**Final Report: August 2012 - July 2015**
Earthquake Hazards Program Assistance Awards

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| **USGS Award Number:** | G12AC20348 (UCB)<br>G12AC20343 (Caltech)<br>G12AC20342 (ETH Zürich)<br>G12AC20339 (USC/SCEC, Yr 1 only) | |
| **Title of award:** | Prototype Implementation and Development of the New CISN ShakeAlert: Collaborative Research with the California Institute of Technology, University of California Berkeley and Swiss Federal Institute of Technology | |
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| **Term covered by the report:** | 1 August 2012 - 31 July 2015 | |
| **Funding expended for the term covered by the report:** | Each organization will submit separately | |


**Abstract:**

In 2006 the USGS began funding the California Integrated Seismic Network's (CISN) Earthquake Early Warning (EEW) group to take a series of EEW algorithms that had been developed and tested offline and begin the process of implementing them on the CISN's realtime system. At that time the seismological community in the US was skeptical that EEW was possible in California. By the beginning of this project, Phase III, in August 2012, the CISN EEW group had implemented and was operating an integrated end-to-end demonstration EEW system. This system routinely detected earthquakes and issued alerts. The alerts were sent to a group of test users with the idea that they would beginning to develop and implement applications. By the end of Phase II, the seismological community had accepted that EEW is possible. Now, at the end of Phase III, many see the implementation of a public system as an inevitable next step in earthquake mitigation.

The focus of Phase III was the transition from the *demonstration* system software from Phase II to a *production* system integrated into the CISN AQMS environment. On-going evaluation of the system and the engagement of users have also been targets of our efforts. Continued research into improving algorithms has largely been supported by other sources of funding, but the results of those efforts are being integrated into the operational systems as appropriate. At the end of the first year of Phase III,

funding to the Southern California Earthquake Center (SCEC) to support evaluation of system performance was discontinued. Here we report on their Phase III, Year 1 activities. ****

Specific goals for the Phase III component of USGS funded support of CISN EEW implementation are:

**Goal 1:** Transfer algorithms to AQMS operational environment to create and operate a prototype *production* system;
**Goal 2:** Continue to support and enhance the existing *demonstration* system;
**Goal 3:** Evaluate system performance on a region-by-region basis, identifying causes of strong/weak performance and providing feedback to algorithm developers;
**Goal 4:** Continue to interact with users in collaboration with the USGS; and
**Goal 5:** Develop an implementation plan with the USGS.

Progress toward these goals is accomplished through discussions among project members at the cooperative institutions to define standards and assign tasks. Project members are organized into thematic groups to cover the goals, that is a Production System group, a Demonstration System group, a Performance Evaluation group and a User Interactions group. General oversight, direction and integration are provided by the Scientific Coordination group.

Work toward **Goals 1 and 5** have been dominated by collaborative team work. Effort to accomplishing them is reported here as being due to common and coordinated effort.

### Goal 1: Create and operate a prototype *production* system

In June 2013, the ShakeAlert EEW group adopted an architecture for a production prototype EEW system based on successful attributes of the ShakeAlert EEW development system. The major improvement goals of the production prototype architecture are to provide redundancy for all of the software, hardware, and communication components of the system beyond the initial seismic data acquisition, so that the system could be effectively implemented with no single points of failure. Careful consideration was also given to how a system implementation could be expanded to incorporate additional seismic regions and data processing centers. Figure 1 shows a diagram of the California components of the EEW production prototype system.

In April 2014, the combined ShakeAlert EEW production and development group, with members from UC Berkeley, Caltech, USGS Pasadena, USGS Menlo Park, University of Washington, and ETH began to hold weekly conference calls to develop and implement an EEW prototype production system with the goals of:

a. Migrating existing EEW demonstration software from Solaris to Linux operating system, which was adopted by the group as the new target OS.

b. Enhancing the EEW software to properly and robustly operated in the redundant architecture adopted by the CISN EEW group.

c. Implementing a production prototype system based on the adopted CISN EEW production prototype architecture in California that could be easily be expanded to the entire contiguous USGS west coast and beyond (Figure 2).

d. Developing, implementing, and documenting requirements procedures for the building, testing, tracking, deploying, and operating both the OS and EEW components of the system.

Milestones on this project are:

1. Adoption of unified OS, software packages, accounts and directory organization for prototype production, testing, and build systems.

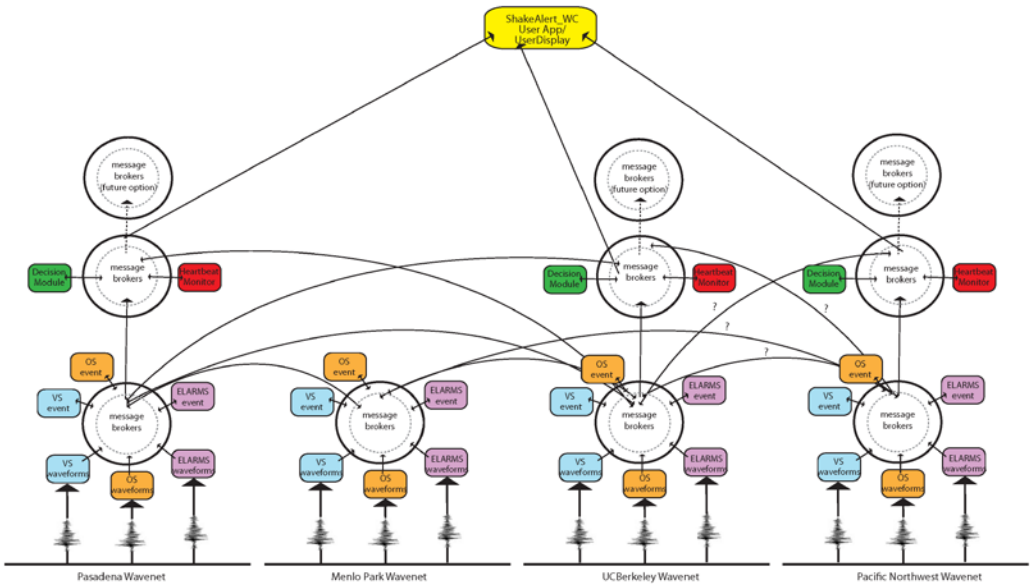


**Figure 1**: Schematic of the prototype production system for the US West Coast Earthquake Early Warning System. In the initial version of the prototype production system (V1.0) only the elements at Pasadena, Menlo Park and UC Berkeley are implemented. Project members are going through the final implementation steps before the prototype system soon becomes the operational system, producing alerts for test users. Note the redundancies. They recently underwent an unforeseen test when the computers at the data center at UC Berkeley were shut down after fire. The other elements of the system remained operational.

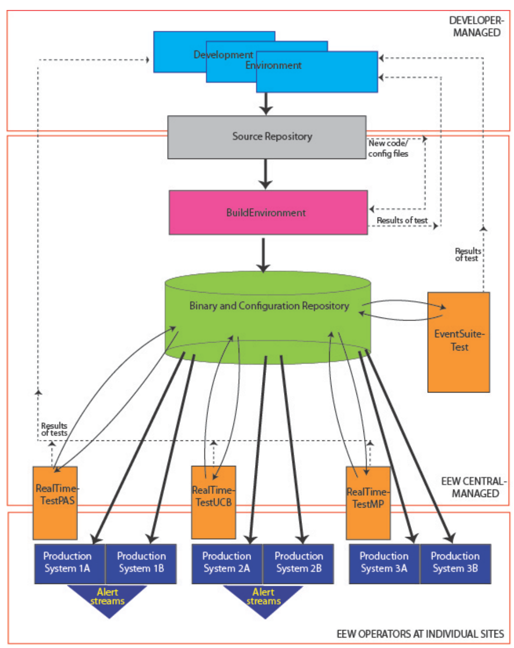


**Figure 2**:Schematic of production testing and certification workflow software and data from new stations for the prototype production system for the US West Coast Early Warning System. The elements at the bottom of the diagram show the actual production system and are shown in greater detail for Pasadena, UC Berkeley and USGS Menlo Park in Figure 1. The "Deveopment Environment" (top) is at the universities, where algorithms are modified or new algorithms are developed. They are checked in to the source repository, from which they enter the test environment. It is tested whether they build correctly, and then are then tested against an event suite and in the realtime test systems before being deployed in the production system.

2. Acquisition of computer systems for new EEW production environment.

3. Initial manual installation of new Linux systems at Berkeley, Pasadena, and Menlo Park using this design to facilitate rapid software porting and development on Linux.
4. Adoption of a consistent *kickstart* procedure, software package selection, and installation procedure to ensure that all computer in an environment would contain identical software, with site-specific configurations well defined and documented.
5. Selection, formal training, and adoption of *puppet*, an open-source configuration management utility, to centraly deploy and maintain the EEW software and configuration information.
6. Design and implementation of multiple *puppet* environments to support the build, testing, and operational production compontents of the EEW prototype system.
7. Design and implementation of a production EEW of EEW systems software build system, offline regression testing system, online testing systems, and production systems
8. Design and implementation of offline testing dataset, test procedures, and analysis routines to quantify the performance of the EEW components and overall system on prior seismic and "spuriously-detected" events.
9. Full system build , software, and configuration installation, and update of all components of the EEW prototype production system are now being managed initial kickstart process and centralized puppet management. This includes: Decision module, DM, Elarms, VS, Onsite, HA (heartbeat aggregator), AMQ (ActiveMQ messaging system), and Earthworm data import components.

