The U.S. West Coast and Alaska Tsunami Warning Center

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The U.S. West Coast/Alaska Tsunami Warning Center (WC/ATWC) was established in Palmer, Alaska in 1967 as a direct result of the great Alaskan earthquake that occurred in Prince William Sound on 27 March 1964. This earthquake alerted State and Federal officials to the need for a facility to provide timely and effective tsunami warnings and information for the coastal areas of Alaska. In 1982 the WC/ATWC's area of responsibility (AOR) was enlarged to include the issuing of tsunami warnings to California, Oregon, Washington, and British Columbia, for potential tsunamigenic earthquakes occurring in their coastal areas. In 1996 the responsibility was again expanded to include all Pacific-wide tsunamigenic sources which could affect the California, Oregon, Washington, British Columbia, and Alaska coasts.

The staff at the WC/ATWC consists of four geophysicists and two electronics technicians. The center is manned during normal weekday work hours. After normal work hours and on weekends and holidays, two duty personnel are on paid standby duty and must respond to the center within 5 min of an alarm. Alarms are activated by two different methods. The first method is triggering by sustained oscillatory motion at individual seismometers. All seismometers recorded by the WC/ATWC within the AOR are alarmed. Alarms are also activated by a real-time seismic processing system when an earthquake exceeds a predetermined magnitude threshold for various regions throughout the Pacific basin.

To issue immediate tsunami warnings at any time during the day or night, it is vital that all electronic equipment, systems, and computers function as expected. The WC/ATWC's electronic staff is responsible for maintaining, monitoring, integrating, and enhancing complex electronic equipment at the remote sites and at the center. The WC/ATWC operates and maintains 14 remote sites in Alaska in addition to the local site at Palmer. Each of these remote systems contains subsystems and other electronic components that are monitored frequently to ensure continuous transmission of quality data. These sites are visited once a year, and as soon as possible after an equipment malfunction. At the WC/ATWC's operations center, there are numerous pieces of electronic equipment, such as communication systems, satellite dishes, microcomputer systems, uninterruptible backup power systems, recording and archiving systems, alarm systems, seismometers, data acquisition systems, calibrators, data telemetry radios, and numerous display monitors.

The 15 sites operated by WC/ATWC consist of 15 short-period, five long-period, and three broadband seismometers. As a result of the NOAA

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Tsunami Hazard Mitigation effort, the flow of real-time seismic data to the WC/ATWC has been significantly increased with the implementation of the Earthworm system (Johnson *et al.*, 1995). This front-end system provides the WC/ATWC the ability to receive or transmit digital seismic data with others who have an Earthworm system. Integrating this front-end with the WC/ATWC processing system permits over 100 channels of seismic data to be recorded and processed at the WC/ATWC. The WC/ATWC exchanges real-time seismic data with the National Earthquake Information Center (NEIC), University of Alaska, Alaska Volcano Observatory, Pacific Tsunami Warning Center, USGS Menlo Park observatory, University of Washington, University of California-Berkeley, Incorporated Research Institutions for Seismology, and the Pacific Geosciences Center in Canada. Data from these other networks are available to the center in real time over dedicated circuits and/or the internet.

The real-time seismic processing system at the WC/ATWC has been developed and enhanced over the last 20 years (Sokolowski *et al.*, 1983; Zitek *et al.*, 1990). Real-time analog and digital data are immediately processed by a P-picking algorithm (Veith, 1978) which determines the onset of a P wave from an earthquake's ground motion. This algorithm works well on short-period or filtered broadband data for both local and teleseismic earthquakes. A location algorithm uses the P-picks to determine parameters for local, regional, and teleseismic earthquakes. As more data are received and processed, automatic solutions continue until a predetermined amount of time has passed with no additional P-picks. The automatically determined earthquake parameters are immediately sent to duty personnel over a radio alarm system. The initial magnitude estimate is based on an Mb, Ml, or Mwp (Tsuboi *et al.*, 1995) depending on the earthquake's size and location. Surface wave magnitude processing is triggered by the automatic locations. Ms magnitudes are automatically computed cycle-by-cycle as Rayleigh waves arrive at the long-period and broadband stations.

