Operational Performance of the Second Generation Deep-ocean Assessment and Reporting of Tsunamis (DART™ II)

Richard Bouchard, Shannon McArthur, William Hansen, Kevin J. Kern, and Lea Locke
NOAA's National Data Buoy Center
1100 Balch Blvd.
Stennis Space Center MS 39529-6000 USA

***Abstract*-In March 2005, the National Oceanic and Atmospheric Administration (NOAA) completed the transition from research to operations of the second generation of the Deep-ocean Assessment and Reporting of Tsunamis (DART™ II). DART™ II systems are a part of NOAA's Tsunami Program, which is part of a cooperative effort to save lives and protect property through hazard assessment, warning guidance, mitigation, research capabilities, and international coordination. NOAA's National Weather Service (NWS) is responsible for the overall execution of the Tsunami Program. Among its responsibilities under the Tsunami Program, NWS acquires, operates, and maintains observation systems required in support of tsunami warning, such as DART™. NWS also supports observations and data management through the National Data Buoy Center (NDBC). The DART™ II systems join NWS base stations, the Tropical Atmosphere Ocean Array, and the Coastal Marine Automated Network stations in the NOAA/NWS/NDBC Ocean Observing System of Systems (NOOSS).**

In the two years since being declared operational:

- **DART™ II systems have replaced all but three DART™ I systems,**
- **DART™ network has expanded to 28 stations stretched across the Pacific and now into the North Atlantic, Caribbean Sea, and the Gulf of Mexico.**
- **Three DART™ II systems have been provided to other countries to aid in their tsunami warning capability,**
- **DART™ II systems provided estimated water-level information for the 2006 events in Tonga, Hawai'i, Kuril Islands, and Taiwan. In 2007, DART™ II systems provided observations for the Solomon Islands event and another Kuril Islands event.**
- **DART™ II data availability for the standard mode observations have been more than 85% exceeding the target data availability goal of 80%.**

DART™ II provides increased capabilities over the DART™ I systems with the most significant improvement being the additional capability of bidirectional communications from NDBC or the Tsunami Warning Centers (TWCs) to the Bottom Pressure Recorder (BPR) using the commercial Iridium satellite communications system. This capability allows the TWC to set a BPR in event mode and provide high-frequency (1-minute interval) estimated water-level observations and allows the retrieval of up to one hour of the highest frequency (15-second interval) original temperature and pressure counts that can be converted to estimated water-level observations. Furthermore bidirectional communications provides troubleshooting and diagnostic capability in real-time.

During the two years since the operational debut of DART™ II, NOAA achieved significant accomplishments in data management, including the development of a Tsunami Data Management plan and the establishment of a 24x7 IOOS Data Assembly Center (DAC) at NDBC. The IOOS DAC continuously monitors the NOOSS, including DART™ systems, and facilitates the exchange of status information between NDBC and the TWCs. Improvements to the real-time data distribution system included increased system reliability by moving the Iridium communications server and a fail-over web site to Silver Spring MD to co-locate with the National Weather Service Telecommunications Gateway.

NDBC's plans include replacing the last three DART™ I systems with DART™ II systems, the completion of the 39-station DART™ network by the end of 2008, increasing the reliability of the systems, and the engineering development of a multi-capability platform.

I. Introduction

In March 2005, the National Oceanic and Atmospheric Administration completed the transition from research to operations of the second-generation of the Deep-ocean Assessment and Reporting of Tsunamis (DART II) systems [1]. NOAA defines operations as: *Sustained, systematic, reliable, and robust mission activities with an institutional commitment to deliver appropriate, cost-effective products and services* [2]. The DART II systems constitute a critical element in NOAA's Tsunami Program. NOAA's National Weather Service (NWS) is responsible for the overall execution of the Tsunami Program. This includes operation of the U.S. Tsunami Warning Centers and the acquisition, operations and maintenance of observation systems required in support of tsunami warning such as DART. NWS also supports observations and data management through the

National Data Buoy Center (NDBC) [3]. NDBC operates and maintains the DART system as part of the NOAA/NWS/NDBC Ocean Observing System of Systems (NOOSS). The NOOSS consists of the moored weather and oceanographic buoys, the Coastal-Marine Automated Network, the DART I and DART II systems, and with its transition from research to operations nearly complete, it includes the Tropical Atmosphere Ocean Array (TAO) [4]. NDBC assigns World Meteorological Organization Station Identifiers to all NOOSS buoys (e.g., 46403).