UCB-specific contribution to the EEW production prototype system and demonstration systems:

- Chaired the EEW prototype and production working group.
- Developed initial design of production prototype system adopted by the CISN EEW group.
- Performed initial code modification to Elarms, the Decision Module, and activemq broker configuration to demonstrate full software and messaging redundancy for the prototype production system. Continued enhancements and improvements to Elarms and the Decision Module.
- Designed the initial *puppet* environments to support the build, test, and production components of the system. Developed many of the initial *puppet* manifests for the production components.
- Migrated Elarms software from Solaris to redundant Linux systems.
- Installed enhanced Decision Module to support redundant EEW algorithms in the EEW development environment.
- Continued operation and support of Decision Module (DM), Elarms, AMQ, and message distribution system for EEW beta test users.

Caltech-specific contribution to the EEW production prototype and demonstration systems:

- Port of Onsite, FinDer1 (Matlab) and GPSlip algorithms to Linux completed, ensuring linux-compliant builds and consistent algorithm output. Solaris-built algorithms for Berkeley and Menlo Park demonstration system servers continue to be supported.
- Improved the system health messages, managed by the heartbeat aggregator, which now supports hierarchical status information to accommodate redundant components.

**Goal 5: Develop an implementation plan with the USGS**.

The development of the implemenation plan (**Goal 5**) was spearheaded by Doug Given of the USGS. The team included members from Caltech, UC Berkeley, USGS Menlo Park and the University of Washington. It is published as the "Technical Implementation Plan for the ShakeAlert Production

System — An Earthquake Early Warning System for the West Coast of the United States", USGS Open-File Report 2014–1097.

In this Final Report on Phase III (2012 - 2015) of the "Prototype Implementation and Development of the New CISN ShakeAlert: Collaborative Research with the California Institute of Technology, University of California Berkeley and Swiss Federal Institute of Technology (and Southern California Earthquake Center)", each organization has contributed a summary of its activities toward achieving **Goals 2, 3 and 4**.

## **Final Report Caltech:** August 2012 -July 2015

**Goal 2: Continued support and enhancement of the existing demonstration system.**

- Continued participation in discussions of the Demonstration and Scientific Coordination Groups.
- Maintained and modified the Onsite algorithm:
    - Updated the strong motion filtering to improve performance in northern California
    - Developed a fast, offline testing framework that includes fast replay of events from waveform files
    - Significantly increased configurable parameters and generalized code creation and handling; testing and optimization of parameters
    - Updated the associator logic to: allow stations to be made 'non-authoritative' so that noisy stations cannot generate false alerts but data are still used once an event has been identified by other stations; intelligently select information from co-located stations
    - Updated the single-station code: added new phase discrimination methods (three ground motions and horizontal/vertical ratio), updated single station location calculation
- Maintained and enhanced UserDisplay (UD) codes as necessary in response to performance and feedback from users:
    - Support for full rupture information provided by FinDer and GPSlip
    - Support for all six combinations of predicted and observed ground motion parameters
    - Investigating support for users with multiple locations of interest
    - Optional NTP restart no longer blocks GUI
    - Warn user if system clock has drifted too far from NTP time which usually results in dropped status messages
    - Support for Java version 1.7.
    - Started adding event history to allow for "late" (negative warning time) events to reduce "blindzone" effect
    - UserDisplay 2.4.1 was released in fall 2014.
    - Expanded option to provide intensity at multiple locations providing an intensity color-coded “ShakeMap”.
- Maintained and developed FinDer:
    - FinDer1 is now contributing to live demonstration system.
    - FinDer2 (C++) is currently being developed.
- Started implementation of Filter Bank algorithm.
- Provided support for CRADA (co-operative research and development agreement) users and other external developers. A web-based test tool, allowing replay of final output from the ShakeAlert system, was further developed jointly with USGS and is being used to aid third party initiatives.
- Established additional data feeds to the FinDer1 algorithm including 100 CSN (community seismic network) stations sited in LAUSD schools. This furthers the earthquake early warning group's aim to incorporate low-cost sensor networks into the ShakeAlert system.

- Established GPS data feeds from the USGS Pasadena office and from CWU (Central Washington University), for future use by new algorithms GPSlip, BEFORES and FinDer-BEFORES. This furthers the earthquake early warning group's aim to incorporate high-rate GPS data into the ShakeAlert system.
- Started to develop new extended xml-ShakeAlert message format to account for requirements by various GPS algorithms with Scientific Coordination Group.
- Completed development of framework for end-to-end offline testing of ShakeAlert system for archived and simulated waveform data using Earthworm tankplayer; performed initial test runs for Onsite, FinDer (ffd), GPSlip, Virtual Seismologist, ElarmS and Decision Module; encountered various problems (such as E2 sending out too many reports) which are being addressed.

**Goal 3: Evaluation of system performance on a region-by-region basis.**

- Analyzed all earthquake reports from all three operating earthquake early warning algorithms (Onsite, ElarmS, Virtual Seismologist) and the Decision Module for all earthquakes, missed events, and false alarms for all regions of California 2012-present.
- Assessed the regional variability of earthquake detection and false alarms for all algorithms.
- Assessed performance of all algorithms for different earthquake magnitudes.
- Began work on updated Decision Module that takes advantage of the observed system performance including potential regional differences in performance.
- Began work on improving the capability of the Decision Module to recognize missed events and false alarms including potential regional differences in the rates of missed events and false alarms for each algorithm.
- Independent testing of the Onsite algorithm gave the following performance for the current algorithm and settings:
    - Large events (greater than M5) are reliably detected by Onsite in both southern and northern California
    - At lower magnitudes, detection rates are noticeably higher in southern California compared with northern California, largely due to variation in station density
    - Magnitudes for smaller events tend to be over-estimated, due to the preference within the algorithm to detect and measure the larger amplitude arrivals
    - P-wave detection and accuracy is generally high, but events outside of, or near the edges, of the network are less reliably detected and their parameters have larger uncertainties
    - Large magnitude regional events (relatively close to network boundaries) can cause false alerts, but large teleseisms (including those at depth) are correctly ignored
    - Environmental noise can lead to alerts being issued, but these are correctly cancelled, with the 'delete' messages generally issued within 3 or 4 seconds of the original alarm

**Goal 4: Continued interaction with users in collaboration with the USGS**

- Participated in Beta User group, USGS implementation plan, communications working group and Cal OES education and outreach group
- Continued regular interaction with 45 Beta Test User organizations:
    - Maintain email lists of all Beta Test Users
    - Document and share user feedback
    - distribute updates and critical user information
    - Provided training and technical support
    - Run tests of UserDisplay software during slow seismic intervals for regular feedback

    - Continued to identify EEW advocates essential in providing critical support of the early warning system and public/private partnerships
    - Facilitated Earthquake Research Affiliate (ERA) meetings about EEW
    - Handled requests for information regarding EEW from potential users and media
- Identified separate ShakeAlert user categories:
    - Technical: automated alert responses
    - Non-technical: manual alert responses
    - Public: individual response and information

  from broad base (transportation, medical facilities, laboratories, manufacturing, financial entities), emergency responders (fire, police, emergency operation center), dispatch centers, sea ports, airports, lifelines (water, power, communication), entertainment facilities and universities.
- Collaboration with private industry partners working with USGS to create mechanisms necessary to perform potential operations for technical users.
- Provided EEW presentations to stakeholders which included demonstration of the ShakeAlert software for awareness, educational and support purposes
- Implementation of ShakeAlert with 4 private companies as Beta developers of products to perform early warning operations
- Continual interaction with Beta Users provides feedback on performance and insight into their organizational needs as well as individual perceptions and responses. Example requests include:
    - Multiple user location alerts
    - Finite fault rupture information
    - Extended rupture animation
    - Shaking intensity map visualization
    - Silenced alerts (e.g. for use in dispatch centers, laboratories, surgeries)
    - User modification of audible alerts:
        - apply specific user messages
        - alter alarm tones

**Research**

Continued EEW research: detection and processing of finite-fault ruptures (FinDer); usage of GPS-data for slip and magnitude estimation; improved ground-motion prediction for large earthquakes with consideration of finite-fault, directivity, and basin response effects (using SCEC CyberShake waveform simulations); refined method to predict shaking in high-rise buildings using community instrumentation; refined method to analyze complex earthquake sequences; refined concept of a simple gut check algorithm for DM; refined framework for automated decision-making, including elevator control; developed Filter Bank algorithm to reduce blind-zone.

Onsite:
- Testing of new magnitude determination and location method
- Testing of polarization filter for phase discrimination

- Presented and discussed results at various meetings, workshops, and conferences.
- Documented research results in scientific papers, on webpage etc.

