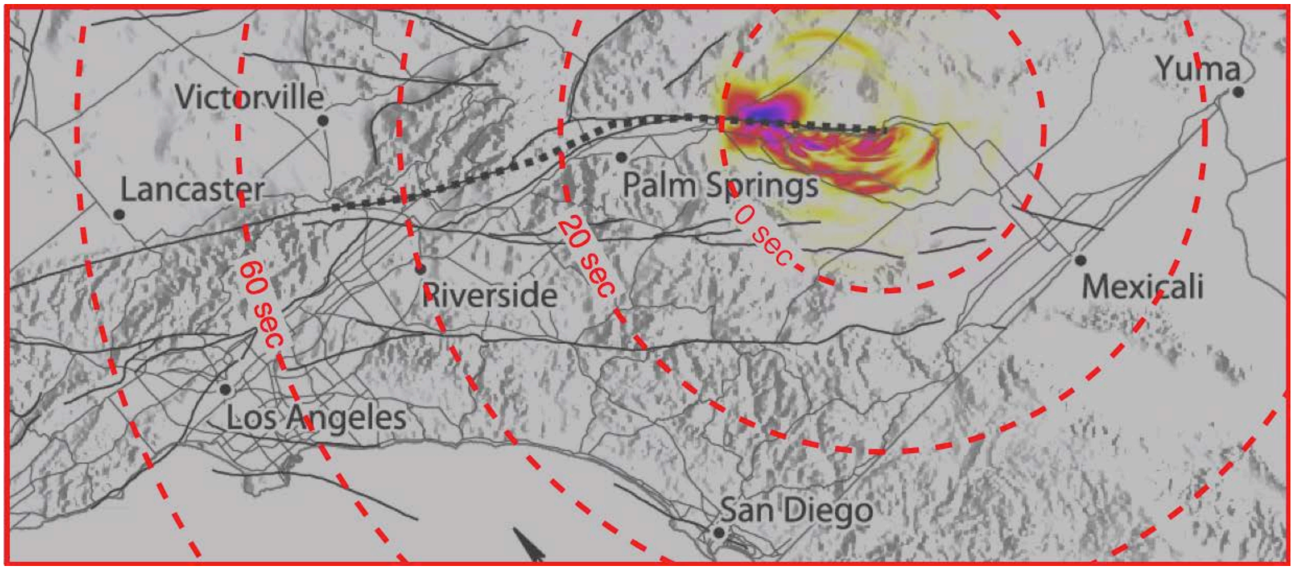
Technical Implementation Plan for the ShakeAlert Production System—An Earthquake Early Warning System for the West Coast of the United States



Open-File Report 2014–1097

U.S. Department of the Interior
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COVER IMAGE: Map generated from the ShakeAlert earthquake early warning system showing the initial 10 seconds of an *M*7.8 scenario earthquake on the southern San Andreas Fault. Expected warning times for the scenario earthquake are shown by red dashed lines with warning time labeled. Faults (solid dark-gray lines), length of the scenario rupture (dotted black line), and major cities (black dot with city name labeled) are shown. Purple, red, and yellow colors show instantaneous surface velocity of the earthquake, and this data is modified from the TeraShake simulation (www.scec.org/terashake).

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Executive Summary

Earthquake Early Warning (EEW) systems can provide as much as tens of seconds of warning to people and automated systems before strong shaking arrives. The United States Geological Survey (USGS) and its partners are developing such an EEW system, called ShakeAlert, for the West Coast of the United States. This document describes the technical implementation of that system, which leverages existing stations and infrastructure of the Advanced National Seismic System (ANSS) regional networks to achieve this new capability. While significant progress has been made in developing the ShakeAlert early warning system, improved robustness of each component of the system and additional testing and certification are needed for the system to be reliable enough to issue public alerts. Major components of the system include dense networks of ground motion sensors, telecommunications from those sensors to central processing systems, algorithms for event detection and alert creation, and distribution systems to alert users. Capital investment costs for a West Coast EEW system are projected to be $38.3M, with additional annual maintenance and operations totaling $16.1M—in addition to current ANSS expenditures for earthquake monitoring. An EEW system is complementary to, but does not replace, other strategies to mitigate earthquake losses. The system has limitations: false and missed alerts are possible, and the area very near to an earthquake epicenter may receive little or no warning. However, such an EEW system would save lives, reduce injuries and damage, and improve community resilience by reducing longer-term economic losses for both public and private entities.

Introduction

The purpose of this document is to describe what must be done to build a reliable Earthquake Early Warning (EEW) system for the highest-risk areas of the West Coast of the United States (California, Oregon, and Washington). A successful demonstration of this system, called ShakeAlert, has delivered alerts to beta users since January of 2012 for earthquakes occurring in California. This plan calls for continued development of all components of the ShakeAlert system to (1) advance it from its current demonstration mode to an operational prototype or “production system,” and (2) expand its area of effectiveness. Initial development of the ShakeAlert system, including algorithm creation and demonstration system design, was funded by the U.S. Geological Survey (USGS) and the Gordon and Betty Moore Foundation.

Some of the steps required to further develop the ShakeAlert system are outlined in USGS-approved, Phase III (2012–2015) project proposals submitted by the following participating groups: California Institute of Technology, University of California at Berkeley, the University of Washington,

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[1] U.S. Geological Survey
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[4] University of Washington

and Swiss Federal Institute of Technology, Zürich. The Phase III plan focuses on one component of the system: the software and algorithms that analyze ground motions and generate alerts.

This report has a broader scope that includes furthering development of all system components: the sensor network, field telecommunications infrastructure, central processing systems, alert communications to users, and user interaction. Other topics, including policy, liability issues, management structure, interactions with stakeholders, funding strategies, and user implementation, require separate consideration outside the scope of this report, but are briefly considered here where they impact the technical aspects of the EEW system implementation.

Background

Earthquakes pose a national challenge because 75 million Americans live in areas of significant seismic risk across 39 states (USGS Fact Sheet 2006-3016). Most of our Nation’s earthquake risk is concentrated on the West Coast of the United States. The Federal Emergency Management Agency (FEMA) has estimated the average annualized loss from earthquakes, nationwide, to be $5.3 billion, with 77 percent of that figure ($4.1 billion) coming from California, Washington, and Oregon, and 66 percent ($3.5 billion) from California alone. In the next 30 years, California has a 99.7 percent chance of a magnitude 6.7 or larger earthquake (Uniform California Earthquake Rupture Forecast, Version 3) and the Pacific Northwest has a 10 percent chance of a magnitude 8 to 9 megathrust earthquake on the Cascadia subduction zone (Uniform California Earthquake Rupture Forecast, Version 2).

Today, the technology exists to detect earthquakes, so quickly, that an alert can reach some areas before strong shaking arrives (fig. 1). The purpose of an EEW system is to identify and characterize an earthquake a few seconds after it begins, calculate the likely intensity of ground shaking that will result, and deliver warnings to people and infrastructure in harm's way.

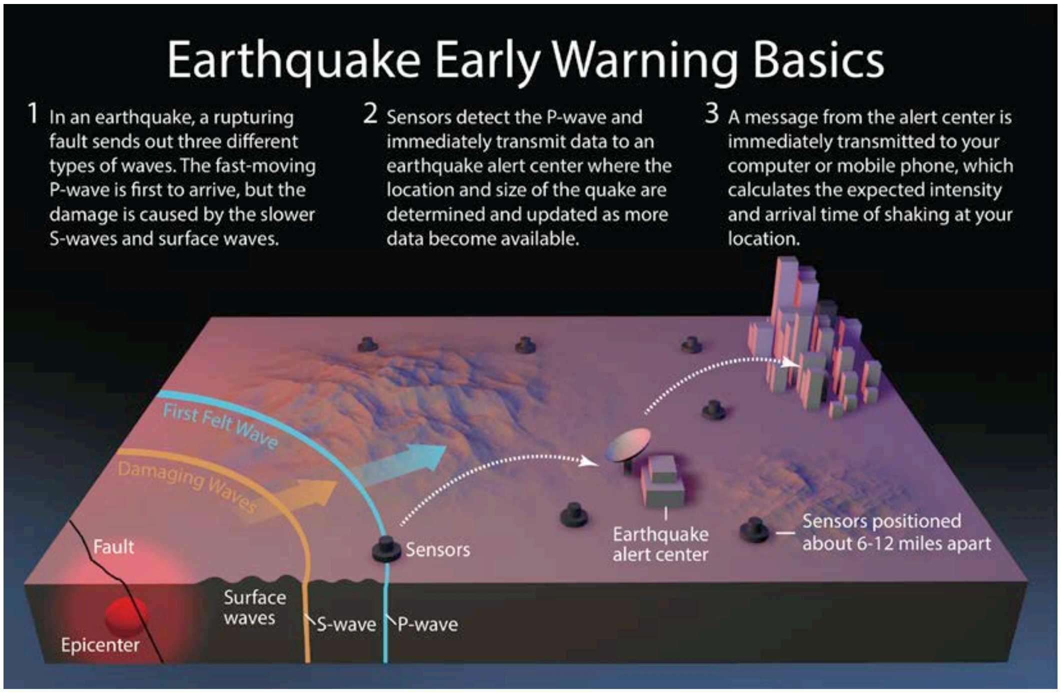

Figure 1. Schematic, three-dimensional diagram illustrating travel path of Earthquake Early Warning (EEW) system alerts to the public during an earthquake event. Figure by Orange County Register.

