A Real-Time Earthquake Alert System for the Greater San Francisco Bay Area: A Prototype Design to Address Operational Issues

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Abstract

The purpose of the earthquake alert system (EAS) is to "outrun" the seismic energy released in a large earthquake using a geographically distributed network of strong motion sensors that telemeter data to a rapid CPU-processing station, which then issues an area-wide warning to a region before strong motion will occur. The warning times involved are short, from 0 to 30 seconds or so; consequently, most responses must be automated. The San Francisco Bay Area is particularly well suited for an EAS because (1) large earthquakes have relatively shallow hypocenters (10- to 20-kilometer depth), giving favorable ray-path geometries for larger warning times than deeper focus earthquakes, and (2) the active faults are few in number and well characterized, which means far fewer geographically distributed strong motion sensors are required (about 50 in this region).

An EAS prototype is being implemented in the San Francisco Bay Area. The system consists of four distinct subsystems: (1) a distributed strong motion seismic network, (2) a central processing station, (3) a warning communications system, and (4) user receiver and response systems.

We have designed a simple, reliable, and inexpensive strong motion monitoring station that consists of a three-component Analog Devices ADXL05 accelerometer sensing unit, a vertical component weak motion sensor for system testing, a 16-bit digitizer with multiplexing, and communication output ports for RS232 modem or radio telemetry. The unit is battery-powered and will be sited in fire stations. The prototype central computer analysis system consists of a PC data-acquisition platform that pipes the incoming strong motion data via Ethernet to Unix-based workstations for data processing. Simple real-time algorithms, particularly for magnitude estimation, are implemented to give estimates of the time since the earthquake's onset, its hypocenter location, its magnitude, and the reliability of the estimate. These parameters are calculated and transmitted with frequent updates as an 80-character digital string sent from the central analysis computer to pagers throughout the Bay Area in less than 2 seconds. We anticipate that the commercial sector will supply numerous and varied warning receiver systems once an EAS is considered operational. We focus on two prototype demonstration systems: (1) a pager-driven closure switch for opening fire station doors and (2) a pager display sign showing an alert message and a display of warning packet information. We will discuss the specific design features of this prototype system.

1 Introduction

"A very simple mechanical contrivance can be arranged at various points from 10 to 100 miles from San Francisco, by which a wave of the earth high enough to do damage will start an electric current over the wires now radiating from this city and almost instantaneously ring an alarm bell, which should be hung in a high tower near the center of the city." This quote [1], the first suggestion of a real-time earthquake warning system, appeared in the *San Francisco Daily Evening Bulletin* on November 3, 1868. The idea is not new.

In 1985, when the modern concept of a real-time earthquake warning system was introduced [2], it consisted of a distributed network of strong motion monitoring stations that telemetered data in real time to a central analysis facility. The central facility could transmit earthquake parameter information (e.g., magnitude, location) to an area in advance of the arrival of elastic wave energy.

In 1989, a report commissioned by the State of California was released [3] on the technical and economic feasibility of a real-time earthquake warning system for the state. The study attempted a cost-benefit analysis for implementing and operating a dedicated earthquake warning system. The estimate for installing a dedicated system for the Los Angeles Basin was $3.3 million to $5.8 million with an annual operation cost of $1.6 million to 2.4 million. Questionnaires were sent to public and private institutions to determine the value of seconds of warning before an earthquake. The study admitted that "an assessment of the value of an EWS [earthquake warning system] is inherently difficult because potential users are asked to identify uses for a nonexistent system." The study concluded: "It would not be justified, on a cost–benefit basis, to construct an EWS at this time."

A report issued in 1991 by the National Academy of Sciences [4], entitled *Real-Time Earthquake Monitoring*, drew heavily on the State of California study but reached the opposite conclusion. The study concluded that a survey to determine the utility of a system that has never existed "is not reliable." The study cited examples of new technologies that were initially turned down by potential users, such as telephones, which in 1876 were rejected by the British Post Office in favor of messenger boys. The study strongly urged that prototype real-time warning systems be developed for use in earthquake-prone areas.

Although the concept of a real-time earthquake monitoring and warning system has been around for a long time and such a system has been technically feasible to implement, there is no history of an operational system in the United States. Issues such as false alarms and accuracy of the real-time earthquake parameter estimates cannot be fully anticipated from a theoretical or computer study. An actual operational prototype will shine light on areas requiring further research and development.

This paper describes a real-time earthquake alert system (EAS) prototype in the San Francisco Bay Area. Our approach is pragmatic, attempting to establish a prototype real-time warning system at a low cost and quickly. As operational experience with a functioning prototype system is gained, the most important system enhancements will become apparent.

