

U.S. Deep-Sea Tsunameter Network Fully Operational

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Abstract - In March 2008, the National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) completed the deployment of the last of the 39-station network of deep-sea tsunameters. This effort was an integral part of the National Tsunami Hazard Mitigation Program. The Tsunami Program 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. This includes operation of the U.S. Tsunami Warning Centers (TWC) as well as leadership of the National Tsunami Hazard Mitigation Program. It also includes the acquisition, operations and maintenance of observation systems required in support of tsunami warning, such as NOAA's Deep-ocean Assessment and Reporting of Tsunamis (DART®), local seismic networks, coastal, and coastal flooding detectors. NWS also supports observations and data management through the National Data Buoy Center (NDBC). As part of NOAA's effort to strengthen tsunami warning capabilities, NDBC expanded the network from the original six stations to 39 stations and upgraded all stations from first-generation DART® I technology to second-generation DART® II technology. Consisting of bottom pressure recorder and a surface buoy, the tsunameters deliver sea-level data from the sea bottom to tsunami warning centers in less than three minutes. A significant capability of DART II is the two-way communications between the bottom pressure recorder and the Tsunami Warning Centers/NDBC using the Iridium Satellite LLC's commercial satellite communications system. The two-way communications allow the Tsunami Warning Centers to set stations in event mode in anticipation of possible tsunamis or retrieve the high-resolution (15-s intervals) data in one-hour blocks for detailed analysis. DART II systems transmit standard mode data, containing 24 estimated sea-level height observations at 15-minute intervals, once every six hours. The two-way communications allow for real-time troubleshooting and diagnostics of the systems. NDBC receives the data from the DART II systems, formats the data into messages and then delivers them to the National Weather Service Telecommunications Gateway (NWSTG) that then distributes the data in real-time to the Tsunami Warning Centers via NWS communications and nationally and internationally via the Global Telecommunications Systems. NDBC positioned the tsunameters between Hawaii and every seismic zone that could generate a tsunami that would impact the state and beyond, including the U.S. west coast. The effort in expanding the tsunameter network in the Pacific and to the western Atlantic, Gulf of Mexico and Caribbean required hundreds of thousands of kilometers of ship deployments. NDBC assumed operational responsibility for the tsunameter network in 2004 and the network became operational in 2005. In addition to the expansion, NDBC and its technical services contractor, SAIC, have

- Completed the transition of the DART II technology from research to operations
- Planned and executed 16 deployment missions needed to expand the array
- Assisted four international partners with deployment and operation of DART II systems
- Conducted DART II technology test procedures to facilitate and validate the commercial application of the DART II technology
- Developed and maintain a DART observation ingest and dissemination
- Maintained data availability in excess of the network goal of 80%
- Introduced innovations and efficiencies in the logistics and operations that reduced the costs of maintaining the array
- Increased the reliability of the network

1. INTRODUCTION

In March 2008, the National Oceanic and Atmospheric Administration's (NOAA's) National Data Buoy Center (NDBC) completed the 39-station tsunameter array for the United States. This marked the completion of a five-year effort to transition two technologies to operational status and expand the array from six to 39 stations to bolster the tsunami warning system [1]. The tsunameters employ NOAA's Deep-ocean Assessment and Reporting of Tsunamis (DART®) technology. The initial transition, completed in 2004 from Research to Operations at NDBC [2], included the initial six tsunameters that employed the first generation of DART technology (DART® I). NDBC followed with the transition of the second-generation technology (DART® II) in 2005 [3]. 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 (TWCs) and the acquisition, operations and maintenance of observation systems required in support of tsunami warning such as the tsunameters. NWS also supports observations and data management through the National Data Buoy Center (NDBC) [4].