Earthquakes generate two main types of waves: P-waves and S-waves. P-waves, or primary waves, travel at high speeds outward from the earthquake source, but rarely cause damage. S-waves, or secondary waves, travel more slowly, lag behind P-waves, and result in more intense ground shaking, that causes damage. The location and magnitude of an earthquake can be determined rapidly by analyzing the first energy to radiate from an earthquake—the P-wave energy. Expected ground-shaking levels across a region can then be estimated and warnings sent to local populations before larger, more damaging, shaking arrives (with or after the S-wave). Unfortunately, the area very close to an epicenter will receive little or no warning and the size of this so-called "blind zone" depends on how close seismic sensors are to an epicenter and reaction speed of the EEW system.

EEW systems have been successfully implemented in Japan, Mexico, Taiwan, China, and other nations with varying degrees of sophistication and coverage. The United States could likewise benefit from implementation of an EEW system. Since 2006, the USGS has supported EEW system development with university partners and the State of California. Those efforts resulted in a demonstration system called "ShakeAlert" that began sending test notifications to beta users in January 2012. While that system has demonstrated the feasibility of EEW in California, the system is not yet sufficiently tested or robust enough for public alerts, or, for institutional users to initiate potentially costly actions to mitigate the effects of strong ground shaking.

Vision

Our vision is to reduce the impact of earthquakes and save lives and property in the United States by developing and operating a public EEW capability.

Mission

The USGS, along with partner organizations, will develop and operate an EEW system, ShakeAlert, for the highest-risk areas of the United States, that leverages current earthquake monitoring capabilities of the Advanced National Seismic System (ANSS). We will provide alerts, free of charge, to the public via all practical emergency alert channels. We will also provide more information-rich alert streams to specialized users, including value-added service providers, for use in user-specific applications. The USGS will promote public education about the EEW system, its capabilities, its limitations, and its benefits to users. This mission will be accomplished in cooperation with both public and private partners and stakeholders through various partnerships and agreements.

Goal

The USGS will issue public warnings of potentially damaging earthquakes and provide warning parameter data to government agencies and private users on a region-by-region basis, as soon as the ShakeAlert system, its products, and its parametric data meet minimum quality and reliability standards in those geographic regions. Product availability will expand geographically via ANSS regional seismic networks, such that ShakeAlert products and warnings become available for all regions with dense seismic instrumentation.

Authorities

The USGS will issue public EEW system notifications under collaborative authorities with FEMA, as established by the Disaster Relief Act (P.L. 93-288, popularly known as the Stafford Act) and the National Earthquake Hazard Reduction Program, as enacted by the Earthquake Hazards Reduction Act of 1977, 42 U.S.C. §§ 7701 *et seq*.

Implementing the ShakeAlert System

The ShakeAlert system is a set of components and sub-systems that interprets ground motions to detect earthquakes, so quickly, that warnings can be sent to people and machines, allowing them to take protective action before strong shaking arrives. As the system is developed, work on each system component can proceed independent of the progress of others.

The main components of the system are listed below:

- Networks of stations with sensors and dataloggers that detect and record seismic and geodetic ground motions generated by earthquakes.
- Telecommunications systems that reliably transmit real-time data from those stations to central processing locations with minimal latency (delay).
- Computer algorithms that analyze seismic and geodetic data to rapidly detect earthquakes, reject non-earthquake signals, determine earthquake characteristics, and estimate resulting ground motions.
- Decision algorithms that evaluate and manage these results, generate notifications and parametric data streams when appropriate, and transmit them to users.
- Data processing facilities with hardware infrastructure, including computers, networks, and uninterruptable power systems that run algorithms.
- Diverse communications methods that transmit notifications and data streams rapidly and reliably to users.
- Research and testing facilities that evaluate system performance, refine and tune algorithms, and assess and approve new methods.

Evolutionary Implementation

An EEW system is being developed for the West Coast within existing operational environments of three ANSS regional seismic networks in southern California (Southern California Seismic Network, SCSN), northern California (Northern California Seismic System, NCSS), and the Pacific Northwest (Pacific Northwest Seismic Network, PNSN). This enables USGS and ANSS to leverage their substantial investment in sensor networks, data telemetry systems, data processing centers, and software for earthquake monitoring activities residing in these network centers. This approach also takes advantage of considerable institutional expertise and experience at the centers that have demonstrated competence in the production of rapid, automatic data products such as earthquake locations, focal mechanisms, moment tensors, ground shaking estimates, and public messages that are used by emergency responders, scientists, engineers, policy makers, and the public. EEW can be thought of as a new, faster, albeit more demanding, earthquake information product.

This evolutionary development of EEW has been underway for many years within the California Integrated Seismic Network (CISN), which is the California region of the ANSS. CISN is a collaboration among SCSN (USGS and Caltech), NCSS (USGS and UC Berkeley), the California Geological Survey (CGS), and the California Office of Emergency Services (Cal OES). ShakeAlert is currently being extended to the PNSN, and ultimately, could propagate to other ANSS regional centers throughout the nation. Funding is the primary constraint on how quickly this can be accomplished. It is imperative that development and implementation of ShakeAlert have no adverse impact on the ability of the ANSS centers to fulfill their current seismic monitoring mission. Likewise, transition of ShakeAlert to production must not interrupt delivery of notifications to beta users who currently participate in the demonstration system.

Large-Scale System Architecture

Large-scale architecture of a West Coast system calls for processing and warning centers at the three existing ANSS “Tier 1” regional network centers in northern California, southern California, and Seattle (fig. 2). There are several reasons for this. Most obviously, ShakeAlert is an extension of existing regional network operations at these centers, as described above. Second, sensor networks and telemetry systems must be installed, monitored, and maintained within the regions of earthquake risk. Regional processing ensures close coordination and cooperation among personnel engaged in all aspects of the system: field operations, data management, and data processing. Also, this improves reliability and reduces latency by minimizing the number of “router hops” for data (from sensor to center), and for alerts (from center to user). In addition, this approach makes it practical for the system to share telemetry directly with local and regional entities like utility companies as well as police and fire departments. Finally, this approach ensures close communication and cooperation among operators, users, decision makers, and elected officials in each region.

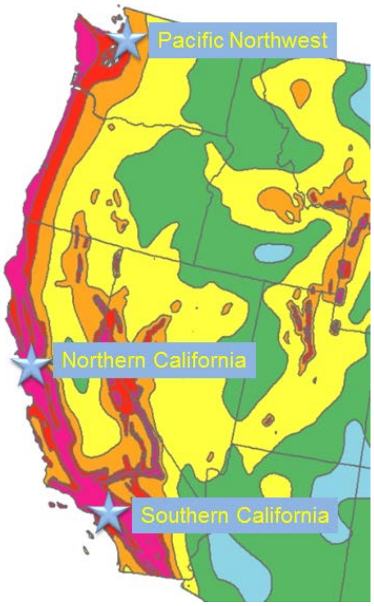

Figure 2. National earthquake hazard map of the West Coast, Unites States, showing locations of three ANSS regional network centers (stars) and seismic hazard levels. Warm colors (yellow to pink) indicate higher seismic hazard, whereas cool colors (blue and green) correspond to areas of lower hazard.

Processing Architecture

ShakeAlert is a distributed system with several interconnected components. This system architecture allows for independent development of individual components, including data sources, algorithms, event associator, and user alert generation and delivery (fig. 3). Data sources include continuous streams of various types of ground motion measurements and EEW parameters derived from those streams that are provided by regional seismic networks. In the future, data streams from cooperating groups can be incorporated when they meet system quality standards. Future developments will include real-time, high-precision Global Positioning System (GPS) data streams and displacement streams that combine GPS and seismic time series.

