Bulletin of the Seismological Society of America, Vol. 104, No. 1, pp. 162–173, February 2014, doi: 10.1785/0120130146

Designing a Network-Based Earthquake Early Warning Algorithm for California: ElarmS-2

by H. Serdar Kuyuk, Richard M. Allen, Holly Brown, Margaret Hellweg, Ivan Henson, and Douglas Neuhauser

Abstract The California Integrated Seismic Network (CISN) is developing an earthquake early warning (EEW) demonstration system for the state of California. Within this CISN ShakeAlert project, three algorithms are being tested, one of which is the network-based Earthquake Alarm Systems (ElarmS) EEW system. Over the last three years, the ElarmS algorithms have undergone a large-scale reassessment and have been recoded to solve technological and methodological challenges. The improved algorithms in the new production-grade version of the ElarmS version 2 (referred to as ElarmS-2 or E2) code maximize the current seismic network's configuration, hardware, and software performance capabilities, improving both the speed of the early warning processing and the accuracy of the warnings. E2 is designed as a modular code and consists of a new event monitor module with an improved associator that allows for more rapid association with fewer triggers, while also adding several new alert filter checks that help minimize false alarms. Here, we outline the methodology and summarize the performance of this new online real-time system. The online performance from 2 October 2012 to 15 February 2013 shows, on average, ElarmS currently issues an alert 8.68 ± 3.73 s after the first *P*-wave detection for all events across California. This time is reduced by 2 s in regions with dense station instrumentation. Standard deviations of magnitude, origin time are 0.4 magnitude units, 1.2 s, and the median location errors is 3.8 km. E2 successfully detected 26 of 29 earthquakes ($M_{ANSS} > 3.5$) across California, while issuing two false alarms. E2 is now delivering alerts to ShakeAlert, which in turn distributes warnings to test users.

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 (Allen, 2004, 2006, 2007; Kuyuk and Allen, 2013a). Both onsite and 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 (Olson and Allen, 2005; Kuyuk and Allen, 2013b). In 2007, the California Integrated Seismic Network (CISN) embarked on a multiyear EEW project in California. The project, named CISN ShakeAlert, is implementing, testing, and integrating three distinct EEW algorithms into a single, end-to-end production-grade system to provide warnings to test users from industrial, government, and corporate groups, with a view to eventually provide warnings to the general public (Böse *et al.*, 2013). The system uses seismic data from networks across the state (~400 stations), which contribute to the CISN (Fig. 1).

ShakeAlert is based on three research EEW algorithms: (1) Earthquake Alarm Systems (ElarmS), developed and maintained at the University of California Berkeley (this article); (2) OnSite, developed and maintained at the California Institute of Technology (Böse *et al.*, 2009); and (3) Virtual Seismologist, developed and maintained at ETH Zurich (Cua *et al.*, 2009). Each of these algorithms has different methods of detecting the *P* wave, associating triggers with events, estimating magnitude, and filtering out false alarms. ShakeAlert combines information from all three of these algorithms and, through a DecisionModule (DM), it recognizes when the algorithms identify the same event and produces a single summary for each earthquake. This combined event information is sent as a single sequence of updated alert messages across the Internet to registered test users. The three algorithms (including ElarmS) provide source information (location, magnitude, etc.) to the DM. Source information is then passed forward to users who use the UserDisplay (UD) to (automatically) determine the expected shaking intensity and time until shaking at their location.

There are a variety of ways early test users of the project can receive and use the alerts. The most common use at this stage is to receive the alerts on computer desktops using the project's UD software. When the UD receives an alert

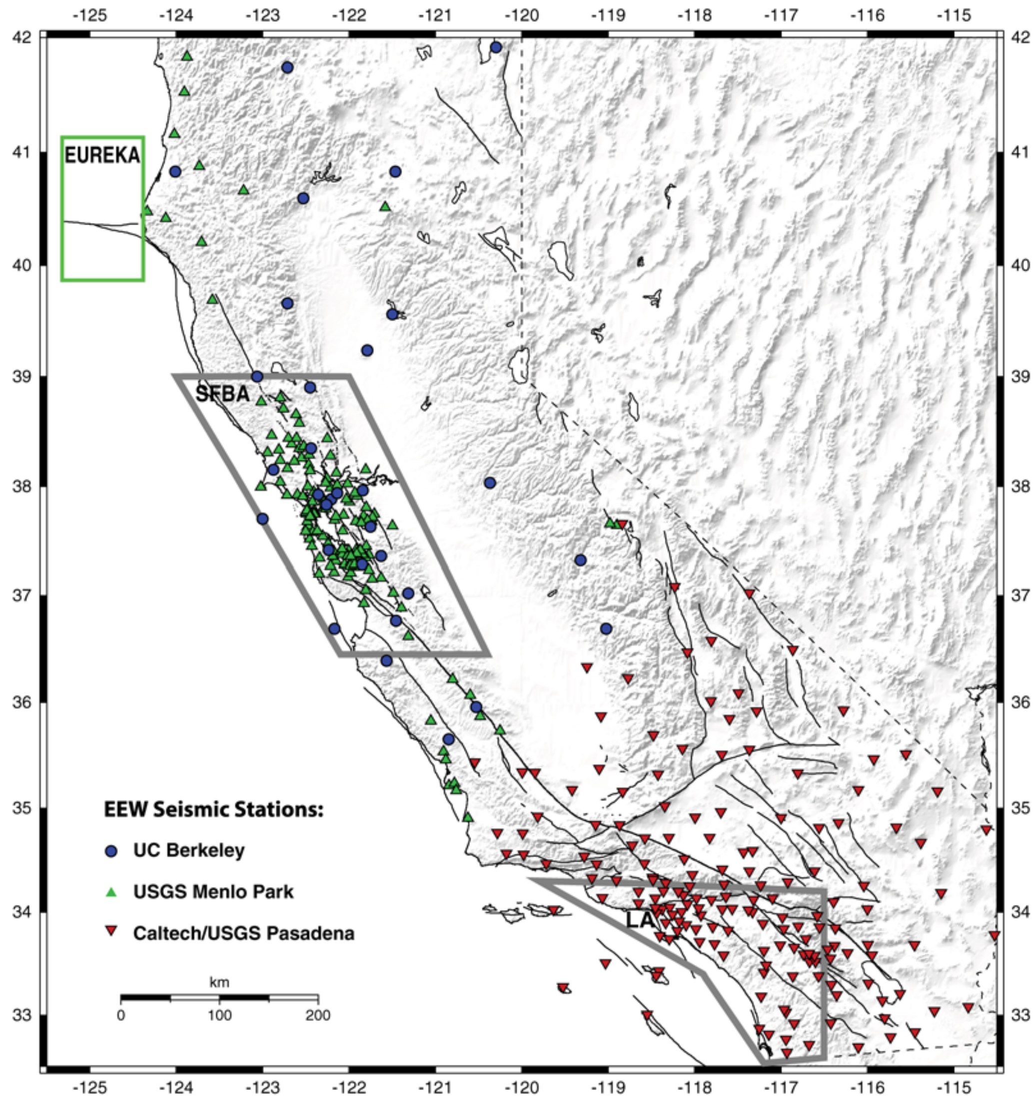

Figure 1. Map of CISN seismic stations that contribute to E2 processing. The two alert regions described in the text are shown as the San Francisco Bay Area (SFBA, northern) and Los Angeles (LA, southern) boxes and are areas with high densities of both population and seismic stations. The Eureka box illustrates the region where we release the requirement that a station must be within 100 km of an epicenter in order to contribute to the magnitude estimate. This is necessary to account for offshore earthquakes in the Mendocino Triple Junction and Gorda plate regions. The color version of this figure is available only in the electronic edition.

message that meets the user's configured criteria (such as magnitude, intensity, and/or likelihood thresholds), a pop-up 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 signal also accompanies this information. A summary of the ShakeAlert system is provided in Böse *et al.* (2013). Test users from the San Francisco Bay Area Rapid Transit (BART) train system have developed a secondary response layer that also triggers when an observed ground-motion threshold is exceeded. The BART automated train control system then decelerates trains when a significant event is detected. This system is currently in place and is the first automated earthquake response of a transit system in the United States.