A. DART II System Description

Like the DART I systems, which completed transition in 2004, the DART II systems consists of a Bottom Pressure Recorder (BPR) that sits on the seafloor making measurements that are communicated to a surface buoy that relays the data to NDBC for distribution to the Tsunami Warning Centers (TWC), national and international tsunami community. DART II systems contain the same tsunami detection algorithm on-board the BPR as DART I. The algorithm initiates more rapid reporting of data (Event Mode) whenever estimated water-level values exceed the predicted values by a threshold [5]. However, DART II provides significant capabilities over DART I - primarily with two-way communications and the inclusion of data acquisition times in the data messages (Fig. 1). Data acquisition time for DART I had to be inferred from the message receipt times. The Iridium commercial satellite communications system allows the TWCs and NDBC to place the BPR in Event Mode or interrogate the BPR for one-hour of the high-frequency data [6]. It also allows NDBC to reset detection thresholds and conduct long-distance troubleshooting.

B. DART II Status April 2007

With the completion of the transition, the DART II prototype in Hawai'i was kept in service (Station 51407). The first DART II operational deployments occurred in September 2005 with the establishment of stations 46403 and 46409 in the Gulf of Alaska. With new station establishments, expansion to the Atlantic and Caribbean, and the upgrade of Pacific DART I stations to DART II, by April 2007, 28 DART II stations were established and only three DART I stations 46404, 46405, and 46411 remained. NDBC will upgrade 46404 in August 2007 and the remaining two DART I stations by the end of 2008. DART II systems have been provided to Chile (Station 32401), Thailand (Station 23401), and Australia (Station 55401) with plans for a DART II for Indonesia and a second system for Australia. The plan is for a total of 39 DART stations to be completed by March 2008 (Fig. 2).

C. Data Management

In the aftermath of Hurricane Katrina, the primary Iridium receive server and its failover web server were moved from NDBC's south Mississippi location and co-located with NDBC's real-time processing servers at the NWSTG in Silver Spring MD.

In 2005, NDBC established a 24x7 a Data Assembly Center (DAC) operated in support of the Integrated Ocean Observing System (IOOS). Experienced analysts monitor the NOOSS and observations from NDBC's IOOS partners. The DAC provides information to the TWCs on the status of the network, communications and DART data message decoding parameters, and verifies the validity of triggered events. In February 2006, the concept was proposed for NDBC to function as the Primary Data Assembly Center for *in situ* marine observations for the IOOS [7].

In January 2007, NOAA distributed its Tsunami Data Management Report [8] that developed the Operational Concept for DART data management. In support of that Report, NDBC is developing a DART Data Management Plan that supports both the NOAA and IOOS Operational Concepts.

II. OPERATIONAL PERFORMANCE

A. Standard Mode Data Availability

The BPR collects temperature and pressure values every 15 seconds. The temperature-corrected pressure measurements are converted to an estimated water-level by multiplying the pressure by 670 mm per pound per square inch absolute. The resulting water-level measurements pass through the tsunami detection algorithm. If two consecutive values do not exceed the predicted water-level values, then the BPR remains in Standard Mode. In Standard Mode, once an hour the BPR collects four of the 15-second water-level estimates at 15-minute intervals, computes a checksum, and transmits them to the surface buoy. The surface buoy tests the checksum. If the test is successful, the buoy inserts an "Intact" indicator and formats the one-hour observations. If the checksum test fails, the buoy assigns a "Corrupt" indicator and formats the observations. The buoy collects six hours of messages and transmits the data to NDBC for distribution.

(a) DART I Hourly Message

```
SXXX46 KWAL 281916
 B140962A 209191630T$4 I 153  43 4264811 4264846 4264872 426489
1
213 02 02 007 x 000 00 000 0000 000*6B 46-4NN  80W
```

(b) DART II Collective of Hourly Messages

```
SXXX46 KWBC 281218
 DDDDDD4E 209121837D$1I 07/28/2007 06:15:00 1514143 3772720
3772627 3772529 3772429  2* 30D$1I 07/28/2007 07:15:00 1514143
3772327 3772229 3772133 3772040  1* 3FD$1I 07/28/2007 08:15:00
1514143 3771952 3771869 3771791 3771722  1* 3BD$1I 07/28/2007
09:15:00 1514143 3771657 3771603 3771561 3771527  1* 38D$1I
07/28/2007 10:15:00 1514143 3771505 3771488 3771482 3771486  1*
33D$1I 07/28/2007 11:15:00 1514143 3771501 3771523 3771556
3771592  1* 3A 00-0NN  00E
```

