Seismic-wave contributions to bottom pressure fluctuations in the North Pacific—Implications for the DART Tsunami Array

Harold O. Mofjeld[1], Paul M. Whitmore[2], Marie C. Eble[1], Frank I. González[1], and Jean C. Newman[1,3]

[1]***NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington, U.S.A.***
[2]***West Coast and Alaska Tsunami Warning Center, Palmer, Alaska, U.S.A.***
[3]***JISAO/University of Washington, Seattle, Washington, U.S.A.***

Abstract. Over the period October 1999–January 2001, there were four separate occasions in which real-time reporting tsunami DART systems, deployed by NOAA in the North Pacific, were set into tsunami event reporting mode by regional earthquakes. Fortunately, none of these generated a dangerous tsunami. To go into event mode, the high-frequency fluctuations in the bottom pressure (BP) had to exceed a pre-programmed threshold of 3 cm H_2O. An explanation for the events was found by examining the seismic surface waves generated by earthquakes. By Newton's third law, they produced BP fluctuations in response to the vertical bottom acceleration induced as the waves propagated along the water-bottom interface. This hypothesis was verified for the 1999 Hector Mine, California, earthquake by analyzing seismic data from the nearby SAO seismic station and the travel time for the seismic surface waves to reach a DART system deployed off Monterey Bay, California. These results are consistent with previous studies of BP fluctuations due to seismic waves. They further suggest that the 3 cm H_2O threshold, applied to 15-second averaged BP data, works well to activate the DART tsunami event mode for earthquake magnitudes $\geq$7.0 and epicenter distances $\leq$610 km, while ignoring much smaller magnitude earthquakes (M $\leq$ 6) in the region.

1. Introduction

As part of the U.S. National Tsunami Hazard Mitigation Program, the NOAA/Pacific Marine Environmental Laboratory has deployed an array of real-time reporting systems in the Northeastern Pacific Ocean (Milburn *et al.*, 1996; González *et al.*, 1991, 1998; González, 1999). Called the systems for Deep-ocean Assessment and Reporting of Tsunamis (DART), they are designed to transmit information about tsunami waves near source regions to be used by the U.S. Tsunami Warning Centers in the Pacific Region. In their present configuration, the systems use an automatic tsunami detection algorithm to activate the rapid reporting event mode in order to provide adequate temporal resolution of the tsunami waves.

An empirical approach was used to choose the value for the 3 cm H_2O threshold that sets the DART systems into event mode. A large number of year-long BP time series had been collected by PMEL in the northern Gulf of Alaska and on the Juan de Fuca Ridge off Oregon. These are the same regions where the present DART array is deployed. After high-pass filtering

[1]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Building 3, Seattle, WA 98115, U.S.A. (mofjeld@pmel.noaa.gov, eble@pmel.noaa.gov, gonzalez@pmel.noaa.gov, jnewman@pmel.noaa.gov)

[2]West Coast and Alaska Tsunami Warning Center, 910 South Felton Street, Palmer, AK 99645, U.S.A. (Paul.Whitmore@noaa.gov)

[3]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Box 351640, Seattle, WA 98195, U.S.A.

Table 1: Seismic DART trigger events during the period October 1999–January 2001.

	Earthquake		DART System	Location		Relative to Epicenter	
Region	**Name**	**Magnitude**	**Name**	**Latitude**	**Longitude**	**Distance**	**Bearing**
California	Hector Mine Oct 16, 1999 09:46:44 UTC	7.1 M_w	D123	34° 35.4′N 36° 28.5′N	116° 17.3′W 122° 36.2′W	610 km	290°T
Alaska	Kodiak Island Dec 6, 1999 23:12:34 UTC	7.0 M_w	D157A	57° 24.6′N 52° 05.2′N	154° 29.4′W 156° 39.4′W	608 km	193°T
Off Oregon	Blanco FZ Jun 2, 2000 11:13:50 UTC	6.2 M_w	D130	44° 33.0′N 42° 54.2′N	130° 04.8′W 130° 54.7′W	195 km	200°T
Alaska	Kodiak Island Jan 10, 2001 16:02:44 UTC	7.1 M_w	D157	57° 04.8′N 52° 05.2′N	153° 12.6′W 156° 39.4′W	598 km	202°T

