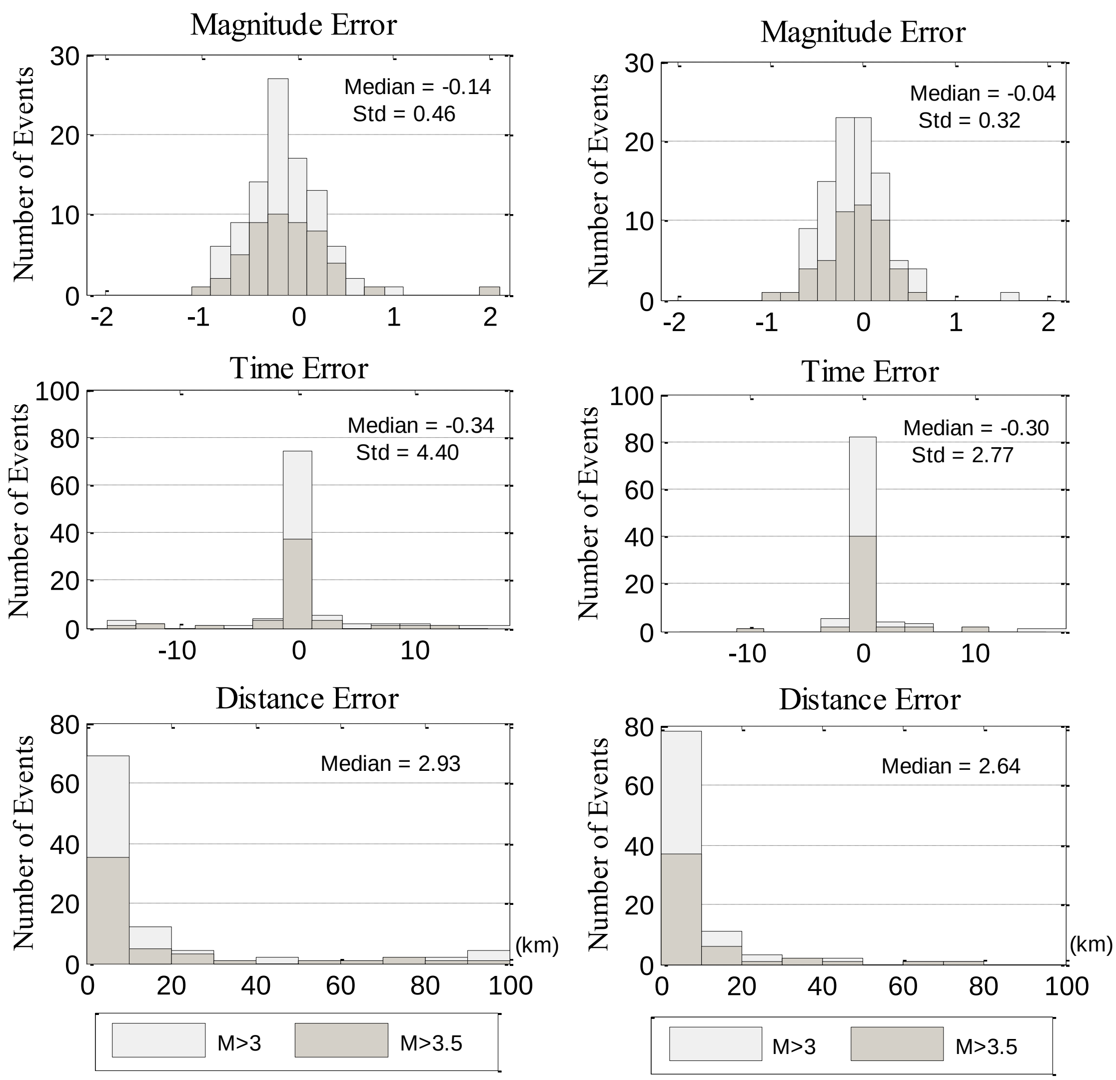

Figure 7. Histograms of magnitude, time and location errors for Online E2 (left) and Version E2.3.1 (right). The light gray histograms are errors for all events with $M_{ANSS}\geq3.0$ and dark gray histograms are for events with $M_{ANSS}\geq3.5$. For a comparison of the statistics, see Table 5.

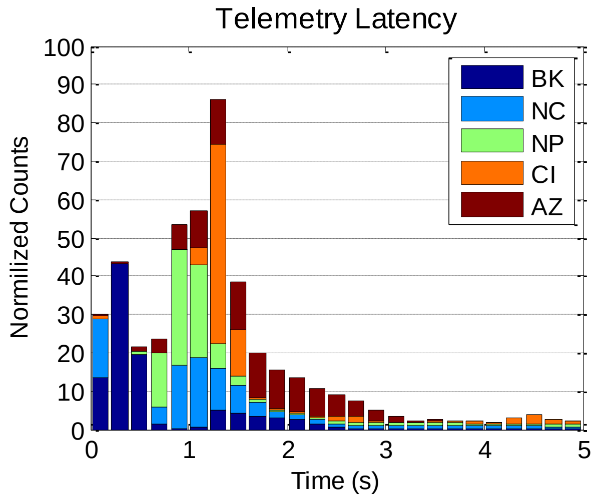

Figure 8. Histogram of telemetry latencies by seismic network. The telemetry latency is the time it takes for a completed packet to be transmitted from the station to its network processing hub. The y-axis is normalized so that each network is represented in the histogram by the same area. As the networks are different sizes, the histogram does not correctly represent the overall average delay seen by E2. On average telemetry latency is 1.14 s (see Table 4).

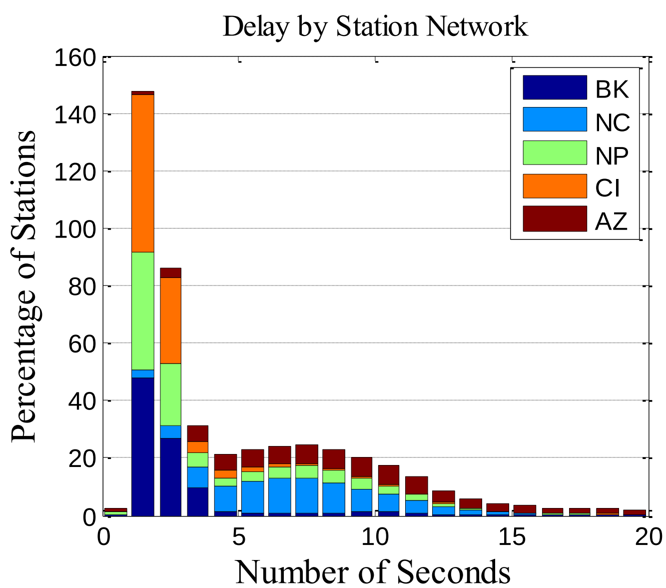

Figure 9. P-wave latencies by seismic network. This is the time that a WP module detects a P-wave minus the time of the P-wave. It includes data packetization, transmission to the network hub and WP processing. Data latencies are normalized for each network. On average P-wave latency is 2.07 s (see Table 5).

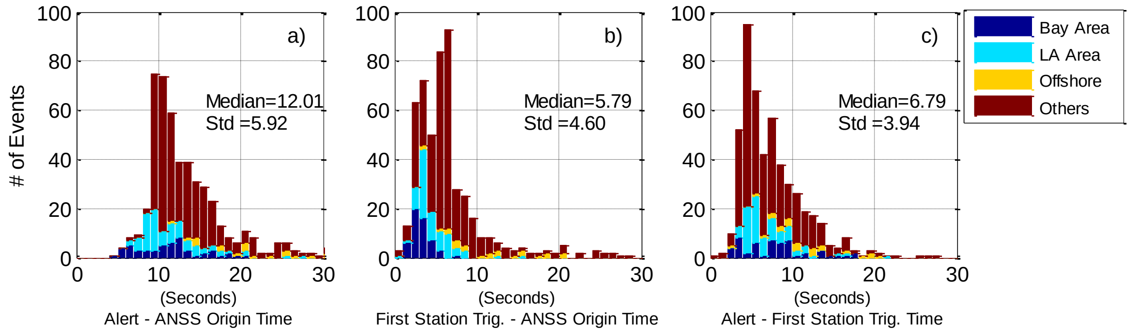

Figure 10. Various latencies for earthquakes detected by online E2 from April 12, 2012, to August 31, 2012. a) E2 alert latency is the difference between the time an alert is first published and the origin time for the earthquake in the ANSS catalog. The median is 12.01 ± 5.92 seconds. b) The time it takes the first P-wave arrival to travel to the first station. This is derived by subtracting ANSS origin time from the trigger time at the first station. The median is 5.79 ± 4.60 seconds. c) E2 total processing latency, which is alert time minus the time of the first P-wave station trigger. This shows total time the network and E2 require to alert on an event. The median is 6.79 ± 3.94 sec. Alerts are faster for the San Francisco Bay and Los Angeles areas (see Table 6).

Table 1. Modifications to the various versions of E2.

	E2 12 Apr - 26 Apr	E2.1 27 Apr - 30 Apr	E2.2 1 May – 28 Aug	E2.3 28 Aug – 01 Oct	E2.3.1 02 Oct ~
One Second packet	BK implementation			CI implementation	
WP	WP2 and heartbeats implemented				
Association				Relocation of epicenter in association algorithm	Association of triggers up to 1500 km Eq (1) implemented
Magnitude	nCA; MTp,MPd sCA : MPd	Network Magnitude Correction	Eureka Magnitude Box		nCA; MPd sCA : MPd
Location		2 km grid implemented	5 km approximation combined with 2 km exact grid		Rejection if epicenter is on edge of grid
Alert Criteria	50% of stations within distance of most distant trigger must have triggered 4 station triggers required	Linear teleseismic filtering implemented		40% of station must have triggered	Break out of association and go to alert if 10 stations have triggered

Table 2. Detected, missed and false events for Online E2 and Version E2.3.1.

California	Online E2	Version E2.3.1
Detected	48	49
Missed	5	4
False	6	0
Bay Area		
Detected	3	4
Missed	1	0

False	0	0
Los Angeles		
Detected	6	6
Missed	0	0
False	1	0

Table 3. Magnitude, time and location error statistics for online ElarmS and E2.

	Online		Version E2.3.1	
	Median	Std	Median	Std
Error	M_{ANSS}>3.0			
Magnitude	-0.15	0.41	-0.10	0.35
Time	-0.24	5.08	-0.25	3.65
Distance	2.55	-	2.64	-
	M_{ANSS}>3.5			
Magnitude	-0.14	0.46	-0.04	0.32
Time	-0.34	4.40	-0.30	2.77
Distance	2.93	-	2.64	-

Table 4. Median telemetry latencies.

	Median	Std
All	1.14	0.90
BK	0.36	0.62
CI	1.34	0.92
AZ	1.64	0.63
NP	1.00	0.88
NC	1.19	0.98

Table 5. Median P-wave latency by network.

	Median	Std

All	2.07	3.35
BK	1.97	2.29
CI	1.92	1.79
NC	7.09	3.30
NP	2.29	3.62
AZ	8.84	4.72

Table 6. Statistics of various E2 latencies for all California and various regions. All latencies are for the Online E2 from April through August 2012.

	Alert - ANSS Origin Time Median ± Std (sec)	First Station Trig - ANSS Origin Time Median ± Std (sec)	Alert - First Station Trig Median ± Std (sec)
Others	12.27 ± 5.75	6.07 ± 4.82	6.21 ± 3.89
Offshore	21.49 ± 7.17	11.34 ± 5.34	10.32 ± 4.80
Los Angeles	10.25 ± 3.98	3.98 ± 2.22	5.56 ± 3.10
Bay Area	11.22 ± 4.10	3.02 ± 1.19	7.81 ± 4.03
All	12.01 ± 5.92	5.79 ± 4.60	6.79 ± 3.94

c. Event Detector 3: Virtual Seismologist (ETH Zurich)

The Virtual Seismologist (VS) early warning approach was originally formulated by Cua and Heaton (2007) as a Bayesian approach that combined various types of potential prior information (network topology, fault maps, previously observed seismicity, along with the processing and interpretation of real-time information (envelope amplitudes, picks) to provide the most probable earthquake point-source characterization at a given time. VS implementation efforts have thus far been focused on real-time processing of incoming picks and waveform data. The software architecture and real-time data processing is described in detail in Cua et al (2009). Optimal use of prior information is part of on-going research of ETH PhD student Men-Andrin Meier (funded by ETH). Enhancements to the VS codes over Phase II of the project include the development of the Virtual Seismologist Multiple Threshold Event Detection (VS-MTED) approach (Fischer et al, 2009) and the addition of Vs30-based correction factors (Caprio et al, 2011).

Virtual Seismologist Multiple Threshold Event Detection: The goal of VS-MTED is to increase the available warning time for subscribers who have higher tolerance for false alerts, while not compromising the needs/requirements of subscribers who have lower tolerances for false alerts. VS-MTED features 5 different threshold levels involving independent instances of the Earthworm Binder associator (Dietz et al, 2002) to provide location estimates. Level 0 can initiate event declarations based on a single station, if amplitudes are high enough, and produces 2- and 3-station estimates if picks of high enough quality become available. Level 0 evolves to using Binder location estimates once 4 or more stations are available. Offline testing (using data from the SCEC continuous waveform data archive) of the experimental VS-MTED system was summarized in Fischer et al (2009). Given the VS source codes, one can choose at compile time whether to compile as VS-MTED, or as “standard” VS, which requires a minimum of 4 picks to initiate an event declaration. All VS messages sent to the Decision Module, and all VS reports that had been sent to the Testing Center, were generated using a “standard” VS configuration, ie, one instance of Binder requiring a minimum of 4 stations to initiate an event declaration. The VS-MTED codes are being tested in real-time in Switzerland. Further research is necessary to optimize the configuration of these VS-MTED experimental codes.

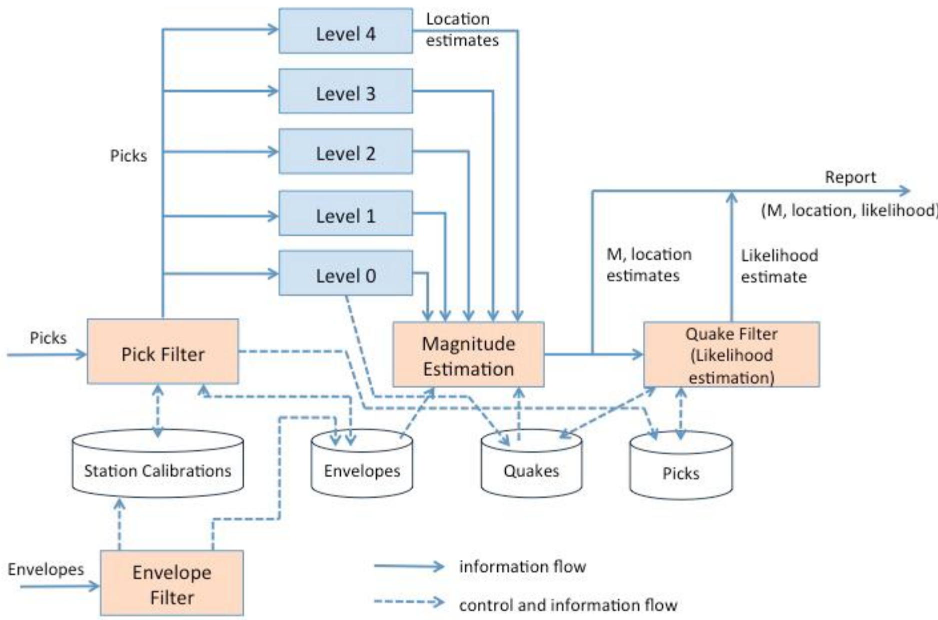

Figure xx: Block diagram for Virtual Seismologist Multiple Threshold Event Detection (VS-MTED).

Use of Vs30-based correction factors: The current generation of VS codes now also allow use Vs30-based correction factors to account for site amplification effects. How the VS codes use Vs30 information follows the ShakeMap implementation (Wald et al, 1999) of the frequency-dependent Borcherdt (1994) approach. ETH PhD student Marta Caprio has evaluated different approaches to site correction (empirical envelope station corrections, Vs30, empirical overall magnitude corrections) for early warning (Caprio et al, 2011). Caprio's work shows that use of Vs30-based corrections is better than use of empirical envelope station corrections for improving VS magnitude estimation. Given the VS source codes, one can choose, at compile time, whether to use the Vs30 corrections or not.

Likelihood parameter: ETH PhD student, Men-Andrin Meier is working on extending the use of Voronoi cells and not-yet-arrived data (Horiuchi et al, 2005) to take into account the heterogeneity and uncertainty in station latencies within a seismic network (Meier et al, 2011). His research aims to quantifying how the probability of correct detection (or likelihood parameter) should evolve as a function of time and available waveform and phase information. He will also be evaluating the systematic use of prior information in EEW. In addition to the contributions of network topology (accounted for in the Voronoi cells and not-yet-arrived data), he will also evaluate whether the systematic use of fault and earthquake forecast information is beneficial in EEW. His research will improve the empirical likelihood parameter assignments currently used in the VS codes.

Single state-wide VS installation: VS continues to run as 3 separate and independent installations at SCSN, BDSN, and Menlo Park. It was a goal for Phase II to work on integrating these separate installations into a single state-wide installation. In particular, it was important to merge the BDSN and Menlo Park installations, which were complete independent of each other, despite covering the same geographic region. Michael Fischer, ETH software developer who had worked on VS since the start of Phase I (2006), had begun exploring approaches and initial implementation steps for this integration. In September 2011, Michael Fischer announced his intention to leave ETH. We negotiated a transition period until March 2012. During this transition period, we stopped development of new features to the code (including the integration efforts), and focused instead on documentation of existing codes and transferring VS software know-how to existing IT staff at ETH. Yannik Behr joined ETH in March 2012, as the new VS scientific software developer/post doc. Other ETH IT staff members are now also knowledgeable about the VS software.

