Tsunami Data Management

An Initial Report on the Management of Environmental Data Required to Minimize the Impact of Tsunamis in the United States

Prepared for the

National Tsunami Hazard Mitigation Program

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NOAA Data Management Committee Special Report

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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The National Tsunami Hazard Mitigation Program, a partnership involving relevant Federal agencies and coastal States, provides the organizational framework needed to execute the President's tsunami initiative in the near-term and shall develop, coordinate and sustain an effective and efficient tsunami risk reduction effort in the United States over the long term. Specific actions called for in this plan are:

- Develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories.

- Improve tsunami and seismic sensor data and infrastructure for better tsunami detection and warning.

- Enhance tsunami forecast and warning capability along our coastlines (Pacific, Atlantic, Caribbean, and Gulf of Mexico) by increasing the number of Deep-ocean Assessment and Reporting of Tsunamis (DART™) buoys, tide gauges, and seismic sensors feeding real-time data into online forecast models.

- Ensure interoperability between U.S. national system and other regional tsunami warning systems.

- Provide technical expertise and assistance, as appropriate, to facilitate development of international tsunami and all-hazard warning systems, including for the Indian Ocean.

- Encourage data exchange and interoperability among all regional tsunami and all-hazard warning systems, such as The Intergovernmental Oceanographic sub-commission for the Caribbean (IOCARIBE).

- Promote development of model mitigation measures and encourage communities to adopt construction, critical facilities protection and land-use planning practices to reduce the impact of future tsunamis.

- Increase outreach to all communities, including all demographics of the at-risk population, to raise awareness, improve preparedness, and encourage the development of tsunami response plans.

- Conduct an annual review of the status of tsunami research and develop a strategic plan for tsunami research in the United States.

Text taken from *Tsunami Risk Reduction for the United States: A Framework for Action*, December 2005.

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Preface

NOAA's Tsunami Mission is to provide reliable tsunami forecasts and warnings, and to promote community resiliency. To accomplish the forecast and warning, NOAA relies on real-time access to global environmental data including seismic, Deep-ocean Assessment and Reporting of Tsunamis, and coastal water level (tide gauge) data. This Report focuses on the acquisition, processing, distribution, long-term archive of, and access to, these data. Gaps in the end-to-end system are identified and recommendations made to address vulnerabilities.

A robust tsunami warning and mitigation system also relies on the free and open exchange and long-term management of high quality data and science products. The Report does not currently address all of the tsunami observation and product archive concerns. Among the additional topics not addressed are: the long-term archive and access of the non-U.S. coastal water level data, including Global Sea Level Observing System (GLOSS); archive of tsunami models including model inputs (computational grids, deformation sources, boundary conditions and forcings) and outputs; published tsunami technical reports from NOAA and the National Tsunami Hazard Mitigation Program (NTHMP); published evacuation maps and safety brochures; post-event survey reports; and the role of the International Tsunami Information Center. All of these topics required additional discussion within NOAA and with the NTHMP and other partners nationally and internationally.

Long-term management of data implies stewardship of data consisting of the application of rigorous analyses and oversight to ensure that data meet the needs of users. This includes documenting measurement and processing practices; providing feedback on observing system performances; intercomparisons of data for validation; reprocessing; and, recommending corrective action for errant or non-optimal systems. Close collaboration between system developers, operational users, data centers, and researchers—within, and external to NOAA—strengthen our data stewardship.

This Report will form a basis for on-going work to identify, document, and enable integration of NOAA's tsunami data, data management, and data delivery systems. Since observational streams, data formats, standards, archive roles and partnerships evolve over time, it is envisioned that the Report will be a living document, with revisions made available on line.

Introduction

Although the frequency of damaging tsunamis in the United States is low compared to many other natural hazards, the impacts can be extremely high (Figure 1). Tsunamis have caused a considerable number of fatalities, inflicted major damage, and caused significant economic loss to large sections of the United States' coastlines. Since 1900, more than 200 tsunami events affected the coasts of the United States and its territories, causing more than 500 deaths. Currently more than 53% of the U.S. population lives in coastal communities and contributes to 60% of our Nation's Gross Domestic Product. As the trend continues for coastal economic growth and population density increases, the risk of death and economic damage will climb.

Figure 1. Tsunami damage in Hilo, Hawaii, 10,000 km from the 1960 Chilean earthquake. Hilo suffered 61 deaths and $24 million (not adjusted for inflation) in damage.

In 2005, the National Science and Technology Council (NSTC) released a joint report by the sub-committee on Disaster Reduction and the U.S. Group on Earth Observations titled *Tsunami Risk Reduction for the United States: A Framework for Action*. The document outlines the President's strategy for reducing loss of life and property, and improving community resiliency. The NSTC is the principal means for the President to coordinate science and technology policy across the Federal government. In December 2006, the President signed into law The Tsunami Warning and Education Act (Public Law 109–424), which specifies the National Oceanic and Atmospheric Administration (NOAA) as the lead agency responsible for:

- Operating the U.S. Tsunami Warning System;
- Organizing the National Tsunami Hazard Mitigation Program (NTHMP);
- Conducting a tsunami research program;
- Providing technical assistance and training to the global tsunami warning system; and
- Reporting to Congress on tsunami warning system capabilities.

The NTHMP is a partnership of U.S. coastal States, territories, and Federal agencies, including the NOAA and the U.S. Geological Survey (USGS). To support the national strategy for minimizing the impact of tsunamis as outlined in *Tsunami Risk Reduction for the United States* and meet the requirements of the Tsunami Warning and Education Act, NOAA relies on a network of global data, acquired and processed in real-time, as well as high-quality global databases supporting advanced scientific modeling. NOAA is upgrading its sea level stations for near-shore monitoring, upgrading and expanding the network of seismic stations in partnership with the USGS, and expanding the network of Deep-ocean Assessment and Reporting of Tsunami (DART™) stations in the Atlantic, Caribbean, Gulf of Mexico, and Pacific regions as part of the Global Earth Observation System of Systems (GEOSS). NOAA, in collaboration with the recently expanded NTHMP, is advancing modeling and mapping activities, hazard assessment and data stewardship, quantitative assessment of socioeconomic impacts, and increased preparedness via the TsunamiReady™ recognition program.

At the heart of the NOAA Tsunami Program is the capability to forecast tsunamis using advanced measurement and modeling technologies in order to develop scenarios of potential tsunami impacts along our coastlines. This capability relies on rapid access to data for real-time evaluation, and reliable access to quality retrospective data for research and hazard assessment. This document is the first attempt at identifying the flow of data from acquisition to archive, documenting observation transmission formats and pathways, single points of failure and vulnerabilities, distribution of tsunami products, and eventual long-term preservation and access of data essential for the Nation's Tsunami Program.

Seismic Data

Background

NOAA's primary mission-critical operational observation network for tsunami warning is the seismic network required to rapidly locate, size, and otherwise characterize major earthquakes. The Tsunami Warning Centers (TWCs) must also determine an earthquake's tsunamigenic potential, predict tsunami arrival times, predict coastal runup when possible, and disseminate appropriate warning and informational products based on this information. The first step in this process begins with seismic data acquisition.

The TWCs record approximately 225 channels of seismic data. Many different agencies operate and fund the seismic networks proving essential data, including USGS, Incorporated Research Institutions for Seismology (IRIS) Global Seismic Network (GSN), NTHMP, various universities throughout the country, other national networks, and the TWCs. Access to data (Figure 2) is provided through dedicated circuits funded by the NTHMP, by private satellite networks and leased lines, and through the Internet. Several GSN stations in the Pacific are telemetered by satellite directly to a GSN master earth station at the Pacific Tsunami Warning Center (PTWC), established by IRIS and supported by USGS and NOAA.

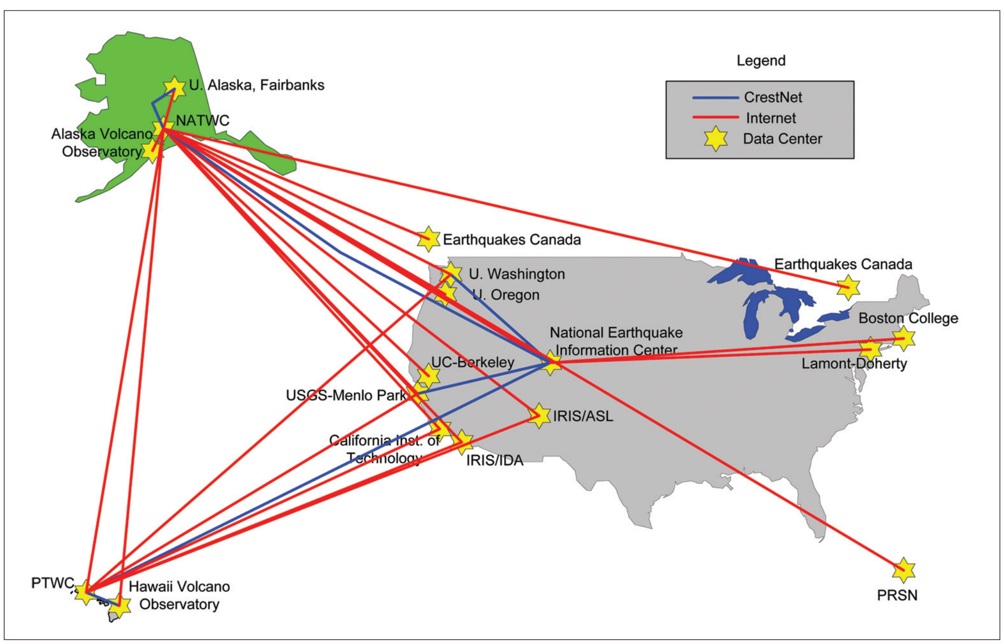

Figure 2. Tsunami warning center network connection.

Observation Acquisition and Transmission

The TWC seismic network is essentially a virtual private network. Seismic data from the centers listed in Appendix C (page 65) are available to the TWCs upon request. Those data centers acquire the seismic signals through many different paths including lease line, satellite, and Internet. The Consolidated Reporting of Earthquakes and Tsunamis (CREST) has a digital leased line circuit funded by NTHMP and USGS that form the primary private network for the TWCs. The CrestNet circuits provide signal from 105 vertical broadband channels of seismic data at sample rates from 20 to 50 samples per second to the TWCs. A business case has been completed to replace the CrestNet leased lines with drops into the NOAANet. As a backup, these same data are sent via the Internet. Additionally, approximately 120 other seismic signals are transmitted directly through the Internet from other data centers. All data, whether via CrestNet or Internet, are transferred among data centers using the USGS Earthworm software, the *de facto* standard for seismic data and hypocenter parameter exchange. See Appendix C and http://wcatwc.arh.noaa.gov/comms/seisnet/seisdesc.htm for further information on TWC seismic data providers.

Warning centers are connected to the USGS National Earthquake Information Center (NEIC) with 128 Kbs leased lines, and are connected to in-State regional seismic networks. The West Coast Alaska TWC (WCATWC) is connected to the Alaska Earthquake Information Center in Fairbanks, and the PTWC is connected to the Hawaii Volcanoes Observatory (HVO). The centers also have independent Internet connections, which provide alternate data routes. For example, the WCATWC has a 512 Kbs local Internet Service Provider (ISP) and a T1 NOAA Multiprotocol Label Switching connection through the National Weather Service (NWS) Regional Headquarters along with a satellite-based backup. The WCATWC also operates its own satellite-based backbone seismic network consisting of 15 three-component digital broadband or single-component vertical seismometers, and acts as a data recording center for the Alaska Volcano Observatory’s Amchitka seismic array consisting of 17 seismometers. The PTWC is presently upgrading its seismic network on the Hawaiian Islands. When complete, the PTWC network will consist of approximately eight digital broadband sensors and twelve digital accelerometer stations.

The TWCs have greatly enhanced seismic data transmission and processing in recent years. USGS Earthworm software import/export and other data transport modules are used to transmit data between the TWCs and cooperating networks. Data are received from the GSN using liss2ew, import_ida, and slink2ew Earthworm modules. Use of the Earthworm formats data consistently for processing and storage, enabling interoperability between the TWCs. For further information on seismic data transmissions see: http://wcatwc.arh.noaa.gov/comms/seisnet/seisdesc.htm.

Data Management

TWC seismic processing systems are used for both real-time and post-processing of seismic data. Real-time seismic data are processed by a P-picker, which determines the onset of the primary wave

(P-wave). An associating/locating algorithm then uses the P-picks to determine parameters for local, regional, and teleseismic earthquakes. As more data are received and processed, the location and magnitude are refined. A watchstander can add or adjust P-wave data used in the automatic locations through a graphical interface. Several types of earthquake magnitude are determined by the TWCs:

- Body-wave magnitude (mb)—based on P-wave amplitude and frequency;
- Local magnitude (Ml)—the traditional Richter magnitude;
- Surface-wave magnitude (Ms)—based on Rayleigh wave amplitude and frequency;
- P-wave moment magnitude (Mwp)—based on the integrated P-waveform; and
- Moment magnitude (Mw)—based on either Rayleigh wave spectra or body wave inversions.

The initial magnitude estimate is based on an mb, Ml, or Mwp depending on the earthquake's size and location. Surface wave magnitude processing is triggered by the automatic locations, and is computed cycle-by-cycle as Rayleigh waves arrive at broadband seismometers. Moment magnitudes are also computed from surface wave spectra and moment tensor inversions. Two identical systems are active for redundancy and for added ability to process multiple aftershocks that are common with tsunamigenic earthquakes. Locations computed in the processing system are displayed on geographic information systems (GIS) (see http://wcatwc.arh.noaa.gov/DataProcessing/earthvu.htm for further information).

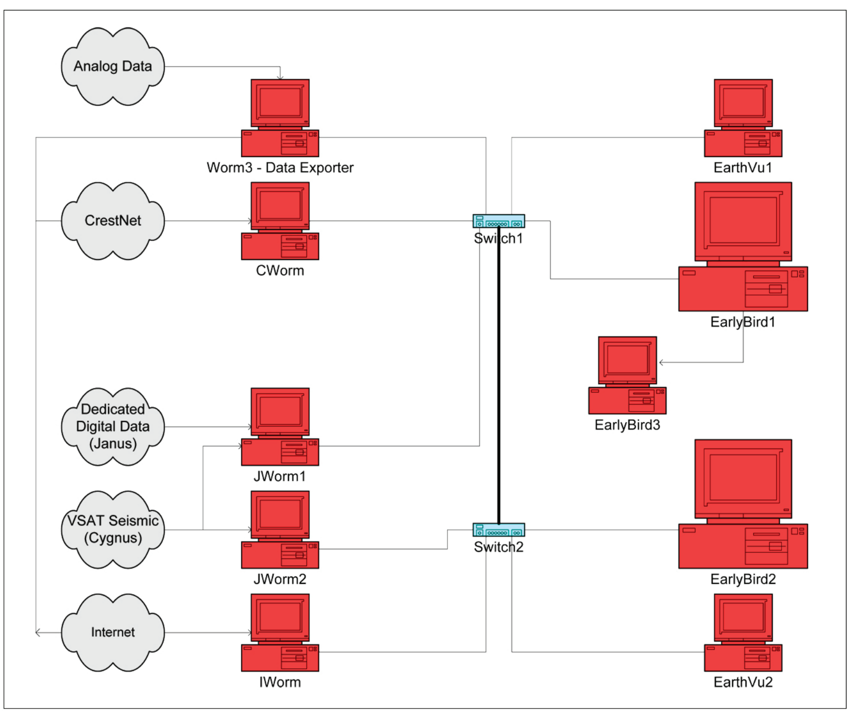

Figure 3. Simplified diagram of the seismic data flow at the Alaska Tsunami Warning Center.

As an example of data flow within a TWC, Figure 3 (prior page) shows the simplified seismic data distribution throughout the WCATWC (detailed diagram contained in Appendix C). Seismic data arrive at the TWC by four basic paths: digital broadband data via leased circuits, digital broadband data transmitted via the CrestNet, digital broadband data transmitted over the Internet, and digital data transmitted via a very small aperture terminal system. Data are exported to other centers using the CrestNet or Internet (see http://wcatwc.arh.noaa.gov/comms/seisnet/seisdesc.htm). Data are first ingested at the center by computers whose sole function are to transmit seismic data between observatories and record data from the local network (systems Cworm, Iworm, Worm3, and Jworm1/2). These computers pass data to the processing systems: Earlybirds 1, 2, and 3. Switches, routers, computers, and data paths are configured to eliminate any single points of failure within the centers. Earlybird 2 is a concurrently running backup system for Earlybird1. Earlybird3 is a training and development system, which obtains the same data as the other systems.

Figure 4 displays the data processing flow within EarlyBird1. Earthworm rings are shared memory locations. The windows icons indicate modules that accommodate user interaction and review. Both trace data and processed hypocenters from other observatories are first placed in the INPUT_RING. Here, the information is either decimated or copied as is into the WAVE_RING. The hypocenter information is manipulated by the HYPO_print module for display on a GIS. The rest of the modules operate on trace data. The Earlybird processing system is described in detail at http://wcatwc.arh.noaa.gov/DataProcessing/ew-eb.htm.

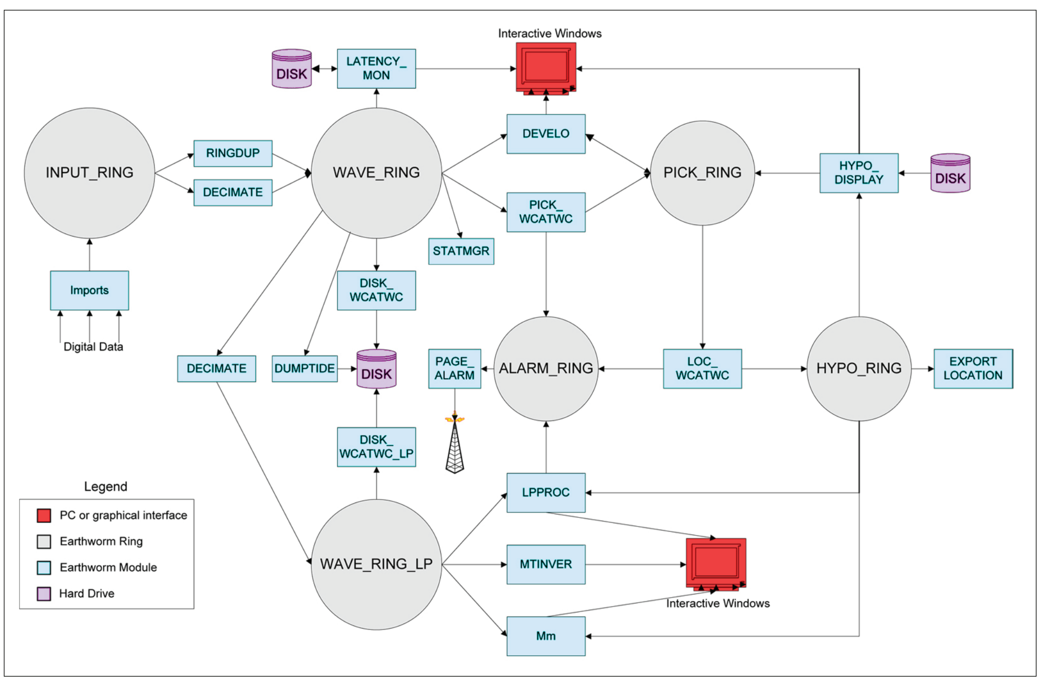

Figure 4. EarlyBird1 seismic data processing flow.

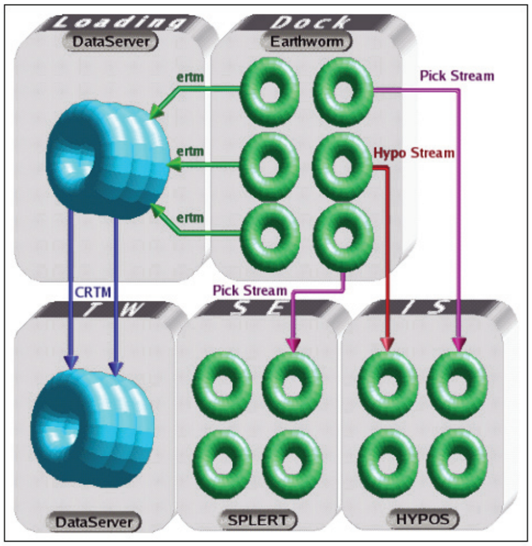

Figure 5. PTWC's data management.

PTWC organizes data flow and management in a similar manner to that described for the WCATWC. In the schematic in Figure 5, the green doughnuts represent earthworm message rings and the blue doughnuts are seismic and sea level waveform Data Servers. Like WCATWC, PTWC makes heavy use of the USGS Earthworm system. Systems called "loading docks," running Earthworm processes, collect all incoming data. Some preliminary analysis is performed on the loading docks, such as P-time picking. Waveform data are transferred from Earthworm rings to Data Servers. Earthworm data-rings are multiplexed while Data Server rings have a cylindrical architecture where each section of the cylinder represents an individual data stream. The Data Server has an easy-to-use application program interface (API) and allows easy access to the data for a myriad of analysis programs. Data are shuttled from the loading docks to the PTWC seismic processing systems, TWSEIS, where further analysis is performed (location, magnitude, etc.) and data are stored.

PTWC's System for Processing Local Earthquakes in Real Time (SPLERT) is a derivative of the USGS Earthworm and Earlybird. SPLERT locates and assigns preliminary magnitudes to earthquakes that occur in the Hawaii region. HYPOS are Earthworm rings dedicated to the collection of hypocenters and other parametric information forwarded to PTWC from other sources. Earthquake locations are displayed on a graphical interface with a GIS layer showing the location of the earthquake and the historical seismicity in the vicinity of the earthquake as well as the stations that were used in the determination of the hypocenter.

Archive and Access

The TWCs do not permanently archive continuous seismic data. Event data for large earthquakes (M>6) are saved during daily seismogram interpretations. The IRIS Data Management System, which consists of several components or "nodes," is the seismological communities' primary data acquisition, archive, and distribution system. The IRIS nodes work together to insure the smooth flow of data from participating stations to the seismological research community. The IRIS data nodes include the Data Management Center (DMC) and numerous data collection centers and networks.

The IRIS DMC is responsible for the long-term archive and distribution of all IRIS-generated seismic data. The IRIS DMC receives real-time data from the WCATWC, the Puerto Rico Seismic Network, the new USGS Caribbean Seismic Network, data from many of the U.S. National Network and CREST stations as well as data from many of the International Federation of Digital Seismograph Networks (FDSN) participating networks. At present, PTWC sends its network data to the HVO and NEIC and does not send data to IRIS for archive. Discussions are underway concerning possible archive of the PTWC data at IRIS. Data from stations in Northern California are archived at the Northern California Earthquake Data Center. More information and a list of networks participating in the IRIS DMC is available from http://www.iris.edu/. Figure 7 shows the IRIS GSN.

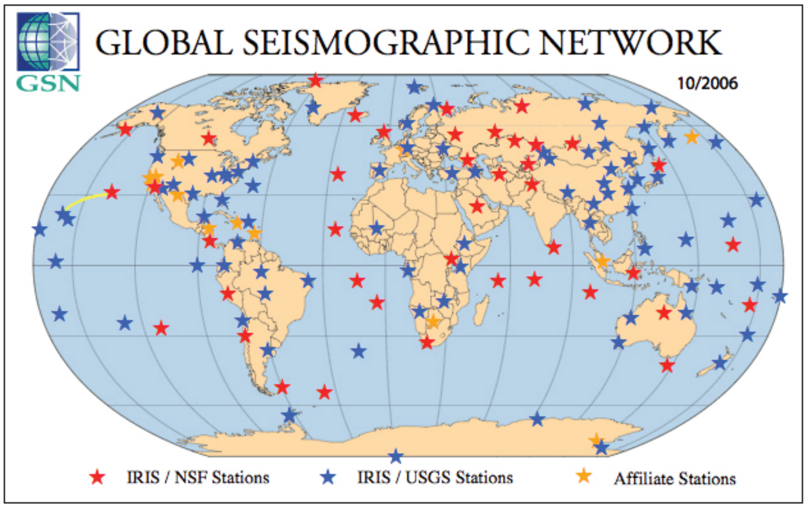

Figure 7. IRIS Global Seismographic Network, 2006.