The original ElarmS code, most recently described in Brown *et al.* (2011), has been running in real time since 2007 for the entire state of California (Allen *et al.*, 2009) using data from the CISN seismic networks. Although this algorithm has been in place for approximately six years, the alerts were only issued to a small group of testers of the system. The theoretical foundations of the code were first developed by Allen and Kanamori (2003) for southern California and by Wurman *et al.* (2007) for northern California. The algorithm has also been tested offline with datasets of large earthquakes ($4 < M_{JMA} < 8$) in Japan (Brown *et al.*, 2009) and Italy (Olivieri *et al.*, 2008). Since 2009, more than 150 events from the greater San Francisco Bay Area were detected by ElarmS and forwarded to the ShakeAlert DM. Between 2010 and 2011, the research prototype system underwent

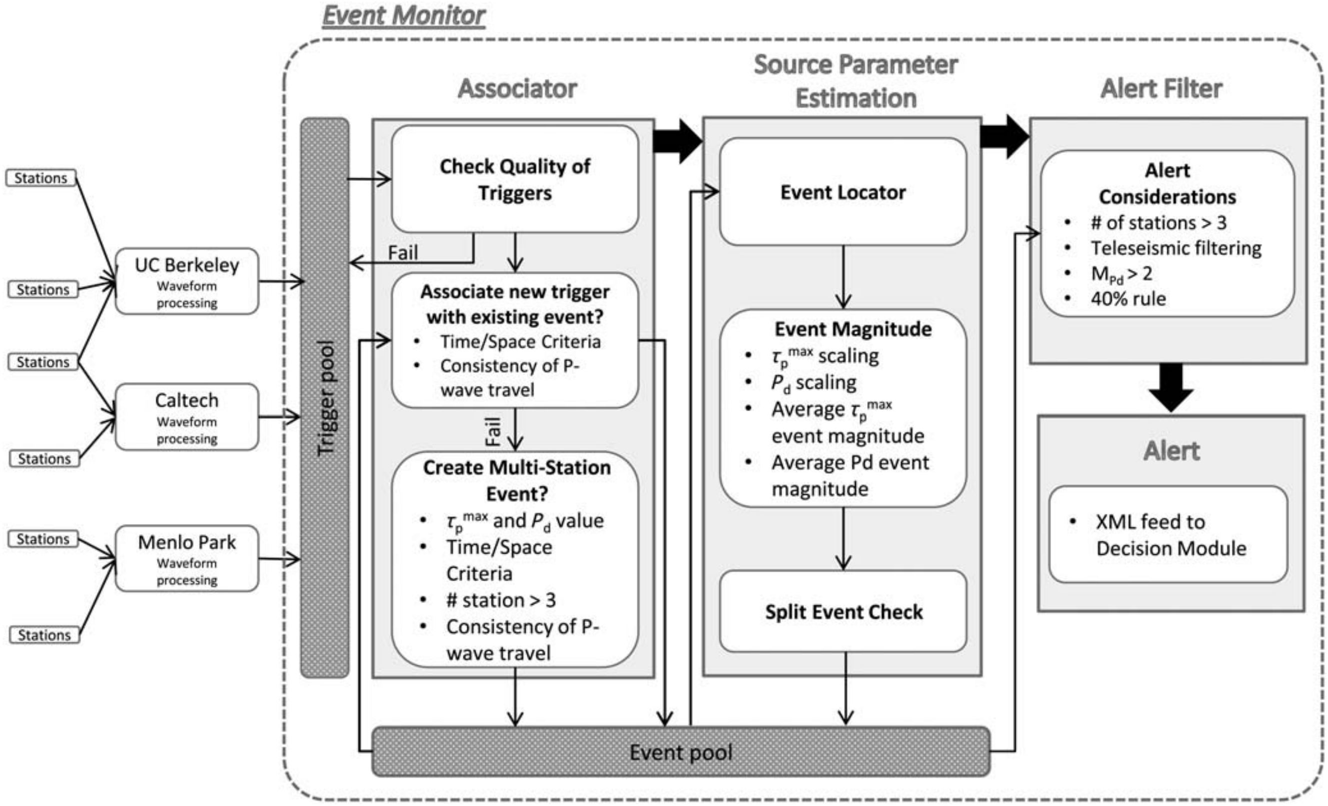

Figure 2. Processing flow for E2. Station waveform feeds are processed at the three CISN network hubs, UC Berkeley, Caltech, and Menlo Park. *P*-wave triggers, amplitudes, frequencies, and other parameters are generated at the three processing centers and forwarded to a single, statewide trigger pool 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 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. Magnitude is then 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. An alert filter continuously checks the event pool to identify any events that pass another set of criteria and can be published to the ShakeAlert DM. Currently, event alerts are only published to test users.

a complete rewrite and rebuild. Existing processing elements have been rewritten to become a streamlined production code, and we have developed new algorithms to improve performance. In early 2012, the second-generation ElarmS system replaced the first-generation code as the authoritative version reporting to the ShakeAlert DM. This new version of the algorithm detects and sends alert information for all California earthquakes. In this article, we describe the significant methodology and code development and the performance of ElarmS version 2 (referred to as ElarmS-2 or E2) that is now in operation in California.

ElarmS-2 Methodology

The E2 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++, which, compared with the previous scripting language (FORTRAN), improves processing speed and takes advantage of the power of the networking environment. In addition, the speed of data transmission recently has increased. Many of the data loggers at the seismic stations of the CISN's networks were replaced with funding through the recent American Recovery and Reinvestment Act (ARRA). These stations can now send data in 1 s packets to the waveform processing (WP) centers; this is an improvement over the previous system, in which packet transmissions could take several seconds. Since April 2012 (for the UC Berkeley [BK] network) and August 2012 (for the Southern California Seismic Network [CI] network), these data are now processed directly, shaving up to 6 s from alert times.