Within seconds of an event's initiation (origin time), algorithms detect and characterize earthquakes. Three EEW algorithms are currently implemented in the system: τ_c-P_d Onsite, Virtual Seismologist, and ElarmS. An associator, called the Decision Module (DM), then uses estimates of source parameters and uncertainties (determined by the algorithms) to calculate, update, and report the most probable earthquake location and magnitude. Next, user alerts report rapid estimates of earthquake magnitudes, locations, expected seismic intensities, and probabilities that an alarm is correct (likelihood parameter). Then, user alert messages, generated by the DM, are distributed as XML messages that are updated at least once per second as the earthquake occurs. These data streams were designed to be used in a wide variety of end-user applications, including mobile phone apps, other mass-distribution alert applications, and engineering applications. As a proof of concept, alert messages are received and displayed in real-time by an application called "User Display" that runs on a user's computer.

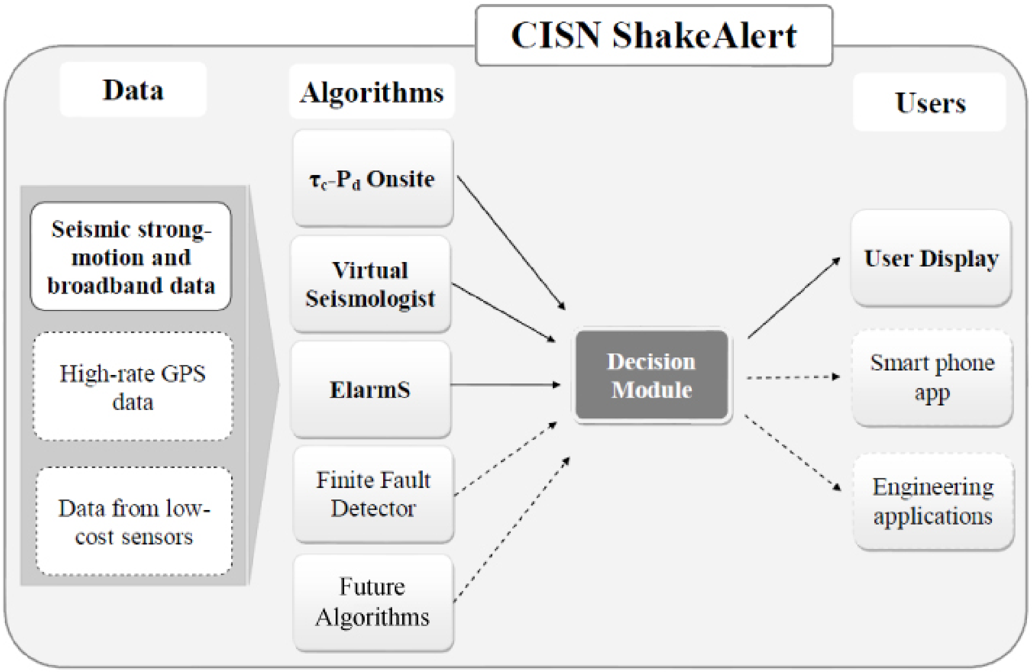

Figure 3. Diagram showing existing (solid lines, bold text) and future (dashed lines) modules and architecture of the ShakeAlert system.

Detection Algorithms and Decision Module

All EEW systems depend on algorithms that rapidly evaluate ground-motion observations from a network of sensors to estimate the location and magnitude of an earthquake and associated likelihood. As described above, three algorithms currently process real-time seismic data and geodetic-based algorithms are also being tested. Algorithm outputs are evaluated by the DM to recognize events declared by more than one algorithm, combine event location and magnitude estimates, and output a synthesis of event information and probabilities. Development of these algorithms and the DM is underway by university partners and is supported by funding from the Gordon and Betty Moore Foundation through 2014.

Algorithm and DM implementation will include the following steps:

- Test existing algorithms and DM to demonstrate they meet performance standards (see "Quality and Performance Standards" section of report).
- Continue improving existing algorithms and encourage development of better ones.
- Expansion of detection capabilities will include the following steps:
    - Improving large-magnitude event warnings by including real-time fault modeling to estimate total rupture length and slip distribution.
    - Implementing new detection algorithms that incorporate real-time GPS displacement data.

Ground-Motion Data Sources

Current EEW algorithms use ground motions of various types to rapidly detect and characterize moderate to large earthquakes. Seismic instruments record ground velocity and acceleration that can be numerically integrated to displacement, whereas real-time GPS instruments record ground displacement directly.

Seismic Data

Ground motions used for earthquake early warnings are currently based primarily on seismic observations from broadband and strong-motion seismic sensors. The three EEW algorithms have been developed and refined using recorded seismic data from global events as well as real-time network data from CISN. Whereas data flow and EEW parameter determination is well-established, optimal density and distribution of seismic sensors on the West Coast has not yet been achieved, and more stations are needed. To maximize warning time and minimize the "blind zone" (the area too close to the earthquake epicenter to receive a warning), earthquake sensors must be located near active faults. The current goal is to operate a network of seismic stations that are spaced no more than 20 km apart and within 5 km of all mapped fault traces. However, experience tells us that damaging earthquakes can occur even where faults have not been mapped; therefore, 20-km spacing or closer is also needed throughout all high-risk areas. Even denser station spacing of about 10 km would be needed to minimize the blind zone in more densely populated areas. The sensors, currently operated by the West Coast ANSS seismic networks, are not sufficiently dense in all areas to accomplish EEW without unacceptable delays; therefore, new stations must be added and existing stations must be upgraded to achieve station density needed for EEW.

Greater station density will be achieved in several ways:

- Install new stations—It is estimated that about 440 new and upgraded seismic stations are needed in California and about 280 in Washington and Oregon (table 1). As funding opportunities arise, new stations will be added to ANSS to fill coverage gaps, especially along active faults zones and in populated areas.
- Upgrade sensors and dataloggers—Many older existing stations, not suitable for EEW now, could be upgraded to contribute. There are a total of about 250 such stations in the CISN and another 250 in the PNSN. Those that fill gaps in the network distribution are candidates for upgrade.
- Add telemetry to and upgrade selected strong-motion stations—There are many strong-motion accelerometer stations that do not send data in real-time and therefore cannot contribute to EEW. The California Strong Motion Instrumentation Program operates approximately 840 free-field sites, most of which have no real-time telemetry. The USGS National Strong-Motion Project operates

about 335 free field stations on the West Coast of which only about 40 have real-time telemetry. Many of these could be used for EEW if telemetry was added and the equipment was upgraded.

- Encourage cooperators to install stations—We will continue to encourage organizations with sufficient interest and resources to install seismic equipment and send the real-time data to ANSS.
- Integrate data from inexpensive sensor networks—We will continue to pursue the use of inexpensive MicroElectroMechanical System sensors hosted by volunteers (for example, Quake Catcher Network and Community Seismic Network).

Table 1. New and upgraded seismic and Global Positing System (GPS) stations needed for West Coast Earthquake Early Warning (EEW) system.

[ANSS, Advanced National Seismic System; NCSS, Northern California Seismic System; PNSN, Pacific Northwest Seismic Network; SCSN, Southern California Seismic Network]

	California (CISN)		Pacific Northwest	Total: West Coast U.S.
Instrumentation Type	NCSS	SCSN	PNSN	(NCSS+SCSN+PNSN)
Seismic: Type A[1]	100	25	66	191
Seismic: Type B[2]	239	75	210	524
GPS	100	50	156	306

[1] ANSS station; broadband plus strong-motion instrumentation.
[2] Only strong-motion instrumentation.

GPS Data

While the use of real-time GPS data for EEW is less developed than the use of seismic data, there is ample evidence that GPS will make a significant contribution to the calculation of large magnitudes and characterization of large fault ruptures. Both UC Berkeley and University of Washington have been funded by the Gordon and Betty Moore Foundation to develop and test such algorithms. Other researchers are also developing methods to use GPS data in EEW applications, including techniques to combine seismic and geodetic data to produce real-time displacement time series. Additional work is needed to develop, test, and integrate GPS data into the ShakeAlert system.