The IRIS DMC currently has approximately 53 terabytes of seismic waveform data available in digital format from as early as 1966. The seismic waveform data also include complete metadata. Figure 8 shows the growth of data in the IRIS DMC. Data represent, from bottom to top, GSN, FDSN, Joint Seismic Program, other data, U.S. regional networks, engineering sensor data, Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) program, and the new EarthScope data.

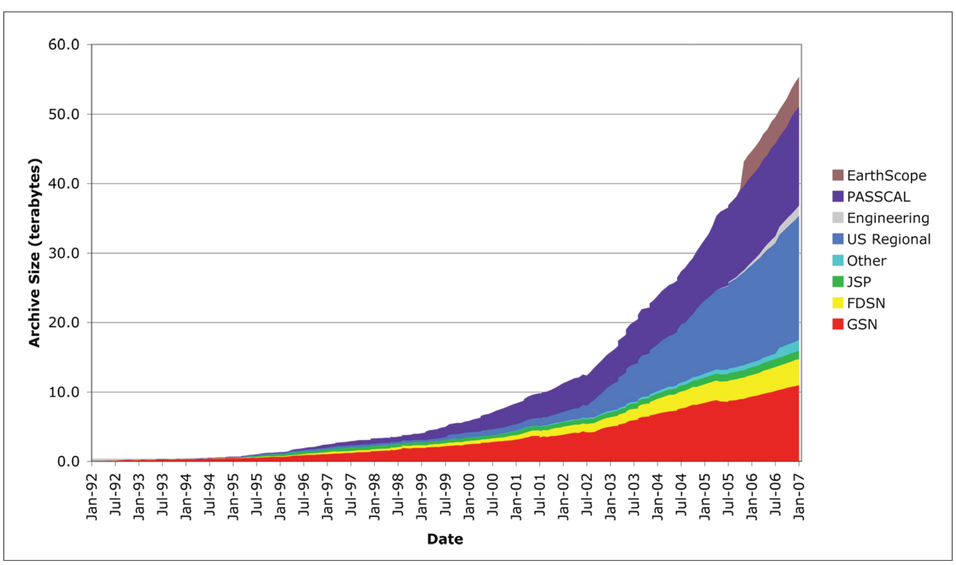

Figure 8. Growth of the IRIS DMC archive since 1992.

IRIS has developed a rich suite of data access tools that include email-based tools, Web-based tools, as well as APIs. The initial APIs were constructed using the Common Object Request Broker Architecture (CORBA) and IRIS is currently developing similar APIs developed using Web technologies (Simple Object Access Protocol (SOAP), Extensible Markup Language (XML), Web Service Definition Language, etc.). Figure 9 shows the various access tools for data in the Archive, the real time Buffer of Uniform Data (BUD) system and for windows of time series data after larger earthquakes in the Fast Archive Recovery Method (FARM) and IRIS' System to Provide You Data from Earthquakes Rapidly (SPYDER®) products. The tools on the right hand side are conventional tools based upon email and Web-browser access methods. The newer CORBA and Web services based tools are depicted on the left hand side of the diagram where the three services of Waveform, Network and Event Data Centers are shown.

The IRIS DMC is very active in the distribution of seismic waveform data to the scientific and monitoring communities. The DMC delivered more than 36 seismograms every second of every day in 2006 with a sustained rate of roughly four megabits per second. The IRIS DMC projects nearly 275,000 unique requests for data in 2006. The volume of data shipped to end users will be roughly 15 terabytes in more than one billion seismograms. Figure 10 (next page) shows the growth in data shipments through conventional request methods (not using CORBA) over the past two decades.

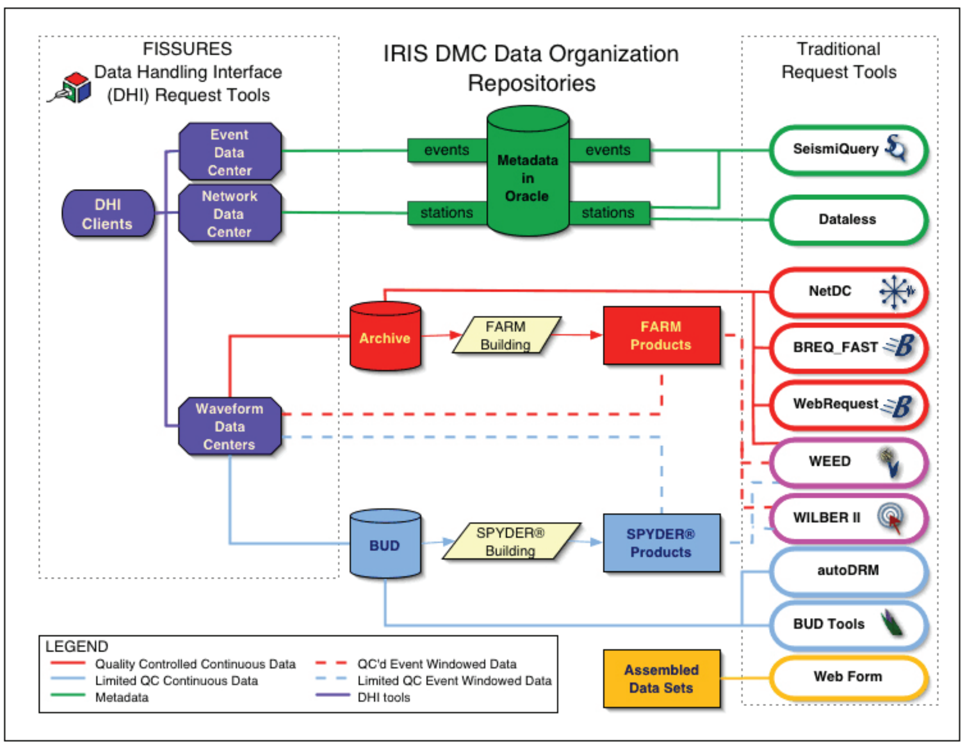

Figure 9. IRIS DMC access tools.

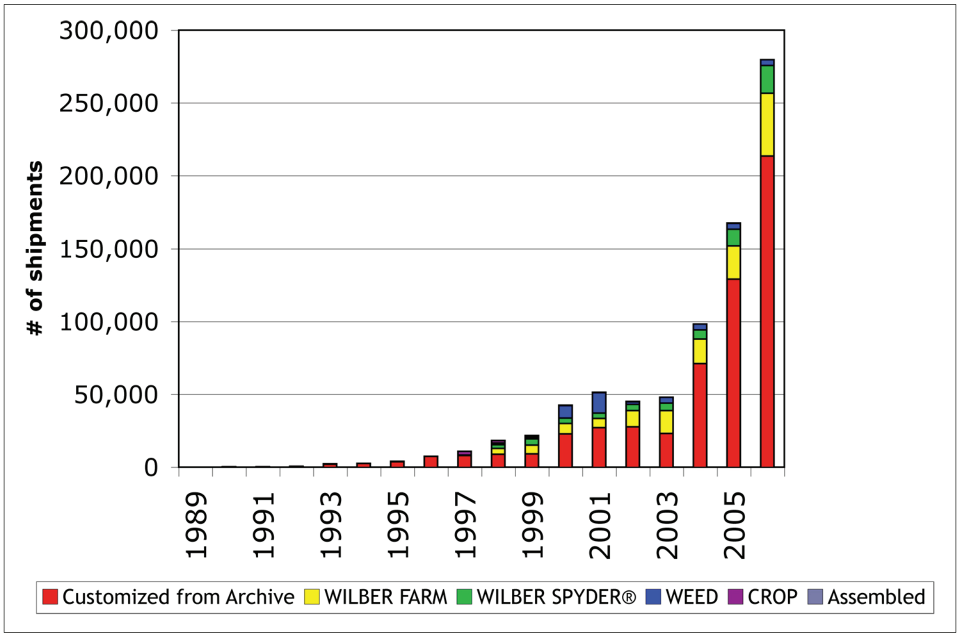

Figure 10. Growth in data shipments from the IRIS DMC, not including real time.

End-to-End Vulnerabilities

Single Points of Failure

Local seismic networks

- Intelsat Corporation transponder or satellite, any or all satellite modems, low-noise blocks, and block-up converters

CrestNet

- NEIC server or NEIC to TWC leased lines
- Alaska Earthquake Information Center and HVO servers and leased lines to the TWCs
- Leased lines from other data centers to NEIC

Internet

- Local ISP or telephone company failure, load due to heavy usage

Data Vulnerabilities

- Communications outages from any single points of failure
- Latency due to data compression during large events

Gaps and Recommendations

- Insufficient bandwidth on private networks (CrestNet)

- Insufficient bandwidth to acquire Comprehensive Nuclear Test Ban Treaty Organization seismic array data
- Insufficient bandwidth at cooperating networks to provide timely seismic data to TWCs (e.g., Puerto Rico Seismic Network)
- Replace the CrestNet leased lines with drops into the NOAANet.
- Provide redundant and spare equipment for the local networks.

Deep-ocean Assessment and Reporting of Tsunamis

Background

The Deep-ocean Assessment and Reporting of Tsunamis (DART™) is an ongoing, multi-agency cooperative effort to maintain and improve the capability for the early detection and real-time reporting of tsunamis in the open ocean. The DART™ network is an essential component in the provision of timely warnings to U.S. coastal communities. DART™ data support the NOAA Tsunami Program observation requirements for Tsunami Offshore Real-Time and Post-event observations, as well as Global Water Level Observations, as described in NOAA's Consolidated Observational Requirements List (CORL).

DART™ stations are sited to provide *in situ* tsunami detection and water-level observations for NOAA's tsunami forecast, warning, and mitigation responsibilities. The original six DART™ buoy operational array, completed in 2001, is on schedule to grow to an operational array of 39 DART™ II systems in the Pacific and Atlantic Oceans, the Caribbean Sea, and the Gulf of Mexico by March 2008. Unlike the original DART™ system, DART™ II has the capability of two-way communication. We refer to either system throughout this document as DART™.

Each DART™ system consists of an anchored seafloor bottom pressure recorder (BPR) acoustically coupled to a moored surface buoy (Figure 11). Iridium transceivers and the acoustic modems provide real-time communication between each DART™ system and the Tsunami Warning Centers (TWC) in Ewa Beach, Hawaii and Palmer, Alaska. Additionally they provide limited communications from the TWC to the BPR.

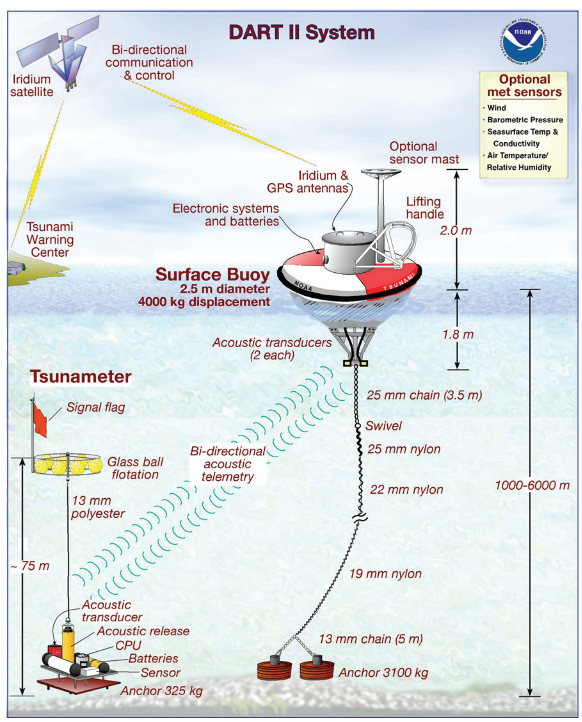

Figure 11. Schematic of the DART™ system.

DART™ BPR packages are deployable for 48 months at depths up to 6000 meters and are typically on a 24-month service schedule. The BPR is recovered by sending a signal to trigger an acoustic release causing it to mechanically separate from the anchor. Flotation brings the unit to the surface, leaving the anchor on the seafloor. Meinig et al. (2005a, 2005b) provides a description of DART™ and its performance characteristics.

Observation Acquisition and Transmission

Sources of potentially damaging tsunamis are widespread, as are the coastal communities they threaten. With a limited number of DART™ systems available to deploy and maintain, it is vital that they be positioned to provide high quality observations at the earliest possible time. Siting of the DART™ buoys involves addressing: (1) optimization of site locations based on scientific considerations; (2) logistical needs of deployment; (3) modeling and detection requirements imposed by potential sources of tsunamis; and (4) the identification of at-risk coastal communities.

The TWCs have responsibility for selecting DART™ sites. NOAA's Pacific Marine Environmental Laboratory (PMEL) produces specific siting recommendations based on the propagation database to characterize expected travel times and amplitudes for tsunamis. Depth and local bathymetry of the seafloor exclude some sites, as does the threat of submarine landslides (data provided by the USGS). Locations within United States or International waters are favored to enable unrestricted access for deployment and maintenance. Once the TWCs have identified and accepted a limited number of approximate sites, NOAA's National Geophysical Data Center (NGDC) provides the National Data Buoy Center (NDBC) with detailed bathymetric siting maps in Portable Document Format (PDF) for final adjustments to the deployment positions (Figure 12). The pre-deployment siting maps provide valuable information for shore-side planning and decision-making, and afford a substantial savings in operational time and money. When possible, NOAA conducts a multibeam bathymetric survey of the

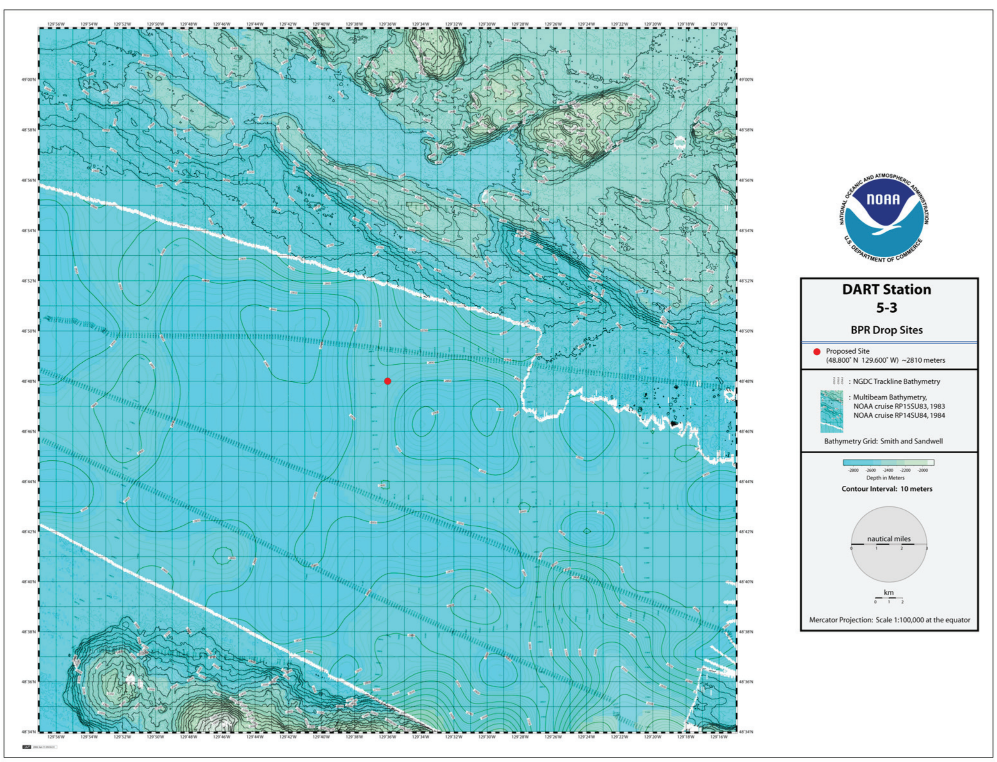

Figure 12. Siting map 5-3, northeast Pacific Ocean, west of Vancouver Island.

area at deployment. NDBC sends these data to NGDC for inclusion in the bathymetric data archive, adding to and thereby improving the quality of the archive.

Once deployed, each DART™ system provides a suite of data to fulfill NOAA's responsibilities for timely and effective warnings, and creating tsunami-resilient communities. DART™ provides internally stored high frequency data, triggered event data, and lower frequency data for system monitoring. PMEL engineers provide system enhancements through continued research and development efforts.

High frequency data consist of temperatures and pressures averaged over 15-second intervals for the entire bottom package deployment period. Observations are stored on a flash card in the BPR until the bottom package is retrieved and the data are recovered by NDBC. PMEL and NGDC process the high frequency data then add the raw, edited, and processed data to the NGDC tsunami data archive along with all available metadata. These data are retrospective in nature and so will be referred to as such to distinguish them from data transmitted in real-time. In addition to internally recorded 15-second data, DART™ systems report a combination of 15-second data and one-minute averages when triggered to do so by the detection of an event. These data provide the TWCs with deep ocean tsunami observations essential for evaluating the potential risk to coastal communities within their jurisdiction. In addition, each DART™ system delivers spot pressure observations at 15-minute intervals in near real-time for system monitoring by NDBC.

Near real-time bidirectional communication (Figure 13) allows access to internally set system parameters and allows the TWCs to manually trigger event-reporting mode. Additionally, bidirectional communication can be used to retrieve a one-hour block of internally recorded pressure and temperature frequency counts from the flash storage card. There are a finite number of these after-the-fact requests due to battery life considerations. In order to maintain this capability for the deployment life of a given system, the TWCs coordinate this activity among interested parties.

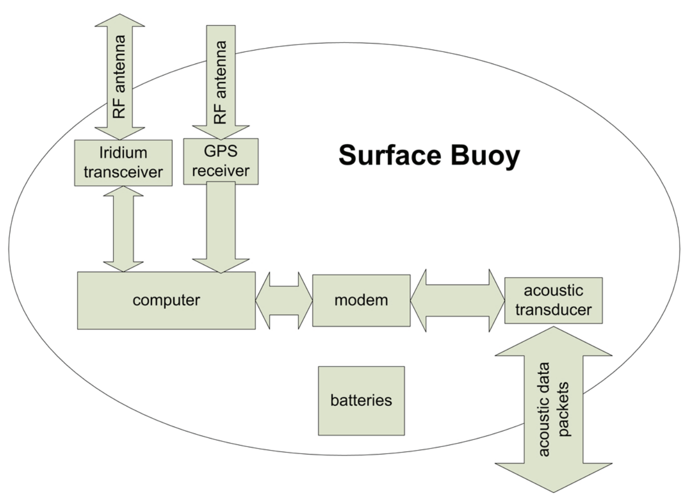

Figure 13. Block diagram of DART™ Surface Buoy; independent duplicate system is not shown.

Interrogation Protocol

1. The TWCs coordinate DART™ trigger activation during events. Normally, if triggers are not activated by the earthquake or tsunami they will be activated at the TWCs. NDBC assistance may be required.
2. The TWCs perform after-the-fact interrogation of internally recorded 15-second data. Specific requests by interested agencies should be made no earlier than a day or two following an event, as TWC personnel will be focused on operations. TWCs will advise appropriate agencies when data have been downloaded unrelated to specific requests.

NDBC acquires and manages all original real-time DART™ data. NDBC monitors the hourly messages containing real-time 15-minute data for quality and overall system operation. These data along with real-time event data are displayed and made available for download in near real-time on the NDBC Web page. The Web offers two data time-series—the original observations, and residual data with a predicted tidal signal removed. NDBC generates the predicted tide using tidal harmonic constants provided by the NOAA Center for Operational Oceanographic Products and Services (CO-OPS). NDBC transfers event data to NGDC for scientific management and long-term archive within three months of an event. PMEL also acquires these data for modeling and other scientific applications.

Retrospective data are available upon bottom package recovery by NDBC. The complete record of binary temperature and pressure counts is downloaded from a flash card and examined by NDBC personnel for quality. These data are then transferred by NDBC to NGDC and PMEL within one month following the return of the service crew retrieving the BPR. NGDC manages and archives these data. PMEL develops research quality deep-ocean water level data and products. All data products are transferred to NGDC for management, long-term archive, and Web site access. Data quality control and verification, model validation and improvement, maximizing siting considerations, and research into better understanding tsunami dynamics all require the retrospective data.

Observations

The BPR performs the functions of data acquisition and storage, processing, event detection, message formatting, and initiation of communication with the surface buoy (Figure 14). The Paroscientific™ digiquartz pressure transducer, residing in the BPR, makes all DART™ pressure observations. An oscillating quartz crystal beam is piezo-electrically induced to vibrate in its

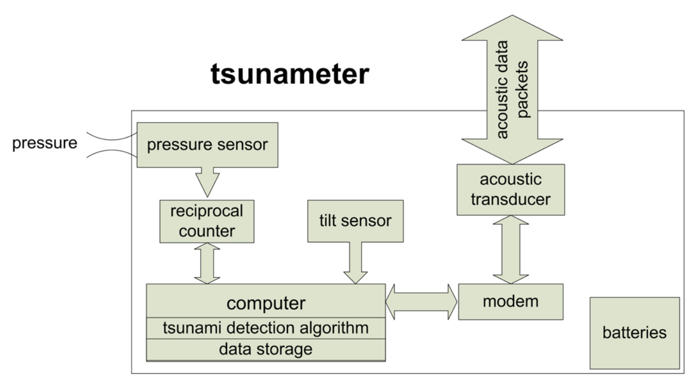

Figure 14. Block diagram of DART™ Bottom Pressure Recorder adapted from Meinig et al., 2005a.

lowest resonant mode (Wearn and Larson, 1982). Changes in external fluid pressure alter the natural vibrational frequency of the beam. The output frequency is then a measure of applied pressure. The measurement sensitivity of the Paroscientific™ pressure transducer is less than 1 millimeter in 6000 meters (Meinig et al., 2005a). Since the pressure transducer is influenced by ambient temperature, an additional oscillating quartz crystal is in close proximity to provide frequency counts reflective of temperature changes.

Table 1. DART™ Observations

Measurement	Original Units	Sampling Interval	Measurement sensitivity	Transmission Units
Water Pressure	pressure frequency count	15-second averaged samples	Less than 1 mm in 6000 meters sea water	Estimated water level in mm
Temperature	temperature frequency count	15-second averaged samples	N/A	N/A

The original 15-second average pressure and temperature frequency-count (Table 1) are written in one-hour blocks with a date-time stamp on the BPR internal flash card. Continuously running software on board the BPR converts frequency counts to engineering units of pressure in pounds per square inch absolute (psia) and temperature (degrees Celsius) according to the method described in Eble et al., 1989. In addition, each 15-second temperature-corrected pressure observation is converted into an estimated water level using the constant conversion factor of 670 mm per psia (Equation 1) prior to real-time transmission. The conversion factor is based on nominal values for the water-column averages of the *in situ* seawater density and the acceleration of gravity. The Tsunami Detection Algorithm (Mofjeld, Web article) monitors the estimated water level to detect changes in successive 15-second values (tides removed) exceeding a threshold. This threshold is pre-programmed to 30-mm, but can be changed remotely to values in the range of 30- to 90-mm after deployment. Observations are formatted into messages for transmission to the surface buoy.