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

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE SEP 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE U.S. Deep-Sea Tsunameter Network Fully Operational				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Data Buoy Center, ,Bldg 3205 Stennis Space Center,Stennis Space Center,MS,39529				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002176. Presented at the MTS/IEEE Oceans 2008 Conference and Exhibition held in Quebec City, Canada on 15-18 September 2008.					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

distribution to the TWC, and the 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. Data acquisition time for DART I had to be inferred from the message receipt times. The Iridium® (Iridium Satellite LLC) 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. The DART II systems have proven to be a robust and versatile system that has supported tsunami assessment for a number of seismic and tsunami events [7].

In this paper, the progress of the DART network expansion is first described. Then, the development and considerations of deploying DART buoys are discussed. One of the important parts of the U.S. tsunami program is to assist international partners. There is a section that presents how we work with our international partners. Then the development of DART data management, DART data availability and the issues of innovations and efficiencies are discussed.

2. DART NETWORK EXPANSION

Planned DART network expansion resulted from a decision to expand the U.S. tsunami detection and warning capabilities as a contribution of the Global Earth Observation System of Systems, or GEOSS — the international effort to develop a comprehensive, sustained and integrated Earth observation system [8]. This DART network expansion was part of a more comprehensive program to provide better coverage for tsunami detection in the Pacific and Atlantic Oceans, Gulf of Mexico and Caribbean Sea. Additional support and development was also included in the expansion proposal to aid international communities in developing their own tsunami early warning systems [9].

At the same time, plans were announced to expand the DART network, the original six DART systems in place, maintained by the Pacific Marine Environmental Laboratory (PMEL), was being turned over to the National Data Buoy Center (NDBC) for operations. NDBC became responsible for maintaining the existing DART array and for the preparation, management, execution and facilitation of the DART network expansion. Over the next three years, NDBC was able to expand the DART network from its original six systems to 39 systems in the domestic array and assist four international partners in deploying their DART II systems.

In order for NDBC to be able to execute this DART network expansion, a strategy was needed on where to place the DART systems. This strategy was formulated in July 2005, when a large group of technical representatives gathered for the DART-NOW Workshop. The primary focus of this workshop was to determine an optimal network configuration that met multiple operational, logistical, and mitigation objectives [10]. These objectives, or considerations, were scientific, technical, operational and politically based drivers that would steer the course of the DART network implementation.

The scientific considerations were based on seismic source information, computer tsunami modeling, tsunami travel times from potential tsunami sources, positions relative to tsunami propagation paths to U.S. impact sites and the suitability of bottom conditions for hardware deployment. The DART stations also needed to be placed close enough to the source to minimize the time to acquire the first direct evidence of a tsunami from the DART buoy. The goal was to allow sufficient time for evacuation should a damaging tsunami be forecast and for cancellation of a tsunami warning should a tsunami be assessed as nondestructive.

The technical considerations were based on the system requirement that was tightly bounded by the design capability of the DART II system. These systems were designed to be placed in 6,000 meters of water depth and operate in an environmental operating condition of Beaufort nine. They were also designed to automatically trigger when the tsunami detection algorithm was exceeded or when given an on-demand command for the Tsunami Warning Centers. The final technical consideration was to ensure that these DART systems could communicate back to the Tsunami Warning Centers within three minutes of an actual triggered event.

The operational considerations were based on funding, resource allocations, ability to procure material necessary to build the systems, ship deployment availability and the overall maintenance requirements for the array. Another strong operational consideration was the mitigation strategy associated with each buoy and also within regional areas. One system might fail but there would be sufficient redundant stations in the region to allow for that failure, but in other regions, one system failure would be a significant degradation to the warning capability for that region.

Operational considerations were also discussed at the Tsunami Warning Center level to address their specific needs to support tsunami warning forecasts, timely dissemination of information to local and regional parties and the ability to determine the presence of tsunamigenic waves.

Political considerations addressed the ability to deploy systems into Exclusive Economic Zones (EEZ) of countries that had special rights in the area considered for a station establishment. The EEZ is a seazone over which a country has special rights over the exploration and use of marine resources. In most cases, this is considered to be 200 nautical miles from the respective country's shoreline. One of the most time-consuming requirements of placing a scientific system into another country's EEZ is awaiting permission to do so and then continually requesting permission to return and maintain or service the system. In all cases except one, the DART II systems were able to be placed outside of other countries' EEZs.