Multiple events: VS occasionally sends multiple messages (with distinct eventids) into the Decision Module. These are due to Binder occasionally proposing new hypocenter solutions with picks further away from the epicenter, and not associating them with an existing eventid. It is a known problem that VS will sometimes produce spurious secondary events (phantom events), particularly in the case of large events which will have picks exceeding the VS event declaration thresholds at distance from the epicenter. Events in central California, which may potentially trigger all VS installations (SCSN, BDSN, and Menlo Park), are also another source of multiple VS messages to the DM for the same event. These particular cases will be resolved once a statewide VS installation is implemented. In Phase III, we hope to address how to optimally configure VS to minimize phantom events, while maintaining some capability to resolve near-simultaneous events, as well as the matter of a statewide VS installation.

Summary of VS Performance from 2009 through 2012

The Virtual Seismologist (VS) algorithm began real-time data processing at the Southern California Seismic Network (SCSN) in July 2008, and was installed at the Berkeley Digital Seismic Network (BDSN) and the Menlo Park strong motion network in February 2009. Since the initial installations, VS has continued operating as three separate, independent installations at the SCSN, BDSN, and Menlo Park networks to the present day.

Figure 1 shows maps of VS correct and missed detections since the start of VS real-time testing in July 2008 through June 2012, as well as summary maps over individual years. For a detection to be labeled "correct", there must be an event in the ANSS catalogue within 120 km of the VS epicenter with an origin time difference between -5 and +25 seconds. VS correctly detected over 2200 M>=2.5 events in California during Phase II of the project, with 1023 of these events with M>=3.0. In general, VS performs better in southern California (SC) than in northern California (NC). The fact that the VS installations at BDSN and Menlo Park are independent of each other and do not share data certainly contributes to the underperformance in northern California. In addition, the differences in station distribution between southern (more uniform over a wide region) and northern (highly concentrated in Bay Area, significantly sparser coverage in other regions) California potentially contributes to the differences in VS performance. The total number of missed events during Phase II is dominated by missed events from 2010, which in turn were dominated by the aftershock activity following the 4 April 2010 Mw 7.2 El Mayor-Cucapah earthquake in Baja California. In many of the following summary figures, the statistics for 2010 are dominated by the contributions of the aftershocks of this event, ie, higher than normal seismicity on the outskirts of the network.

Figure 2 shows histograms of initial VS estimate times (time stamp of first VS estimate – earthquake origin time) in northern and southern California. The improvement in 2011 average initial estimate times for NC and SC relative to previous years takes into account the reduction in data latency due to adoption of the Waveform Processing Libraries provided by Caltech. VS is generally faster in SC than in NC due to higher station density in SC. The 2010 histogram in SC is wider than other years due to the aftershocks following the 4 April 2010 Mw 7.2 El Mayor-Cucapah earthquake in Baja California. The aftershock sequence of this event, with a large number of events on the outskirts of the network, results in a large number of events with larger initial estimate times and larger location errors in 2010.

Figure 3 shows histograms of initial VS location errors in northern and southern California. Most initial VS location estimates are within 15 km of the network location. There have been no significant changes in the location estimation approach for VS in Phase II. That is, we continue to use the Earthworm Binder associator (Dietz et al, 2002) to provide location estimates once a minimum of 4 picks are available. The VS Multiple Threshold Event Detection (VS-MTED, Fischer et al 2009) approach was formulated (and implemented in code) with the goal of providing faster estimates. VS-MTED is capable of initiating event declarations based on data from a single station, if amplitudes are high enough. One can choose, at compile time, whether to generate binaries that run as "standard" VS (with a minimum of 4 stations to initiate event declaration), or as VS-MTED. All VS installations in California are "standard" VS installations. VS-MTED is currently being tested in real-time in Switzerland.

Figures 4 and 5 show the evolution of VS magnitude error as a function of the rank of the VS estimates (ie, 1st estimate, 2nd estimate, etc). Figure 4 uses events where the initial VS location error is less than 15 km, while Figure 5 places no constraint on location error. The 2009 southern California subplot (in Figure 4) showed VS magnitude errors increasing with time. This observation served as the initial motivation for accounting for site amplification effects. We followed the ShakeMap (Wald et al, 1999) approach for using the Borchert (1994) frequency-dependent approach for correcting for site amplification using Vs30. The 2010 results take into account the effects of using Vs30 corrections. While the 2011 results show some systematic overestimation, we find that this effect is small enough (average magnitude error less than 0.1 magnitude units) to consider the issue of site corrections adequately accounted for. In general, we find that, if the location is "good" (for instance, within 15 km of the eventual catalogue location), the VS magnitude estimation is very stable.

For individual events, large location errors translate to large magnitude errors. On average, this results in larger 1-Sigma levels in Figure 5 (which has no constraint on VS location quality) as compared to Figure 4 (which only includes "good" locations, ie, location errors less than 15 km.)

Figure 6 shows a map of VS correct detections, color-coded according to the initial magnitude error of a particular event. (This is equivalent to looking at the spatial distribution of the rank 1 estimates Figure 4.) In Figure 7, the events are color-coded according to initial location errors. In general, VS performs well in terms of magnitude (average magnitude error essentially 0) and location estimates (usually within 10 km of catalogue location) for events within the network. As would be expected, performance degrades at the outskirts of the network.

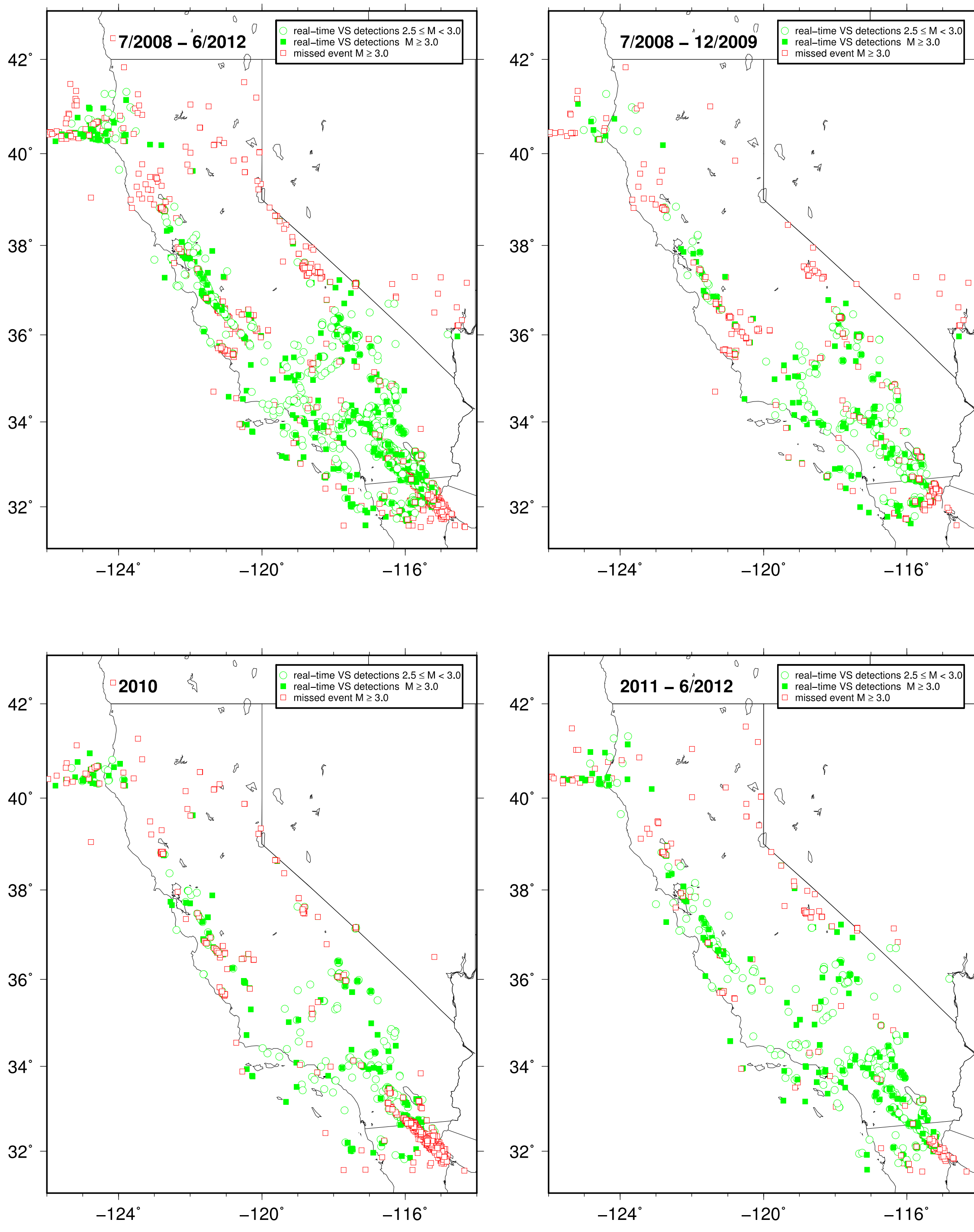

Figure 1: Summary of VS correct (M>=2.5) and missed detections (M>=3.0) in both northern and southern California from 2009 through 2012. The large number of missed events M>3.0 events in 2010 is dominated by the aftershock activity following the Mw 7.2 El Mayor-Cucapah earthquake in Baja California.

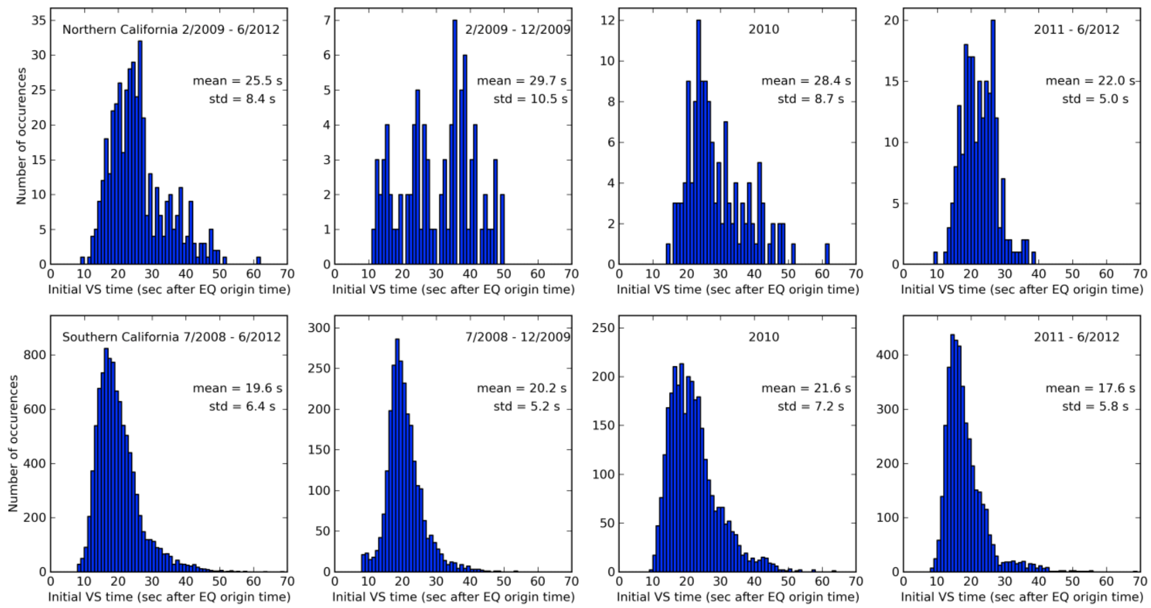

Figure 2: Histograms of initial VS estimate times for northern (top row) and southern (bottom row) California.

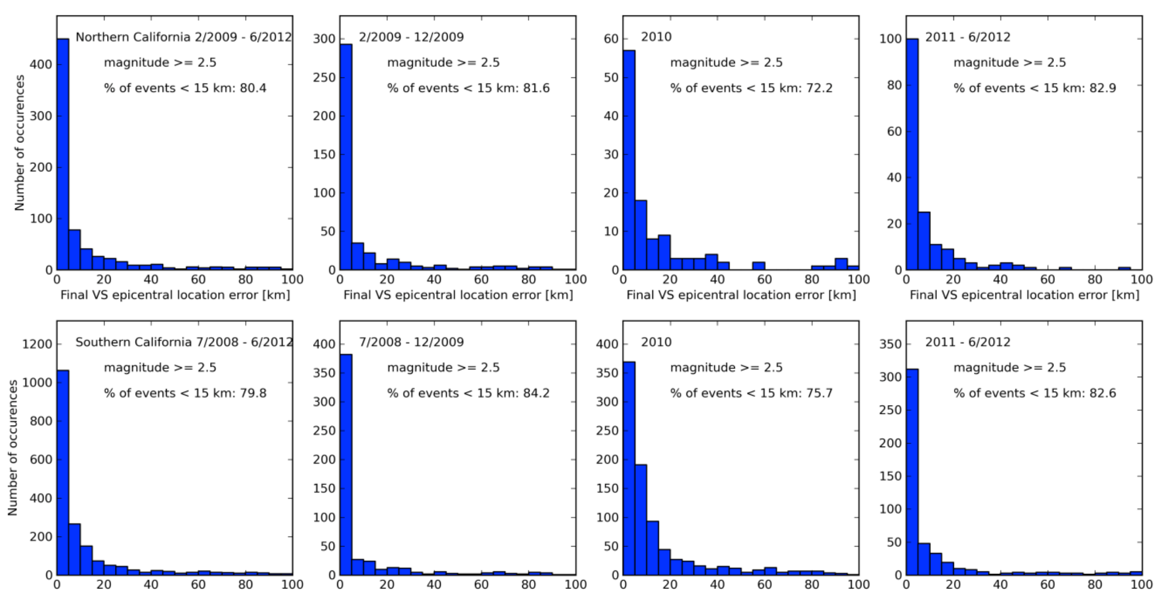

Figure 3: Histograms for VS final location error for northern (top row) and southern (bottom row) California.

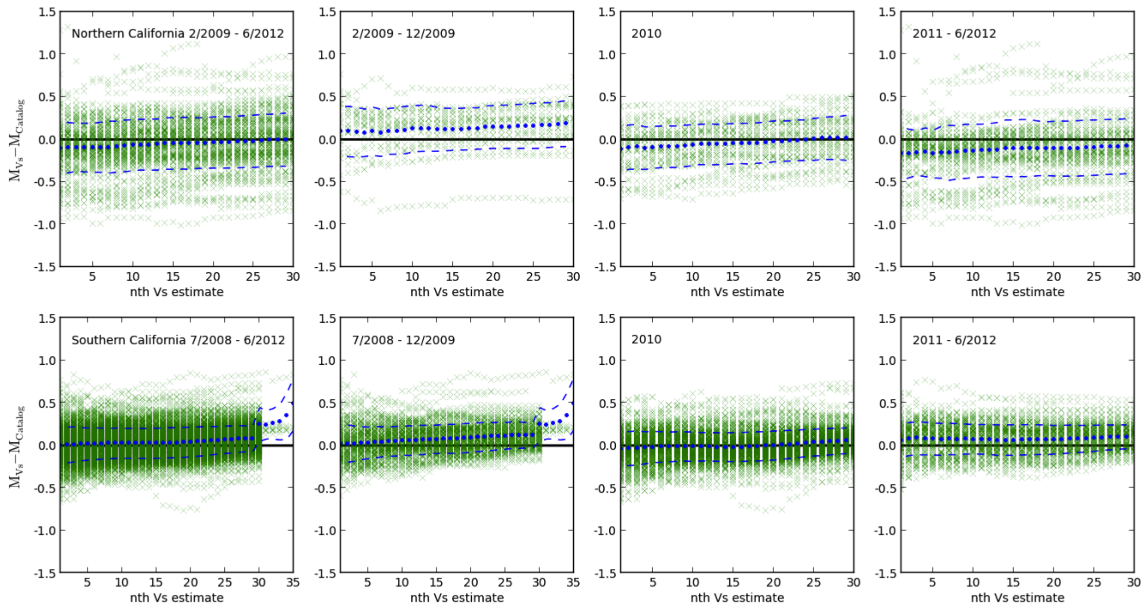

Figure 4: VS magnitude error as a function of rank of VS estimate for events with initial location errors less than 15 km for northern (top row) and southern (bottom row) California from 2/2009 through 6/2012. The blue symbols denote the average VS magnitude error for the nth estimate. The dashed lines denote the 1-sigma level. (Note: the average error/uncertainty beyond the 30th estimates in 2009 for Southern California should not be over-interpreted, as they are based on only a handful of events.)

