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TSUNAMETER NETWORK DESIGN FOR THE U.S. DART® ARRAYS IN THE PACIFIC AND ATLANTIC OCEANS

Michael C. Spillane[1,2]
Edison Gica[1,2]
Vasily V. Titov[1,2]
Harold O. Mofjeld[2,3]

[1]Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
University of Washington, Seattle, WA

[2]Pacific Marine Environmental Laboratory
Seattle, WA

[3](retired)

Pacific Marine Environmental Laboratory
Seattle, WA
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Carlos M. Gutierrez
Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

William J. Brennan
Acting Undersecretary for Oceans and Atmosphere/Administrator

Office of Oceanic and Atmospheric Research

Richard W. Spinrad
Assistant Administrator

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Tsunameter network design for the U.S. DART® arrays in the Pacific and Atlantic oceans

M.C. Spillane[1,2], E. Gica[1,2], V.V. Titov[1,2], and H.O. Mofjeld[2,3]

Abstract. In March 2008 a significant milestone in the quest to provide adequate warning of propagating tsunami waves in the Pacific and Atlantic Oceans was accomplished with the completion of the U.S. array of 39 tsunameters (`www.noaanews.noaa.gov/stories2008/20080310_buoy.html`). In conjunction with five additional instruments, deployed in cooperation with other nations (including two sites in the Indian Ocean), this network is monitored continuously by the U.S. Tsunami Warning Centers in Hawaii and Alaska and the data stream provided freely in real-time to the international community. While the occurrence of a significant submarine earthquake can be detected rapidly to provide a basis for an early warning, not all such events generate significant waves. Unambiguous quantitative observation of the passage of tsunami waves in the deep ocean can permit either early warning cancelation or, in conjunction with numerical models, forecasts of the hours-long trains of potentially damaging waves at threatened sites. This report documents the considerations and methodology used in site selection.

1. Introduction

Following the Indian Ocean tsunami disaster of December 2004, which demonstrated the catastrophic and widespread potential for death and destruction inherent in tsunami waves, an early decision was made to greatly expand the then-existing capability for warning U.S. coastal communities. Tsunami Warning Centers (TWCs) were established in Hawaii and Alaska in the wake of destructive tsunamis, caused by seismic activity in the Aleutian Islands (1946), Chile (1960), and Alaska (1964). By monitoring submarine earthquakes the staff at these centers have been able to quickly establish a potential for tsunami generation, and promulgate warnings to the regions most threatened.

However, in addition to there being non-seismic mechanisms for tsunami generation, there is not as yet the ability to relate tsunami amplitude to earthquake magnitude and associated parameters, at least within a time frame that might provide timely warnings. Perhaps due to the triggering of submarine landslides, as appears to have occurred in the case of the Papua-New Guinea event of 1998 (Synolakis *et al.*, 2002), an earthquake of lesser intensity can be highly dangerous. Conversely, a sizeable earthquake may generate only minor tsunami waves. The significance of the former eventuality is self-evident, but the costs associated with "false alarms" are not negligible. An unwarranted evacuation can cost millions of dollars and, while the costs associated with the loss in public confidence are less easy to quantify, the effectiveness of a warning system is ultimately grounded in credibility.

[1]Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington, Seattle, WA, 98195

[2]NOAA, Pacific Marine Environmental Laboratory, Seattle, WA, 98115

[3](retired)

A proven technology for the unambiguous detection and assessment of tsunami waves as they propagate had been available since the 1980s, though it has been significantly improved since then. A bottom pressure recorder (BPR), installed on the seafloor and communicating to shore in real time via a surface buoy and satellite link (Fig. 1), can register the amplitude and timing of a tsunami wave train. Combined with a pre-computed database of propagation models, the time series from one or more such DART® (Deep-ocean Assessment and Reporting of Tsunami) instruments can be "inverted" to produce basin-wide estimates of the tsunami's threat and the input needed to drive site-specific forecast models of inundation for those communities most at risk. While the signature of the Indian Ocean tsunami was discernable in hindsight from satellite altimetry (Smith *et al.*, 2005), and schemes relying on GPS receivers on surface buoys have been proposed, their capabilities in actual real-time emergency situations have yet to be demonstrated. [GPS-derived ground motion estimates have the potential to improve early estimates of seismic moment (Blewitt *et al.*, 2006), and the quality of the seismic forecast.] Another technology that has been successfully proven in the field (`www.gloria-symposium.com/pdf/22-7Kaneda.pdf`) has been deployed off Japan and incorporates BPR units and seafloor seismometers, with communication to shore via submarine cable. The latter, with a capacity for high-frequency data transfer, is well suited to the locally generated tsunamis that pose the greatest hazard to Japan. Cabled systems in the Northeast Pacific too are under development, or operating in research mode, with the potential to provide valuable input for local tsunami detection. NSF's Ocean Observatories Initiative and the NEPTUNE Canada project envisage (`www.ooi.washington.edu/`) regional scale nodes extending offshore with a variety of sensors providing real time data via the internet. Bottom pressure sensors off Monterey Bay (`www.mbari.org/mars/`), and in the Strait of Georgia east of Vancouver Island (`www.neptunecanada.ca`), currently deliver such data and the promise of things to come. Such systems are, however, expensive and DART® systems provide a more cost-effective, readily available and scalable solution given the global extent of potential tsunami sources. The "Ring of Fire" spans thousands of kilometers along the peripheries of the Pacific and Indian Oceans and other extended source regions occur in the Atlantic, Caribbean, and Mediterranean.

The utility of the early, limited array of DART® buoys off Alaska and the U.S. west coast, and the forecast methodology for generating a usable forecast was demonstrated during an actual tsunami event (Titov *et al.*, 2005). A full-featured system with the acronym SIFT (Short-term Inundation Forecasting for Tsunamis) for processing seismic and DART® data, and generating a suite of forecast products, is in the process of being installed at the Pacific (PTWC) and West Coast/Alaska (WCATWC) Tsunami Warning Centers. SIFT has been described elsewhere (Gica *et al.*, 2008) and has performed well during several mild tsunamis since 2004 (Wei *et al.*, 2008a). Installation and servicing of elements of the U.S. DART® array (and other sites instrumented in cooperation with Australia, Chile, Indonesia, and Thailand) by the National Data Buoy Center (NDBC) has been proceeding apace. The initial deployment of the full U.S. array of 39 DART® systems was com-