E2 consists of a new WP module and a new event monitor (EM) module, plus several new alert filters that check each event just prior to forwarding alerts to the DM. The new modular code design of E2 makes it easy to upgrade individual elements of the algorithm (location, magnitude, etc.) at any time, without disrupting the processing stream (Fig. 2). E2 now also has a replay capability, allowing us to compare results from new algorithms or components with

Table 1

Modifications to the Various Versions of E2

	E2	E2.1	E2.2	E2.3	E2.3.1	E2.3.2
	12–26 April 2012	27–30 April 2012	1 May–28 August 2012	28 August–01 October 2012	02 October 2012–22 January 2013	22 January 2013–present
1 s packet	BK implementation			CI implementation		
WP	WP2 and heartbeats implemented					Data packets processed immediately (not waiting for integer second)
Association				Relocation of epicenter in integrated into association algorithm	Association of triggers up to 1500 km equation (1) implemented	Trigger pool updated
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; four station triggers required	Linear teleseismic filtering implemented		40% of station must have triggered; still 4 stations required	Break out of association and go to alert if 10 stations have triggered	

*nCA, northern California; sCA, southern California; MTp, magnitude estimated from TauPmax; MPd, magnitude estimated from Pd.

past performance and thereby to optimize configuration changes. The replay capability is key to improving the system, and modules within the E2 algorithms have been updated several times (Table 1). The latest version, E2.3.2, has been operational since 22 January 2013.

Waveform Processing

The new WP module is currently operating at the three CISN network hubs (UC Berkeley, Caltech, and the U.S. Geological Survey [USGS] at 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 EM, which runs at UC Berkeley (Fig. 2). WP processes waveforms in 1 s segments. 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 short-term-average to long-term-average 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 the EM. During the 4 s following the *P*-wave trigger time, parameters providing information on the frequency content of the *P* wave (τ_p^{max}) and on the peak displacement (P_d) and peak velocity (P_v) amplitude are computed every 0.1 s and forwarded to the EM. More information on the determination of these parameters is found in Brown *et al.* (2011).

An Apache ActiveMQ server running at UC Berkeley handles communication between the WP centers and the EM at Berkeley. The WP clients send compressed binary messages via the Java Message Service API to the ActiveMQ message broker, which provides a publish–subscribe message environment for E2 and any other message-receiving clients. E2 and all WP programs send heartbeat messages every 5 s 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 UD.

Event Monitor

The second component of E2 is the EM (Fig. 2). Its main tasks are to associate *P*-wave triggers in order to identify earthquakes in progress, characterize the source, and to filter out false events. The EM consists of a C++ code designed for efficiency, a revised trigger associator, and a new alert filter, which verifies each event before sending an alert to the DM for release to test users. Additional improvements include

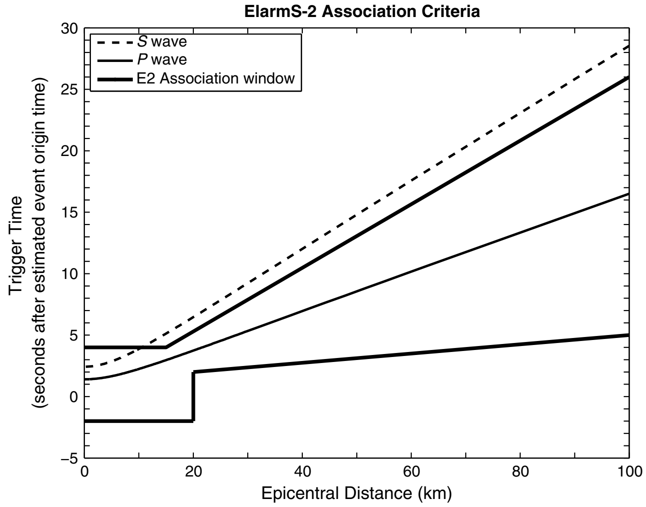

Figure 3. Time–space association criteria for E2. Expected *P*- and *S*-wave arrival times are shown as solid and dashed lines, respectively, for 8 km focal depth. If a new trigger falls within the E2 association time and space window (between thick solid lines), relative to an existing event, it is associated with the event, and its parameter information contributes to the event location, origin time, and magnitude.

trigger and event pools. The EM can handle multiple events in the event pool at the same time. Currently, there is only one EM running at UC Berkeley, but the modular design allows for multiple EMs to be active simultaneously. The EM operates on data from the entire state, which it receives as trigger and ground-motion information from WP modules at each of the three data centers.

Before association, the quality of each trigger is evaluated. For example, the signal-to-noise ratio must be greater than 0.5. Also, two additional criteria must be satisfied: $-5.5 < \log(P_d) < 3.5$ and $-0.9 < \log(\tau_p^{max}) < 1$, in which P_d and τ_p^{max} are in centimeters and seconds, respectively. Requiring triggers to fall in this range filters out many noise spikes. The EM can declare an event by associating just two triggers, but the trigger criteria are more strict in this case, requiring $0.5 < \log(P_d) < 3$ and $0.3 < \log(\tau_p^{max}) < 1$. If a trigger from any channel fails to satisfy the criteria, it is sent back to the trigger pool. This iterative process continues until both P_d and τ_p^{max} pass the quality checks.

Next, the EM's associator attempts to link qualified triggers with existing events from the event pool. To be associated, the trigger time must fall within a defined time–space window (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 requirement prevents E2 from creating separate (false) events using triggers from stations far from the epicenter and allows the algorithm 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

$$|t_{new} - t_n| < \Delta d / V_P + 3, \qquad (1)$$

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

The new E2 associator has an additional level of event detection. If a new trigger cannot be associated with an existing event, it is added to the trigger pool, which is a hopper containing unassociated triggers. When otherwise unoccupied, the algorithm scans through the hopper, looking for any set of three or more triggers that can be associated into an event based on the space–time parameters (Fig. 3 and equation 1). This multitrigger event step is critical because it can identify a large portion of California earthquakes in regions of dense station coverage, which typically coincide with regions of dense population. In these regions, *P*-wave triggers can occur at multiple stations in rapid succession. If the algorithm cannot generate a multitrigger event, it scans through the hopper again, looking for any two triggers that are less than 100 km apart and separated by fewer than 16.5 s. Any trigger not associated with an existing event, or used to generate a new event, remains in the trigger pool. A trigger not associated with any other events will be returned to the trigger pool until an expiration time of 30 s is exceeded, at which point the trigger is deemed anomalous and subsequently deleted from the pool.

If an event is created based on two triggers, the locator assigns an epicenter located between them, but one-third closer to the station that was triggered first. If an event is determined from triggers at three or more stations, the locator estimates its position and origin time using a grid-search algorithm. This algorithm assesses points within a 400×400 km grid, with grid points every 5 km, located at the centroid of the three stations. Each station is assumed to be located at the nearest grid point, and an approximate epicenter is estimated based on arrival-time residuals. To obtain a higher-resolution location, the search is repeated on a 40×40 km grid, with 2 km grid-point spacing, based on the approximate epicenter determined from the first cycle iteration. As accurate magnitude estimation relies on a good distance correction factor, this location step is important to the E2 system process.

