System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997–2001

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Abstract. As part of the U.S. National Tsunami Hazard Mitigation Program, the Deep Ocean Assessment and Reporting of Tsunamis (DART) Project is an ongoing effort by the Pacific Marine Environmental Laboratory (PMEL) to develop and implement a capability for the early detection and near real-time reporting of tsunamis in the open ocean. A DART system consists of a seafloor system, capable of detecting tsunamis as small as 1 cm, and a surface buoy for near real-time communications. An acoustic link is used to transmit the data from the seafloor system to the surface buoy. The data are then relayed via a NOAA Geostationary Operational Environmental Satellite (GOES) satellite link to ground stations, which demodulate the signals for immediate dissemination to Tsunami Warning Centers and PMEL. A DART quality control page is made available to the public in near real time via the World Wide Web (`http://tsunami.pmel.noaa.gov/dartqc/WaveWatcher`). The general system design is fundamentally as envisioned in 1996, but many technical challenges had to be overcome during the development process. The surface buoys now incorporate redundant electronic packages to improve reliability and data return, and the seafloor system design now allows for 2-year deployments, to reduce the cost and effort of maintaining the oceanic network. The end-to-end DART system concept has been proven through numerous deployments, starting in July 1997 and continuing up to the present configuration of five operating DART stations. Performance measures such as cumulative data return, scheduled test transmissions, triggered transmissions, data dropouts, and system failures will be discussed. The results will show that during the past 5 years, the DART Project has successfully developed and tested a prototype system, which will lead directly to an operational Pacific DART Network.

1. Background and Motivation

The Pacific Marine Environmental Laboratory (PMEL) has developed and installed a prototype Deep Ocean Assessment and Reporting of Tsunamis (DART) buoy array for the near real-time reporting of tsunamis in the open ocean. DART is a component of the larger U.S. National Tsunami Hazard Mitigation Program and addresses one of the four issues identified in the Plan: *Quickly Confirm Potentially Destructive Tsunamis and Reduce False Alarms* (Tsunami Hazard Mitigation Federal/State Working Group, 1996).

The DART system (Fig. 1) consists of a bottom pressure recorder (BPR) that resides on the ocean floor and uses an acoustic modem to transmit data to a moored surface buoy, which then relays the information to shore via a NOAA GOES satellite link. A DART system operates "tide" and "tsunami" mode. Tide mode sends four 15-min data points every hour to verify the system is properly functioning. The system is tripped into tsunami mode if two 15-s water level values exceed the predicted value by a threshold limit (usually >3 cm).

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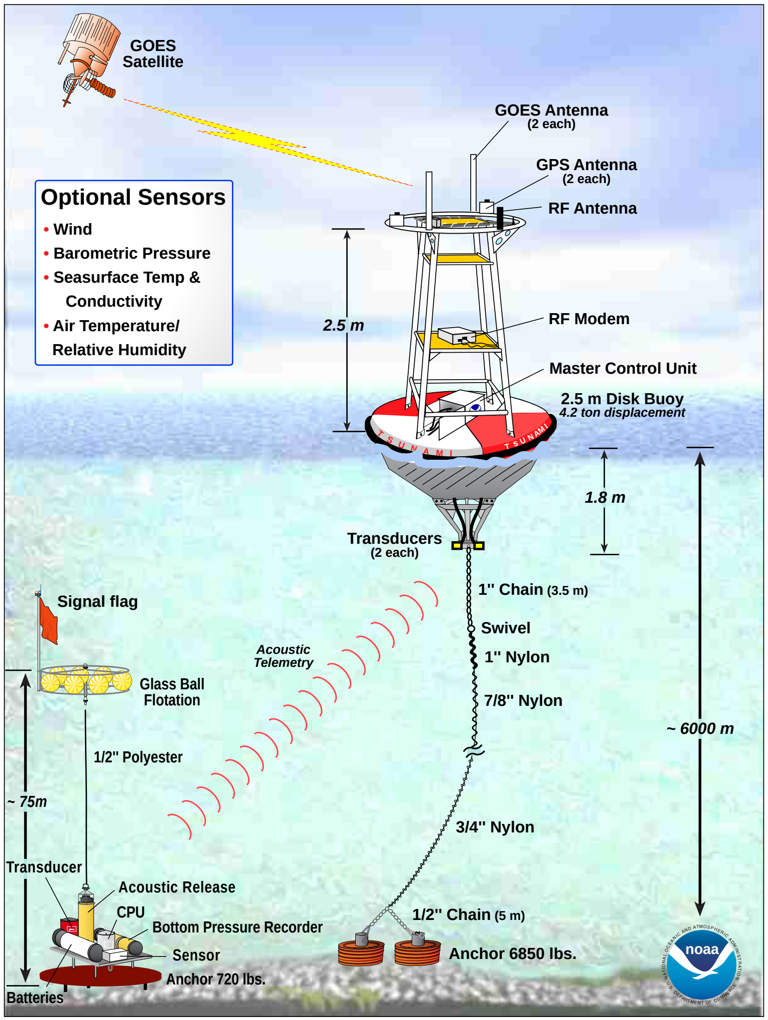

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Figure 1: DART mooring system.