The steps to integrate GPS observations into the EEW system are as follows:

- Identify GPS-based algorithms that best contribute to fast and reliable characterization of large-source, large-magnitude events.
- Upgrade or install real-time, high-precision GPS receivers near active faults.
- Establish standard data processing methodologies for solving real-time displacements.
- Establish a thoroughgoing flow of real-time GPS data to the ShakeAlert system.
- Test and implement selected GPS EEW algorithm(s) in the production system.

Equipment Life Cycle

This plan assumes a 10-year operational life for both seismic and GPS field equipment, therefore about 10 percent of network equipment would be replaced each year. In a funding scenario where no capital construction costs are provided, but maintenance and operation funds are granted as proposed, the life cycle replacement plan completely upgrades obsolete field equipment within existing networks in 10 years or less.

Network Telemetry

Data communications from field sites to central processing sites must be hardened against loss of connection. Absolute reliability of each site would be cost prohibitive, however, the system shall be engineered to fulfill its warning function during and after strong shaking by minimizing the impact of loss of regional electrical power and collapse of commercial telecommunications systems. System design cannot depend on the notion that notifications will be sent before fragile communication links are destroyed by a quake. Such a system would fail to warn the public of aftershocks following the mainshock. In addition, the system must be resilient to routine outages and failures.

The best strategy, as demonstrated by the current ANSS networks, is to use diverse telecommunication technologies for communicating data from the field sites. These methods include the public Internet, a variety of commercially leased telecommunications technologies from different carriers (T-1, cellular, DSL, satellite), USGS-owned-and-operated radio and microwave, and cooperator-owned-and-operated systems.

Path Diversity and Fault Tolerance

We will inventory existing data paths within CISN and PNSN and develop a plan to maximize diversity and fault tolerance. If funding permits, we will commission a study by an outside contractor to survey all available telemetry options and develop a plan to maximize reliability of field telemetry. Current activities to improve telemetry will continue. These include replacing Very High Frequency radios and frame relay circuits with cellular or Internet Protocol radio communications, improvements to USGS microwave backbones, and carrying data over cooperator systems. We will monitor new technology developments in telecommunications as they become available and evaluate their applicability to the task of EEW. Funding from the sale of government radio spectrum to migrate to other frequencies may afford the opportunity to improve and expand USGS-operated telecommunications systems.

The steps for achieving greater diversity and fault tolerance in the telemetry system are as follows:

- Document the current telemetry infrastructure of CISN.
- Document bandwidth requirements for real-time data from all instrument types.
- Document bandwidth and latency characteristics of available telemetry options.
- Understand the characteristics of new telecommunication technologies and commercial solutions (for example, mesh radio networks, Multiprotocol Label Switching, and cloud services).
- Establish memorandas of understanding with cooperator organizations that include use of their telecommunications infrastructure for field data.
- Develop two plans to achieve highly reliable data return from field sensors; one assuming modest capital budget and one assuming a large funding increase. This planning may be outsourced.

Data Latency

Telemetry options will be evaluated to minimize data latency. Generally, latencies in modern telecommunications systems are acceptably low for EEW.

Central Site Infrastructure

Computer Hardware

A new “production system” will be built to support current beta users who receive alerts from the demonstration system. That system will include redundant, cooperating production systems at the three regional ANSS centers (SCSN, NCSS, and PNSN). All central site infrastructure, computers, and networking shall be engineered to fulfill their warning functions during and after disasters, including strong shaking (up to 2.0 *g*), loss of commercial electrical power for up to 1 week, and collapse of commercial telecommunications systems.

The use of commercial cloud services to provide some or all of the computational and data transmission needs of the ShakeAlert system should be more thoroughly evaluated. Cloud computing may solve some robustness and redundancy issues more cost effectively than locally operated centers; however, moving to the cloud might also introduce new fragilities and risks, making them harder to manage. These risks include greater dependence on public Internet and rapidly changing technical and pricing models that are beyond our control. The main attraction of the cloud computing model for many users is elasticity: automatically allocating computing resources on demand. Today this on-the-fly addition of computer resources is too slow for EEW applications.

This plan assumes a 5-year life cycle for 20–30 computer servers at each regional network center, to perform data handling, processing, product production, alert distribution, and testing.

Building the operational infrastructure will include the following activities:

- Build stable hardware infrastructure for the production system to take over support of current beta users from the demonstration system. This includes defining and documenting the following items:
    - overall system architecture.
    - standard hardware platform requirements.
    - standard OS environment, libraries, and user and directory structures.
- Develop and document standard operating procedures to manage network changes, patches, and updates.
- Develop and document standard operating procedures to monitor network traffic and state-of-health for all sub-systems and the system as a whole.
- Ensure resilience of the system by operating redundant instances of all critical components.

Development and Testing Environment

To ensure reliable operation of the EEW system, development and testing functions must be independent of the production system. Also, testing and evaluation of new code, system upgrades, and configuration changes must be done in an operational environment that is identical to production. This environment must include live data input streams and the ability to play back test datasets, both real and synthetic. Finally, all code and configuration changes certified for use in production must be documented and preserved. This will be accomplished by creating independent but identical computer environments for development, testing and staging, and production as shown schematically in figure 4. All code and configuration changes will be preserved in a journaling code repository.

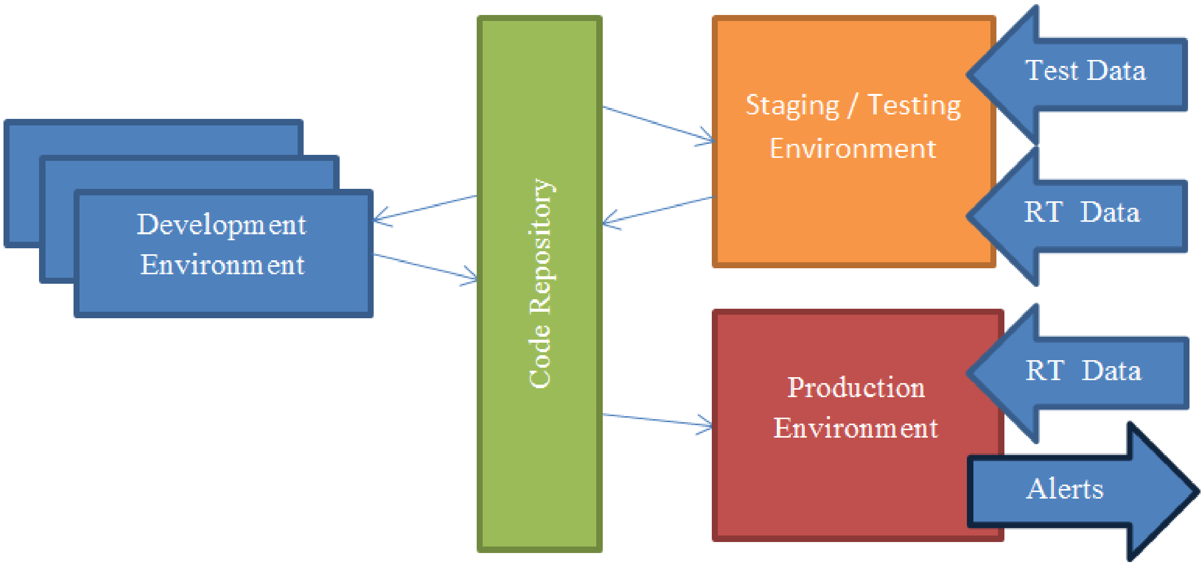

Figure 4. Schematic diagram showing interaction of development, staging, and production computer environments. All code and configurations reside in a code management repository. All new and changed code and configurations are tested with real-time data streams and play-back of synthetic streams.

Central Site Software

Software from the demonstration ShakeAlert will be ported to new, robust processing threads that will run in close cooperation with current ANSS Quake Monitoring System (AQMS) operations. AQMS is a real-time earthquake monitoring system that has been adopted by ANSS for use in regional networks. The same real-time ground motions that feed into AQMS are the input data to ShakeAlert. Project programmers for EEW will port the current development thread of processing to new production machines, thus freeing the current machines for further development efforts. This may require code changes to adapt to the new operational environment. It may also involve adding more rigorous exception handling to improve robustness of error code reporting. To eliminate single points of failure, redundant processing threads will be established within and among ANSS regions. Notifications to outside users will originate from several geographically diverse URLs in the *usgs.gov* domain.

Creation of the production prototype system will include the following activities:

- A standard operational environment for EEW software will be established, documented, and used on all EEW production computers.
- EEW software will be installed on dedicated computer servers.
- Policies and standard operating procedures will be established for documenting and managing software and configuration changes in the system. This version management will include network and computer environment changes, patches, and updates to ensure reliable system operation.
- Personnel responsible for routine operations of AQMS will be trained to operate and monitor EEW processing threads.
- Production systems will be replicated and installed at all three West Coast regional ANSS centers (SCSN, NCSS, PNSN).