Rapid magnitude estimation is at the heart of ElarmS and is accomplished using empirically derived scaling relationships between magnitude and the frequency (τ_p^{max}) and/or displacement (P_d) and velocity (P_v) amplitude content of the *P* waves. An empirical scaling relationship between magnitude and τ_p^{max} was first calibrated from a southern California earthquake catalog (Fig. 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). Prior to late August 2012, E2 used

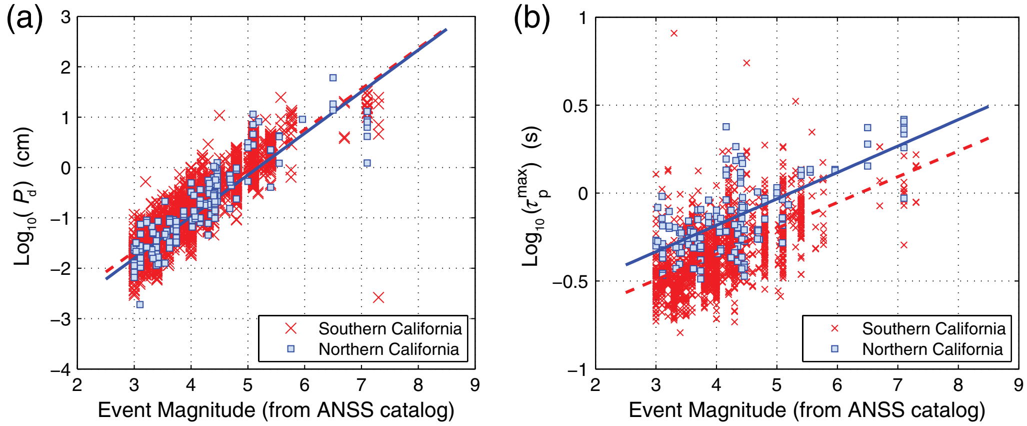

Figure 4. *P*-wave parameters scaling relationships. Crosses and squares represent (a) displacement (P_d) and (b) *P*-wave frequency (τ_p^{max}) values from the calibration datasets in southern and northern California, respectively (modified from Brown *et al.*, 2011). Diagonal lines are the resulting magnitude scaling relations used by E2 to estimate event magnitudes. The color version of this figure is available only in the electronic edition.

both the P_d and τ_p^{max} relationships for northern California and only the P_d relationship for southern California. However, since September 2012, only the P_d–magnitude relationship is used in both parts of the state, because it provides a more accurate estimate of magnitude with less variation in the absolute error. Initially E2 only included triggered stations within 100 km of the epicenter to contribute to magnitude calculations. However, this created a problem determining the magnitude of offshore events, particularly around the Mendocino Triple Junction region, where many earthquakes are more than 100 km offshore. To avoid this problem, we do not enforce the 100 km restriction near the Mendocino Triple Junction in a region we refer to as the Eureka box (Fig. 1).

The original EM occasionally struggled with split events, in which the system produces two separate but simultaneous events for a single earthquake. This occurs when a small subset of triggers falls outside the initial association criteria. This can occur, for example, from a poor initial earthquake location. To avoid this problem, we define a blackout window around existing events encompassing time–space windows of 15 s and 90 km. Before the associator generates a new event, it first checks all existing events in the blackout window. If the proposed new event epicenter is a match with an existing event in the blackout window, the associator cancels the new event. All triggers associated with the canceled 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 four filters that have been added at the end of processing and before an alert message is sent to the DM for release. The purpose of these filters is to minimize the publication of false events. First, the event magnitude must be greater than 2, and the estimated epicenter should not be on the edge of a location grid-search area. Second, an event must have triggers contributed from at least four stations. Although an event can be generated internally within ElarmS based on triggers from only two stations, we find the false alarm rate is significantly reduced if we require four stations to be associated before an alert is issued to the DM. We have also developed an artificial neural network-based approach to improve performance when only two or three triggers are available. This method is currently under consideration for inclusion in a future version of E2. The current E2 requires four station sites to trigger an alert rather than only four vertical channels (many sites have a velocity and acceleration instrument). This may seem like a minor technicality, but the seismic network in California has many stations installations that have more than one sensor, such as collocated accelerometers and broadband seismometers. Given this, the old requirement of triggers from four channels could potentially be satisfied by just two stations, which we have determined are not enough to accurately determine an epicenter.

Our third filter was designed to assure that sufficient stations were triggered near the epicenter prior to issuing an alert message. To accomplish this, the algorithm first counts the number of triggered stations and determines the largest source–station distance (D_{max}). Next, a circle of radius D_{max} is constructed around the earthquake epicenter, and the number of stations within this circle is counted. The filter checks that at least 40% of these stations issued trigger alerts. If the percentage is below 40%, the event remains in the event pool until the 40% criteria is satisfied.

Our fourth filter discriminates between local and teleseismic events. This filter was created to avoid false events from large-magnitude teleseisms. The initial *P*-wave displacements of large teleseismic earthquakes generally have displacement amplitudes similar to those of smaller local events. The difference between the two is that waveforms from the local events tend to have shorter-period content (τ_p^{max}) than the waveforms of the teleseismic events. This type of filter is also used by the Onsite algorithm (Böse *et al.*, 2009). For ElarmS, we have developed a simple linear discriminant based on the events' average τ_p^{max} and P_d (Fig. 5).

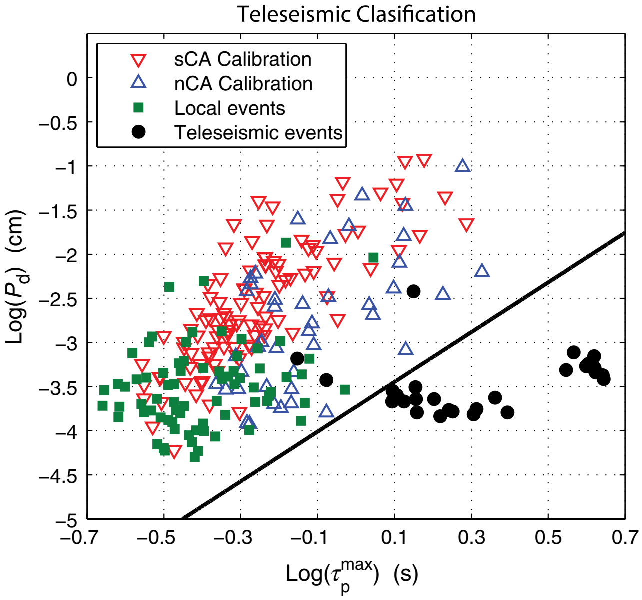

Figure 5. Linear filter to discriminate teleseismic events from local earthquakes. Triangles are the average τ_p^{max} and P_d for the events of the calibration dataset from the southern California network (sCA; inverted triangles) and northern California network (nCA; upward pointing triangles). Squares are average values from local events recorded by the real-time system. Average τ_p^{max} and P_d for E2 events caused by teleseismic events are shown as circles. The line is the linear discriminant function that divides most local and teleseismic events. Teleseismic events can have P waves with displacements similar to local events, but they are also longer period. The discriminant is not perfect, as three teleseismic events fall on the wrong side of the line. The color version of this figure is available only in the electronic edition.

To separate local and (most) teleseismic events, we use the following discriminant:

$$F = K + L^* I^T \begin{cases} F < 0 & \text{Teleseismic} \\ \text{else} & \text{Local earthquake} \end{cases}, \quad (2)$$

in which $K = 32.75$, $L = [-24.75 \quad 8.78]$, and $I = \log[\tau_p^{max} \quad P_d]$.