Initial expansion plans were laid out to establish two additional DART stations on the U.S. west coast to enhance warning capability. In September 2005, a DART team consisting of an oceanographer, a senior electronics technician, a mechanical

technician and a systems engineer deployed two DART I stations off the California coastline. At the same time these stations were being established, plans were in the works to begin the building of the DART II systems that would support further array expansion over the next few years. By the end of 2005, the DART array consisted of one DART II prototype system and nine DART I systems in the eastern Pacific Ocean; 2006 would see the expansion of the array to other ocean basins and bring the array's totals to 22 DART II systems and three DART I systems.

In the beginning, a typical DART team consisted of an electronic technician, an engineer, a mechanical technician or two and an oceanographer. The composition of the team was driven by the newness of the project, newness in the actual deployment of the tsunameter material and the buoy electronic packages, newness of the hull deployment techniques, and newness of the deployment location selection and bottom composition. As time went on, the DART team composition was reduced from the initial four to five people to two to three people. This reduction was the result of learning the deployment processes and becoming more experienced in all deployment requirements. Towards the end of the network expansion, the DART program was deploying two-man teams to complete all deployment requirements.

A team of DART engineers, technicians and mechanics traveled to the home of PMEL, at the Western Regional Center, Seattle, Washington, and began construction on six new DART II systems. These six systems were built to support the deployment of three stations in the Atlantic Ocean and one each in the Caribbean Sea and the Gulf of Mexico, which were deployed. In March 2006, DART II stations were established off the South Carolina coast; two stations north of Puerto Rico; one station south of Puerto Rico; and one station in the Gulf of Mexico, 325 nautical miles south of New Orleans, Louisiana (See Fig. 1).

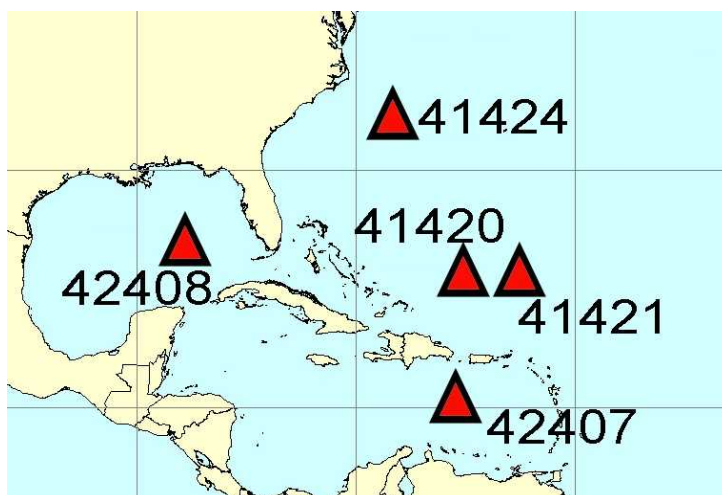


Fig. 1: Atlantic Station Establishments

A tremendous amount of lessons were learned from this first expansion deployment. The deployment vessel, the University-National Oceanographic Laboratory System (UNOLS) Research Vessel (R/V) *Seward Johnson* from Harbor Branch Oceanographic Institute home ported in Fort Pierce, Florida, U.S.A., afforded an opportunity to learn and develop deployment skills that would be needed over the course of the next few years. Actual deployment procedures were tested, evaluated and modified to become more effective and efficient. The ship transited nearly 3,800 nautical miles over the course of 28 days in support of this deployment. The deployment team deployed 24,461 meters of mooring material, moved 92,275 pounds of material from shore to the ship, and then into the ocean, and returned to home after 35 days underway. The initial "Clean Sweep" broom was hoisted in recognition of a job well done.

