

## The CREST Project: Consolidated reporting of earthquakes and tsunamis

David Oppenheimer<sup>1</sup>, Alex Bittenbinder<sup>2</sup>, Barbara Bogaert<sup>2</sup>, Raymond Buland<sup>2</sup>, Lynn Dietz<sup>1</sup>, Roger Hansen<sup>3</sup>, Steve Malone<sup>4</sup>, Charles S. McCreery<sup>5</sup>, Thomas J. Sokolowski<sup>6</sup>, and Craig Weaver<sup>7</sup>

<sup>1</sup>*U.S. Geological Survey, Menlo Park, California, U.S.A.*

<sup>2</sup>*U.S. Geological Survey, Golden, Colorado, U.S.A.*

<sup>3</sup>*Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, U.S.A.*

<sup>4</sup>*Geophysics Program, University of Washington, Seattle, Washington, U.S.A.*

<sup>5</sup>*Pacific Tsunami Warning Center, Ewa Beach, Hawaii, U.S.A.*

<sup>6</sup>*West Coast and Alaska Tsunami Warning Center, Palmer, Alaska, U.S.A.*

<sup>7</sup>*U.S. Geological Survey, Seattle, Washington, U.S.A.*

**Abstract.** In 1997 the U.S. Geological Survey, National Oceanographic and Atmospheric Administration, and the five western states joined in a partnership to enhance the quality and quantity of seismic data provided to the NOAA tsunami warning centers in Alaska and Hawaii. The project, named the Consolidated Reporting of Earthquakes and Tsunamis (CREST), now provides the warning centers with real-time seismic data over dedicated communication links and the Internet from regional seismic networks monitoring earthquakes in the five western states, the U.S. National Seismic Network in Colorado, and from domestic and global seismic stations operated by other agencies. The goal of the project is to reduce the time needed to issue a tsunami warning by providing the warning centers with high-dynamic range, broadband waveforms in near real-time. An additional goal is to reduce the likelihood of issuing false tsunami warnings by rapidly providing to the warning centers parametric information on earthquakes that could indicate their tsunamigenic potential, such as hypocenters, magnitudes, moment tensors, and shake distribution maps. At the end of the 5-year project new or upgraded field instrumentation will be installed at about 56 seismic stations in the five western states. Data from these instruments has been integrated into the CREST network utilizing Earthworm software. The CREST system has significantly reduced the time needed to respond to teleseismic earthquakes. Notably, the West Coast/Alaska Tsunami Warning Center responded to the 28 February 2001  $M_w$  6.8 Nisqually earthquake beneath Olympia, Washington within 2 min, compared to an average response time of over 10 min for the previous 18 years.

---

<sup>1</sup>U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, U.S.A. (oppen@usgs.gov, dietz@usgs.gov)

<sup>2</sup>U.S. Geological Survey, Box 25046, MS 967, Denver Federal Center, Denver, CO 80225, U.S.A. (alex@usgs.gov, bogaert@usgs.gov, buland@usgs.gov)

<sup>3</sup>University of Alaska Fairbanks, Geophysical Institute, P.O. Box 757320, 903 Koyukuk Drive, Fairbanks, AK 99775, U.S.A. (roger@giseis.alaska.edu)

<sup>4</sup>Geophysics Program, Box 351650, University of Washington, Seattle, WA 98195, U.S.A. (steve@geophys.washington.edu)

<sup>5</sup>Pacific Tsunami Warning Center, 91-270 Fort Weaver Road, Ewa Beach, HI 96706, U.S.A. (mccreery@ptwc.noaa.gov)

<sup>6</sup>West Coast and Alaska Tsunami Warning Center, 910 South Felton Street, Palmer, AK 99645, U.S.A. (wcatwc@wcatwc.gov)

<sup>7</sup>U.S. Geological Survey, Box 351650, University of Washington, Seattle, WA, 98195, U.S.A. (craig@usgs.gov)

## 1. Introduction

Before the widespread availability of high-speed computer networks, regional seismic networks in the nation operated as independent reporting entities. Seismic waveform data was, by necessity, telemetered to a single, regional center because of the high cost of long-distance communications. As a consequence, each center located earthquakes using only its own data. Although there were many seismic stations operating around the world, their data were not available to the tsunami warning centers in real time. Likewise, the tsunami warning centers operated their own, limited seismic network to serve their immediate needs, and, consequently, made critical public safety decisions based on a small subset of the available seismic data. In particular, it could take as long as 5 min for seismic waves from tsunamigenic earthquakes occurring in Cascadia (the coastal region of northern California to the Canadian border) to reach the stations operated by the West Coast/Alaska Tsunami Warning Center (WC/ATWC). Since the first tsunami waves could reach the shore in tens of minutes, the added time due to seismic wave propagation made it even more difficult for the WC/ATWC to issue a warning in time to alert communities at risk.