## Final Report ETH: August 2012 -July 2015

### *1a) Finite-Fault Rupture Detector Algorithm – **FinDer***

Constraining the finite-source dimensions of large earthquakes is essential for accurately estimating seismic ground-motions in events with magnitudes **M**>6. Detecting and modeling finite-fault ruptures in real-time is thus crucial to earthquake early warning (EEW). Following a period of extensive offline and real-time testing (including the 2014 **M**6.0 South Napa and **M**5.1 La Habra earthquakes), we successfully integrated our Finite-Fault Rupture Detector algorithm, *FinDer* (Böse *et al.*, 2012), into the Californiawide *ShakeAlert* EEW demonstration system in April 2015 (Böse *et al.*, 2015). This extension is expected to improve *ShakeAlert's* ground-motion predictions in large earthquakes, because rupture-to-site distances can be taken into account, which is not feasible in a pure point-source-algorithm-based system ($\tau_c$-$P_d$ *Onsite*, *ElarmS*, and *Virtual Seismologist*).

*FinDer* is currently implemented in MATLAB (Böse *et al.*, 2012; 2015) and analyzes real-time strong-motion amplitudes from 420 CISN accelerometers computed by a C++ waveform-processing library (developed by Caltech). The algorithm compares spatial images of observed peak ground acceleration (PGA) with theoretical templates modeled from empirical ground-motion prediction equations. If the spatial and temporal correlation between the observed and theoretical PGA patterns is sufficiently high, an automatic report is sent to *ShakeAlert* including the estimated rupture centroid position, length, and strike (along with their uncertainties); rupture estimates are continuously updated as new data arrives.

In a joint effort of ETH Zurich, USGS Menlo Park, and Caltech, we have started to rewrite *FinDer* in C++ to obtain a faster and more flexible implementation (Böse *et al.*, 2015, AGU). *FinDer 2* also has a number of algorithmic changes that allow detecting much smaller earthquakes. The new algorithm provides a consistent EEW approach to both small-magnitude point-source and large-magnitude finite-fault ruptures.

**Key features of *FinDer* algorithm:** (mostly developed during Phase III)

- estimation of rupture centroid, length and strike from seismic real-time data (Böse *et al.*, 2012)
- uncertainty estimates based on misfit-derived likelihood functions (Böse *et al.*, 2015)
- applicable to subduction-zone environments (Böse *et al.*, 2015)
- independent of other algorithms, i.e. no triggering required
- estimates are true network solutions, not station averages
- simple and robust alternative to pick association and thus suited for application in noisy environments (low-cost sensor networks, such as Community Seismic Network, CNS)
- allows constraining GPS-based inversions of fault slip and magnitudes (see below)

**Implementation and Installation in California: (in collaboration with Caltech)**

- *FinDer* algorithm: MATLAB stand-alone code installed at Caltech
- waveform-processing and socket_adapter: C++ code installed at Caltech/USGS PAS, UC Berkeley and USGS MP
- real-time data:
    - continuous data from 420 CISN strong-motion stations (connected to *ShakeAlert* since 04/2015)
    - triggered data from ~100 CSN low-cost stations (test mode since 08/2015)
- performance (since April 2015):
    - 2015/07/10, 03:29:49 UTC M3.8 NW of The Geysers: $loc_{err}$=2.5 km, $M_{err}$=0.5 (not reported to *ShakeAlert* because of misconfigured socket_adapter)
    - 2015/09/05, 04:55:33 UTC M2.7 ENE of Marina del Rey: $loc_{err}$=1.5 km, $M_{err}$=0.2; detection included data from 4 low-cost CSN stations (not reported to *ShakeAlert* because too small)

*1b)* ***FinDer 2*** *– A Consistent EEW Approach to Small and Large Earthquakes*

The current *FinDer* MATLAB code supports utilization of a single ground-motion threshold only. In the present *ShakeAlert* installation we are using a threshold of 70 cm/s$^2$, which is usually exceeded in moderate to large magnitude earthquakes, for example within 20 km from the fault rupture for ~ **M**6.0, or within 40 km for ~ **M**7.0 (Cua and Heaton, 2009). This high threshold provides robust detections of large earthquakes, however, at the cost of reduced detection speed and missed detections of smaller events. To enable the detection of both small (~ **M**3.0) earthquakes and large events shortly after nucleation, we have modified our original algorithm: *FinDer 2* computes multiple contour lines of high-frequency PGA and correlates these with the templates. *FinDer 2* thus provides a modeling approach for both small-magnitude point-source and larger-magnitude finite-fault ruptures with consistent error estimates for the entire event magnitude range (Böse *et al.*, 2015, AGU).

In a joint effort of ETH Zurich, USGS Menlo Park, and Caltech, we have recently also started to translate the current *FinDer* MATLAB code to C++. The goal is to obtain a faster and more flexible implementation of the *FinDer 2* algorithm that allows easier maintenance and better integration into various seismic processing systems, including *EarthWorm/AQMS* (as currently used in *ShakeAlert*) and *SeisComp3*. The new C++ code utilizes widely tested open-source libraries for computer vision (*Open Source Computer Vision* – OpenCV*;* http://opencv.org) and geographic mapping (*The Generic Mapping Tools* – GMT; Wessel *et al.*, 2013).

**Note:** The implementation and testing of *FinDer* 2 could not be finalized in Phase III. No funding has been provided to ETH to continue these efforts.

**Key features of *FinDer 2* algorithm:**

- tracking of multiple PGA contour lines using normalized correlation coefficients to provide a consistent approach to both small point-source (with radial-symmetric ground-motion distributions, GMD) and finite-fault (with quasi-elliptical GMD) earthquakes

**Implementation of *FinDer 2*: (with USGS Menlo Park and Caltech)**

- utilizes C++ and open-source libraries, thus free and portable
- faster than the current *FinDer* code, even with multiple ground-motion thresholds
- more accurate strike estimates (improvements: La Habra: ~3$^{o}$, South Napa: ~19$^{o}$)
- structuring into an API (Application Programming Interface) allows easy integration into a variety of seismic monitoring systems like *EarthWorm/AQMS* and *SeisComp3*

*Seismic-Geodetic Approaches to EEW (with USGS Menlo Park and Caltech)*

*FinDer* source dimensions and uncertainty estimates can constrain Global-Positioning-System (GPS)-based inversions of fault slip and magnitudes without saturation in large earthquakes (Böse *et al.*, 2015). *FinDer-GPSlip* (Böse *et al.*, 2013, AGU) and *FinDer-BEFORES* (Minson *et al.*, under USGS internal review) provide the first seismic-geodetic algorithms to EEW that are consistent with both seismic and geodetic observations at any time after rupture nucleation. By tradition, finite-fault slip models are inverted for a known fixed fault geometry; in an EEW setting, however, rupture geometry is unknown *a priori*. This requires a simultaneous inversion for fault geometry and slip, which is a nonlinear and computationally expensive inverse problem. Using both seismic and geodetic real-time observations helps constrain both source geometry and slip (and thus magnitude without saturation).

*Further Applications of FinDer*

*FinDer*, by-itself, does not predict how far a rupture will likely propagate. However, the algorithm allows identifying with high confidence the causative fault along which rupture is occurring. This information, along with observed slip amplitudes and known fault characteristics, has potential to provide estimates of future rupture evolution (Böse and Heaton, 2010). The *FinDer* output can also constrain the direction in which a fault rupture is propagating, and thus can help to enhance ground-motion predictions with consideration of directivity effects, as we demonstrated for the Southern California Earthquake Center CyberShake dataset (Böse *et al.*, 2014).

### *2) Virtual Seismologist*

The Virtual Seismologist (VS) method is a Bayesian approach to earthquake early warning (EEW) that estimates earthquake magnitude, location, and the distribution of peak ground shaking using observed picks and ground motion amplitudes, predefined prior information, and envelope attenuation relationships (Cua, 2005; Cua and Heaton, 2007; Cua et al, 2009). The application of Bayes' theorem in EEW (Cua, 2005) states that the most probable source estimate at any given time is a combination of contributions from prior information (candidate priors include network topology or station health status, regional hazard

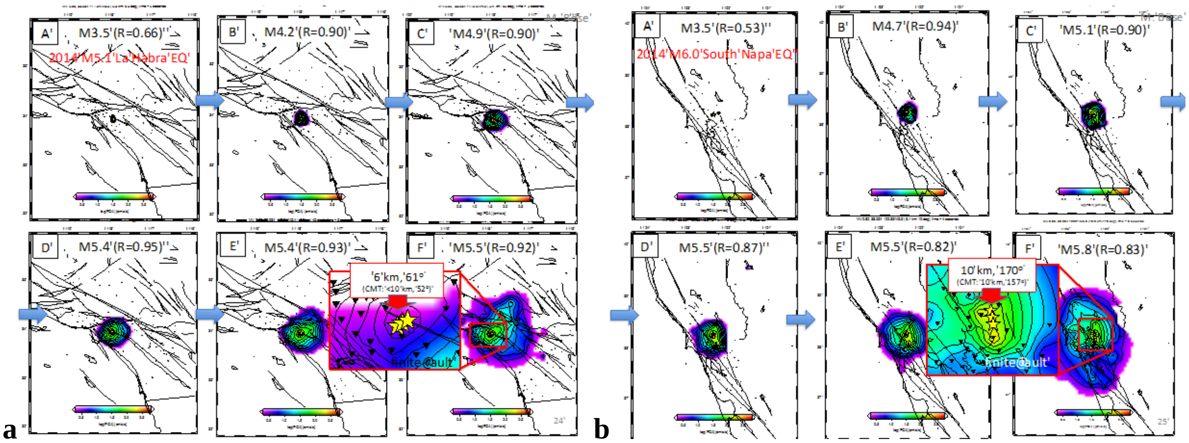


**Figure 3 (a)** Demonstration of *FinDer 2* for the 2014 M5.1 La Habra earthquake.**(b)** Demonstration of *FinDer 2* for the 2014 M6.0 South Napa earthquake.

maps, earthquake forecasts, and the Gutenberg-Richter magnitude-frequency relationship) and constraints from the available real-time ground motion and arrival observations. VS is envisioned as an intelligent, automated system capable of mimicking how human seismologists can make quick, relatively accurate "back-of-the-envelope" interpretations of real-time (and at times, incomplete) earthquake information, using a mix of experience, background information, and real-time data.