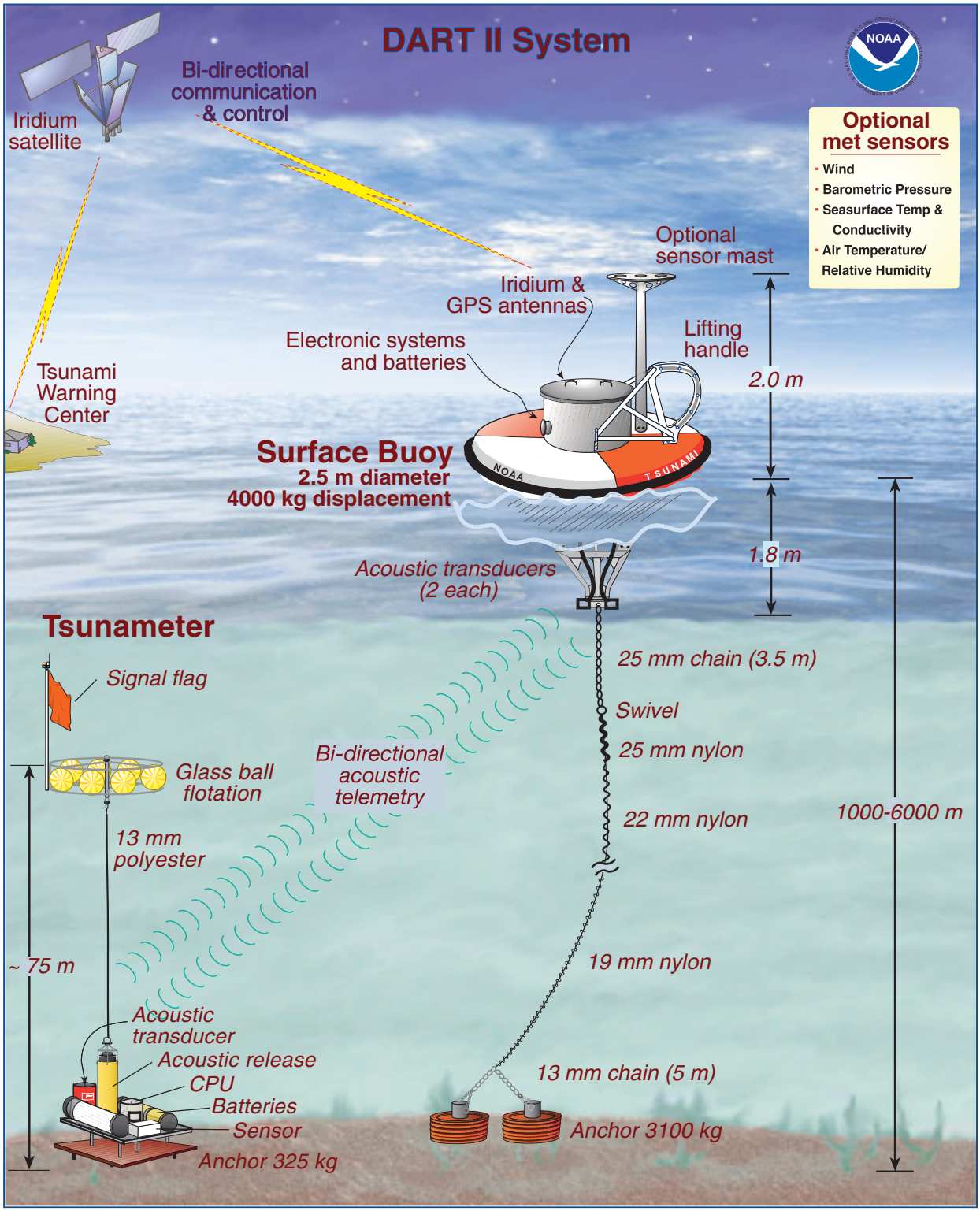

Figure 1: Schematic of a DART® site.

pleted in early 2008. The rationale and methodology for the siting decisions is the subject of this Technical Memorandum. Based on Site Recommendation Reports produced at the NOAA Center for Tsunami Research (NCTR) in consultation with the TWC's, and with input from the NDBC and the U.S. Geological Service (USGS), and other interested parties, the goal is to provide information of use in refining and extending the U.S. array, and to aid efforts by the international community to extend the coverage. As the 2004 event demonstrated, a tsunami may wreak destruction over many nations, and can only be effectively combated through education and cooperative detection efforts.

2. Tsunami Detection and the DART® Technology

Before proceeding to array considerations it is well to summarize in brief those characteristics of tsunami waves and DART® instrumentation that influence site selection. While they may be generated by several phenomena, the most frequent source of tsunami waves is seismic activity beneath the sea floor (González, 1999). A submarine earthquake, particularly one associated with a subduction fault, can displace upward and/or downward a large area of seafloor (Wei *et al.*, 2008b). The resulting displacement of the overlying water column then propagates outward from the source region in all directions as a wave train of peaks and troughs. The waves have a long wavelength, with the distance between successive peaks often being several hundred kilometers in the deep ocean. As a consequence, though it seems counterintuitive, tsunamis behave as "shallow-water" waves since their wavelengths significantly exceed even the greatest ocean depths.

2.1 Tsunami Detection in Deep Water

Shallow-water waves travel with a speed (c) that depends on water depth through the relationship

$$c = \sqrt{gH} \tag{1}$$

where H is the water depth and g the gravitational acceleration ($\sim$9.8 m/s). In the deep ocean, where the mean depth is $\sim$3,800 m, a tsunami may travel at a speed comparable to an airliner! As the waves spread out their amplitude decreases from an initial value, typically of the order of a meter, to a few centimeters or less. However, as the wave approaches land and the water depth decreases, the wave train slows, becomes compressed along the direction of travel, and grows in amplitude again. Seafloor features can act to focus the tsunami in particular locales, resulting in a mass onshore movement of water, better described as a "bore" rather than a wave. Sometimes the leading crest may be preceded by a noticeable drawdown of water level, which, to a knowledgeable person on the beach, should be a signal to seek high ground. There may be several waves in succession over a period of minutes to hours; the leading wave may not be the greatest and indeed, due to reflection by seafloor features away from the direct path, the most dangerous waves may arrive many hours after the first. Extended monitoring of the DART® network in the hours following the generation of a significant tsunami can provide valuable guidance to the emergency response.

Tsunami wave properties, such as those described above, have several implications for the instruments that might detect them. Because of their greater speed in the deep ocean, the waves can arrive earlier at detectors

placed offshore, than at a site at a lesser distance from the source but in shallower water. Measurements at coastal sea level gages, or the direct observation of tsunami waves by persons in impacted areas, may provide further indication of the presence of a destructive tsunami. However, due to topographic focusing, such observations are generally more complex and less suited to analysis and basin-wide prediction than a "clean" time series in deep water.

The reduced amplitude of tsunami waves in deep water may seem to mitigate against detection, particularly as their amplitudes of a few centimeters are much less than the several-meter heights of ambient wind waves. This would be true for a surface-based detector, but a BPR in deep water senses the pressure signal associated with changes in the water column height and essentially filters out high-frequency wind wave fluctuations or swell. A typical DART® signal (see Fig. 2) appears, at first glance, as a smooth tidal variation with an episode of high-frequency activity of much lesser amplitude highlighted in red. The data in units of pressure (PSIA) have been converted to units of water depth in meters using a conversion factor (670 mm/PSIA). Once the tides are removed, by suitable prediction and filtering algorithms, the high-frequency variability can be examined in detail.