At the same time that the initial Atlantic Ocean DART II stations were being deployed, another three-man team was traveling to the West Coast in order to return two DART I stations to operations. The team traveled to the WRC Seattle and prepared to board the University-National Oceanographic Laboratory System (UNOLS) research vessel (R/V) *Wecoma*. From Seattle, they transited to locations off the Washington and Oregon coast to re-establish the DART I stations before pulling into Newport, Oregon. This mitigation deployment would add another layer of planning and executing during the expansion of the DART array.

After the initial success in getting the first five buoys in the expansion plan in the water and restoring two existing stations, plans were already being put together for the next phase of expansion. The next area to receive expansion was going to include the Northeast Pacific, Gulf of Alaska, and areas in the vicinity of the Aleutian Islands of Alaska. Early in July 2006, a six-man team once again went to the WRC Seattle to prepare five DART stations for deployment. Once the systems were tested and approved for deployment, they were loaded onboard the commercial Motor Vessel (M/V) *Bluefin*. Using a two-team approach the deployment was split into two legs, with the first three-man team traveled from Seattle to Kodiak. Once reaching Kodiak, Alaska the team was relieved by a second four-man team that continued from Kodiak to near the International Dateline and returned to Seattle. This second team added additional stations to the existing tsunameter network and also serviced stations that were already established.

By the end of August 2006, ten new DART II tsunameters had been added to the network. In September and October, a team traveled to two existing stations, one near San Diego, California, and the other 2,100 nautical miles southeast of Honolulu, Hawaii, to swap out DART I tsunameters with DART II versions. This action completed a 50% upgrade from the original DART I stations to DART II.

In early November 2006, a team again prepared for another major deployment to the Western Pacific. Loading six DART II systems on board the R/V *Melville* in Honolulu, Hawaii, a four-man team set sail for Guam. Along the way, they established three new DART II tsunameters in the western Pacific Ocean between Thanksgiving and early December. The ship arrived in Guam where the team was swapped out with a two-man team that took over. The ship set sail and established another three DART II tsunameters before arriving in the Truk Islands just before Christmas. The team disembarked and flew home for the

Christmas holiday with their families after successfully traveling nearly 7,500 nautical miles, deploying nearly 33,600 meters of mooring material, moving over 100,000 pounds of material from shore to sea, and receiving notification that the initial operational capability of the tsunameter network had been obtained on December 18, 2008.

In early 2007, a three-man team sailed twice, once to the Atlantic Ocean and once to the Gulf of Mexico, to service failed systems. Using available research vessels on short notice the teams successfully restored two stations in minimal time.

March 2007 saw a three-man team preparing for another deployment, this time along the Central American west coast. Shipping three DART II systems to San Diego, California the team loaded their material onboard the R/V *New Horizon* and got underway on March 15, 2007. After traveling nearly 5,000 miles, the team successfully deployed 10,000 meters of mooring material in support of three new tsunameter stations.

After this last deployment, teams began to combine deployment requirements to include servicing existing tsunameter stations and also servicing other buoys in the NDBC network. Earlier in the year, the NDBC had contracted a commercial vessel capable of meeting the needs of tsunameter deployment and service. This vessel, the M/V *Bluefin* from Seattle, had been used before in the Alaskan region and proved more than adequate to the task.

On June 16, 2007, the M/V *Bluefin* left Seattle enroute to Guam to pick up a two-man team that was flying out to meet the ship. After arriving in Guam in early July, the team met the ship and set sail on July 8, 2007, heading northward. During the first leg of this deployment, the team established four new tsunameter stations, serviced three existing tsunameters and serviced three critical weather buoys in the Alaskan region before pulling into Dutch Harbor, Alaska, 25 days later. Along the way, the team deployed 21,700 meters of mooring material, moved nearly 100,000 pounds of material from ship to sea and traveled nearly 16,000 nautical miles.

