Consolidated Reporting of EarthquakeS and Tsunamis
An Interim Plan to NOAA

Introduction

In December of 1996 NOAA initiated work on the Tsunami Hazard Mitigation Implementation Plan in cooperation with the USGS and FEMA. The USGS is responsible for upgrading seismic equipment and monitoring facilities of seismic networks operating in Cascadia, Alaska, and Hawaii where tsunamigenic earthquakes could occur. The purpose of the upgrade is to enable these networks to provide rapid, reliable, and relevant seismic data to the Alaska and Pacific Tsunami Warning Centers to improve NOAA's ability to assess the likelihood of a tsunami.

The USGS either directly operates these networks or contracts with universities to operate networks. Data from these regional networks will be used to augment broadband data already provided to the Warning Centers by the US National Seismic Network (USNSN), also operated by the USGS. We herein refer to this group of USGS-sponsored seismic networks monitoring regional and global seismicity as the Consolidated Reporting of EarthquakeS and Tsunamis (CREST) system. In a later phase of this project we plan expanding the CREST system to include seismic information from a network operated by the Pacific Geoscience Center in British Columbia. In this initial plan we outline how the USGS intends to upgrade the relevant regional networks and how the CREST system will rapidly provide data from both the regional and USNSN networks to the Warning Centers.

Tsunami Alert Chronology And The Role Of CREST

To understand how CREST can assist the Warning Centers in their assessment of the tsunamigenic potential of an earthquake, it is useful to briefly review how the Warning Centers function. Time is of the essence in issuing a tsunami warning for earthquakes occurring near the coast of the US, because the time interval the tsunami wave can reach land within 15 minutes. Even though automated monitoring systems are now capable of providing hypocentral and magnitude estimates within minutes, the Warning Center staff must review this information to prevent the issuing of a false warning.

There is only a short time interval for the Warning Center staff decide whether to issue a warning. The response begins in less than 5 minutes and must be concluded in 15 minutes. Consequently, the decision to issue a warning presently depends on only two criteria -- magnitude and location. Even if the mainshock is non-tsunamigenic, it is quite possible that secondary processes resulting from a quake could trigger submarine landslides or movement on secondary faults that could also generate a tsunami. Consequently, if the earthquake magnitude exceeds about M 7 and locates offshore or near the coast, a warning is issued. During this initial time interval there is little time to review other types of information such as depth, mechanism, and spectral content. Even if the Warning Center staff 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 most useful information that CREST can provide the Warning Centers during the first few minutes is more broadband seismic waveform data for improving their ability to locate the earthquake and determine its magnitude.

After the Warning Centers issue the initial warning, they use additional data to either support their decision to continue the warning (and refine the extent of the warning area) or to cancel the warning. This process is critical in that it drives local evacuation decisions. While tide-gauges provide the most important observations for this process, regional networks participating in the CREST system could provide unique seismic information to support this decision process during this critical period.

Regional seismic networks can supply a variety of data to assist in this process. Networks now automatically determine hypocentral parameters for earthquakes as small as magnitude (M) 1.5 within minutes. Whereas the main shock hypocenter only indicates the point of rupture nucleation, the extent and depth of rupture can be rapidly determined using aftershocks locations. Maps of peak amplitudes (acceleration, velocity, displacement) from nearby stations similarly image the region of strongest shaking within minutes. Spectra from near-field accelerometers can reveal energy release at periods greater than 50 seconds and thus indicate the occurrence of slow, tsunamigenic earthquakes. The type of fault motion can be inferred from regional network focal mechanisms. Regional networks are now routinely computing first-motion mechanisms in about 3 minutes and moment tensors from inversion of body and surface waves within 10 minutes. Similarly, regional networks provide independent and locally calibrated magnitude estimates (duration, local, moment). All of this information is critical for properly assessing the tsunamigenic potential of earthquakes during this review period.

Hardware Upgrade

Most of the instrumentation in use by regional seismic networks of the CREST system were installed in the 1970's. Most networks operate only stations with a single-component vertical seismometer and continually transmit this 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, networks routinely compute coda-duration magnitude, which becomes increasingly unreliable as earthquake magnitudes exceed *M* 5.0. 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, we will purchase dataloggers that generate 24- bit digital data at each field unit to ensure on-scale recording of all waveforms.