In the early hours of 13 January 2007 an earthquake of moment magnitude (M_w) 8.1 occurred beneath the seafloor in the vicinity of the Kuril Islands. Seismic waves from the event epicenter, radiating outward at 2–3 km/s, triggered DART® 46408 (among others) from its regular 15-min reporting mode into event mode. One-minute data stored aboard the instrument were transmitted for a period preceding the trigger and the transmissions of 1-min samples continued for several hours. The seismic noise signal, aliased since its frequency is much higher than the 0.0333 Hz Nyquist frequency of the event mode reports, died away to a level not much greater than the ambient noise level before the event, allowing the true tsunami signal to stand out clearly though its peak-to-trough amplitude is only 4 cm. DART® 46408 lies 2,650 km east of the epicenter. Like the November 2006 Kuril event that preceded it, the tsunami waves caused some damage in Crescent City, CA (6,220 km away) where waves of 37 cm peak-to-trough were reported. Such mild events are providing useful unscheduled tests of the DART® and SIFT systems in addition to assisting in TWC operations (Geist *et al.*, 2007; `soundwaves.usgs.gov/2007/04/research2.html`).

2.2 Noise Reduction

While communication with a seafloor BPR via a seafloor cable would be the "gold standard" in terms of the sampling rate with which the signal could be monitored, the distances of tens to hundreds of kilometers to suitable shore stations make the costs of such installations prohibitive. With a limited number of BPRs to employ (the current U.S. array is based on 39 instruments) individual instruments need to be placed well offshore in order to monitor a significant stretch of potential source and derive the benefits

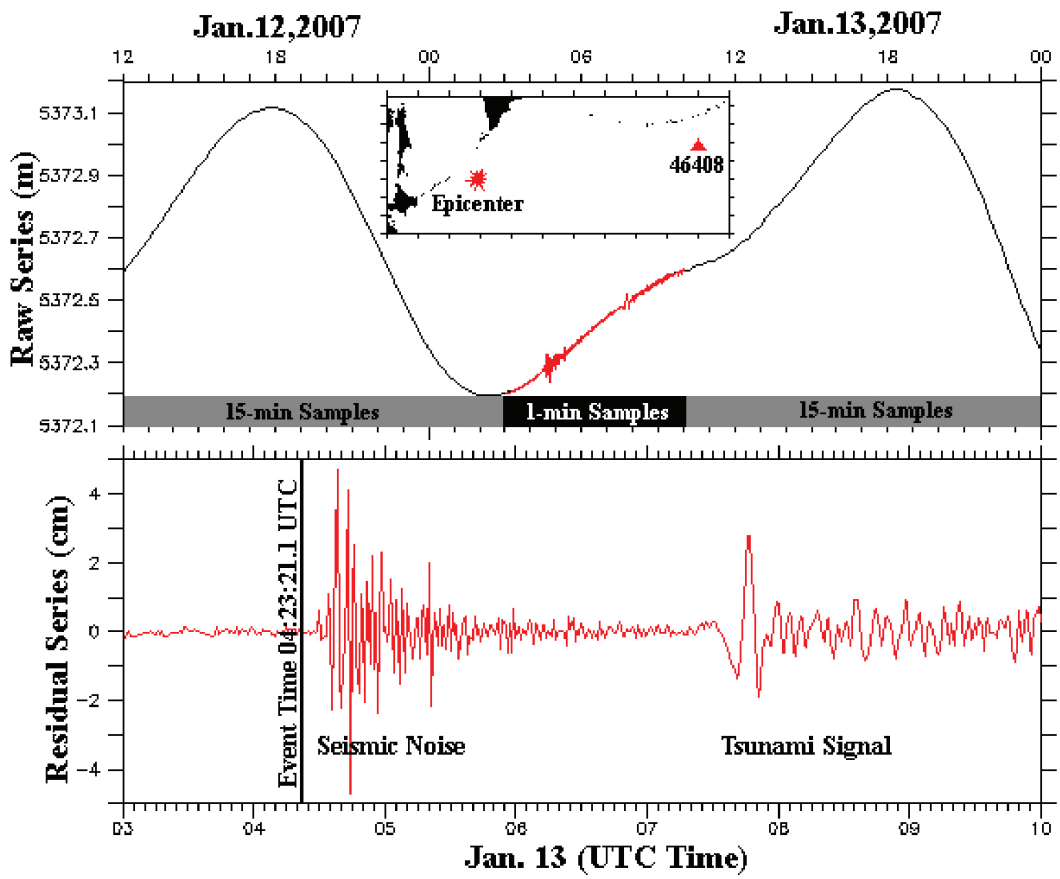

Figure 2: The mild Kuril Island tsunami of 13 January 2007 as seen by DART® 46408.

of deep-water detection. The earth's subduction zones, which are the major source of tsunamigenic earthquakes, extend for thousands of kilometers.

Offshore placement has other benefits for DART® operations. In addition to generating a tsunami, a submarine earthquake is the source for a variety of seismic waves that propagate through the surface layers and body of the earth. Indeed, these waves, which travel through the solid earth considerably faster than the tsunami's speed through water, are detected at land-based seismometers around the globe providing an early indication of the epicenter and magnitude of the event. Even though no changes to water level are caused by these fast-moving seismic waves, their effect is high-frequency "seismic" noise in the BPR (see Fig. 2). Frequently it is this seismic signal that trips the BPR from its stand-by reporting interval of 15 min to the 1-min interval needed to "see" a tsunami. The amplitude of this noise signal may exceed the true water column signal associated with the tsunami and, to avoid contamination of the latter, the BPR should be sufficiently removed from the tsunami source region so that the fast-moving seismic noise signal will have died away before the desired tsunami signal arrives. There is clearly a trade-off here between the need for avoidance of seismic noise contamination (and suitable spacing of BPRs) and the desire to provide an early assessment of tsunami amplitude to the SIFT forecast

system upon whose predictions early warning cancelations or inundation forecasts depend.

2.3 Bathymetric Considerations

Next to consider in DART® siting is water depth and the character of the bathymetry, both local and in the direction of a tsunami source. As illustrated in Fig. 1, the BPR signal, measured at the seafloor, is sent to an adjacent surface buoy via an acoustic link. From there, the signal is transmitted to shore by a satellite link. In early versions of the DART® this communication was one-way, with the BPR operating autonomously when a "trigger" condition in the BPR signal was detected. Current versions of the DART® permit two-way communication, allowing an instrument to be controlled by an operator on shore. This may be desirable during a tsunami event to initiate or extend the pre-programmed interval of 1-min sampling, or to circumvent the premature seismic triggering of a remote DART® that would drain battery power without returning relevant data. (In addition, two-way communication facilitates testing, system resets, and software update.) The acoustic link requires separations of between 1,500 and 6,000 m between the seafloor and surface units. This, and the need for a reasonably flat seabed on which the BPR will sit, are constraints to DART® site selection. Relatively uniform depth is also needed in order to pre-cut the cables needed to anchor the surface unit with a suitable watch circle. While sites that are generally suitable can be selected in advance using bathymetry datasets (such as that of Smith and Sandwell, 1997), the precise positioning is usually chosen during deployment, based on an on-site shipboard survey.