Applying this filter, our algorithm correctly separates 70 local events from 23 teleseisms and only misidentifies 3 teleseisms in our test dataset.

The alert filter continuously applies the above criteria to events in the event pool. Once an event passes the criteria, it is released as an alert to the DM. After the initial alert, the event information can still be updated when event parameters are refined based on additional data becoming available from stations that have already triggered (within the 4 s window) or based on data from newly triggered stations. These updates are forwarded to the DM.

Defining the optimal alert criteria is one of the biggest challenges in EEW 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 for moderate-size events. In this case, an alert message is delayed or not sent at all (i.e., missed event). On the other hand, criteria that are not strict enough can result in an issued alert message when there is no real event (i.e., a false event). Our newly developed replay capability has allowed us to efficiently explore the application of multiple filters and multiple thresholds.

Table 2

Number of Detected, Missed, and False Events for E2 $M_{ANSS} \geq 3.5$ California Earthquakes that Occurred between 2 October 2012 and 15 February 2013

	California	Bay Area	Los Angeles
Detected	26	3	1
Missed	3	0	0
False	2	0	0

$M_{max} = 5.3$.

Performance

To test our new E2 system, we use a catalog of California earthquakes that occurred between 2 October 2012 and 15 February 2013. All statistics we present are derived from the first alert issued by E2. We choose the first alert, as it is clearly the most important for early warning. However, the first alert, when compared to subsequent alerts, generally has the largest errors in magnitude, location, and origin time (i.e., iterative updates are more accurate than the first alerts). Each earthquake identified by E2 is compared with California earthquakes in the merged catalog of the Advanced National Seismic System (ANSS). E2-generated earthquakes are then categorized as being detected, false, or missed (Table 2). An earthquake is deemed detected if its E2 location and origin time match an earthquake in the ANSS catalog to within 100 km distance and within ±30 s. A false alert is one that does not correspond to an earthquake in the ANSS catalog within these limits, and a missed event is an earthquake with M ≥3.5 listed in the ANSS catalog for which no E2 alert message was issued. E2 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 are thus considered detected.

The performance statistics we present here are for the online real-time E2 system version E2.3.1 and E2.3.2, which have been running in real time since 2 October 2012 (Fig. 6). The changes made in E2.3.2 only affect the performance speed, so we are maximizing the time window and number of events by considering performance for both versions. We find that E2 detected 26 of the 29 $M_{ANSS} \geq 3.5$ ANSS earthquakes. We also investigate the performance in the most populated, and the most instrumented regions of the state, the San Francisco Bay Area, and Los Angeles regions and find that all events in these regions were detected and there was only one false event (Table 2, Fig. 6). E2 also successfully detected most earthquakes just outside the CISN networks,

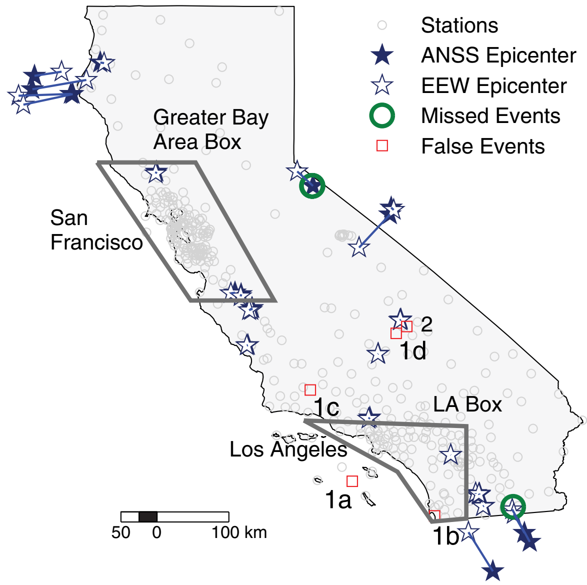

Figure 6. All detected California events (29), false events (squares, 2), and missed events (circles, 3) with $M_{\mathrm{ANSS}} \geq 3.5$ that occurred between 2 October 2012 and 15 February 2013. ANSS epicenters (filled stars) and the corresponding E2 epicenters (open stars) are connected with a line. Errors in source parameters are minimal within regions of high station density and increase in regions offshore and outside of California, such as near Cape Mendocino and south of the California–Mexico border. The two alert regions described in the text are shown as the San Francisco Bay Area (SFBA, northern) and Los Angeles (LA, southern) boxes and are areas with high densities of both population and seismic stations. The color version of this figure is available only in the electronic edition.

including offshore of Cape Mendocino in northern California and south of the California–Mexico border. However, these estimates for earthquakes that are at the edge or outside of our network have larger errors than typical detections within the network footprint.

E2 issued five false alert messages, none of which were in the highly populated San Francisco Bay Area and Los Angeles regions (Fig. 6, Table 2). Instead, these false alerts were caused by events outside of California. One was the M_{w} 6.3 earthquake, off the west coast of Baja California on 14 December 2012, which was more than 300 km from the network yet triggered many southern California stations. These triggers were associated into four simultaneous separate/split events because the offshore event had a poor first-location estimation (false events 1a–d in Fig. 6). The other false event was from an M_{w} 5.1 earthquake 72 km west of Tonopah, Nevada, on 13 December 2012. The closest station to this Nevada event was 80 km away, resulting in a significant initial mislocation. The E2 algorithm did adequately locate this earthquake in later iteration; however, later station triggers also generated another event (false alert 2 in Fig. 6). While the E2 teleseismic filter prevented alerts from several dozen events created from triggers caused by teleseismic arrivals, these more regional events did pass the teleseismic filter and thus generated false alerts. We plan to optimize association criteria to handle these earthquakes in the next version.

Of the California earthquakes, E2 missed three $M_{\mathrm{ANSS}} \geq 3.5$ events (Fig. 6), all of which occurred at the margins of the CISN networks. One was at the California–Mexico (and network) boundary, and two were just south of Lake Tahoe near the California–Nevada border. Our associator works well in regions of dense station and azimuthal coverage where interstation spacing is ~20 km or less (Kuyuk and Allen, 2013a). For example, we had a 100% success rate identifying local earthquakes in the San Francisco Bay and Los Angeles regions. Performance can, however, be compromised by seismicity swarms or aftershock sequences. For example, a previous E2 version (E2.2) missed 14% of the large earthquakes ($M > 3.5$) in the 2012 Brawley swarm on 26–29 August. There were 21 $M_{\mathrm{ANSS}} \geq 3.5$ events, and E2.2 reported only 18 of them. The three missed earthquakes occurred within 2 min of a larger event, and the overprinting of the signal from the larger event on the signals of the smaller events made the smaller events undetectable. Overprinting of earthquakes in an aftershock sequence is a well-known problem (Kilb *et al.*, 2007) and was also an issue for the Japanese EEW system during the 2011 M 9 Tohoku-Oki earthquake aftershock sequence (Hoshiba *et al.*, 2011). We are currently investigating how to improve the associator scheme to recognize and properly account for aftershock and swarm sequences.