No sensor currently has the capability or sensitivity to record the range of ground motion from teleseisms and local earthquakes with magnitudes ranging from *M* 1.5 to greater than *M* 8. Hence, we plan to install two types of sensors at each site. To provide static displacements and maps showing the distribution of shaking for large quakes, we plan to install strong-motion sensors. We also plan to install broadband sensors to provide information on regional and teleseismic earthquakes to the Warning Centers. Data from such sensors are invaluable for computing moment tensors of regional earthquakes and detection of slow earthquakes with spectra that are relatively enriched at periods > 20 sec and which could be tsunamigenic.

CREST/Warning Center Information Exchange

Before the widespread availability of high-speed computer networks, regional seismic networks operated as independent reporting entities. Seismic data was, by necessity, telemetered only to a single regional center, and the center processed only its own data. Consequently, it was common for several regional networks to report different information on earthquakes occurring between networks. If the event was sufficiently large (*M*>4.5) to be observed globally, the NEIC would also issue a report. At the same time, the Warning Centers would respond to these same events using data recorded by, perhaps, yet another set of seismic stations. Warning Centers were thus forced to make critical public safety decisions based on a subset of the available data, and potentially conflicting ancillary reports.

Recently, the USGS has developed a new earthquake reporting system for regional seismic networks called Earthworm. This system has been designed to upgrade the real-time reporting capability of individual seismic networks, and to take advantage of high-speed long-distance digital links by permitting automatic exchange of waveforms and parametric information such as arrival times, amplitudes, first-motions, hypocenters, and magnitudes between seismic processing centers. Complete Earthworm systems or systems that utilize a subset of its functionality are currently installed at 11 regional networks as part of a program to create a National Seismic System. Some of the networks participating in the CREST system already have the capability to automatically exchange information about earthquake activity. The next step is to install compatible Earthworm systems at all of the CREST centers, including the Warning Centers. We will provide appropriate interfaces from the CREST system to the Warning Center systems so that they will have immediate access to all of the available seismic information in a useable format.

Figure 1 illustrates how this interconnected, hierarchical network will function. At the lowest level, each seismic network (regional, global, Warning Center) receives its information from its own continuously telemetered seismic stations. Real-time systems continuously monitor digital signals and declare an earthquake if the number of logically associated P-times exceeds some defined criteria. Regional networks immediately exchange travel-times and magnitude information. This exchange reduces the likelihood that bordering network will report differing hypocenters, since they are now able to associate travel times from the adjoining networks in which the earthquake was recorded. Non-adjoining networks exchange hypocentral parameters (location, magnitude, focal mechanism, amplitudes), so that at all times each network has authoritative information on all seismic activity anywhere in the CREST system. All CREST participants have the capability to issue waveform requests of any network in the CREST system.