Another bathymetric consideration, not unique to the DART® technology, is the avoidance of tsunami scattering. Scattering can result when the seafloor terrain between the tsunami source and the detection site is overly rugged. Bathymetric features, such as seamounts, cause zones of shadowing or of reinforcement in their lee. To the extent that these effects are imperfectly represented in the tsunami propagation model database on which the SIFT inversion scheme relies, forecast quality will be adversely affected. Confirmation of general site suitability is performed in advance by NDBC personnel, who also provide guidance for the avoidance of seabed infrastructure, sea lanes and excessive fishing pressure, high probability of vandalism, and issues such as strong currents that might impact mooring design.

2.4 Territorial Issues

While tsunami detection can produce benefits to all, which would ideally suggest that sites for DART® systems be selected strictly on scientific and engineering grounds, in reality elements of the U.S. DART® array are placed either in U.S. or international waters. This choice is primarily for logistical reasons. Access to a foreign EEZ (Exclusive Economic Zone) generally requires several months of advance notice. With deployment cycles of two or

more years this might not be a problem, but unplanned visits at irregular intervals may be required due to instrument failure or to avail of ship-of-opportunity cruises. Generally this has not been a major inconvenience since the need to avoid the immediate vicinity of earthquake source regions usually dictates sites outside the 200 nm limit. However in some locations, such as the Caribbean and the southwest Pacific, most of the seabed falls within some nation's EEZ. A database of EEZ boundaries is available online from the Flanders Marine Institute (VLIZ, 2005).

There is one exception to the siting of the U.S. DART® array in international or U.S. waters. The site of 46419 off Vancouver Island is within the Canadian EEZ, reflecting the joint U.S.-Canada interest in tsunami warnings for the Pacific Northwest coast.

2.5 A Note on DART® Site Identification Numbers

DART® sites and other marine buoy locations are assigned 5-digit World Meteorological Organization (WMO) identification numbers. The first two digits are based on WMO association areas and sub-areas (see `www.wmo.int/pages/prog/amp/mmop/Images/wmo_area_sub_area.gif` for a chart of these areas). In the case of U.S. DART® sites the third digit is consistently "4," providing a convenient means of distinguishing them from buoys with other purposes. The final two digits are generally sequentially assigned. A consequence of this naming procedure is that sites with adjacent WMO numbers may be widely separated or vice versa, as in the case of 46413 (mid-Aleutians) and 46412 (off Los Angeles) whose closest neighbor to the south is 43412!

3. From Initial Concept to the Final Design

So far, tsunami sources in relation to suitable DART® sites have only been discussed in general terms, based on considerations of signals and noise, engineering issues, and a loose statement that an array, with a finite number of elements, cannot be very closely spaced. To proceed further one needs to consider the sources of tsunami risk and the assets, both of human life and property, in need of protection.

3.1 Initial Array Concept

In the early days following the Indian Ocean tsunami of 2004, when there were seven U.S. and one Chilean DART® systems in place, it was estimated that to protect U.S. interests in the Pacific and Atlantic Oceans the U.S. array or network should be increased to 39 sites. This number, based on experience with the existing instruments off the Aleutians, the West Coast, and Chile and, no doubt, some "back of the envelope" estimates, was in retrospect quite a reasonable starting point. Figure 3 illustrates the initial concept for the network with 32 U.S. sites in the Pacific (P1–P32) and 7 in the Atlantic (A1–A7). Five of the occupied locations (01–05) were to be adjusted; two others (06 in the Equatorial Pacific and 07 off Hawaii, whose main role is to provide warning of a local source) were to remain unchanged.

3.2 The DART® Siting Workshop

The first step in refining the conceptual array was to convene a meeting of experts and interested parties to identify the major threats, and impact sites at greatest risk, in order to make a general allocation of the resources. This was done in July 2005 at a joint NOAA-USGS DART® Siting Workshop held at NOAA's Pacific Marine Environmental Laboratory in Seattle, Washington. A brief report of the discussion is available online (Geist *et al.*, 2005; `soundwaves.usgs.gov/2005/10/meetings.html`). Some salient points from the discussion are repeated here and in Appendix A.

Attendees identified the primary source types, which, in addition to the historically dominant submarine earthquake mode, include volcanic activity (both submarine and sub-aerial), landslides (again both submarine and sub-aerial with the latter including potential massive slope failure in the Azores as well as the notable event in Lituya Bay, Alaska), and extraterrestrial impact. In light of the historical record in the Pacific, earthquake sources would appear to pose the dominant threat. The paucity of long-term records outside of Japan pointed to the difficulty in assigning recurrence probabili-

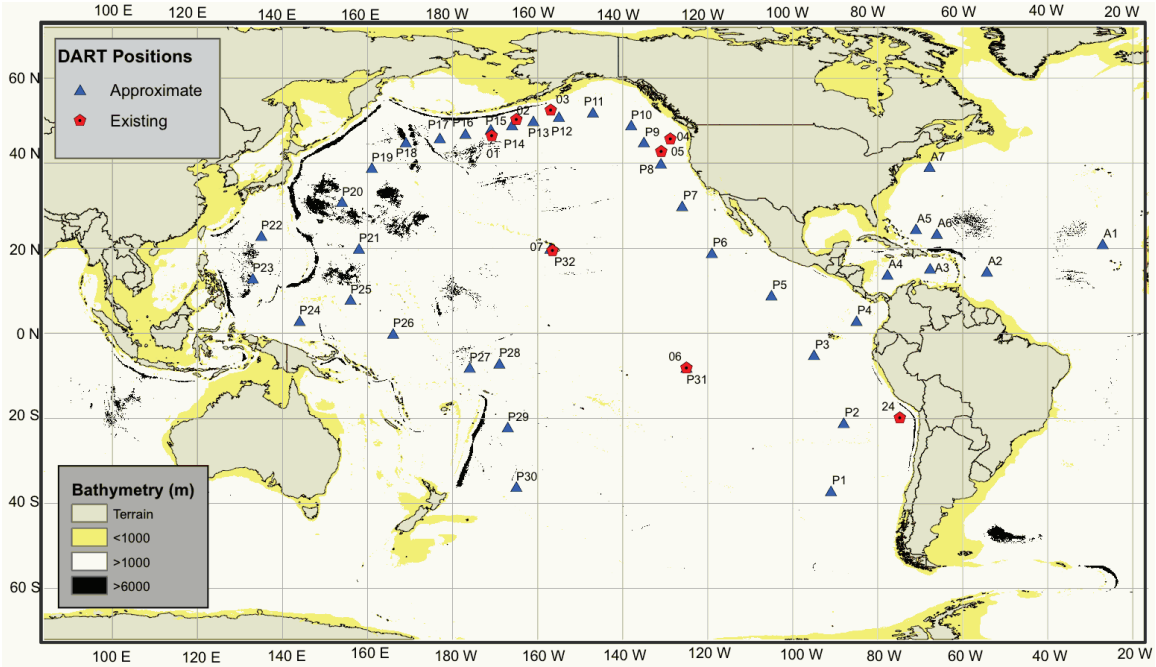

Figure 3: Initial concept for the expanded U.S. DART® network. Sites marked in red were in place at the time of the Indian Ocean disaster; included is the Chilean tsunameter not counted in the U.S. allocation of 39 instruments (32 Pacific, 7 Atlantic).