The differences between ANSS and E2 source parameters are calculated for $M_{\mathrm{ANSS}} \geq 3.5$ and $M_{\mathrm{ANSS}} \geq 3.0$ events. We compute errors in earthquake magnitude, origin time, and location by subtracting the E2 results from ANSS results (Fig. 7). For $M_{\mathrm{ANSS}} \geq 3.0$ events, we find the median magnitude error is -0.05 ± 0.39, in which the negative -0.05 value indicates that on average E2 slightly overestimates the magnitude by 0.05 magnitude units. For only the larger events ($M_{\mathrm{ANSS}} \geq 3.5$), the errors are 0.09 ± 0.46 (Table 3).

Errors in origin time and location are both strongly influenced by the location algorithm. The origin time errors are not normally distributed; instead, the mean and standard deviations (S.D.) of the origin time errors (in seconds) are -0.29 ± 1.16 for $M > 3$ and -0.10 ± 1.59 for $M > 3.5$. The median error in the epicentral location (i.e., distance between true and estimated epicenters) of E2 is 3.78 km. The median location error decreases to 2.01 km for larger events ($M > 3.5$).

System Latency

We define system latency as the time between the origin of an earthquake and the E2 publication of the first alert for the event. This time window includes the time it takes for the *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 satisfied and an alert is published. At each stage the data are passed from one piece of hardware or processing software to another, introducing a delay.

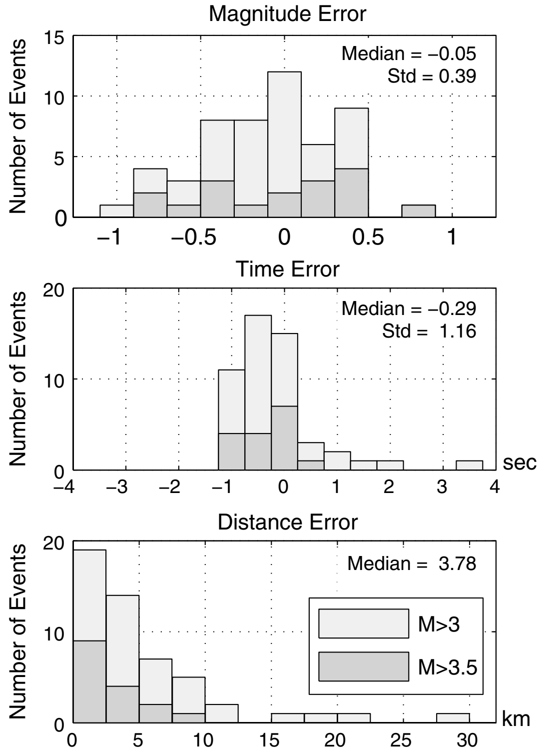

Figure 7. The magnitude, time, and location errors for E2. The lighter histograms are errors for all events with $M_{\mathrm{ANSS}} \geq 3.0$, and darker histograms are for events with $M_{\mathrm{ANSS}} \geq 3.5$. For a comparison of the statistics, see Table 5.

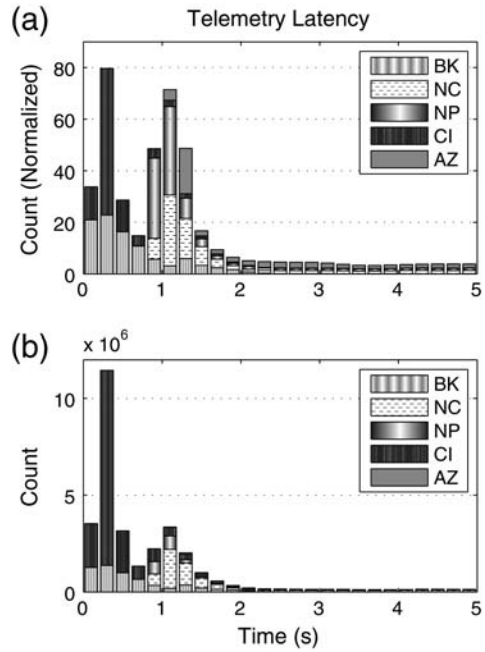

Figure 8. The telemetry latencies by seismic network: UC Berkeley Digital Seismic Network, (BK), USGS Northern California Seismic Network (NC), USGS National Strong Motion Program (NP), USGS/Caltech Southern California Seismic Network (CI), and UC San Diego Anza Network (AZ). The telemetry latency is the time it takes for a completed packet to be transmitted from a station to its network processing hub. (a) The *y* axis is normalized so that each network is represented in the histogram by the same area. (b) Histogram displayed with true counts, which correctly represents the average telemetry delay seen by E2. On average, the telemetry latency is 0.44 s (see Table 4).

We evaluate four measures of latency: (1) Telemetry latency is the delay in sending waveform data packets from a seismic station to the network WP processing hub. (2) The WP processing delay is the delay in processing the waveforms by the WP module to generate parameters. (3) The *P*-wave latency is the time between the *P*-wave arrival at a seismic site and the time when that trigger is detected and processed by one of the WP modules. (4) The alert latency encompasses all components of latency from the origin time of an earthquake to the first published alert from E2.

Telemetry latency is the transit time of data from the station to its network processing hub (e.g., UC Berkeley for BK; USGS Menlo Park for the Northern California Seismic Network [NC] and some for National Strong Motion Program [NP]; Caltech for CI, the Anza Network [AZ], and some NP stations), where the WP module is applied to the data. This is independent of data packet size, because it is calculated as the time difference between a data packet's arrival at a WP 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 from an ~1.5 month time window (20 December 2012 to 4 February 2013).

Table 3
Magnitude, Origin Time, and Location Error Statistics for E2 Algorithms

	$M_{\mathrm{ANSS}} > 3.0$		$M_{\mathrm{ANSS}} > 3.5$	
Error	Median	S.D.	Median	S.D.
Magnitude	−0.05	0.39	0.09	0.46
Time	−0.29	1.16	−0.10	1.59
Distance	3.78		2.01	

Table 4
Median Telemetry Latencies for the Networks Used by E2

	Median (s)	S.D. (s)
All*	0.46	1.84
BK†	0.44	1.38
NP‡	1.06	1.80
NC§	1.36	2.50
CI‖	0.31	0.96
AZ#	4.57	3.41

Although distribution of latencies is not normal distributed, we list the standard deviations to provide some measure of the variability.
*The top row, labeled 'All,' is a summary of all combined networks.
†UC Berkeley Digital Seismic Network (BK).
‡USGS National Strong Motion Program (NP).
§USGS Northern California Seismic Network (NC).
‖USGS/Caltech Southern California Seismic Network (CI).
#UC San Diego Anza Network (AZ).