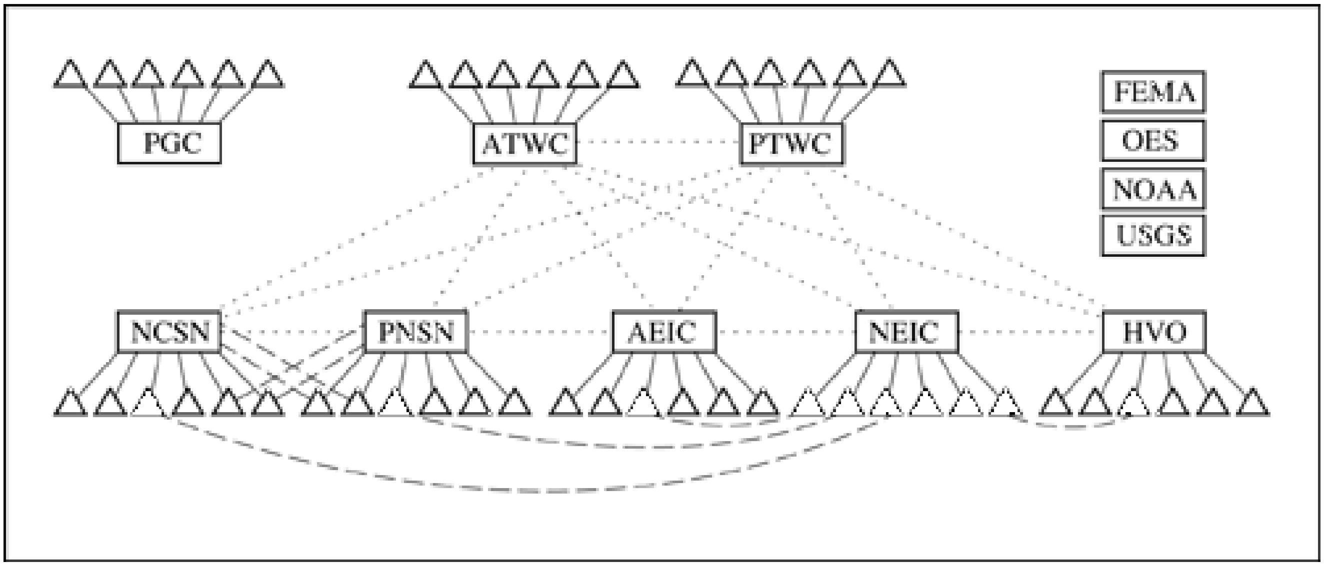

Figure 1. Schematic of CREST communications network. Triangles depict seismic stations. Boxes depict either seismic network centers, tsunami warning centers, or clients with critical needs. Solid lines depict dedicated telemetry paths from seismic station to seismic or warning centers (via telephone, radio, microwave, satellite). Dashed lines indicate split telemetry paths from seismic station to multiple seismic centers. Dotted lines represent redundant computer links (leased line, DOI-intranet, Internet, satellite) between seismic centers and warning centers for transferring waveform and parametric data. Solid triangles indicate regional network seismic stations also telemetered directly to NEIC via satellite. Pacific Geoscience Center network (upper left) and clients with need for authoritative information (upper right) could also connect to CREST network.

Networks with global monitoring capability (*e.g.*, ATWC, PTWC, NEIC) would also participate in the information exchange. The CREST system permits a logical method of determining the optimal authoritative solution over time. Thus, if a regional network accurately locates the earthquake, its earthquake information will take precedence over information from global networks, since the former information is more reliable. Conversely, the CREST system deems earthquake information from global networks to be authoritative if no regional information exists. The CREST system would use a hierarchy of reliability even for information reported only by global networks. Information from networks with more stations (*i.e.*, NEIC) could take precedence over information from sparse networks (*i.e.*, PTWC). Not only would this reliability hierarchy be a function of spatial location, but it would also be a function of time. Since the Warning Centers are frequently first to report on large earthquakes worldwide, their information would be authoritative until superseded by information from NEIC. This scheme ensures that all participants in the CREST system have access to the most reliable information. Even if a major quake totally disrupts the ability of the most authoritative regional network to communicate with the CREST system, there would be information available to participants.

The Earthworm connectivity has been designed keeping in mind that large earthquakes may cause significant disruptions. Failures of communication links and of the member processing systems are immediately detected. Notifications are issued via e-mail and pagers, and processing continues with the remaining facilities.

Emergency response officials will be able to respond most effectively if they have the most authoritative information at their disposal. Those clients with a critical need for seismic and tsunami information, such as state offices of emergency services (OES) and federal agencies (FEMA, USGS, NOAA), could link their reporting systems to CREST to obtain authoritative seismic information as rapidly as it is available. The PTWC and ATWC could also provide tsunami warnings and related information, such as predicted tsunami isochrons, to emergency officials through CREST. We will develop suitable interfaces to CREST/Warning Center information only after consultation with these clients.

CREST/Warning Center Software Link-up

Initially we will mainly devote our efforts to providing interfaces between CREST and the two Warning Center systems. It is important that any introduction of CREST information not disrupt any Warning Center operations. Using the experience gained from this initial link-up, we could work toward a more seamless integration with existing Warning Center systems. The CREST programming staff has expertise in communications, network protocol, DBMS, and graphics interfaces. In addition, there is experience in writing applications that operate under DOS, OS/2, Solaris, and VMS operating systems. Because platform-independence is a design requirement of the Earthworm system, the Earthworm staff could also assist in combining existing software running on divergent operating systems. This effort would require an active collaboration between the Warning Centers and Earthworm technical staffs.

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 bring down commercial telephone exchanges during large quakes (Loma Prieta and Northridge). Rats chewing through power cables bring down critical Internet hubs for days (Stanford). Satellite failures bring down large portions the USNSN for weeks until VSATs can be re-pointed. Telephone companies occasionally and unexpectedly take down Frame Relay networks for system upgrades (Pacific Telephone). 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 will independently transmit seismic information to the USNSN via a satellite (Figure 1). In addition, regional networks with common borders will jointly record stations where feasible.