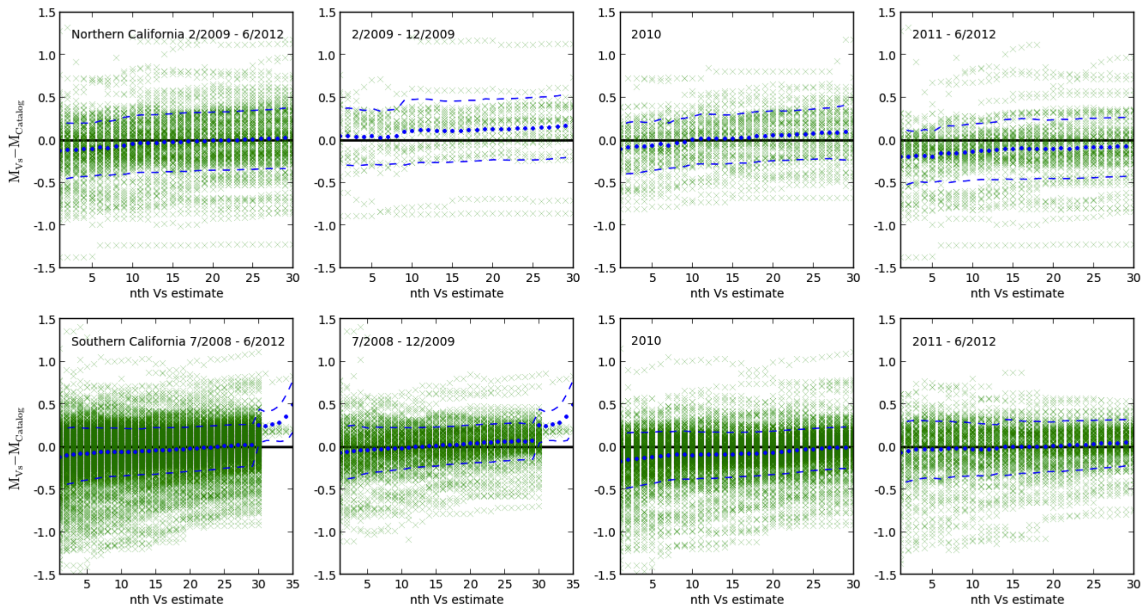

Figure 5: VS magnitude error as a function of rank of VS estimate for all VS correct detections for northern (top row) and southern (bottom row) California from 2/2009 through 6/2012. The blue symbols denote the average VS magnitude error for the nth estimate. The dashed lines denote the 1-sigma level.

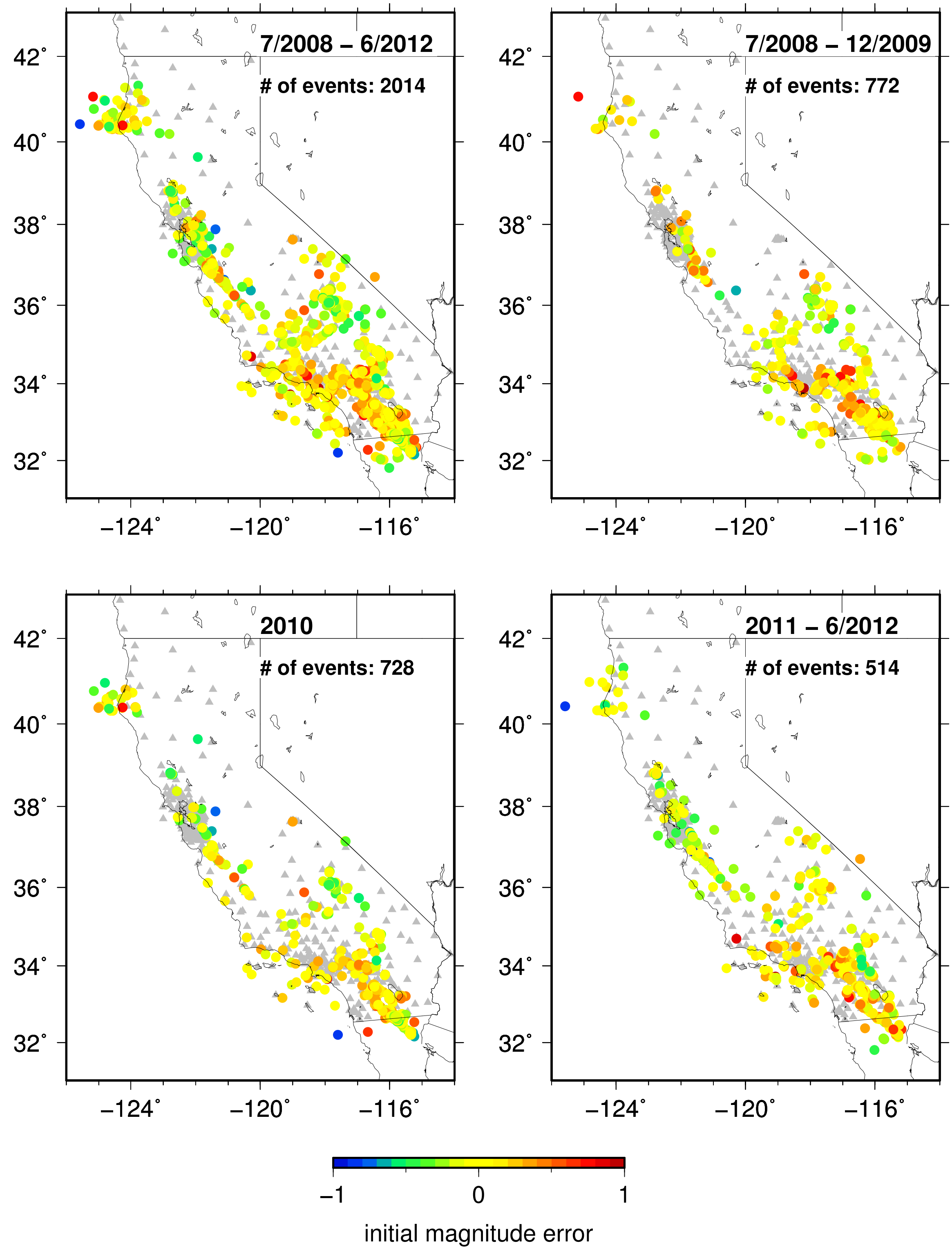

Figure 6: Initial VS magnitude error as a function of location for events with M>=2.5 and initial location errors less than 15 km.

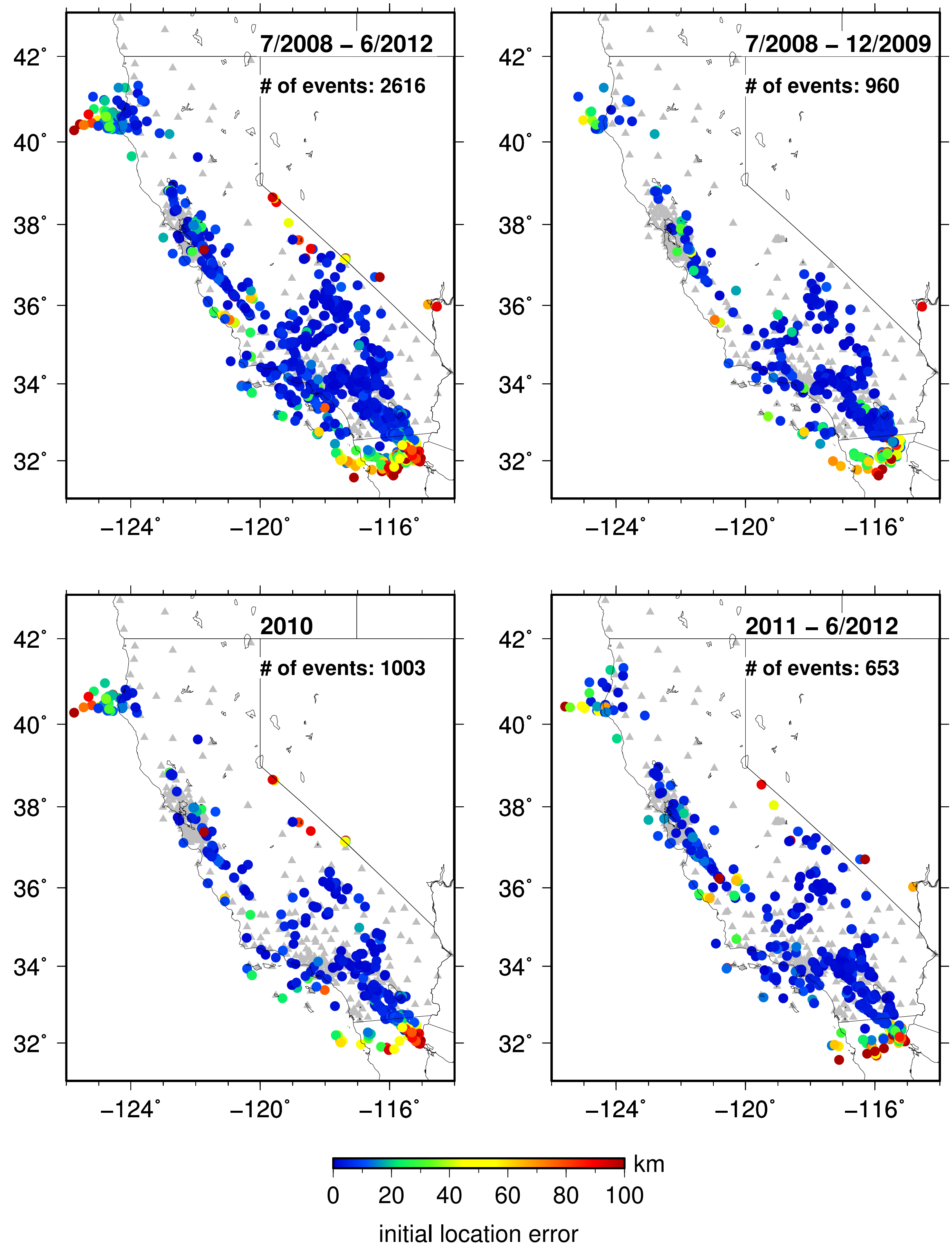

Figure 7: Initial location error for real-time M>=2.5 VS detections. In general, the initial VS locations for events within the network are typically within 10 km of the catalogue location. As expected, location errors increase at the outskirts of the network.

References (Virtual Seismologist)

Borcherdt, R. (1994). Estimates of site-dependent response spectra for design (methodology and justification), Earthquake Spectra, 10, 617-653. http://dx.doi.org/10.1193/1.1585791

Caprio, M., Cua, G., Wiemer, S., Fischer, M., Heaton, T., CISN EEW Group, 2011. CISN ShakeAlert: Accounting for Site Amplification Effects and Quantifying Time and Spatial Dependence of Uncertainty Estimates in the Virtual Seismologist Earthquake Early Warning Algorithm. AGU Fall Meeting, San Francisco, December 2011.

Cua, G. 2005. Creating the Virtual Seismologist: developments in ground motion characterization and seismic early warning. PhD dissertation, California Institute of Technology. http://resolver.caltech.edu/CaltechETD:etd-02092005-125601

Cua, G., and Heaton, T., 2007. The Virtual Seismologist (VS) method: A Bayesian Approach to Earthquake Early Warning. In Earthquake Early Warning Systems, ed. P. Gasparini, G. Manfredi, J. Zschau, 97-132. Berlin and Heidelberg: Springer.

Cua, G., Fischer, M., Heaton, T., Wiemer, S. Giardini, D., 2009. Real-Time Performance of the Virtual Seismologist Earthquake Early Warning Algorithm in Southern California, Seism. Res. Lett, 80 (5), p740-747.

Cua, G., Allen, R., Boese, M., Brown, H., Given, D., Fischer, M., Hauksson, E., Heaton, T., Hellweg, M., Liukis, M., Jordan, T., Khainovski, O., Maechling, P., Neuhauser, D., Oppenheimer, D., Solanki, K., 2009. CISN ShakeAlert: Three Years of Comparative Real-Time Earthquake Early Warning Testing in California. AGU Fall Meeting, San Francisco, December 2009.

Cua, G., Fischer, M., Caprio, M., Heaton, T., Clinton, J., CISN EEW Group, 2010: Faster Alert Information Through Multiple Threshold Event Detection in the Virtual Seismologist Early Warning Algorithm. AGU Fall Meeting, NH33A-1371, San Francisco, December 2010.

Dietz, L., 2002. Notes on configuring BINDER_EW: Earthworm's Phase Associator; http://www.isti2.com/ew/ovr/binder_setup.html.

Fischer, M., Cua, G., Caprio, M., Heaton, T., Clinton, J., 2009. Multiple Threshold Event Detection in the Virtual Seismologist Earhtquake Early Warning Algorithm. AGU Fall Meeting, San Francisco, December 2009.

Meier, M.-A., Cua, G., Wiemer, S., Fischer, M., CISN EEW Group, 2011: CISN ShakeAlert: Improving Virtual Seismologist Earthquake Early Warning Framework to Provide Faster, More Robust Warning Information. AGU Fall Meeting, December 2011.

Wald, D., Worden, C.B., Quitoriano, V., Pankow, K., 2005. ShakeMap Manual: Technical Manual, User's Guide, and Software Gui

d. Finite Fault Detector (Caltech)

Seismic ground motions can be seriously underestimated for large earthquakes (M>6.5) when predicted from hypocentral rather than rupture-to-site distances in empirical ground-motion prediction equations. Using rupture-to-site distances, however, requires real-time information on finite fault rupture extent.

To provide rapid estimates of fault rupture extent during large earthquakes, we have developed the Finite Fault Rupture Detector algorithm (*FinDer*) that is based on strong-motion data (Böse, Heaton *et al.*, 2012b). *FinDer* uses image recognition techniques to detect automatically surface-projected fault ruptures in real-time (assuming a line source) by estimating their current centroid position, length *L*, and strike ϑ (Figure 1). The approach is based on a rapid high-frequency near/far-source classification of ground motion amplitudes in a dense seismic network (station spacing < 50 km), and comparison with a set of pre-calculated templates using Matching by Correlation. *FinDer* keeps track of the current dimensions of a rupture in progress. Errors in *L* are typically on the same order as station spacing in the network. The continuously updated estimates of source geometries as provided by *FinDer* make predicted shaking intensities more accurate and thus more useful for EEW, because they can be estimated from rupture-to-site distances. The applicability of the algorithm has been demonstrated for several recorded and simulated earthquakes with different focal mechanisms (Böse, Heaton *et al.*, 2012b). We are currently extending the *FinDer* algorithm to subduction-zone earthquakes with possible application to Cascadia.

Since September 2012, Caltech is running *FinDer* in real-time mode for earthquakes in Southern California. The Matlab code has not been translated to C++ code yet. Even though the processing delays are in the order of several seconds, *FinDer* has successfully detected and processed a number of small earthquakes (using lower thresholds for testing). We have started to develop but not implemented a new xml format for ShakeAlert messages for finite fault ruptures (such as determined by *FinDer* or other finite fault detectors) that can be processed by the User Display.

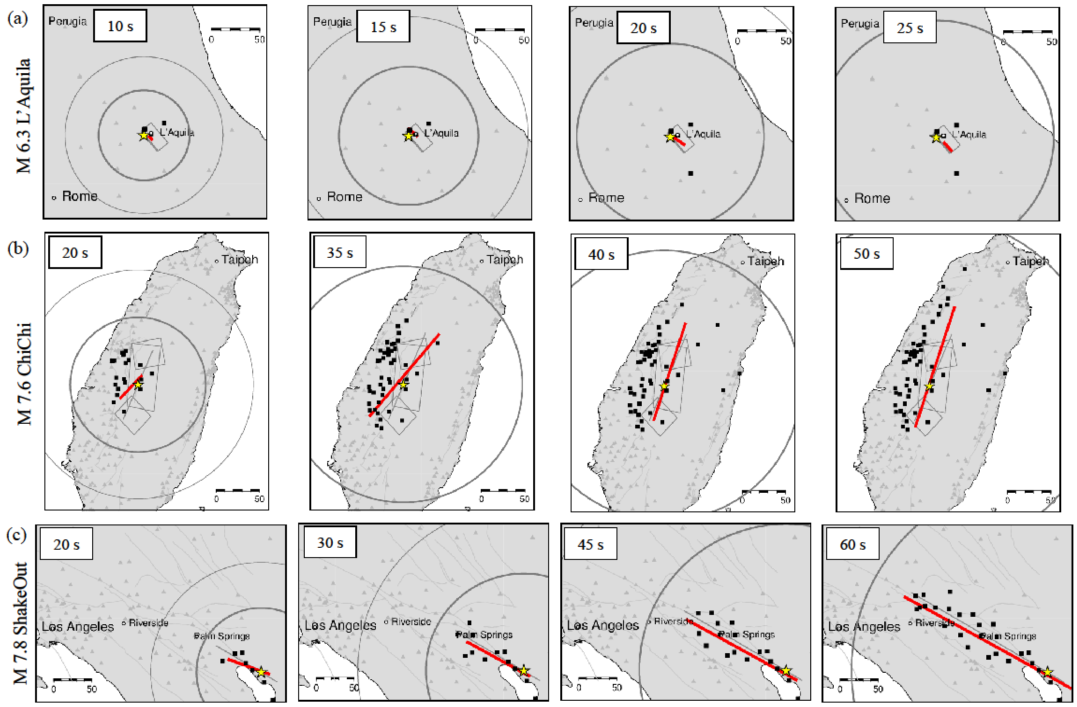

Figure 1. Near/far-source classification and predicted (surface-projected) ruptures (red) for the (a) Mw 6.3 L'Aquila (Italy), (b) Mw 7.6 ChiChi (Taiwan), and (c) Mw 7.8 ShakeOut scenario (southern California) earthquakes at four time steps after rupture nucleation using *FinDer*. Black squares mark near-source, gray triangles far-source classified stations determined from high-frequency thresholds (here: 70 cm/s^2). Circles show the P- and S-wave fronts; gray lines show observed rupture evolution (Böse, Heaton *et al.*, 2012b).

III. **Decision Module** (UC Berkeley with TOT/SOT)

The CISN ShakeAlert system incorporates several separate waveform processing and event detection methods into a single detection system. Each event detection method independently examines raw waveform data, associates arrivals into events, computes magnitudes and sends the location, time, magnitude, and uncertainty values along with station ground motion observations and predictions to a central process called the Decision Module (DM). The Decision Module decides which incoming reports correspond to the same event, for which it calculates a set of combined event attributes and issues an alert message. This strategy results in a more robust system that profits from the different strengths of the independent detection methods while minimizing their different weaknesses.