ties with any reliability. Though the likelihood of an event might be greater where there is a "seismic gap," and there may be grounds to make spatial estimates of the greatest event magnitude likely, the consensus seemed to be that it would be unwise to discount any portion of the circum-Pacific stretches of subduction zone as a potential source. Likewise, though the Hawaiian Islands are perhaps most exposed to tele-tsunamis from widespread sources and clearly warrant extra consideration, the West Coast has areas under high threat (associated with the Cascadia subduction zone) or with severe risk exposure both of population and infrastructure in the case of California. There are, in addition, widespread centers of U.S. interest spread throughout the Pacific and Atlantic basins. Based on the consensus of opinion at the workshop (which assumed that additional Chilean DART®s to the south of the existing one were likely), the approximate allocation indicated in Fig. 4 was decided.

The placement of DART® buoys in the Atlantic region was considerably revised as a result of the Siting Workshop discussion. With the exception of the Caribbean, where tsunamis are not infrequent, the source distribution is less well defined. In addition to the subduction zone that arcs from Trinidad to Hispaniola on the Atlantic side of the island chain, there are the incompletely documented sources that caused earthquake and tsunami activity near Lisbon in 1755. In addition to the volcano/landslide threat from the Azores there was a landslide-generated event off Newfoundland in 1929 and the potential exists for slope failure along the U.S. mid-Atlantic coast (Driscoll *et al.*, 2000; Chaytor *et al.*, 2007). In the Gulf of Mexico there

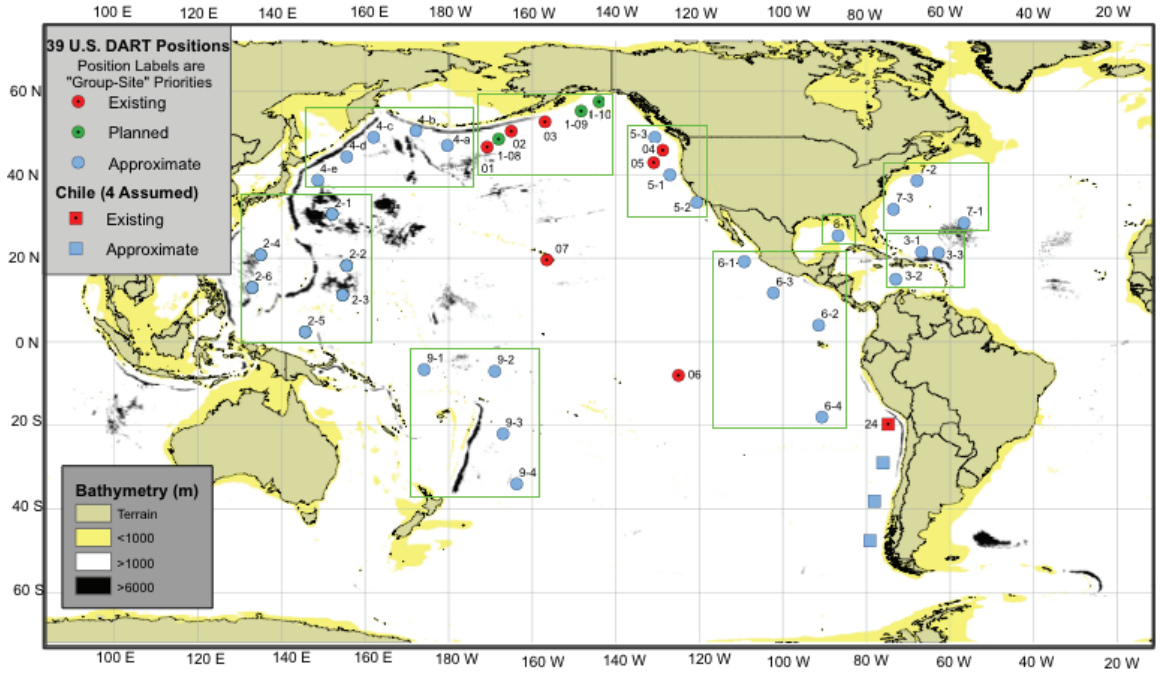

Figure 4: Refined concept of the DART® network resulting from the Siting Workshop. Sub-regions were identified (outlined in green) and deployment priorities assigned to each. The Aleutian-Alaska sub-region had highest priority (1), the Southwest Pacific lowest (9). Allocations presumed expansion of the Chilean network to the south of their existing tsunameter (labeled 24 in the figure).

is some threat of seismically generated tsunamis from subduction zones off Panama and Venezuela, though waves would be greatly attenuated by the Yucatan Strait (or the Florida Strait in the case of seismic activity to the east). There are, however, potential landslide sources (McAdoo *et al.*, 2000). The south coast of Puerto Rico and U.S Virgin Islands are at some risk due to the Muertos Trough subduction zone immediately to its south (see Fig. 45), and from other seismic sources off South America and along the island chain to the east as well as the submarine volcano Kick'em Jenny and other island volcanoes. Bearing all these factors in mind, the consensus of the workshop attendees was to allocate one DART® each to the Caribbean and the Gulf of Mexico, two north of Puerto Rico, two inshore along the East Coast and the final DART® well to the east to provide a long lead time for ill-defined threats in the eastern Atlantic.

3.3 The Completed Array

Figure 4 and Table 1 summarize the recommendations of the workshop in terms of asset allocation and the priorities for deployment. Sub-groups within the array were established which, to a large extent, were followed in the site recommendation reports that are included as appendices. The status of the array, and both data and metadata, are available online (`www.ndbc.noaa.gov/dart.shtml`); the situation in March 2008, following the completion of the array, is shown in Fig. 5. This image, adapted from the NDBC