Fig. 1: (a) DART I Hourly Message, (b) DART II Collective with first data acquisition time following D$1I

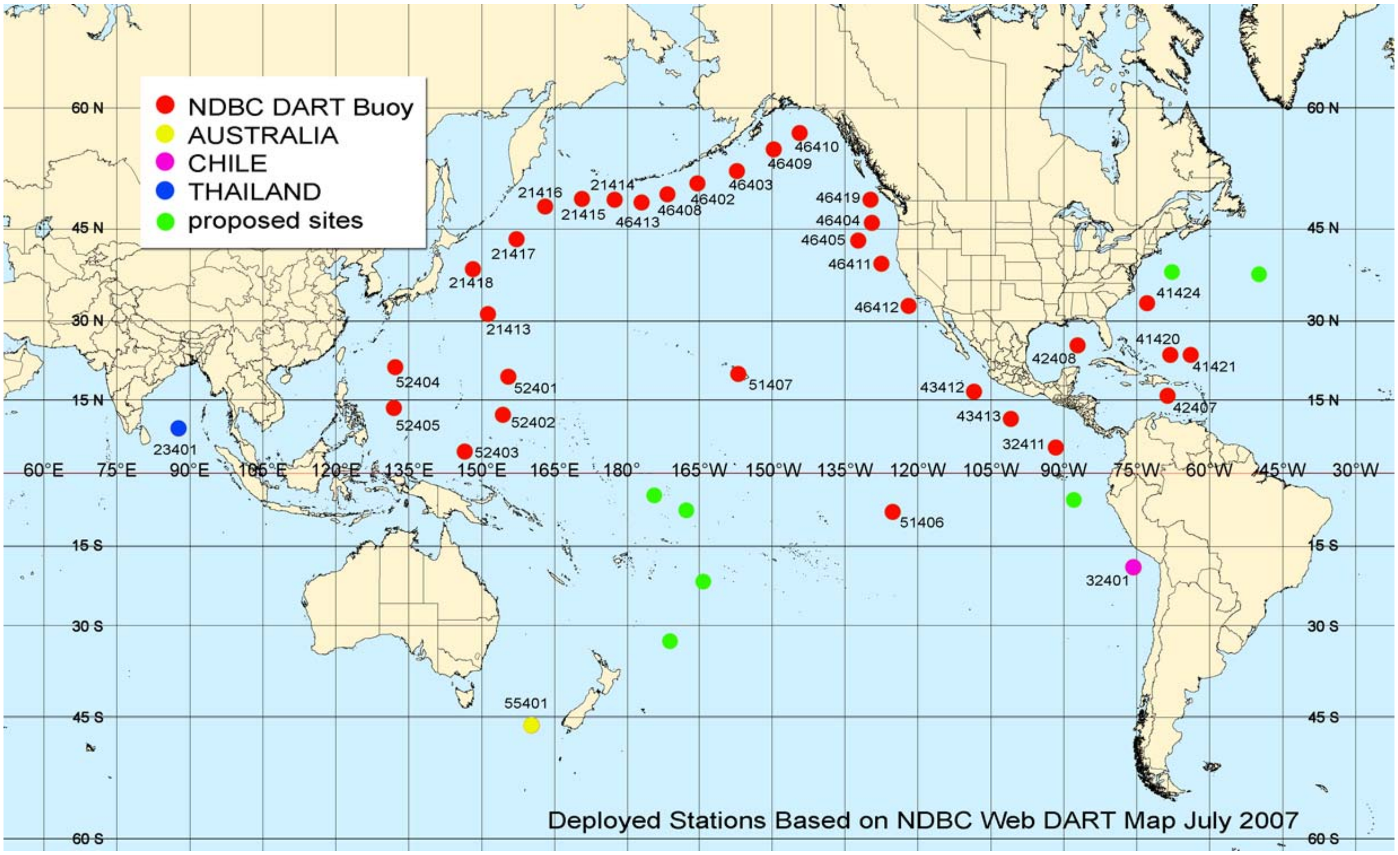

Fig. 2: Existing and Planned DART Stations

For US operated and maintained stations, NDBC monitors the receipt of the one-hour messages and reports the availability of the one-hour messages as a performance measure on a monthly basis. The performance goal is 80% availability of the expected one-hour messages. Since the deployment of the first operational DART II stations in September 2005 through March 2007, the data availability has been 85.7%. The monthly DART II data availability has ranged from a high of 100% to a low of 75%. The DART II prototype and DART II stations operated by foreign countries are not include in the reportable statistics.