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 UC Berkeley Digital Seismic Network (BDSN) and the USGS Menlo Park Northern California Seismic Network (NCSN) in February 2009. VS' real time implementation does currently not include any prior information and determines the epicenter solely based on P-wave detections.

The focus of developments in Phase III has been on improving the existing implementation in anticipation of VS' inclusion in the production system. We further developed a probabilistic framework to estimate the speed of EEW algorithms in general, based on the characteristics of the algorithm and the underlying seismic network.

### *2a) Enhancing the reliability of VS alerts*

In Phase II of the ShakeAlert project, VS was operating as three separate, independent installations at the SCSN, BDSN, and Menlo Park networks. By changing the inter-process communication method, a single instance of VS can now receive waveform amplitude information from all three networks. This increases the network density as seen by VS in central and northern California and, therefore, improves the precision and speed of detections in these areas.

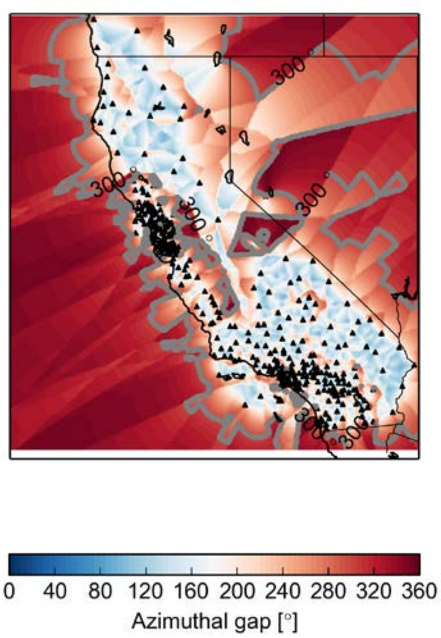


**Figure 4a**: Azimuthal gap for detections with 4 arrivals. The thick grey line marks the 300° contour. Black triangles show real-time CISN stations used for EEW.

To further improve the reliability of VS alerts we also implemented an additional quality check that evaluates the azimuthal gap of the stations contributing to an alert. If the azimuthal gap is >= 300° the alert will be rejected. Figure 4a shows the azimuthal gap for any potential epicentre and its closest 4 stations. For an azimuthal gap threshold of 300° mainly epicentres offshore and outside the state boundary will be rejected with few exceptions in the central valley and the Mammoth lakes area. Swarm sequences in the latter have produced false detections caused by mis-locations with large azimuthal gaps. These can be prevented with our additional quality criterion. Note that as the number of stations contributing to a detection increases, the number of epicentres within California with a large azimuthal gap vanishes.

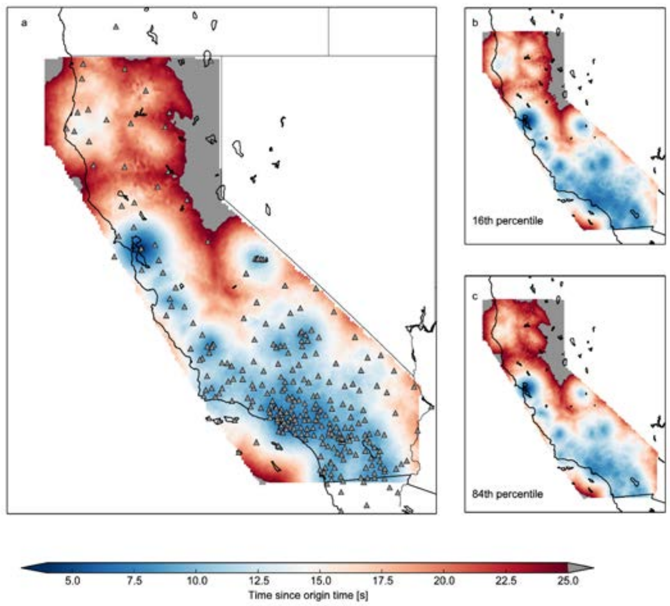


Figure 4b: Colors show epected delay of the initial VS alert based on the observed delays of the system components. Grey triangles mark the locations of broadband sensors currently used for detection in ShakeAlert

*2b) Probabilistic estimates of EEW alert speed*

Optimizing EEW alert times requires a thorough understanding of the time delay that is added by every component of an EEW system (e.g. network density, data communications, EEW algorithm processing). These delays typically have irregular distributions and may vary significantly between different stations and algorithms. We developed a probabilistic approach to modeling expected alert times based on delay measurements of different EEW system components using Monte Carlo simulations [*Behr et al., 2015*]. Figure 4b shows the expected alert times (median, $16^{th}$ and $84^{th}$ percentile) for VS for any possible epicenter within the colored area assuming the first detection is made by the first four available P-wave detections from broadband sensors. These estimates are based on the network density as well as the distribution of data latencies for each station and the distribution of VS processing delays.

*3) Enhancing the accuracy of the earliest event characterizations: the Gutenberg Algorithm*

A particular challenge for EEW systems is to provide timely warnings for medium size events (M<7) in which the strongly affected sites are located close to the epicenter and where, as a consequence, the onset of strong ground motion is shortly after the event origin time. The same holds for proximal sites to the epicenter in large events. For these sites, regional-type EEW systems that wait until data from several stations are available before issuing a warning and that require fixed data windows following a trigger are sometimes not fast enough. Single-station algorithms, on the other hand, have high uncertainties that compromise their usefulness. Over the past three years we have developed a novel probabilistic algorithm for estimating EEW magnitudes that is tailored to these challenging scenarios of EEW alerts for proximal sites. The Gutenberg algorithm uses a filter bank for a time–frequency analysis of the real-time signals and estimates the posterior probabilities of both magnitude and source–station distance directly from the observed frequency content. It starts off as a single-station algorithm and then naturally evolves into a regional-type algorithm, as more data become available. Using an extensive near-source waveform data set, we have demonstrated the Gutenberg parameter estimates reach the estimation accuracy and precision of existing regional-type EEW systems with only 3 s of data from a single station. The magnitude estimates, however, saturate at a threshold magnitude that depends on the available signal length that is used for the estimation.

The Gutenberg Algorithm is intended to provide the earliest warnings, while at later stages, if an event grows beyond the size of M~6.5, complementing algorithms that account for source finiteness and rupture complexity, such as FinDer, should take over the event characterizations. We are currently working on a real-time implementation of the Gutenberg algorithm, both at the Swiss Seismological Service as well as at the Caltech Seismological Laboratory.

**Final Report UC Berkeley**: August 2012 - July 2015

It is difficult to separate the activities at UC Berkeley during Phase III of the ShakeAlert project between supporting and enhancing the demonstration system and evaluating algorithm and system performance on a region-by-region basis. During Year 1 of Phase III, we at UC Berkeley developed a web-based interactive review tool for ElarmS to improve our ability to review performance and to evaluate the effects of modifications to the algorithm. At the beginning of Year 2 we used that tool as a basis for implementing a Decision Module (DM) review tool, to support evaluation of ShakeAlert system performance, which was shared with other project members. Here, we report on both tools, as well as on the operation of and improvements to ElarmS (now ElarmS-2, or E2) in the demonstration system and the operation of and improvements to the DM.

In addition to working on ElarmS and the DM, members of the UC Berkeley team participated in the committees supporting the development of the California Earthquake Early Warning (CEEWS) process, and in the implementation of the ShakeAlert prototype production earthquake early warning system. Doug Neuhauser from UC Berkeley chaired the prototype production committee.

**Goal 2:** Support and enhance the existing *demonstration* system and
**Goal 3:** Evaluate system performance on a region-by-region basis

## **ElarmS** Performance

During the project period (2012-08-01 - 2015-07-31), ElarmS detected and characterized the majority of moderate (M≥4.0) earthquakes that have occurred in California (Figure 5, Table 1). ElarmS correctly detected 111 earthquakes with magnitudes greater than or equal to 4.0 that are also listed in the ANSS catalog. Of these, the most notable was the M6.0 South Napa earthquake (August 24, 2014). The first alert for this event was sent to the DM 5.1 s after the rupture began, with an initial magnitude estimate of M5.7. The alert provided approximately 5 s of warning to UC Berkeley's police department, and 8 s of warning to the Department of Emergency Management (DEM) in San Francisco. The magnitude estimate increased to a final value of M6.0 within 15 seconds of the initial alert.