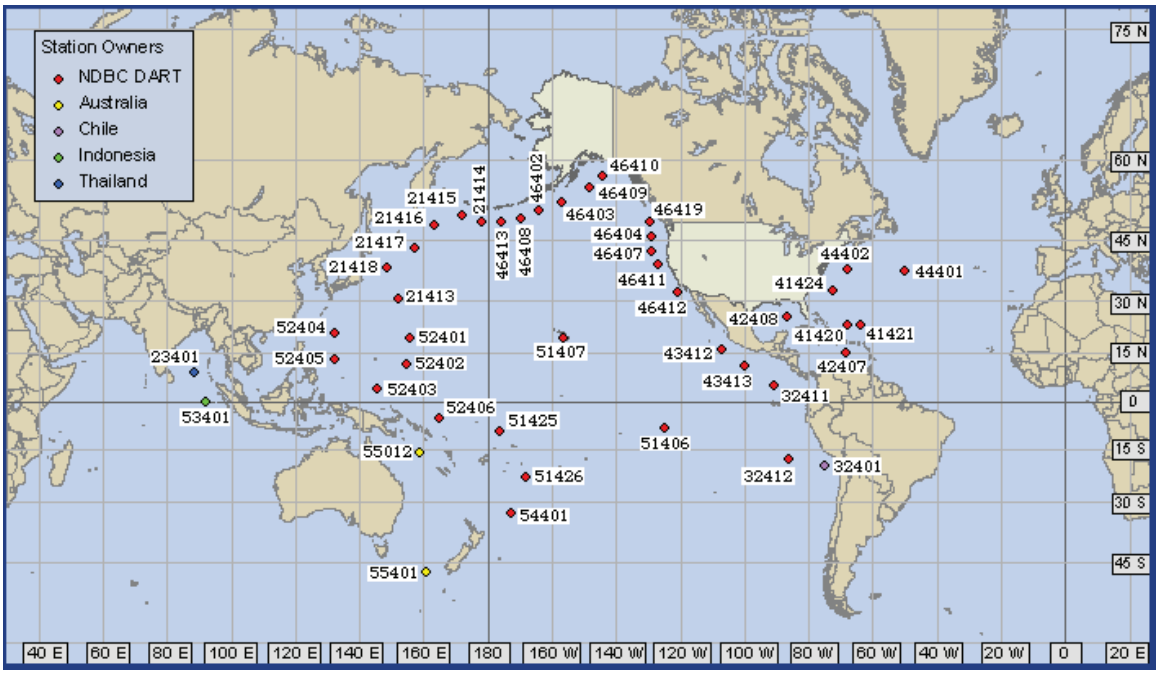

Figure 5: The completed U.S. DART® array in March 2008 (shown in red) and other tsunameter stations that report via NDBC (adapted from the locator image at: `www.ndbc.noaa.gov/dart.shtml`).

website to include the 5-digit WMO buoy identifiers, can be compared with the initial array concept (Fig. 3) and the revised design (Fig. 4) that emerged from the Workshop. Figure 5 includes non-U.S. sites that employ DART® instruments and report freely through NDBC. NCTR staff members have cooperated in international siting decisions with Chile and Australia for the Pacific, and Thailand and Indonesia in the case of the Indian Ocean. USAID contributed to these Indian Ocean sites and it clearly benefits both the U.S. and the global community to collaborate in the positioning of tsunameters and in sharing the data they provide. India and Germany have deployed tsunameters in the Indian Ocean and plans from other nations under the IOTHWS umbrella will be monitored to ensure cooperative efficiencies. [In October 2008 two new DART® sites were established by Australia, in the North Australian Basin, south of the Java Trench.]

3.4 A Note on Optimization

Following the DART® Siting Workshop the utility of optimization was explored. To the extent that the constraints on siting can be quantified, and the benefits expressed in functional form, array design might be approached as a problem in optimization. This avenue was explored with the assistance of John Dennis (of Rice University) and his colleagues, using their tool NOMAD (`www.gerad.ca/nomad/`). Routines were added at NCTR to communicate to NOMAD (implemented in Matlab) via Ferret (`ferret.pmel.noaa.gov/Ferret/`, a PMEL-designed analysis tool) data

Table 1: Sub-region allocations and priorities within the overall U.S. array.

Array Sub-Group	Instruments Assigned	Pre-existing Sites	Priority
Alaska/Aleutians	6	3	1
Western Pacific	6	0	2
Puerto Rico/Caribbean	3	0	3
West Coast	5	2	4
Southwest Pacific	4	0	5
Central/South America	4	0	6
Atlantic	3	0	7
Gulf of Mexico	1	0	8
Northwest Pacific	5	0	9
Hawaii/Mid-Pacific	2	2	N/A

extracted from the propagation database (see Section 4) and the Smith-Sandwell bathymetry. Constraints on water depth and bottom roughness were easily incorporated as a mask; NOMAD would then position a selected number of DART® sites within a sub-region of the ocean so as to optimize the detection time for a set of unit sources.

The scheme was tested for a relatively simple case: siting six DART® off the Aleutians and Alaska. Here the linear source arrangement, and the lack of EEZ constraints, resulted in a solution that conformed to expectation. Another case explored was that of the western Pacific, where the source distribution is considerably more complex. The array suggested by NOMAD had some similarity to that finally adopted, but required considerable adjustments to accommodate the limitations imposed by territorial issues. Other issues, such as the representation of scattering and the expression of the optimization function, could not be addressed within the time constraints of the site selection process. Some of the difficulty lay no doubt in the fact that the NOMAD expertise resided offsite while the voluminous datasets and Ferret expertise were local to NCTR. Thus, though in principle NOMAD and the optimization approach may yet be employed in fine-tuning the existing array, the siting recommendations were based on calculations performed at NCTR, implemented using the analysis and graphic capabilities of Ferret alone.

4. The Propagation Database: A Tool in the Array Design

The refraction due to the depth-dependence of tsunami wave speed, together with scattering and reflection from bathymetric features, can result in complex patterns for the spread of tsunami waves even in the deep ocean. In consequence, numerical modeling is required to make basin-wide predictions. This is illustrated in Fig. 6, where the pattern of maximum amplitude (occurring during a 24-hour model hindcast) is color contoured for the relatively weak Kuril Island tsunami of 15 November 2006. The pattern shows lobes or fingers of enhanced energy pointed in various directions. Although there was little overall damage associated with this event, some communities such as Crescent City, California experienced unusually strong waves and currents.

4.1 Unit Sources and the SIFT System

The numerical models that can produce charts such as that shown in Fig. 6, require detailed bathymetry and can be quite demanding of computer resources. The overall task is generally partitioned into two components:

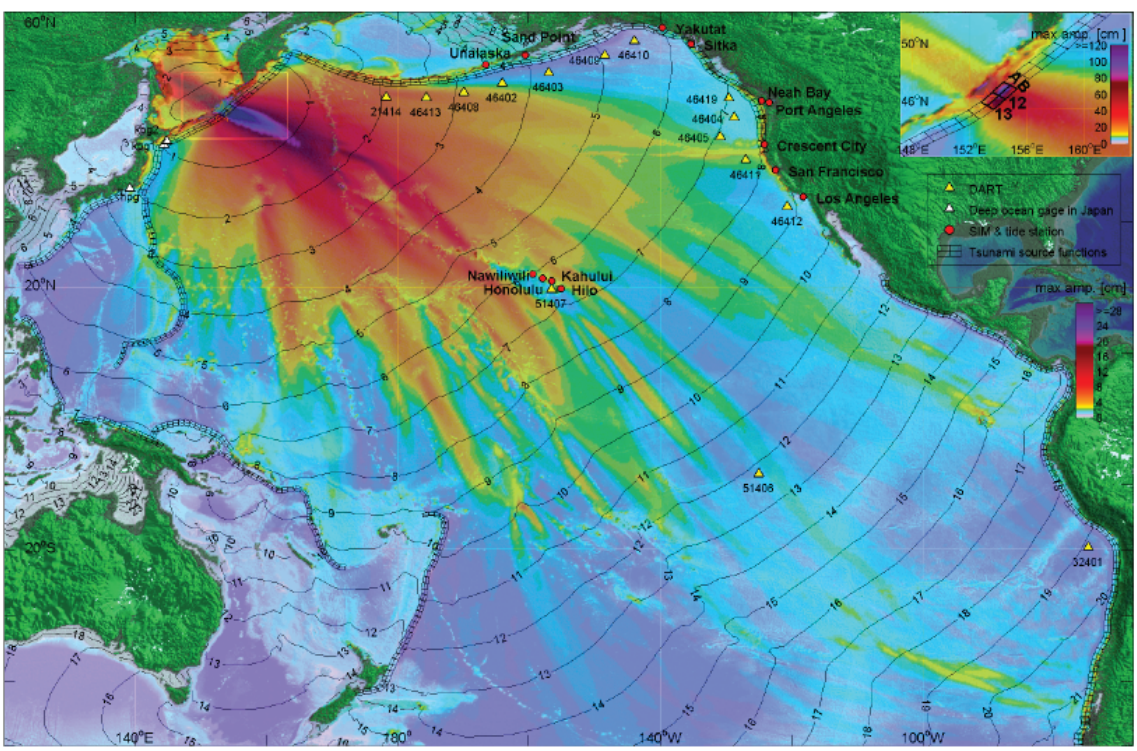

Figure 6: The maximum amplitude pattern for the 15 November 2006 Kuril Island tsunami.

open ocean propagation and coastal inundation. While the latter process is strongly nonlinear, and in consequence requires real-time, event-specific computer runs, the propagation of tsunami waves in deep water can be treated linearly and stored as a database. The seismic source regions are partitioned into blocks, or "unit sources" (see the inset panel in Fig. 6) each representing an earthquake of moment magnitude 7.5 in a 100 × 50 km rectangle whose long side is aligned with the subduction zone axis. This "strike" direction and the associated dip and source depth are chosen based on seismological knowledge with the assistance of the USGS, resulting in a tiled layout covering the source regions. The "rake angle" of each unit source is set to 90°, since normal or reverse faulting generates the greatest vertical seafloor deformation. The distribution of seafloor deformation, as computed using the algorithms of Okada (1985), provides the initial condition for sea surface elevation.

The propagation and evolution of the initial elevation can be computed using the MOST (Method Of Splitting Tsunamis) hydrodynamic code (Titov and González, 1997). Usually 24 hours of propagation is modeled and the results for velocity and surface elevation stored at 1-min intervals. For situations where 24 hours is not adequate for wave propagation to extend to all potential impact points, or where major reflections can cause later waves to be of concern, the model run is extended appropriately. For these propagation runs a coastal "wall" is placed, typically at the 20-m isobath, to exclude the non-linear processes that can occur in shallow water. When the results have been quality-controlled, to ensure that no numerical instabilities have occurred, they are loaded to the propagation database. This database now contains in excess of 1,450 unit sources covering all likely seismic sources in the Pacific, Atlantic, and Indian Oceans.

Because of their underlying linearity, the unit source propagation solutions can be scaled up or down to represent event magnitudes other than $M_w = 7.5$, or combined with those of neighboring unit sources to form composite sources of greater spatial extent than the 100 × 50 km appropriate to each. In operational use, within the SIFT system, the propagation database is employed as follows:

1. Detection of an earthquake with potential tsunami risk prompts the TWCs to issue a preliminary warning. The epicenter coordinates and magnitude estimate identify which unit sources are likely involved.

2. The composite solution for these unit sources, with appropriate scaling, generates a chart (similar to that shown in Fig. 6), timing information, and other products such as a coastal estimate. These quickly identify the communities most threatened should a significant tsunami in fact have been generated.

3. While historical information concerning the source region may indicate the likelihood that a damaging tsunami has been generated, the expense of evacuation and the loss of public confidence that can result from a false alarm requires that unambiguous evidence of the tsunami be obtained to refine the initial warning. This validation is provided

by the DART® array, whose BPR sensors measure and transmit via satellite the height of the water column above them. A DART® may be triggered into event-reporting mode (one sample per minute; the standby mode has a 15-min interval) by the seismic signal or, based on the predicted arrival time at the DART® predicted by the propagation database, may be triggered by an operator at a TWC.

4. The time series reported by one or more DART® buoys are ingested by the SIFT system and used to establish which linear combination of unit sources best represents the observations. Now, an actual forecast of the size and distribution of tsunami energy is possible and perhaps a warning cancelation or revised warning can be issued.

5. In the event that significant impacts are forecast for one or more communities, the propagation database performs its second function. As noted earlier, the propagation model results exclude the coastal zone itself and do not have the spatial resolution to represent, for example, a harbor and its infrastructure. However, the composite propagation solution in deep water is adequate to produce the boundary conditions for a set of nested model runs of increasing spatial resolution that culminate in inundation predictions of use to local emergency managers. The SIFT system launches this phase of detailed model runs under the direction of TWC operators. Referred to as SIMs (Standby Inundation Models), these are optimized to run quickly in real time so that the detailed forecasts are available while the tsunami is still far from land. Some graphical examples of nested SIM models and the finely resolved topographical data needed to forecast inundation are given by (Tang *et al.*, 2008).

6. If a severe tsunami has occurred, extended monitoring over many hours of the DART® array can lead to refined predictions, detection of reflected waves, damage estimates in the face of possible communications difficulties, and other information of value to emergency responders until tsunami energy in the basin has dissipated.

Further detail on the SIFT system and its development can be obtained elsewhere (Gica *et al.*, 2008). However, the issues raised, and the availability of the propagation database, do have a direct bearing on the design of the DART® array as discussed below.

The goal of the array is to provide timely observations, on which an accurate forecast can be based, while adequate time remains for emergency procedures to be initiated. TWC guidelines indicate that a 3-hour lead-time is desirable. This requirement is most appropriate in the case of remote sources and may not be practicable in situations where an impact site lies in close proximity to a potential source. For example, tsunami waves from a rupture of the Cascadia Subduction Zone would impact the coasts of Washington, Oregon, and California in less than an hour. It is however to be noted that, even where a forecast cannot be provided with sufficient or indeed any lead time, it is not without value. An accurate though delayed

"forecast" may be late in terms of the first waves, but may establish the likelihood of later waves and the extent of the damage: information of value to emergency responders.