Equation 1. Reported Water-level in millimeters = 670 mm/psia * Pressure_{TC}
Where Pressure_{TC} is the Temperature-Corrected Pressure in pounds per square inch absolute

Real-Time Transmission of Data

The real-time transmission of messages varies depending on the operating mode of the BPR as described below. Transmission of real-time water level heights occurs when the Tsunami Detection Algorithm triggers a suspected event, when interrogated by the TWCs or NDBC, or at pre-scheduled

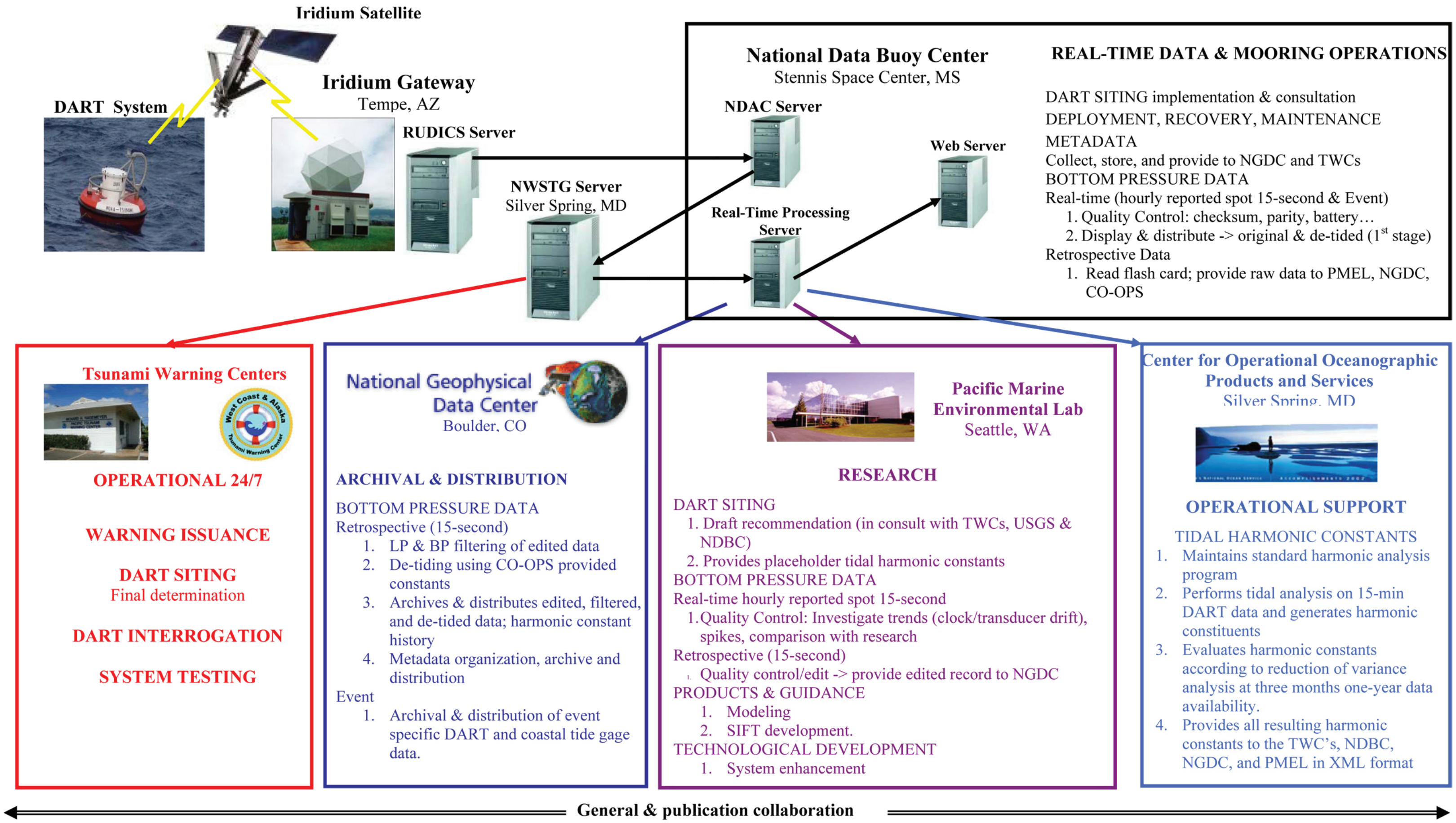

Figure 15. Flow of DART™ data from buoy to archive.

intervals. Data flow is shown in Figure 15. The BPR transmits the messages to the surface buoy via underwater acoustics systems. The surface buoy is equipped with duplicate and independent communications systems to transmit data to the Iridium satellite and then on to the Iridium Gateway in Tempe, Arizona, where an Iridium Router-based Unrestricted Digital Internetworking Connectivity Solution (RUDICS) routes the data to NDBC's RUDICS Server at Stennis Space Center, Mississippi. RUDICS then routes the messages to a Data Acquisition Center server located at the Stennis Space Center. There, NDBC attaches NOAA header information and message identifiers and sends the data to the National Weather Service's Telecommunications Gateway (NWSTG) in Silver Spring, Maryland, for Internet distribution via the global telecommunications operation center. The TWCs and NDBC pick up the data from the NWSTG broadcast. NDBC decodes and reformats the data for real-time Web display and database storage. If the buoy is unable to establish the connection to the NDBC RUDICS Server, information does not move from the buoy's communication buffer.

A TWC or NDBC can initiate an interrogative data retrieval mode, or set the BPR in Event Mode. However, the Iridium receivers on-board the surface buoys have a limited amount of receive time. Upon receipt of the command to retrieve high-frequency data, the BPR transmits one-hour of 15-second pressure and temperature data. The data parameters are in a similar format as that written to the on-board memory card. (See Appendix C.) NDBC will maintain a catalog of these data for possible archive.

DART™ Operating Modes

DART™ systems operate in one of several data reporting modes: standard, event, and extended (Table 2, next page). In addition, DART™ systems provide on-demand access to the internally recorded 15-second data that resides on the flash card. The 15-second sampling generates about 18 megabytes of data per year. The system operates routinely in low-power standard mode. Standard mode provides 15-second reports of the water-level observations at 15-minute intervals in a single message sent from the BPR every six hours. A total of 24 individual water-level measurements are included in each message. Standard mode messages include component-specific information useful for monitoring system performance. Message ID, message status, date, time, battery voltage, acoustic modem digital signal processing battery voltage, acoustic modem battery voltage, number of tries to deliver tsunameter data, checksum delimiter, and parity are parameters regularly monitored.

When the internal tsunami detection software identifies an event, the system switches from standard reporting mode to event reporting mode. Transmissions of 15-second values occur for two minutes following BPR trigger, after which time an extended-reporting mode begins, with transmission of a series of messages containing 15 one-minute average values (one-minute averages are computed from four 15-second values).

Table 2. DART™ Transmission

Mode	Data Sample Interval	Data Transmission Packet	Data Latency	Duration
Standard	15-second	Four discrete 15-minute samples per hour in 6-hour packets	Up to 6 hours	Outside of Event mode
Event	15-second	15-second	< 3 minutes	1st two messages after Event Trigger -0.75 minutes before event and 2 minutes after event
	1-minute average	15-minute	< 3 minutes	4 hours if no further events are detected
Interrogative	15-second	15-second	Up to 1 hour	1 hour
Extended Reporting	1-minute average	120 minute	Up to 1 hour	1 hour prior to event until *several hours* event free

In extended-reporting mode data are retrieved for the hour prior to the event. Therefore, messages consist of 120 one-minute averaged values transmitted every hour. The one-minute values consist of the average of four 15-second values. This mode transmits data for four hours following event detection. If the system detects additional events, extended reporting mode transmission will continue past the four-hour window. Cessation of activity during extended reporting mode returns the BPR to standard mode of operation.

The DART™ bidirectional communications capability enables commands to be sent to the BPR via the buoy. This provides the capability to put the BPR into event mode or to request a one-hour block of 15-second binary pressure and temperature counts. All DART™ transmission modes, with the exception of the interrogation mode, transmit estimated water level. For additional information on the message content, see Appendix C, Data Formats.

Data Management

Responsibility for management of the DART™ data involves the NDBC, PMEL, NGDC, the TWCs, and CO-OPS. The NWS supports observations and data management through NDBC (Green and Smith, 2006) and collaborates with the other offices to accomplish these activities. NGDC, working with NDBC, PMEL, and CO-OPS, archives the original data, the edited (calibrated and validated) data, provides filtered data and algorithms, validates the metadata, and provides access to the integrated tsunami data archive.

As applicable, NDBC conducts pre- and post-deployment calibrations and measurements of the BPR components to support PMEL in obtaining drift rates and new operating coefficients. NDBC also develops and distributes necessary metadata records and forwards the off-loaded observations, calibration and observation files, and metadata files to PMEL and NGDC. PMEL and CO-OPS work with TWCs, NDBC, and NGDC to provide operational support products and guidance with respect to tidal harmonic constants, de-tiding algorithms, quality control, siting considerations, and modeling activities. The major operational and retrospective responsibilities are described below.

Operational Real-Time Data Responsibilities

NDBC

Mooring Operations

- Siting
- Instrument calibration
- Deployment, recovery, maintenance
- Operational monitoring, quality control
  - ✔ Monitor message parity, checksum, battery, buoy location, etc.
- Display de-tided data (first stage de-tiding)

Data Management

- Real-time data access
  - ✔ Monitor DART™ data communications and initiate corrective or preventative action to meet implementation data latency requirements.
  - ✔ Provide online access to DART™ data until data become available through NGDC.
  - ✔ Provide NGDC access to event-specific data within three months of an event.
  - ✔ Make available the retained real-time data to CO-OPS for tidal harmonic analyses.
- Documentation and distribution of metadata
- Provide metadata (Appendix C) to NGDC within 30 days of the return of the service crew following mooring operations.

NGDC

Mooring Operations

- Bathymetric siting maps

Data Management

- Acquire, archive, and distribute event-specific data within 1 month of receipt.
- Provide filtering algorithms and supporting documentation.
- Provide integrated access to tsunami data, including runup, coastal and deep-ocean sea-level data.

PMEL

- Provide new and updated DART™ site recommendations to the TWCs as the DART™ array evolves, and in response to observed events.
- Provide startup harmonic constants, based on global tidal models, until sufficient *in situ* observations allow computation of data-based constants by CO-OPS.
- Perform quality control tests on the data stream, including unscheduled tests associated with minor tsunami events.
- Incorporate engineering research and development into improved DART™ systems.

CO-OPS

- Harmonic tidal constants
    - ✔ Compute at both three-month and one-year data availability intervals.
    - ✔ Provide data to TWCs, NDBC, PMEL, and NGDC in XML format (Appendix C).

Tsunami Warning Centers

- Decode autonomous operational DART™ data stream.
- Monitor DART™ network and issue warnings.
- Initiate DART™ system interrogations for high-frequency, on demand data.

Retrospective Data Responsibilities

In addition to the real-time reporting operation modes and the two-way communication interrogation capability, each DART™ BPR records 15-second data internally on a flash card for the entire BPR deployment period. These data are retrieved following scheduled bottom package recovery, typically two years after deployment. Upon the recovery of a BPR, NDBC technicians remove the flash memory card containing the continuous 15-second pressure and temperature frequency counts and one-hour time stamps for delivery to PMEL for processing and to NGDC for long-term archive.

PMEL edits the retrospective data, removing the pre-deployment and post-recovery signals and spikes using editing techniques to avoid altering the observations in any way. PMEL, with CO-OPS, also examines the record drift and time base stability and performs specific filtering and tidal signal removal for tsunami modeling activities. To convert pressure in psia to metric units, a constant, derived using Levitus climatology to estimate vertically average density, is applied to retrospective data in place of the constant applied to real-time transmissions (Eble et al., 1989).

NDBC

- Recover BPR.
- Conduct post-calibrations and measurements.
- Provide short-term retention of data until safely transferred to NGDC and PMEL.
- Notify and provide NGDC and PMEL with original data within 30 days of the return of the recovered BPR.
- Provide accompanying metadata to NGDC and PMEL.

NGDC

- Maintain a long-term, easily accessible archive of research quality DART™ BPR data:
    - ✔ Original (frequency count data);
    - ✔ Calibrated data using Paroscientific™ conformance equation coefficients;
    - ✔ Edited data provided by PMEL;
    - ✔ Two- and 40-hour low pass filtered data; and
    - ✔ Residual bottom pressure record (de-tided research quality data).
- Maintain a long-term, easily accessible archive of associated metadata.
- Provide filtering algorithms and supporting documentation.
- Provide integrated access to DART™ and other tsunami data.
- Interface with the GEOSS liaison in Geneva, Switzerland for data distribution standards.

CO-OPS

- Maintain and provide the standard harmonic analysis program to be used for the de-tiding of the data.
- Perform the harmonic analysis upon the DART™ data by downloading data from the NDBC Web site. Conduct the preliminary analysis on three months of data, followed by a final analysis after one year of data are accumulated.
- Perform quality control of analyses via a predicted vs. observed residual analysis to check for discontinuities, datum shifts, and invalid data. Evaluate harmonic constants according to reduction of variance analysis for both three months and one year data availability intervals.
- Provide tidal harmonic constants to PMEL for quality control and research, and to NGDC for archive.

PMEL

- Process original data.
- Convert original data from binary counts to scientific units for pressure (psia) and temperature (Celsius) using Paroscientific™ conformance equation coefficients.
- Perform quality checks and provide feedback to NDBC.
    - ✔ Check for drifts in pressure and time base and make adjustments to data series as warranted.
    - ✔ Perform drift analysis.
    - ✔ Flag missing data; indicate outlier values with poor quality flags.
- Process raw data.
    - ✔ Remove pre- and post-deployment data segments.
    - ✔ Flag outliers and replace with coded values.
    - ✔ Remove any easily quantified drift.
- Acquire, as appropriate, all available high-frequency data following tsunami of interest.
- Provide edited data and associated metadata to NGDC for long-term archive.
- Publish data reports and peer reviewed journal articles with interagency collaboration.

Archive and Access

NDBC maintains the real-time data, provides early access to these data through their Web site (http://www.ndbc.noaa.gov/dart.shtml), and transfers the event-specific and original BPR data to NGDC for archive. NGDC manages the archive according to National Archives and Records Administration (NARA) standards, storing data on approved archive media with complete Federal Geographic Data Committee (FGDC) standards-compliant metadata. Archive data are written to two Linear Tape Open (LTO) II tapes stored on-site and off-site in climate-controlled environments with chemical fire suppression systems. In addition, NGDC winds and re-winds the tapes regularly to prevent data corruption and the archive undergoes complete media refresh every five to seven years. To clarify archive roles, NGDC develops standard Data Submission Agreements with data providers. NDBC, PMEL, and CO-OPS are working with NGDC to record technical, metadata, and archival contact information, data formats, data submission packets, quality information, data validation processes, data lineage, and distribution and access requirements. The DART™ Data Submission Agreement is available from NGDC.

NDBC maintains the sea level heights embedded in standard and event mode transmissions. These data are available for download from the NDBC Web site. Additionally, NGDC archives the event mode transmissions as part of an event-specific data archive. Figure 16 (next page) shows the general flow of data in the archive.

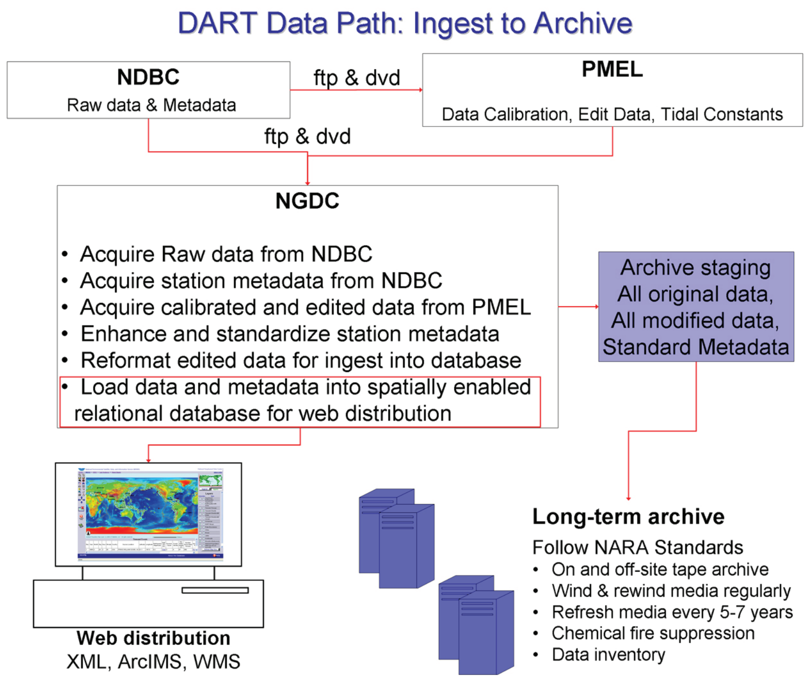

Figure 16. DART™ archive data flow.

NGDC archives the retrospective 15-second averages of pressure in psia and temperature in degrees Celsius following at-sea BPR recovery operations. Original data are available following preliminary quality control checks. Edited data are processed by PMEL and then provided to NGDC for inclusion in the archive. In addition to these data, NGDC maintains extensive metadata on each deployment record. Free and open access to the calibrated, edited, retrospective data and metadata enabling search, select, plot, filtering, and downloads is via a Web interface from the NGDC Web site at: http://www.ngdc.noaa.gov/hazard/DARTData.shtml.

End-to-End Vulnerabilities

Single Points of Failure

- Communications components: Iridium Gateway, NDBC RUDICS Server, NWSTG, communications between the NWSTG and the TWCs
- Surface buoy: Either due to catastrophic loss or mooring failure that will cause the buoy to move beyond range of the underwater acoustic transmissions
- Failure of the BPR's acoustic release system, so that the BPR cannot be recovered
- Failure of any BPR components involved—the pressure sensor, the computer, the oscillator, clock, or the flash memory card

Data Vulnerabilities

- Ocean conditions may reduce the effective range of the acoustic transmissions or acoustic interference (Milburn et al., 1996) may cause intermittent interruptions of data stream to the surface buoy.
- In heavy seas, the buoy may pitch and roll to such an extent that Iridium transmissions may not have optimum gain from the omni-directional antenna, or may suffer attenuation in extreme cases due to the conical radiation pattern of the Iridium right-hand circularly polarized antenna. Additionally, water from very high waves breaking over the antenna could block transmission.
- The Internet, NWSTG, and NWSTG–to–TWC communications may experience outages.
- Excessive drift or inaccuracies of the pressure sensor, oscillator, or clock could cause degradation of observations including time and frequency of observation.
- Though infrequent, the BPR may shift after settling.
- Data may be interrupted or partially written to the flash memory card.

Gaps and Recommendations

- At present, there is a single point of failure in the communications stream. NOAA is addressing this by establishing a primary communications path from the Iridium RUDICS server to the NWS Telecommunications Gateway, retaining the communications between the Iridium Gateway to the NDBC RUDICS Server as a secondary or alternate communications path, and establishing secondary paths from the TWCs to the NWSTG.
- NDBC has responsibility for real-time data and communications monitoring, but is not a 24x7 center. Integrated Ocean Observing System (IOOS) supplemental funds were used to establish 24x7 data monitoring during FY06 and FY07, but other sustainable alternatives must be explored.
- Additional calibration functions, on-scene measurements, and data management activities associated with the expanded network of DART™ systems and identified in this report may require additional technical and data management resources at NDBC.
- CO-OPS will provide access to harmonic constants from DART™ buoy stations over the Internet via a file transfer protocol (FTP) site and download from the CO-OPS home page.
- Develop an observing system architecture to design, build, deploy and operate tsunami observation and data management systems in conjunction with IOOS and the all-hazards GEOSS. Tsunami real-time observing system (including seismic, water-level, and oceanographic) and data management systems (including modeling and archiving) are key elements of IOOS and GEOSS. A tsunami program can be developed with the IOC and IOCARIBE frameworks or within bilateral or regional agreements. The observing and data management systems could leverage and drive the IOOS Data Management activities as part of the U.S. Ocean Action Plan with Federal/State and regional partnerships. Observing

architecture is needed to optimize integration and to clarify priorities for local, regional, and national versus international projects and sustainment versus durability.

- Establish Program Management and Affordability Management for a distributed program of national and international activities. NOAA's Tsunami Program was established in 2005 in parallel with Supplemental funds to strengthen domestic and international tsunami programs. This requires by mandate inter-Line Office, interagency and intergovernmental coordination. There is a need for increased expertise in program management, scheduling and business case/financial analysis to maintain the integrated national and international program. Staff could be tasked from NOAA Lines and Offices and other programs to serve this role. Additional contract support including acquisition of integrated program affordability and collaboration tools can assist in planning, implementation and operational tracking, coordination, and reporting.

Coastal Tide Data

Background

NOAA's Tsunami Program relies on coastal water level data from two primary sources: (1) the National Ocean Service (NOS) CO-OPS; and (2) the Global Sea-level Observing System (GLOSS) data from the University of Hawaii Sea Level Center. At present, this report only covers the CO-OPS and NOAA TWC coastal water-level data.

CO-OPS has been involved with tsunami warning and mitigation since the Coast and Geodetic Survey started the Tsunami Warning System in 1948 to provide warnings to the Hawaiian Islands. The Pacific Tide Party (PTP), established following the deadly Unimak Island tsunami of 1946 and supported by the U.S. Navy, was based out of Pearl Harbor. The PTP primary mission was to install and maintain tide stations for the Tsunami Warning System, including a few in foreign countries—Japan, French Polynesia, Fiji, Samoa, and New Zealand. Tides, tidal datums, and sea level measurements were secondary products for this network. The PTP continued to maintain tsunami tide stations in accordance with a 1970s memorandum of understanding with the National Weather Service (NWS). Gradually, NWS took over the station maintenance at the tsunami-only stations. However, CO-OPS continued to maintain tsunami-reporting capability for NWS from the National Water Level Observation Network (NWLON).

After the December 2004 Indian Ocean tsunami, CO-OPS was tasked to coordinate with the NOAA Tsunami Warning Centers in upgrading existing stations with new Data Collection Platform (DCP) and communications technology, and with expanding the tsunami warning capabilities of NWLON. Work began in 2005 to upgrade 33 existing water level stations and install 16 new stations from the Pacific Ocean to the Caribbean Sea by October 2006. As of September 2006, all 33 upgrades were complete, as well as 15 of the 16 new installations. As of October 2006, NWLON consisted of 196 long-term water level stations along all U.S. coasts, including the Great Lakes, Alaska, Hawaii, the Pacific Ocean Island Territories, Puerto Rico and the U.S. Virgin Islands (Figure 17). The TWCs also operate sea level networks that supplement NOS and GLOSS networks as needed. The PTWC operates many gauges throughout the Pacific Basin and locally in Hawaii. The WCATWC operates several gauges in Alaska and supports equipment at some

Figure 17. Tsunami tide station in Christiansted, Virgin Islands.

NOS gauges which transmit 15-second sample data in real time. These NOAA stations, along with GLOSS, establish a core network of sea level stations for local and distant tsunami monitoring. High-frequency real-time sea-level data support the Tsunami Program observation requirements for Regional and Global Water Level Observations as described in the Consolidated Observational Requirements List (CORL).

Observation Acquisition and Transmission

Great care is taken to obtain long-term continuous and valid water level data from the NWLON stations. The tide houses containing the equipment are designed to last 30–40 years and underwater components are designed to withstand harsh coastal wave and current environments. All stations have an associated network of benchmarks surveyed to ensure vertical stability of the gauge, and to preserve a consistent data record in case of vertical movement due to pier deterioration, earthquakes, ship/dock collisions, or station destruction by coastal storms. If destroyed, a new station can be established relative to the same vertical reference datum. Differential leveling is done on a yearly basis between the water level sensor and the benchmarks to ensure vertical stability of the sensor relative to the land, and to ensure consistency and vertical stability between the benchmarks. Each station undergoes annual routine operation and maintenance, including any required sensor recalibration.