For events over the past three years, the median absolute magnitude error of the ElarmS estimate is 0.400 magnitude units, with a standard deviation of 0.337 units (Figures 6 and 7). The median error for onshore earthquakes is slightly lower, 0.300 magnitude units with a standard deviation of 0.294 units (Figure 6). While onshore and offshore event magnitude estimation errors do not differ significantly, the location accuracies for both onshore and offshore events varies by location in the state, due to sparse station coverage. The median location estimate error for all earthquakes detected by ElarmS during the project is 6.9 km with a standard deviation of 28.9 km (Figures 8 and 9). In contrast, the median location error for onshore events only is 3.34 km with a standard deviation of 11.9 km (Figure 8).

ElarmS failed to detect 17 events with M≥4.0. All but two of them occurred in regions with sparse network coverage. The remaining two were in the Bay Area, both aftershocks. A M4.0 aftershock immediately followed a M4.4 earthquake, and a M4.4 aftershock was in the coda of the M6.0 South Napa earthquake.

|  | M≥4.0 California | M≥4.0 Bay Area | M≥4.0 Los Angeles |
|---|---|---|---|
| Matched Events | 111 | 17 | 11 |
| ANSS Missed Events | 17 | 2 | 0 |
| False Alerts | 21 | 0 | 2 |

Table 1. ElarmS performance from 2012-08-01 through 2015-07-31 for earthquakes with either ElarmS or ANSS catalog magnitude M≥4.0.

From August 2012 through July 2015, ElarmS disseminated 21 false alerts. Ten of these false alerts were due to large, deep teleseismic earthquakes. An extraordinarily deep (678km) M7.8 teleseism in Japan on May 30, 2015 generated 5 false events with magnitudes greater than M4.0 within a minute. They were due to the simultaneous arrival of the P-waves from Japan at stations throughout California. Although ElarmS uses a teleseismic filter to prevent alerts this filter was unsuccessful for the Japan event. The ElarmS team is exploring ways to prevent these alerts from being disseminated. As a preliminary measure messages about teleseisms from a PDL client program was installed after the May 2015 deep teleseism. This java program receives teleseismic event messages, computes phase arrival times and sends the information via an ActiveMQ server to the

ElarmS associator program, which can then ignore triggers that are close in time to the predicted arrivals of the teleseismic P-wave at each station.

ElarmS exihibits excellent performance in the well-instrumented and heavily populated Bay Area and Los Angeles regions of California (Table 1). The high density of stations in these regions means that ElarmS is able to detect, locate and estimate the magnitude of the events more rapidly than in other areas of the state, and with much greater accuracy. For example, in the Bay Area, 17 earthquakes with M≥4.0 were detected over the past three years. Only two events were missed, as described above. In the LA region, 8 earthquakes were correctly detected and two false alerts (due to teleseisms) were generated.

One of the most important measures of the performance of an earthquake early warning system is the amount time it takes to generate an alert after an earthquake occurs. In areas of California where station density is low, takes an average of 15.5 seconds for ElarmS to generate an alert (Figure 10). In the more densely instrumented (and more heavily populated) Bay Area and Los Angeles regions, ElarmS has issued first alerts on average in 9.96 and 5.88 s, respectively. For one relatively deep M3 earthquake in the Los Angeles basin, ElarmS first alert was delivered 3.3 s after the origin time, before the arrival of the S-waves at the surface! The ElarmS team continues develop modifications of ElarmS to improve alert times. Figure 10 shows, however, that the best way to reduce alert times is add seismic stations throughout the state.

The BSL has developed a web interface for interactively reviewing ElarmS performance. To support the evaluation, the information being logged from both the ElarmS waveform processor and the event associator programs has been increased and reorganized. Additional information is logged about event creation and events that do not pass the alert criteria. This latter information is useful in evaluating the criteria used to publish alerts to the Decision Module. A Postgres database has been setup and ElarmS log messages are now also sent via an ActiveMQ message server to a new Java program that continuously inserts rows into database tables that record event creation information. Other improvements and additions to Elarms include more rapid alerts by reducing the wait time before magnitude information is allowed to be released; adding an option to specify regional magnitude formulae, adding an option for regional minimum $P_d$-SNR and $P_v$-SNR magnitude requirements and adding an option to use azimuthal station coverage as an event creation criterion.

*Decision Module*

During the project period, the DM for the demonstration system was modified several times, mainly to control which alerts are published to the User Display or as XML messages to any user. It has been altered, for example, to accept rules for the publication of algorithm alerts based on the algorithm's magnitude and the event's location. Rules based on past regional algorithm performance have been used to restrict the use of information received from algorithms allow publishing alerts only from specific regions and with specific magnitudes. Currently in the Bay Area, the DM will only pass on ElarmS alerts with M≥3.0. In Northern California outside of the Bay Area, the DM will only publish ElarmS alerts with M≥5.0. In Southern California, the DM combines alerts from all of the algorithms, Elarms, VS, and Onsite, for events with M≥2.5.

The Decision Module (DM) has been modified to work in the new production environment, where, for redundancy, four machines will be providing algorithm alerts. The DM can now handle four alerts from the same algorithm. Event hypocenter parameters are averaged for each algorithm and the algorithm averages are combined using the uncertainty weights to create the DM event. The DM alert message has been modified to include information about all of the contributing messages from algorithms running redundantly on multiple machines. We are testing this modified DM in the new production environment.

*Interactive web-based Review Tools for the Decision Module and ElarmS*

Starting in August 2012, UCB developed a tool to review ElarmS performance. In 2013, when SCEC was no longer supported as a member of the collaboration, we modified that tool to allow the review of Decision Module (DM) event and aggregate performance. Both tools are interactive web pages that allow the evaluation of the performance of the ElarmS algorithm and the ShakeAlert EEW demonstration system, respectively. They provide information about event detections and alerts. The information is updated every few minutes, so that even the performance in current events can be evaluated in near-real-time.

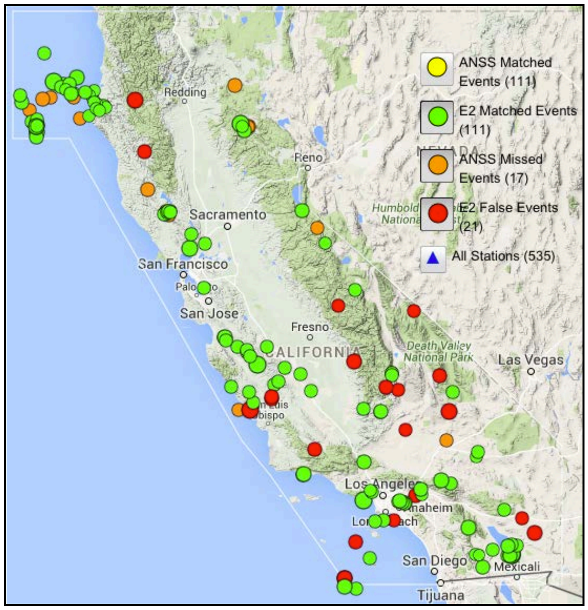


Figure 5. ElarmS earthquake detections (green circles), missed events (orange circles), and false alerts (red circles) from 2012-08-01 through 2015-07-31.

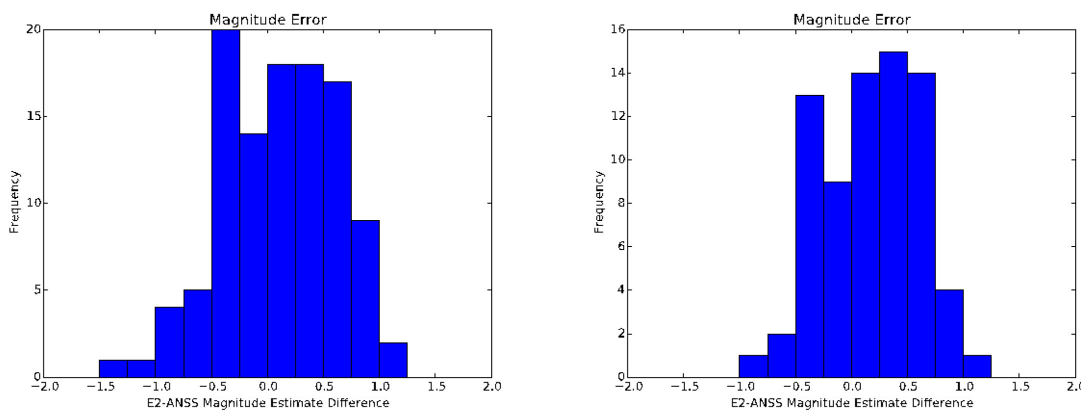


Figure 6. Magnitude error. Left: All events including offshore. Median absolute magnitude error: 0.400 magnitude units. Standard deviation: 0.337. Right: Offshore events excluded. Median magnitude error: 0.300 magnitude units. Standard deviation: 0.294.