In 1997 NOAA implemented the Tsunami Hazard Mitigation Implementation Plan (1996) in cooperation with the USGS and the five western states of Hawaii, Alaska, Washington, Oregon, and California. One aspect of the mitigation plan focused on improving the amount and quality of seismic data telemetered to the WC/ATWC and Pacific Tsunami Warning Center (PTWC). The USGS was given the responsibility for upgrading seismic equipment and monitoring facilities of seismic networks operating in Cascadia, Alaska, and Hawaii. The upgrade was designed to decrease the time required to issue a tsunami warning for earthquakes occurring within these regional networks and to reduce the likelihood that false tsunami warnings would be issued.

## 2. What Was Promised

The Tsunami Hazard Mitigation Plan (1996) and preliminary seismic system design documents called for (a) new instrumentation for seismic networks monitoring earthquakes in tsunamigenic regions in the U.S., (b) improved telemetry to the warning centers in order to enable the warning centers to rapidly receive the improved seismic information, and (c) rapid distribution of earthquake information to state emergency services agencies. The plan called for upgraded instrumentation at approximately 36 seismic stations and the installation of 16 new stations in networks operated by the USGS in northern California and Hawaii and networks operated by universities in Oregon, Washington, and Alaska under support from the USGS. At all sites the plan called for the installation of digital data loggers, broadband sensors to record waveforms from large teleseisms, and accelerometers to record on-scale waveforms from large, local earthquakes. Some of the identified stations already utilized digital dataloggers and had broadband instrumentation, but

**Table 1:** 1997–2001 CREST budget.

<b>Fiscal Year</b>	<b>Requested</b>	<b>Available</b>	<b>In-kind contributions*</b>
1997	\$1,000,000	\$976,000	\$375,000
1998	1,000,000	780,800	375,000
1999	1,000,000	780,800	18,700,000
2000	1,000,000	705,360	18,700,000
2001	600,000	546,148	18,700,000
<b>Total</b>	<b>\$4,600,000</b>	<b>\$3,789,108</b>	<b>\$56,850,000</b>

\*See text for explanation.

lacked accelerometers. About 30 sites utilized obsolete analog technology with only short-period sensors.

The plan called for upgrading and replacing field telemetry links for regional seismic networks in northern California, and augmenting telemetry capacity in Oregon, Washington, Alaska, and Hawaii. Dedicated telemetry links from regional network processing centers to the PTWC and WC/ATWC were recommended to enable the warning centers to receive in real time the seismic data from the upgraded CREST stations as well as from global stations recorded by the USNSN. Software was to be installed at all of the regional seismic networks to facilitate acquisition of the new seismic data and to build an appropriate interface so that the warning centers could receive this information. The goal was to enable the warning centers to be able to respond within 2 min after a major earthquake in the coastal regions of the five western states and have complete information on the earthquake within 5 min. With such rapid information, it would be possible for the warnings to be issued in advance of the first arrival of a tsunami wave.

Early in the design of the project it was recognized that seismic data from other networks performing global and regional earthquake monitoring could also be integrated into this expanded seismic network for the tsunami warning centers. In particular, dedicated telemetry links from the U.S. National Seismic Network (USNSN) to the warning centers were proposed. Access to real-time data from global stations would enable the warning centers to respond more rapidly to teleseisms and reduce the likelihood of issuing false warnings.

This system of upgraded seismic stations from regional networks, global stations, and the software that links them to the tsunami warning centers in Alaska and Hawaii was named the Consolidated Reporting of Earthquakes and Tsunamis (CREST) system. The CREST project was to be implemented over a 4-year period, but due to lower funding levels the project was spread over a 5-year period (Table 1). Even though the total expenditures were less than the amount requested in the plan, funding for the CREST project was sufficient to upgrade and install all of the proposed hardware for the seismic field stations and to complete the system software integration at the conclusion of the fifth year of the project.

In-kind contributions by the USGS and USGS-supported networks are difficult to quantify. The annual salary contribution averaged over the 5-year period is approximately \$375K. Salary contributions were considerably higher in the first 2 years when software was being developed. Midway through the CREST project the warning centers were able to access all seismic data collected by the USGS. Whereas the cost of operating seismic networks is approximately 40% of the USGS earthquake program (\$46.7M) in FY2001, we show this as a cost share.