B. Event Performance

If two consecutive estimated water-level measurements exceed the detection threshold, the BPR goes into Event Mode. In Event Mode the BPR initially reports 16 of the 15-second measurements within the first 3 minutes of the tsunami detection time and reports the tsunami detection time or trigger time. After the initial reporting, the BPR then reports at 8-minute intervals and provides 1-minute average water-levels for several hours. Geophysical activity, either the passage of tsunami or more likely the seismic activity, will set a BPR into Event Mode. The TWCs can also set the BPR in Event Mode by manually sending a command to the BPR that adds 100mm to six of the water-level measurements and thus forces the BPR into Event Model.

The design specification is that Event data must be received at the TWCs within 3 minutes of measurement. Data routinely arrives at the primary Iridium receive server in about 30s. The messages are formatted so that the National Weather Service Telecommunications Gateway (NWSTG) can distribute the data messages to the TWCs via NWS circuits, to the public via NOAAPort, and the international community via the Global Telecommunications System. The NWSTG Replacement (which has reached Initial Operating Capability) can route more than 50 routine messages per second, within one minute, 99.9 percent of the time and perishable observation messages in 10 seconds [9].

Also a BPR can go into Event Mode with no Geophysical or Manual triggering and thus produces “false” events. During the period of September 2005 through March 2007, DART II BPRs went into Event Mode on 62 occasions – 16 of those are considered false because there is no associated Geophysical activity, 23 are Geophysical triggers, and 23 are Manual triggers. Most of the false events are easily identifiable in the data plots (Fig. 3 vs Fig. 4). The Manual triggers are also easily distinguishable as their data plots resemble “mesas” or “table-tops” (Fig. 5).

One of the earliest opportunities to take advantage of DART II capabilities was associated with the Tonga Event. On 03 May 2006, 15:27 UTC, a 7.8 Magnitude earthquake occurred at 19.9S and 174.2W (Earthquake data for this and all events are from the Pacific Tsunami Warning Center's message archives at *http://www.prh.noaa.gov/ptwc/index.php?region=1*). Although 4797 km from the quake's epicenter, the Hawai'i Station 51407 was interrogated using the two-way communications to retrieve the one-hour highest frequency data to examine the data for a possible small tsunami below the detection threshold. On 15 October 2006, Station 51407 was once again called upon to support a seismic event when a magnitude 6.8 earthquake occurred within 70 km of its location at 17:08 UTC. At 17:09:30 UTC, 51407 went into Event Mode due to the seismic activity.

After less than a month after being established, station 52404 in the western North Pacific Ocean went into event mode on 26 December 2006, 12:32:45 UTC following a 7.2 magnitude earthquake, approximately 1216 km from 52404, in the vicinity of Taiwan at 12:26 UTC.

On 01 April 2007, an 8.1 magnitude earthquake occurred near the Solomon Islands at 20:39:56 UTC. Station 52403, in the western North Pacific Ocean approximately 1804 km from the quake's epicenter, went into Event Mode at 20:48:30 UTC. This was followed by a Manual trigger from the Pacific Tsunami Warning Center at 01:24:00 UTC on 02 April 2007.

Most illustrative of the employment of the DART array in support of tsunami warnings are the DART events associated with the two Kuril Island seismic events of November 2006 (Table I) and January 2007 (Table II). The Geophysical activity caused most of the initial triggers to occur, followed by the TWCs placing BPRs in event mode to extend the reporting times. The November 2006 event caused all operating US Pacific DART stations to go into Event Mode either by the Geophysical activity or Manual trigger from the TWCs.

C. System Failures

There have been 4 failures of DART II stations deployed before April 2007 (Table II). Three of the failures were due to BPR failure and only one due to surface buoy communications failure. The shortest life-span was for station 52401 that failed after only 220 hours of operation. 52401, in the extreme western Pacific, also had the longest wait to restoration of 8 months.

III. Plans

Scheduled milestones for the DART array include the completion of the 39-station array by the end of March 2008 and the replacement of the final two DART I stations by the end of Fiscal Year 2008. NDBC is undertaking a systems engineering effort to optimize the NOOSS to increase cost-efficient, multi-purpose operations and to fulfill both NOAA and IOOS data management operational concepts.