4.2 Using the Propagation Database in Array Design

With regard to array design, the availability of the propagation database allows the prediction of what a DART® would "see" under various source scenarios. The timing of the expected signal allows an estimate of whether the seismic noise is likely to have dissipated or whether an adequate warning time can be produced by a DART® in a given location. While the number of actually observed seismic and tsunami wave trains is limited, the typical speeds with which each propagates suggests that to reduce seismic noise contamination a DART® not be placed closer than 30 min of tsunami travel time from the closest source. The locus of points meeting this criterion, referred to as the 30-min envelope, can be computed from the propagation database and is frequently quoted in the site recommendation reports provided in Appendices B–I. Sites are generally recommended at or outside this line. In the case of Aleutian and Alaskan sources, the placement of a DART® at or outside the 30-min envelope would not provide a 3-hour warning for the Hawaiian Islands. A number of sites in this region have been chosen closer to the 15-min envelope. While the quality of the signal may be expected to be somewhat degraded by seismic noise at the closest DART®, the observations should be adequate to establish the presence/absence of a significant tsunami and an initial forecast of its impact. The alongshore spacing of the array off the Aleutians and Alaska has been reduced to permit improved new forecasts to be generated as less contaminated peripheral DART® time series are added to the SIFT inversion process. Mofjeld (personal communication) has noted that, due to similar travel times from adjacent unit sources, data obtained directly offshore may be ill-suited to discriminate between potential source scenarios.

Simulated time series at potential DART® sites can be used to pick those that should provide the largest and least complex tsunami signals. The lobe-like patterns seen in a tsunami "beam plot" such as Fig. 6 identifies locations that are in the lee of some bathymetric feature such as a seamount and therefore less suited as a DART® site. Such shadow regions where excessive scattering might be expected are to be avoided. The full suite of beam plots available from the propagation database were not examined due to the time constraints imposed by the need to deploy the array as soon as was practical. Instead, an analytic study by Mofjeld *et al.* (2001) was often consulted to identify regions to be avoided. The study showed that scattering becomes significant when a feature extends to within 1,200 m of the surface. Thus, in selecting DART® sites to provide warning to threatened coasts by a given source region, locations were chosen that had as "clear" a view of the sources as possible. The choices made may be subject to revision in light of further analysis and the accumulation of experience from deployed instruments.

4.3 Site Selection Using Travel Time Only

Since they provide information on both the amplitude and timing of tsunami waves emanating from a source region, numerical results, such as those produced by MOST and available in a propagation database, are highly valuable in array design. Such a comprehensive database may however not be available when decisions regarding tsunameter placement are being made. Since the wave speed for shallow-water wave speed is related to depth, various computer programs exist to derive travel time contours for waves produced by a point source. With a set of such solutions, originating from a set of points spaced along a plate boundary, or within a region subject to submarine landslide, minimum travel time envelopes, detection times, and estimates of impact times can be derived for a study region. This approach was taken in site selection for DART® sites 23401 and 53401 in the Indian Ocean. The sites were selected to provide the best possible warning times to surrounding nations by the placement of two tsunameters. Clearly, given the extent of the source region, two instruments are only the starting point for a more extensive array that can be designed with the aid of the subsequently available Indian Ocean propagation database. A similar approach, also employing the TTT (Tsunami Travel Time) program by Paul Wessel/Geoware (`www.geoware-online.com/tsunami.html`) was taken for the U.S. East Coast and Gulf of Mexico where some of the threat is from landslides, as noted in Section 5.2 below, and illustrated in Appendix C.

5. Strong Current Regimes and Mooring Feasibility

One aspect in which the initially recommended sites could have been better thought out is that of mooring feasibility. While the BPR on the seabed is not impacted directly by ambient currents, the surface unit that serves as a link between the BPR and shore via acoustic and satellite transmission must be capable of surviving in the marine environment. In choosing the locations for the Gulf of Mexico and off New England, representations of the Loop Current and Gulf Stream were employed that failed to adequately represent the position and strength of these currents. A likely result of this failure was a loss of data from these sites as the surface unit dragged beyond the range of acoustic contact or even broke free. The early loss of DART® 21417 off the Kuril Islands may have a similar origin though the movement of the surface unit suggests contact with a vessel.

5.1 Availability of Current Data

A comprehensive siting study should include the accumulation of in situ current data and involve the expertise of a mooring designer. Again, due to time constraints and the sparseness of such data in the global ocean, this was not possible and, in proposing alternate sites, numerical model results have been employed. Available online (`www7320.nrlssc.navy.mil/global_nlom32/skill.html`) are hindcast currents for the global ocean from the operational Navy Layered-Ocean Model (NLOM). This model, which assimilates altimetry data, is described by Shriver *et al.* (2007) and provides daily current estimates on a $\frac{1}{32}$nd degree grid. Some 32 months of model results were acquired and analyzed to extract relevant statistics for the Loop Current and Gulf Stream regions to produce revised site recommendations. Parameters derived include the spatial distribution of overall maximum and median speeds in the siting areas, and the likelihood of recurrence of excessive speed episodes. The results, presented in Appendix D for the New England case, employ a 1% exceedance criterion. Based on the available modeled surface current speed data, the colored contours of Fig. D3 represent the speed that is expected to be exceeded on only 1% of deployment days. Since a DART® deployment cycle may be 2 years or more, decisions based on this criterion may be somewhat optimistic and the overall maximum from the full set of model days more appropriate.

A more thorough study of the vertical structure of model currents could provide relevant parameters for future mooring design and siting recommendations. With the time constraints of the initial array deployment, and the production of this technical memorandum, a limited surface current study has been performed at each of the chosen DART® sites. At each, 600 days

of surface speed hindcasts were obtained in a 5° × 3° region adjacent to the site. Statistical results in the form of a 5% exceedance contour in the vicinity of the recommended (and occupied) sites and the estimated NLOM surface speed history and histogram are included in the graphics presented in the next section.

5.2 Landslide Avoidance in Site Selection

Some other factors relevant to site selection are also incompletely assessed. For example, the potential for submarine landslides is relevant, both in terms of possible tsunami generation and potential destruction of a BPR. The speed and extent of the 1929 landslide off Newfoundland were estimated from the times at which a series of seafloor telegraphic cables were ruptured. Such observations are rare; typically the sites of ancient submarine slides are inferred from seafloor surveys. Preliminary results from a survey of submarine features associated with offshore sediment transfer, for the eastern U.S., were provided by the USGS (Geist, personal communication) and employed to determine locales to be avoided during the selection of a site for DART® 41424.

Of more direct concern of course is the potential for tsunami generation by mass movements like submarine landslides. The implications of the survey mentioned above, spanning the continental slope and rise between Georges Bank and the Blake Spur, were assessed by Chaytor *et al.* (2007) in regard to tsunami hazard. Identifying past landslides requires detailed seafloor mapping, and dating such events is difficult. Numerical modeling of landslide-generated tsunamis, more complex than seismic generation, is an active area of current research. The rarity of such events limits the observational base, but laboratory models can provide measurements with which to test numerical predictions. In the coming years, it is hoped, a propagation database of landslide-generated tsunami waves will be available to complement the seismic source database and, in particular, serve to guide future siting studies. As an interim step in East Coast site selection, an analysis of travel times from potential landslide sources was conducted (see Appendix C). The travel time calculation program TTT (available from Paul Wessel/Geoware, `www.geoware-online.com/products.html`) was employed to generate propagation times for point "sources" evenly spaced along the shelf break. As noted earlier, though it does not provide amplitude estimates, TTT may also play a useful role in studies where a propagation database of seismic sources is not available; such was the case in the early days of selecting DART® sites for the Indian Ocean.