Early detection and real-time reporting of deep-ocean tsunamis

Eddie N. Bernard[1], Frank I. González[1], Christian Meinig[1], and Hugh B. Milburn[2]

NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington, U.S.A.[1]

Abstract. The National Oceanic and Atmospheric Administration's (NOAA) Deep-ocean Assessment and Reporting of Tsunamis (DART) Project is an effort of the U.S. National Tsunami Hazard Mitigation Program (NTHMP) to develop an early tsunami detection and real-time reporting capability. Although seismic networks and coastal tide gauges are indispensable for assessing the hazard during an actual event, an improvement in the speed and accuracy of real-time forecasts of tsunami inundation for specific sites requires direct tsunami measurement between the source and a threatened community. Currently, only a network of real-time reporting, deep-ocean bottom pressure (BPR) stations can provide this capability. Numerous NOAA deployments of ever-improving prototype systems have culminated in the current operating network of DART stations in the North Pacific. DART data can be viewed online at `http://tsunami.pmel.noaa.gov/dartqc/WaveWatcher`. Network coverage is presently limited to known tsunamigenic zones that threaten U.S. coastal communities. Because tsunamis can be highly directional, DART stations must be properly spaced to provide reliable estimates of the primary direction and magnitude of the energy propagation. A method for detector siting will be presented that considers various tradeoffs between early tsunami detection, adequate source zone coverage, and DART system survivability. A proposed network will be presented that is designed to provide adequate coverage of tsunamis originating in source regions that threaten U.S. coastal communities: the Alaska Aleutian Subduction Zone, the Cascadia Subduction Zone, and the South American Seismic Zone.

1. Introduction

The development of tsunami detection buoys addresses one of the four issues identified in the 1996 Implementation Plan developed by the Tsunami Hazard Mitigation Federal/State Working Group: *Quickly Confirm Potentially Destructive Tsunamis and Reduce False Alarms* (NTHMP Steering Group, 1996).

Current tsunami warnings are based on seismic data and coastal tide gauge observations. Because neither provides direct measurement of tsunami energy propagating toward coastal communities, an understandably conservative tsunami warning philosophy has prevailed, producing an unacceptably high false alarm rate: approximately 75% since 1975. False alarms pose serious problems and have long-term implications for emergency planners. They are expensive, they undermine the credibility of the warning system, and they place citizens at physical risk of accidental injury or death during an evacuation (Bernard, 1998).

The speed and accuracy of tsunami warnings are improved by real-time reports of deep-ocean tsunami data collected near the source region within a few minutes of generation (Bernard, 1997). These data enable a more direct and rapid assessment of the hazard and, when coupled with model fore-

---

[1] National Oceanic and Atmospheric Administration (NOAA), Pacific Marine Environmental Laboratory (PMEL), 7600 Sand Point Way NE, Building 3, Seattle, WA 98115-6349, U.S.A. (bernard@pmel.noaa.gov)

[2] Retired from NOAA.

Table 1: Resources.

DART Buoys				
Fiscal Year	Requested	Available	Ship Time/Labor	
1997	$800,000	$780,800	$246,168	
1998	$800,000	$683,200	$546,090	
1999	$800,000	$683,200	$659,485	
2000	$800,000	$617,190	$645,000	
2001	$600,000	$870,374	$420,000	TOTAL
	$3,800,000	$3,634,764	$2,516,743	$6,151,507

casting tools, a more accurate prediction of the impact on specific coastal communities (Mileti, 1999). For example, Hawaii Civil Defense must make evacuation decisions within 1 hour of a large earthquake in the Alaska Aleutian Subduction Zone (AASZ). Deep-ocean stations between the AASZ and Hawaii can provide tsunami measurements before that decision must be made, so that destructive tsunamis will be identified more reliably and the number of false alarms and unnecessary evacuations will be reduced.