The Decision Module receives event messages from the ElarmS, OnSite, and Virtual Seismologist detection systems. These three detection systems run as separate processes on the same or different computers. Each system processes raw waveforms for triggers that are associated into events using different association and magnitude estimation algorithms. Each detection system sends event messages to the Decision Module. These messages are in XML format and are transmitted via an ActiveMQ Messaging Broker.

The Decision Module builds a DM event from the messages from the three detection systems. The Decision Module tries to associate an arriving event message with previously stored event messages using a location and time metric. It does not allow messages from the same detection system to be associated with each other, unless the message is specified as a parameter update to a previous message. When an arriving message is associated with an existing DM event, the combined earthquake attributes are recomputed and published. If an arriving message cannot be associated with an existing DM event, it becomes a new DM event that is immediately published to alert users, such as the CISN ShakeAlert UserDisplay.

A detection system can send an update-message to the Decision Module that updates the values of a previous message from the same system. The update message causes the Decision Module to recompute the misfit of the event association. If the misfit is still acceptable, the recomputed combined event attributes are published. If the misfit is too large, the DM event is dismantled and new associations are attempted from the saved messages. This can result in the creation of a new DM event.

A detection system can also send a cancel message that refers to a previous event message from that system. This type of message will also cause the Decision Module to recompute the combined event misfit, again with the possibility that the corresponding DM event could be dismantled and a new event created. In all cases, the Decision module checks that the arriving messages from the three detection systems have parameter values within acceptable ranges and the origin time is recent enough to allow a warning message to be effective.

The table below shows the number of events created by the Decision Module from May 1, 2012 to October 24, 2012. The Decision Module sent alerts messages for a total of 629 events. The rows of the table shows the number of events in several magnitude ranges. The columns show the number of events with either one, two, or three contributing detection systems (ElarmS, OnSite, and VS). In the lowest magnitude range, 2.5 to 3.0, most of the DM events were created by only one of the three detection systems. Almost none were created from all three detection systems. This is partly because the OnSite system was not designed to alert on low magnitude events.

For higher magnitude ranges, there are more events with all three detection systems contributing. For magnitudes greater than or equal to 4.0, there were 27 DM events created from a single detection system, 5 DM events created from two of the detection systems and 32 DM events created from all three detection systems. For all magnitude ranges, there were 339 DM events that were created from a single detection system, 210 DM events created from two detection systems and 80 DM events created from all three detection systems.

DM Events 2012/05 /01- 2012/10/24 by Magnitude and Number of Contributing Systems

	1 contributor	2 contributors	3 contributors	total
2.5 <= Magnitude < 3.0	205	146	2	353
3.0 <= Magnitude < 3.5	78	45	18	141
3.5 <= Magnitude < 4.0	29	14	28	71
Magnitude >= 4.0	27	5	32	64
total	339	210	80	629

IV. **UserDisplay** (Caltech with TOT)

The UserDisplay (UD) has two purposes: (1) to translate alerts (origin time, location, magnitude) from the Decision Module to site-specific warnings (expected MMI intensity, remaining warning time), and (2) to display these values on a map to alert users (Böse, Solanki *et al.*, 2010; Solanki, Böse *et al.*, 2011).

The User Display is written in Java and is thus platform-independent. A desktop version is available since 2010. Distribution of version 2.3 to a selected group of test users from the business, utility and transportation sectors in California has started in early 2012. User-specific changes to the UserDisplay as requested by BART were supported. The UserDisplay has the following capabilities (Böse, Allen *et al.*, 2012):

- calculation & display of remaining warning time for a given user
- calculation & 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 & 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 ShakeAlert message is received (Figure 1).

The user can set thresholds for intensities, magnitudes and probability 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. Some beta testers have reported problems trying to run the UD from behind a firewall. We are currently evaluating the use of a different service port number normally reserved for HTTPS web connections. Preliminary reports indicate this may be working for users who were having problems using the original port. Installation and operation of the UserDisplay have been documented in the Operations Guide (Böse, Hauksson *et al.*, 2011).

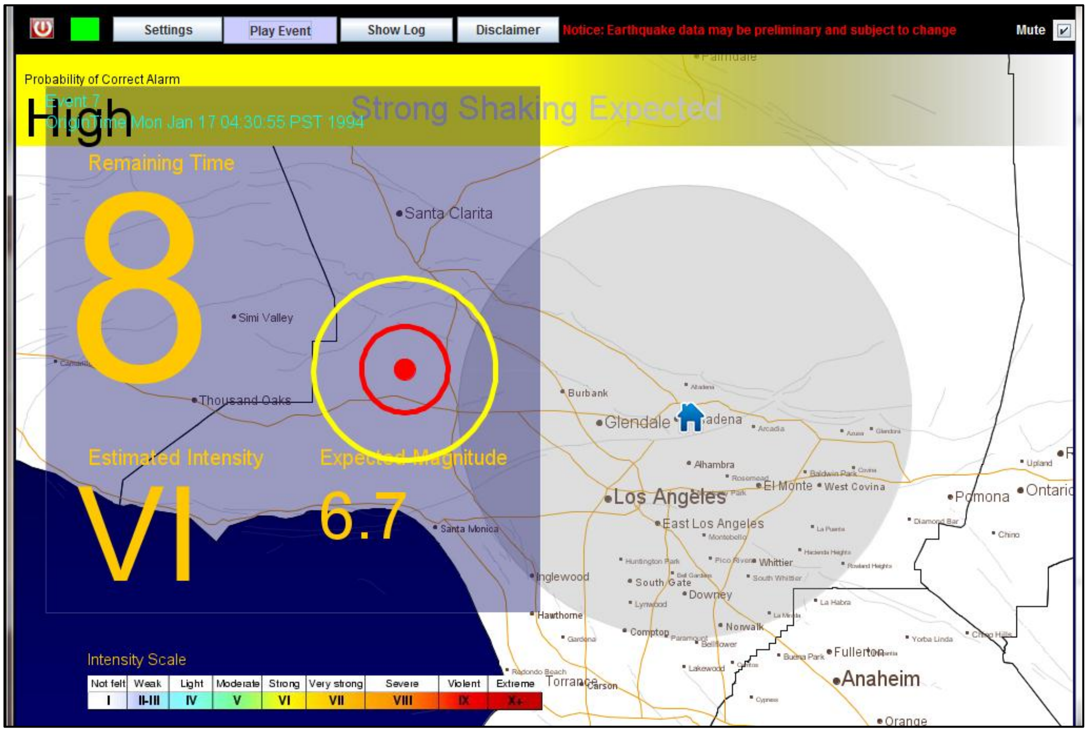

Figure 1. Simulated performance of the UserDisplay for the 1994 M6.7 Northridge earthquake in southern California with a user at Caltech (blue house). Yellow and red circles show P- and S-wavefronts. The shaded area around the user gives an approximation of the current blindzone of CISN ShakeAlert (Böse, Allen *et al.*, 2012).

We have started to develop (but not implemented) a new format for ShakeAlert messages for finite fault ruptures, such as provided by *FinDer*, that can be processed and displayed by the UserDisplay. Furthermore, Caltech is currently developing an Android app for the UD.

V. Performance Testing Center (SCEC)

SCEC and CISN ShakeAlert researchers have developed an operational testing system for the CISN ShakeAlert system that we call the CISN Testing Center (CTC; Maechling et al., 2009). CTC ShakeAlert performance summaries are now posted on the CTC web site showing ShakeAlert performance summaries for the time period between September 2011 and the present.

The CTC generates ShakeAlert performance summaries for each significant California event, and cumulative performance summaries over specific periods of time. Many of the CTC ShakeAlert performance summaries compare ShakeAlert forecast parameters, such as location and magnitude, against final observed parameters in the ANSS earthquake catalog.

The CTC processing system uses the SCEC CSEP testing framework software to help automate the test processing. The CSEP testing framework provides tools to retrieve catalog data retrieval for ANSS and other catalog sources, software utilities for filtering earthquake catalogs by region and magnitude, and utilities for automating performance summary generation.

The CTC system calculates performance summaries for the CISN ShakeAlert system on a daily basis. Each day, twenty-four hours of California earthquakes are retrieved from the ANSS catalog, and the testing center retrieves ShakeAlert logs for each event, and compares the forecasts to the observations.

The CTC testing approach is intended to be open, transparent, and well defined so that all testing center results can be reproduced externally. The CTC logs a significant amount of metadata for each performance summary that can be analyzed to understand the results.

The CTC uses a forecast validation testing approach, so CTC ShakeAlert performance results have a significant dependence on the earthquake catalog used as observations. CTC ShakeAlert performance summaries may be affected, positively or negatively, when the ANSS catalog changes. CTC save copies of the inputs used because both the ANSS catalog information, and the ShakeAlert log files may be volatile. The CTC supports reprocessing of ShakeAlert performance summaries if the ANSS catalog is updated.

Types and Locations of Data Sets:

CTC performance summary information is posted online in several formats. Data files are posted in XML format. Images are posted in PNG format. ASCII text format metadata files that describe the input data and processing programs used are posted for each summary.

As of 1 Oct 2012, the total CTC data storage on SCEC systems is approximately 465 Gb of data that includes archives of ANSS catalogs used, archives of ShakeAlert log files used, and the sum of all existing CTC ShakeAlert data products including xml data, metadata, and image files.

CTC ShakeAlert Event Summaries:

CTC ShakeAlert event summaries are generated for each M3.0 and larger ANSS catalog California earthquake. Event summaries show performance of the individual ShakeAlert algorithms, and the performance of the Decision Module that sends the public communications.

ShakeAlert event reports are organized by date and then by ANSS event, due to the way the forecast testing is designed as a comparison between observations (ANSS catalog) and a forecast (ShakeAlert Alerts).

CTC ShakeAlert Events Summaries are posted by date at this URL:

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert/results/

This data set contains CTC ShakeAlert Event Summaries for ANSS events M3.0 and larger in the RELM California Testing region from 1 Sept 2011 through 22 Oct 2012.

The CTC ShakeAlert performance summary file names are cryptic but consistent. Typically, a URL to a specific CTC event summary files can be generated using the ANSS Event Date, the ANSS Event ID, and filename generation scripts from the CTC testing center. This enables automated retrieval of CTC performance information, if desired.

As one example, the CTC ShakeAlert Event Summary for ANSS Event CI15164105, a June 14 2012 M4.0 Yorba Linda earthquake, can be found at the following CTC location:

Event Summary Image [Figure 1]:

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert/results/2012-06-14/scec.eew.ShakeAlertTest.eewTest_ShakeAlertEvent-Test_CI15164105.png.1351107503.296361.1

Contents of the ShakeAlert Log files used to produce this plot are posted at:

http://scec.usc.edu/research/eew/summary/California/shake-alert/forecasts/archive/2012_6/ShakeAlert_6_14_2012.dat

CTC ShakeAlert Cumulative Summaries:

In general terms, CTC ShakeAlert Cumulative summaries show ShakeAlert performance for a given catalog. ShakeAlert performance results will change with the catalog used as observations.

We have posted CTC ShakeAlert Cumulative summaries for four different version of the ANSS California earthquake catalog, based on different filter criteria for catalog start and end dates, and different event selection criteria.

The Full ShakeAlert Time Period is defined as 1 Sept 2011 through 22 Oct 2012 inclusive. The Elarms2 Era Time Period is defined as 12 April 2012 to 31 August 2012 inclusive. We use a catalog of ANSS events in the RELM California Testing region. We also use a catalog of ANSS events in the RELM California Testing region limited to only network codes CI or NC. The following CTC ShakeAlert cumulative summaries are based on M3.5 and larger events found in the ANSS catalog on 22 Oct 2012 ANSS catalog.

(1) RELM Testing Region - Full ShakeAlert Time Period

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegion/shake-alert/results/

(2) CI and NC Code - Full ShakeAlert Time Period

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert/results/

(3) RELM Testing Region - Elarms2 Era Time Period,

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegion/shake-alert-ElarmsV2/results/

(4) CI and NC Code - Elarms2 Ear Time Period

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/

The types of CTC ShakeAlert Cumulative Performance Summaries posted for each catalog are the same. We expect the ShakeAlert Cumulative performance results will vary between each catalog because ShakeAlert logs will be compared against different event sets.

We can use the narrowest catalog (4) in the CTC ShakeAlert performance summaries. We might expect ShakeAlert performance will be best for this catalog, because it contains fewer events on the edge of the network, and because it measures the performance of ShakeAlert during a period when an improved versions of some EEW algorithms were running. In any event, we can describe the CTC ShakeAlert cumulative summaries using this version of the catalog because it contains the same types of CTC ShakeAlert performance summaries as other three catalogs.

CTC ShakeAlert Cumulative performance summaries are updated on a daily basis. To find the cumulative summary for a time period, select the final data in the time period of interest. For example, the CTC ShakeAlert cumulative summaries for the full Elarms2 Era time period are posted at the following URL:

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/

URLs to the six main types of CTC ShakeAlert Cumulative Performance Summaries are shown below:

1. Catalog Event Map [Figure 2]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_ObservedEventsMap-Test_ShakeAlert.png

2. Location Error [Figure 3]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_LocationError-Test_ShakeAlert.png

3. Magnitude Distribution [Figure 4]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_MagnitudeDistribution-Test_ShakeAlert.png

4. Magnitude Error [Figure 5]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_MagnitudeError-Test_ShakeAlert.png

5. Time to First Alert [Figure 6]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_Speed-Test_ShakeAlert.png

6. Cumulative Performance Summary Table [Figure 7]

http://scec.usc.edu/research/eew/summary/USGSReport/RELMTestingRegionANSSNetworkFilter/shake-alert-ElarmsV2/results/2012-08-31/summary.eewTest_Summary-Test_ShakeAlert.png

Discussion (CTC):

In this section, we will discuss known limitations in current CTC ShakeAlert testing results. Then, we will make some general comments about ShakeAlert performance based on preliminary review of the currently available CTC ShakeAlert testing results. Then we will make some recommendations for ShakeAlert improvements based on current testing. Then, we will conclude with recommendations for improvements to current CTC testing system.

Known Limitations in CTC ShakeAlert Results:

We base the credibility of CTC Testing results heavily on the traceability of any particular result. Through examination of CTC processing logs, we believe the CTC system can determine how any particular result was calculated. Any incorrect results can be fixed, and performance summaries updated.

We note that CTC ShakeAlert performance results, such as measures of ShakeAlert hits and misses, often differ from performance results presented by CISN Algorithm developers. When we have evaluated these differences, the source of the differences tends to be related to the earthquake catalog used in the analysis. ShakeAlert performance evaluation from algorithm groups may differ between groups, and between CTC results, because the California regions used are defined differently, which impacts the input catalog, which impact the ShakeAlert performance measures. In many of cases, the results are not strictly inconsistent because they are showing results for slightly different problems.

Another possible source of differences between CTC results and algorithm developer results is the source of ShakeAlert data used. CTC results depend on automated system access to specific ShakeAlert logs files. Algorithm developers may base their results on other ShakeAlert performance data, such as communication logs, which are not currently used by the CTC. In some cases, the ShakeAlert performance logs are not available when the CTC evaluation runs, which can cause CTC to declare ShakeAlert missed events. Algorithm developers may have alternative access to ShakeAlert performance information that they can use to build more complete, but manual, performance results.

We believe that that most significant source of incorrect results in CTC performance summaries result from the simple event association method used by CTC. The CTC processing uses an ANSS event as starting point, then associates any ShakeAlerts that occurred from origin time up to 60 seconds with the ANSS event.

A benefit of this simple approach is that it can be easily automated. The disadvantage is that it can easily introduce errors into several types of performance summaries. In a scenario where there is a ShakeAlert for a smaller ANSS event in the south, and a ShakeAlert for a large distant ANSS event in the north say 30 seconds later, CTC will associate the second ShakeAlert with the first ANSS event. Then, ShakeAlert location errors will be reported for the first ANSS event, when the ShakeAlert location for event 2 is compared against ANSS location for event 1.

This kind of association error can also impact the time to first alert performance summaries. These association issues are not easily resolvable for an automated testing system. As a result, we believe that the cumulative summaries are most useful showing general ShakeAlert performance trends. Any individual measurement, especially anomalous results such as very large location, magnitude, or timing error should be examined in detail before accepted as correct.

In the CTC ShakeAlert cumulative performance summaries we present in this report, we have examined results for a number of data outliers including large magnitude errors [CI15200001], large location errors [CI15189073], and very short time to first alert [NC71812891] in the (4) catalog results. At this point we do not believe any of the outliers can be attributed to association errors, but the actual cause of these outliers may need further analysis to understand completely.

General Comments about ShakeAlert Performance Based on CTC Results:

The CTC results show that the ShakeAlert processing system has good availability, although not yet 7x24x365. The CTC successfully retrieved ShakeAlert logs for the great majority of ANSS events.

The CTC results indicate that the most obvious issue for ShakeAlert is a tendency to issue multiple ShakeAlerts (split events), often with widely different locations, during larger events. The CTC ShakeAlert event summaries show that ShakeAlert DM split most M4.0+ and larger events over the last year. These split events are the source of several poor CTC performance measures including time to first alert, location, and magnitude errors.

The CTC results indicate that a number of ShakeAlerts are issued with very large location errors, including multiple location errors that exceed 200km. These large location errors may be due to split events, and they may be largely resolved if the split event issue can be resolved.

Several of the CTC ShakeAlert cumulative performance summaries show results for first alert, and for last alert, and the CTC results show, as might be expected, that the final estimates are typically more accurate than the initial estimates.

The CTC ShakeAlert cumulative summary table provides some insight into the performance of individual algorithms. Even allowing for some inaccuracies in the table due to association errors, general performance characteristics are clear.