### 3. What Was Accomplished

#### 3.1 CREST Design

To understand how CREST was designed to assist the tsunami warning centers in their assessment of the tsunamigenic potential of an earthquake, it is useful to briefly review how the centers operate. Time is of the essence in issuing a tsunami warning for earthquakes occurring offshore of the five western states, because the time interval between the origin of the earthquake and the time the first tsunami wave reaches land can be as little as 15 min. Even though automated monitoring systems are now capable of computing seismological parameters about an earthquake within minutes, the warning center seismologists must review this information to prevent the issuing of a false warning. Their response begins in less than 5 min after notification of the occurrence of a strong quake and must be concluded in 15 min. Consequently, the decision to issue a warning presently depends on only two criteria—magnitude and location. Even if the main shock does not directly generate a tsunami through displacement of the seafloor, it is possible that secondary processes resulting from the quake could trigger submarine landslides or movement on secondary faults that could generate a tsunami. Consequently, if the earthquake magnitude (M) exceeds M 7 and locates offshore or near the coast, a warning is issued.

During this initial response there is little time to review other types of information such as depth, mechanism, and spectral content. Even if the warning center seismologists had access to this information during this time interval, the presentation of large volumes of information could conceivably slow down their response time and potentially confuse the analyst. Thus, the primary design goal of the CREST system was to provide the warning centers with more broadband, high dynamic range seismic waveform data so that they could improve their ability to locate the earthquake and determine its magnitude.

After the tsunami warning centers issue an initial warning, they use additional data to either support their decision to continue or cancel the warning. This process is crucial because the decision to evacuate coastal communities at risk is disruptive and has large economic impacts on society. While tide-gauges and ocean-bottom pressure-recorders provide the most important observations for this process, the CREST system can provide additional information that can support this decision process. Maps of peak amplitudes (acceleration, velocity, displacement) from stations in the epicen-

tral region can be computed within minutes to image the region of strongest shaking. These “ShakeMaps” (Wald *et al.*, 1999) provide an important complement to the hypocentral location because the main shock hypocenter only indicates the point of rupture nucleation. For large ( $M > 7$ ) earthquakes the fault length can extend 10’s to 100’s of km, and the hypocenter location does not reflect the geographical extent of the rupture, particularly if the nucleation point is at one end of the rupture zone.

Regional seismic networks now automatically determine hypocentral parameters for earthquakes as small as  $M$  1.5 within minutes, and locations of aftershocks occurring within the first hour can also begin to image the extent and depth of rupture as well as confirm the aerial extent portrayed by the ShakeMap. Earthquake spectra can reveal enhanced energy release at long periods and indicate the occurrence of “slow,” potentially tsunamigenic earthquakes. Seismic data can be used to infer whether the earthquake would be likely to generate seafloor displacement through the calculation of focal mechanisms. Regional networks are now routinely computing first-motion focal mechanisms in about 4 min and moment tensors from inversion of body and surface waves within 10 min. Lastly, regional networks provide independent and locally calibrated location and magnitude estimates (duration, local, moment) that the warning centers can use to confirm their determination of these parameters. The CREST system was designed so that the above parametric information from regional seismic networks can automatically be provided to the warning systems to assist them in determining the tsunamigenic potential of earthquakes.

### 3.2 Hardware Upgrade

Most of the instrumentation in use by regional seismic networks participating in the CREST system was installed in the 1970’s. A typical regional seismic station of this vintage consists of a single, vertical-component seismometer that continually transmits its data via analog telemetry to a central processing site. As a result of the limited dynamic range of the analog telemetry, the waveforms of most  $M > 2.0$  earthquakes are clipped. Consequently, most regional networks routinely compute coda-duration magnitude, but this magnitude becomes increasingly unreliable above  $M$  4.5. To increase the usefulness of regional network data to the warning centers, the data must have the extended frequency response and dynamic range to record the entire range of earthquake ground motion. To improve the dynamic range of the waveform data and ensure on-scale recording of all waveforms, we installed dataloggers that generate 24-bit digital data at all stations in the CREST system.