An added benefit of the real-time deep ocean data stream is continued offshore tsunami monitoring. Because tsunamis are a series of waves, dangerous conditions can persist for several hours after the first wave strikes a community. Large tsunamis can have periods as long as 1 hour and the largest wave may arrive as late as the third or fourth wave in the series. Offshore tsunami monitoring provides important guidance for decision-makers, who must judge the risk of deploying rescue and recovery personnel and equipment and, when the area is safe for the return of residents, sound the "all clear."

A DART mooring system consists of an anchored seafloor package and a moored surface buoy for real-time communications. Each seafloor system couples acoustic modem technology with bottom pressure recorders (BPRs) that are capable of detecting and measuring tsunamis with amplitude as small as 1 cm in 6000 m of water. An acoustic link is used to transmit the BPR data from the seafloor system to its accompanying surface buoy. The data are then relayed via a NOAA GOES satellite link to ground stations, which demodulate the signals for immediate dissemination to NOAA's Tsunami Warning Centers in Alaska and Hawaii, and to PMEL for quality control. Quality control data are plotted and available for download at `http://tsunami.pmel.noaa.gov/dartqc/WaveWatcher.`

The capability to transmit data from the deep ocean to ground stations in real time did not exist before the DART Project successfully developed the necessary technology to solve formidable engineering problems. The development required the sustained efforts over the past 5 years of over 25 scientists, engineers, technicians, and software developers who are listed in Table 2. The NTHMP provided $3,634,764 or 96% of the funds requested in the Implementation Plan. However, the true cost of development and implementation was $6,151,507, which includes the expenses of NOAA ship time and additional labor (Table 1).

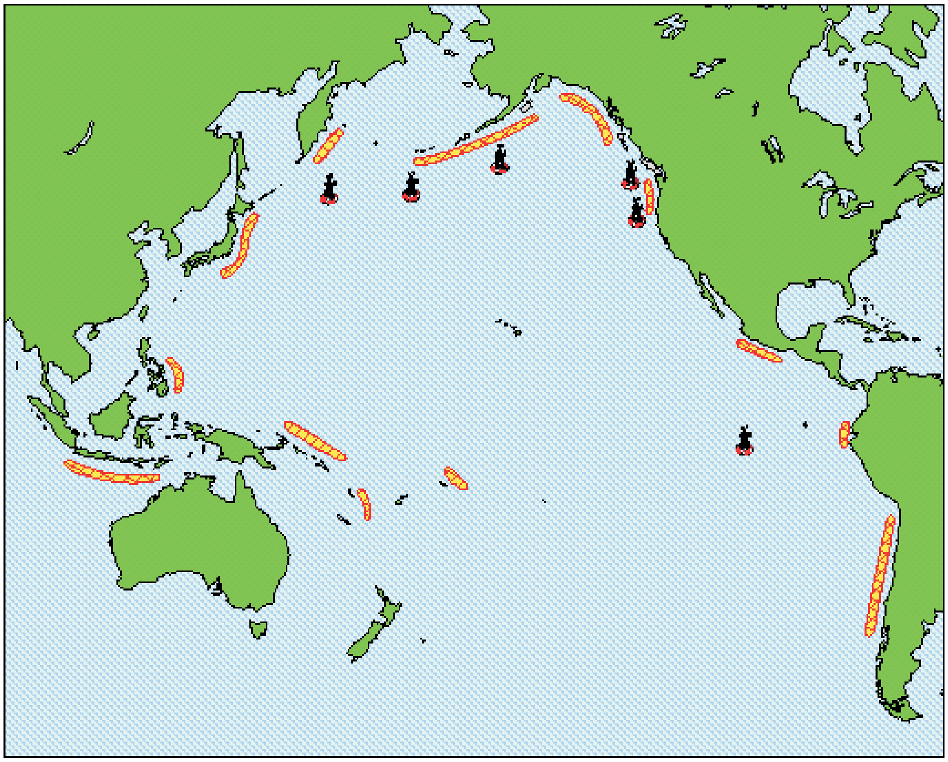


Figure 1: NOAA proposed siting of real-time tsunami detectors.