Overall, ShakeAlert is generating ShakeAlerts for a great majority of the ANSS events at M3.5 and larger. The VS algorithm is the most consistent, with ElarmS second. OnSite, as might be expected, generated ShakeAlerts for the fewest number of ANSS events. Our experience with earthquake monitoring systems suggests that there is often a trade-off for associator/locator-based system between completeness for smaller events, or robustness in solution for large events, so the algorithm with the most complete catalog is not necessarily the one that will perform best for large events.

Recommendations for CISN ShakeAlert System Improvement:

The CTC results should provide information to both algorithm developers and ShakeAlert system operators can then provide their own interpretation of the results. To support USGS efforts to move ShakeAlert toward public availability, we will describe a number of recommendations for ShakeAlert development based on both our experiences implementing the CTC and on our own interpretation of current CTC results.

During implementation of the CTC ShakeAlert testing, we identified a number of improvements that would improve the information logged by the ShakeAlert in real-time. Since the CTC performance results are retrieved from ShakeAlert log files, consistency and completeness of the ShakeAlert logs is important for good performance summary results. During the current implementation, we have identified some fairly minor inconsistencies in the data formats logged by individual algorithms. We recommend that data logs for each algorithm are reviewed to insure all algorithms log information in a consistent manner.

We also note that current ShakeAlert log format is a combination of timestamps and XML data. We believe the log format should be updated to be fully XML, which would make the processing simpler and less prone to mis-interpretation. Finally, the performance evaluation information that CTC can routinely analyze depends on what is logged by the ShakeAlert systems. Certain possibly useful ShakeAlert performance information, such as communication delays, is not available in the currently processed ShakeAlert logs, but could be included in CTC ShakeAlert Performance summaries if additional parameters are added to ShakeAlert log files.

We recommend that the ShakeAlert logs are updated to contain version information for each of the individual algorithms and for the Decision module. Currently, CTC ShakeAlert cumulative summaries may combine performance measures of different versions of the algorithms. ShakeAlert developers are interested in learning whether new ShakeAlert modules improve ShakeAlert performance. If software versions are added to the ShakeAlert logs, it will be easier for the CTC testing to distinguish performance between ShakeAlert system versions.

Some information logged by ShakeAlert algorithms, and decision module is either not displayed (magnitude uncertainty) or are fixed (decision module likelihood). The CTC ShakeAlert event summaries uncertainty time series show the ShakeAlert algorithms send likelihood estimates into the decision module, and that the DM current sends a fix value of 0.7 likelihood for all output messages.

In the CTC results, we note that the CTC was not able to generate performance summaries for every ANSS California event given time periods. In our analysis of CTC results, we've determined that missing summaries can be caused by a number of different causes including unexpected changes to the ShakeAlert log file format, and to missing, or inaccessible, log files. This can be observed in the CTC data as missing dates (e.g. July 18 2012 – July 25 2012). At least some of these data gaps are indicators that the CTC processing system could not locate ShakeAlert log files for these days. As a result, ShakeAlert missed events may originate from multiple causes, including no ShakeAlert trigger, or ShakeAlert system downtime. We believe the CTC ShakeAlert testing provides information needed to analyze the cause and properly attribute the cause of any particular missed event.

In the overall ShakeAlert system performance, the split event issue seems to be a top priority. This ShakeAlert performance characteristic seems to emerge most clearly for larger events, where Early Warning notifications are most needed.

Due to the current low frequency of large events in California, it is difficult to exercise the ShakeAlert system under the necessary large earthquake scenario. As a result, ShakeAlert development would likely benefit from tools for re-running observe seismograms from historical California earthquakes into ShakeAlert processing in offline mode. Such a capability may be valuable in stress testing ShakeAlert under large event scenarios to reduce such split events.

Recommendations for CTC System Improvement:

Our efforts developing and using the current CTC testing system have lead to several recommendations for improvements for the testing center itself.

The CTC development priorities have been to establish basic routine operations that produce useful CTC performance results, which we think we have done. Presentation of CTC results has been a much lower priority. As a result, the current CTC Testing web site presentation is poor. The CTC Web site is hard to find. Once on the web site, specific results are hard to find. ShakeAlert performance summary files have long, cryptic file names, with inconsistent file type extensions (e.g. CTC PNG files names do not end in .png), and there is no clear organization to the multiple types of CTC data results.

We have avoided implementation presentation approach until we better understood how the CTC performance results are used. Once we better understand the presentation needs of users, we will update and improve the presentation of CTC results.

The CTC ShakeAlert evaluations were implemented largely based on the priorities defined by the CISN Technical group and in the 2008 CISN ShakeAlert testing document. The CTC performance measurements currently do not include ShakeAlert "False Alarms". This measure is important, but not yet implemented because it requires a different manner of scanning ShakeAlert log files, as well as a careful full definition of a ShakeAlert "False Alarm." In the current CTC processing, ShakeAlert logs are scanned for information at time of ANSS events. To implement False Alarms metric, CTC must be modified to scan all time periods for ShakeAlert activities. We have avoided developing a full definition of a ShakeAlert False Alarm because it can be complex and contentious. However, we recommend that this definition should be created within the ShakeAlert group and then implemented in CTC processing.

A significant limitation of the current CTC system is the timeliness of CTC performance results. Currently, CTC ShakeAlert performance summaries are available approximately two days after a California Event. We introduce this delay so the information (event parameters) in the ANSS catalog is "stable". However, for users, the information is not available when users are most interested, that is, immediately after a significant California event. We believe these processing delays can be reduced or eliminated by changing the CTC processing approach to either a short update time periods, or to an event driven processing model.

We have learned that CTC users want to generate cumulative performance summaries for alternative catalogs. As currently implemented, the CTC catalog definitions are not user configurable. The CTC might be more useful if it allowed the user to select the catalog used in cumulative performance summary. Currently, CTC data including input catalogs, input logs, and output performance results, are stored in XML formats. To provide flexible queries, it would be necessary to introduce a database into CTC processing. We have avoided this so far, due to the time and effort required to develop and maintain a database approach. However, future versions of CTC might be improved (at greater cost) by introduction of data relational data storage.

Finally, we recognize that ShakeAlert system developers plan to replay historical events into the ShakeAlert processing system for the purpose of regression and stress testing of the ShakeAlert system. In this case, it would be valuable to make use of CTC testing capabilities in an offline, retrospective mode. The current CTC implementation will require a moderate level of modification to support such offline testing.

Summary CTC:

We believe that the CTC ShakeAlert testing system, as current implemented, provides standardized, and repeatable, testing of ShakeAlert system performance. The current CTC system implements a neutral third-party, consistent, testing approach to ShakeAlert algorithm and decision module performance evaluation. The current CTC implementation provides robust testing capabilities with low development and operations cost by leverages capabilities of the SCEC CSEP testing center software. We believe the current CTC ShakeAlert testing efforts have produced useful ShakeAlert testing capabilities, useful ShakeAlert testing results, and a better understanding of what is needed to perform routine ShakeAlert performance evaluations.

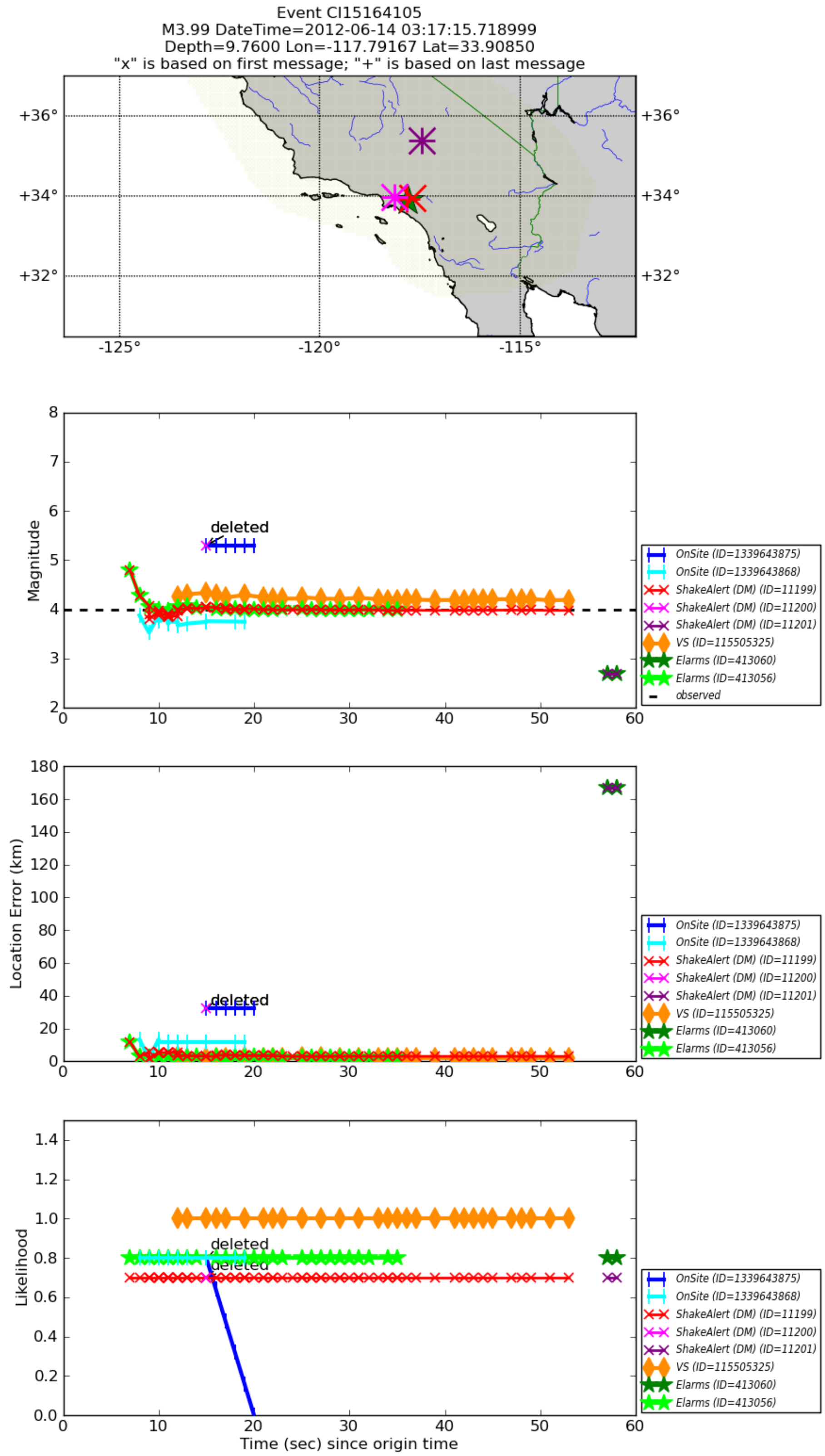
Event CI15164105
M3.99 DateTime=2012-06-14 03:17:15.718999
Depth=9.7600 Lon=-117.79167 Lat=33.90850
"x" is based on first message; "+" is based on last message
deleted
Magnitude
Location Error (km)
Likelihood
Time (sec) since origin time
OnSite (ID=1339643875)
OnSite (ID=1339643868)
ShakeAlert (DM) (ID=11199)
ShakeAlert (DM) (ID=11200)
ShakeAlert (DM) (ID=11201)
VS (ID=115505325)
Elarms (ID=413060)
Elarms (ID=413056)
observed

Figure 1.

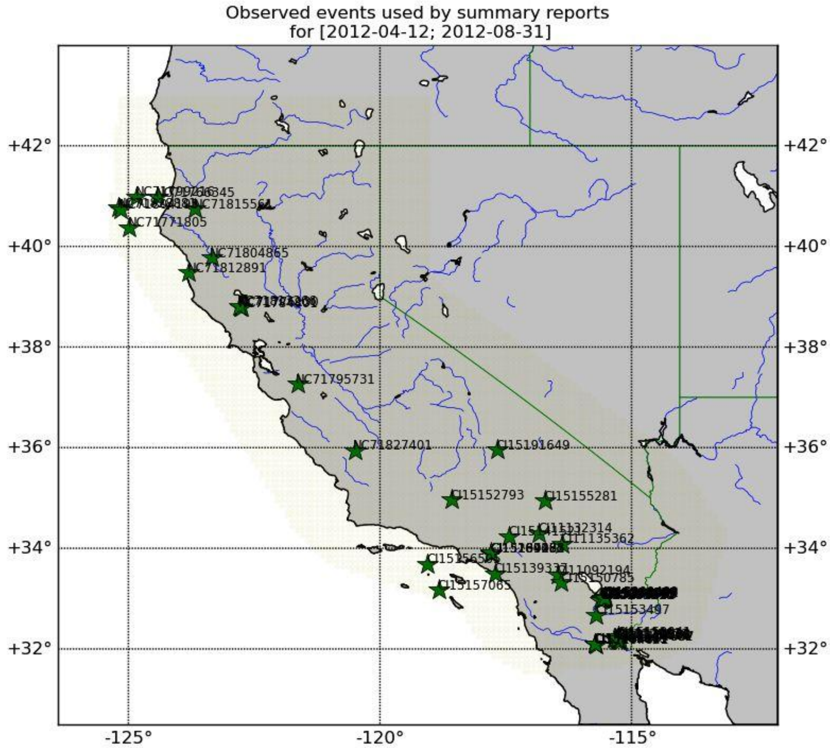

Figure 2.

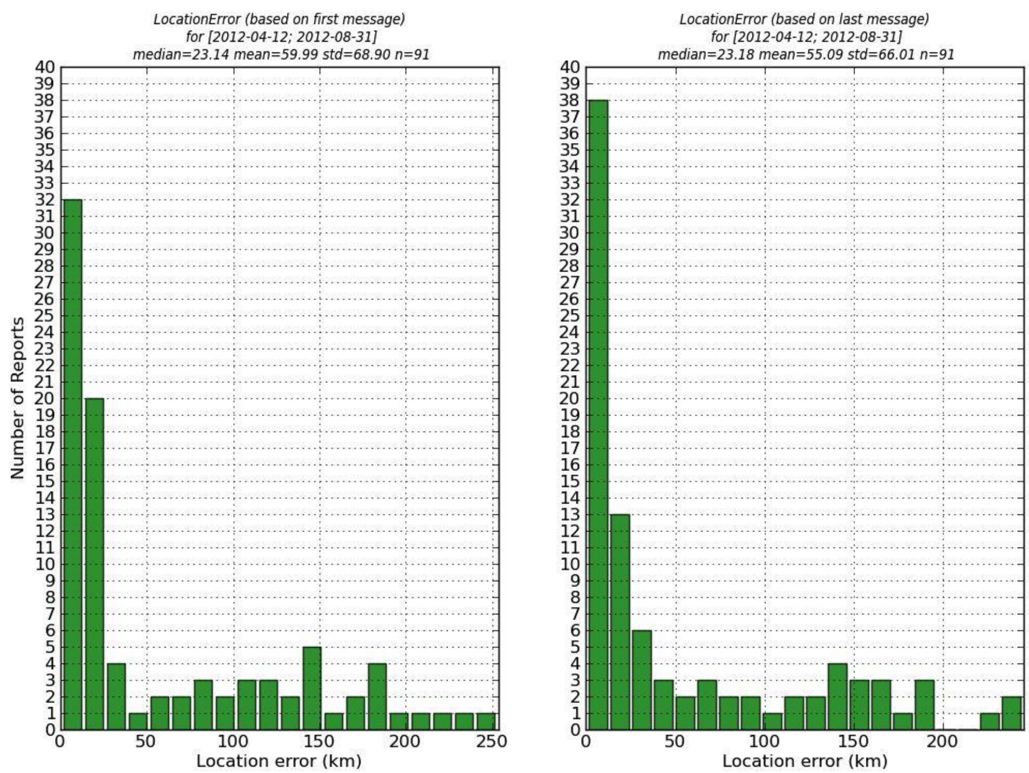

Figure 3.

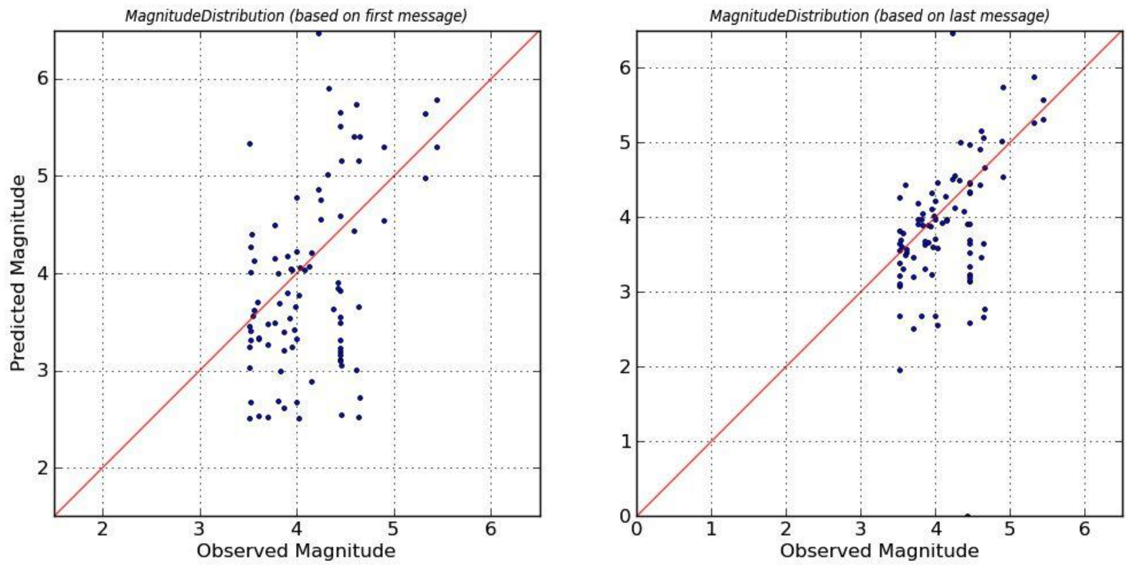

Figure 4.