the series to remove the tides and lower-frequency BP fluctuations, their high-frequency fluctuations were found to be generally less than 1 cm H_2O in amplitude and only on very rare occasions did they exceed 2 cm H_2O. The theory of extreme value distributions then suggested that the probability of these fluctuations exceeding a threshold of 3 cm H_2O was extremely small, if they were simply due to the random superposition of small-amplitude noise fluctuations.

A project is also presently underway that will use the DART data to tune a pre-computed tsunami database in order to predict tsunami wave heights for U.S. coastal communities, hours before the first tsunami waves strike these communities. Called the Short-term Inundation Forecasting for Tsunamis (SIFT) Program, it is being done in collaboration with the Pacific Disaster Center and the Maui High Performance Computer Center. The background noise also affects the interpretation of the transmitted data during tsunami events since it influences the confidence limits for the SIFT wave height predictions.

During the period October 1999 to January 2001, there were four occasions (Table 1) in which regional earthquakes set DART systems (Fig. 1) into event mode. Rather than being activated by tsunami waves, this was done by seismic waves from the earthquakes. Seismic-wave activation of the DART systems has proven to be a very useful mechanism for alerting the Warning Centers that a tsunami may have been generated and to set in motion an analysis of the real-time reported DART data. These events also provided valuable tests of the GOES-satellite data downloading, processing, and display components of the overall system. As it turned out, no dangerous tsunami was produced by any of the four earthquakes.