2. What Was Promised?

Program goals for this work are detailed on page 8 of the Tsunami Hazard Mitigation Implementation Plan (Tsunami Hazard Mitigation Federal/State Working Group, 1996), and are reproduced here, for convenient reference:

Establish real-time tsunami detection network — NOAA: $800,000/year; out years: $600,000/year.

Historical and paleoseismic data show that earthquakes capable of producing significant Pacific-wide tsunamis are identified in the shaded coastal regions in Fig. 1. The proposed siting of buoys will ensure the detection of any tsunami within these regions within 30 minutes of the generating earthquake. NOAA has built and tested a prototype deep-ocean tsunami detection buoy that measures the tsunami in the open ocean and transmits these data to shore in near real time. To U.S. coastlines, a six-buoy array is proposed to quickly detect the propagation of a tsunami from areas where earthquakes generate destructive tsunamis and relay tsunami data to the warning centers and the states (Fig. 1).

To establish the array over 4 years, NOAA proposes the following schedule:

Table 2: Participants.

PMEL Engineering Division Personnel

Mike Craig
Nicholas Delich
Jeff Harmon
Dennis Holzer
Kevin Kinsey
David Lewis
Mark Lindley
Floyd Mader
Christian Meinig
Hugh Milburn
Hendrick Miller
Alex Nakamura
John Shanley
Stephen Smith
Carl Snodgrass
Scott Stalin
Michael Strick
Dirk Tagawa

PMEL Tsunami Program Personnel

Marie Eble
Frank González
Harold Mofjeld
Jean Newman

PMEL Computer Division Personnel

David Borg-Breen
Eugene Burger
Tran H. Nguyen

Other People and Companies

Company	**Product**
Datasonics	Acoustic Modems
Paroscientific	Pressure Sensors
Sunbacker	Buoy Hulls
Western Titanium	Rod, tubes, hardware
Prometco	Buoy towers/frames
SnoLynn	Machine Shop
H & S Machine	Machine Shop
Telonics	GOES Transmitters
WV Communications	GOES Amplifiers
REPCO	RF Modems
Impulse	Cables/Connectors
MacArtney	Underwater Connectors
Synergetics	GOES Antenna
VITEL	GOES DRGS
LW Products	Buoy Wells
Gardico	Rubber Gaskets
International Belt	Buoy Bumpers
Energy Sales	Batteries
AQC	Printed Circuit Boards
Port Plastic	Lids/Covers
Bucconeer Rope	Nylon Mooring Line
Obelt Marine	Chain and Shackles
Subconn	Cable and Connectors
J & S Fabrication	Aluminum Towers
Benthos	Acoustic Modems and Flotation

60 other suppliers for everything from integrated circuits to railroad wheels

Year 1

Engineering and software developments will advance the prototype buoy to operational robustness. Procurement and fabrication of two buoy systems will be completed.

Year 2

First two systems will be deployed in Alaska and materials and supplies will be purchased to build two more systems. Engineering and software development will continue.

Year 3

Next two systems will be deployed off the West Coast. Materials and supplies will be purchased to build two more systems. Improvements in engineering and software will continue.

Year 4

Two more systems will be deployed near Kuril Islands and the equatorial Pacific. Materials and supplies will be purchased to build one system. Maintenance visits will be made to two Alaska sites and continued on a 2-year cycle.