The present seismic processing system uses Pentium III PCs with the Windows 2000 operating system. Two identical PC systems are active for redundancy, and for the added ability to process multiple aftershocks that are common with tsunamigenic earthquakes. A third system, another backup, is also operational to locate an earthquake's parameters, using just the WC/ATWC's analog network, and to generate critical messages. A fourth backup is also available for interactive locations and message generation. The seismic processing PCs use a four-monitor card which displays information on four separate monitors. The displays permit a geophysicist to view the real-time data, automatic P-picks, continuous long- and short-period waveform data, and an earthquake's data and solution parameters. They also permit a geophysicist to rapidly change P-picks and recompute the quake parameters. Helpful aids are also displayed during the issuance of a tsunami warning, such as: warning procedures, Rayleigh wave arrival times at various locations, and time elapsed from the origin time. Options are available for transferring data between monitors and for message generation. All seismic data are archived on disk for specified periods of time for later review and/or reprocessing.

All real-time processing PCs are networked together using the Windows 2000 peer-to-peer LAN. In addition to the systems described above, two other PCs with four monitors each are dedicated to the geographical information system (GIS) software developed at the WC/ATWC. Once an earthquake's parameters are determined, the GIS displays its location on a global and a smaller local map. The global map supports overlays of historical seismicity, tsunamis, plate boundaries, major cities, seismometers, tide gages, recent earthquakes, modeling results, and tsunami travel time contours. The localized map also supports many overlays, such as cities, earthquakes ranked by magnitude and depth, roads, topography, pipelines, power lines, tide gages, seismometers, airports, railroads, place names, and tsunamis. Detailed information on historical earthquake and tsunami data bases (Lander *et al.*, 1989; Soloviev *et al.*, 1984) can be retrieved and viewed by a mouse click.

Tsunami warnings, issued by the WC/ATWC, are of two types: regional warnings for tsunamis produced in or near the AOR and warnings for tsunamis generated outside the AOR. Regional warnings are issued within 15 min of earthquake origin time and are based solely on seismic data. Warnings are issued for any coastal earthquake in the WC/ATWC's AOR over magnitude 7. Warnings outside the WC/ATWC's AOR are issued after coordination with the Pacific Tsunami Warning Center in Ewa Beach, Hawaii. These warnings are based on seismic data, along with historical tsunami records and recorded tsunami amplitudes from tide gages. Since 1981, 10 regional tsunami warnings have been issued by the WC/ATWC. The response times to issue a warning from the origin time of an earthquake has ranged from 8–14 minutes with an average response of 10.6 minutes. Of these warnings, only two out of the ten occurred during the work day. All others occurred after normal work hours when the personnel were in standby duty status.

Tsunami warning messages are computer generated by interactively selecting from a menu of possible messages. Messages are composed automatically based on earthquake location, magnitude, and origin time. Appropriate earthquake parameters are automatically included in the messages, along with the tsunami ETAs for 24 coastal locations in WC/ATWC's AOR. The geophysicist can add to or alter a message prior to dissemination. Messages are disseminated in several different ways. There are four primary methods: reading the message over the National Warning System (NAWAS), transmission over the NOAA Weather Wire satellite system (NWWS), transmission over a dedicated Federal Aviation Administration (FAA) teletype system (NADIN2), and transmission over dedicated National Weather Service circuits. Messages read over the NAWAS phone are heard by emergency personnel from the federal to the county levels along the U.S. west coast, Alaska, British Columbia in Canada, and by the U.S. Coast Guard stations. The NWWS transmits a printed copy of the message to the state emergency services, provincial emergency preparedness in British Columbia, Canada, and to National Weather Service (NWS) offices. The NWS offices forward the message to NOAA Weather Radio, the Emergency Alert System, the Emergency Managers Weather Information Network, and other communication systems available to the public and media. The FAA teletype system is used to send a printed copy of the message to various governmental offices, military installations, and foreign countries. Secondary dissemination methods are e-mail, web page (http://wcatwc.gov), phone calls, and digital pager messages.

In addition to tsunami warning messages, the WC/ATWC also issues information messages for earthquakes which may be felt strongly by local citizens but are not large enough to generate a tsunami. Each year, the WC/ATWC staff responds to more than 250 alarms averaging approximately five each week. These messages are important in preventing needless evacuations since citizens near coastal areas are taught to move to higher ground when severe earthquake shaking occurs. Other messages issued by the WC/ATWC include seismic data exchanges among other centers, and tsunami information messages for large earthquakes outside the AOR that are not potentially dangerous to the AOR.