No sensor currently has the capability to record the range of ground motion from teleseisms and local earthquakes from  $M$  1.5 to greater than  $M$  8. Broadband sensors provide the bandwidth to record long-period energy in waveforms generated by large earthquakes, and this makes it possible to compute accurate magnitudes, determine moment tensor solutions, and detect “slow” earthquakes. However, their signal will clip in the near-field of local earthquakes as small as  $M$  4.5. Accelerometers will remain on-scale

**Table 2:** Distribution of CREST stations by state.

State	Stations
Hawaii	3
Alaska	21
Washington	11
Oregon	11
California	10
<b>Total</b>	<b>56</b>

during large, local earthquakes so that ShakeMaps can be generated, but they are too insensitive to record teleseismic waveforms.

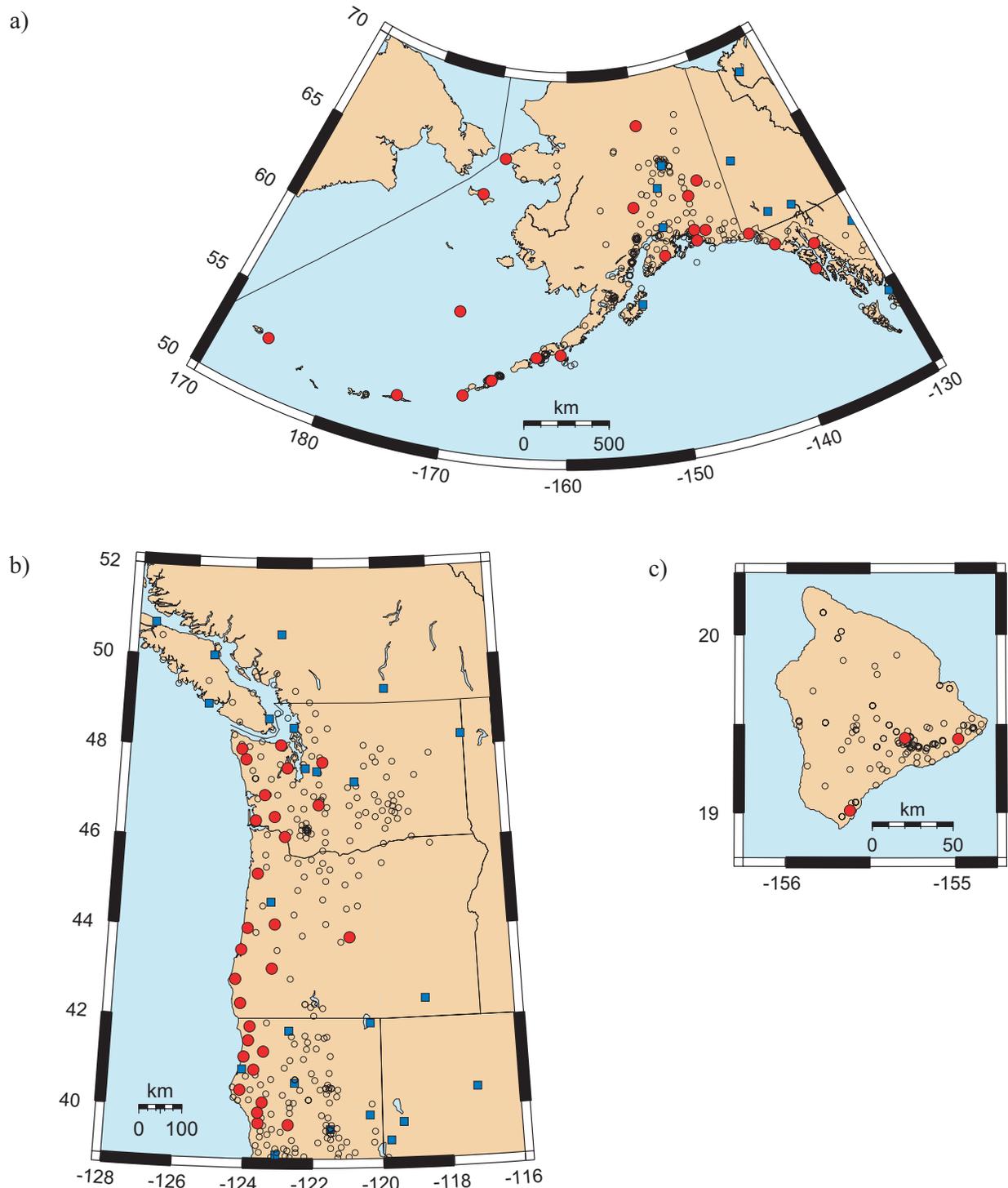
To meet the above requirements we installed tri-axial broadband sensors and accelerometers at 56 CREST sites using 24-bit digital dataloggers (Fig. 1). At about half the sites we simply upgraded analog equipment, and for the remaining stations we installed equipment at new locations because nearby sites with existing analog equipment were unsuitable. At the beginning of the project we performed evaluations of sensors and dataloggers and set minimum performance specifications. A variety of dataloggers met these specifications and each network was allowed to purchase equipment most compatible with the local requirements of the installation. Likewise, two different broadband sensors were purchased but the same accelerometer was installed at all locations.