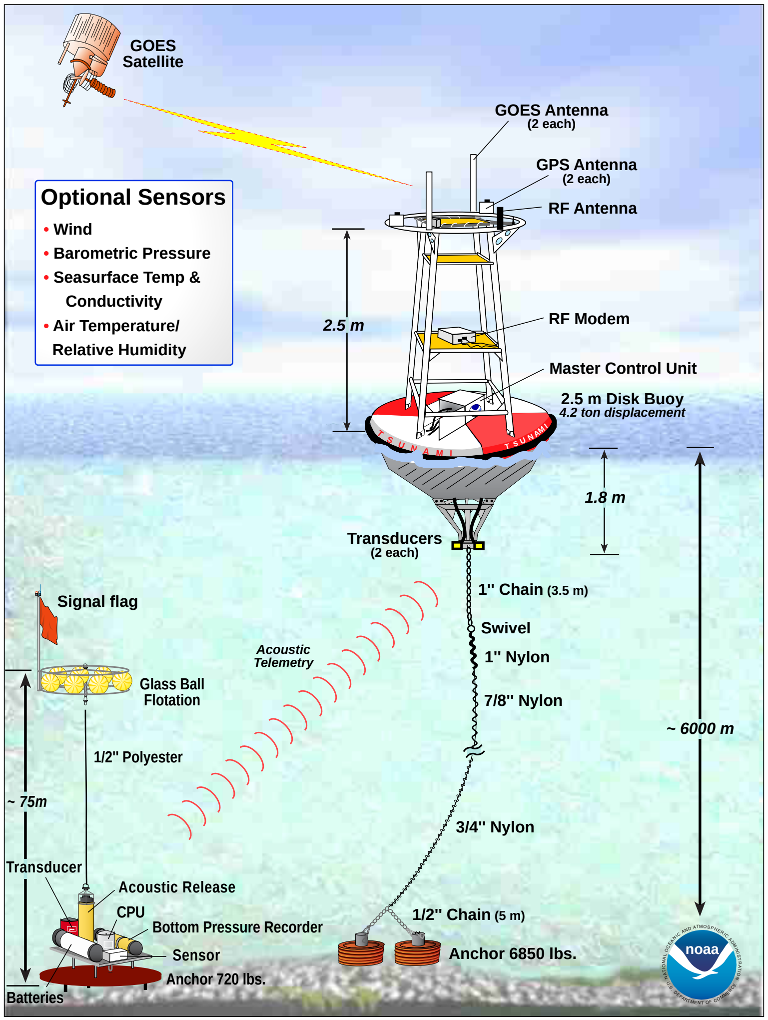
Out years

Each year three sites will be visited for maintenance and replacement parts for the equivalent of one system will be purchased. Engineering and software support will be provided to maintain the six-site array.

3. What Was Accomplished?

The six-buoy detection array will be in place by August 2001, and the DART systems currently deployed are achieving a data return rate of approximately 98%. This is equal to or better than other operational ocean buoys. A typical DART system configuration is presented schematically in Fig. 2.

Because of the budget reduction in year two of the program, the DART development was spread out over 5 years. During this time additional features were incorporated that were not envisioned in the original design. The most significant addition was the development of a real-time DART data web page to facilitate quality control by PMEL personnel (`http://tsunami.pmel.noaa.gov/dartqc/WaveWatcher`). This web site is accessible to all interested parties including State officials and the Tsunami Warning Centers. Tsunami Warning Centers, however, rely on separate, dedicated data streams to acquire their operational data. Other design changes included the addition of redundant equipment that improves data return rates. A DART system operates in two modes. Tide mode provides 15-minute data every hour to verify that the system is operating properly. Tsunami mode



1/01JCN12/00KLBV/NOAA/PMEL

Figure 2: DART mooring system.

transmits 15- and 60-second data when the BPR is triggered by a deviation from predicted sea level that exceeds a pre-set threshold value (typically, 1–3 cm). Although there has been no detected tsunami generated since the array has been installed, end-to-end tests of each DART system have been conducted in-situ with pre-programmed, artificial signals used to trigger the initiation of the tsunami reporting mode. Additionally, DART stations have been triggered into tsunami reporting mode on several occasions when seismic surface waves from local earthquakes have imparted vertical acceleration to the BPR that induced a change in the apparent pressure. Evaluation of tsunami mode data from both types of triggering events indicates that the system is functioning as designed. In summary, the DART buoy array is installed and operating according to the original design with over 98% data return rates and a worldwide distribution capability.

DART represents a major engineering achievement. The resulting real-time data stream will make tsunami warnings more timely and accurate.

Table 3: Highlights.