Figure 18 illustrates a typical NWLON station configuration featuring both acoustic and backup pressure sensors. Due to the severe effects of ice and because downward looking acoustic

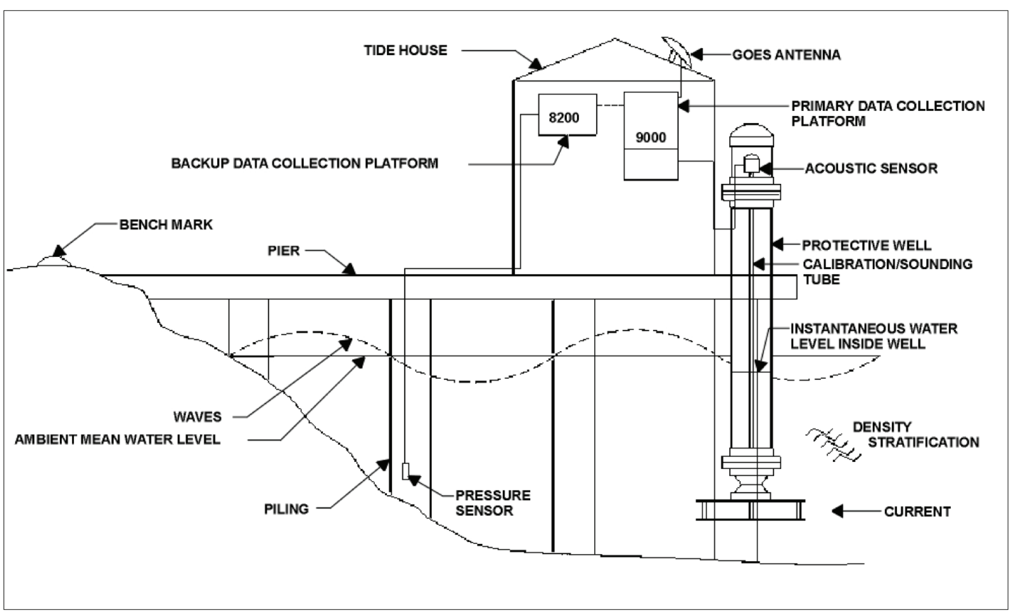

Figure 18. Common tide station configuration. Acoustic and pressure sensors have a primary and backup DCP.

sensors cannot measure the correct water levels when the water is frozen or ice accumulates in the sounding tube, many Alaska NWLON feature a primary dual orifice pressure sensor configuration. Two vented high precision Paroscientific™ transducer sensors are connected to two bubbler-driven or gas-purging orifices that are separated by a meter or two to resolve water density corrections. There are primary and backup DCPs at every station. Lower precision strain-gauge Druck pressure sensors are typically used for the backup system. This two DCP configuration limits the potential for data gaps associated with equipment malfunction and, in tsunami station configurations, the primary DCP records both one- and six-minute averaged water level values while the backup DCP records 15-second and six-minute averaged water level data that can be accessed following an event. To ensure data collection during the winter ice season, the Great Lakes NWLON stations consist of a float driven shaft angle encoder enclosed in a sump well located inland from the water and connected to the water by a horizontal inlet pipe.

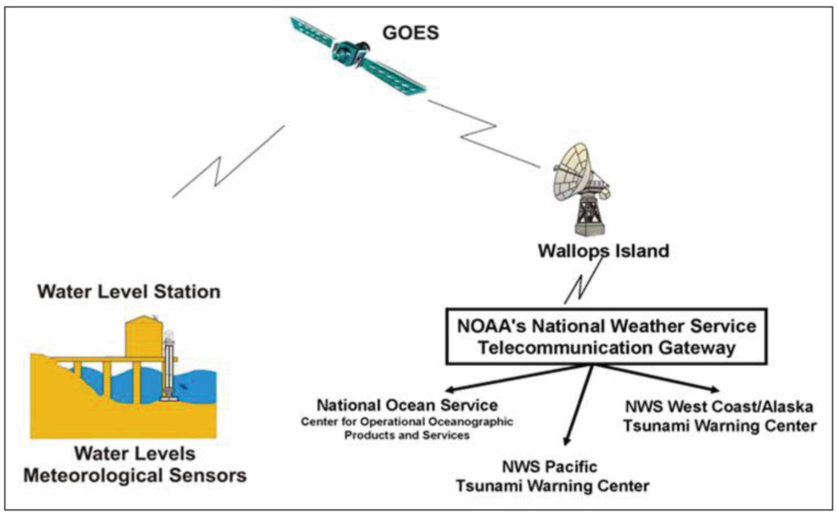

Figure 19. NOAA water level data transmission via GOES satellite.

The recently completed upgrades developed by CO-OPS and the TWCs are a landmark achievement for CO-OPS and its National Water Level Program. Information is transmitted via the Geostationary Operational Environmental Satellites (GOES) for both the primary and backup DCPs (Figure 19). For the first time, the upgraded DCPs will be transmitting one-minute averaged water levels every six minutes. These stations also store 15-second data on a flash drive for post event analyses and modeling. The 15-second data can be manually downloaded from the station itself or remotely using the DCP modem. The TWCs have direct access via GOES, remote phone dial-in, and the CO-OPS Web pages to the six-minute and one-minute data (one-minute data in emergency mode only for the older systems).

All new and upgraded CO-OPS coastal tsunami water level stations utilize Sutron Xpert DCPs (Table 3, next page). This is a significant improvement from the previous generation Sutron 8200 (backup) and Sutron 9000 (primary) DCPs, which utilized hourly transmissions of six-minute averaged water level values, requiring a switch to emergency mode to transmit high-resolution data.

Table 3. NWLON Tsunami Water Level Station Transmissions

	Normal Mode		Emergency Mode	
DCP Type	**Data Sample Interval**	**Data Transmission**	**Data Sample Interval**	**Data Trans-mission**
Sutron 9000 (primary)	1-minute averages logged but not transmitted	6-minute average water level hourly via GOES	1-minute average water level	5-minute random transmission via GOES
Sutron 8200 (backup)	Continuous sampling at 15-seconds with 5-days of storage on RamPak	6-minute data transmitted via serial cable to primary DCP. Hour and half-hour values sent with primary GOES transmission	Continuous sampling at 15-seconds with 5-days of storage on RamPak	Manual removal of RamPak cartridge
Xpert (primary)	Six 1-minute average water level and One 6-minute average water level	6-minutes via GOES	No longer required	
Xpert (backup)	15-second and 6-minute average water level	6-minutes via GOES; Modem or direct serial connection to Xpert primary for 15-second		

Emergency mode is triggered either manually or when the system algorithm detects a potential tsunami. Emergency mode for these older systems, still operating on many of the CO-OPS tide stations, consisted of five-minute random transmissions of averaged one-minute water level data and recording one-minute averages by the primary DCP and 15-second averages by the backup DCP for up to five days. The 15-second data, of primary importance for research in the event of a tsunami, were stored on a RamPak and have to be manually retrieved within five days or data was overwritten due to limited RamPak memory.

There are currently 73 NWLON stations on the West Coast, Alaska, and in the Caribbean operating with an Xpert DCP. The Xpert system utilizes six-minute GOES transmissions of one six-minute averaged water level data point and six one-minute averaged water level data points. The secondary DCP records one six-minute averaged water level data point, which is also stored on the primary DCP

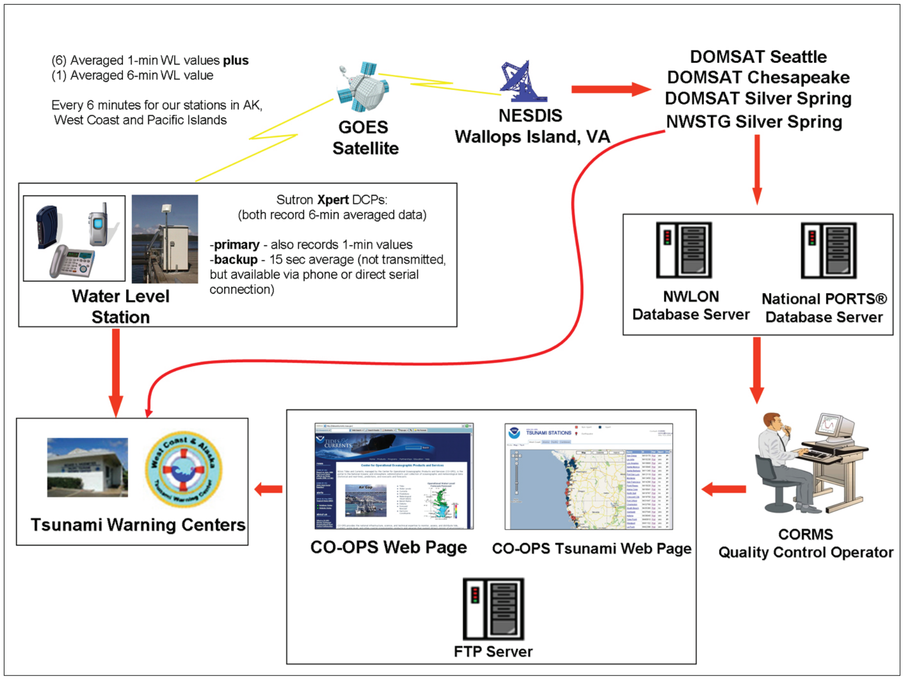

Figure 20. CO-OPS water level data flow.

and transmitted in the primary DCP GOES transmission. The secondary DCP also records 15-second data required by PMEL for modeling applications that can be remotely downloaded via modem or direct serial connection. Xpert DCPs eliminate the 5-day memory overwrite problem and the need for Emergency Mode transmission. CO-OPS is continuing to upgrade the NWLON stations to the Xpert system through Fiscal Year 2007, extending the same capability to the East and Gulf Coast stations.

Figure 20 shows data flow of the CO-OPS station water level data. Data are transmitted via GOES to the Wallops Island Retransmission Ground Station (operated by the NOAA National Environmental Satellite, Data and Information Service). Then data continue via a Domestic Satellite (DOMSAT) to the Local Readout Ground Stations (LRGS) in Seattle, Washington; Chesapeake, Virginia; Silver Spring, Maryland; and also to the NWSTG. CO-OPS attempts to retrieve data from the DOMSAT LRGS in Seattle first, followed by Chesapeake, and the Silver Spring DOMSAT if there are problems. If CO-OPS cannot retrieve the data from the DOMSAT, it acquires the data from the NWSTG for entry into the NWLON Database Server.

The TWCs can currently access water level data in two independent ways: (1) GOES over the NWSTG; and (2) via the recently developed Tsunami Stations Web site (Figure 21, next page) at http://tidesandcurrents.noaa.gov/tsunami/. CO-OPS assisted the TWCs in developing software to decode the pseudo-binary encoded GOES messages and transmission IDs so they are able to decode

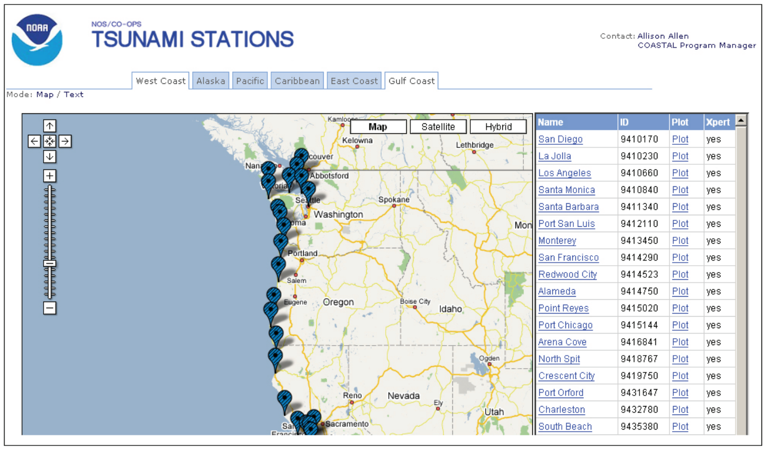

Figure 21. CO-OPS Tsunami Stations Web page.

and display raw, uncorrected (not on datum) water level data. The TWCs can also access one-minute and six-minute near real-time vertically corrected (on datum) water level data through the Web page. One-minute water level data from several coastal tsunami stations are also available via FTP for three days following transmission. These data are pulled directly from the database, and are not processed or quality controlled in any way.

Xpert DCPs are also equipped with modems and are accessible by phone for diagnostics, firmware upgrades, reconfiguration, troubleshooting, and data retrieval wherever phone or cellular service is available. CO-OPS can utilize this existing capability to support the Tsunami Warning Centers. Continuous real-time 15-second data cannot be accessed through Xpert DCPs by phone at this time, but efforts are being made by Sutron and CO-OPS to reach this goal.

Data Management

CO-OPS monitors water level data as they arrive using a Continuous Operational Real-Time Monitoring System (CORMS). CORMS provides primary real-time quality assurance and control through a combination of human analysis and flags set for various tidal parameters, such as rate of change, that alert watchstanders of events, changes, or potential problems. All CO-OPS data and products are monitored and reviewed on a 24x7 basis by experienced watchstanders on 12-hour rotations. When a problem is detected, appropriate action is taken immediately to either remedy the situation within CORMS or notify the appropriate field, headquarters, or IT personnel to take corrective measures. Dissemination of data are temporarily stopped if necessary until the problem is solved, to ensure dissemination of accurate data only.

While CORMS provides a preliminary, near real-time quality control measure, all six-minute water level data are quality controlled by a trained expert during post processing and routine product dissemination. Data processing involves checking the data for errors, such as false spikes, checking it for consistency, filling any data gaps, tabulating high and low tide heights, deriving hourly tide data, tabulating extremes, and calculating monthly means and tidal datums. There are several measures taken to detect shifts, biases, or changes. Routine checks include those for abnormal rates of change, abnormal flat spots, and abnormal out-of-range data. In addition to data quality flags, based on the checks listed above, gain and offsets for the backup pressure data are routinely calculated and checked for abnormalities between primary and backup sensor data. Comparisons are made with predicted tides and with data from nearby stations. If any significant errors are noted in this process, corrective action can be taken, either to correct the data or to repair malfunctioning sensors or DCPs at the station. A verifier then checks the data and subsequent products to ensure accuracy, and verified data are stored in a database and made available online, typically within one month of the end of each calendar month.

In addition to currently operational NWLON stations, and the augmenting network of short-term stations operating around the country for various projects (such as hydrographic surveys) CO-OPS has tide information from several thousand historical locations. CO-OPS protocol is to install a network of tidal benchmarks in association with a tide gauge. Therefore, many of these historical locations have recoverable benchmarks to document the water level elevations relative to the land. In the event of re-occupation, the historical time series data can be related to the most current data. However, while records and summary information exist for these historical water level stations, high rate digital data was not available until the introduction of digital punched paper tape data loggers in the mid 1960s. Prior to that, analog strip chart recorders were used. Tsunami signals were read manually off the strip charts to determine the amplitudes and phases after tsunami events. Archived strip charts are available from CO-OPS.

Changing record mediums, ranging from paper punch tape to 15-second digital tsunami data, different sampling rates over time, different data management systems, and tidal datums computed on different 19–year National Tidal Datum Epoch time periods all pose data management challenges. Measures have been taken to digitize archived historical hourly height and monthly mean water level records for long-term NWLON stations. Old hardcopy metadata records are now being scanned. However, recovering and digitizing all of the old hand written tabulations from thousands of historical stations and recovering digital six-minute data from the 1960s and 1970s are monumental tasks.

Archive and Access

CO-OPS maintains the water level data and harmonic constants (for both coastal tide gauges and DART™s) internally in a spatially-enabled relational database. Although CO-OPS backs up water level data locally, no formal data archive exists. NOAA needs to address this significant gap in data management. Presently, water level data are backed up through normal systems back-up using LTO technology.

A full backup is performed once a week with incremental backups performed daily. The FTP server is backed up on the first and third week of each month. At this time, there is no routine collection, quality review, or archive for the 15-second data. Backup tapes are maintained on a rotating four-week basis. The two most current tapes are kept in the CO-OPS Computer Room. The third oldest

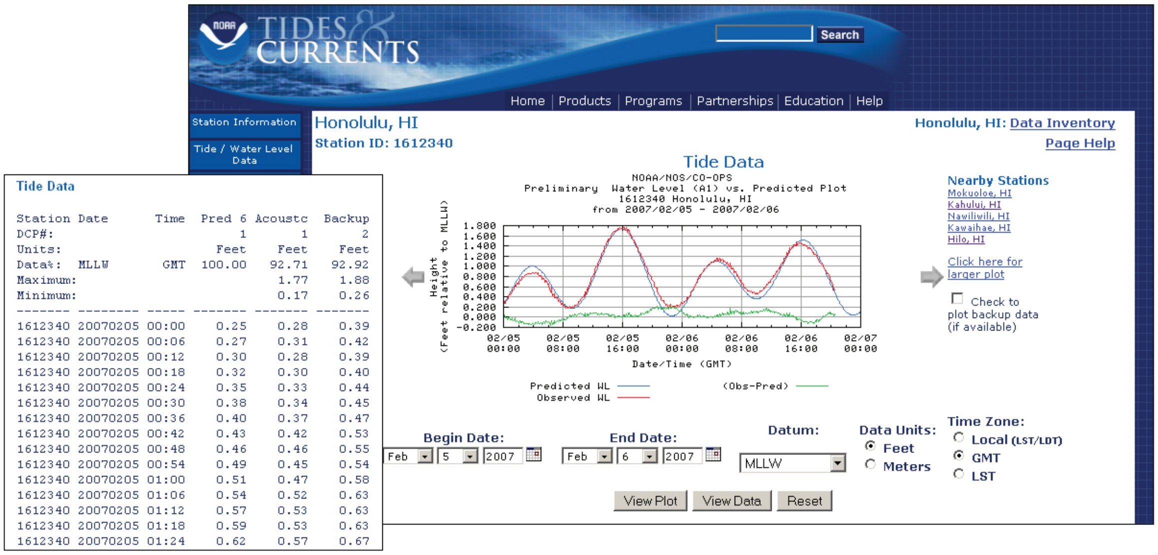

Figure 22. Web access to coastal water level data.

tapes are stored in an on-site fireproof vault while the oldest tapes are stored in a fireproof safe at the CO-OPS Pacific Regional Office in Seattle, Washington. Tapes are rotated once a month and the tapes from Seattle are returned for re-use or kept as quarterly backups. The first full backup of each quarter is kept for one year. At the system administrator's discretion, tapes may be marked for retention of more than one year. All backups report errors if the process did not successfully complete. System administrators check for the errors and correct the issue. Backup tapes are tested quarterly by doing a test restore to verify that the tape is still in good condition. Data from the TWC water level stations are not currently incorporated into the CO-OPS data management or archived to NARA standards.

As a first step towards archive compliancy, efforts are underway to determine resources required to develop FGDC-compliant station metadata, transfer the historical data to a NOAA Data Center, and establish routine transfer of the retrospective (non-real time) data for archive. FGDC-STD-001 (1998) describes the standard FGDC metadata format structure. The goal is to develop standard metadata and transfer the data and metadata to a formal NOAA archive center in 2007. At this time, there is no quality control protocol in place for one-minute tsunami data. CO-OPS will need to determine what quality control algorithms, specific to this tsunami data, must be developed and implemented before these data are made available to the public.

CO-OPS makes its data available in two primary standard formats: (1) American Standard Code for Information Interchange (ASCII); and (2) Open-source Project for a Network Data Access Protocol (OPeNDAP). The ASCII format is space-delimited with self-describing column headers (Figure 22). The comma-separated OPeNDAP format provides description boxes that contain metadata information about a particular parameter. In addition to the OPeNDAP server, CO-OPS supports basic Web services, using SOAP via JAVA, for data download. The data are returned in an XML schema with an XML style sheet. While the XML conforms to the World Wide Web Consortium standard, NOAA is exploring the evolving international Marine XML standard for data distribution. Other methods of data distribution include FTP, voice, fax, CDs, model network Common Data Form files, and hard copies.

End-to-End Vulnerabilities

Single Points of Failure

- No formal long-term archive for the CO-OPS and TWC coastal water-level data
- No routine acquisition of the 15-second data and no retention of the these data
- No easy access to retrospective data from either CO-OPS or the TWCs
- Continuity of Operations Plan (COOP) not fully functional; awaiting completion of new facility in Chesapeake, Virginia, for backup Web site

Data Vulnerabilities

- Tsunami Warning Centers cannot directly phone in and view real-time data from latest generation DCP (Sutron Xpert DCPs).
- One-minute data are not currently quality controlled to same level as the six-minute data.
- 15-second data are only collected on request and has no quality control or archive.

Gaps and Recommendations

- FGDC compliant station metadata
- Formal data archive for both CO-OPS and TWC data and metadata
- Fully functional COOP
- An operational Web site providing from tsunami station water level data
- Address one-minute quality control issue in unison with archive issue to ensure quality of archive.

Bathymetry and Near-shore Topography

Background

Near-shore bathymetric and topographic data necessary for developing high-resolution tsunami inundation digital elevation models (DEMs) are collected by a number of different Federal, State, and local government agencies, academic institutions, and private companies. NOAA's NGDC obtains data and performs data evaluation and quality assessment prior to DEM generation (Figure 23). NGDC provides the DEMs to the NOAA Center for Tsunami Research at PMEL. These combined bathymetric–topographic DEMs are part of the NOAA tsunami forecast system, Short-term Inundation Forecasting for Tsunamis. The Method of Splitting Tsunami model developed by PMEL to simulate tsunami generation, propagation, and inundation require these DEMs.

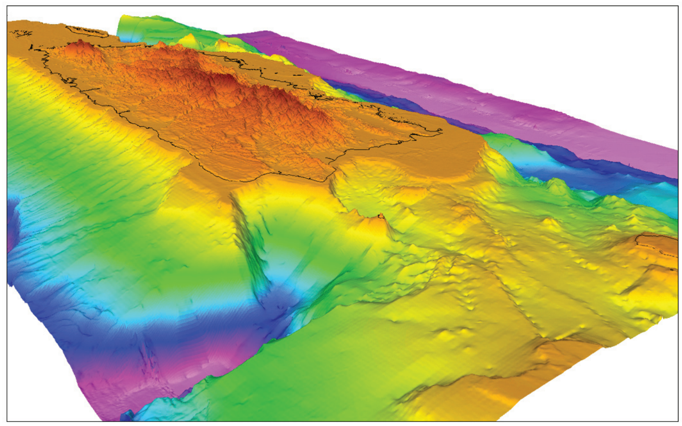

Figure 23. 3-D graphic of the Puerto Rico DEM.

NOAA's NOS is the principal Federal agency involved with near-shore bathymetric data collection for the U.S., primarily for nautical chart production and locating navigational hazards. NOS data standards meet or exceed those required for the tsunami inundation DEMs, and an established process exists for data quality assessment by NOS and data archiving by NGDC. The following sections detail the collaborative effort to acquire, process, and archive the NOAA data utilized for both the Marine Transportation System Program and the Tsunami Program inundation DEM development. These data and resulting DEMs are also applicable for the Weather and Water Goal storm surge modeling activities.