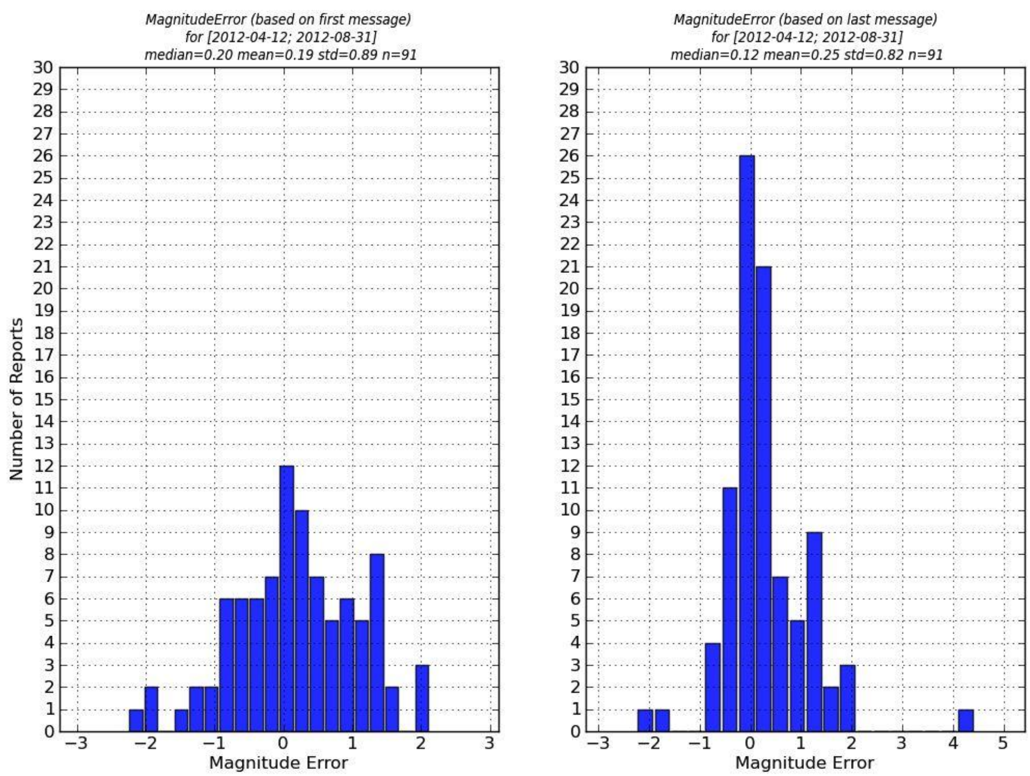

Figure 5.

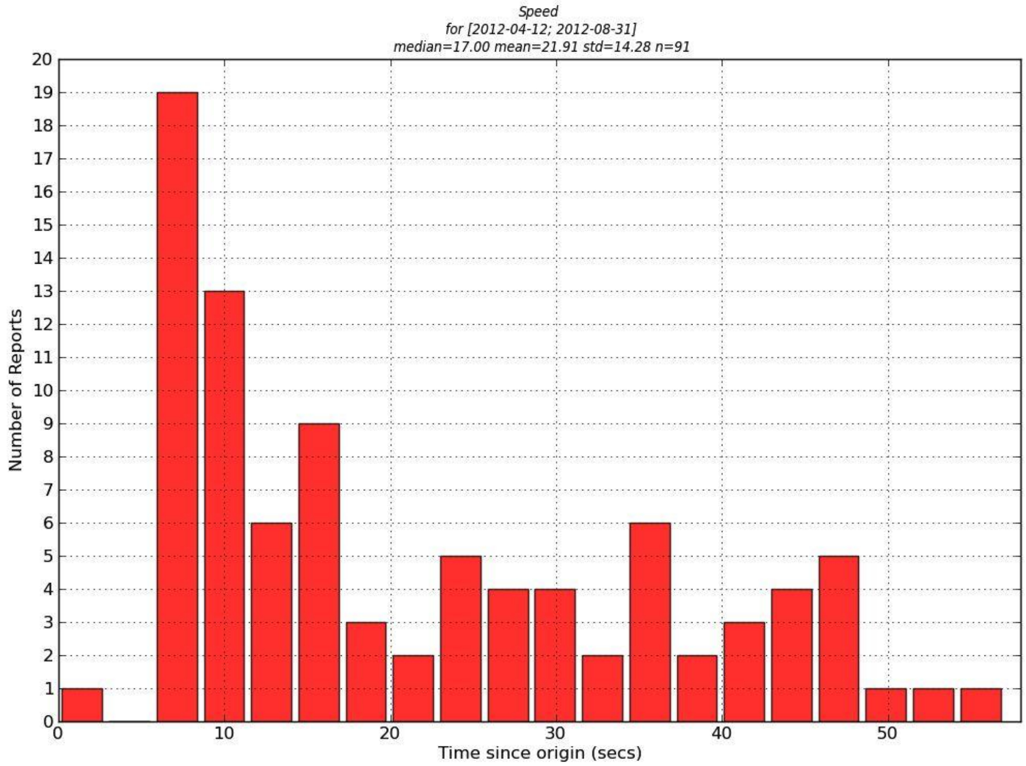

Figure 6.

Overall Performance for [2012-04-12; 2012-08-31]
Using reference ANSS events: M>=3.5; ['CI', 'NC'] codes; 60 seconds since origin

	ANSS Events [#]	Hits [#(%)]	Misses [#(%)]
ShakeAlert	63	58 (92)	5 (8)
VS	63	57 (90)	6 (10)
Onsite	63	38 (60)	25 (40)
ElarmS	63	49 (78)	14 (22)

Hits: Number of ANSS events with one or more ShakeAlerts within 60 seconds after origin time.
Misses: Number of ANSS events with no ShakeAlerts within 60 seconds after origin time.

Figure 7.

VI. Engagement of End Users in EEW and Outreach (Caltech, UC Berkeley)

We have started in 2011 to work with a group of 15 selected Beta Test Users from institutions and industries throughout California that have potential uses for EEW information (Vinci et al., 2009; Hellweg et al., 2012). ShakeAlert Beta Test Users are currently running the ShakeAlert UserDisplay. In return, they provide feedback which includes suggestions to improve the UserDisplay and other alert delivery mechanisms, as well as information on their potential uses of EEW. Beta Test User suggestions are incorporated into revisions of the UserDisplay and other elements of the ShakeAlert system, as appropriate. To form a knowledge base for EEW implementation into a public system, we also collect feedback detailing implementation costs and challenges within the Test User organizations, as well as anticipated benefits and savings. Thus, Beta Test Users are contributing to an operational Earthquake Early Warning system that will meet the needs of the public.

In both Northern and Southern California the role of the CISN ShakeAlert Education and Implementation Group is two-fold. First, to reach out to strategic users of a California Earthquake Early Warning System (EEW) to extract important information regarding the performance and accuracy of ShakeAlert and potential applications within their organization. This information is essential to the future development of a robust and user friendly early warning system in California. Second, is to educate potential users about the importance of earthquake early warning in California due to the ever-present threat of damaging earthquakes in a complex seismic area.

A select group of strategic early warning organizations who were willing to make a commitment to be ShakeAlert Beta Test Users were recruited with the following criteria:

- Trusted organizations that will be strategic users of early warning and able to provide the time, manpower and equipment necessary to perform the necessary tests of ShakeAlert and provide quality feedback regarding the operation, usage and deliver mechanism of the system. Beta Test Users need to utilize ShakeAlert in their daily operations;
- Identify key personnel within the organization to approve and facilitate a plan to activate ShakeAlert and provide feedback from their team of users;
- Test users need to understand that ShakeAlert is a system under development with limitations on the current system (and EEW in general), uncertainties in earthquake parameters and reporting (false positives and negatives) and user tolerance of uncertainties

Regular interaction is necessary with Beta Test Users to provide support and assist them with any implementation issues, additional training and to ensure productive feedback. Beta Users are asked to investigate the real-world performance of ShakeAlerts and document their feedback for research and development and identify the following:

- How will ShakeAlert (or EEW in general) be useful to the organization
- Necessary needs for each user to implement ShakeAlert
- Identify delivery mechanisms and implementation issues
- Industry-by-industry assessment of uses for early warning
- Cost benefit analyses in the context of shaking risk
- Cost to the organization to implement ShakeAlert
- Develop templates and instructions for users of early warning
- Limitations of the system
- Make adjustments to ShakeAlert based on users feedback

a. **Efforts in SoCal** (Caltech)

In Southern California we were able to utilize current relationships developed through the Caltech Earthquake Research Affiliates (ERA, http://www.caltech-era.org/) program to recruit a select group of Beta Test Users. Partners in the ERA program are currently critical users of earthquake products such as CISN Display, ShakeMap, ShakeCast, Did you Feel It and earthquake notification, and they have an understanding of the importance and need for early warning in California. In areas where there are no prior contacts new relationships were cultivated.

Implementation steps

<u>Step 1: User selection and initial contact</u>

Proper selection of Beta Test teams and implementation of the ShakeAlert software has proven to be a time consuming process. Initial contact is made to identify key personnel within the organization who will be instrumental in providing the required authorization and criteria to perform the necessary monitoring of ShakeAlert and provide quality feedback. It is important to find advocates committed to seeing that ShakeAlert is implemented, notifications monitored and who actively explore uses within their organization and utilize ShakeAlert in their daily operations.

A letter of invitation is then sent to the selected contact person (team leader) along with EEW documents (Operations Guide and FAQ) to enable the team leader to acquire the necessary authorizations and select his team which would usually include emergency management and IT. This process would sometimes require two or three meetings and continued follow-up to acquire any required authorizations, compile the best Beta User Team and provide adequate on-site training to the team.

Table1. Selected Beta Test Users in SoCal and current status of implementation and testing.

Southern California Beta User	Date of first on-site training	Date Activated	Implementation Feedback
Amgen International (research laboratory) (Emerg. Mgmt.)	4/3/12	4/5/12; 4/30/12	IT access had to be acquired; download to lap top and then to computer; lost feed when IT system reworked
CalEMA Warning Center	4/6/12; 5/2	3/15/12; 5/2/12	Authorization for access granted
CalEMA Los Alamitos	5/2/12	5/12	Installed in a few days with some assist
Caltech (safety/security)	8/2/12	8/23/12	IMSS authorized download/training
Los Angeles City EMD	2/27/12	3/2/12	No implementation issue
Los Angeles City Police Dept.	8/1/12	8/28/12	Issues with firewall – IT solved
Los Angeles County OEM	6/22/12; 8/21	8/8/12	Issue with firewall authorization
Los Angeles County Sheriff	6/22/12	7/12/12	Firewall authorization
Los Angeles County Fire	5/8/12; 6/25		Difficulty with fire wall; downloaded to lap top; using port xxx to activate in dispatch

LA Metro Rail (dispatch)	9/25/12	10/12	IT access granted for firewall but some trouble downloading
Metrolink (dispatch)	3/28/12	4/12	No implementation issue
Riverside County OEM	10/15/12	10/12	No implementation issue
San Bernardino County OEM	10/30/12	10/30/12	No implementation issue
Southern California Edison (safety/environ/IT)	4/3/12; 9/6	9/28/12	Difficulty in accessing firewall – Strict access - Opened new port xxx to access
Pending:			
Caltrans (Eng/innov/design)			Invite letter – waiting for authorization and formation of teams
Disneyland (Eng/Emerg. Mgmt)	December 6th		Invite letter 7/25/12;
LADWP (Emerg.Mgmt/Eng)			Invite letter – waiting for authorization and formation of team
Los Angeles City Fire	November 13th		
So Cal Gas (Emerg. Mgmt)			Identifying proper contact
San Diego Gas & Electric			Identifying proper contact

Step 2: On-site Training/Education

ShakeAlert Beta Users were implemented one at a time in order to provide each user with adequate assistance in properly implementing the UserDiplay and obtaining quality feedback and to resolve any download issues before implementing another User. Once ShakeAlert is activated continual communication with the Beta Test User is essential in keeping them engaged. Providing follow-up and addressing questions and exploring answers to problems allowed the User to become familiar with the system. This interaction is time consuming but provided quality feedback.

Through our one-on-one training sessions we were able to educate our Beta Test Users on the importance of the CISN as the backbone in providing essential data to do early warning in California, the operation of the ShakeAlert UserDisplay, and the limitations, challenges and benefits of earthquake early warning to their organizations in general. Presentations included scientists and members of the outreach team. Education of users of earthquake early warning is an essential part of the success of earthquake early warning.

At the one-on-one trainings each Beta User organization was supplied with a packet which contained the Operations Guide (see Appendix A), Frequently Asked Questions, sample of the feedback questions and feedback log. To keep control of who has access, the ShakeAlert software is password protected and request for access needs to be granted before the password is issued. A flash drive is provided each Beta User containing their personnel password and username, digital copies of each of the documents and the ShakeAlert software.

Step 3: Feedback Process

The feedback process is performed via email with survey questions. The number of inquiries is kept to a minimum as to not overburden the Beta User. Emails are sent periodically every 3 weeks to check continual performance of ShakeAlert and keep Beta Users involved. In the event of an unusual event (larger magnitude or swarm) an email survey is sent for that particular event ID number. Information we are looking for is: receipt of notification, intensity, warning time, and description of operation that could have been performed, potential uses.

We observed that the more familiar the Beta User becomes with ShakeAlert, the more productive the feedback becomes. A form was devised to assist new Beta Users in becoming familiar with ShakeAlert by posting entries and comparing accuracy of warning time with the CISN Display. Some Beta Users will forward feedback without being prompted but the majority of feedback is prompted by a short periodic survey. Interaction with users has prompted response.

Initial Feedback

The performance of ShakeAlert has been generally evaluated as very good and accurate (keeping in mind that there were only a few felt earthquakes during the testing so far). Users have reported that the system is working so well that they become complacent and forget it is not a "ready" product.

Since the initial implementation of the UserDisplay was more time consuming as expected, we are still at the early stage of the feedback process. Here a few issues that were raised by one or more Beta Test users (a detailed compilation can be found in Appendix B of this report):

- All Beta Users in SoCal were able to download and install the ShakeAlert software easily if on a personal lap top, however, connecting through their organizations system proved to be more difficult. Some users were able to download and connect to their internal internet within a couple of days, but others took as long a few months. The more secure the firewall the more difficult it was to get authorization for a test product. In one instance, access was delayed due to the lack of IT manpower to address the problem. In response to this problem, we decided to open a special port on our messaging server, which is normally reserved for HTTPS web connections, allowing the more secure organizations to gain access to the ShakeAlert feed.
- Some users reported problems with the displayed warning time caused by inaccurate computer internal clocks. It seems that some users have trouble connecting to the ntp-server for time synchronization (as implemented in the UserDisplay). We are currently investigating whether time stamps can be added to the ShakeAlert heartbeats or alert messages.
- We have been able to identify a number of user issues in the operation of ShakeAlert, such as turning off the hibernation in their computers; otherwise ShakeAlert messages will not be received. These issues have prompted the development of a "Troubleshooting" page in the Operations Guide" for User based issues.
- Some users requested that the UserDisplay should provide customized alerts with instructions of how to respond to a warning, e.g. "Drop-cover-hold on", "Open Fire Station Doors", …
- We have had repeated requests by some Users for ShakeAlert to be on a hand held (mobile) device that can locate their location by GPS as they are in the field. An Android app is currently in test mode.
- The ShakeAlert system, including the UserDisplay, allows sending test messages to users. To prevent confusion these messages are clearly marked as test events. On October 18, 2012 (Great California ShakeOut) we sent 2 test alerts to our Beta Test users: in Northern California with a M6.9 on the Loma Prieta Fault at 2:00pm and in Southern California with a M7.8 in the Cajon Pass on the San Andreas Fault at 3:00 pm. All authorized ShakeAlert users were notified of the test beforehand. Aside from one user, who had issues with the computer clock time, the feedback indicated that the test messages were received correctly and in time. The test

provided information on the performance of ShakeAlert at a higher magnitude and allowed us to engage all ShakeAlert users. All test users indicated their wish to receive test messages on a regular basis.

- Suggested operations that could be triggered by EEW:
  - Initiate immediate statewide notification via an automated messaging system called NC4. Could also utilize the CMAS (Commercial Mobile Alert System aka PLAN - Personal Localized Alerting Network). Alert can be programmed into automated notification systems to avoid the human-reaction. Not enough time form manual activation of EAS (emergency alert system).
  - Hospital operating room – warning at nurse's station to notify rooms (automated); use fire alarm system to trigger elevator doors to open (automated)
  - Research labs - trigger operations to turn off gas and hazardous material; turn off machinery; preserve research data
  - Alert researchers in labs and student on campus to get into safe place
  - trigger backup of medical records (automated)
  - Operation – trigger "save" button on computers (automated)
  - keep planes in the air or cancel take off (automated/manual)
  - notification of upper level management out of area before loss of power/communications
  - open fire station doors; turn on lights; pull out fire/rescue tools; protection of personnel in field especially in search and rescue operations (automated and manual)
  - personnel safety especially those in hazardous situations (on electrical poles or in baskets in air to make repairs; electrical vaults; repairs to underground water pipes)
  - broadcast warning to all patrol personnel; jail facilities, courts and county buildings (manual/automated)
  - Trains (light and heavy rail) – if sufficient time, a dispatcher could open a key to a strong radio and give general warning to trains to slow trains and wait for instructions. Since trains are currently being equipped with computers that will talk to signals (PTC), tying the EEW into this would give many a real-time warning. They could slow down trains to minimize impact to passengers and equipment.
  - Buses – automated signal to pull over to the side of the road to avoid a secondary disaster

  - Emergency response organizations - first and foremost is the protection of employees and facilities as a critical component to our state's emergency management to maintain continuity of operations. Cost isn't a factor when considering the benefit. Many emergency operation centers are already staffed 24/7 and implementation of EEW or integrating it into existing systems is cost-neutral.
- Tolerance to false alarms: in a preliminary assessment users have indicated they would tolerate 2 – 3 false alarms per year when an operation is executed.