The information technology architecture will incorporate a global load balancer to switch the incoming Iridium DART messages between the primary and secondary Iridium servers to ensure continuity of operations by providing continuous data flow from DART stations in the event of failures on either server.

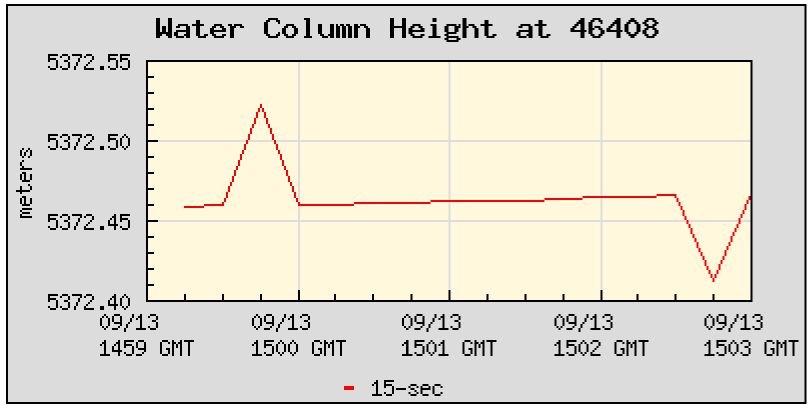

Fig. 3: Example of False Trigger Event

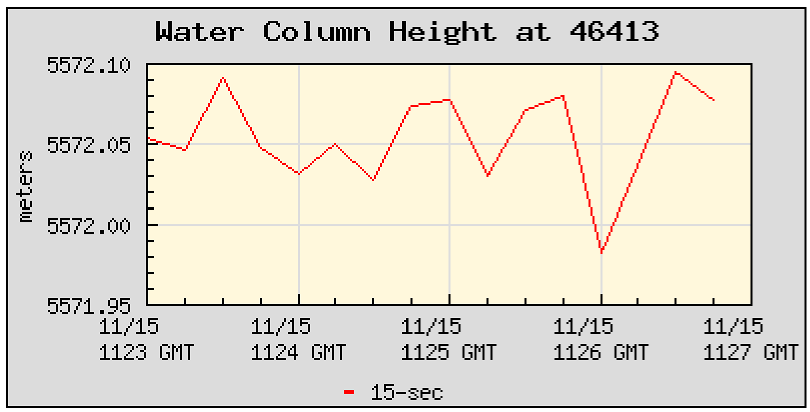

Fig. 4: Example of Geophysical Trigger Event

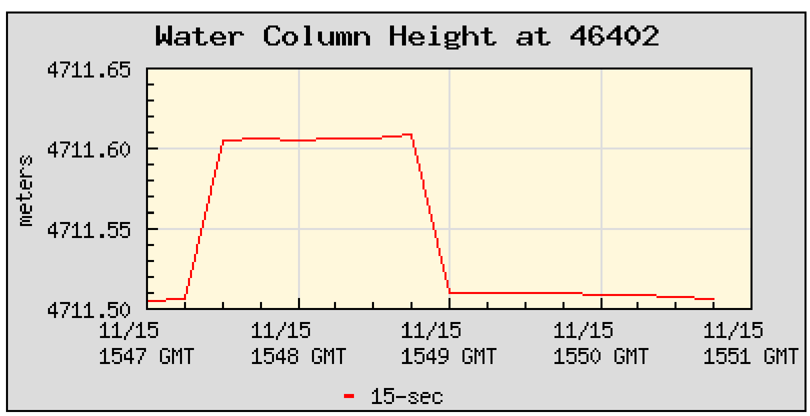

Fig. 5: Example of Manual Trigger Event

IV. Epilogue

In August 2007, NDBC completed a month-long cruise in the North West Pacific Ocean and the Gulf of Alaska that restored 3 failed stations, established 4 new stations, and completed scheduled service of 3 stations. At the conclusion of that cruise on August 9, 2007, the DART network had 32 of 32 stations reporting for both 100% network availability and 100% data received. At the time of the *MTS-IEEE Oceans07 Conference*, the DART network will consist of 34 operating stations of the planned 39, and the number of DART II systems operated by the international community will reach five.