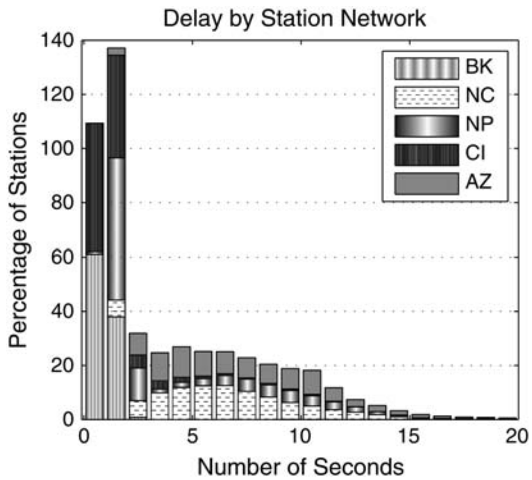

Figure 9. *P*-wave latencies by seismic network. This is the time that a WP module detects a *P* wave minus the arrival time of the *P* wave at the seismic station. It includes data packetization, transmission to the network hub, and WP processing. Data latencies are normalized for each network so that each network is represented by the same area in the histogram, allowing comparison of the delays for different networks. On average *P*-wave latency is 1.14 s (see Table 5).

Figure 8 shows the resulting telemetry latencies for each seismic network, in which 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 (Fig. 8a). Comparing actual counts provided by networks, CI provides the most and BK and NP provide about the same amount of information (Fig. 8b). This histogram correctly represents the average telemetry delay of E2. On average, pure telemetry latency is 0.46 s (Table 4). The BK network has a median latency of 0.44 s, whereas the NC network has a median of 1.36 s. The CI network has the smallest latency of 0.31 s, and the AZ network has the longest latency of 4.57 s because the AZ transmission is not direct to the WP hub at Caltech, but requires a two-leg transmission.

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

Next, we consider the *P*-wave latency (Fig. 9), which combines a series of delays. It includes the data packetization by data loggers at the stations. A data logger will not send its data to the data center where WP 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 E2 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 ARRA), most of these data loggers have been replaced with more modern units that send data in 1 s packets. The *P*-wave latency also includes the telemetry latencies and the WP processing latencies described above.

Table 5

Median *P*-Wave Latency by Network

	Median (s)	S.D. (s)
All	1.14	2.72
BK	0.88	0.37
NC	6.20	3.28
NP	1.93	3.77
CI	1.03	1.82
AZ	6.80	3.86

Network codes are as in Table 4.

To evaluate *P*-wave latency (Fig. 9 and Table 5), we collected all triggers from all channels/stations and networks from 20 December 2012 to 4 February 2013 for about one and a half months. The median *P*-wave latency for all data (and thus for all networks) is 1.14 ± 2.72 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.

Before the ARRA upgrade of data loggers at 22 of the BK stations and the implementation of processing code to take advantage of the upgrades, the median *P*-wave latency was 3.83 s. Currently, with the upgrades and new system, the latency has been reduced by about 3 s to 0.88 ± 0.37 s. The equipment operated by the CI network was also upgraded in August 2012, and the median latency for CI is now 1.03 ± 1.82 s. Latencies for the NC network follow a more Gaussian-shaped distribution, with a larger median latency of 6.20 ± 3.28 s. The median latency for NP stations is 1.93 ± 3.77 s. In the NP network, there are a significant number of stations with large latencies resulting in a larger standard deviation. AZ has the highest median latency, 6.80 s, because there is an extra telemetry step in which the data are forwarded from the Scripps Institute of Oceanography to the regional processing center at Caltech.

Finally, we investigate how many seconds the entire E2 system requires, on average, to publish an alert for an event (Fig. 10a). This alert latency is determined for the E2 dataset and represents the entire delay, including the time for the *P* wave to propagate to the 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. We calculate alert latencies for the 469 events that E2 detected between 2 October 2012 and 15 February 2013, including small earthquakes. We find that, on average, E2 needs 12.37 ± 5.21 s to issue an alert to users. The tail in the alert time histogram is mainly caused by events offshore of Cape Mendocino and events located in poorly instrumented areas, such as the north and northeastern regions of

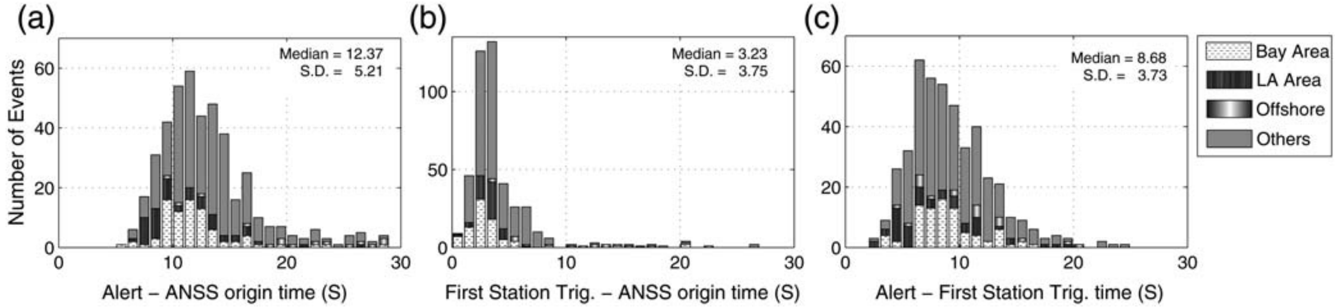

Figure 10. E2 latencies for earthquakes detected in real time from 2 October 2012 to 15 February 2013. (a) The E2 alert latency is the difference between the time an alert is first published and the origin time for the earthquake in the ANSS catalog. The median is 12.37 ± 5.21 s. (b) The time it takes the first *P*-wave arrival to travel to the first station is derived by subtracting ANSS origin time from the trigger time at the first station. The median is 3.23 ± 3.75 s. (c) The E2 processing latency, which is alert time minus the time of the first *P*-wave arrival at a seismic station shows total time the network and E2 require to alert on an event. The median is 8.68 ± 3.73 s. Alerts are faster for the San Francisco Bay and Los Angeles areas (see Table 6).

California. We also find that alerts for offshore events and those that occur south of the California–Mexico border typically take more than 20 s, whereas alerts for events in the San Francisco Bay and Los Angeles regions take less time, averaging 11.36 ± 3.55 and 9.88 ± 5.54 s, respectively. The remaining California onshore events typically have alert times of 12.84 ± 4.88 s (Table 6).

We also determine both the time for the *P* wave to reach the first seismic station and the time from the first *P*-wave trigger to the alert for the same set of events. From the first *P*-wave trigger time, we subtract the ANSS origin time to determine how long it takes for a network station to first receive information about the earthquake. This duration has a median of 3.23 ± 3.75 s (Fig. 10b). For events in regions of sparse network coverage, it takes more than 10 s 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 2–3 s. The E2 processing latency, which is the alert time minus the time of the first *P*-wave arrival at the closest stations, has a median time of 8.68 ± 3.73 s (Fig. 10c and Table 6). Currently E2 processing latency is the smallest in the Los Angeles area, with a median of 6.72 ± 3.96 s, which is almost 2 s faster than the latency in the San Francisco Bay Area. This is due to the additional delays from NC stations, which comprise a large fraction of the stations in northern California.