Conclusions (Caltech Outreach)

Time is being taken to carefully select our Beta Test Users and implement ShakeAlert to insure the quality of the feedback we are looking to extract and to keep control of the project. As of this date we have implemented all but three of our original selected Beta Test Users in SoCal and they should start providing feedback within the next few month. Delays in implementing these Users have been caused by limited man hours on our end and the time taken for the potential user to acquire authorization to be a part of the project, put together their Beta User team and find an available date to meet and provide the training and tools to start the Beta Test. Additional Beta Users were added to the original list of which all have been implemented but two.

We continue to provide a working relationship with the Beta Users and try to keep requests for input to a minimum (as warranted but no less than monthly) and email surveys short. However, there is daily interaction with Beta Users to address various User questions. We are able to interact personally with many of the Beta Users at our semi-annual ERA meetings and plan to conduct a telephone discussion as soon as all Beta Users from the current list are on board and have become familiar with ShakeAlert.

The majority of the feedback at this time focuses on the UD; Beta Users need to take time to become familiar with the UD first before they can thoroughly examine the operations that can be performed that would benefit their organization. Some of the uses/operations that have been identified to date are listed above. However, identifying uses and operations will become more of the focus in weeks to come along with an evaluation of the benefits to the organization and any costs they expect to their organization to utilize earthquake early warning. We will continue to perform scheduled test alerts and survey current real-time events. Some Beta Test Users have already expressed a strong interest in working with us to develop a system within their organization to utilize EEW, especially in respect to transportation, and a discussion meeting has been planned.

b. **Efforts in NoCal** (UC Berkeley)

UC Berkeley's efforts to engage users have been a coordinated and collaborative effort with Caltech. Here we summarize our activities with two groups that have been a specific focus at Berkeley: (1) external public and private institutions, and (2) the BSL focus group. One of the key lessons learned during the USGS Phase II EEW project is that engagement with external groups requires continual maintenance and is therefore *very* time consuming. Also, the local connection is important, most organizations think of earthquakes as a local problem and want to engage with local organizations and be part of a community. The BSL is now investing in this engagement by hiring into a new position to specifically engage external groups in BSL research activities, including EEW. This new person will start in November 2012 (but is not funded by USGS projects). The decision to invest in this position is an outcome of the experience gained engaging users in this project.

Engagement of external public and private institutions

Engaging external groups in the development of a demonstration/prototype EEW system is an extremely time consuming activity. Firstly these groups need to be convinced that earthquakes pose a hazard to their institution/employees/business that is significant enough that they should focus effort on the problem now. Secondly, they need to be convinced that EEW is a useful mechanism to mitigate those earthquake hazards and that is it feasible for them to make use of the alerts in the long term. Finally, they need to identify individuals with the appropriate expertise, responsibility and time to repeatedly engage in the project. For this reason we have focused our efforts on groups that are willing to make a commitment up front to distribute the alerts internally and develop specific actions that the organization should take when an alert is received. The groups that fall into this category and that we currently deliver ShakeAlert output to are BART, the City and County of San Francisco, Google, and the UC Police and Emergency Response Departments. We have not pursued expressions of interest from other groups given our limited resources. These include the US Coast Guard, US Internal Revenue Service, Lafayette School District, City of Berkeley, Berkeley School District.

BART (the Bay Area Regional Transit train system) has been interested in developing an EEW capability since early 2009. At that time Berkeley Seismological Laboratory (BSL) partnered with them to develop a demonstration system for the anniversary of the 1989 Loma Prieta earthquake. They already operated 10 accelerometers along their tracks that sounded an alert in the control room when the acceleration exceeded some threshold. They wanted to build on this capability in small incremental steps. The first step was to start delivering peak ground motion data to them from all the seismic stations across the greater San Francisco Bay Area. A rapid data feed was possible by taking an output from the ElarmS-WP module and streaming peak amplitude values from every station every second to the BART control center. By the time of the Loma Prieta anniversary (October 2009) they were receiving this feed and used a stand-alone computer at the back of the operations center to sounds an alarm when shaking above some threshold was observed. At the time of the anniversary we streamed synthetic data for the Loma Prieta earthquake as part of a drill. The alert sounded in the control room. The train operations chief ordered an emergency system stop, and all trains where brought to a standstill. The upper management watching the drill timed the delay between the alarm sounding and the emergency stop command being issued as 23 sec. Immediately there was a consensus in the room that the emergency stop should be automated.

The next step in the development of the BART alerting system was to implement an automated system to stop trains. This involved ensuring a robust data feed from BSL and the development of the appropriate train control codes. This development continued as a BSL-BART collaboration resulting the implementation of the first automated EEW response by a transit system in the US. In August 2012 the system went live and the BART system now stops trains using the peak ground shaking data feed. The next step is to start using the P-wave based alert feed. BART has been receiving the P-wave based alert feed since early 2012 and is developing confidence in the system. Their first step was to further develop the UserDisplay code so that it would integrate the P-wave based alerts with the peak-shaking observations that they also receive. This allows them to see the P-wave based alerts, and the peak shaking alerts in a single display. We continue to work with them to further enhance the system.

The City and County of San Francisco Department of Emergency Management (DEM) partnered with the BSL in 2012 to start receiving EEW alerts and begin the process of educating various city departments about the capability and asking them to develop specific uses. To date the only people receiving the alerts are within the DEM. Other city groups that have expressed an interest in using the alerts include the Fire Department, the Police, Public Works and the airport (SFO). We are currently working to help facilitate this outreach across city departments.

Google has been receiving the alerts since early 2012. Their primary interest at the beginning of the collaboration was to gather data. The specific applications that they wanted to pursue were (1) providing alerts to Google employees, (2) providing alerts to their data centers, and (3) developing mechanisms that could be used to deliver the alerts broadly to the public in the future (when the system becomes public). They continue to receive the feeds, though we have not been successful in gathering much feedback to date.

The UC Police and Emergency Response Departments are based at UC Berkeley. This provided an opportunity to engage with an emergency response organization responsible for a significant number of people, i.e. all 10 UC campuses comprising of 230,000 students and 200,000 employees. To date, the UserDisplay has been installed at their headquarters (located on the UC Berkeley campus) and is running continuously in their operations/dispatch center. They are currently developing a series of response protocols based on the alerts and have indicated that they will be happy to share these with the EEW group once complete. They are also developing plans to make use of ShakeAlert in several other sensitive facilities including a level 4 biohazard lab, the campus data/server center, the fire department, and within the Lawrence-Berkeley National Laboratory (adjacent to the UC Berkeley campus).

The BSL focus group

This is an informal group of private users that have expressed interest in receiving the EEW alerts and providing us with feedback. The group currently consists of ~20 people who are all UC Berkeley employees in various units across the campus. It includes some scientists, but mostly non-scientists with an interest in the project. Feedback has been gathered from this group on an informal basis. Perhaps the most important lesson learned is that despite people's initial interest, most do not continue to run the UserDisplay beyond a few days. Improving the UserDisplay so that once installed it automatically re-starts when a computer boots and also automatically updates can alleviate this problem. In the longer term it will be key for the delivery mechanisms for any public EEW system to be automatic, e.g. embedded in operating systems for computers and mobile devices. There are a few dedicated users who continue to re-start and run the UserDisplay (now ~8 months since initially signing up). Their regular feedback on system operation has been very valuable. This feedback includes comments on the clarity of the information in the UserDisplay, their tolerance for false alerts, the need for clearer "cancel" messages when appropriate, and the value of test alerts such as the October 18, 2012 ShakeOut test alerts.

Publications

Allen R.M., 2011: Earthquakes, Early and Strong Motion Warning in Encyclopedia of Solid Earth Geophysics, Harsh Gupta (ed) p226-233, Springer.

Allen R.M., 2011: Seconds before the big one, Scientific American, April 2011.

Allen R.M., P. Gasparini, O. Kamigaichi, M. Bose, 2009: The Status of Earthquake Early Warning around the World: An Introductory Overview Seismo. Res. Lett., 80, (5) p682-693, doi: 10.1785/gssrl.80.5.682

Allen R.M. , Ziv A., 2011: Application of real-time GPS to earthquake early warning Geophys. Res. Lett., 38 L16310, doi:10.1029/2011GL047947.

Barba M., Böse M., Hauksson E., 2010: The Earthquake Early Warning Demonstration Tool (EEWDT), 2010 Southern California Earthquake Center (SCEC) Meeting, September 11-15, Palm Springs, California.

Böse M., Allen R., Brown H., Cua G., Fischer M., Hauksson E., Heaton T., Hellweg M., Liukis M., Neuhauser D., Maechling P. & CISN EEW Group, 2012: CISN ShakeAlert – An earthquake early warning demonstration system for California, in: '*Early Warning for Geological Disasters - Scientific concepts and current practice*', eds. Wenzel, F. & Zschau, J., Springer, accepted.

Böse M., Hauksson E., Hellweg, M., Cua, G., and CISN EEW Group, 2011: CISN ShakeAlert: UserDisplay-Operations Guide V 3, SeismoLab, California Institute of Technology, Pasadena, California

Böse M., Hauksson E., Solanki K., Kanamori H., Wu Y.-M., Heaton T.H., 2009a: A new trigger criterion for improved real-time performance of on-site earthquake early warning in southern California, Bull Seism Soc Am 99 (2-A): 897-905, doi: 10.1785/0120080034.

Böse M., Hauksson E., Solanki K., Kanamori H., Heaton T.H., 2009b: Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29 2008 Mw5.4 Chino Hills earthquake, Geophys Res Lett 36, L00B03, doi:10.1029/2008GL036366.

Böse, M., Hauksson, E., Solanki, K., Heaton, T. and the CISN EEW group, 2009c: Recent Developments in CISN Earthquake Early Warning Testing for California, 2009 Annual SCEC Meeting, Palm Springs.

Böse M., Heaton T.H., Hauksson E., 2012a: Rapid estimation of earthquake source and ground-motion parameters for earthquake early warning using data from single three-component broadband or strong-motion sensor, Bull Seismol Soc Am 102(2), doi: 10.1785/0120110152.

Böse M., Heaton T.H., Hauksson E., 2012b: Real-time Finite Fault Rupture Detector (FinDer) for Large Earthquakes, Geophys J Int, 191(2), doi: 10.1111/j.1365-246X.2012.05657.x.

Böse M., Solanki K., Allen R.M., Brown H., Cua G.B., Given D., Hauksson E., Heaton T.H., CISN Earthquake Early Warning Project Team, 2010: CISN ShakeAlert: Development of a Prototype User Display for Providing Earthquake Alerts to End Users, American Geophysical Union, Fall Meeting 2010, abstract #NH33A-1369.

Böse, M., Solanki, K., Khainovski, O., Neuhauser, D., Fischer, M., 2009: Coding Development Plan for the CISN ShakeAlert System by the Technical Operations Team (TOT), V3.

Brown H.M., Allen R.M., Faster Earthquake Alerts with Assistance from an Artificial Neural Network BSSA (in review).

Brown H., Allen R.M., Grasso V., 2009: Testing ElarmS in Japan Seismo. Res. Lett., 80, (5) p727-739, doi: 10.1785/gssrl.80.5.727.

Brown H.M., Allen R.M., Hellweg M., Khainovski O., Neuhauser D., Souf A., 2011: Development of the ElarmS methodology for earthquake early warning: Realtime application in California and offline testing in Japan, Soil Dyn. Earthquake Eng. 31 188-200, doi:10.1016/j.soildyn.2010.03.008

Caprio, M., Cua, G., Wiemer, S., Fischer, M., Heaton, T., CISN EEW Group, 2011. CISN ShakeAlert: Accounting for Site Amplification Effects and Quantifying Time and Spatial Dependence of Uncertainty Estimates in the Virtual Seismologist Earthquake Early Warning Algorithm. AGU Fall Meeting, San Francisco, December 2011.

Colombelli, S., Allen, R. and Aldo Zollo A., Application of real-time GPS to Earthquake Early Warning in subduction and strike-slip environments (in prep).

Cua, G., Fischer, M., Heaton, T., Wiemer, S. Giardini, D., 2009. Real-Time Performance of the Virtual Seismologist Earthquake Early Warning Algorithm in Southern California, Seism. Res. Lett, 80 (5), p740-747.

Cua, G., Allen, R., Boese, M., Brown, H., Given, D., Fischer, M., Hauksson, E., Heaton, T., Hellweg, M., Liukis, M., Jordan, T., Khainovski, O., Maechling, P., Neuhauser, D., Oppenheimer, D., Solanki, K., 2009. CISN ShakeAlert: Three Years of Comparative Real-Time Earthquake Early Warning Testing in California. AGU Fall Meeting, San Francisco, December 2009.

Cua, G., Fischer, M., Caprio, M., Heaton, T., Clinton, J., CISN EEW Group, 2010: Faster Alert Information Through Multiple Threshold Event Detection in the Virtual Seismologist Early Warning Algorithm. AGU Fall Meeting, NH33A-1371, San Francisco, December 2010.

Fischer, M., Cua, G., Caprio, M., Heaton, T., Clinton, J., 2009. Multiple Threshold Event Detection in the Virtual Seismologist Earhtquake Early Warning Algorithm. AGU Fall Meeting, San Francisco, December 2009.

Hauksson, et al., in prep: The 2012 Brawley earthquake swarm, Seismol. Res. Lett.

Hellweg M., Vinci M., Allen R.M., Böse M., Henson I.H., Felizardo C., 2012: CISN ShakeAlert: Beta Test Users Receive Earthquake Early Warning Alerts and Provide Feedback for Improving Alert Delivery, 2012 AGU Fall Meeting.

Kuyuk H.S., Brown H., Henson I., Allen R.M., Hellweg M., Neuhauser D.: ElarmS-2: Designing a network-based earthquake early warning system for California (in prep).

Maechling P.J., Jordan T.H., Liukis M., Callaghan S., 2009: Developing Performance Measures for the CISN Earthquake Early Warning Testing Center. Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract S13A-1717.

Meier, M.-A., Cua, G., Wiemer, S., Fischer, M., CISN EEW Group, 2011: CISN ShakeAlert: Improving Virtual Seismologist Earthquake Early Warning Framework to Provide Faster, More Robust Warning Information. AGU Fall Meeting, December 2011.

Neuhauser D.S., Khainovsky O., Böse M., Solanki K., Cua G., Heaton T.H., Allen R. ,2010: CISN ShakeAlert: The Decision Module for earthquake alerts. AGU Fall Meeting, NH33A-1370. San Francisco, December 2010.

Solanki K., Böse M., Hauksson E., Heaton T.H., CISN EEW Group, 2011: CISN ShakeAlert: Protoype User Display for providing earthquake early warnings to test users. AGU Fall Meeting, S53A-2250, San Francisco, December 2011.

Vinci M., Hellweg M., Jones L.M., Khainovski O., Schwartz K., Lehrer D., Allen R.M., Neuhauser D.S., 2009: CISN ShakeAlert: Using early warnings for earthquakes in California. Eos, 90(52), Fall Meet. Suppl., S13A-1720.

Wu Y.-M., Kanamori H., Allen R.M., Hauksson E., 2007: Determination of earthquake early warning parameters, τ_c and Pd, for southern California. Geophys J Int 170: 711 – 717, doi:10.1111/j.1365-246X. 3732007.03430.x

Appendix A. UserDisplay Operations Guide

CISN Caltech UC Berkeley ETH Zurich SCEC USGS

CISN ShakeAlert

An Earthquake Early Warning Demonstration System for California

UserDisplay – Operations Guide

Version 2.3d

Contents:

1. **Disclaimer:**

The CISN ShakeAlert system, which includes the UserDisplay, is a system under development. We are continuously enhancing the software, including improving the robustness and speed of alert messages. Do not share this software with others.

Disclaimer of Earthquake Information

The preliminary earthquake data provided by the CISN ShakeAlert system are computer generated, and are subject to change. Earthquake records are subsequently reviewed by seismologists. In the acceptance process, details of the information about the event are likely to change, possibly significantly. These include changes to magnitude, location and origin time; or the earthquake information may be deleted as being a false event. The data are not intended to, nor do they provide early warning or a prediction of future seismic activity. All efforts have been made to provide accurate information, but reliance on or interpretation of earthquake data from a single source is not advised. Consumers of the earthquake messages are strongly cautioned to consider carefully and use common sense in any decisions relating to personal or public safety, and the conduct of business that involves substantial financial or operational consequences.