	About 90 days at sea were used on 18 cruises utilizing 8 different ships during the development and installation of the array.
1997	Designed and built new surface mooring and redesigned BPR package for real-time reporting. By testing acoustic modems in the spring in Puget Sound and off Hawaii, the design was changed to increase the transmit level of bottom modem. In July, the first deployment failed, but by September we had a successful deployment off Oregon coast. The first system worked for about 3 months.
1998	Continued refinement of surface transducer placement, improved reliability of surface buoy tower welds, improved redundant communications, and developed, tested, and implemented a GOES downlink capability to receive data and place on the internet in real time. Tested new generation modems off the *Moana Wave* near Honolulu and tested improved software off *Shana Rae* near Monterey. In September second generation DART deployed with new modems at 50°N, 145°W that operated 86 days with 96% data return. Web site was on line in September.
1999	Improved reliability of GOES transmitters, improved redundancy with engineering data transmitted with ocean data and built an operational prototype. During May and October four operational prototypes were deployed off Alaska (3) and California (1). Data return rates from these prototypes varied from from 96% to 99%. Earthquakes in California and Alaska in the fall of 1999 produced seismic surface waves that triggered two of the four systems into "tsunami mode." The systems worked as designed in both the "tide" and "tsunami" modes. Data were also being received by both warning centers through an independent communication system.
2000	Continued improvements in the operational prototype which is now called DART. Three moorings, which were deployed in October 1999 and survived the harsh North Pacific winter, transmitted real-time data with greater than 95% data return rates. In August recovered and redeployed three DART systems in Alaska and recovered and redeployed one DART off Oregon. Each DART system was successfully cycled through a pre-programmed test designed to verify system operation during a simulated trigger event. In November 2000 the first training course in interpreting deep-ocean tsunami data was held in Hilo, Hawaii for warning center leaders and state tsunami advisors.
2001	Continued improvements in DART software and web display of real-time data and completed the six DART arrays as originally planned.

The engineering challenge was formidable, and a total of 18 ocean cruises over 5 years were required, but success was achieved through the dedicated leadership of Hugh Milburn and the efforts of supporters listed in Table 2. As a result of this work, deep ocean tsunami data are now available in real time to the NOAA Warning Centers, the five affected States, and anyone with an Internet connection. A summary of major activities in DART development is outlined in Table 3.

In November 2000, the first training session on the interpretation of deep-ocean data was held in Hilo, Hawaii. The session was attended by the chiefs of the NOAA Warning Centers and State Tsunami Advisors who were instructed by Dr. Vasily Titov, co-director of the NTHMP's Center for Tsunami Inundation Mapping Efforts (TIME).

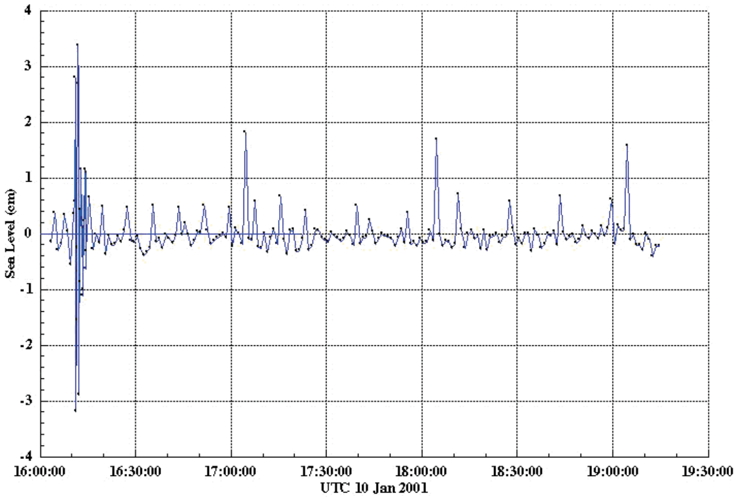


Figure 3: Real-time DART mooring data for the 10 January 2001 Kodiak, Alaska earthquake (tides removed).