In this paper we briefly review the sources of BP noise, based on recent

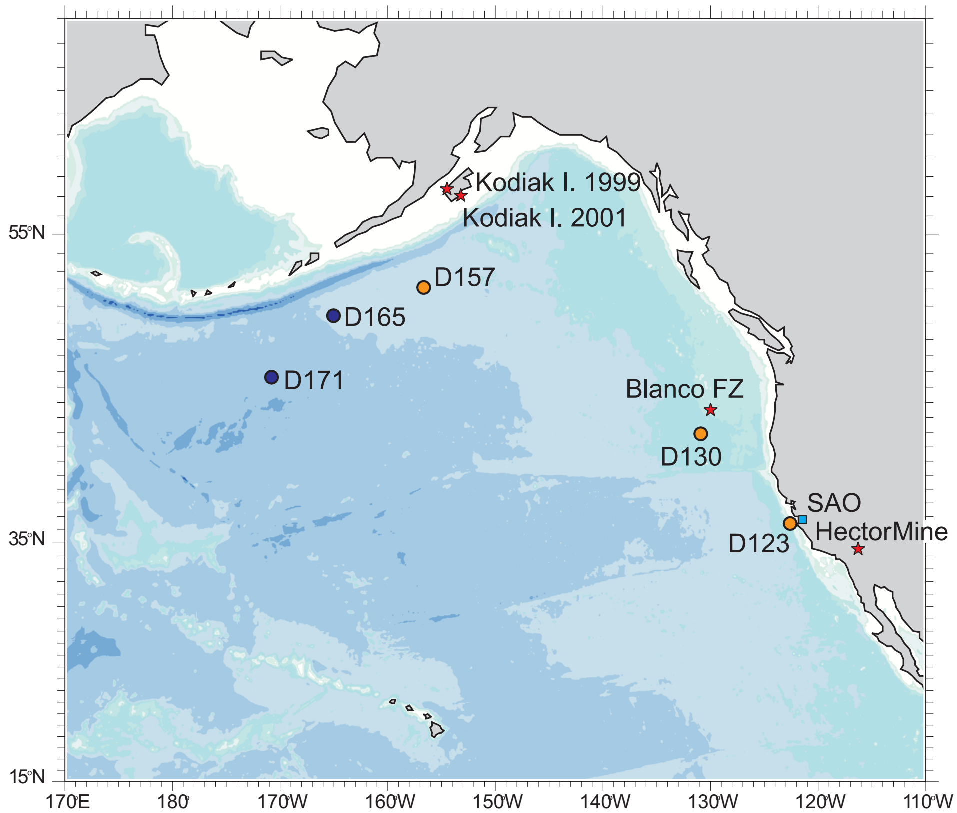

Figure 1: Map of the Northeast Pacific Ocean showing DART stations, the SAO seismic station (square) and the epicenters of earthquakes (stars) that have set DART systems into tsunami event mode. These DART systems (dots) are indicated in orange while other DART systems, presenting in place, are shown in blue.

seismic studies in the open ocean. We then use as an example the event that occurred during the test deployment of a DART system off California. It was the result of the well-documented M_w 7.1 Hector Mine earthquake that occurred in Southeastern California on 16 October 1999 (Parsons and Dreger, 2000). The study of this and the other three events are used to address the practical issue of whether the threshold value in the operational DART systems is appropriate for regional earthquakes that are potentially capable of generating dangerous trans-Pacific tsunamis.

2. Background Noise—A Brief Review

Over the past 5–10 years, observations from broadband seismometers, deployed on and below the ocean bottom, have led to a better understanding of the background seismic noise in the open ocean. Much of this work has been done as part of pilot studies (e.g., Collins *et al.*, 2001) designed to overcome technical difficulties of making such measurements in the deep water. They

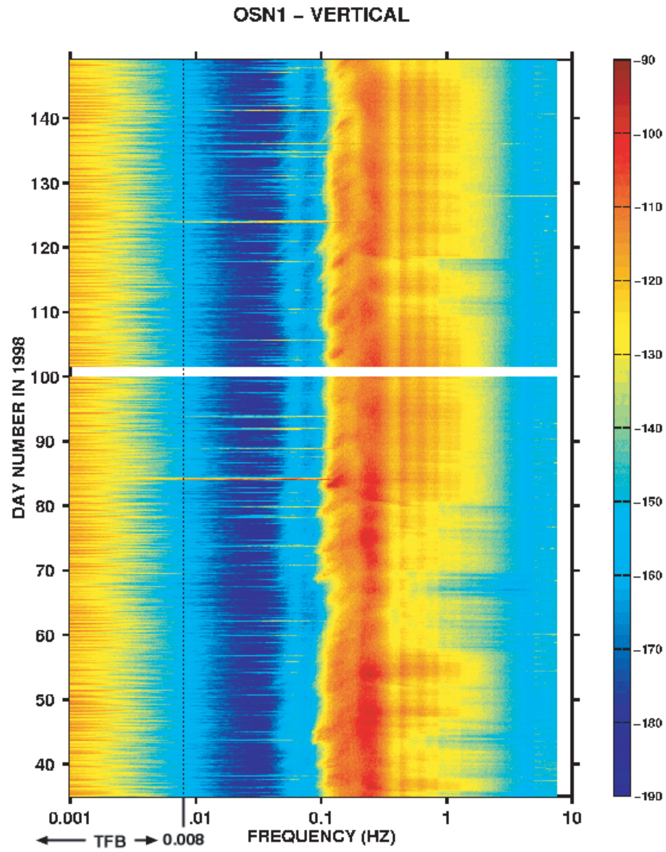

Figure 2: Time/frequency plot of the vertical component of acceleration observed at the ocean bottom seismometer station OSN1, located south of Hawaii (R. Stephen, personal communication). Units of the spectral density function (color bar) are decibars relative to 1 $(\mathrm{m/s}^2)^2/\mathrm{Hz}$. The dark blue strip running vertically indicates the noise notch (a very low-energy frequency band) separating the infragravity and microseismic bands.

are also designed to assess the merits of adding real-time reporting stations in the open ocean to the global seismic network.