Observation Acquisition and Transmission

Hydrographic Survey Data

Data collection and compilation for nautical charts are the principle objectives of an NOS hydrographic survey. The survey data support a variety of maritime functions including safe navigation, port and harbor maintenance (dredging), coastal engineering (beach erosion and replenishment studies), coastal zone management, and offshore resource development. The primary data associated with hydrographic surveys are water depth (bathymetry) and object detection (Figure 24, next page). However, there is also considerable interest in sea-floor texture and composition

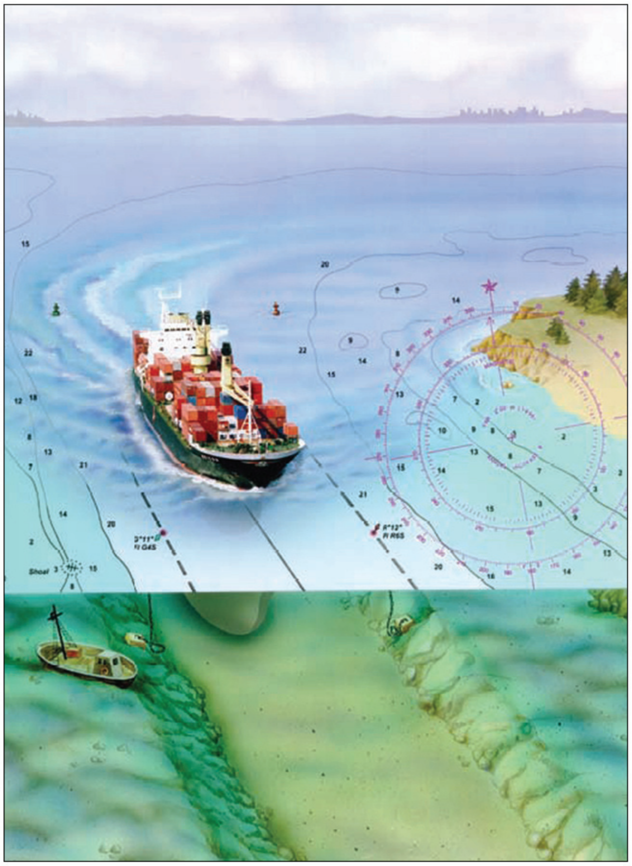

Figure 24. Accurate bottom survey data are essential to safe navigation.

(i.e., sand, mud, rocks) due to their implications for anchoring, dredging, marine construction, pipeline and cable routing, tsunamis, and storm surge modeling. Such backscatter and side-scan sonar data can also be used to support other NOAA missions such as fish habitat characterization, bottom type classification, and submerged cultural resources management.

Data acquisition begins with the selection of a survey area and deployment of resources to accurately and efficiently conduct the survey. Following extensive planning, NOAA or contractor field units conduct hydrographic survey operations. Survey teams calibrate all sonar and vessel orientation and positioning systems prior to data acquisition to assure proper equipment operation. Data accuracy complies with predetermined specifications, and each individual depth measurement is corrected for velocity of sound through the water column, vessel heave, pitch, and roll, vessel configuration offsets, state of tide, and other factors in effect at the time each measurement was acquired. Field units conduct frequent conductivity, temperature, and depth measurements to ensure that proper sound velocity corrections are applied to sounding data. Tide gauges are installed to monitor water level variations in the survey area, providing corrections to reduce data to the proper tidal datum. NOAA's CO-OPS receives tide gauge information via geostationary satellites and continuously monitors transmissions to detect instrument malfunctions.

Global Positioning System (GPS) satellite systems provide positioning for survey data. Additional accuracy is determined using the U.S. Coast Guard Differential GPS (DGPS) network. Fixed land stations monitor variations in GPS satellite signals and transmit correctors to survey platforms during data acquisition. DGPS broadcast sites provide correctors for most survey areas, but remote areas, such as some areas in Alaska, require the placement and maintenance of independent DGPS ground reference stations.

Modern primary depth measurements are acquired with multibeam sonar with the ability to obtain hundreds more soundings per unit time than older single beam systems. Multibeam technology provides from 100% to 200% bottom coverage of the sea floor, greatly enhancing the ability to detect hazards undiscovered by earlier surveys. Data volumes for multibeam and sidescan sonar surveys are also several orders of magnitude greater than the previous single beam surveys, impacting data transmission, archive, and access. During the October 2005 to September 2006 time-period, the hydrographic data archive supporting tsunami inundation modeling increased from 900 Gigabytes (Gb) to 7,400 Gb.

Light Detection and Ranging (LiDAR) Data

NOAA also uses Light Detection and Ranging (LiDAR) technology to collect hydrographic data in near-shore areas where conditions are suitable. LiDAR collection systems use powerful laser sensors comprised of a transmitter and receiver, a geodetic-quality GPS receiver, and an Inertial Navigation System unit. The laser sensor is precision mounted in an aircraft (Figure 25). Once airborne, the sensor emits rapid pulses of infrared laser light that are used to determine ranges to points below.

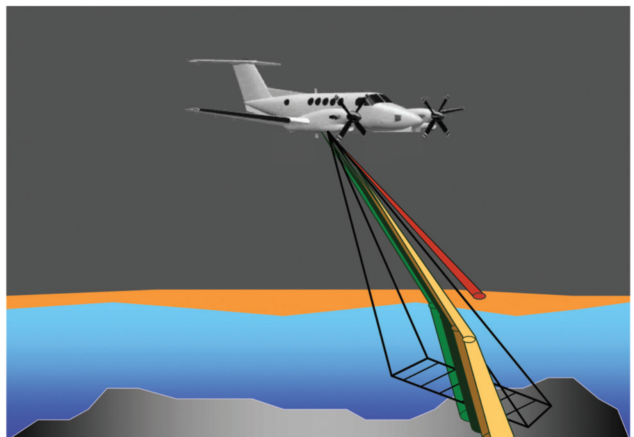

Figure 25. Airborne LIDAR data collection.

It is important to differentiate between the two types of LiDAR. Bathymetric LiDAR uses a laser wavelength that can penetrate water. The light reflects off the bottom, allowing computation of a range to the seafloor. Topographic LiDAR data does not penetrate water and computes elevations of terrain only. Bathymetric LiDAR has a slower pulse rate and larger footprint. Typically, point spacing is about one depth or point every two to four meters, with the spot size being several meters across and increasing with depth. Bathymetric LiDAR provides good general depths; however, the large spots and wide spacing may make it difficult to detect small objects on the seafloor. Topographic LiDAR has a much higher pulse rate and smaller footprint. Spot spacing can easily be less than a meter with a footprint size of less than half a meter. Bathymetric LiDAR systems can compute elevations as they cross from sea to land; however, that topographic data will not be at the resolution of a true topographic LiDAR system.

LiDAR systems use a scanning mirror to generate a swath of light pulses. Swath width depends on the mirror's angle of oscillation, and ground-point density depends on factors such as aircraft speed and mirror oscillation rate. Ranges are determined by computing the amount of time it takes light to leave an airplane, travel to the ground or seafloor, and return to the sensor. A sensing unit's precise position and attitude, instantaneous mirror angle, and the collected ranges are used to calculate 3-D positions of points. A topographic LiDAR system may collect as many as 10,000 positions or “mass points” every second. Post-processing filter techniques are used to remove trees and buildings to produce “bare-earth” data sets.

Using bathymetric LiDAR technology in near-shore areas makes launch operations more efficient by allowing vessels to spend less time in the shallower regions where narrower sonar swath widths are less effective. Bathymetric LiDAR, however, does not provide the object detection capabilities of multibeam. Therefore, some follow-up multibeam work is generally required in irregular sea-floor areas initially surveyed with LiDAR, to resolve ambiguities in the LiDAR data and to perform least depth measurements on significant obstructions.

In addition to contracting for bathymetric LiDAR surveys to support nautical charting activities, NOAA collaborates with the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) to obtain near-shore bathymetric/topographic LiDAR. JALBTCX performs operations, research, and development in airborne LiDAR bathymetry and complementary technologies to support the coastal mapping and charting requirements of the U.S. Army Corps of Engineers (USACE), U.S. Naval Meteorology and Oceanography Command, and NOAA. JALBTCX staff includes engineers, scientists, hydrographers, and technicians from the USACE Mobile District, Naval Oceanographic Office, USACE Engineer Research and Development Center, and NOAA National Geodetic Survey.

JALBTCX executes survey operations using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system and industry-based coastal mapping and charting systems. CHARTS includes an Optech, Inc., SHOALS-3000 LiDAR instrument integrated with an Itres Compact Airborne Spectrographic Imager (CASI) 1500 hyperspectral imager. It collects either 20 kHz topographic LiDAR data or 3 kHz bathymetric LiDAR data, each concurrent with digital Red, Green, Blue (RGB) channel and hyperspectral imagery.

Bathymetric LiDAR data are collected from the shoreline out to approximately 50 meters depth, depending on water clarity. In highly turbid waters, bathymetric LiDAR is not possible as it can’t penetrate into the water. Topographic LiDAR data are collected from the shoreline to 0.5 km onshore at 1 m spacing. The topographic data are collected in opposing flight directions, resulting in 200% coverage of the land portion of the survey. All data are positioned using post-processed kinematic GPS and National Geodetic Survey monumentation. The RGB digital imagery have a ground resolution of 20 cm per pixel and the CASI imagery have a ground resolution of 0.5 to 2 m per pixel, depending on the operational survey requirement. Both sets of images are georeferenced using CHARTS positioning and attitude sensor data. GIS products derived from these data include seamless bathymetric–topographic relief grids, bare earth grids, building footprints, the North American Vertical Datum of 1988 shoreline vector, and RGB or hyperspectral image mosaics.

Historical NOS Surveys

Observational data from historical NOS surveys have been inventoried and prioritized for digitization. Approximately 90% of analog sounding sheets have been digitized to fill in areas with no digital soundings and augment other areas with low quality data.

Data Management

Responsibility for management of the sonar and LiDAR data involves several offices. NOS has primary responsibility for acquisition, real-time monitoring, calibration and validation of observations, but collaborates with other NOAA offices and utilizes private contractors to accomplish some of these activities.

Sonar or LiDAR data acquisition produces millions of measurements, which need to be verified and compiled to produce an accurate, understandable graphic depiction of the survey area. A digital version of the survey and/or a hard copy Smooth Sheet are produced for final quality assurance, nautical chart compilation, and archiving. A descriptive report accompanies each survey and provides detailed descriptions of items that cannot be explained in graphic form. A hydrographic survey incorporates other measurements or observations. These include precise positioning of aids to navigation, conspicuous landmarks, and offshore drilling structures, and sampling of the sea floor bottom material to determine adequate anchorage areas. Also documented are the variations in the shoreline location or features along the shore (e.g., new piers, pilings, bulkheads).

Once a NOAA field unit or contractor completes the hydrographic surveying fieldwork and initial data processing, data are sent to one of the NOS Hydrographic Survey Division (HSD) Processing Branches: the Atlantic Hydrographic Branch (AHB) in Norfolk, Virginia, or the Pacific Hydrographic Branch (PHB) in Seattle, Washington. AHB and PHB conduct final data verification and processing. The raw survey data are loaded onto a digital storage device at the Processing Branch, and then sent from the Branch to NGDC for archive and public distribution. AHB and PHB conduct final data verification, processing, and product generation, then send the final data sets to NGDC for off-site back-up and distribution purposes. In addition, the Branches produce the final chart compilation and sends it to the NOAA Marine Chart Division for production of the final marine navigation products distributed to the maritime community. The Descriptive Report, a detailed survey metadata document, is produced through the survey collection process, approved at the HSD Data Acquisition Control Branch, and sent to NGDC via FTP.

NGDC acquires a variety of coastal relief data from numerous sources for each DEM developed. Integrating ocean depths with land elevations into seamless representations of coastal relief requires reliable vertical geodetic and tidal datums based on an accurate geoid model and a stable control network. Vertical control networks require the establishment of surveyed topographic benchmarks, which are permanently monumented. These networks are observed by geodetic leveling, which can achieve extremely high degrees of accuracy, typically, less than two to four millimeters per kilometer. As discussed under the Coastal Tide Data section, establishing the relationship between geodetic and tidal datums requires leveling of local tide station bench marks to the vertical control network. The current geodetic reference system for North America is the North American Datum of 1983. This datum is essential for leveling coastal data for the conterminous United States to one common reference frame. Without such a datum, the accuracy of the DEMs is seriously compromised.

Comprehensive, accurate vertical control networks for Puerto Rico, the U.S. Virgin Islands and most of western Alaska do not currently exist. A recent tsunami hazard assessment (Dunbar and Weaver, 2006 draft) for the NTHMP, based on past tsunami events and earthquake frequency, identified Alaska, the U.S. Virgin Islands, and Puerto Rico as having a high to very high tsunami hazard. This lack of vertical geodetic datums for these regions results in large uncertainty in orthometric heights (i.e., heights relative to the ellipsoid). This is unacceptable for applications such as tsunami inundation modeling that require highly accurate elevation data. This lack of vertical control also affects the ability to merge bathymetric and topographic datasets seamlessly at the coastline. Local tide stations are not leveled to any geodetic datum, so the relationship between tidal and geodetic datums must be "guessed." This introduces large coastal elevation errors into a corresponding inundation DEM, thus limiting the validity of tsunami inundation studies based upon the DEMs.

Archive and Access

NGDC receives the raw and final processed NOS data and data products from AHB and PHB either through the mail using an external digital storage device, or electronically using FTP. NGDC's primary responsibilities are for the archive and dissemination of the hydrographic survey data. The critical digital data associated with each survey are received by NGDC, entered in an accession database, organized by survey in a common file structure, and archived on a reliable and secure tape archive system. A metadata database maintained at NGDC is used to provide standard metadata records and an online search interface to the public as a means of discovering and identifying the survey data. The data may then be downloaded over the Internet directly from NGDC servers at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html. NGDC data managers respond to data and data access inquiries made to the Hydro.Info@noaa.gov contact email, which is posted on NOS Hydrographic Survey Division and NGDC Web sites.

All raw and processed non-NOAA data utilized in the tsunami inundation DEMs, as well as the final ASCII grid-formatted DEMs are archived at NGDC according to NARA standards as described in the DART™ Archive and Access section. NGDC does not currently archive LiDAR data, with the exception of data from the NOAA Coastal Services Center, which is part of a recent (December 2006) agreement.

End-to-End Vulnerabilities

Single Points of Failure

- Although NGDC archives NOAA's Coastal Services Center LiDAR data, there is no national archive for U.S. LiDAR data.

Data Vulnerabilities

Integrating ocean depths with land elevations into seamless representations of coastal relief requires reliable vertical geodetic and tidal datums based on an accurate geoid model and a stable control network. These highly accurate combined bathymetric–topographic DEMs are part of the NOAA tsunami forecast system. A recent tsunami hazard assessment (Dunbar and Weaver, 2006 draft) for the NTHMP identified Alaska, the U.S. Virgin Islands, and Puerto Rico as having a high to very high tsunami hazard. These areas have no vertical geodetic datum. There is a clear need to establish comprehensive vertical control networks for Puerto Rico, the U.S. Virgin Islands, and Alaska so that tsunami inundation modeling and forecasting can be improved in these regions.

Gaps and Recommendations

There is a critical need for modern near-shore surveys to augment or replace historical data collected with older technology. To meet its charting mandate, NOAA maintains a suite of approximately 1,000 nautical charts that cover the U.S. Exclusive Economic Zone. Nearly half of the soundings published on current nautical charts were acquired using lead line techniques before 1940. Historical soundings, often spaced 500 meters apart, do not provide the high resolution necessary for inundation mapping. In shallow water, tsunamis are affected by morphologic features that are not resolved by historical NOS surveys.

Historical surveys are insufficient for modern charting and inundation mapping for many reasons. Present sounding inventories contain significant gaps, and so represent an incomplete representation of the seafloor. Many navigation areas are dynamic; shoals, wrecks, and changing shorelines are hazards that warrant routing measurement. Anthropogenic and natural changes to the coastline that have occurred after the older surveys were conducted are not reflected in the historical data. This presents a challenge when using the data to develop inundation DEMs that must accurately represent current shoreline conditions for effective tsunami modeling. Historical sounding positions are also less accurate than those computed by technology available to modern vessels using the GPS and Electronic Chart Display and Information Systems, resulting in potential mislocation of submarine features in the tsunami inundation DEMs.

NOAA Programs that rely on accurate coastal DEMs for inundation modeling (i.e., storm surge, flooding, and tsunami) need to work with the National Geodetic Survey to develop and implement appropriate solutions to the geodetic datum issues for Puerto Rico, the U.S. Virgin Islands, and Alaska.

Global Historical and Prehistorical Tsunami Event Data

Background

The NGDC and co-located World Data Center maintain global observations of tsunami sources and tsunami runup databases. These related databases contain information on both the tsunami source and where the tsunami arrived on land. Worldwide data from 2000 B.C. to the present include instrumental observations, observer comments, site reports, deposits, the date and location, plus a summary of measurements and effects. The runup database includes the date and location of the observation as well as details of the runup measurements and effects at the location. These two databases have been significantly improved over the last few years by careful checking of historical entries, verifying source information, and flagging questionable or meteorological events. In addition to the information about the location and affects, the database contains information on deaths, injuries, dollar damage, buildings destroyed, and photos of the damage. The number of deaths and dollar damages present a simple method of assigning an initial qualitative tsunami hazard. The historical and prehistorical tsunami data are a first tool in decision-making by the warning centers and are useful for hazard assessment and validating tsunami propagation and inundation models.

Observation Acquisition and Transmission

Local tsunamis are infrequent high impact events that can cause death, injuries, and inflict major damage to the U.S. coastlines within minutes. In addition, an ocean wide tsunami can cause damage on the coastline of many nations. A single ocean wide event such as the Indian Ocean tsunami of December 2004 (Figure 26) may have recorded runups in hundreds of separate locations.

Figure 26. Tsunami damage in Sri Lanka resulting from the Indian Ocean tsunami of 2004.

Unlike much of the data essential for tsunami research, the historical database is often based on site reports, observer reports, catalogs, and historical documents including letters, diaries, and newspaper articles rather than on instrumental data. When entering information into the historical database, each event and runup must have a date, location, and valid source reference to cite as the origin of the information. NGDC collaborates with the TWCs, other Federal agencies, State and local agencies, U.S. and non-U.S. university and non-governmental organizations, the International Tsunami

Information Center (ITIC), and individual researchers to acquire data for inclusion in the database. Data delivery methods include email, FTP, and CD/DVD for digital data, and normal mail for non-digital reports and publications. Although the database search results can be saved in spreadsheet-compatible format, the primary method of distribution is via the Web, as maps, publications, and data tables from the NGDC Natural Hazards Web site (http://www.ngdc.noaa.gov/hazard/).

Data Management

NGDC has discovered during the intensive quality-control effort that it is important to review not only historical tsunami catalogs, but also catalogs and reports of other types of tsunamigenic phenomena (e.g., earthquakes, volcanic eruptions, and landslides). The analysis of these other data sources has increased the possibility of separating the effects of the tsunami source and the tsunami. In addition, analyzing these other sources has enabled NGDC to increase or decrease the validity of a tsunami event. For example, when a tsunami catalog states that an earthquake generated a tsunami in a particular location and none of the earthquake catalogs for that region mentions an earthquake with a magnitude large enough to cause a tsunami, the validity of the tsunami is reduced. To improve this type of cross-discipline review, NGDC has increased collaborative reviews with the USGS, Smithsonian, and other agencies involved in researching these phenomena. In addition, NGDC developed a suite of Web-based tools to enable direct editing and updating of the database by "trusted partners." The tools allow data managers password-controlled access to the database to search, select, correct, annotate, and add data to the tsunami databases (Figure 27).

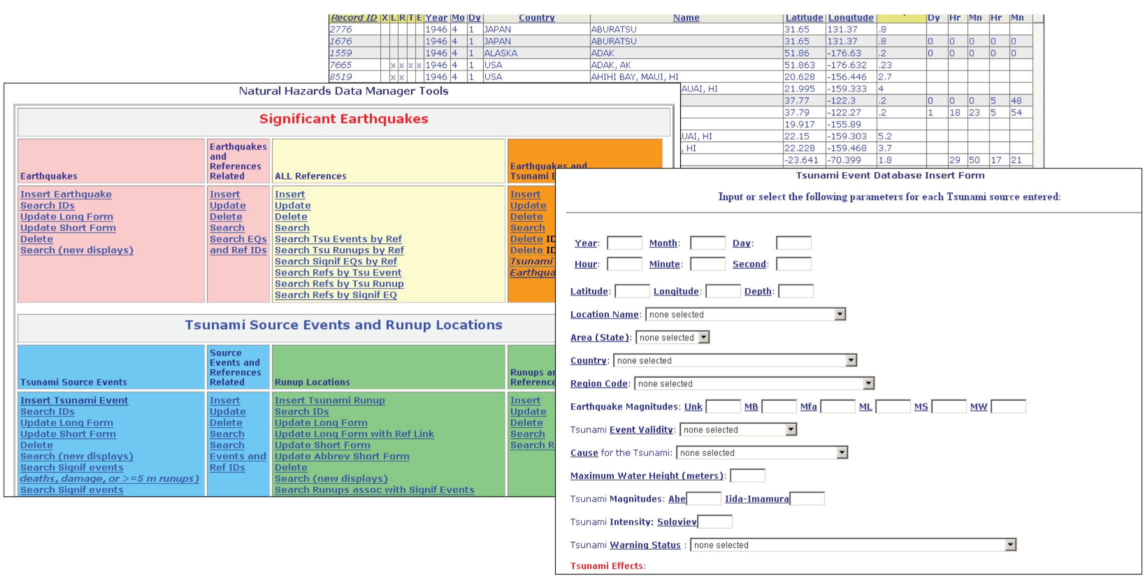

Figure 27. Web-based data management tools enable collaboration.

The historical and prehistorical tsunami data are useful for hazard assessment, validating tsunami propagation and inundation models, and decision-making by the TWCs. For events pre-dating the observational record, NGDC relies on researchers, catalogs, personal reports, and geological deposits. For modern events, it is important that all of the instrumental and descriptive observations of a tsunami event are included in the database. Therefore, NGDC works with researchers, CO-OPS and GLOSS, NDBC, and the TWCs to incorporate coastal and deep-ocean tide observations and photographic imagery. It is especially important that coastal tide data analyzed by the TWCs for arrival times and peak amplitudes are transferred to NGDC. The Alaska TWC is now working with NGDC to review, correct, and update the databases.

The first step in a hazard assessment involves the process of estimating the probabilities of the occurrence of a potentially damaging phenomena of given magnitudes within a specified time. To undertake this assessment, the historical record of occurrence of the phenomena is analyzed. For hazards that occur infrequently, such as tsunamis, historical data are insufficient to accurately assess the long-term hazard. Therefore, use of geologic deposits can extend or fill in the record significantly. NGDC is beginning to build a database that includes locations where tsunami deposits have been identified, the approximate age of the deposit, how the age was determined, and descriptions of the deposit and the setting in which the deposit was laid down.

Archive and Access

Source data for the historical tsunami databases include both digital and analog (paper, microfilm, and microfiche) information. Original digital data are archived on NARA approved media with on-site and off-site copies as described in the DART™ Archive section. Analog data are stored in a climate-controlled room and, where resources permit, scanned to digital form for on-site and off-site archive. There are numerous original analog observations on deteriorating media that are not readily available to researchers. Materials include aging catalogs and observations, paper marigrams (located both at CO-OPS and NGDC), and original photographs. With support from the Climate Data Modernization Program, NGDC is converting non-digital reports and approximately 3,000 original photos to digital format (Figure 28). These data will be available online through the integrated Tsunami Hazards Web site hosted by NGDC.

Figure 28. March 28, 1964 Prince William Sound, Alaska. Tsunami damage at Seward, Alaska.