Software enhancements include the following improvements:

- State of health monitoring and exception notification will be implemented.
- EEW software will be modified to use ANSS network metadata availability and access to AQMS databases.
- Streamline earthquake event id numbers and versioning between EEW and existing AQMS processing outputs.
- UserDisplay application will be modified to automatically switch among alternate redundant servers in the event of connection loss or server failure.
- New or updated algorithms will be added to productions systems only after they have met performance standards (see “Quality and Performance Standards” section).

These collaborative efforts will be gradual and iterative to ensure no loss of functionality to current users. This effort will take into account the fact that some unique solutions may be needed at each regional center because AQMS and ShakeAlert implementations and staffing vary across centers.

Standards

Data Formats

Data and message formats must be standardized throughout the system. Standard formats will simplify internal operations, facilitate maintenance of test data sets, and allow groups outside the project to more easily contribute data to and receive data from the system. In some cases, viable formats already exist and need only to be adopted and documented. If required, project staff and (or) working groups will extend existing formats or develop new ones.

Incoming Data

Several standards already exist for incoming seismic time series, (mSEED and Earthworm TraceBuf, for example). The geodetic community is working on standards for real-time time series based on existing standards for GPS data. Standard formats for EEW parameters, generated in dataloggers or cooperator equipment, will be based on those already developed for the demonstration phase of the EEW. Publishing of these standards will enable commercial vendors to make products capable of contributing data directly to ShakeAlert without the need for format conversion.

A standard data communication protocol (application programming interface), by which time series and parameters from both seismic and geodetic sensors will be communicated from data producers to the EEW system, will be developed, documented, and made available to partners. The standard must address metadata related to these parameters, data-quality description parameters, security, and validation.

Outgoing Notifications

Outgoing EEW notification formats exist and are documented. These are XML messages that contain information about an earthquake’s location, magnitude, and likelihood. Additional optional information includes finite-fault parameters and stations that have detected ground motion. Because the format is XML, it can be expanded to accommodate additional information as new sensor types or data streams are developed. The current standard data communication protocol is ActiveMQ, an open-source data communications protocol. It is well-documented and has wide support in the IT community.

Common Alert Protocol messages will be generated and submitted to the Integrated Public Alert and Warning System (IPAWS) for public distribution. This will require additional logic within the EEW system to decide the level of likelihood that public notifications will be sent. Additional output streams will be developed to support specific output paths, for example, to private companies and other stakeholders.

Quality and Performance Standards

Standards, performance goals, and uniform procedures are critical to the success, acceptance, and proper operation of the EEW system. These standards must include meaningful, realistic metrics. All work of the USGS, including EEW, is governed by several orders and authorities. First, we are required to follow the DOI Secretary’s Order No. 3305 and related guidance concerning science quality and integrity. This includes a process for scientific peer review of all research and development. Second, the ANSS has national standards for management, system performance, data completeness and quality, sharing of seismic data, and validation of methods for creation and distribution of public earthquake information.

The National Earthquake Prediction Evaluation Council (NEPEC) will review and approve the EEW system before public notification can be issued. NEPEC is the official entity for validation of prediction and related scientific research for USGS, in compliance with the Federal Advisory Committee Act. The NEPEC may, at its discretion, delegate this task to the California Earthquake Prediction Evaluation Council.

During the equipment procurement process, technical specifications for seismic sensors, dataloggers, and GPS receivers and antennas are rigorously defined, and vendor equipment is tested on shake tables before contracts are awarded.

Establishing quality and performance standards will include the following activities:

- Standards will be developed and documented that define the following items:
  - Minimum and optimum seismic and geodetic station spacing.
  - Sensor and data types useful to the system.
  - Maximum allowable telemetry latency and minimum quality of service for data sources.
  - System security standards that, at a minimum, conform to applicable government standards, including Federal Information Security Management Act of 2002 (44 U.S.C. § 3541, et seq.).
  - Acceptable levels of “false alarms” or missed events as a function of event magnitude for all detection algorithms as well as for the final output from the DM.
  - Where and when early warning results are sufficiently reliable for release to different user groups. For example, criteria for public release may be more stringent than those for more sophisticated institutional users.
  - Best practices for software coding, software testing, and certification procedures.
- A set of earthquake scenario waveforms will be developed to test new and modified code in a realistic simulated real-time operational environment. This set will include synthetic waveforms that simulate events larger than those available in existing data sets, including Cascadia subduction zone events.
- Solution output from each algorithm, and from the DM, will be archived to allow evaluation and troubleshooting of system component performance.
- Methods and tools developed to evaluate system performance will be integrated into the AQMS operational environment.

Warning Notification

The primary product of ShakeAlert is not a single alert notification; rather, the strategy is to provide a stream of information about an earthquake as it evolves so that end users can make decisions about what actions they should take in their own context. For this reason, the system sends alert streams for small earthquakes—sometimes less than *M*3.0. This has the added benefit of exercising the system frequently, even though most events will not result in end-user actions.

For some applications, however, like public alerts to IPAWS/Wireless Emergency Alerts (WEA) or schools, ShakeAlert must perform a decision function to determine when “drop, cover, and hold on” is warranted and only issue a single alert.

To provide both capabilities, the following project items must be completed:

- Develop a decision and notification architecture that allows multiple DM services to synchronize and coordinate to eliminate single points of failure while ensuring consistent messages to users.
- Develop decision logic, possibly implemented via an alternative DM-like service that will determine when to send a public EEW alert message.
- Develop geotargeting algorithms to calculate the area that will experience ground shaking above a pre-defined threshold.
- Work with EEW message redistributors and consumers to properly receive, interpret and respond to geotargeting information.

Distribution of Notifications to the Public

ShakeAlert notifications will be sent over existing public alert systems to the extent their capabilities allow. Public mass notification systems like IPAWS (fig. 5) and WEA are operated by FEMA. This system carries Amber Alerts as well as various hazard alerts. USGS will become an “alert authority” for the IPAWS system. EEW developers will participate in the IPAWS development process to ensure that operators of these systems consider the low latency requirements of earthquake early warning notification in their planning. Alerts may also be sent via public state, county, and local alert and notification systems as well as through private redistribution channels like cell phone apps, push notification channels, social media providers and other instant communications technologies as they develop. Commercial mass notification companies can also redistribute alerts to their customers.