Once a warning has been issued, the nearest tide gages are monitored to confirm the existence or nonexistence of a tsunami, and its degree of severity. The WC/ATWC has access to more than 90 tide sites throughout the Pacific Basin. Approximately 75% of these sites are maintained by NOAA's National Ocean Survey (NOS). In addition to the NOS, other agencies such as the Pacific Tsunami Warning Center and the Japan Meteorological Agency operate tide gages. The WC/ATWC maintains real-time telemetry equipment at seven NOS gages in Alaska and fully maintains an eighth tide gage at Shemya, Alaska. These eight gages provide real-time data sampled every 15 s, and transmitted via dedicated circuits to the WC/ATWC where they are processed and displayed on PCs.

The NOS sites' data are sent via satellite on regularly scheduled transmissions, every 1, 2, or 3 hours. The data are transmitted to a satellite downlink on the U.S. east coast and then to the WC/ATWC over a dedicated circuit. In addition to the scheduled hourly transmissions of 6-min data, there is dial-in capability to receive 1-min data, transmitted every 5 min, for a period of 1 hour. Many of the NOS gages have tsunami triggering software at the site which enables immediate transmission of water level data if a tsunami has been detected. Software which was developed at the WC/ATWC displays the real-time water level data, triggered tsunami data, and the scheduled data transmissions on PCs. The scheduled transmission time is also shown on a graph displaying each site's water level data. Superimposed upon the water level data is a marker indicating the expected tsunami arrival time for any given earthquake. The predicted and filtered tides are also shown for many sites. The tsunami warning is canceled or extended based on the information from the tide gages, historic tsunami records, and pre-computed tsunami models.

An ongoing project at the WC/ATWC is the prediction of tsunami amplitudes outside the tsunami generating area (Whitmore and Sokolowski, 1996). The basic idea behind this technique is that pre-computed tsunami models can be scaled by recorded tsunami amplitudes during an earthquake to give a reasonable amplitude estimate outside the source zone. Tsunami models for moment magnitude 7.5, 8.2, and 9.0 earthquakes have been computed along the Pacific plate boundary from Honshu, Japan to the Cascadia subduction zone, and for Chile. Maximum amplitudes are predicted for approximately 80 sites along the western North American coast, and approximately 20 sites in Hawaii. The modeling technique was verified by comparison to historic tsunamis from the different regions. At present, the results from the scaled models are not distributed to emergency officials during warnings, but are used internally as an aid in canceling or extending warnings.

Another current project at the WC/ATWC is to receive tsunami data from tide sites via a satellite phone system. Currently, there is a delay of 1–3 hours in receiving tide data from most NOS gages. The idea is to retrieve selected windows of data from these tide sites using a satellite phone, antennae, PC, and special hardware inserted into the current NOS field packages. This would permit a geophysicist at the WC/ATWC to review, via a PC, a window of data from selected tide sites nearest the tsunami source. A prototype is currently in development to test this concept. The software is nearing completion. The NOS tide site at Seward, Alaska, nearest the WC/ATWC, is being equipped with hardware which will enable the WC/ATWC to request and receive data which can be displayed by a PC. The advantages of this method over current methods are to significantly decrease the current time delay of 1–3 hours; permit retrieval of tsunami data from gages for which there is no telephone dial-in; have reasonable costs; reduce/eliminate the need for costly dedicated circuits; not affect or impact the operations of another agency or center; and decrease the time that an area is placed in a warning while waiting for tide data to confirm the existence or nonexistence of a tsunami. Once this proof-of-concept is completed for one site, additional sites will follow as time and funding are available.

The ability of any warning system to successfully save lives and reduce property damage depends upon getting the information to the public and getting them to respond to the emergency. For over 20 years the WC/ATWC has operated a community preparedness program. The WC/ATWC is now implementing a program known as TsunamiReady which provides advice and training sessions to coastal citizens and emergency managers to aid in pre-event planning. The aim of this program is to educate the public to help themselves if they are caught in the middle of a violent earthquake and/or tsunami, and to be aware of safety procedures, safe areas, and the limitations of the Tsunami Warning System. All staff members participate in a three-part preparedness effort which includes visits to distant coastal communities from Adak to southern California; visits to local group facilities and schools that are within commuting distance of the WC/ATWC; and tours through the WC/ATWC's facilities. In addition to this ongoing program, special visitations are made by the staff to the communities that were evacuated during an actual tsunami warning and no significant wave action materialized. The purpose of these visitations is to explain the warning actions to the public and to stress the continued need to respond to emergency tsunami warnings.

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