2. System Development

The DART system development is an ongoing 5-year effort by PMEL engineers and researchers to report near real-time open ocean data to make tsunami warnings more timely and accurate (Bernard *et al.*, 2001). The engineering challenge was formidable and involved 19 ocean cruises and over 100 days at sea. The system design had to meet two fundamental technological challenges: 1) The deep-ocean buoy mooring must survive the hostile environment of the North Pacific; 2) The deep ocean-to-surface acoustic data link must perform with high reliability in a hostile ocean environment.

A DART development timeline from 1996–2001 is shown in Fig. 2. The general system design is fundamentally as envisioned in 1996; however, many technical improvements were implemented to increase the reliability and reduce the cost of the system. Four major developments and results are highlighted below.

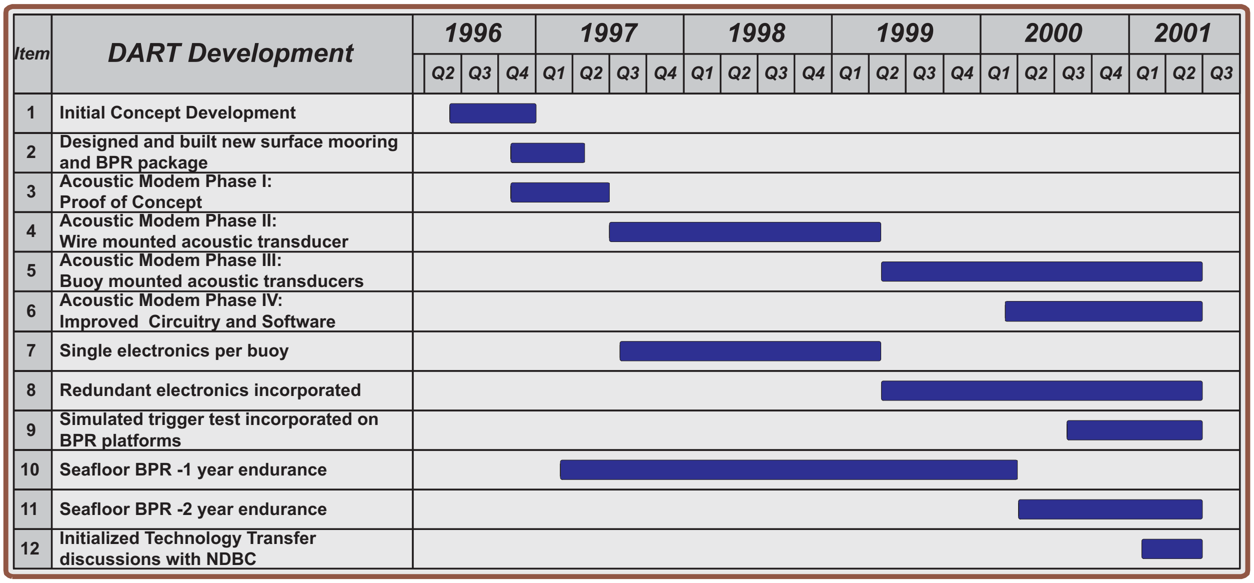

Figure 2: DART development timeline.

2.1 Acoustic modem

The majority of system failures from 1997–1999 can be attributed to acoustic modem and electrical cable failures. Acoustic modem hardware and software developments progressed through four distinct phases as noted in Fig. 2. Each phase was marked by extensive lab and field testing and ultimately resulted in a more reliable communication link. Many versions of hardware and software evolved through four primary phases of development. The acoustic transducer was moved from a wire-mounted version to a buoy bridle depth of 1.8 m and greatly improved the longevity and deployment ease of the system. The amount of ship time is dramatically reduced per station by having all transducers and cable mounted to the buoy bridle.

Result: Improved reliability and deployment operations, decreased cost.

2.2 Redundant electronics

Two complete and independent sets of master control units were incorporated in each DART buoy beginning in 1999. A Master Control Unit includes the central processing unit (CPU), acoustic modem, GPS receiver, GOES transmitter, and power supplies. Redundant electronic systems greatly improve the reliability of the DART system at a modest cost.

Result: Improved reliability.

2.3 2-year BPR seafloor package

Advances in memory storage devices and acoustic modem upgrades were made to the BPR in an effort to improve longevity and reduce deployment

Figure 3: DART buoy deployment from *Ronald H. Brown*.

costs. All systems deployed in April 2000 and beyond are designed for 2-year longevity. Deploying and recovering the BPR package every other year reduces production and shiptime costs.