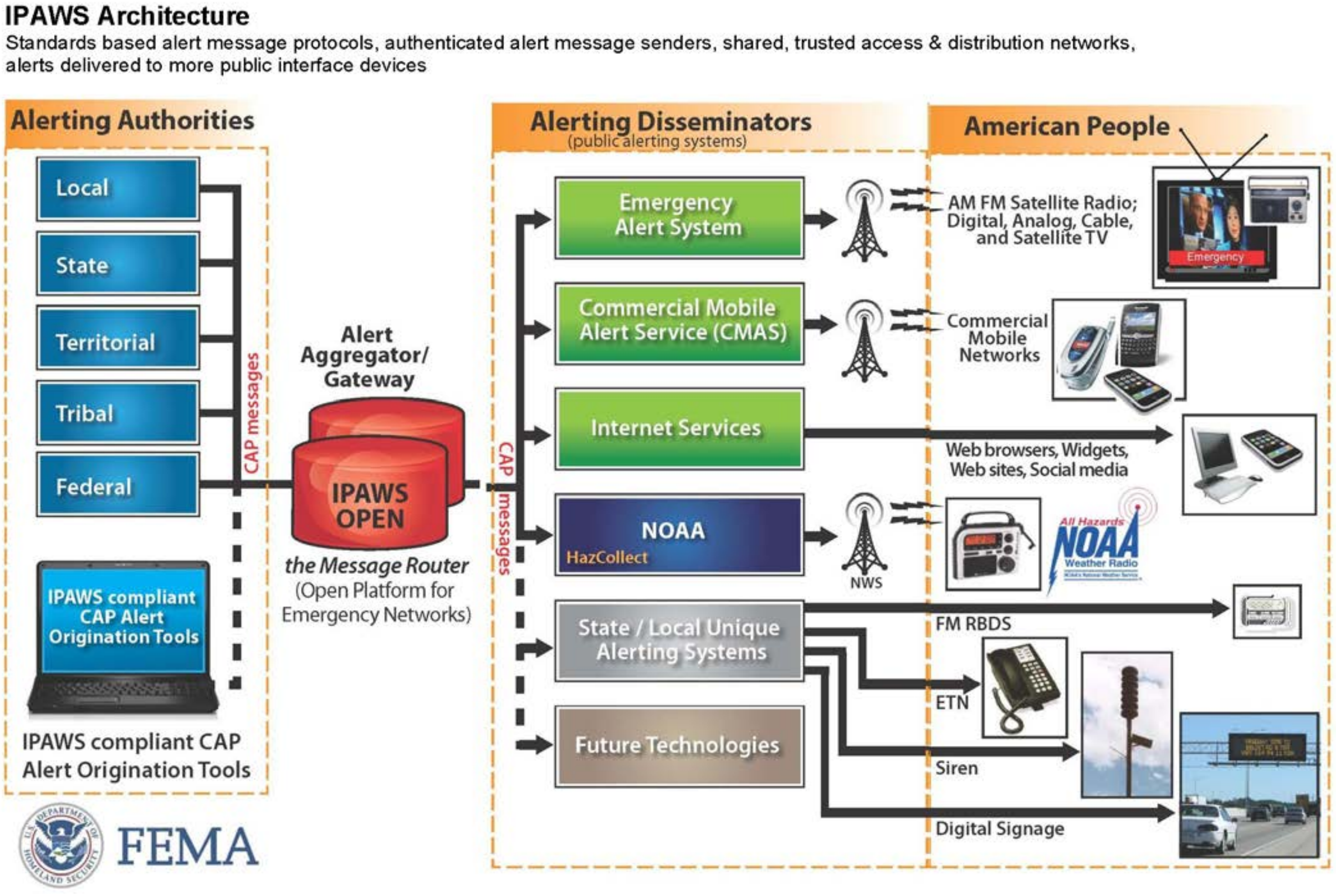

Figure 5. Schematic diagram showing architecture of the IPAWS alert dissemination system (figure from *www.fema.gov*).

Sending public notification messages will require the following activities:

- IPAWS/WEA
  - Establish USGS as an “alert authority” with the IPAWS system.
  - Understand the limitations and latencies in the IPAWS/WEA system.
  - Implement a message service to send Common Alert Protocol (CAP) messages to IPAWS.
  - Implement message services to send both long and short WEA messages to IPAWS.
  - Explore other notification paths.
- Smartphone Apps
  - Develop a smartphone app to receive EEW messages on multiple platforms. This may be accomplished in cooperation with commercial developers.
  - Develop and implement the message services to support these apps.
- Other Technologies
  - Internet.
  - Radio Broadcast Data System (RBDS).
  - Private emergency alert systems (Google Public Alerts, for example).
  - Other technologies as they develop.

Notification to Institutional Users

One of the most important applications of EEW is the initiation of automatic protective actions by utilities, transportation, and industry. While some organizations have the internal expertise to implement EEW effectively in their own context, most will need outside support. The ShakeAlert project cannot provide individualized help to thousands of potential institutional clients, each with a need to customize actions to their own requirements. Therefore, the system will encourage value-added customization and redistribution of notifications by third parties. In Japan, this niche is filled by the Real-time Earthquake Information Consortium, a non-profit organization that promotes the use of EEW information and acts as a liaison between the Japan Meteorological Agency system and external users. The Real-time Earthquake Information Consortium includes more than 70 companies that provide consulting services and products for the practical application of EEW notifications. The USGS and its partners, being publicly funded, must provide the public safety services it offers to all users without charge as it does now in the case of the Earthquake Notification Service, ShakeMap, and the National Hazard Maps. Office of Management and Budget Circular A-130 recognizes that "government information is a valuable national resource, and ... the economic benefits to society are maximized when government information is available in a timely and equitable manner to all." However, USGS may enter into technical co-development agreements with public or private organizations to promote the effective use of EEW information. Also, USGS-funded partners may develop and provide specialized, value-added information or services to users that are not supported by government funds.

Encouraging the development of user-specific applications of EEW will require the following activities:

- Document the APIs available to end users for receiving EEW notifications.
- Document the format and behavior of the message stream, including the meaning of "likelihood" so end users can effectively understand and use the data received.
- Provide sample code for connecting to EEW servers and receiving messages.
- Develop demonstration applications or devices that can receive EEW messages, execute user logic, and initiate actions at user sites. This may be accomplished through cooperation with end users, agreements with private companies, or by internal development.

Roles and Responsibilities

The project will be managed like other important projects of the USGS Earthquake Hazards Program (EHP). At the Federal level, oversight of the larger program will include review by the Scientific Earthquake Studies Advisory Committee, the ANSS Advisory Committee, and the Earthquake Program Council. Coordination with FEMA and National Institute of Standards and Technology is also necessary to fulfill Stafford Act and National Earthquake Hazard Reduction Program responsibilities.

The USGS EHP will have overall responsibility for the development and operation of the national EEW system. However, cooperation and coordination among many stakeholders will be needed for success. In particular, state emergency management agencies must be key players in the system.

EEW is an extension of the responsibilities of the ANSS and will be governed by the same management and organizational structures. For example, in California, CISN network operators at the two ANSS Tier 1 centers will continue to operate their parts of the system in coordination with the USGS and Cal OES and will participate in decision making for the system through existing or expanded ANSS governing structures.

Development and testing of ShakeAlert software have been and will continue to be accomplished by the ANSS USGS and its partner universities through cooperative agreements and grants. The USGS ANSS Coordinator, in coordination with the USGS Earthquake Early Warning Coordinator, will have overall responsibility for the EEW system and will work closely with cooperating ANSS partners to achieve system goals. Additional advisory or working groups may be formed as needed.

ANSS regional operators and the EEW Coordinator will need to harmonize their activities with Federal, State, and local entities that have a stake in the EEW system. These include NEHRP agencies including FEMA, National Institute of Standards and Technology, and National Science Foundation as well as National Oceanic and Atmospheric Administration, state, county, and city emergency management departments, geological surveys, and other organizations with emergency preparedness and response missions.

During the transition from the demonstration phase to the production phase, EEW algorithm developers will collaborate with USGS staff to transfer the existing ShakeAlert demonstration codes into the ShakeAlert production environment to create the "operational prototype." Once tested and certified, this will become version 1 of the production system. The four working groups organized during development of the demonstration system will be retained and one group added. These are the production system group, the demonstration system group, the scientific coordination group, the performance evaluation group, and the user interactions group.

Public-Private Partnerships

Partnerships with stakeholder organizations are important to ANSS operation of seismic networks and will increase as EEW is implemented. Today, ANSS receives real-time ground-motion data streams from both public and private partners. In addition, some partners provide data communications and secure sensor locations. This addition significantly improves performance of the entire system. Published EEW algorithms will be available to seismic sensor manufacturers who can implement them on their products, thereby increasing their value while providing more information to the system. Market demand may result in consumer level EEW sensor/receiver devices to send data to ShakeAlert while, at the same time, receiving alerts, sounding alarms, and taking actions. Some high-vulnerability users may benefit from additional capabilities to augment the ShakeAlert system. For example, an on-site system may provide faster warning when an event is very close to that location. In Japan, more than 70 businesses have registered to provide such products and services.

There will be significant business opportunities for companies to provide consulting services to help users develop business plans and decision models for actions to take during an early warning alert. Interpretation of warning messages and redistribution to clients can add significant value to the ShakeAlert warnings. Because specific impacts of predicted shaking are site-dependent and depend on the infrastructure at a given location, private sector services will be necessary to ensure that warnings are fully utilized by the public and businesses to minimize earthquake damage, injuries, and deaths.

Participation by diverse communications companies will undoubtedly be important for effective distribution of alerts to the public and business. Mass notification companies, cellphone carriers, internet service providers, cable and satellite companies, and TV and radio stations are in an ideal situation to provide these services as they have done in Japan. Software developers will undoubtedly develop creative EEW applications for various platforms, including smartphones and tablets.

Extensive outreach and education for both public and institutional users will be necessary to maximize EEW benefits. All users must be educated on the appropriate actions to take upon receiving a warning, and understand limitations and reliability of warning information. Partnerships with appropriate organizations, both public and private, will be needed to ensure that this education occurs (for example, FEMA, State Emergency Management Agencies, communications specialists, and specific sector groups such as transportation, utility companies, and hospitals).