The primary form of access to the databases is through the Web, via Web-based search forms and ArcIMS Web-maps (Figure 29). Using these tools, users can search for events, runups, and common tsunami-generating events (e.g., earthquakes and volcanic eruptions) by a variety of criteria. For example, a user can request all deadly tsunami events with runups in Hawaii, all events with source locations in the Caribbean, or all events causing deaths.

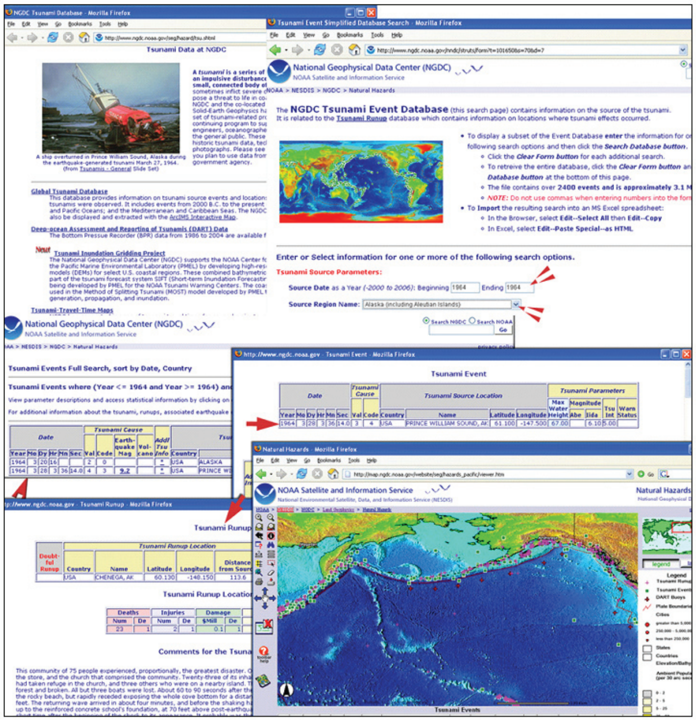

Figure 29. Web-based access to historic tsunami data.

Users can also access data via a Web-map interface, displaying different data layers (i.e., tsunami events, tsunami runups, earthquakes, volcanic eruptions, bathymetry, geopolitical data) and zoom to selected areas on the map. The databases are now integrated so that a user can select a specific event, view the information about the source of the tsunami and all runups generated by this event, identify the sources of information in the database, view any available damage photos, and link to the original DART™ and, increasingly, coastal sea-level data related to the event.

End-to-End Vulnerabilities

Single Points of Failure

- Although hosted on redundant machines, there is no mirror site for the NGDC tsunami Web site. The NOAA Data Centers are investigating mirroring Web sites.

Data Vulnerabilities

- Historical tsunami data reports are often few in number and on deteriorating media. NOAA's Climate Data Modernization Program helps address this issue, but additional resources and collaborations are needed to identify, acquire, and digitize reports.

Gaps and Recommendations

There is a gap in ensuring two-way flow of information from the TWCs and the NGDC archive. NOAA is addressing this, initially with NGDC and Alaska TWC collaboration to improve access to and utility of the database and review of the content by scientists at Alaska TWC. The database is one of the tools the TWC uses when issuing warnings and alerts. NGDC added an additional field to indicate whether a warning or alert was issued and the region to which it was issued. This field is not fully populated. NGDC hopes to expand collaboration to include all TWCs and strengthen collaboration with ITIC.

The historical database contains more than 2,000 events and 9,000 runup locations from 2000 B.C. to the present. An ongoing challenge is in accurately locating and describing events and associated runups, identifying source references, and resolving discrepancies between sources. NGDC is working with partners nationally and internationally to complete a major review and improve database content.

Tsunami researchers often want to see the original source for a tsunami event. Therefore, it is important that NGDC has a complete digital archive of all the analog records used to compile the database. Along with NGDC, ITIC has considerable paper archives that should be made available in digital form.

The primary distribution for the historical data is via the Web. This has the advantage that the content is easy to update and keep current. The disadvantage is that Web access is not universally available at desired bandwidths, may not be available following an event, and may not be the most convenient form for viewing information about a region or event. NGDC is now working on a dynamic report, built from the database for current content and designed to be easily printed and referenced off-line.

Tsunami Warning Dissemination

Background

NOAA's Tsunami Warning System mission is to protect life and property from the tsunami hazard by providing timely, accurate, reliable, and effective tsunami products to coastal populations and emergency management within the area-of-responsibility, as well as by advancing other aspects of tsunami hazard mitigation such as community preparedness and public education. This mission is conducted primarily through the operation of NOAA's two TWCs in the United States: the West Coast and Alaska Tsunami Warning Center (WCATWC) and the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC) (Figure 30). The WCATWC's area-of-responsibility (AOR) consists of Canadian coastal regions and the ocean coasts of all States except Hawaii. The PTWC's AOR consists of Hawaii, other U.S. interests in the Pacific Basin, countries participating in the Tsunami Warning System in the Pacific, Puerto Rico, U.S. Virgin Islands, and, on an interim basin, various Indian Ocean and Caribbean Sea countries. The two centers collaborate to provide tsunami-warning service, and mutual backup to tsunami-threatened areas throughout the United States and many other countries throughout the world.

Figure 30. The WCATC (left) and Richard H. Hagemeyer PTWC (right).

To accomplish this mission, the TWCs detect, locate, size, and analyze earthquakes throughout the world. Earthquakes that activate the centers' alarm systems initiate an earthquake and tsunami investigation, which includes four basic steps:

1. Automatic locating and sizing of the earthquake;
2. Earthquake analysis and review;
3. Sea level data analysis to verify the existence of a tsunami and to calibrate models; and
4. Dissemination of information to the appropriate emergency management officials.

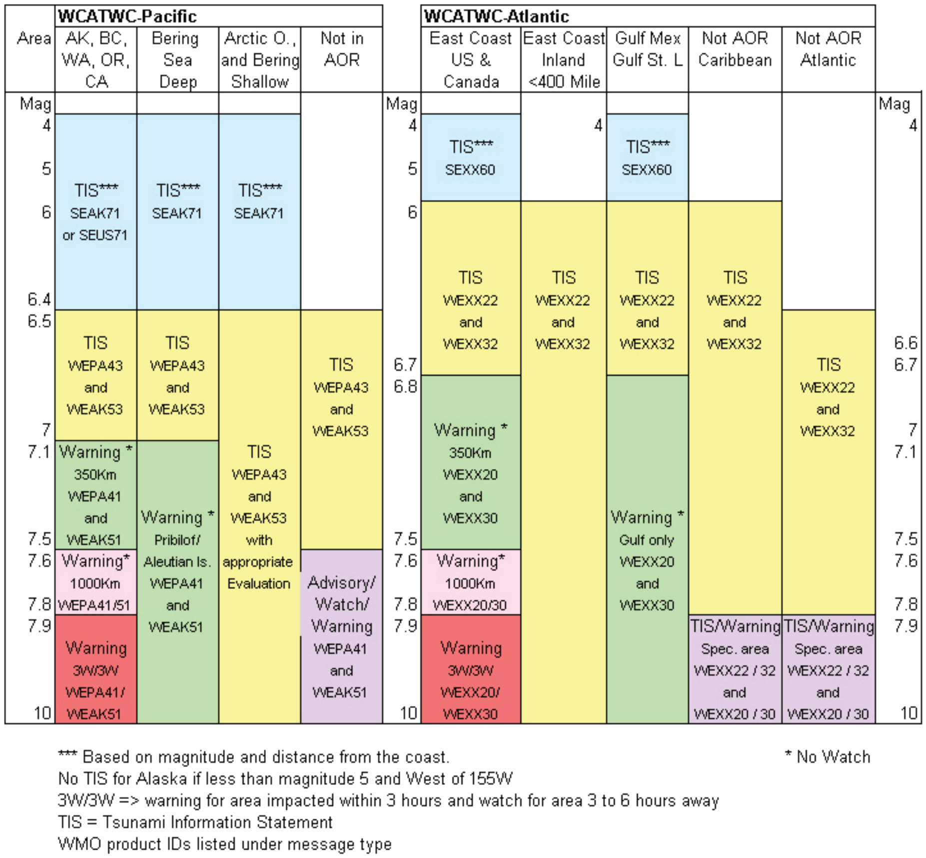

Figure 31. Tsunami Warning Center procedure summary.

Observation Acquisition and Transmission

TWC Procedures

Initial issuance of a tsunami bulletin is based solely on seismic data. After the initial bulletin has been issued, the TWCs monitor recorded tsunami effects and issue a cancellation, extension, or final bulletin as appropriate. TWC procedures are summarized in Figure 31.

Dependence solely on seismic data for the initial warning sets TWCs apart from most natural hazard warning centers. Typically, natural hazard warning centers can monitor observational data for which their warnings are issued (e.g., hurricanes, tornadoes, solar activity). However, in most cases tsunamis cannot be directly observed prior to impact on the nearest coasts. Warning centers must rely on seismic data as this easily monitored signal is the closest indicator with which the centers can estimate the threat. In general, the larger an earthquake's moment magnitude, the more likely it is to trigger a tsunami. Large quakes are also known to trigger sub-sea landslides that can generate tsunamis. However, there are many examples of events in which moment magnitude does not relate well to the generated tsunami size. Due to these events, TWCs must be conservative when developing procedures based on earthquake parameters.

Tsunami history and pre-event modeling along with observed tsunami amplitudes are taken into account for determining the extent of danger. TWCs may refrain from issuing a warning or issue the warning for only selected areas if tsunami history (and modeling if available) indicates there is no danger, or danger only to selected areas. Historical events have shown that tsunami damage is possible if waves reach 50-cm or more in amplitude above sea level. Therefore, if a tsunami is expected to reach 50-cm or more, or if the tsunami potential can not be accurately judged, warnings are normally continued.

The TWCs have access to more than 200 tide gauge stations throughout the Pacific, Indian, and Atlantic Oceans. Many of these sites are maintained by NOS. In addition to the NOS sites, other agencies such as the TWCs, the Canadian Hydrographic Survey, University of Hawaii Sea Level Center, and Japanese Meteorological Agency provide sea level information to the centers. Twenty-five DART™s have been installed in the Pacific and Atlantic Oceans with 14 more planned for installation by the spring of 2008. These data are also available in near real-time. Available sea level data are shown in Figure 32.

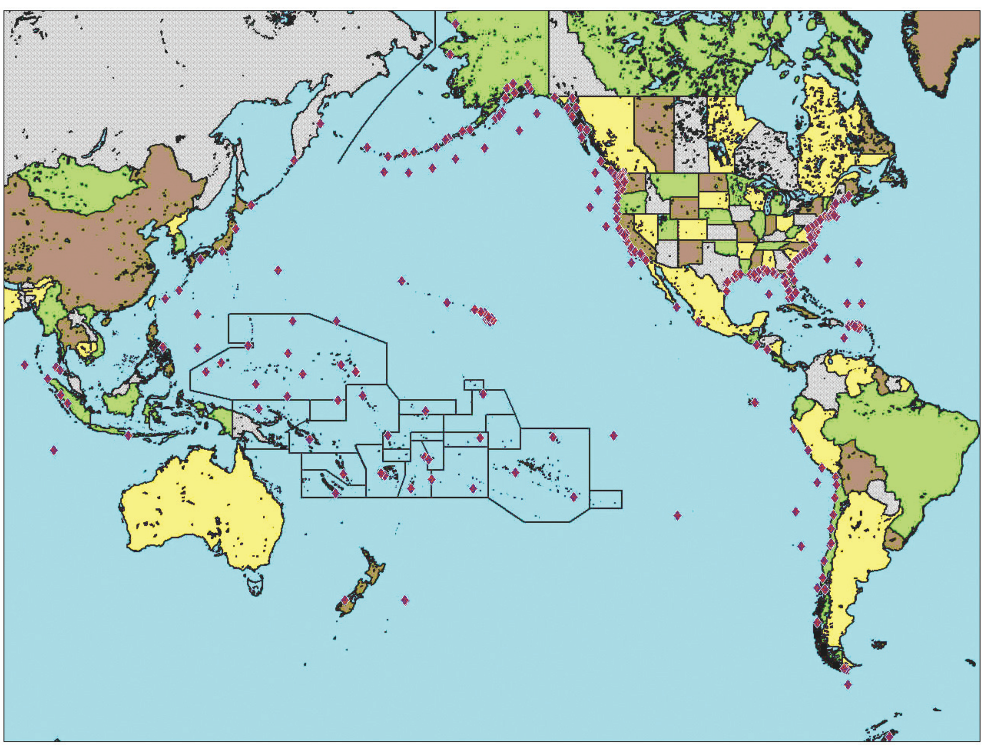

Figure 32. Sea level data available to TWCs.

TWC Product Types and Transmission

There are four categories of tsunami messages. These are:

1. **Tsunami Warning.** Warnings are issued when a potential tsunami with significant inundation is imminent or expected. Warnings alert residents that widespread, dangerous coastal flooding accompanied by powerful currents is possible and may continue for several hours after arrival of the initial wave. Warnings also alert emergency management officials to take action for the entire tsunami hazard zone. Appropriate actions to be taken by local officials may include the evacuation of low-lying coastal areas and the repositioning of ships to deep waters when there is time to safely do so. Warnings may be updated (at least hourly), adjusted geographically, downgraded, or cancelled. To provide the earliest possible alert, initial warnings are normally based only on seismic information.

2. **Tsunami Watch.** Watches are issued to alert emergency management officials and coastal residents of an event that may later impact the Watch area. The Watch may be upgraded to a Warning or Advisory (or cancelled) based on updated information and analysis. Therefore, emergency management officials and coastal residents should prepare to take action in case the Watch is upgraded. Watches are normally issued based on seismic information without confirmation that a destructive tsunami is underway.

3. **Tsunami Advisory.** Advisories are issued due to the threat of a potential tsunami that may produce strong currents dangerous to those in or near the water. Coastal regions historically prone to damage due to strong currents are at the greatest risk. The threat may continue for several hours after the initial wave arrival, but significant widespread inundation is not expected for areas under an Advisory. Appropriate actions to be taken by local officials may include closing beaches and evacuating harbors and marinas, and the repositioning of ships to deep waters when there is time to safely do so. Advisories are normally updated at least hourly to continue the Advisory, expand/contract affected areas, upgrade to a Warning, or cancel the Advisory.

4. **Information Statement.** Information Statements are issued to inform emergency management officials and coastal residents that an earthquake has occurred. In most cases, Information Statements indicate there is no threat of a destructive tsunami. These are issued to prevent unnecessary evacuations as the earthquake may have been felt in coastal areas. An Information Statement may, in appropriate situations, caution about the possibility of destructive local tsunamis. Information Statements may be re-issued with additional information, though normally these messages are not updated. However, a Watch, Advisory or Warning may be issued for the area, if necessary, after analysis and/or updated information becomes available.

Tsunami warning bulletin texts include warning/watch extent, earthquake parameters, evaluation, and the tsunami estimated arrival times for sites throughout the AOR. Tsunami products are described in greater detail and examples are provided at http://wcatwc.arh.noaa.gov/Products/product.htm.

Bulletins are disseminated from the TWCs by various methods (Figure 33). The primary methods are:

- Reading the message over the National Warning System (NAWAS) circuit;
- 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 throughout the AOR, 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 NWS offices. The NWS offices forward the message to NOAA Weather Radio All-Hazards, the Emergency Alert System, Emergency

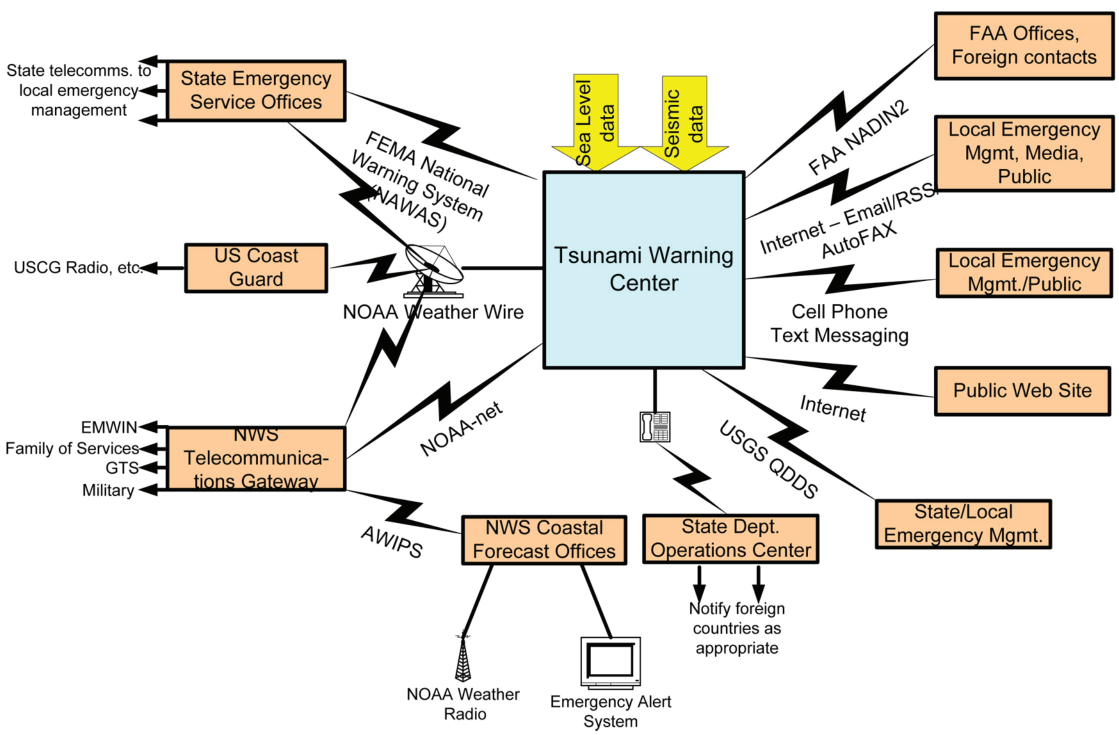

Figure 33. TWC main communication pathways and recipients.

Managers Weather Information Network, Global Telecommunications System, 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.

Secondary dissemination methods are email, Web page, phone calls, USGS dissemination systems, Rich Site Summary (RSS) feeds, and digital cell phone text messaging. These secondary systems provide redundant methods for emergency management to receive tsunami messages, and provide methods by which the media and general public can receive messages. Text messages are automatically composed by the message generation software. The wording of the text is dependant on the size and location of the earthquake, and options chosen by the analyst. More can be found on local access of messages at http://wcatwc.arh.noaa.gov/Products/productret.htm. Many States, counties, and communities have developed their own methods for disseminating messages to their local populations once received from the TWCs (i.e., sirens, automatic phone calls, local CB radio, All Hazard Alert Broadcasting radio, etc.). Tsunami dissemination is described in greater detail at http://wcatwc.arh.noaa.gov/Products/messagesumm-nolink.htm.

Figure 34. TsunamiReady™ sign.

TsunamiReady™

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. To help attain this goal, NWS has implemented a program known as TsunamiReady™ which sets forth guidelines for communities to follow to improve tsunami preparedness (Figure 34). This program, begun in 2000, is based on the NWS StormReady® program. The TsunamiReady™ program's purpose is to recognize communities that have taken the steps necessary to be as prepared as possible for a tsunami. This requires the communities to follow a set of guidelines. The guidelines show that the community can receive and disseminate warnings, have a tsunami hazard plan in place, have posted evacuation routes, designated shelters, and have worked to enhance tsunami awareness throughout their community.

As of January 2007, 38 communities and counties along the U.S. west coast, east coast, Alaska, and Hawaii are recognized as TsunamiReady™. National Weather Service Warning Coordination Meteorologists with support from TWC personnel actively work with local emergency officials to attain the TsunamiReady™ recognition. In addition to the TsunamiReady™ program, NOAA staff participates in preparedness efforts that include:

- Visiting distant coastal communities within the AOR;
- Assisting local and State jurisdictions in tsunami exercises;
- Visiting local facilities and schools that are within commuting distance of the centers;
- Providing public tours describing TWC's mission and facilities; and
- Providing tsunami information upon request through the internet, phone, or mail.

Archive and Access

Tsunami products are locally archived at the TWCs, and are externally archived by NOAA's National Climatic Data Center (NCDC). NCDC follows NARA guidelines for archive of data. These archived products are not easily accessible by the public.

End-to-End Vulnerabilities

The vulnerabilities listed here are limited to those at the point of tsunami product origination and its major communication paths—at the tsunami warning centers and their associated message dissemination links. Other vulnerabilities exist downstream.

Single Points of Failure

- Message dissemination systems have multiple redundancies in case of failure. Primary vulnerabilities include the loss of NADIN2, NAWAS and/or Alaska Warning System, the NWS private circuits, NOAA Weather Wire, Internet, and telephone. However, as these output channels have internal redundancies, it would require the loss of most or all of these systems to seriously impact message dissemination. The most likely scenario for full loss of primary circuits is the loss of regional communications or a building catastrophe (e.g., fire, terrorism). In that scenario, the TWCs rely on back-up systems such as satellite phone to notify each other to take over. In some cases, limited backup may be required if only partial communications loss occurred at either center.
- Loss of electricity to the TWCs is prevented by backup generators that can be run by natural gas lines. If these are severed, a separate tank of propane can power it for multiple days. In the rare event of complete electrical outage at a center, backup plans would be enacted.

Data Vulnerabilities

- Communications outages may occur, as listed above.
- Archive of past warning products are not easily accessible.

Future Plans

TWCs must constantly evolve with state-of-the-art communication methods. As technology continues to advance at unprecedented rates and novel means of communication become commonplace (e.g., cellular phones, RSS internet feeds), TWCs must offer their products through these new means.
As part of the National Weather Service, TWCs can leverage many of the NWS communication pathways. TWC staff are involved in a variety of projects and studies to improve the Center's products and dissemination, such as:

- Upgraded Web-based messages and graphics
- Cell-phone text messaging
- RSS feeds
- Improvement of XML-based format messages

Appendix A: References

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Appendix B: Abbreviations and Acronyms

AHB	Atlantic Hydrographic Branch of NOS
API	Application programming interfaces
ASCII	American Standard Code for Information Interchange
BPR	Bottom pressure recorder
BUD	Buffer of Uniform Data
CASI	Compact Airborne Spectrographic Imager
CHARTS	Compact Hydrographic Airborne Rapid Total Survey
COOP	Continuity of Operations Plan
CO-OPS	Center for Operational Oceanographic Products and Services
CORBA	Common Object Request Broker Architecture
CORL	Consolidated Observational Requirements List
CORMS	Continuous Operational Real-Time Monitoring System
CREST	Consolidated Reporting of Earthquakes and Tsunamis
DART™	Deep-ocean Assessment and Reporting of Tsunamis
DCP	Data Collection Platform
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DMC	Data Management Center
DOMSAT	Domestic Satellite
FAA	Federal Aviation Administration
FARM	Fast Archive Recovery Method
FDSN	International Federation of Digital Seismograph Networks
FGDC	Federal Geographic Data Committee
FTP	File Transfer Protocol
Gb	Gigabyte
GEOSS	Global Earth Observation System of Systems
GIS	Geographic information system
GLOSS	Global Sea-level Observing System
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
GSN	IRIS Global Seismic Network
HSD	Hydrographic Surveys Division of NOS
HVO	Hawaii Volcanoes Observatory
IOOS	Integrated Ocean Observing System
IRIS	Incorporated Research Institutions for Seismology
ISP	Internet Service Provider
ITIC	International Tsunami Information Center
JALBTCX	Joint Airborne LiDAR Bathymetry Technical Center of Expertise
LiDAR	Light Detection and Ranging
LRGS	Local Readout Ground Stations

LTO	Linear Tape Open
mb	Body-wave magnitude
Ml	Local magnitude
Ms	Surface-wave magnitude
Mw	Moment magnitude
Mwp	P-wave moment magnitude
NARA	National Archives and Records Administration
NAWAS	National Warning System
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center
NEIC	National Earthquake Information Center
NESDIS	National Environmental Satellite, Data, and Information Service
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSTC	National Science and Technology Council
NTHMP	National Tsunami Hazard Mitigation Program
NWLON	National Water Level Observation Network
NWS	National Weather Service
NWSTG	National Weather Service Telecommunications Gateway
NWWS	NOAA Weather Wire Satellite system
OAR	Office of Oceanic and Atmospheric Research
OPeNDAP	Open-source Project for a Network Data Access Protocol
PASSCAL	Program for Array Seismic Studies of the Continental Lithosphere (IRIS)
PDF	Portable Document Format
PHB	Pacific Hydrographic Branch of NOS
PMEL	Pacific Marine Environmental Laboratory
psia	Pounds per square inch absolute
PTP	Pacific Tide Party
PTWC	Pacific Tsunami Warning Center
P-wave	Primary seismic wave
RGB	Red, green, blue channel image
RSS	Rich Site Summary
RUDICS	Router-based Unrestricted Digital Internetworking Connectivity Solution
SIFT	Short-term Inundation Forecasting for Tsunamis
SOAP	Simple Object Access Protocol
SPLERT	System for Processing Local Earthquakes in Real Time
SPYDER®	System to Provide You Data from Earthquakes Rapidly (IRIS)
TWC	Tsunami Warning Center
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
UTC	Coordinated Universal Time
WCATWC	West Coast Alaska Tsunami Warning Center
XML	Extensible Markup Language

Appendix C: Data Formats

Seismic Data Formats

The TWCs record data from seismometers operated by several different data centers in addition to its own network. As of October 2006, approximately 225 channels of seismic data were routinely processed. Data from these networks are transmitted to the TWCs over both the Internet and private networks. Other agencies that provide seismic data directly to the TWCs are the NEIC; IRIS–Albuquerque Seismological Laboratory; IRIS–International Deployment of Accelerometers (University of California, San Diego); California Institute of Technology; USGS–Menlo Park; University of California, Berkeley; University of Washington; Earthquakes Canada; University of Alaska; Puerto Rico Seismic Network; HVO; and the Alaska Volcano Observatory. Figure 35 shows data transmission paths from each of the sites.