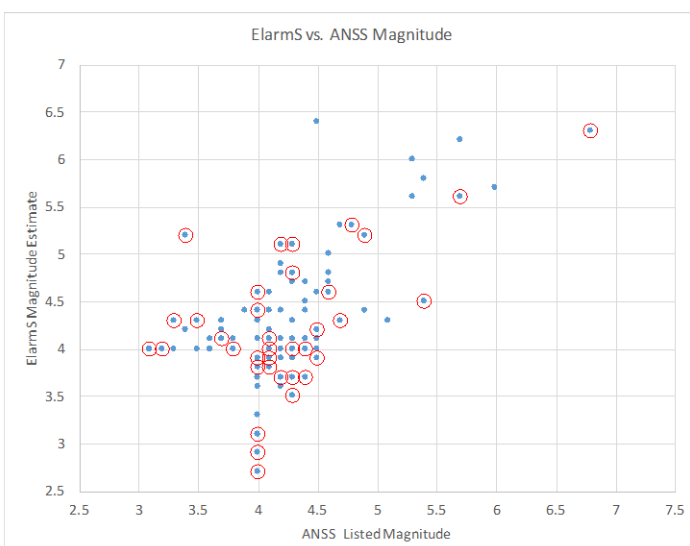


Figure 7. ElarmS vs. ANSS magnitudes for ElarmS detected events with M≥4.0. Offshore events circled in red.

The database supporting the web pages contains information for all events detected since April 2012. The review pages shows the alert history, normally for 30 seconds after the first alert. The history shows the changes in origin time, magnitude, and location as more stations are added to an event. Basic statistics for these event parameters can be computed for the events in any time period and within several geographical regions, especially the Greater Bay Area and Los Angeles regions. The DM review tool hosted by UCB is being used by all project members.

Since its beginnings, there have been several improvements to the DM Review page. The FDSN event server at comcat.cr.usgs.gov replaced the NCEDC server at www.ncedc.org. The geojsonp server at earthquake.usgs.gov is used for recent event parameters. Information from these catalogs is used to evaluate the EEW alerts. The DM Review page now has an option to download an event-replay-zip file that can be read by the ShakeAlert UserDisplay program to replay the warnings for any event since April 2012. The capability to handle duplicate and cancelled alert messages has been added to the Summary table, while the DM XML message tab now only shows DM messages for the selected event, instead of all messages for the event day.

The ElarmS Review page has improved station information for the selected event. This information is obtained from the new version of the ElarmS event assocation program, E2, that now monitors station availability via the one-packet-per-second data streams. For the selected event, the ElarmS Review page shows the stations that triggered, the stations that were available but did not trigger, and the nearby stations that did not contribute to the alert because their data latency was too large. This information is displayed in text format and with color-coded station symbols on the map. The ElarmS Review page Trigger table has a new tool for analysing poorly located events. The user can edit a trigger's time or deselect a trigger and recompute a new event location based on the modified trigger table. The revised event location is displayed on the map.

We continue to make improvements to the DM and ElarmS Review tools. Recently, an option was added to include variations in event magnitude along with origin time and location as one of the parameters for matching DM or ElarmS events with ComCat hypocenters,. The DM Review page now contains a state-of-health table that shows if all processes are running. A Station Monitor webpage was created that displays a snapshot of the current station data transmission latencies. The mean and standard deviations of the packet latencies over the current ten minute period are displayed for each station. The latency table also shows data packet lengths and the adjusted latency, which is the latency plus one half of the packet length. All stations being used by the system are displayed on the map with color coded symbols. The station color code can represent the latency, packet length, or adjusted latency. Individual networks can also be displayed.

In support of the webpage review tools, a Postgres database was setup with tables for DM and ElarmS event information. ElarmS was modified to send log information as messages to the ActiveMQ server and a new java program was developed to read the DM event messages and the ElarmS messages and insert corresponding rows into the database tables. The webserver for the DM and ElarmS tools was modified to work with the database.

**Goal 4:** Continue to interact with users in collaboration with the USGS

For early warning alerts to be useful, people, companies, and institutions must know beforehand what actions they will perform when they receive the information. Beta user interactions allow the ShakeAlert team to learn which alert delivery options are most effective, what changes would make the UserDisplay more useful in a pre-disaster situation, and most importantly, what actions users plan to take in various scenarios. User interactions are coordinated among project partners in California and the Pacific Northwest. We collect feedback detailing actions and challenges within the beta user organizations, as well as anticipated benefits and savings. This allows us to create a blueprint for a fully operational system that will meet the needs of the public.

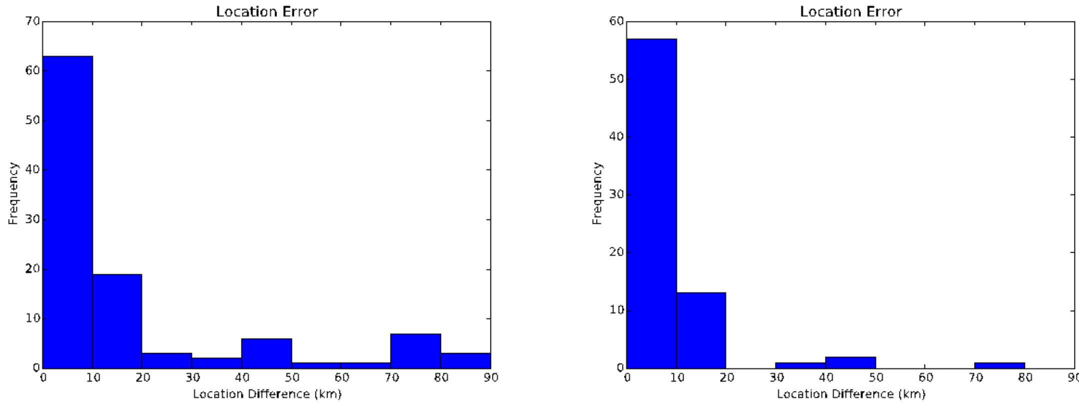


Figure 8. ElarmS vs ANSS epicentral location error. Left: All events including offshore. Median location error: 6.90 km. Standard deviation: 28.9 km. Right: Offshore events excluded. Median location error: 3.34 km. Standard deviation: 11.9 km.

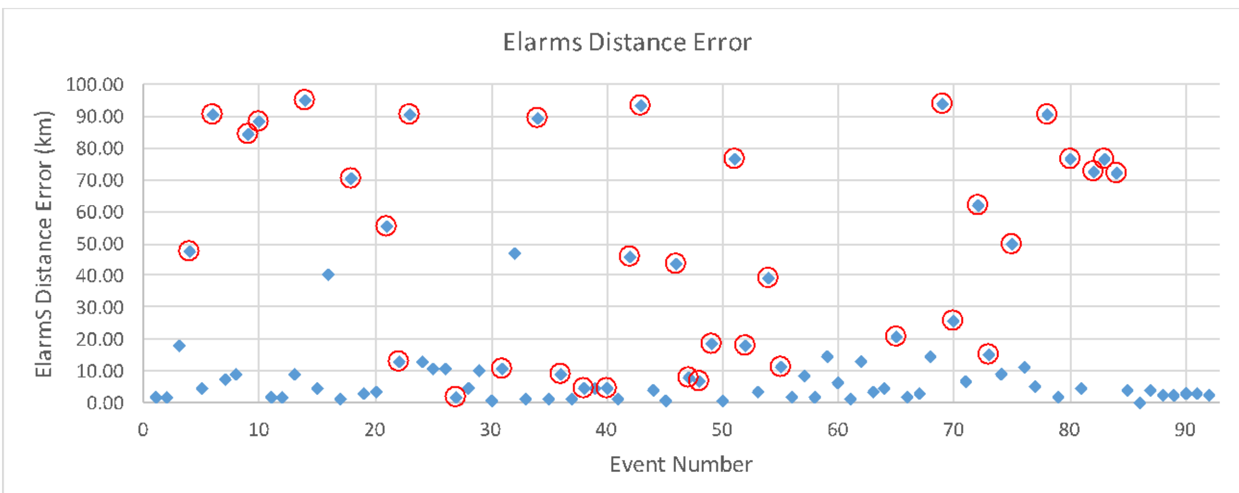


Figure 9. Location error by event. Note that the offshore events (circled in red) have poorer epicentral locations that the onshore events.