Project Communication

This project will be coordinated by the same mechanisms used during development of the ShakeAlert demonstration system: by the use of conference calls, face-to-face meetings, collaborative documents, shared websites, wikis, and code repositories. We will hold bimonthly “all-hands” conference calls to exchange updates about project components and decide on project-wide strategies. Each of the working groups will also hold its own calls as necessary throughout the project.

Project managers will continue holding calls with a broader group of USGS representatives every six months. Representatives from the Earthquake Hazards Program headquarters in Reston, the Earthquake Science Center in Menlo Park, the National Earthquake Information Center in Golden, and a representative of Natural Hazards Mission Area: Science Application For Risk Reduction project will participate along with others interested parties. These calls are an opportunity to provide updates and get feedback on project priorities. Annual progress reports will be submitted to USGS by externally funded partners.

Cost Estimate

The projected cost of an EEW system for the West Coast includes initial capital investment as well as ongoing maintenance and operations. The capital investment costs for the West Coast EEW system are projected to be $38.3M. Capital investment includes purchasing and installing seismic and GPS equipment to increase monitoring station density to the minimum levels required for providing warnings to urban areas of the West Coast of the United States. Additional capital costs cover improved telemetry robustness and resiliency between the station and regional centers. Annual maintenance and operation costs of the EEW system total $16.1M. This includes life cycle hardware replacement, telemetry costs, staff, and staff support (described below). It is important to note that these projected costs are in addition to current ANSS funding at the three regional ANSS centers and assume no reduction in support for those efforts. Additional details, including a regional breakdown, are provided in tables 5–9 shown in appendix B.

An alternative funding model, without upfront build-out funding and with the annual maintenance and operation funding level alone, would result in building the system more slowly. The pace of build-out in this scenario would be determined by the 10-year field equipment life cycle.

Staffing

Implementation and operation of the EEW system will require new staff over and above those currently involved in ANSS seismic network operations (table 2). Reliable operation of the ShakeAlert system requires additional technical staff at each of the regional centers to augment current staff in the areas of project management, engineering and maintenance of new field stations and telemetry infrastructure, computer system operation and administration, programming, and local outreach (table 2). In addition, new personnel are required to coordinate the system-wide effort (table 3). The distribution of new personnel among the university partners and USGS will be determined as the project moves forward. Because ShakeAlert is dependent on data from the ANSS/AQMS system, this plan also calls for bolstering Tier 1 network operational staff from their current, bare-bones levels to ensure all major functions are supported by at least two people. This will guarantee coverage during vacations and illness, continuity through personnel turnover, and allow close monitoring of systems.

Continuous system state-of-health monitoring and quality assurance of data streams and results will be automated as much as possible. On-call personnel with remote access will respond to issues 24/7 as they arise. Diligent system engineering and rigorous testing and certification of new and changed code or configurations will minimize problems in the live production system. Because human intervention would not be fast enough to mitigate problems once an event is detected, on-site 24/7 personnel at the regional centers are not called for in this plan.

Expansion of the seismic networks and telemetry infrastructure requires additional field engineers to install and maintain stations and telemetry components and to accomplish the life-cycle replacement upgrade schedule of 10 percent of network stations per year.

Table 2. Additional Advanced National Seismic System (ANSS) and ANSS Quake Monitoring System (AQMS) regional center staff to support Earthquake Early Warning (EEW).

[CISN, California Integrated Seismic Network; NCSS, Northern California Seismic System; PNSN, Pacific Northwest Seismic Network; SCSN, Southern California Seismic Network]

Regional Center Staff	California (CISN)		PNSN
	NCSS	SCSN	
Operations Management and Support			
Project manager	1	1	1
Project assistant	1	1	1
Field Support[1]			
New station maintenance	4	3	3
New telemetry maintenance	2	1	1
IT Support[2]			
AQMS support	4	4	4
EEW production thread operation	2	2	2
Data analyst/quality control	1	1	1
Outreach and user support	1	1	1

[1] Electronics technicians, field engineers.
[2] System administrators, operators, programmers.

Central coordination staff will manage efforts among the ANSS regional centers (table 3). They will implement and test development computer codes to ensure they meet pre-established standards and are ready for distribution to the production environment at the regional centers. They will also monitor overall performance of the whole system and verify that performance standards are being achieved throughout the system.

Table 3. Additional coordination staff to support Earthquake Early Warning (EEW).

System-Wide EEW Coordination Staff	Total
Computer System Architect	1
Implementation Programmers	2
Quality Assurance IT Specialist	1
Product Distribution Coordinator	1
Outreach Coordinator	1

Timeline

Constructing a timeline for EEW implementation is difficult because actual funding levels are not known. At constant or diminishing funding levels, some very limited progress may occur, but a system that is sufficiently tested and supported for public notifications will not be possible. Assuming full funding, including one-time build-out costs, we estimate that it will take three years to hire personnel, build production infrastructure, and test and certify the system to the point of issuing public notifications (fig. 6). As stated earlier, a funding model with annual operations and maintenance funding levels alone, and no upfront funding for build-out, would result in a significantly longer timeline.

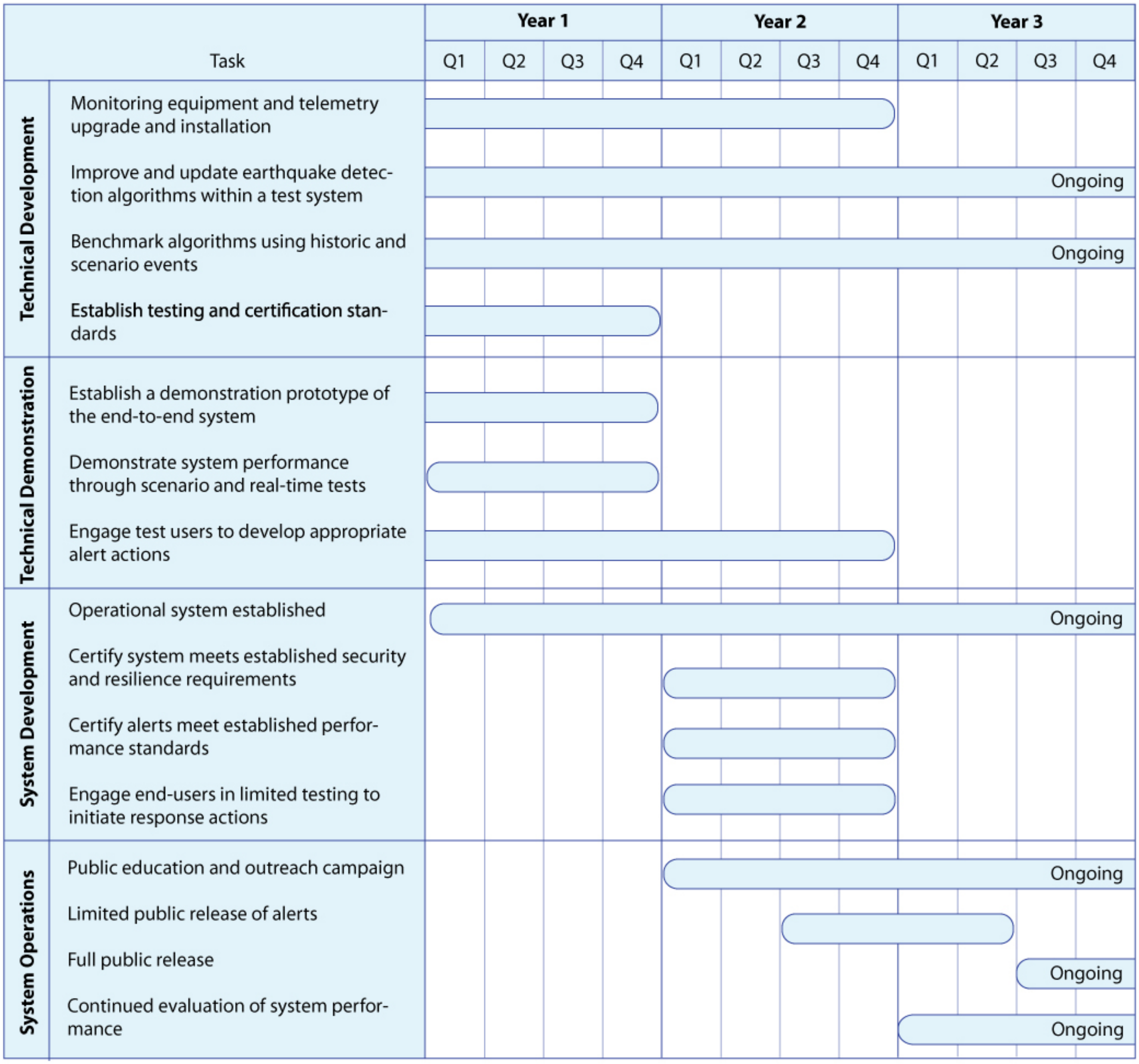

Figure 6. Spreadsheet showing project timeline, assuming full funding. “Ongoing” tasks extend into the operations and maintenance phases of the project.