The distribution of upgraded stations by state is provided in Table 2. The number of sites per state follows the general plan described in the Tsunami Hazard Mitigation Plan (1996), but includes four more stations than specified in that document.

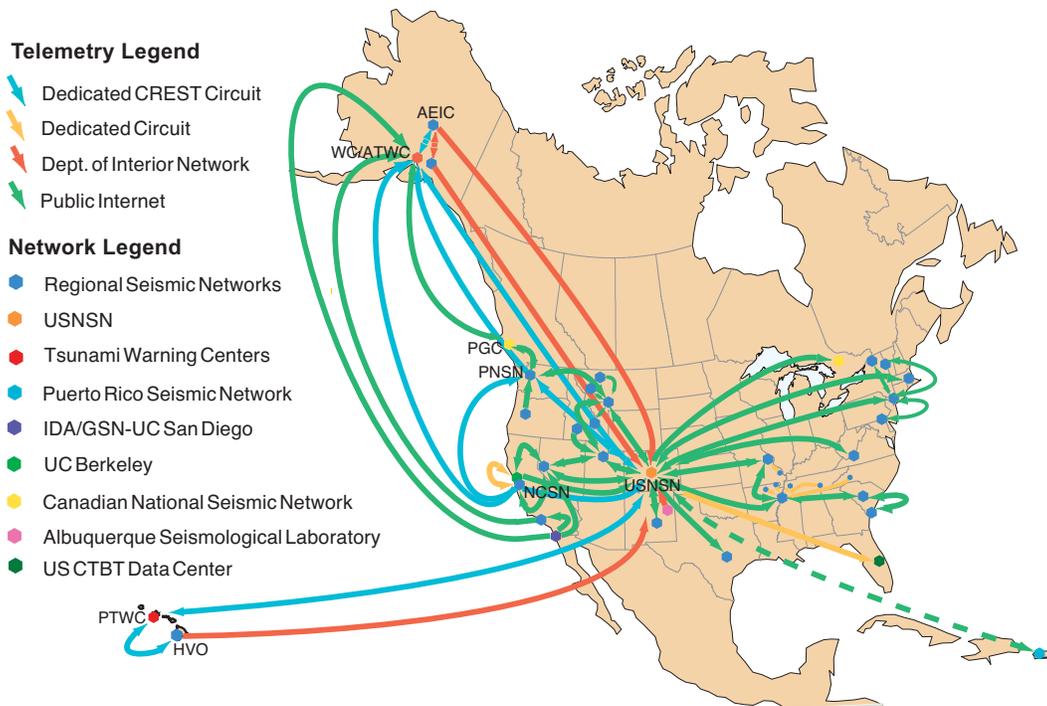
### 3.3 CREST/Warning Center Information Exchange

In 1993 the USGS began developing an earthquake reporting system for regional seismic networks called Earthworm (<http://www.cnss.org/EWAB/>). This system was initially designed to provide real-time earthquake reporting capability for regional networks. It later expanded to enable seismic processing centers to exchange continuous and event waveforms and parametric information such as arrival times, amplitudes, first-motions, hypocenters, and magnitudes. Complete Earthworm systems or systems that utilize a subset of its functionality are currently installed at most regional networks across the United States (Fig. 2).

At the lowest level, each seismic network (regional, global, tsunami warning center) records seismograms from its own stations. All networks can establish continuous waveform exchange with other networks via the Earthworm software. At each regional network the Earthworm software also continuously monitors incoming waveforms and declares an earthquake if the number of logically associated P-travel times exceeds some defined criteria. The system locates the quake, determines its magnitude as well as the related



**Figure 1:** Map of seismic stations in (a) Alaska, (b) Cascadia, and (c) Hawaii. Red circles indicate sites where new/upgraded CREST seismic instrumentation was installed. Open circles indicate locations of existing, short-period, analog stations. Blue squares indicate locations of existing digital, broadband stations, such as those operated by the USNSN, University of California Berkeley, University of Oregon, University of Nevada Reno, and the Pacific Geoscience Center in Vancouver. Two CREST sites in Washington and 2 sites in Oregon are not shown because their locations have not been finalized at time of publication.