A general review of seismic noise in the ocean is given by Webb (1998), based on observations made by ocean bottom seismometers (OBSs). The observations show (e.g., Fig. 2) that the tsunami frequency band (TFB: 0.0002–0.008 Hz) lies on the low-frequency side of the noise notch (very low seismic energy) which separates the infragravity band from the higher-frequency microseismic band. The noise spectrum in the TFB rises rapidly in energy as the frequency decreases toward the tidal bands. Since the non-seismic fluctuations in these bands are due primarily to ocean gravity waves, their intensity varies as the amplitudes of these waves change and hence with the occurrence of storms, shifts in wind patterns, and seasonal variations (Webb, 1998). The noise levels are also observed to be stronger in the Pacific Ocean than in the Atlantic and Indian Oceans, because of its higher wave intensity. Much of the rest of this background is due to seismic waves.

In principle microtsunamis, generated by small earthquakes and submarine landslides occurring throughout the Pacific Region, also contribute to the high-frequency end of the TFB. However, their influence on the background noise level has not been quantified to any extent.

Recent OBS observations made south of Hawaii (R. Stephen, personal communication) show that seismic surface waves, propagating along the water-sediment interface, dominate the bottom pressure (BP) fluctuations at the high-frequency end of the TFB. These seismic waves were first observed in BP observations by Filloux (1982, 1983) at a site off the Pacific Coast of Mexico. He correctly determined that they were the pressure signature of Rayleigh R1 waves, propagating ahead of the tsunami waves that had been generated by the same earthquake. This phenomenon was also seen by Kulikov *et al.* (1983) in the Western Pacific and by Eble and González (1991) in the northern Gulf of Alaska, where most of the DART stations are located.

Using time-frequency plots (e.g., Fig. 2), R. Stephen (personal communication) is able to identify specific earthquake events in the OBS data. The plots also show the dispersion of the Rayleigh waves, in which the lowest frequency waves arrive first. Sediment layer resonances are set up by seismic shear waves, also at the high-frequency end of the TFB (Zeldenrust and Stephen, 2000). These resonances complicate the interpretation of the seismic record and add to the background noise in BP. Like the Rayleigh waves, they are strongest immediately following earthquake events and decay in time after that.

The basic physical mechanism by which Rayleigh waves generate BP fluctuations was shown by Filloux (1982, 1983) to be the pressure reaction of the water as the oscillating bottom attempts to move the water column vertically. When the seismic wave period is long compared with the transit time for sound to propagate to the surface and back to the bottom again, the BP oscillation is proportional to the product of the total water depth and the vertical acceleration of the bottom. A formula for this dependence is given in the next section. At higher frequencies, only a fraction of the water column participates in the pressure response; and the BP amplitude is then less for a given amplitude of the Rayleigh wave. Direct acceleration/BP comparisons (Webb, 1998) indicate that the transition to lesser response occurs at a frequency of about 60 mHz (17 s period). Since this transition is much higher in frequency than the TFB, the latter is in the full-response regime for the Rayleigh waves.

3. The 16 October 1999 Hector Mine Earthquake Event

The example we will use to illustrate seismic wave triggering of DART systems is the event associated with the 16 October 1999 Hector Mine earthquake. The epicenter of the M_w 7.1 earthquake (Fig. 1; Table 2) was located in southeastern California, well away from the ocean. A DART station (D123) was deployed during this time off Monterey Bay in 3138 m of water,

Table 2: Location information for the 16 October 1999 Hector Mine earthquake, the San Andreas Observatory (SAO), and the DART system at Station D123.