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2. Background

Since 2007 scientists from Caltech, UC Berkeley, ETH Zurich, USC/SCEC and USGS have been working on the development and implementation of a prototype earthquake early warning (EEW) system for California (http://www.cisn.org/eew/). CISN ShakeAlert combines the outputs from three independently running algorithms, Tauc-Pd Onsite, Virtual Seismologist, and ElarmS. CISN ShakeAlert provides a continuum of earthquake alert information, including rapid estimates of magnitudes, locations, and expected seismic intensities. To notify users and to rapidly and simply display alert information, we have developed a Java Application that runs on a user's computer and receives xml-messages from the ShakeAlert system. This UserDisplay shows the user's location and the estimated epicenter of the earthquake. As time elapses from the detection and notification of an event, the current locations of the P- and S-wave fronts are also shown, as well as the estimated magnitude, the predicted intensity of shaking at the user's site and the remaining time until this shaking is expected to start. The UserDisplay pops-up automatically once an alert message is received that exceeds the minimum thresholds for magnitude, intensity and probability that the user has specified. Xml-messages received by the UserDisplay are locally stored on the user's computer and can be replayed. To ensure robust communication, the UserDisplay receives and displays heartbeats coming from the three algorithms and the DecisionModule of the ShakeAlert system.

We are making the UserDisplay available to a limited group of users as part of our testing of the EEW algorithms and software. During the testing, software modules may fail and we expect the system to be off-line some of the time. Thus, it will not be reliable and should not be used to make important decisions. We request that users do not distribute the UserDisplay software to others, as they will not be informed about the progress of the EEW testing and/or may not understand the current limitations of the EEW prototype system. We also ask users of the prototype system not to talk to the news media or judge the system performance, because they may not have enough information to explain unexpected system performance. If EEW testing is a success, the USGS plans to raise funds to build an actual EEW system that will be available to the public, and everybody can receive alerts.

3. Download and Installation - Beta Test Users

Currently, the CISN ShakeAlert UserDisplay program is only being distributed to a select group of Beta Test Users and requires a personal username and password issued to the Beta Test User.

The most recent version of the CISN ShakeAlert UserDisplay program can be downloaded from the CISN website but requires a generic username and password:

Windows:	xxx
Mac:	xxx
Unix:	xxx

SoCal Users have been issued a flashdrive that contains the ShakeAlert software and do not need to access the web site but download directly from the flashdrive.

To run the UserDisplay, users must have a personal username and password. Requests for personal username and password should be directed to either:

Prof. Thomas Heaton (Caltech)	heaton at caltech.edu	(for users in SoCal)
Prof. Richard Allen (UC Berkeley)	rallen at berkeley.edu	(for users in NoCal).

Do not share your username and password with others. If you have trouble downloading the UserDisplay contact:

Margaret Vinci (Caltech)	mvinci at gps.caltech.edu	(for users in SoCal)
Dr. Peggy Hellweg (UC Berkeley)	peggy at seismo.berkeley.edu	(for users in NoCal).

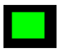
The CISN ShakeAlert UserDisplay is a platform-independent Java Application. The program has been successfully tested on Windows 7, Windows Vista, Windows XP, Linux and Mac OS X. The program requires Java version 1.6 or higher. Please follow the instructions of the installation manager. You must grant the UserDisplay access through your firewall to be able to receive alert messages from the ShakeAlert system.

Once the program is fully installed, you should find a shortcut for the UserDisplay on your desktop. Double-click on the icon and enter your personal username and password to start your CISN ShakeAlert UserDisplay. Do not forget to turn on the volume of your PC to be able to hear the siren and voice announcements, when an alert message is received.

4. Menu

There are menus along the top and bottom of the CISN ShakeAlert UserDisplay. At the top, the following icons and options appear from left to right:

Program exit



Program status:

green: The communication between the ShakeAlert system and your UserDisplay is healthy. You will be able to receive alert messages.

grey: There are either internal problems with the ShakeAlert system or problems in the communication between the ShakeAlert system and your UserDisplay. The communication may still be healthy and you may receive alert messages.

yellow: The ShakeAlert system is only partially operational. You are likely to receive alert messages.

red: There is a problem either in the communication between the ShakeAlert system and your UserDisplay or the ShakeAlert system is down (e.g., for maintenance). You will not receive alert messages.

Program settings:

The Settings window (Figure 1) allows you to enter user-specific parameters.

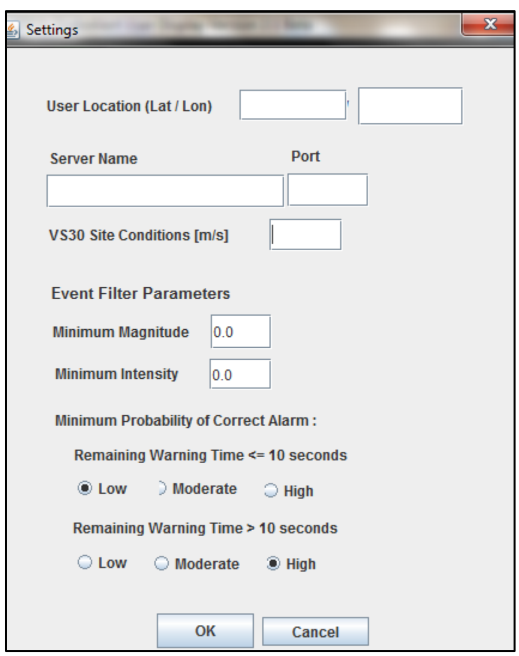


Figure 1. Program Settings.

- **User Location (Lat/Lon):** enter the latitude and longitude of your location; you can use http://geocoder.us/ or other websites to determine the latitude and longitude of your US address

- **Server name & port:** do not change these fields unless requested

- **Vs30 site conditions [m/s]:** enter the Vs30 value (average S-wave velocity of the uppermost 30 m) at your location. This value is important for estimating the seismic intensity at your site. Enter "0" if you do not know the Vs30 value at your site. The program will automatically determine a Vs30 value from a lookup table using the latitude and longitude you entered.

- **Event Filter Parameters:** You can specify three threshold parameters, which must all be exceeded before an event message received by the UserDisplay will be displayed as an alert. Thus, the parameters you set here will control the number of alert messages you will receive.

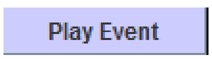
    - **Minimum Magnitude:** enter the minimum magnitude of events for which you will receive alerts. Take care in setting this value. The UserDisplay will receive messages for events with magnitudes as small as "1.0" or even smaller. These events cannot be felt by humans, but can be used to test the alert system. If you set the minimum magnitude too high (e.g. "5.5"), you may not see any alerts in the following weeks or months. We encourage you to try different magnitude thresholds. Start, perhaps, with a small value, like "2.0", and increase the magnitude to "3.0" or "4.5" after a few days when you have become familiar with the UserDisplay.

    - **Minimum Intensity:** enter the minimum seismic intensity (MMI scale) to be expected at your location for which you want alerts. The scale, shown on the lower left of the UserDisplay screen, ranges from "1" (not felt) to "10" (extreme shaking). Bear in mind that you will not receive alert messages, if you choose the threshold too high. Start with a small value (e.g. "1.0") and increase it (e.g. to "5.0") after a few days.

    - **Minimum Probability of Correct Alarm (PCA):** although we are making the CISN ShakeAlert system as robust as possible, we cannot exclude that any particular alert message is wrong. False alerts can result from many different causes, such as instrument failure, noise, or very strong teleseismic (distant) earthquakes. CISN ShakeAlert will often "know" that a certain alert message may be incorrect (e.g. if an "event" is detected by only one or two sensors, but other stations do not trigger) and is capable of providing an estimate of the "Probability of Correct Alarm" (PCA). The PCA has values between "0.0" and "1.0" meaning the alert was most likely incorrect or correct, respectively. For simplicity, we have introduced three PCA levels: "low" (0<=PCA<0.4), "moderate" (0.4<=PCA<=0.7) and "high"

(0.7<=PCA<=1.0). Often, the PCA will increase or decrease as time passes after an earthquake is detected. If an earthquake occurs close to your location and you may thus experience strong shaking soon (i.e. the warning time is <= 10 seconds), you may want to receive all alert messages regardless of their probability. If the earthquake, however, is relatively far away (i.e. the warning time is > 10 seconds), you may want to wait longer and allow the PCA to increase, to make sure that the alert is correct. We therefore recommend specifying a small PCA value ("low" or "moderate") for close events, and a high PCA threshold for distant events ("high").

Press "OK" once you have entered your parameters. The information will be saved and the values immediately applied.



Play Event:

Xml-messages from the ShakeAlert system that have been received by the UserDisplay will be stored on your computer in the "**history**" folder. When you click on "Play Event" button, an open-file dialog appears. You may click on one of the subfolders (the name of these subfolders indicates the ShakeAlert eventID; note that this id is different from the CISN event id that is used in ShakeMap) and replay an event by double-clicking on the file with the ".eew" extension. The event will not be displayed, if the threshold parameters in "Settings" are not exceeded, or if the warning time is zero or negative.

You can find some example earthquakes in the "**examples**" folder.

Show Log:

The log-file lists information for alert messages that have been received. From left to right the file shows: (1) the time when the alert message was received, (2) message type ("NEW", "UPDATE" or "DELETE"), (3) eventID, (4) version (up-date) number, (5) estimated magnitude, (6) estimated event origin time (i.e. when the earthquake occurred/started), (7) estimated earthquake location (lat/lon/depth), (8) estimated seismic intensity (MMI) at your location, (9) Probability of Correct Alarm (PCA), and (10) the (rounded) remaining time (in seconds) until shaking is expected to begin at your location.

Volume control (mute):

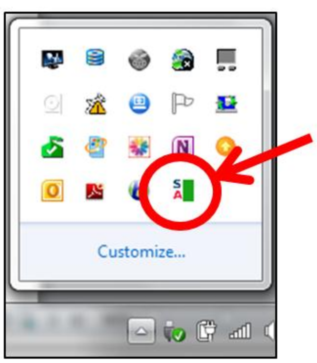
Check this box to mute the volume of your UserDisplay. **You will not hear the siren and voice announcement as long as this box is checked!**

Minimize/maximize and close the UserDisplay window:

Note, that even if you close the window using the "Close Window" button, the UserDisplay will still be running. (Use the "Exit" button on the left of the display to terminate the program.) The UserDisplay will pop-up automatically when an alert message is received that exceeds the settings you have chosen.

Right-click on the ShakeAlert icon in the system tray and select "Show" to reopen the UserDisplay window manually (see below).

Map navigation, zoom in/out



System tray icon:

Right-click the ShakeAlert icon in the Windows system tray (at the lower right corner of your Windows screen) to "Exit" or "Show" your UserDisplay. The color of the icon shows the UserDisplay status (see "Program status" on page 4 of this guide for explanation of color code).

5. Alert Information

When the UserDisplay receives a xml alert message from the CISN ShakeAlert system, the following information will be displayed (provided that your thresholds in "Settings" are exceeded and the remaining warning time is greater than 1 second; Figure 2):

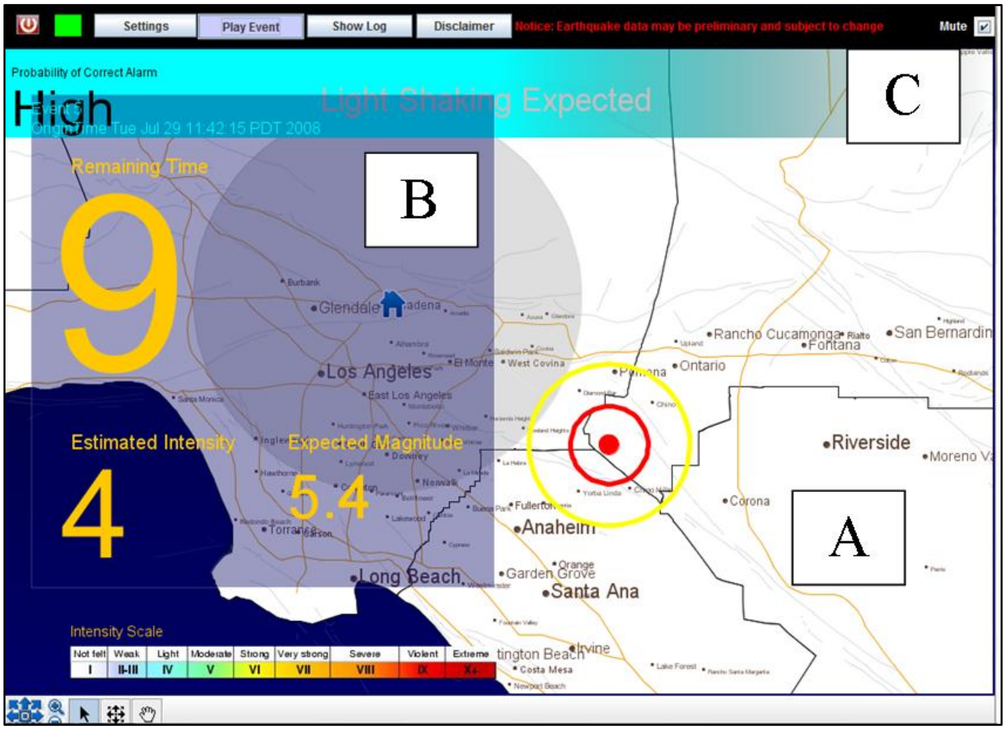


Figure 2. Screenshot of the UserDisplay.

A. Map: Your location is shown by a blue house, the estimated location of the earthquake by a red dot. The map is automatically centered on a point halfway between the two locations. The yellow and red circles show the estimated locations of the P- and S-wavefronts of the earthquake waves, respectively. P-waves, which travel faster than S-waves, rarely cause damage, because amplitudes are smaller and ground motions are predominantly in the vertical direction. The yellow circle, representing the P-wave front at a given time, will always be larger than the red circle (S-wave front). Damage is typically caused by S-waves. The "remaining time" is the estimated time it will take for the S-wavefront (red circle) to reach your location. For some events you will also see estimated ground motions at various sites shown by filled circles. You may notice a grey circle around your location: this approximates the current "blind zone" of the ShakeAlert system. If an earthquake occurs within this area, it is extremely unlikely that you will receive an alert message before you experience the shaking. We are working to decrease the radius of the blind zone in future versions of the ShakeAlert system.

B. **Information Panel:** The panel on the left side of the screen gives the estimated time (in seconds) remaining until shaking is expected to begin at your location, the estimated seismic intensity (MMI scale), and the expected magnitude.

C. **Top Panel:** the top panel describes the level of expected shaking at your site and gives the Probability of Correct Alarm (PCA). We have introduced three PCA levels: "low" (0<=PCA<0.4), "moderate" (0.4<=PCA<=0.7) and "high" (0.7<=PCA<=1.0). The top panel will also display the information "False Alert" or "Test", if an event has been cancelled or if a test message was received.

Important: Do not forget to turn on the volume of your PC and do not check the "mute" box at the top of your UserDisplay if you want to hear alert messages (siren and voice announcement).

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6. Contact information

For questions or feedback please contact:

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Additional information on the CISN ShakeAlert project can be found at http://www.cisn.org/eew/. Thank you very much for your participation. We are looking forward to your feedback.

Appendix B. Feedback from Beta Test Users in SoCal.

Feedback Requests/Issues	**status**
USER DISPLAY	
Verbal action command – drop, cover, hold on Verbal action command – operator	Done Investigating
Quick ID of epicenter location – text or audible display on UD	Investigating
Automatic download upon reboot of computer	Investigating
Bypass login prompt	In progress
Users unable to read log - put M in front of magnitude; move magnitude and intensity to right with warning time	On to do list
Automatic Lat/Long when you scroll over area	Investigating
Different Klaxon sound for higher degree of shaking	Done
Make Intensity and magnitude larger and easier to see (user wants to know magnitude, intensity, warning time and location quickly if they need to perform an operation)	Working on
House icon not centered on location; update open map capabilities to allow use thru US; minor issues on Linux; limit range of values for parameters; limit min mag to greater values;	Done
Users see the high, moderate, low accuracy read out as level of shaking; also difficult to read when it is on black background	On the list
Ability to access history and log files if not connected to internet	Done
Ability for UD to pop up to front if minimized	
For Users with multiple locations such as transportation it is important to be able to monitor more than one area without using several screens	Maybe an issue for the User to create an operation
Mute button needs to revert to unmute after an event is finished (unmuted for far away events with long warning time but will miss next event if mute button still off)	In progress

Auto reminder for UD updates to Users	
Operations Guide update with downloading instructions	Done
Zoom button does not zoom in on epicenter but distance between user location and epicenter. User wants to identify where epicenter is.	Investigating
Default setting to exclude far away EQ's at low magnitude	To Do List
Imbed GPS to track current location of User	Droid will have; investigating for lap top
Use local time and not Greenwich time	Done
ShakeAlert should automatically turn on computer for EEW notification	Investigate
Large "X" should be displayed when there is a false alarm, cancelled event, or test. The "X" should be permanently displayed in case of replay	In progress
TEST – test message stay on UD permanently and not just when playing the notification; if user was not at computer and comes back they see a M7.8 event and no TEST message	
TEST – should have countdown and verbal message of earthquake DCHO as real event	
PERFORMANCE	
Actual magnitude lower than estimate	
USER RESPONSIBILITY/TROUBLESHOOTING	
Computer shuts off – missed events	Set computer to not go into hibernation
No audible sound but visual display	Computer memory/clock
UD does not pop up to front of screen	User needs to close display using the small

	"x" on the right instead of minimizing
Create a feed from ShakeAlert to the LA County map for automatic overlay	
Notification of 900 million seconds of warning	Computer clock off
Computer locks out user	
Computer locking up when alarm sounds w/o displaying EQ location for several sec	Computer memory
Internal security protocols will not let hibernation be turned off	Missed events or time to turn back on when alarm sounded
Delivery Mechanisms	
Identification of various software being used such as WEBEOC and NC4 that users would want to interface with EEW	
Identification of preferred delivery mechanisms used by each organization (Blackberry, Ipad, Android, etc)	
Other Requests	
Repeated requests for ShakeAlert on a mobile unit (Android, Iphone, Ipad) allow those in the field to receive notification – safety of personnel; operations automated	In beta test of ShakeAlert on an Android