**Figure 2:** Seismic network architecture linked via Earthworm software. Octagons indicate regional seismic networks that record seismic stations, and lines indicate continuous telemetry paths between networks. Dedicated CREST circuits connect the Pacific Northwest Seismic Network (PNSN), the Northern California Seismic Network (NCSN), and the U.S. National Seismic Network (USNSN) with the Pacific Tsunami Warning Center (PTWC) and the West Coast/Alaska Tsunami Warning Center (WC/ATWC). CREST circuits also link the Alaska Earthquake Information Center (AEIC) to the WC/ATWC, and the Hawaiian Volcano Observatory (HVO) to PTWC. CREST uses the Internet for additional bandwidth to PTWC and WC/ATWC, to connect the USNSN to other regional networks in the U.S. and to seismic stations around the world, and for exchanging continuous waveform data with the Pacific Geoscience Center (PGC). This network enables the warning centers to have access to data from any seismic stations in the U.S. and many stations around the world.

information described above, and makes this information available to all networks through established exchange protocols. Non-adjointing networks, such as the tsunami warning centers, can exchange hypocentral parameters so that at all times each network has access to authoritative information on all seismic activity anywhere in the CREST system. The Earthworm software also monitors loss of network communications, and notifications are immediately issued via e-mail and pagers.

At the initiation of the CREST project the software was not installed at the USGS Hawaii Volcano Observatory (HVO), USNSN, PTWC, or WC/ATWC. At these networks the CREST project installed new computers, new multi-channel digitizers to make local, analog data accessible to the Earthworm system, and configured the systems in cooperation with local network operators. Later in the project the Geological Survey of Canada Pacific GeoScience Centre in British Columbia installed Earthworm software so that they could participate in the CREST project. CREST also developed

a software interface to the IRIS/GSN system so that continuous data from these global stations could be sent to the tsunami warning centers.

### 3.4 CREST Communications and Redundancy

After several decades of monitoring, seismic networks have learned some painful lessons about telecommunications. Experience has shown that no form of communications is fail-safe. Power failures have brought down commercial telephone exchanges during large quakes. A satellite failure brought down large portions of the USNSN for weeks until VSATs were re-pointed. Telephone companies occasionally and unexpectedly take down Frame Relay networks for system upgrades. Operators of seismic networks learn from these situations and re-design their systems if possible. Despite this progress, no one knows if a regional seismic network will continue to function when a great earthquake occurs in its region. In the event of a total loss of regional earthquake data, the real-time data-exchange scheme described above will ensure that some information is available on the earthquake. However, it does not compensate for the loss of critical seismic information in the epicentral area.

Because the cost and complexity of telemetry generally increase with distance, data from most seismic stations is telemetered to the closest regional network center. However, this situation is vulnerable to single points of failure if earthquake shaking disables a regional center or severs a critical communications link. To ensure that the CREST system maintains the ability to report reliable information from the epicentral region, a small subset of stations in each network independently transmits seismic information to the USNSN via a satellite.

We designed a second level of redundancy into the network-to-network connectivity of the CREST system. While the Internet offers essentially free telemetry between the regional network centers and the tsunami warning centers, it is not a reliable communication medium for applications with real-time reporting responsibilities because the bandwidth is not guaranteed and switches and routers may not operate during power outages. Accordingly, much of the data exchange between CREST participants is transmitted via dedicated, redundant commercial communication circuits (Fig. 2). The utilization of satellite, dedicated point-to-point circuits, and Internet for telemetry to the tsunami warning centers provides some assurance against a single point of failure.

## 4. What Was the Impact

The CREST system now provides the tsunami warning centers with real-time, high-dynamic range, broadband seismic data from regions of the western United States, Alaska, and Hawaii where tsunamigenic earthquakes can occur, as well as from seismic stations around the world. This data decreases the time it takes to issue a tsunami alert by tens of minutes for earthquakes occurring outside the United States. For earthquakes that occur within the CREST networks, the warning time can be issued within a few minutes of

the origin time. As a result of this project, the tsunami warning centers are able to issue more reliable and timely warnings to the public, decrease the likelihood of issuing false warnings, and decrease the likelihood of loss of life from tsunamis.