				Relative to Epicenter	
Name	**Latitude**	**Longitude**	**Depth/Elev.**	**Distance**	**Bearing**
Hector Mine EQ	34° 35.7′N	116° 17.3′W	6 km depth	0 km	n/a
SAO	36° 45.9′N	121° 26.7′W	350 m elev.	525 km	297°T
D123	36° 28.5′N	122° 36.2′W	3138 m depth	608 km	290°T

some 608 km WNW from the epicenter. Providing the broadband seismic data for the analysis was the San Andreas Observatory (SAO in Fig. 1), located 108 km ENE of the D123 station and 525 km from the epicenter.

Since both the D123 and SAO stations were located along similar bearings (290°T and 297°T, respectively) relative to the epicenter, we can assume that the seismic waves observed at SAO (Fig. 3) are similar to those propagating past D123. However, because D123 was 83 km farther away from the epicenter, it took the seismic surface waves (assuming 3.5 km/s) an additional 24 s to reach it; this is compared with the 150 s propagation time from the epicenter to SAO. Using this timing information as a calibration, it was possible to resolve some minor time-base issues in the DART data processing system.

Once the seismic surface (Rayleigh R1) waves reached the ocean, they produced vertical accelerations of the bottom and hence the overlying water. Assuming full water column response to the bottom acceleration a, the induced BP fluctuations are directly proportional to a and in phase with it (Filloux, 1983; Webb, 1998): $\Delta P = (\rho H)a$ for BP fluctuation ΔP, mean water density ρ and total water depth H. At the D123 station ($\rho = 1.035$ g cm^{-3} and $H = 3138$ m), an acceleration $|a| = 0.0093$ cm s^{-2} is required to induce a BP change just equal to the 3 cm H_2O ($\sim$3000 dynes cm^{-2}) threshold.

To achieve sub-centimeter accuracy in water levels, the DART systems take 15-second averages of the period of the pressure-loaded oscillator that is inside the Paroscientific pressure transducer. The effect of this averaging is to low-pass filter the BP fluctuations induced by seismic waves; the frequency response of this averaging is given by Filloux (1983). Applying it to the SAO series results in a low-passed acceleration (Fig. 4) with several fluctuations that exceed in magnitude the 0.0093 cm s^{-2} threshold for the water depth at the DART station. Hence, it is clear that the seismic surface waves from the Hector Mine earthquake set the D123 system into event mode. It is worthwhile noting that a significantly longer averaging period (e.g., 1 min) would have decreased the amplitudes of the seismic BP fluctuations enough ($\leq$0.0078 cm s^{-2}) that they would not have exceeded the 3 cm H_2O threshold. Then, the D123 system would not have gone into event mode.

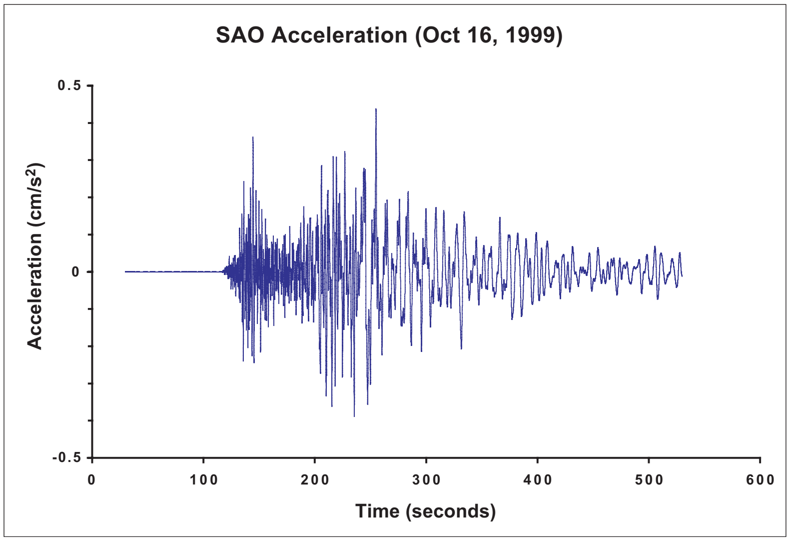

Figure 3: Time series of the vertical acceleration produced by the 16 October 1999 Hector Mine earthquake in Southeastern California, as observed at the broadband San Andreas Observatory (SAO) seismic station.