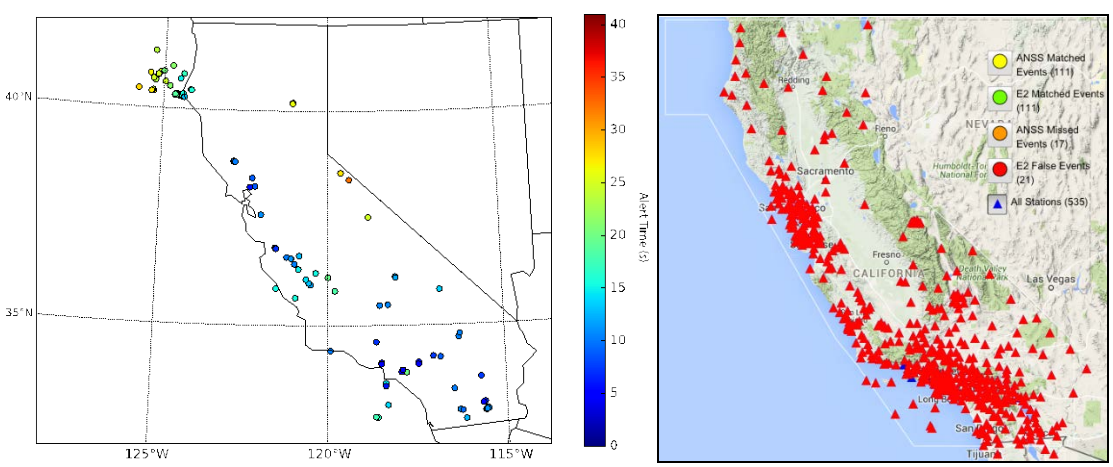


**Figure 10**. Left: Map showing first alert time for ElarmS earthquake detections in California (in seconds). Right: Stations used by ElarmS in California (triangles). There is a clear correlation between high station density (for example, in the Bay Area and Los Angeles regions), and speed of the first alert.

In addition to determining actions, such as personal safety approaches (drop, cover, and hold on); automated controls; or situational awareness, users are beginning to look at policy changes, which may need to be enacted and funding requirements to implement their automated controls.

A major effort was participation in the CEEWS the Education and Training Committee (E&T), which had 22 members. The group determined 17 areas requiring input, including Alert and Warning/Mass Notification; Emergency Management; Seismology/Science Content; Sociology and Public Health; Risk Communications; Education; Community Engagement/Public Education; Public Affairs/ Communications; Non-Profit Education Partners; Private Sector Education Partners; Users – Technical; Users – Organizational; Users – Business; Users – Media; Non-English Language Audiences; Access and Functional Needs; and External Stakeholders (Other States). Jennifer Strauss (UCB) was Chair of the CEEWS Technical Users subcommittee, which addressed the needs, constraints and requirements for an educational program and technical adaptations required for effective use of EEW by critical facilities and lifelines.

The CEEWS E&T process built on work done by the ShakeAlert Beta Test groups. Today about 50 scientists and members from about 50+ organizations receive alerts through the ShakeAlert UserDisplay. Northern California recipients include the state's emergency operations center at the California Office of Emergency Services (CalOES), Bay Area Rapid Transit (BART), Google Inc., and the San Francisco Department of Emergency Management (SFDEM). We hold regular meetings with beta testers in municipalities and with county officials to 1) educate them about the ShakeAlert project, including benefits and limitations 2) strategize on implementing actions, such as opening fire house bay doors in response to an alert, and 3) coordinate continued engagement as the system comes online with more Users and in more areas. UC Berkeley will continue to expand the user base by engaging with new sectors, such as the High Speed Rail Authority.

**Other Activities**

*Third International Meeting on Earthquake Early Warning*

UC Berkeley hosted the Third International Conference on EEW on September 3-5th, 2014, two weeks after the M6.0 South Napa earthquake. Over 200 people from 14 different countries from scientific, industry, governmental, and public sectors attended to share perspectives on EEW, including the advances in the United States ShakeAlert project. Day 1 focused on implementation strategies and policy, with intense interest from California lawmakers and the media because of the South Napa quake. State Senators Alex Padilla and Jerry Hill, Lieutenant Governor Gavin Newsom, San Francisco Mayor Ed Lee, the Director of CalOES, Mark Ghilarducci, and USGS Director Suzette Kimball all spoke in support of EEW for California (Figure 11). They were followed by two panels on policy considerations. Day 2 highlighted the global status of earthquake early warning, featuring talks describing the US, Japanese, Mexican, and European systems, as well as sessions on applications for Great Earthquakes and new concepts for the next generation of early warning systems. Day 3 panels brought a discussion of ways that the public sector and municipalities could apply EEW alerts to improving resiliency. This meeting provided a unique opportunity to bring all stakeholders under one roof for a


Figure 11: Key legislative officials speaking to the importance of EEW at the conference. From left to right: Berkeley Seismological Laboratory director Richard Allen, state Sen. Jerry Hill, Lt. Gov. Gavin Newsom, state Sen. Alex Padilla, Office of Emergency Services director Mark Ghilarducci, San Francisco Mayor Ed Lee and USGS acting director Suzette Kimball.

coordinated discussion. It really moved the process toward a production earthquake early warning system for the United States forward, starting with implementation on the US West Coast. All presentations are available on the web (http://earthquakes.berkeley.edu/3rd_international_conference/agenda.html).

*GlarmS*

At UC Berkeley, we are developing and implementing a geodetic-based EEW algorithm called GlarmS. It was running in testing mode at the time of the M6.0 South Napa earthquake. GlarmS analyzes positioning time series from real-time GPS processors, such as TrackRT or RTNE. It produces high sample rate displacement time series for 62 GPS stations in the greater San Francisco Bay Area with 3-4 s latency, using a fully triangulated network scheme with 165 basestation-rover pairs. GlarmS uses the ShakeAlert alerts to trigger its processing. It estimates the static offset each second at each station pair and inverts these parameters for fault slip. In the South Napa earthquake, the first "large" event within the GlarmS grid since it has been running, the algorithm performed well with an intial solution after 23 s. A bug which delayed the alert by 10 s has been resolved, and we now expect earliest GlarmS results within 10-15 s of a quake. GlarmS has been updated to incorporate processing for multiple fault configurations and to use precise point positioning data. We will soon be processing data from the entire state.

*International ElarmS*

In addition to California, ElarmS is now running in the Pacific Northwest (as part of the US West Coast ShakeAlert system), Hawaii, Korea, Israel, Turkey and Chile. The algorithm as it runs in California is highly customized to the state and its various real-time (RT) networks, with some of the parameters embedded in the code. The customization includes both parameterizations and models, such as the empricial relationships to determine magnitude from displacement ($P_d$) and dominant period ($T_P$) [*Allen et al.*, 2009]), the fixed event depth of 8 km, the velocity model for the California region.

A major push toward the internationalization of ElarmS came with a postdoc Ran Nof from Israel, following the Israeli governments determination to implement an EEW system. Dr. Nof has updated the ElarmS system to allow more flexibility for other regions, while maintaining its optimization to California intact. Just as he completed the effort, interest from other countries such as Turkey and Chile allowed further testing of his improvements. In addition to the direct improvements of the ElarmS waveform processing and algorithm modifications, Nof has also created a set of tools that allow rapid deployment of the package, and analysis of the system's performance. The tools allow real time visual monitoring of ElarmS system modules and components (*ElViS*), enable real time and accelerated time (up to ten times faster than real-time) playback of historical data (*SRTPB*), and the review and investigation of the log files to determine ElarmS performance (*E2ReviewTool*). The tools are available on-line at https://github.com/rannof. Nof has adapted ElarmS to accept input data through SEEDlink and interact with SEEDlink systems, including a program (*E2log2SC*) to convert E2 log files to Seiscomp3 event parameters xml files, enabling the analysis of the ElarmS results using the Seiscomp3 tools and the importing ElarmS results to a Seiscomp3 database. Figure 12 shows and example of ElViS.

**Report University of Southern California:** August 2012-July 2013

**Goal 3: Evaluate system performance on a region-by-region basis. Identify causes of strong/weak performance and feedback to algorithm developers.**

- Operated the existing ShakeAlert performance-monitoring system and monitored the performance of the ShakeAlert demonstration system with the CISN Testing Center at USC with testing results posted at: http://scec.usc.edu/scecpedia/CTC_Results
- Implement new, prototype, “False Alarm” performance summaries in the CTC and began analysis of the ShakeAlerts identified in these summaries that do not correspond with ANSS events.
- Updated the CISN Testing Center to extract performance information from updated ShakeAlert log formats as implemented on the ShakeAlert demonstration system.

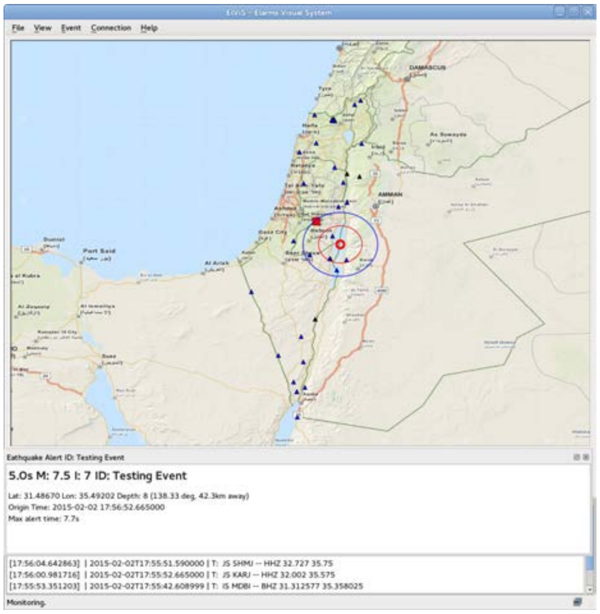


Figure 12: ElarmS Visualization System (ElViS) screenshot. Colors of stations (triangles) indicate maximum acceleration (colors) or inactivity (black). Red square represents point of reference for calculating S wave arrival time and expected intensity. Background maps are rendered online from open street maps (http://www.openstreetmap.org/). This example shows an event alert test. Upon receiving an alert, the event location is marked as a bold red circle, P and S wave real-time propagation is marked as blue and red circles, respectively, and event information is given on a panel below the map, stating calculated magnitude (M: 7.5), expected arrival time of S wave (5.0s) and intensity (I: 7) with respect to the user location (red square). The information include also the event location as latitude, longitude, depth, azimuth and distance from the reference point, the origin time of the event and the maximum alert time (the first S wave arrival time estimation, 7.7 seconds in this case).