Considering the modest cost (about $500,000) in developing a prototype real-time warning system in the greater San Francisco Bay Area and the high potential for substantial earthquake mitigation, it is surprising that the development of such a system has not been attempted. Systems in the Bay Area such as the University of California at Berkeley Rapid Earthquake Data Integration (REDI) system [5] are important developments in rapid notification, giving accurate estimates of earthquake parameters in the immediate earthquake aftermath. These systems do not provide real-time warning capability and are not on a development path that will produce a real-time system in the near future since the data transmission, analysis and information broadcast system all have time delays that preclude true real-time operation.

We stress that real-time earthquake warning is becoming an important new frontier of earthquake mitigation research and development. Such a warning system has the potential to make major contributions in protecting the public and mitigating earthquake damage.

2 System Concept Overview

The purpose of the EAS is to "outrun" the seismic energy released in a large earthquake with radio waves and rapid CPU processing to give some warning time to a region before strong motion will occur. The warning times involved are short, from 0 to 30 seconds or so; consequently, most responses must be automated. Four distinct subsystems make up the EAS:

1. A distributed strong motion seismic network.
2. A central processing station.
3. A warning communications system.
4. User receiver and response systems.

The only way to detect an earthquake soon after it ruptures is to have a sensor near the rupture epicenter. The only way to know the earthquake is large is to have that sensor stay on-scale during large ground motions; i.e., it must be a strong motion sensor. Since we cannot predict where the epicenter will be for the next large earthquake to affect the Bay Area, we must distribute strong motion sensors along all the major faults so that for any anticipated earthquake, sensors will be nearby. This distribution of sensors constitutes the strong motion network.

The strong motion network telemeters data in real time to a central receiving center. The central receiver is connected to a powerful CPU that can perform real-time calculations on the incoming data streams and estimate the earthquake location and size, the time from its initial rupture, and the reliability of the estimate. These estimates are updated as more data arrive from the network. This central receiver and analysis center constitutes the central processing station.

The earthquake parameter estimates calculated by the central CPU are transmitted as a digital information packet via a dedicated pager system that can be received throughout the greater Bay Area. New digital information packets are transmitted when the CPU calculates new parameter estimates as more data arrive from the strong motion network. The dedicated Bay Area paging system constitutes the warning communication system.

The digital information packets are received by a paging receiver and acted on according to the user's needs. The continually updated stream of digital information packets will allow users to develop their own automated decision analysis responses based on a trade-off between the earthquake parameter estimates and their false-alarm tolerance. A fire station door can be opened by a switch controlled by the paging receiver and activated on initial receipt of the first alert information packet. A major gas main could be shut off by a pager/CPU/electromechanical valve system. In this case, however, the receiver CPU would analyze the incoming earthquake parameter estimates and close the valve only when the location, size, time, and reliability estimates met predefined criteria because the cost of a false shutdown is significant. Numerous other useful receiver systems could be developed by the commercial sector because there will be profit opportunities in marketing such receiver systems. The various user systems constitute the user receiving and response systems.

Specific design of each of the EAS systems is outlined in the following sections:

3 Distributed Strong Motion Network

The United States Geological Survey maintains an extensive seismic network in California, called CALNET, with more than 100 seismic stations in the greater San Francisco Bay Area alone. However, numerous system upgrade and institutional use issues must be overcome to incorporate many of these stations into an EAS strong motion network. Consequently, we recommend that a strong motion network specific to the EAS mission be established. There are several advantages to establishing a network dedicated to the EAS mission:

First, unlike microseismic monitoring sites—which measure very small seismic events and therefore must be located in relatively quiet seismic areas, away from cities, roads, and other seismic sources associated with human activities—an EAS strong motion network can be located in relatively high seismic noise environments since strong motion monitoring at levels well above that associated with most human activities is the only function required of such stations. The great advantage of the relaxed siting requirements is that station sites can be established at communication hubs and manned facilities and, in general, can exploit locations where infrastructure and maintenance are maximized.

Second, communication links in a dedicated EAS network can be established with particular attention to the survivability of that link during strong motion conditions. Many existing microseismic monitoring stations take advantage of whatever low-cost communication link is available with no concern for link survivability during strong ground motion conditions.

Third, reliable, very low cost accelerometers can be used in strong motion monitoring that adequately cover the strong motion monitoring amplitude bandwidth (about 0.01 to 1.0 *g*'s). Limited bandwidth focused on the amplitude band of interest will ease the communication bandwidth requirement, particularly important in radio telemetry links. Existing microseismic stations must somehow provide a large communication bandwidth and monitoring amplitude bandwidth to measure and transmit both small and large events.

A fully operational EAS strong motion network in the Bay Area can be accomplished with about 50 strong motion stations distributed more or less uniformly along the major faults in the region [6]. The stations must all communicate data in real time to a central processing facility (Figure 1).