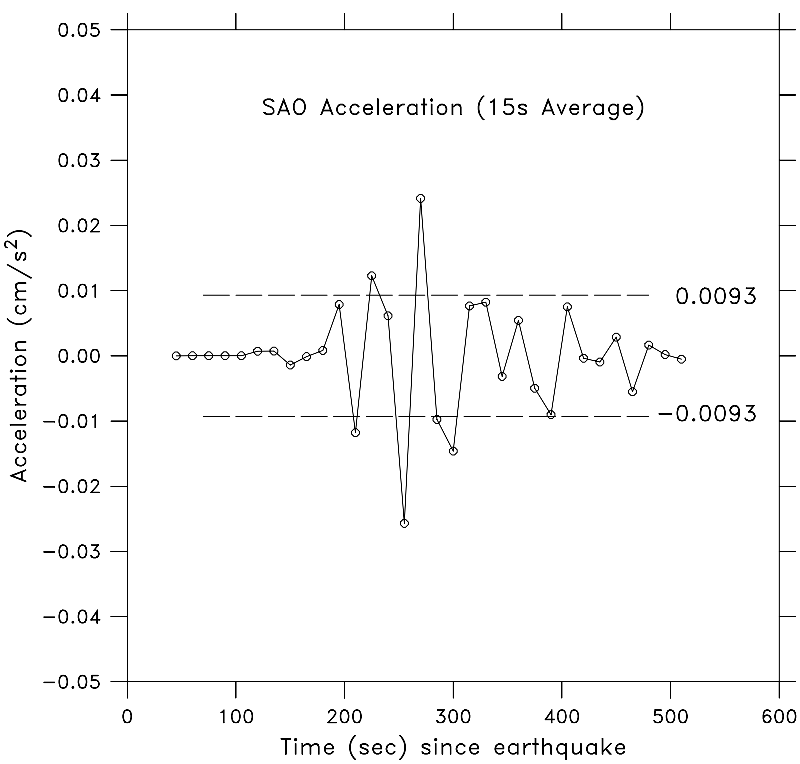

Figure 4: Vertical acceleration (15-second average) produced by the 16 October 1999 Hector Mine earthquake in Southeastern California, as observed at the broadband San Andreas Observatory (SAO) seismic station. Also shown are the threshold values needed to set the D123 DART station into tsunami event mode.

4. Discussion and Conclusions

From an operational point of view it appears that the 3 cm H_2O threshold is fully adequate for the present DART array, in terms of activating the event mode based on seismic surface waves for earthquake magnitudes $\geq$7.0 and epicenter distances $\leq$610 km. DART systems farther away (Fig. 1) from the epicenters were not set into event mode by these same earthquakes. Earthquakes of these magnitudes are the kind that are of concern with regard to generating dangerous trans-Pacific tsunamis, the measurement of which is the primary function of the DART array. The threshold is evidently high enough that the numerous, smaller magnitude aftershocks did not set the DART systems into event mode. This is important because it is necessary to avoid unduly prolonging the period of time during which the systems are in event mode, which will drain the batteries, or setting DART systems into this mode when there is essentially no chance that a dangerous trans-Pacific tsunami has been generated. The M_w 6.2 Blanco Fracture Zone earthquake (Fig. 1; Table 1) did activate the D130 system, but this is the largest magnitude event ever observed in this offshore region.

The recent broadband ocean bottom seismometer projects have provided a much better understanding of the background BP noise as it affects the operation of the DART systems. As these projects expand geographically in the Pacific Region, they will provide very useful information if and when the DART array is expanded into those areas.

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