4. What Was the Impact?

The January 2001 Alaskan earthquake was an excellent example of the value of DART data. The following news item appeared in the NOAA news web page on 11 January 2001. Some excerpts from that story are:

> On January 10, 2001, a magnitude 6.9 earthquake occurred at 0703 local time about 70 miles SW of Kodiak, Alaska. The warning center located the position of the earthquake, assessed its magnitude, and issued an information bulletin at 0708. At 0711 a DART system at 51°N and 157°W picked up the earthquake waves that induced an apparent sea level change of approximately 6 cm and triggered the buoy to start transmitting 1-minute data. By 0713 these data were plotted on the web site at `http://tsunami.pmel.noaa.gov/dart/qc/event/26117_3.html`. The data showed no tsunami present. A plot of these data are shown in Fig. 3.
>
> "The detection buoy, located off the Alaskan coast, performed as designed in detecting an apparent abrupt change in sea level and sending data via the NOAA GOES satellite to the NOAA Tsunami Warning Centers and to its Pacific Marine Environmental Laboratory in Seattle where these data were plotted on a web site. Anyone on the web could view these data 10 minutes after the earthquake ruptured," said Eddie N. Bernard, director of NOAA's laboratory in Seattle, Washington. "More important, the data showed that no tsunami was generated either by the earthquake or an underwater landslide induced by the earthquake."
>
> Charles McCreery, geophysicist in charge of the National Weather

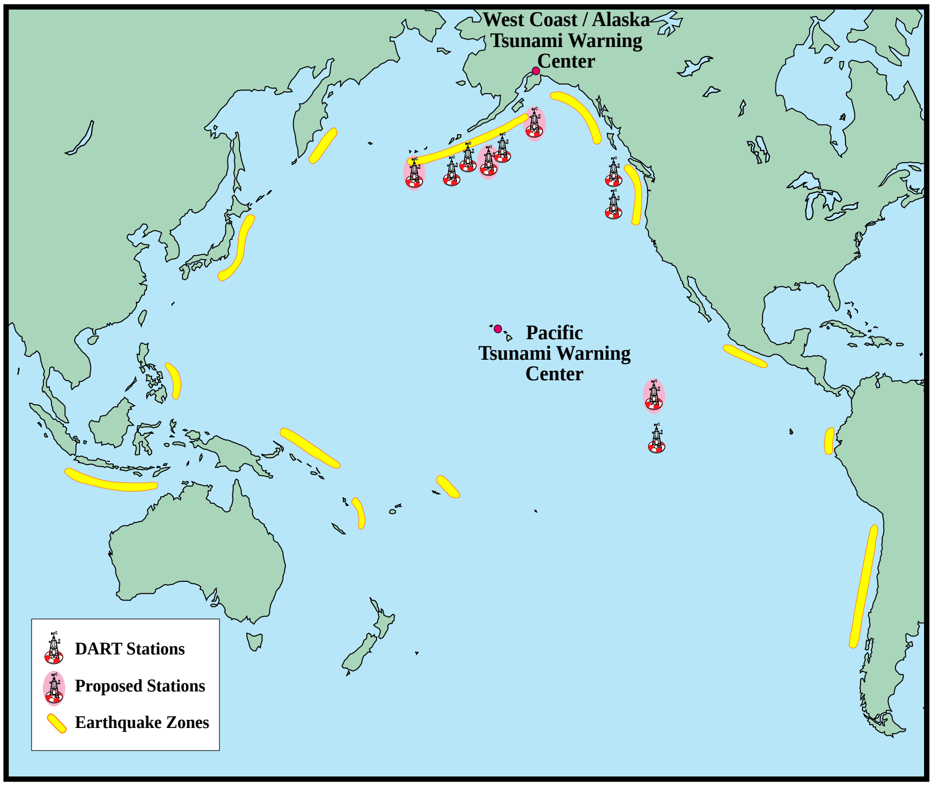


Figure 4: Recommended expansion of DART array.

> Service's Pacific Tsunami Warning Center, one of two such centers —the other is in Alaska—said, "While the earthquake was too small to automatically trigger a tsunami warning, the Pacific Tsunami Warning Center closely monitored the Kodiak buoy data to quickly confirm that potentially destructive tsunami waves were not propagating towards Hawaii or the rest of the Pacific." (For the complete story, visit `http://www.noaanews.noaa.gov/stories/s560.htm`.)