Acknowledgment

The authors wish to thank Mr. Douglas Maxwell, Mr. Robert Weir, Mr. Stuart Hayes, and Mr. Jack Rowley of NDBC's Technical Service Contractor and Mr. Chris Taylor and Mr. Brett Taft of NDBC for providing technical support.

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TABLE I

DART STATION EVENTS FOR NOV 2006 KURIL ISLANDS EVENT

Time (UTC) of Earthquake or Trigger	Station (WMO Number)	Latitude	Longitude	DART System	Triggering Mechanism	Distance (km) from Earthquake
15-Nov-06						
11:14:16	Kuril Islands Earthquake Magnitude 7.8	46.683N	153.223E	N/A	N/A	
11:23:00	21414	48.942N	178.270E	2	Geophysical	1877
11:23:45	46413	48.861N	175.601W	2	Geophysical	2324
11:26:45	46408	49.626N	169.871W	2	Geophysical	2727
11:30:45	46403	52.650N	156.940W	2	Geophysical	3571
11:34:15	46402	51.069N	164.010W	2	Geophysical	3118
15:39:00	46403	52.650N	156.940W	2	Manual	3571
15:47:45	46402	51.069N	164.010W	2	Manual	3118
16:02:30	46410	57.499N	144.001W	2	Manual	4282
16:23:30	46409	55.300N	148.500W	2	Manual	4059
16:40:00	51407	19.634N	156.507W	2 Prototype	Manual	5433
18:32:45	46412	32.246N	120.698W	2	Manual	7186
18:47:45	46419	48.478N	129.359W	2	Manual	5548
19:13:15	46411	39.340N	127.007W	1	Geophysical	6211
19:29:15	46405	42.903N	130.909W	1	Geophysical	5759
20:34:30	46404	45.859N	128.778W	1	Geophysical	5731
16-Nov-06						
0:58:15	51406	8.489S	125.006W	2	Geophysical	10066

TABLE II

DART STATION EVENTS FOR JAN 2007 KURIL ISLANDS EVENT

Time (UTC) of Earthquake or Trigger	Station (WMO Number)	Latitude	Longitude	DART System	Triggering Mechanism	Distance (km) from Earthquake
13-Jan-07						
4:23:20	Kuril Islands Earthquake, Magnitude 8.2	46.288N	154.488E	N/A	N/A	0
4:29:00	46413	48.861N	175.601W	2	Geophysical	2160
4:30:45	21413	30.55N	152.117E	2	Geophysical	1730
4:31:00	21414	48.942N	178.270E	2	Geophysical	1753
4:33:45	46408	49.626N	169.871W	2	Geophysical	2556
4:38:45	52404	20.937N	132.315E	2	Geophysical	3427
4:39:30	46403	52.650N	156.940W	2	Geophysical	3412
4:39:45	52402	11.575N	154.588E	2	Geophysical	3803
4:41:15	46409	55.300N	148.500W	2	Geophysical	3906
4:46:15	46410	57.499N	144.001W	2	Geophysical	4100
4:47:45	51407	19.634N	156.507W	2 (Prototype)	Geophysical	5198
4:51:00	46405	42.903N	130.909W	1	Geophysical	5524
4:53:15	46411	39.340N	127.007W	1	Geophysical	6003
4:56:15	46412	32.246N	120.698W	2	Geophysical	6905
9:03:00	46409	55.300N	148.500W	2	Manual	3906
9:23:45	46410	57.499N	144.001W	2	Manual	4100
9:54:30	51407	19.634N	156.507W	2 (Prototype)	Manual	5198
10:17:30	52405	12.9N	132.3E	2	Manual	5524
10:19:15	52403	4.03N	146.6E	2	Manual	4757
10:33:30	46419	48.478N	129.359W	2	Manual	5489
11:02:45	46412	32.246N	120.698W	2	Manual	6905
Did not trigger	46404	45.859N	128.778W	1		5735
Did not trigger	51406	8.489S	125.006W	2		9962
Did not trigger	52403	4.03N	146.60E	2		4756

TABLE III

DART II STATION FAILURES BEFORE APRIL 2007

Station	Location	Deployed	Failed	Failed Component	Restored
46402	Gulf of Alaska	Aug 2006	Nov 2006	BPR	Aug 2007
41424	Western Atlantic	Apr 2006	Aug 2006	BPR	Feb 2007
42408	Gulf of Mexico	Apr 2006	Jan 2007	Buoy	Feb 2007
52401	Western Pacific	Dec 2006	Dec 2006	BPR	Aug 2007