Result: Decreased cost.

2.4 World Wide Web—data quality control page

The most significant data display addition was the development of a near real-time DART data web page in July 1998 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 NOAA's Tsunami Warning Centers.

Result: Worldwide distribution that is cost-effective and available in near real time.

A timeline of DART system milestones is shown in Fig. 4. The design and development efforts at PMEL are ongoing and have resulted in an array of six DART systems that will be in place by August 2001. The systems are

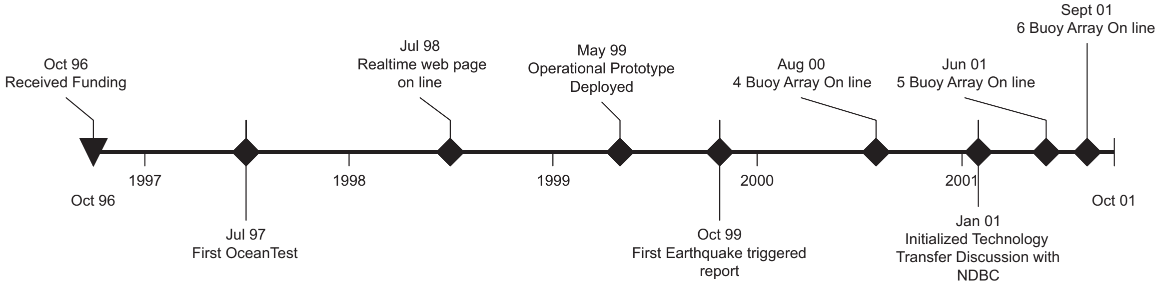

Figure 4: DART development milestones.

reporting near real-time data to NOAA Tsunami Warning Centers and over the World Wide Web.

3. Performance

3.1 Data return

The end-to-end DART system concept has been proven through numerous deployments with overall high percentage data return. A histogram of the station sites, deployment durations, and percentage of data return for the year 1997–2001 is shown in Fig. 5. The percentage of data return, shown as numbers inside each bar, is defined as the number of hourly and triggered transmissions received divided by the total possible transmissions during the station deployment. DART array averages for each year are shown below the bars on the deployment-year axis.

During the 1997 and 1998 R&D years many hardware and software changes were incorporated with improving data return rates of 48% and 96%, respectively. Data return rates for the prototype DART systems in 1999, 2000, and 2001 were 97%, 89%, and 100%, respectively. The lower rate of return in year 2000 array, as compared with that of the previous year, is somewhat misleading. Three of the four DART sites deployed in year 2000 returned data at a rate exceeding 99%. The 4th site, D157, returned data at this same rate until a high current drain caused the batteries to be depleted and the buoy ceased to transmit in March 2001. This is further discussed in Section 4, “Data Dropout.”

3.2 Event reporting

A tsunami with energy directed into the path of a DART buoy has not been generated since the prototype array has been deployed. However, the system has performed well during scheduled test tsunami transmissions (implemented in 2000) and tsunami mode transmissions initiated by earthquakes. Table 1 shows the performance of the DART array responding to scheduled transmissions and random events.