We have designed a strong motion monitoring station that is simple, reliable, and inexpensive. It will consist of a three-component Analog Devices ADXL05 accelerometer sensing unit, a vertical component weak motion sensor for system testing, a 16-bit digitizer with multiplexing, and communication output ports for RS232 modem or radio telemetry. The unit will be battery-powered, and the batteries will be trickle charged via conventional AC power or solar panel.

Fire stations around the Bay Area provide ideal locations for strong motion monitoring stations:

1. There are numerous fire stations in the Bay Area. A subset of 50 stations that provide adequate geographical coverage of the region can easily be determined.
2. The emergency response/mitigation function of the EAS is consistent with the emergency function of a firehouse, offering dual use of emergency response resources, which is in general embraced by emergency service professionals.
3. Fire stations are manned 24 hours a day, providing on-site personnel for station debugging should problems be detected at the central station.
4. AC power is readily available.
5. Many fire stations have good communication systems and communication towers that will provide good options on the seismic data communication link.
6. Many of the fire stations chosen as sites for the seismic network can be prototype users by installing pager-driven station door openers.

The prototype network will consist of about 12 strong motion stations, located at participating fire stations and with as wide a geographical distribution about the Bay Area as the data communications method employed will allow.

4 Central Processing Station

More that any other subsystem of the EAS, the real-time central processing facility must be recognized as a continually evolving capability. As the prototype system is operated, there will be continual refinement of the data-processing algorithms. Consequently, the prototype system will be viewed as an initial effort to obtain real-time earthquake parameter estimates with a minimum of sophistication. The tasks required to produce prototype central processing facilities are to develop:

1. Real-time data flow and buffering architecture.
2. Algorithms to estimate earthquake parameters (location, size, time, reliability).
3. Earthquake playback capability for system testing and development.

4. Raw data and data analysis history archiving features.
5. Algorithms to detect glitches and false alarms.
6. Rigorous system testing via playback scenarios and operational analysis.

Many of the algorithms exist, such as location, and execute rapidly. Some algorithms require an operational system and some operational history before they can be developed (e.g., those to detect glitches and false alarms). The algorithms that will require the most effort and clearly entail a significant ongoing research component are those that attempt to estimate final earthquake magnitude from early characteristics of the earthquake waveform.

Since the earthquake rupture travels at the S-wave velocity (about 3.7 kilometers per second) and large earthquakes can rupture 100 kilometers of fault or more, the rupture process itself can take 10 seconds or more. These facts beg a key question in magnitude estimation: Do large earthquakes initiate differently than do small to moderate earthquakes? Stated another way: Is there information in the characteristics of the waveform radiated early in the rupture process that forecast the final extent of rupture? The jury is still out on this important question.

Magnitude estimation from characteristics of the initial waveform has been attempted by a number of researchers. The Japanese Urgent Earthquake Detection and Alarm System estimates the earthquake magnitude by the dominant period of the initial P-wave arrival [7]. Toksoz [8] has shown that with sensors distributed along specific strike-slip faults, reasonably accurate estimates of fault rupture extent and slip can be made in real time. Using a neural network that is trained on weak and strong motion data, Leach [9] has demonstrated some success in forecasting final magnitude from the first few seconds of the recorded waveform. Anderson [10] has investigated the waveform characteristics of moderate to large earthquakes in the subduction zone off the Pacific Coast of Mexico and concluded that there are no consistent differences between moderate and large earthquakes that appear in the early waveform for this tectonic region.

The magnitude estimation issue, however, does not negate the utility of an EAS. Even if it is eventually determined that magnitude forecasts from the initial waveform data are not reliable in the Bay Area, users may still choose to employ the EAS for false-alarm-tolerant applications that act on the first information packet sent. Furthermore, since the magnitude estimates are updated as more waveform data are received at the central station, the magnitude estimates certainly will be more reliable as the earthquake rupture evolves. Most important for an operational EAS is to have an accurate estimation of the reliability of each magnitude estimate, which requires research on magnitude estimation specific to the Bay Area as well as a functioning prototype system with which to test new algorithms.

5 Warning Communications System

A prototype warning communication system for the EAS has recently been established and is currently operational. The complete system consists of a dedicated paging communication system with paging transmitters on Mount Diablo and at Coyote Hills, near the eastern end of the Dumbarton Bridge. The complete system will employ simulcast transmission from the two transmitters and will be controlled via microwave relay from Lawrence Livermore National Laboratory (LLNL) as shown in Figure 2.

The existing paging communication system employs one paging transmitter at the top of Mount Diablo and is controlled via a microwave relay link from LLNL. Paging broadcasts can be received throughout most of the Bay Area; however, there are some shadow zones along the western flank of the East Bay coastal hills (e.g., Hayward, Fremont, Berkeley). The existing system is completely dedicated to the EAS warning transmission. Consequently, it has been optimized for minimum delay in the paging broadcast. Timing tests demonstrate that an 80-character digital string sent from an LLNL computer is received by pagers throughout the Bay Area is less than 2 seconds.