For example, before CREST the PTWC only recorded nine short-period stations digitized at 20 samples/sec (sps) and five long-period stations at 1 sps from outside of Hawaii using 12-bit resolution. Now they obtain 20 and 40 sps data from about 80 broadband stations with 22-bit resolution. The time required to locate the earthquake is still governed by the time it takes for the P-waves to reach the most distant station in the network. Formerly, it would take 8–16 min depending on the location of the earthquake, but now the time has been shortened to 1–12 min. These added stations enable the warning centers to issue an alarm to the duty seismologists much sooner. More significant is that the time required to compute a surface wave magnitude ( $M_s$ ) on three stations has been greatly reduced. Whereas it formerly ranged from 5–55 min, it now takes a maximum of 20 min. In addition, with higher dynamic range broadband data it is now possible for the warning centers to compute rapid estimates of the moment magnitude ( $M_w$ ) from the initial P-wave instead of waiting for slower propagating surface waves.

There have been few opportunities to evaluate the response of the system for potentially tsunamigenic earthquakes in the U.S. until the 28 February 2001  $M_w$  6.8 Nisqually earthquake beneath Olympia, Washington. The average response time of the WC/ATWC to issue a warning for the period 1982–2000 is 10.6 min (<http://wcatwc.gov/wcatwc.htm>). Because of CREST stations installed in the Pacific Northwest Seismic Network (PNSN), the WC/ATWC had access to waveform data in the epicentral area and was able to locate the earthquake within 2 min after the origin time, whereas the PNSN released their preliminary location 5.5 min after the origin time. The initial WC/ATWC magnitude for the quake was 6.4 based on their observations of the initial body waves, and they issued a statement that the earthquake was not tsunamigenic based on both the location and magnitude of the earthquake. The final magnitude for the earthquake reported by the USGS National Earthquake Information Center was  $M_w$  6.8 based on inversion of long-period body waves observed on data recorded globally, but this magnitude was not available for 1 hour 39 min after the earthquake. At the time of the earthquake, the ShakeMap software was not yet automated. However, about 6 hours later a ShakeMap was available for the epicentral region. The WC/ATWC information about the Nisqually earthquake was automatically transmitted to Grays Harbor County, Washington via the EMWIN (<http://iwin.nws.noaa.gov/emwin/index.htm>) system. Within a few minutes this information was conveyed to other emergency staff and residents of coastal communities were advised that there was no need to evacuate.

As a result of the efforts to link together all the various seismic networks of the CREST system, the Earthworm software has become a standard for linking up all of the seismic networks in the U.S. (Fig. 2). This framework now enables the tsunami warning centers to take advantage of improvements in seismic monitoring capability nationwide as well as globally, even though

**Table 3:** Projected CREST budget (\$000).

Item	Cost	
<b>Annual Operational Costs</b>		
Seismic station telemetry	110	
Dedicated CREST-Warning Center circuits	150	
Non-USGS salary support	150	
Equipment replacement	100	
Institutional overhead	90	
	<b>Subtotal</b>	600
<b>Improvements</b>		
256 Kbps circuits upgrade (recurring)	150	
Redundant CREST-Warning Center Satellite link (one-time)	200	
Seismic station satellite telemetry system	820	
Commercial network support (recurring)	50	
	<b>Subtotal</b>	1220

such improvements may be undertaken by other monitoring agencies. For example, new seismic equipment is being installed by the USGS as part of the Advanced National Seismic System (1999), and the warning centers will have immediate access to this information via the CREST system. Data from seismic stations installed around the world by the other nations are now routinely exchanged in real time via the Internet, and the warning centers now have access to these data via the CREST system. As seismological institutions develop new algorithms such as ShakeMap (Wald, 1999), they are incorporated into periodic releases of Earthworm software. Since the warning centers utilize Earthworm software, they immediately have access to state-of-the-art methods for computing information about earthquakes.

## 5. The Future: Next 5 Years

The biggest challenge is sustained funding to operate the system. Seismic station-to-center telemetry, dedicated CREST center-to-center circuits, and site visits for field maintenance account for most of the operational expenses. Seismic instrumentation manufacturers generally do not support their equipment for more than 10 years, and a plan for continual upgrade and replacement is necessary. Improvements in real-time seismic computations will demand improvements in computer systems at all centers so that information can continue to be exchanged and common systems can be supported. Current estimates for operations and maintenance are provided in Table 3.