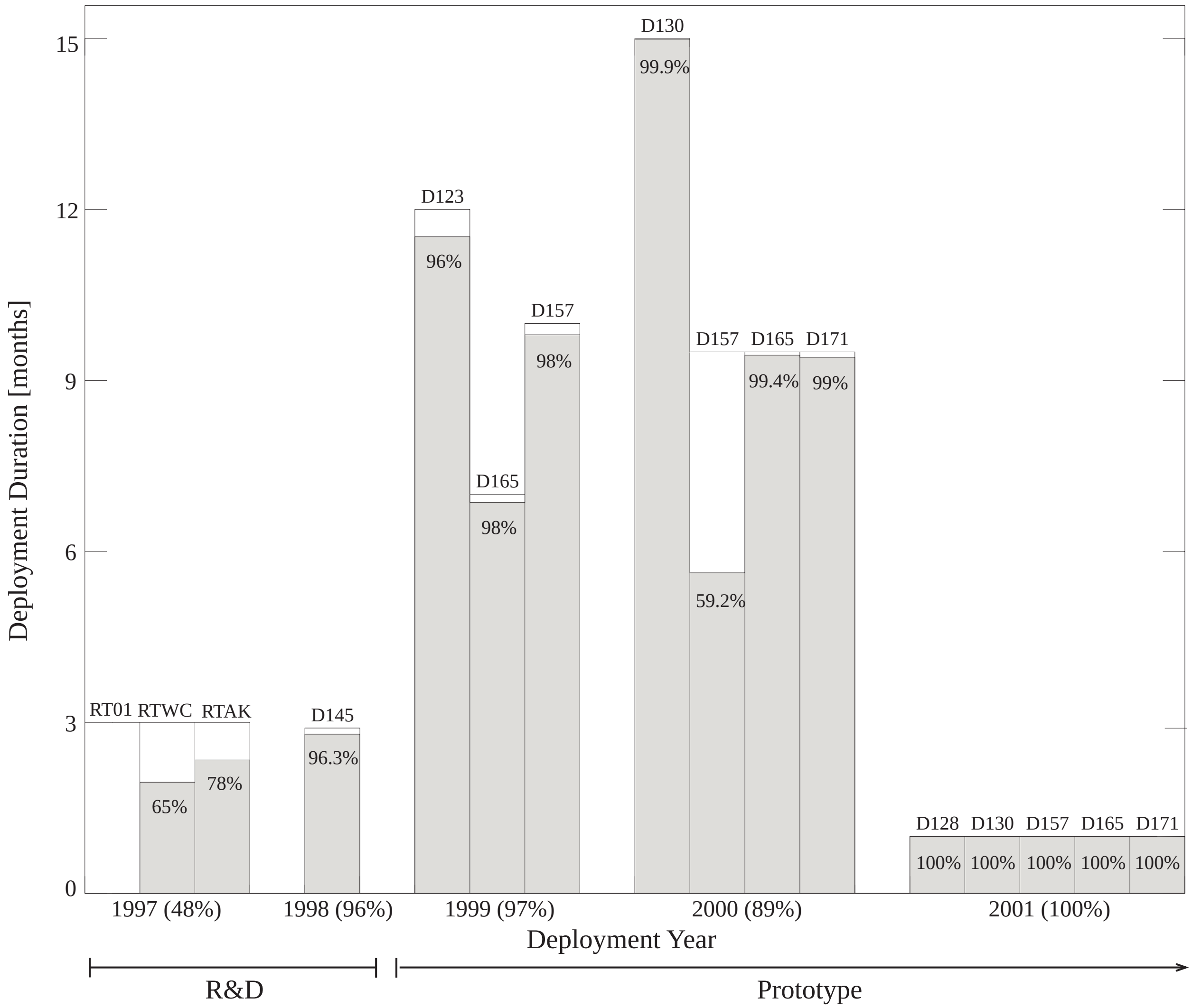

Figure 5: Histogram of station sites, deployment durations, and percentage of data return for the year 1997–2001.

Table 1: Performance of the DART array responding to scheduled transmission and random events.

Events	1997	1998	1999	2000	2001
Scheduled Transmissions					
Scheduled/received tsunami test transmissions	0/0	0/0	0/0	4/4	*
Random Transmissions					
Tsunami	0	0	0	0	0
Earthquake	0	0	2a,b	2c,d	1e
False Trigger	0	0	0	0	0

* Scheduled for July and October 2001
a = D123 station 10/19/99
b = D157 station 12/9/99
c = D130 station 6/2/00
d = D130 station 8/10/00
e = D157 station 1/10/01

In summary, the DART array has gone through two phases of development, "R&D" and "Prototype" array. Many engineering improvement were made during the "R&D" phase to boost reliability and decrease costs. The prototype DART array has performed very well with: 1) high data returns; 2) excellent response to scheduled and random events; and 3) no false alarms during the 5-year development period.

4. Data Dropout

The most significant cause of data dropouts from the 1997 and 1998 R&D deployments was poor acoustic communications with the seafloor BPR. To a large measure, this has been corrected through hardware, software, and packaging changes of the acoustic modems.

The D157 station correctly triggered on a January 2001 earthquake, but failed to return to the low-power "tide" mode after the expected period of time. The buoy remained in the high power "trigger" mode for over 2 months until all battery power was consumed. The buoy has recently been recovered and the cause of this failure is now under investigation. Some additional isolated causes for data losses are listed below:

- GOES satellite: Dropouts have occurred during times of high solar flare activity.
- GOES transmitter: Commercial product failures; changed vendors.
- Isolated cable and connector problems.
- Tower failures: During the harsh winter of 1998, two surface buoy towers were destroyed, severing the satellite link. Aluminum tower construction and weld inspection was improved and the problem has not reoccurred.

5. Future Work

It has been proposed (Bernard *et al.*, 2001) to expand the DART array from six to ten stations over the next 5 years. In order to develop an operational DART Pacific Network, we recommend continuing the development process to improve reliability, expand data products, and decrease costs. Listed below are some possible enhancements:

- Development of next generation of electronics suitable for other buoy platforms and mooring configurations.
- Increasing service life of seafloor BPR from 2 to 4 years.
- Two-way communications from desktop to seafloor BPR.

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6. References

Bernard, E.N., F.I. González, and C. Meinig (2001): Early detection and real-time reporting of deep-ocean tsunamis. International Tsunami Symposium 2001, 7–10 August 2001, Seattle, WA.

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