The paging system employs a single transmission frequency to which all user response systems must be tuned. The frequency is licensed to LLNL by the FCC without altitude restrictions and allows for operation at transmission power up to 25 watts. The pager system on Mount Diablo consists of:

- One Motorola Purc 5000 75-watt paging transmitter capable of simulcasting.
- One Zetron paging terminal.
- Microwave receiver dish, rack, and modem.
- Equipment shelter and 18-meter-high antenna tower.

The length of the character string that summarizes the earthquake location, zero time, magnitude, and reliability has not been fixed but will certainly be less than 80 characters. The protocol and format will be consistent with the CUBE system that sends pages on significant earthquakes within 2 minutes of the event.

6 User Receiver and Response Systems

We anticipate that the commercial sector will supply numerous and varied warning receiver systems once an EAS is considered operational. For prototype development and system demonstration, however, useful warning receiver systems must be explored. We focus on two prototype demonstration systems: (1) a pager-driven closure switch for opening fire station doors and (2) a pager display sign showing an alert message and a display of warning packet information.

The pager-driven closure switch is a simple warning receiver system for false-alarm-tolerant facilities that prefer to maximize lead time at the expense of greater false alarm probability. We have contacted several fire stations that would like to be part of a prototype demonstration system, using the initial warning signal to open their fire station doors. Forming partnerships with fire stations as initial prototype EAS users will be important in demonstrating the potential applications of the system.

The pager display sign system will consist of large, commercially available signs that will be updated with the newest earthquake parameter estimates as they are issued by the EAS. The purpose of this system will be demonstration only. A few systems will be installed at key facilities to demonstrate the system capabilities and promote its use.

7 Future Plans for a Fully Operational EAS

Operational experience with a prototype EAS is a prerequisite to detailed planning for a transition to a fully operational system. Our intent in this section is to list the upgrades and issues that we believe must be resolved before an operational EAS can be established:

- Upgrade number of strong motion stations to about 50.
- Set up independent strong motion network telemetry to a second central processing facility.
- Gain operational experience with false-alarm scenarios.
- Establish paging transmitter coverage for the entire San Francisco Bay Area.
- Develop algorithms for robust real-time earthquake parameter estimation and glitch detection.
- Analyze EAS performance and survivability for large credible earthquakes.
- Integrate the EAS with the emergency response community.
- Expand the group of system users.
- Prepare media releases and promotional material.
- Plan the public awareness and education campaign.
- Establish industrial partners for developing warning receiver systems.
- Analyze and resolve system liability issues.

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8 References

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Figure 1. Artist's conception of the distribution of an EAS strong motion monitoring network in the San Francisco Bay Area. Actual locations will be determined by considering geographical coverage requirements and communication infrastructure.

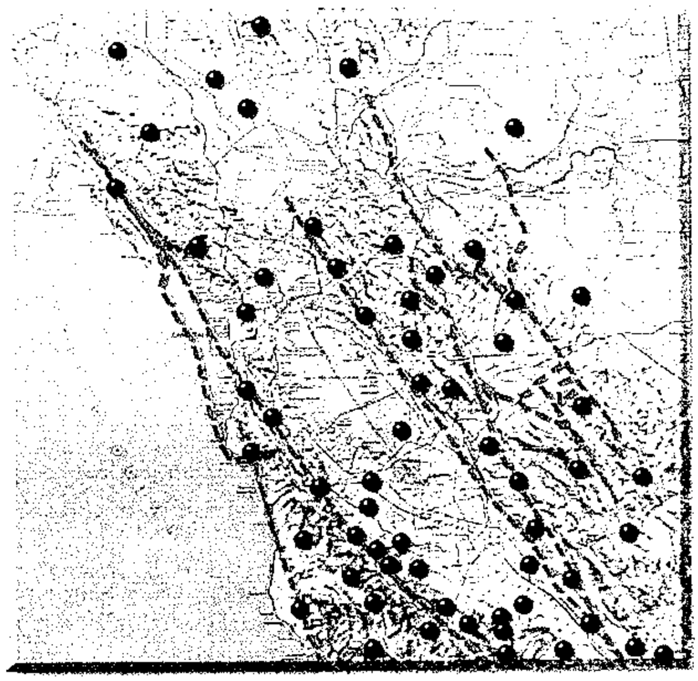

Figure 2. The prototype warning transmission system for the EAS. This system consists of paging transmitters located at Mount Diablo and Coyote Hills that simulcast the warning information packet. The packet is generated at the LLNL central computer and transmitted to Mount Diablo via microwave and from Mount Diablo to Coyote Hills via microwave.