Because of the remote locations of the Pacific and Alaska/West Tsunami Warning Centers, bandwidth limitations and single-point-of-failure remain a challenge to reliable operation of the system. The bandwidth of the dedicated CREST circuits from Colorado to Hawaii and Alaska is completely

utilized. Consequently, the warning centers use the Internet to supplement the capacity of these dedicated circuits. However, the bandwidth of the Internet to the centers is also limited, and its reliability during large earthquakes is a concern. We recommend that the capacity of the dedicated CREST circuits be doubled to 256 Kbps. The increased bandwidth would enable the centers to have access to seismic data in Cascadia, Alaska, and Hawaii. The additional cost of these expanded circuits to Alaska and Hawaii is approximately \$75K/year each.

The current system relies on the Internet and dedicated lines to provide redundancy. However, both of these channels often share the same physical equipment and facilities, usually in the most remote and at-risk areas. Thus, the current system does not offer real redundant communications channels. We recommend the implementation of limited waveform data exchange and full parametric data exchange via satellite. Satellite telemetry ensures that the warning centers have access to critical data (e.g., location, magnitude, ShakeMap, event seismograms) should terrestrial communication links be interrupted by a large earthquake. A modest system would consist of six VSATs and a central hub and would cost approximately \$200K.

A satellite system will also substantially reduce dedicated telemetry costs from seismic stations installed in remote regions such as the Aleutians. Whereas dedicated terrestrial circuits from seismic stations in the Aleutians can cost more than \$30K/year, the cost via satellite is about \$500/year. Satellite telemetry systems cost approximately \$120K for the central receiving site dish and transceiver systems. Data loggers with integrated satellite terminals cost about \$35K (installed), and there are approximately 20 remote CREST stations that could be converted to satellite communications.

Finally, the USGS does not have the staff to support  $24 \times 7$  operations of CREST. The expertise to troubleshoot network problems, computer failures, and software bugs lies with a few key individuals. The USGS has tried to support the warning centers to the extent possible, but the duration of outages has been, on occasion, unacceptable for life-safety standards. Service contracts to respond to network outages should be implemented. The cost of commercial contracts would likely be \$50K per year.

## 6. Conclusion

The CREST project has achieved the goals set forth in the Tsunami Hazard Mitigation Implementation Plan. The new seismic instrumentation deployed in the five western states has greatly improved the ability of the NOAA tsunami warning centers to respond to earthquakes in these regions, but the project has had an even greater impact than anticipated. The tsunami warning centers now have real-time access to seismic data collected around the world at no additional cost. Consequently, they are able to respond more rapidly to teleseismic earthquakes, compute more reliable locations and magnitudes, and be less likely to issue an erroneous tsunami warning.

The tsunami warning centers are now able to rapidly take advantage of seismological developments implemented by other seismic networks because

they are using the Earthworm system. On the other hand, the CREST project has served as a model for the rest of the regional seismic network community, and most of the networks supported by the USGS now utilize the Earthworm system to exchange seismic data. The synergism of all seismic networks and agencies participating in the CREST project has advanced public safety by improving the capabilities of the tsunami warning centers and by improving the quality of information reported by regional seismic networks across the nation.

**Acknowledgments.** The success of the CREST project was made possible by significant contributions from the following individuals: Tom Burdette, Jim Ramey, Pat Ryan, Dave Reneau, Dave Croker, Don Farrell, and Dan McNamara installed seismic stations. Pat Murphy, Rick Jensen, Charlene Fischer, Barbara Stocker, and Carol Lawson configured and installed the dedicated circuits for the CREST project. Gray Jensen, Gary Holcomb, Robert Uhrhammer performed instrument evaluations. Paul Okubo provided field support on the Big Island of Hawaii. Paul Whitmore, Alec Medbery, Guy Urban, Dave Ketchum, Kent Lindquist, and Stuart Weinstein provided software support for CREST. David Chavez wrote the software interface from the IDA/GSN network. We thank the staffs of the California Institute of Technology, University of California Berkeley, and the Global Seismic Network for providing a real-time link to their seismic data. We also thank Jim Luetgert, Tom Yellin, and Eddie Bernard for providing valuable technical reviews of this article.

## 7. References

- Tsunami Hazard Mitigation Federal/State Working Group (1996): Tsunami Hazard Mitigation Implementation Plan—A Report to the Senate Appropriations Committee, 22 pp., Appendices.
- U.S. Geological Survey, Requirements for an Advanced National Seismic System (1999): U.S. Geological Survey Circular 1188, 59 pp.
- Wald, D.J., V. Quitoriano, T.H. Heaton, H. Kanamori, C.W. Scrivner, and C.B. Worden (1999): TriNet “ShakeMaps”: Rapid generation of instrumental ground motion and intensity maps for earthquakes in southern California. *Earthquake Spectra*, 15(3), 537–556.