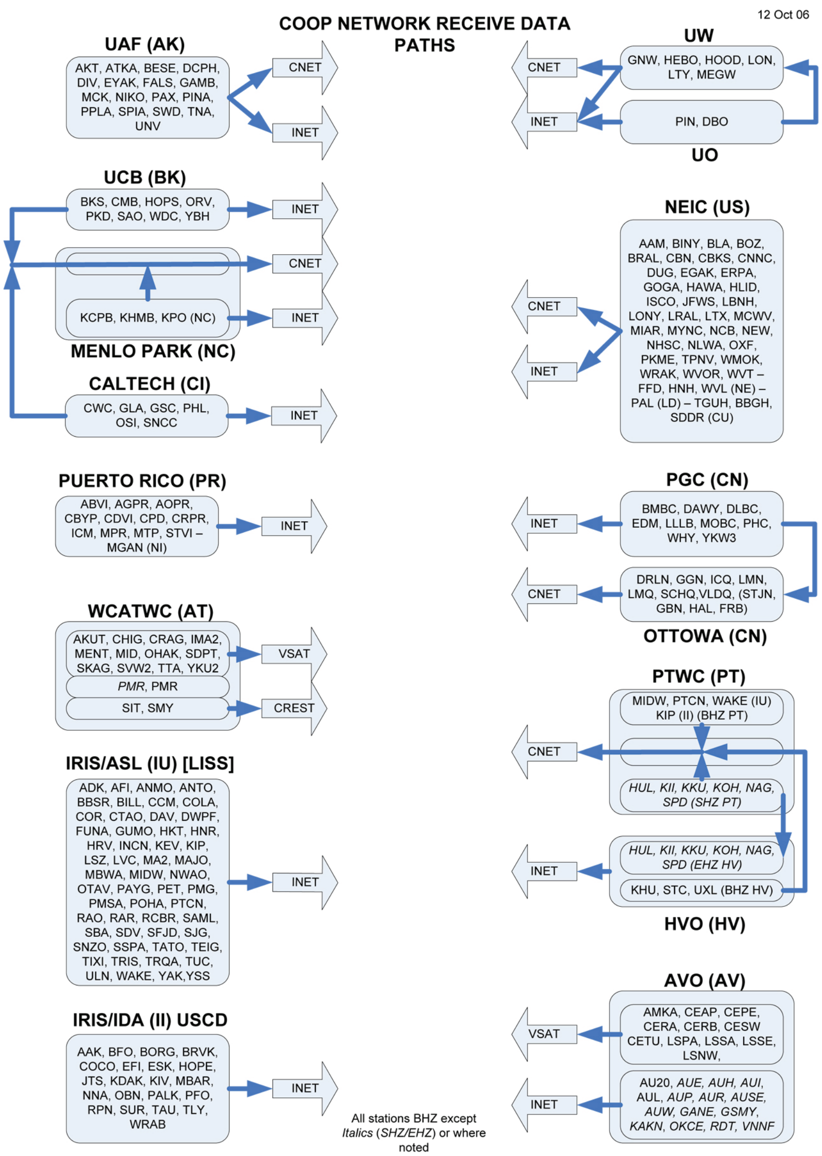

Figure 35. TWC cooperative seismic data transmission paths.

Figure 36 (next page) shows the distribution flow of seismic data at the WCATWC. The EarlyBird1 and EarlyBird2 systems provide redundant data processing with EarlyBird3 serving as an additional processing and training system.

The primary seismic data

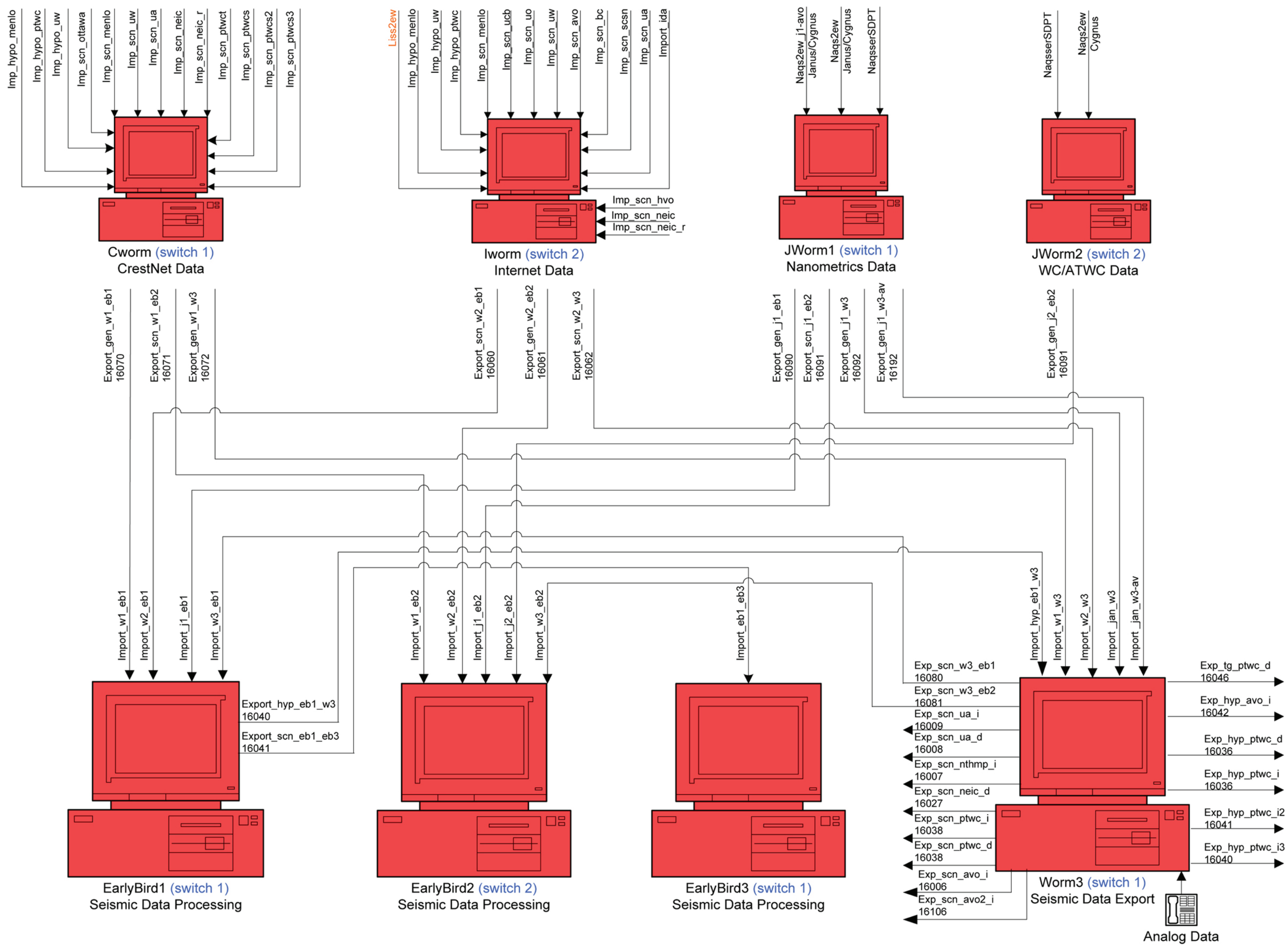

Figure 36. Schematic of the seismic data flow at the WCATWC.

archive for the seismic community is through the IRIS DMC. Information on the data and data formats is available from IRIS at http://www.iris.edu/manuals/DATutorial.htm

DART™ Real-Time Reporting Modes: Iridium Transmissions and Time Series Data Formats

Every Iridium transmission begins with a platform header followed by the message formats as described in this document. The format of the header is:

3f 3f 3f ck ck DARTxxxP/S

3f 3f 3f	=	three bytes to start the transmission (always 3f hex)
ck ck	=	two byte checksum
DART	=	indicates tsunami buoy platform ID follows
xxx	=	three ASCII digit platform ID
P/S	=	P indicates transmission from Primary side; S for Secondary side

Standard Mode Hourly Reporting

Water Level Height Data. Reports four discrete 15-minute water column height values in millimeters via acoustic modem each hour, via Iridium every 6 hours if height data available.

Height Data: Transmitted via acoustic modem every hour, via Iridium every six hours if height data are available.

<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*
<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*
<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*
<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*
<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*
<cr>D$1*C/I date time batv1 batv2 batv3 ht1 ht2 ht3 ht4 tries * checksum*

<cr>	=	0x0D
D$1	=	message id
C/I	=	message status, C=corrupted, I=intact
date	=	month day year
time	=	hour minute second
batv1	=	BPR battery voltage in tenths of a volt, or error code
batv2	=	acoustic modem DSP battery in tenths of volts
batv3	=	acoustic modem battery in volts
ht1 ... ht4	=	water column height in millimeters

tries	=	number of tries to deliver BPR data
*	=	checksum delimiter
checksum	=	exclusive OR of all characters preceding *, 1-byte hexadecimal

Example:

```
D$1I 08/17/2006 12:15:00 1654147 5311813 5311758 5311703 5311652  1* 35
D$1I 08/17/2006 13:15:00 1654147 5311604 5311559 5311516 5311480  1* 34
D$1I 08/17/2006 14:15:00 1654147 5311445 5311414 5311389 5311369  1* 3C
D$1I 08/17/2006 15:15:00 1654147 5311352 5311342 5311336 5311336  1* 36
D$1I 08/17/2006 16:15:00 1654147 5311341 5311353 5311366 5311385  1* 3A
D$1I 08/17/2006 17:15:00 1654147 5311407 5311433 5311466 5311499  1* 32
```

GPS Position Fix: Transmitted once per day or hourly if height data are not available

D$0 N/S lat_deg E/W long_deg * checksum

D$0	=	message id
date	=	month day year
time	=	hour minute second
lat_deg	=	latitude of buoy, DDMM.MMMM
N/S	=	North or South
long_deg	=	longitude of buoy, DDMM.MMMM
E/W	=	East or West
*	=	checksum delimiter
checksum	=	exclusive OR of all characters preceding *, 1-byte hexadecimal

Example:

```
D$0 08/17/2006 13:05:05 4857.0556 N 17816.8330 E* 5D
```

Event Mode Reporting

- First Event Mode Message (Message #0). Reports the water column height in millimeters that triggered the event mode, along with three height deviations (15-second height values 0.75 minutes prior to the event trigger).
- Second Event Mode Message (Message #1). Reports 15-second height values -0.75 to 3 minutes after event trigger.
- Subsequent Event Mode Messages (Messages #2-14). Reports 15 one-minute average height values from the detection of the event until event mode is ceased (Figure 37).

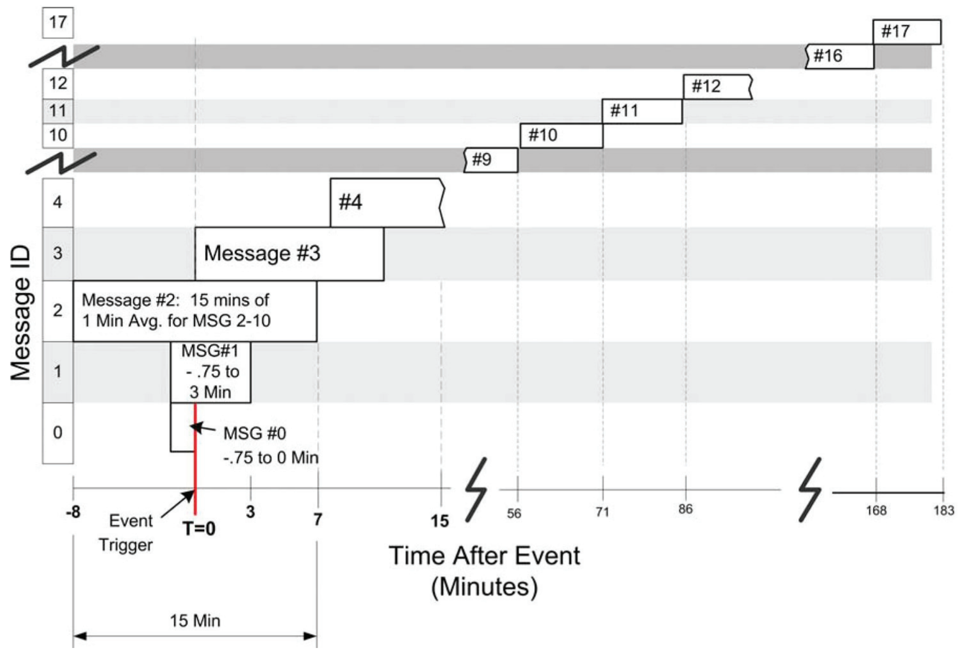

Figure 37. Event mode message schedule.

First Event Mode Message (Message #0)

D$2 C/I msg# tt time ts begin height dev1 dev2 dev3 tries * checksum

DS2	=	message id
C/I	=	message status, C=corrupted, I=intact
msg#	=	message number (0 for the first message)
time	=	time tsunami detected
begin	=	first data point time stamp
height	=	first data point water column height in millimeters
dev1...dev3	=	deviation from height in millimeters, 2-byte hexadecimal
tries	=	number of tries to deliver BPR data
*	=	checksum delimiter
checksum	=	exclusive OR of all characters preceding *, 1-byte hexadecimal

Example:

```
D$2I 00 tt 22:53:15 ts 22:52:30 3259892000000044000001* 28
```

Subsequent Event Mode Messages (Typically, Messages #1 to #14)

D$s C/I msg# tt time ts begin height dev1 dev2 dev3.....dev15 tries * checksum

D$2	=	message id
C/I	=	message status, C=corrupted, I=intact
msg#	=	message number
time	=	time tsunami detected
begin	=	first data point time stamp
height	=	first data point water column height in millimeters
dev1...dev15	=	deviation from height in millimeters, 2-byte hexadecimal
tries	=	number of tries to deliver BPR data
*	=	checksum delimiter
checksum	=	exclusive OR of all characters preceding *, 1-byte hexadecimal

Example:

```
D$2I 01 tt 22:53:15 ts 22:52:30 3259892
000000440000fffffffffffffffffffffffffffffffffffefffefffefffe01* 29

D$2I 02 tt 22:53:15 ts 22:44:00 3259897
fffffffffffefffdfffcfffcfffb000cfffafffafff9fff9fff8fff8fff701* 2C

D$2I 03 tt 22:53:15 ts 22:52:00 3259909
ffeeffeeffedffedffecffecffebffeaffeaffeaffeaffe9ffe8ffe8ffe701* 22
```

Extended Mode Hourly Reporting

<u>Extended Reporting Mode.</u> Reports 120 one-minute average values, transmitted via Iridium each hour for additional data redundancy. Extended reporting mode transmits data from 1 hour prior to the next top of the hour until the Tsunami Detection Algorithm is in non-triggered status (Figure 38).

120, 1-minute Averages Transmitted via Iridium Each Hour

D$3 C/I tt ts height dev dev2 dev3.....dev119 tries * checksum

D$3	=	message id
C/I	=	message status, C=corrupted, I=intact
tt	=	time tsunami detected
ts	=	first data point time stamp
height	=	water column height in millimeters
dev1...dev119	=	deviation from height in millimeters, 2-byte hexadecimal
tries	=	number of tries to deliver CPR data
*	=	checksum delimiter
checksum	=	exclusive OR of all characters preceding *, 1-btye hexadecimal

Example:

```
D$3Itt 22:53:15 ts 23:00:00  3259888
fffffffffffffffffffefffdfffdfffcfffcfffcfffbfffbfffafff9fff9fff8fff8fff7
```

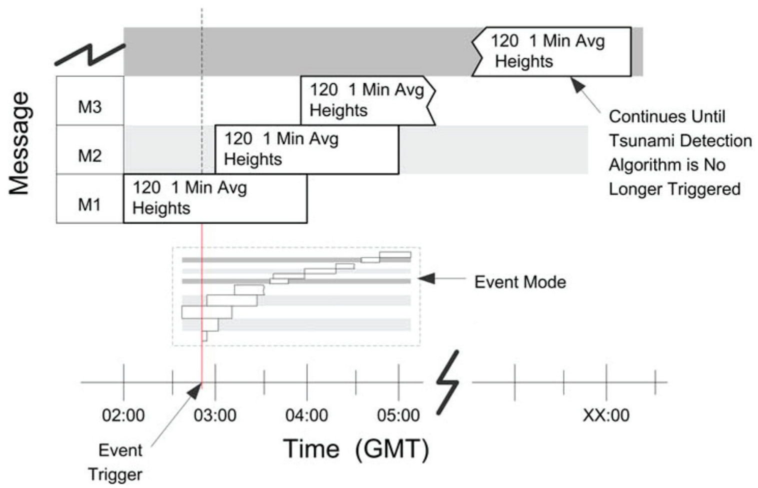

Figure 38. Extended reporting mode message schedule.

```
fff7fff6fff6fff5fff4fff4fff3fff2fff2fff1fff1fff0ffefffefffeeffeeffedffec
ffecffebffebffeaffeaffeaffe9ffe9ffe9ffe8ffe8ffe7ffe6ffe6ffe5ffe4ffe4ffe3
ffe3ffe2ffe2ffe1ffe1ffe1ffe0ffe0ffdfffdfffdeffdeffddffdcffdcffdcffdbffdb
ffe1ffd9ffd9ffd8ffd8ffd7ffd7ffd6ffd6ffd6ffd5ffd5ffd5ffd4ffd4ffd3ffd3ffd2
ffd1ffd1ffd0ffd0ffcfffcfffcfffceffceffcdffcdffcdffcdffccffcbffcbffcbffca
ffcaffc9ffc9ffc9ffc9ffc8ffc8ffc7ffc7ffc6ffc601* 3E
```

DART™ High-Resolution (15-sec), On-Demand ASCII-Hexadecimal Data Format

One-hour's worth of high-resolution 15-second data are sent via Iridium on demand by the warning centers. These data are in ASCII-Hexadecimal Data Format.

1 Hour High-Resolution 15-second Data Transmitted to Iridium

D$5C/Icafedata...
D$6C/Idata...
D$7C/Idata...
D$8C/Idata...

D$5-8	=	message id
cafe	=	2-byte hexadecimal representing the beginning of the data
C/I	=	message status, C=corrupted, I=intact

To decipher:

(1) Remove the message IDs and status (i.e., D$51, D$62, D$71, D$81)
(2) Remaining data block is decoded as Flash Card Data (above)

Example:

```
D$5Icafe4843040a1406110000a707000180b6073fde847<snip…>
D$6I01c388ab014f903a01aa88ab0103903a019388ab00b<snip…>
D$7I003f88ab016d903a006388ab012a903a008888ab00e<snip…>
D$8I011f88ab02bb903a017188ab027b903a01c388ab023<snip…>
```

DART™ Real-time Data Formats - Reformatting Iridium Messages

NDBC reformats the received Iridium messages into SXXX46 messages for distribution via the National Weather Service Telecommunications Gateway.

Raw Standard Mode Message from the Buoy:

```
D$1I 08/22/2006 18:15:00 1474142 4709825 4709819 4709819 4709824  1* 35
D$1I 08/22/2006 19:15:00 1474142 4709831 4709842 4709862 4709883  1* 07
D$1I 08/22/2006 20:15:00 1474142 4709906 4709933 4709962 4709995  1* 3B
D$1I 08/22/2006 21:15:00 1474142 4710033 4710072 4710115 4710155  1* 7F
D$1I 08/22/2006 22:15:00 1474142 4710198 4710244 4710282 4710322  1* 30
D$1I 08/22/2006 23:15:00 1474142 4710363 4710398 4710431 4710457  1* 01
```

NDBC applies bulletin header (SXXX46 KWBC) and Date-Time Group (230012–23rd day of the month at 0012 UTC). Then applies GOES[1] header line (DDDDDDD0 235001256) and end-message line (00-0NN 00E) to keep the DART™ II message compatible with DART™ I, so that decoders can process the messages.

```
SXXX46 KWBC 230012

DDDDDDD0 235001256
D$1I 08/22/2006 18:15:00 1474142 4709825 4709819 4709819 4709824  1* 35
D$1I 08/22/2006 19:15:00 1474142 4709831 4709842 4709862 4709883  1* 07
D$1I 08/22/2006 20:15:00 1474142 4709906 4709933 4709962 4709995  1* 3B
D$1I 08/22/2006 21:15:00 1474142 4710033 4710072 4710115 4710155  1* 7F
D$1I 08/22/2006 22:15:00 1474142 4710198 4710244 4710282 4710322  1* 30
D$1I 08/22/2006 23:15:00 1474142 4710363 4710398 4710431 4710457  1* 01
00-0NN  00E
```

[1]Geostationary Operational Environmental Satellite (GOES) was the data communications for DART™ I.

DART™ BPR Flash Card Data Format

One hour of data is shown.