Thus, although a tsunami was not involved, this event illustrates the value of such data in addressing a primary goal of the NTHMP, i.e., to *Quickly Confirm Potentially Destructive Tsunamis and Reduce False Alarms*.

5. The Future: Next 5 Years

We recommend expansion of the array from six DART buoys to ten buoys in the configuration shown in Fig. 4.

The expanded array would: provide better coverage for tsunamis generated in Alaska, which poses the greatest threat to the five states; add coverage of South America, which has generated destructive tsunamis in the past; and continue the coverage of the Cascadia Subduction Zone.

Siting strategy involves trade-offs between two important, but somewhat conflicting, operational requirements:

1. early detection to maximize the time available for assessment and warning
2. full coverage of tsunamigenic zones, with sufficient spatial resolution to estimate the directional distribution of the tsunami energy. This is critical to the goal of exploiting numerical models for real-time forecast capabilities within the next 5 years.

Figure 5 graphically illustrates these tradeoffs. A minimum of three DART measurements are required to estimate the width of the main beam of tsunami energy. Since the beam widens with increasing distance from the source, DART station spacing increases and fewer stations are required. However, the time available for assessment and warning decreases because the tsunami takes longer to reach the stations.

In addition to these operational considerations, siting decisions are naturally constrained by the total number of stations that can reasonably be established in this 5-year period, given practical logistical problems and budgetary realities.

The cost to purchase a DART buoy is about \$250,000 and the cost to maintain a DART buoy is about \$125,000/year *exclusive* of ship time. We estimate that 20 days of Class I ship time would be required each year to maintain the array as shown in Fig. 4.

To expand (adding one DART/year) and maintain the array with Internet access would cost approximately \$1,200,000/year over the next 5 years; in successive years, maintenance costs would be indexed to inflation. To maintain the existing array of six buoys would cost approximately \$800,000/year *exclusive* of ship time. However, a skeletal array of six buoys would compromise our future ability to accurately forecast wave heights from Alaska. Within this 5-year period, DART operations would be transferred to the National Data Buoy Center, an operational unit within NOAA's National Weather Service.

Classes and workshops would also continue to be held by TIME scientists for Warning Center and State representatives over the next 5 years to provide training in the use of a methodology currently under development for short-term inundation forecasting by tsunami. This methodology uses the deep-ocean data in conjunction with numerical models to provide estimates of coastal wave amplitude and site-specific inundation. Feedback by participants in the training sessions will guide the development of web-based hazard mitigation products and tools.

Acknowledgments. The authors appreciate the support from NOAA, NTHMP, and the five States to make this project successful. In particular, we thank NOAA Research managers Jim Rasmussen, Alan Thomas, and David Evans, who supported early tests of the acoustic modem used for tsunami warnings.