Future Work

Continuing Research and Development

Additional research and development will continue on all aspects of EEW. Algorithms will be improved and new ones developed using both seismic and geodetic data and combining them. Work on sophisticated methods to rapidly characterize fault sources will continue, as will work specific to the Cascadia subduction zone. The Decision Module will continue to be improved. Techniques for estimating ground motions at user locations and the impacts of those motions on the built environment will be developed and folded into the system and end-user applications. The use of new types of sensors, including low cost Microelectromechanical System sensors and those in cell phones, as well as other evolving technologies like crowd sourcing, cloud computing, computer learning, and adaptive networks, will be explored and integrated into the system where applicable.

This work will be supported through external grants to university partners and contractors. We are also optimistic that the private sector will develop and implement innovative applications for EEW and create viable business models to sustain them. Close interaction between the development and operational groups will ensure that new and improved technologies are compatible with the ShakeAlert production system architecture.

Portable Warning Capability

In the event of a large earthquake, additional, temporary stations may be required near the epicenter to improve warnings for large aftershocks. An inventory of portable seismic stations with telemetry (cellular modems, for example) housed at each regional network would allow for rapid deployment following a large event. These stations would increase the station density near the mainshock location and provide reduced warning times of large aftershocks. Eventually, we plan to develop a stand-alone warning system that could be available for rapid deployment in parts of the United States or in other countries following a large earthquake.

Roll-Out to Other Regions

The scope of this plan is limited to implementation of a system for the West Coast which accounts for three-quarters of the national earthquake risk. However, as EEW technology is proven and matures, ShakeAlert will be propagated to other regions with significant seismic risk. A strategy to extend EEW to the other regions of the United States will need to evaluate the cost/benefit in other areas, and focus first on those population centers with highest risk; which include New York City, Salt Lake City/Provo, Anchorage, San Juan PR, Memphis, St. Louis, Boston, and Washington, D.C. All of the investment in development work for a West Coast system is transferrable at minimal cost to the ANSS regional seismic networks that now provided enhanced reporting of earthquakes in the intermountain west and the central and eastern United States.

User Education

Extensive outreach and education of both public and institutional users will be needed to ensure that earthquake early warning achieves the maximum beneficial effect. Users must be taught to take appropriate actions upon receiving a warning, and understand the limitations and reliability of warning information. Partnerships with appropriate agencies (such as FEMA, state emergency management departments, communications specialists, and specific user groups such as transportation, utilities, and hospitals) will be needed to ensure that this education occurs. A full user education plan must be developed and implemented that includes social science and testing of pre-event messaging and visual and audible alerts. This plan is beyond the scope of this document and will be developed separately.

Links

ShakeAlert web pages
http://shakealert.org

ANSS—Advanced National Seismic System web pages
http://earthquake.usgs.gov/monitoring/anss/

ANSS Performance Standards, Rev 2.7, October 5, 2008
http://earthquake.usgs.gov/monitoring/anss/docs/ANSS_Perf_Standardsv2_7.pdf

Instrumentation Guidelines for the Advanced National Seismic System, June 2007
http://earthquake.usgs.gov/monitoring/anss/docs/ANSS_WGD_InstrGuideline_June2007.pdf

CAP Common Alert Protocol—Earthquake CAP Alerts
http://earthquake.usgs.gov/earthquakes/catalogs/cap/

OMB Circular A-130, Memorandum for Heads of Executive Departments and Establishments
http://www.whitehouse.gov/omb/circulars_a130

Appendix A. Key Terms and Abbreviations

ANSS	Advanced National Seismic System
AQMS	ANSS Quake Monitoring System
Blind Zone	Approximately circular area that is too close to the epicenter of an earthquake for an early warning to be produced before strong shaking is experienced
Cal OES	California Office of Emergency Services
CISN	California Integrated Seismic Network
CMAS	Commercial Mobile Alert System (now called WEA)
Datalogger	Field-hardened computer that accepts signals from a sensor, transforms it to digital data and transmits it to the central processing site
EEW	Earthquake Early Warning
EHP	Earthquake Hazards Program (USGS)
FEMA	Federal Emergency Management Agency
GPS	Global Positioning System
IPAWS	Integrated Public Alert and Warning System
Latency	Any delay in the processing chain from the time sensors detect ground motion until end users receive information
NCSS	Northern California Seismic System
NEPEC	National Earthquake Prediction Evaluation Council
PNSN	Pacific Northwest Seismic Network
P-wave	(Primary wave) the faster-moving compressional wave that arrives first
SAFRR	Science Applications For Risk Reduction, a USGS Hazards Mission Area project
SCSN	Southern California Seismic Network
S-wave	(Secondary wave) the slower-moving shear wave that arrives after the P-wave
Telemetry	Telecommunication capability that carries ground motion data from seismic sensors in the field to central processing sites
URL	Uniform Resource Locator (“internet address”)
USGS	United States Geological Survey
WEA	Wireless Emergency Alerts (formerly CMAS)

Appendix B. Budget Details

The following budget estimate was created by the principal partners in the EEW project. It has two major parts: (1) one-time constructions costs to build the system, and (2) ongoing annual operation and maintenance costs. These costs are also broken down by ANSS region (California and the Pacific Northwest) because funding sources may be different for each area. Note that the System-Wide Coordination Personnel and Infrastructure costs should be included in any estimate of the cost for implementation in a single region as that function is required regardless of the regional extent of the system.

Table 4. Summary Cost of an Earthquake Early Warning (EEW) system (in millions of dollars)

	California	Pacific Northwest	West Coast Total
Construction costs	23.1	15.2	38.3
Annual M&O	11.4	4.7	16.1

Table 5. Capital Cost of an Earthquake Early Warning (EEW) system (in thousands of dollars)

	California	Pacific Northwest	West Coast Total
Equipment			
Seismic	7,768.0	4,632.0	12,400.0
GPS	2,400.0	2,496.0	4,896.0
Installation			
Construction, material	3,512.0	2,208.0	5,720.0
Construction, labor	2,195.0	1,380.0	3,575.0
Permitting	1,097.5	690.0	1,787.5
Telemetry			
New	878.0	552.0	1,430.0
Upgrade	165.6	36.0	201.6
Microwave	2,500.0	1,500.0	4,000.0
Telemetry study	100.0	50.0	150.0
USGS overhead (12%)	*2,473.9*	*1,625.3*	*4,099.2*
Total	23,090.0	15,169.3	38,259.3

Table 6. Annual M&O Personnel Expenses (in thousands of dollars)

	California	Pacific Northwest	West Coast Total
Operations Management			
Project management	342.9	171.5	514.4
Project assistants	199.2	99.6	298.8
Field Personnel			
Stations technicians	848.3	363.5	1,211.8
Telemetry technicians	363.5	121.2	484.7
IT Personnel			
Software developers	2,057.6	1,028.8	3,086.4
Data analysts	199.2	99.6	298.8
Outreach			
User support	242.4	121.2	363.6
USGS Overhead (12%)	510.4	*240.6*	*751.0*
Total	4,763.5	2,246.0	7,009.5

Table 7. Annual M&O Operating Expenses (in thousands of dollars)

	California	Pacific Northwest	West Coast Total
Field – Operational expenses	359.6	143.8	503.4
IT – Operational expenses	179.0	97.9	276.9
Telemetry	891.2	388.3	1,279.5
Field hardware replacement	2,594.0	1,130.0	3,724.0
Regional infrastructure	220.0	110.0	330.0
Implementation R&D	500.0	250.0	750.0
User outreach	153.0	76.5	229.5
USGS Overhead (12%)	*587.6*	*263.6*	*851.2*
Total	5,484.4	2,460.1	7,944.5

Table 8. System-Wide Coordination Personnel and Infrastructure (in thousands of dollars)

	California/West Coast
Computer software architect	149.8
Implementation programmers	299.5
Quality assurance specialist	105.9
Product coordinator	149.8
Outreach coordinator	149.8
Central infrastructure	204.3
USGS Overhead (12%)	*127.1*
Total	1,186.2