We will design a second level of redundancy into the network-to-network connectivity of the CREST system. Experience indicates that the Internet is not a reliable communication medium for applications with real-time reporting responsibilities. Thus, much of the data exchange between CREST members will likely take place on dedicated, redundant commercial communication circuits, satellite, or DOI intranet. Intelligent routers, such as those used between the Northern California Seismic Network and the University of California Berkeley Digital Seismic Network, will be configured to automatically reroute traffic in case of failures.

We also plan to develop software that will assure graceful degradation of CREST during seismic crises and system failures. This subsystem will continuously sense the available bandwidth of the communication circuits and the seismic situation known within CREST. It will then use various algorithms to prioritize the exchange of various types of seismic data within CREST and between CREST and the Warning Centers. The objective is to assure that the information transmitted to Warning Centers during periods of degraded operations arrives in an order consistent with their needs given the nature and timing of a seismic event.

Implementation Plan

We prepared the following task list using the best information available to us at the time of plan submission. We present only detailed task lists for Year 1 of the project. Detailed plans for subsequent years will be developed during Year 1. In Year 1 we plan upgrading only a portion of the total network in each region, except Hawaii where all proposed upgrades will be completed. Similarly, we plan to develop software prototypes in Year 1 to demonstrate feasibility.

During Year 1 we will resolve several technical issues; consequently significant changes to the implementation schedule are likely. We are testing the long-period (>50 sec) response of accelerometers in the presence of high amplitude, short-period signal for several models of accelerometers. Similarly, we are testing a relatively new broadband sensor that offers significant cost savings at the expense of a slightly higher noise floor. If these sensors prove inadequate to the task, the cost per site may rise significantly. We are also testing dataloggers to ensure that they have the necessary communications options and can operate satisfactorily in the temperature ranges found in Alaska and Hawaii.

We are assessing the relative cost benefits of different options for communications between the regional centers and the Warning Centers. Dedicated, leased communication lines do not require any in-house maintenance effort, but have significant long-term operating costs that may be difficult to fund in outyears. The recent availability of the DOI intranet may be another option, but we need to evaluate the amount of available bandwidth. In the first phase of the project we plan to utilize only Internet or DOI intranet for communications (waveform and parametric exchange) between the Warning Centers and the regional centers. In the second phase of the project we plan to implement redundant communication links between computers, as described above.

We are also assessing the optimal method for transmitting digital data from field sites to the seismic regional centers. Each region has specific telemetry requirements and options. For example, sites installed along the Aleutian chain have access to commercial telephone communications. In contrast, those in Cascadia are usually installed in remote locations and utilize radio communication to reach microwave systems. We need to ascertain whether there is sufficient capacity on the existing microwave systems, whether we can link the microwave systems used by the PNSN and NCSN, and whether the significant costs for upgrading the capacity of the microwave system justify the long-term savings when compared to the costs of dedicated leased- lines. The advent of low-earth-orbit satellites in the next few years may also prove to be a suitable alternative to the microwave system if sustained operational costs are reasonable.

Task list - Year 1

- Detailed system design, including test design, failure modes analysis, task list, milestone, schedule and budget.
- Sensors and data loggers:
  Testing
  Procurement for 18 sites (AEIC/ATWC-7; HVO-3, PNSN-4; NCSN-4).
- Site selection.
- Site preparation (concrete pads, power, huts, communications)
- Installation (if equipment delivered in Year 1).
- Investigation and selection of telemetry options for:
  Alaska
  Hawaii
  Cascadia
- Develop digital telemetry interface module for Earthworm system.
- Communication link between Warning Center and regional center (RC)
  Prototype system using Internet link
  Investigation and selection of alternative communication channels (DOI, satellite, dedicated lease-line)
- Computer systems at Warning Center to interface between com-link and local systems
- Site visits to clients with "need-to-know"
- Select seismic processing algorithms and develop prototype code

---

David Oppenheimer
U.S. Geological Survery, 345 Middlefield Road, MS 977, Menlo Park, CA 94025

Contact: oppen@alum.wr.usgs.gov
Last modification: 3 March, 1997