Table 6
E2 Latencies, Measured from Real-Time E2 Performance from October 2012 to February 2013

	Alert—ANSS Origin Time Median ± S.D. (s)	First Station Trig—ANSS Origin Time Median ± S.D. (s)	Alert—First Station Trig Median ± S.D. (s)
Others	12.84 ± 4.88	3.30 ± 3.07	8.90 ± 3.81
Offshore	22.59 ± 7.44	12.07 ± 7.36	11.40 ± 4.46
Los Angeles	9.88 ± 5.54	3.26 ± 3.16	6.72 ± 3.96
Bay Area	11.36 ± 3.55	2.66 ± 3.26	8.62 ± 2.81
All	12.37 ± 5.21	3.23 ± 3.75	8.68 ± 3.73

Latencies are shown for various regions (LA and SFBA boxes in Fig. 1). Latencies are smaller in the San Francisco Bay Area and Los Angeles due to dense station coverage.

Conclusions

We are now operating a completely new version of the ElarmS algorithms on the CISN real-time systems in California. E2 was rewritten and rebuilt from what was a research prototype algorithm to production-quality code for faster operation and easier maintenance and modification. At the same time, improvements to the algorithms were developed and implemented. The new code maximizes the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. E2 is designed as a modular code and consists of a new WP module that provides data more rapidly to the EM. The new EM 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, which in turn minimizes false alarms.

E2 detects and generates alert information for earthquakes throughout California. E2 detected 26 of 29 $M_{\mathrm{ANSS}} > 3.5$ events in California, missing three events and issuing two false alerts during the real-time testing period (October 2012 to February 2013). None of the three missed events were in the San Francisco Bay or Los Angeles regions, but were instead in more remote parts of California where seismic station density is low. The two false alerts resulted from large regional earthquakes outside of the footprint of our network, and large teleseismic earthquakes generated no false alerts. Standard deviations of magnitude, origin time, and median location errors are 0.39 magnitude units, 1.16 s, and 3.78 km, respectively. E2 currently issues an alert on average 8.68 ± 3.73 s after the first *P*-wave detection for all events across California. We continue to review E2's performance to reduce the delays still further.

Data and Resources

In order to evaluate the E2 performance, we used California earthquakes in the merged catalog of the ANSS (http://www.ncedc.org/anss/; last accessed March 2013) for earthquakes from 2 October 2012 to 15 February 2013. Our analysis uses standardized E2 output provided to the ShakeAlert project, and these are the same output data provided to the EEW DM. The analysis programming codes were written in MATLAB (http://www.mathworks.com/; last accessed June 2013).

Acknowledgments

This project was only possible because of the collaborative efforts of many people working at the CISN operating institutions: UC Berkeley, Caltech, USGS Menlo Park, and USGS Pasadena. This work is funded by USGS/National Earthquake Hazards Reduction Program Awards G09AC00259 and G12AC20348 and by the Gordon and Betty Moore Foundation through Grant GBMF3024 to UC Berkeley. Figure 1 was produced using Generic Mapping Tools by Wessel and Smith (1995).

References

Allen, R. M. (2004). Rapid magnitude determination for earthquake early warning, in *The Many Facets of Seismic Risk*, G. Manfredi (Editor), University of DegliStudi di Napoli "Federico II", Naples, Italy, 15–24.

Allen, R. M. (2006). Probabilistic warning times for earthquake ground shaking in the San Francisco Bay Area, *Seismol. Res. Lett.* **77,** no. 3, 371–376.

Allen, R. M. (2007). The ElarmS earthquake early warning methodology and application across California, in *Earthquake Early Warning*, P. Gasparini (Editor), Springer, Milan, Italy, 21–44.

Allen, R. M., and H. Kanamori (2003). The potential for earthquake early warning in southern California, *Science* **300,** 786–789.

Allen, R. M., H. Brown, M. Hellweg, O. Khainovski, P. Lombard, and D. Neuhauser (2009). Real-time earthquake detection and hazard assessment by ElarmS across California, *Geophys. Res. Lett.* **36,** L00B08, doi: 10.1029/2008GL036766.

Böse, M., R. Allen, H. Brown, G. Cua, M. Fischer, E. Hauksson, T. Heaton, M. Hellweg, M. Liukis, D. Neuhauser, P. Maechling, and CISN EEW Group (2013). CISN ShakeAlert: An earthquake early warning demonstration system for California, in *Early Warning for Geological Disasters—Scientific Methods and Current Practice*, F. Wenzel and J. Zschau (Editors), Springer, Berlin, Germany, ISBN: 978-3-642-12232-3.

Böse, M., E. Hauksson, K. Solanki, H. Kanamori, Y.-M. Wu, and T. H. Heaton (2009). A new trigger criterion for improved real-time performance of on-site earthquake early warning in southern California, *Bull. Seismol. Soc. Am.* **99,** no. 2A, 897–905, doi: 10.1785/0120080034.

Brown, H. M., R. M. Allen, and V. F. Grasso (2009). Testing ElarmS in Japan, *Seismol. Res. Lett.* **80,** 727–739.

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

Cua, G., M. Fischer, T. Heaton, and S. Wiemer (2009). Real-time performance of the virtual seismologist earthquake early warning algorithm in southern California, *Seismol. Res. Lett.* **80,** no. 5, 740–747.

Hoshiba, H., K. Iwakiri, N. Hayashimoto, T. Shimoyama, K. Hirano, Y. Yamada, Y. Ishigaki, and H. Kikuta (2011). Outline of the 2011 Off the Pacific Coast of Tohoku earthquake (M_w 9.0)—Earthquake early warning and observed seismic intensity, *Earth Planet. Space* **63,** 547–551.

Kilb, D., V. G. Martynov, and F. L. Vernon (2007). Aftershock detection thresholds as a function of time: Results from the ANZA seismic network following the 31 October 2001 M_L 5.1 ANZA, California, earthquake, *Bull. Seismol. Soc. Am.* **97,** 780–792.

Kuyuk, H. S., and R. M. Allen (2013a). Optimal seismic network density for earthquake early warning: A case study from California, *Seismol. Res. Lett.* **84,** no. 6, 946–954.

Kuyuk, H. S., and R. M. Allen (2013b). A global approach to provide magnitude estimates for warthquake early warning alerts, *Geophys. Res. Lett.* **40,** doi: 10.1002/2013GL058580.

Olivieri, M., R. M. Allen, and G. Wurman (2008). The potential for earthquake early earning in Italy using ElarmS, *Bull. Seismol. Soc. Am.* **98,** 495–503, doi: 10.1785/0120070054.

Olson, E. L., and R. M. Allen (2005). The deterministic nature of earthquake rupture, *Nature* **438,** no. 7065, 212–215.

Tsang, L., R. M. Allen, and G. Wurman (2007). Magnitude scaling relations from *P* waves in southern California, *Geophys. Res. Lett.* **34,** L19304, doi: 10.1029/2007GL031077.

Wessel, P., and W. H. F. Smith (1995). New version of the Generic Mapping Tools released, *Eos Trans. AGU* **76,** 329.

Wurman, G., R. M. Allen, and P. Lombard (2007). Toward earthquake early warning in northern California, *J. Geophys. Res.* **112,** no. B08311, doi: 10.1029/2006JB004830.

Seismological Laboratory
University of California
McCone Hall, UC Berkeley
Berkeley, California 94720
skuyuk@seismo.berkeley.edu

Manuscript received 5 June 2013;
Published Online 24 December 2013