- Prepared and presented ShakeAlert performance summaries for significant California Earthquakes and for selected performance periods to CISN technical and management groups during project coordination calls.

**Research:**

- Implemented two new prototype cumulative summaries that provide new information about ShakeAlert system False Alarm performance. Currently, the CTC performance summaries only described ShakeAlert performance during significant California events found in the ANSS Catalog. We have now introduced two new performance summaries that show the total number of ShakeAlerts issued by the Decision Module (and individual Algorithms) and the number of these ShakeAlerts that can be easily associated with ANSS events. Any ShakeAlerts not associated with ANSS Events are considered False Alarms (or False Alerts). Below are examples of these two new performance summaries, the False Alerts Table (Table 2), and False Alerts Magnitude Distribution (Figure 13). These show ShakeAlert system performance from 1 Jan 2013 through 31 July 2013 (212 days). We will review these performance summaries with the ShakeAlert development team and, after group review, we will install final implementations of these performance summaries in the operational CTC ShakeAlert Testing Center, so they are produced routinely along with existing CTC ShakeAlert performance summaries.

*Overall Performance for [2013-01-01; 2013-07-31]*
*Using reference ANSS events: M>=0.0; U codes; 60 seconds since origin*

| | All ShakeAlerts During Catalog Period [#] | ShakeAlerts Associated with an ANSS Event (All Magnitudes) [#(%)] | ShakeAlerts With No Associated ANSS Events (No Cancellation) [#(%)] | ShakeAlerts with No Associated ANSS Events (With Cancellation) [#(%)] |
|---|---|---|---|---|
| ShakeAlert | 637 | 574 (90) | 54 (8) | 1 (0) |
| VS | 493 | 449 (91) | 44 (9) | 0 (0) |
| Onsite | 58 | 48 (83) | 4 (7) | 1 (2) |
| ElarmS | 795 | 756 (94) | 39 (5) | 0 (0) |

**Table 2:** False Alert performance summary for ShakeAlert system for catalog period 1 Jan 2013 - 31 July 2013 (212 days) shows total number of ShakeAlerts issued to public by Decision Module and the fraction of these ShakeAlerts that are not clearly associated with earthquakes of any magnitude in the ANSS catalog for the California region.

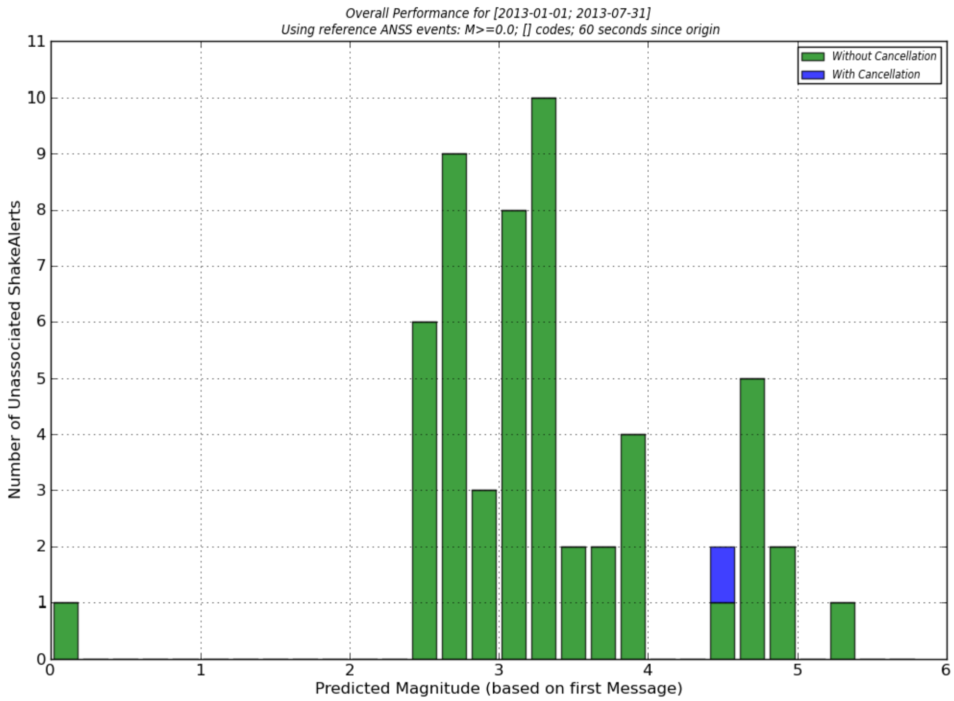


**Figure 13:** False Alert Magnitude Distribution shows the magnitude distribution of the Unassociated ShakeAlerts and shows what fraction of these False Alerts were cancelled by the system.

**Publications and Presentations**

1. Meier, M. A.; Heaton, T. H.; Clinton, J., 2013: A filter bank approach to earthquake early warning, AGU Fall Meeting 2013, abstract # S43C-08.
2. Caprio, M.; Wiemer, S.; Hiemer, S.; Meier, M. A.; Spada, M., 2013: Sibyl: a system for evaluating the performances of ideal Earthquake Early Warning based on stochastic seismicity models, AGU Fall Meeting 2013, abstract # S41A-2404.
3. Behr, Y.; Cua G.; Clinton, J.; Racine, R.; Meier, M. A.; Cauzzi, C., 2013: What to Expect from the Virtual Seismologist: Delay Times and Uncertainties of Initial Earthquake Alerts in California, AGU Fall Meeting 2013, abstract # S41A-2415.
4. Meier, M. A.; Heaton, T. H., Clinton, J., 2014: A Filter Bank Approach to Earthquake Early Warning, EGU General Assembly 2014, abstract # EGU2014-8630
5. Böse, M., R. Graves, D. Gill, S. Callaghan, P. Maechling: CyberShake-Derived Ground-Motion Prediction Models for the Los Angeles Region with Application to Earthquake Early Warning, *Geophys. J. Int.*, minor revision needed.
6. Böse, M., T. Heaton, K. Hudnut, 2013: Combining Real-Time Seismic and GPS Data for Earthquake Early Warning (Invited), *American Geophysical Union*, Fall Meeting 2013, abstract #G51B-05
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8. Given, D.D., Cochran, E.S., Heaton, T., Hauksson, E., Allen, R., Hellweg, P., Vidale, J., and Bodin, P., 2014, Technical implementation plan for the ShakeAlert production system—An Earthquake Early Warning system for the West Coast of the United States: U.S. Geological Survey Open-File Report 2014–1097, 25 p.
9. Karakus, G., T. Heaton, 2013: Reality Check Algorithm for Complex Sources in Early Warning, A*merican Geophysical Union*, Fall Meeting 2013, abstract #S44A-02.
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11. Cheng, M.H., Wu, S., Heaton, T.H. & Beck, J.L., 2014: Engineering application for buildings in earthquake early warning system, *Engineering Structures*, 60, p.155-164.
12. Cheng, M., M. Kohler, T. Heaton, R.W. Clayton, M. Chandy, E. Cochran, J. Lawrence, 2013: The Community Seismic Network and Quake-Catcher Network: Monitoring building response to earthquakes through community instrumentation, *American Geophysical Union*, Fall Meeting 2013, abstract #S51A-2292.
13. Tamaribuchi, K., Yamada, M. & Wu, S.: A new approach to identify multiple concurrent events for improvement of Earthquake Early Warning, *Zisin2*, accepted.
14. Wu, S., Beck, J.L. & Heaton, T.H., 2013: Earthquake Probability-based Automated Decision making Framework for Earthquake Early Warning Applications, *Computer-Aided Civil and Infrastructure Engineering*, 28, p.737-752.
15. Wu, S., M. Cheng, J. Beck and T. Heaton, 2014: Uncertainty Analysis of Decision Making for Early Warning Application in Elevator Control, *Tenth U.S. National Conference on Earthquake Engineering,* Frontiers of Earthquake Engineering, July 21-25, Anchorage, Alaska.
16. Wu, S., Cheng, M.H., Beck, J.L. & Heaton, T.H., An engineering application of earthquake early warning: ePAD-based decision framework for elevator control, *Soil Dynamic and Earthquake Engineering*, submitted.
17. Yamada, M., Tamaribuchi, K. & Wu, S., Faster and more accurate Earthquake Early Warning system - combination of velocity and acceleration-type seismometers, *Journal of Japan Association for Earthquake Engineering*, submitted.

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