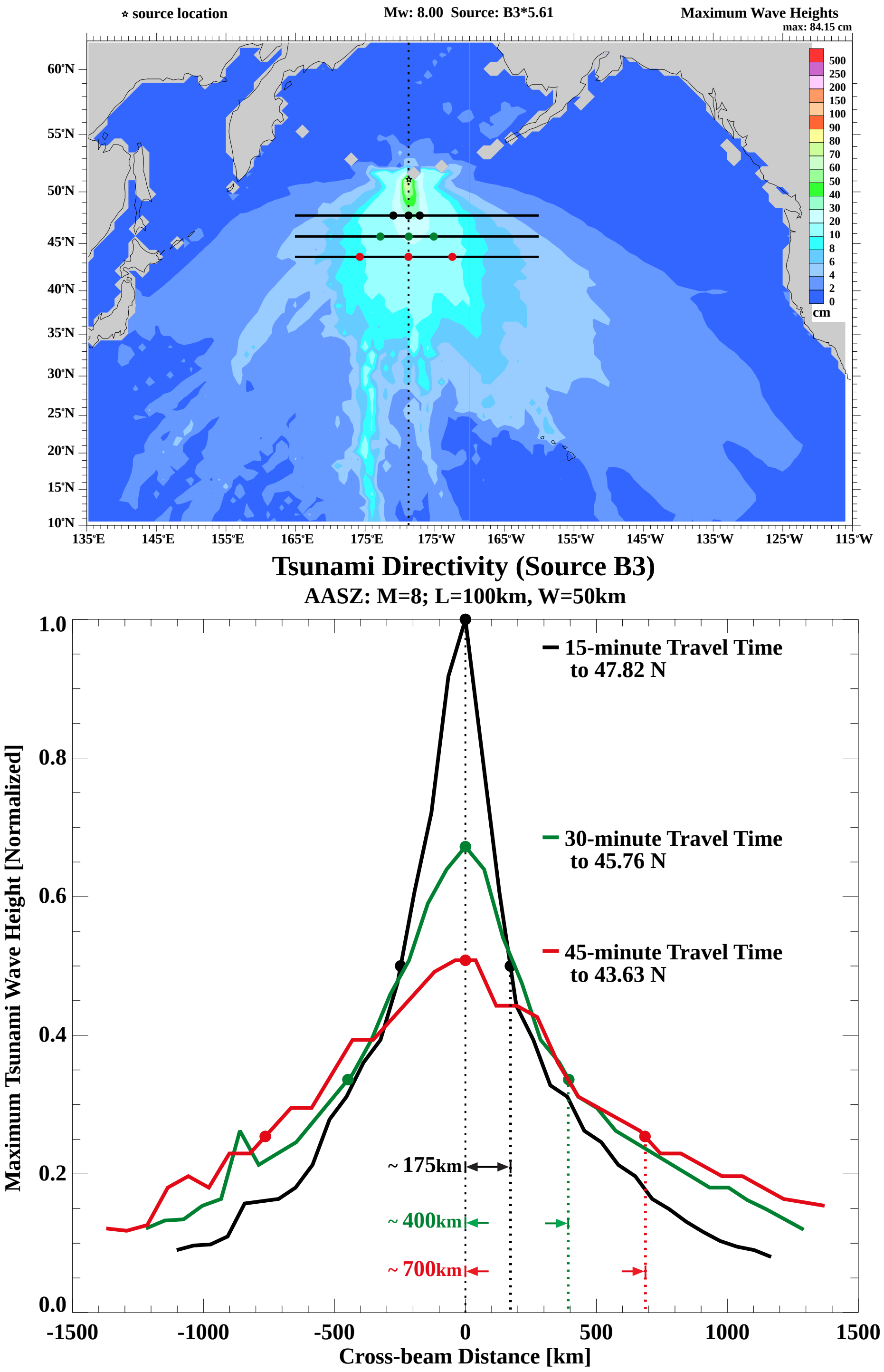


Figure 5: Trade-off between early detection and source coverage. **Top Frame**: Maximum wave height model results for a magnitude 8.0 earthquake in Alaska, with horizontal lines indicating location of computed maximum wave height profiles, shown below. **Bottom Frame**: Maximum wave height profiles taken across horizontal lines in top frame. Dots indicate hypothetical DART measurements at the "half-amplitude" points, and the dashed horizontal lines suggest minimum DART station spacing required to estimate the height and width of the profile for detection 15, 30, and 45 minutes after the earthquake main shock.

6. References

Bernard, E.N. (1998): Program aims to reduce impact of tsunamis on Pacific states. *Eos Trans. AGU, 79*(22), 258, 262–263.

Bernard, E.N. (1997): Reducing tsunami hazards along U.S. coastlines. In *Perspectives on Tsunami Hazards Reduction*, edited by G. Hebenstreit, Kluwer Academic Publishers, 189–203.

Mileti, D.S. (1999): *Disasters by Design: a reassessment of natural hazards in the United States*. Joseph Henry Press, Washington, D.C., 351 pp., 186.

Tsunami Hazard Mitigation Federal/State Working Group (1996): Tsunami Hazard Mitigation Implementation Plan—A Report to the Senate Appropriations Committee, 22 pp., Appendices.