Header	HH:00:00 Data PC PV TC TV	HH:00:15 Data PC PV TC TV	HH:00:30 Data PC PV TC TV	. . .	HH:59:45 Data PC PV TC TV
0 29	30 37	38 45	46 53		2022 2029

HEADER Section Contents:

BYTE	DESCRIPTION	BYTE	DESCRIPTION
0	hex: 'CA'	15	Pressure Sensor Serial No.
1	hex: 'FE'	16	Pressure Sensor Serial No. (LSB)
2	checksum MSB	17	Reference Oscillator Serial Number
3	checksum LSB	18	Reference Oscillator Period (MSB)
4	Data Start: Month	19	Reference Oscillator Period
5	Data Start: Day	20	Reference Oscillator Period
6	Data Start: Century	21	Reference Oscillator Period
7	Data Start: Year	22	Reference Oscillator Period
8	Data Start: Hour	23	Reference Oscillator Period
9	Data Start: Minute (00)	24	Reference Oscillator Period
10	Data Start: Second (00)	25	Reference Oscillator Period (LSB)
11	BPR CPU Battery Voltage	26	BPR Pressure Divider
12	BPR Serial Number	27	BPR Temperature Divider
13	Pressure Sensor Serial No. (MSB)	28	BPR Heterodyne Divider
14	Pressure Sensor Serial No.	29	BPR Sample Interval (seconds)

DATA Section Contents:

BYTE	DESCRIPTION	
30	xx:00:00	Pressure Counts (MSB)
31	xx:00:00	Pressure Counts (LSB)
32	xx:00:00	Pressure Vernier Counts (MSB)
33	xx:00:00	Pressure Vernier Counts (LSB)
34	xx:00:00	Temperature Counts (MSB)
35	xx:00:00	Temperature Counts (LSB)
36	xx:00:00	Temperature Vernier Counts (MSB)
37	xx:00:00	Temperature Vernier Counts (LSB)
…repeat pattern…		
2022	xx:59:45	Pressure Counts (MSB)
2023	xx:59:45	Pressure Counts (LSB)
2024	xx:59:45	Pressure Vernier Counts (MSB)
2025	xx:59:45	Pressure Vernier Counts (LSB)
2026	xx:59:45	Temperature Counts (MSB)
2027	xx:59:45	Temperature Counts (LSB)
2028	xx:59:45	Temperature Vernier Counts (MSB)
2029	xx:59:45	Temperature Vernier (LSB)

Tidal Harmonic Constants Ideal Format (XML)

NOS CO-OPS Tidal Harmonic Constants

All tidal harmonic constants should be reported in standard units. Amplitudes should be reported in centimeters and phase in Coordinated Universal Time (UTC). Requested format is XML.

Document Type Definition (DTD):

Requested Format, field description:

```
<!--DTD for TFS Seismic Data -->
<!-- ? = optional, not repeatable -->
<!-- + = required and repeatable -->
<!-- * = optional and repeatable -->

<!-- name, id, latitude, longitude, mean_depth and date_last_modified only need be specified once.
  constituent is repeatable for each valid constant for a given station.  mean_depth is in
  meters.  date_last_modified should be in UTC.  -->
<!ELEMENT station (name, id, latitude, longitude, mean_depth, date_last_modified, constituent+)>

<!-- date_last_modified is to stamp the harmonic constant file with a valid meta tag so other
  users/organizations know the last time the values were last reviewed/modified -->
<!ELEMENT date_last_modified EMPTY>
<!ATTLIST date_last_modified
year CDATA #REQUIRED
month CDATA #REQUIRED
day CDATA #REQUIRED
hour CDATA #REQUIRED
minute CDATA #REQUIRED
second CDATA #REQUIRED>

<!-- constituents are made up of the constant name, amplitude, phase and speed.  If a constant name has no valid
amplitude and phase, it can be left out as only those constant names with valid values are necessary.  Repeatable
for each station.  -->
<!ELEMENT constituent EMPTY>
<!ATTLIST constituent
name CDATA #REQUIRED
amplitude CDATA #REQUIRED
phase CDATA #REQUIRED
speed CDATA #REQUIRED>

<!ELEMENT comment (#PCDATA)>
```

XML File Sample:


```
<xml version="1.0">
 <station>
   <name>crescent city, ca</name>
   <id>9419750</id>
   <latitude>41.745</latitude>
   <longitude>124.183</longitude>
   <mean_depth></mean_depth>
   <date_last_modified year=»» month=»» day=»» hour=»» minute=»» second=»»/>
   <constituent name=»m2» amplitude=»0.176» phase=»211.0» speed=»28.9841042»/>
   <constituent name=»s2» amplitude=»0.183» phase=»231.7» speed=»30.0000000»/>
   <constituent name=»n2» amplitude=»0.152» phase=»185.2» speed=»28.4397295»/>
      repeatable for number of constituents...
<comment="note that all constituent names are case insensitive"/>
 </station>
</xml>
```


Sample of preliminary format file for harmonic constants

Station 46401

East of ADAK, AK
ID 1600002
Latitude 46.63 N
Longitude 170.79 W
Mean depth 5525.797
Date last modified 20060628 17:50:36 GMT

Constituent	H(A)	Kappa Prime
M(2)	0.234	342.60
S(2)	0.097	341.20
N(2)	0.064	329.80
K(1)	0.291	299.50
O(1)	0.197	285.40
NU(2)	0.011	335.90
MU(2)	0.010	295.00
2N(2)	0.010	306.90
OO(1)	0.009	317.20
S(1)	0.014	79.10
M(1)	0.011	309.70
J(1)	0.018	311.10
RHO(1)	0.007	279.30
Q(1)	0.035	277.20
T(2)	0.007	330.30
2Q(1)	0.005	296.40
P(1)	0.088	292.90
K(2)	0.026	333.80

Metadata Formats

The Coastal and Deep-Ocean data archived at NGDC and CO-OPS follow the FGDC content standard for geospatial metadata. In general, the metadata standard allows for recording identification, data quality, location, distribution, entity and attributes information in a transportable form. Complete information on the standard is available from http://www.fgdc.gov/standards/standards_publications/index_html .

DART™ Metadata Collected by NDBC

- For the station location:
  - ✔ Station ID (this is the World Meteorological Organization number for the station)
  - ✔ Nominal (ship measured) water depth in meters
  - ✔ Position—latitude, longitude, datum. Latitude and longitude to at least 1/10000 of a degree or thousandths of a minute. Accuracy and precision of the position. Method of position determination.
- For the deployment and recovery of the recorded data:
  - ✔ Start of the deployment: year, month, day, hour and minute
  - ✔ End of the deployment: year, month, day, hour and minute
  - ✔ Deployment and recovery platforms (ships and cruise numbers)
  - ✔ Comments on the deployment and recovery
- The start and stop dates and times (to the nearest second) of the data
- The type, make, model, and serial numbers, operational mode, valid ranges, accuracy, stability, sampling rate, and precision, as applicable, to the pressure transducer, the oscillator, and the "electronic board," and any temperature device. Dates of calibrations, installations, and removal of those instruments.
- Pre– and post–deployment ancillary measurements
- The tsunami detection threshold and the date and time it went into effect
- Reference to the tidal constituents used in the de-tiding at NDBC including the start and stop dates to which they are applied.

XML FGDC Standards-based Metadata Developed by NGDC

Data in the archive are described by standards compliant metadata. The current standard is version 2 FGDC-STD-001. The Metadata *Ad Hoc* Working Group (1998) describes the metadata standard. A clip of one DART™ buoy metadata record is shown. All published metadata are available from NGDC's Web site: http://www.ngdc.noaa.gov/metadata/published/DART_BPR/


```
<?xml version=”1.0” encoding=”ISO-8859-1”?>
<metadata>
 <idinfo>
  <datsetid>gov.noaa.ngdc.dart_bpr:D171_2003</datsetid>
  <citation>
   <citeinfo>
    <origin>DOC/NOAA/OAR/PMEL &gt; Pacific Marine Environmental Laboratory, OAR, NOAA, U.S. Department of Commerce</origin>
    <origin>DOC/NOAA/NWS/NDBC &gt; National Data Buoy Center, National Weather Service, NOAA, U.S. Department of Commerce</origin>
  <descript>
   <abstract>As part of the U.S. National Tsunami Hazard Mitigation Program (NTHMP), the Deep Ocean Assessment and Reporting of Tsunamis (DART™) Project is an ongoing effort to maintain and improve the capability for the early detection and real-time reporting of tsunamis in the open ocean. DART™ stations have been sited in regions with a history of generating destructive tsunamis to ensure early detection of tsunamis and to acquire data critical to real-time forecasts. DART™ systems consist of an anchored seafloor bottom pressure recorder (BPR) and a companion moored surface buoy for real-time communications. An acoustic link transmits data from the BPR on the seafloor to the surface buoy. The data are then relayed via a GOES satellite link to ground stations, which demodulate the signals for immediate dissemination to NOAA's Tsunami Warning Centers, NDBC, and PMEL. The National Geophysical Data Center (NGDC) serves as the archive center for these data and provides historical data to users.</abstract>
  </descript>
</metadata>
```

Appendix D: Tsunami Warning and Education Act

PUBLIC LAW 109–424: TSUNAMI WARNING AND EDUCATION ACT

An Act

To authorize and strengthen the tsunami detection, forecast, warning, and mitigation program of the National Oceanic and Atmospheric Administration, to be carried out by the National Weather Service, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Tsunami Warning and Education Act."

SEC. 2. DEFINITIONS.

In this Act:

(1) The term "Administration" means the National Oceanic and Atmospheric Administration.

(2) The term "Administrator" means the Administrator of the National Oceanic and Atmospheric Administration.

SEC. 3. PURPOSES.

The purposes of this Act are—

(1) to improve tsunami detection, forecasting, warnings, notification, outreach, and mitigation to protect life and property in the United States;

(2) to enhance and modernize the existing Pacific Tsunami Warning System to increase coverage, reduce false alarms, and increase the accuracy of forecasts and warnings, and to expand detection and warning systems to include other vulnerable States and United States territories, including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico areas;

(3) to improve mapping, modeling, research, and assessment efforts to improve tsunami detection, forecasting, warnings, notification, outreach, mitigation, response, and recovery;

(4) to improve and increase education and outreach activities and ensure that those receiving tsunami warnings and the at-risk public know what to do when a tsunami is approaching;

(5) to provide technical and other assistance to speed international efforts to establish regional tsunami warning systems in vulnerable areas worldwide, including the Indian Ocean; and

(6) to improve Federal, State, and international coordination for detection, warnings, and outreach for tsunami and other coastal impacts.

SEC. 4. TSUNAMI FORECASTING AND WARNING PROGRAM.

(a) IN GENERAL.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, shall operate a program to provide tsunami detection, forecasting, and warnings for the Pacific and Arctic Ocean regions and for the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico region.

(b) COMPONENTS.—The program under this section shall—

(1) include the tsunami warning centers established under subsection (d);

(2) utilize and maintain an array of robust tsunami detection technologies;

(3) maintain detection equipment in operational condition to fulfill the detection, forecasting, and warning requirements of this Act;

(4) provide tsunami forecasting capability based on models and measurements, including tsunami inundation models and maps for use in increasing the preparedness of communities, including through the TsunamiReady™ program;

(5) maintain data quality and management systems to support the requirements of the program;

(6) include a cooperative effort among the Administration, the United States Geological Survey, and the National Science Foundation under which the Geological Survey and the National Science Foundation shall provide rapid and reliable seismic information to the Administration from international and domestic seismic networks;

(7) provide a capability for the dissemination of warnings to at-risk States and tsunami communities through rapid and reliable notification to government officials and the public, including utilization of and coordination with existing Federal warning systems, including the National Oceanic and Atmospheric Administration Weather Radio All Hazards Program;

(8) allow, as practicable, for integration of tsunami detection technologies with other environmental observing technologies; and

(9) include any technology the Administrator considers appropriate to fulfill the objectives of the program under this section.

(c) SYSTEM AREAS.—The program under this section shall operate—

(1) a Pacific tsunami warning system capable of forecasting tsunami anywhere in the Pacific and Arctic Ocean regions and providing adequate warnings; and

(2) an Atlantic Ocean, Caribbean Sea, and Gulf of Mexico tsunami warning system capable of forecasting tsunami and providing adequate warnings in areas of the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico that are determined—

(A) to be geologically active, or to have significant potential for geological activity; and

(B) to pose significant risks of tsunami for States along the coastal areas of the Atlantic Ocean, Caribbean Sea, or Gulf of Mexico.

(d) TSUNAMI WARNING CENTERS.—

(1) IN GENERAL.—The Administrator, through the National Weather Service, shall maintain or establish—

(A) a Pacific Tsunami Warning Center in Hawaii;

(B) a West Coast and Alaska Tsunami Warning Center in Alaska; and

(C) any additional forecast and warning centers determined by the National Weather Service to be necessary.

(2) RESPONSIBILITIES.—The responsibilities of each tsunami warning center shall include—

(A) continuously monitoring data from seismological, deep ocean, and tidal monitoring stations;

(B) evaluating earthquakes that have the potential to generate tsunami;

(C) evaluating deep ocean buoy data and tidal monitoring stations for indications of tsunami resulting from earthquakes and other sources;

(D) disseminating forecasts and tsunami warning bulletins to Federal, State, and local government officials and the public;

(E) coordinating with the tsunami hazard mitigation program described in section 5 to ensure ongoing sharing of information between forecasters and emergency management officials; and

(F) making data gathered under this Act and post-warning analyses conducted by the National Weather Service or other relevant Administration offices available to researchers.

(e) TRANSFER OF TECHNOLOGY; MAINTENANCE AND UPGRADES.—

(1) IN GENERAL.—In carrying out this section, the National Weather Service, in consultation with other relevant Administration offices, shall—

(A) develop requirements for the equipment used to forecast tsunami, which shall include provisions for multipurpose detection platforms, reliability and performance metrics, and to the maximum extent practicable how the equipment will be integrated with other United States and global ocean and coastal observation systems, the global earth observing system of systems, global seismic networks, and the Advanced National Seismic System;

(B) develop and execute a plan for the transfer of technology from ongoing research described in section 6 into the program under this section; and

(C) ensure that maintaining operational tsunami detection equipment is the highest priority within the program carried out under this Act.

(2) REPORT TO CONGRESS.—

(A) Not later than 1 year after the date of enactment of this Act, the National Weather Service, in consultation with other relevant Administration offices, shall transmit to Congress a report on how the tsunami forecast system under this section will be integrated with other United States and global ocean and coastal observation systems, the global earth observing system of systems, global seismic networks, and the Advanced National Seismic System.

(B) Not later than 3 years after the date of enactment of this Act, the National Weather Service, in consultation with other relevant Administration offices, shall transmit a report to Congress on how technology developed under section 6 is being transferred into the program under this section.

(f) FEDERAL COOPERATION.—When deploying and maintaining tsunami detection technologies, the Administrator shall seek the assistance and assets of other appropriate Federal agencies.

(g) ANNUAL EQUIPMENT CERTIFICATION.—At the same time Congress receives the budget justification documents in support of the President's annual budget request for each fiscal year, the Administrator shall transmit to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives a certification that—

(1) identifies the tsunami detection equipment deployed pursuant to this Act, as of December 31 of the preceding calendar year;

(2) certifies which equipment is operational as of December 31 of the preceding calendar year;

(3) in the case of any piece of such equipment that is not operational as of such date, identifies that equipment and describes the mitigation strategy that is in place—

(A) to repair or replace that piece of equipment within a reasonable period of time; or

(B) to otherwise ensure adequate tsunami detection coverage;

(4) identifies any equipment that is being developed or constructed to carry out this Act but which has not yet been deployed, if the Administration has entered into a contract for that equipment prior to December 31 of the preceding calendar year, and provides a schedule for the deployment of that equipment; and

(5) certifies that the Administrator expects the equipment described in paragraph (4) to meet the requirements, cost, and schedule provided in that contract.

(h) CONGRESSIONAL NOTIFICATIONS.—The Administrator shall notify the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives within 30 days of—

(1) impaired regional forecasting capabilities due to equipment or system failures; and

(2) significant contractor failures or delays in completing work associated with the tsunami forecasting and warning system.

(i) REPORT.—Not later than January 31, 2010, the Comptroller General of the United States shall transmit a report to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives that—

(1) evaluates the current status of the tsunami detection, forecasting, and warning system and the tsunami hazard mitigation program established under this Act, including progress toward tsunami inundation mapping of all coastal areas vulnerable to tsunami and whether there has been any degradation of services as a result of the expansion of the program;

(2) evaluates the National Weather Service's ability to achieve continued improvements in the delivery of tsunami detection, forecasting, and warning services by assessing policies and plans

for the evolution of modernization systems, models, and computational abilities (including the adoption of new technologies); and

(3) lists the contributions of funding or other resources to the program by other Federal agencies, particularly agencies participating in the program.

(j) EXTERNAL REVIEW.—The Administrator shall enter into an arrangement with the National Academy of Sciences to review the tsunami detection, forecast, and warning program established under this Act to assess further modernization and coverage needs, as well as long-term operational reliability issues, taking into account measures implemented under this Act. The review shall also include an assessment of how well the forecast equipment has been integrated into other United States and global ocean and coastal observation systems and the global earth observing system of systems. Not later than 2 years after the date of enactment of this Act, the Administrator shall transmit a report containing the National Academy of Sciences' recommendations, the Administrator's responses to the recommendations, including those where the Administrator disagrees with the Academy, a timetable to implement the accepted recommendations, and the cost of implementing all the Academy's recommendations, to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives.

(k) REPORT.—Not later than 3 months after the date of enactment of this Act, the Administrator shall establish a process for monitoring and certifying contractor performance in carrying out the requirements of any contract to construct or deploy tsunami detection equipment, including procedures and penalties to be imposed in cases of significant contractor failure or negligence.

SEC. 5. NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM.

(a) IN GENERAL.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, shall conduct a community-based tsunami hazard mitigation program to improve tsunami preparedness of at-risk areas in the United States and its territories.

(b) COORDINATING COMMITTEE.—In conducting the program under this section, the Administrator shall establish a coordinating committee comprising representatives of Federal, State, local, and tribal government officials. The Administrator may establish subcommittees to address region-specific issues. The committee shall—

(1) recommend how funds appropriated for carrying out the program under this section will be allocated;

(2) ensure that areas described in section 4(c) in the United States and its territories can have the opportunity to participate in the program;

(3) provide recommendations to the National Weather Service on how to improve the TsunamiReady™ program, particularly on ways to make communities more tsunami resilient through the use of inundation maps and other mitigation practices; and

(4) ensure that all components of the program are integrated with ongoing hazard warning and risk management activities, emergency response plans, and mitigation programs in affected areas, including integrating information to assist in tsunami evacuation route planning.

(c) PROGRAM COMPONENTS.—The program under this section shall—

(1) use inundation models that meet a standard of accuracy defined by the Administration to improve the quality and extent of inundation mapping, including assessment of vulnerable inner coastal and nearshore areas, in a coordinated and standardized fashion to maximize resources and the utility of data collected;

(2) promote and improve community outreach and education networks and programs to ensure community readiness, including the development of comprehensive coastal risk and vulnerability assessment training and decision support tools, implementation of technical training and public education programs, and providing for certification of prepared communities;

(3) integrate tsunami preparedness and mitigation programs into ongoing hazard warning and risk management activities, emergency response plans, and mitigation programs in affected areas, including integrating information to assist in tsunami evacuation route planning;

(4) promote the adoption of tsunami warning and mitigation measures by Federal, State, tribal, and local governments and nongovernmental entities, including educational programs to discourage development in high-risk areas; and

(5) provide for periodic external review of the program.

(d) SAVINGS CLAUSE.—Nothing in this section shall be construed to require a change in the chair of any existing tsunami hazard mitigation program subcommittee.

SEC. 6. TSUNAMI RESEARCH PROGRAM.

The Administrator shall, in consultation with other agencies and academic institutions, and with the coordinating committee established under section 5(b), establish or maintain a tsunami research program to develop detection, forecast, communication, and mitigation science and technology, including advanced sensing techniques, information and communication technology, data collection, analysis, and assessment for tsunami tracking and numerical forecast modeling. Such research program shall—

(1) consider other appropriate research to mitigate the impact of tsunami;

(2) coordinate with the National Weather Service on technology to be transferred to operations;

(3) include social science research to develop and assess community warning, education, and evacuation materials; and

(4) ensure that research and findings are available to the scientific community.

SEC. 7. GLOBAL TSUNAMI WARNING AND MITIGATION NETWORK.

(a) INTERNATIONAL TSUNAMI WARNING SYSTEM.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, in coordination with other members of the United States Interagency Committee of the National Tsunami Hazard Mitigation Program, shall provide technical assistance and training to the Intergovernmental Oceanographic Commission, the World Meteorological Organization, and other international entities, as part of international efforts to develop a fully functional global tsunami forecast and warning system comprising regional tsunami warning networks, modeled on the

International Tsunami Warning System of the Pacific.

(b) INTERNATIONAL TSUNAMI INFORMATION CENTER.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, in cooperation with the Intergovernmental Oceanographic Commission, shall operate an International Tsunami Information Center to improve tsunami preparedness for all Pacific Ocean nations participating in the International Tsunami Warning System of the Pacific, and may also provide such assistance to other nations participating in a global tsunami warning system established through the Intergovernmental Oceanographic Commission. As part of its responsibilities around the world, the Center shall—

(1) monitor international tsunami warning activities around the world;

(2) assist member states in establishing national warning systems, and make information available on current technologies for tsunami warning systems;

(3) maintain a library of materials to promulgate knowledge about tsunami in general and for use by the scientific community; and

(4) disseminate information, including educational materials and research reports.

(c) DETECTION EQUIPMENT; TECHNICAL ADVICE AND TRAINING.— In carrying out this section, the National Weather Service—

(1) shall give priority to assisting nations in identifying vulnerable coastal areas, creating inundation maps, obtaining or designing real-time detection and reporting equipment, and establishing communication and warning networks and contact points in each vulnerable nation;

(2) may establish a process for transfer of detection and communication technology to affected nations for the purposes of establishing the international tsunami warning system; and

(3) shall provide technical and other assistance to support international tsunami programs.

(d) DATA-SHARING REQUIREMENT.—The National Weather Service, when deciding to provide assistance under this section, may take into consideration the data sharing policies and practices of nations proposed to receive such assistance, with a goal to encourage all nations to support full and open exchange of data.

SEC. 8. AUTHORIZATION OF APPROPRIATIONS.

There are authorized to be appropriated to the Administrator to carry out this Act—

(1) $25,000,000 for fiscal year 2008, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(2) $26,000,000 for fiscal year 2009, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(3) $27,000,000 for fiscal year 2010, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(4) $28,000,000 for fiscal year 2011, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6; and

(5) $29,000,000 for fiscal year 2012, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6.

Approved December 20, 2006.

Acknowledgments

This report was prepared for the National Tsunami Hazard Mitigation Program under the sponsorship of the National Oceanic and Atmospheric Administration Tsunami Program and with the approval of the NOAA Data Management Committee. The NESDIS–National Geophysical Data Center was the lead office for NOAA in preparing the report, which would not have been possible without the participation of the following:

NOAA Participants:

- NESDIS–National Geophysical Data Center
  - Captain John Adler (NOAA Corps), Paula Dunbar, Barry Eakins, Joy Ikelman (editor), Susan McLean (report compiler), Kelly Stroker, Lisa Taylor
- NOS–Center for Operational Oceanographic Products and Services
  - Allison Allen, Natalia Donoho, Andrea Hardy, Rolin Meyer
- NOS–Hydrographic Survey Division
  - Jeffrey Ferguson, Maureen Kenny
- NWS–National Data Buoy Center
  - William Burnett, Richard Bouchard, Darrell Duncan, Kevin Kern, William Hansen, Shannon McArthur, Kathleen O'Neil (formerly with), Chris Taylor, Mark Webster
- NWS–Pacific Tsunami Warning Center
  - Stuart Weinstein
- NWS–West Coast and Alaska Tsunami Warning Center
  - Paul Whitmore, Alec Medbery, Justin Ferris
- OAR–Pacific Marine Environmental Laboratory
  - Marie Eble, Harold Mofjeld (retired), Vasily Titov

Other participants:

- IRIS–Incorporated Research Institutions for Seismology–Data Management Center
  - Tim Ahern