In Dutch Harbor, Alaska the first leg deployment team was relieved by another three-man team that included a Mechanical Technician in training to support the tsunameter network. The second team's primary mission was to service existing tsunameters and also service two critical weather buoys in the Gulf of Alaska. The M/V *Bluefin* departed Dutch Harbor, Alaska and pulled into Seattle, Washington on August 29, 2007 after traveling 2,800 nautical miles. The team met all deployment requirements and proved the feasibility of a multi-purpose deployment vessel.

During the remaining months of 2007, DART teams established two more tsunameters in the Atlantic Ocean, one more along the Central American west coast and a new station along the west coast of the United States. This action brought the tsunameter network to 35 active stations.

The completion of the array expansion to 39 stations and the last DART I systems replaced with DART II systems characterized 2008. Early in 2008, the M/V *Bluefin* was again contracted to make another western Pacific deployment. This time, the deployment plan called for establishing DART II stations in the southwest Pacific Ocean on the first leg of the deployment, conducting an international DART II station establishment in the Coral Sea, and then beginning a service run through the western Pacific and Alaskan portions of the DART network. Sending a build team to Seattle in January 2008, the DART team put together six systems and loaded them on the *Bluefin* in deployment preparation. On January 15, 2008, the M/V *Bluefin* departed the west coast of the United States enroute to the islands of Western Samoa.

The M/V *Bluefin* arrived in Apia, Samoa, on February 5, 2008, and took on fuel and stores. The ship was met by a two-man DART team that had flown from Mississippi. The ship departed Apia on February 7, 2008, and spent the next 12 days establishing two DART II stations in the southern Pacific Ocean northeast of New Zealand. The ship returned to Apia, Samoa, to pick up some additional riders and then proceeded westward to establish two additional DART II stations. On March 3, 2008, in the vicinity of 5°21'48" S 165°2'48" E, the DART team established DART Station 52406, which was the 39th station in the DART network. On March 5, 2008, the National Data Buoy Center received notification that the DART network had reached full operational capability (See Fig. 2)

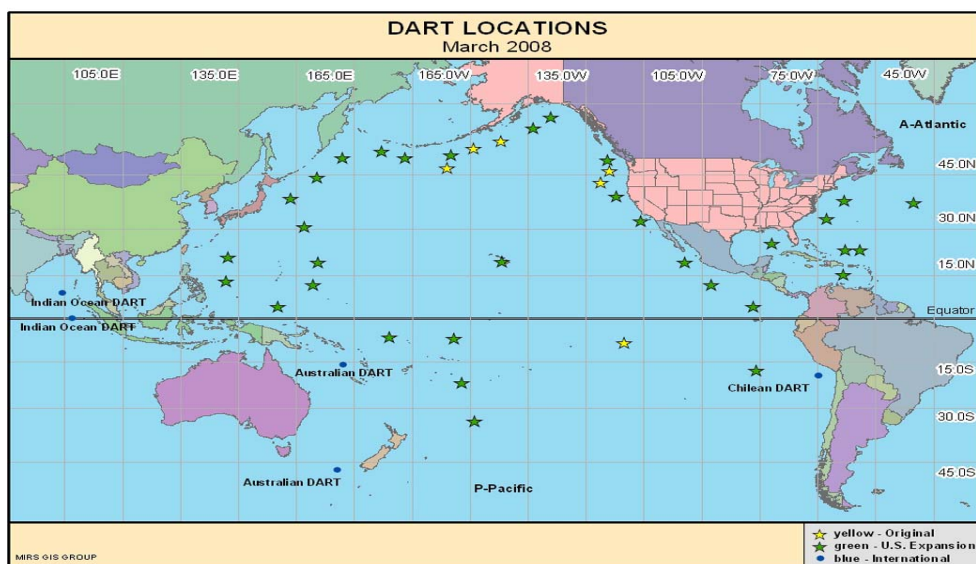


Fig. 2: Completed DART® Network March 2008

Over the course of nearly three years, the DART team deployed 33 domestic DART II stations, traveled over 100,000 nautical miles in the air and on the sea, and moved over 600,000 pounds of oceanographic equipment, contributing to faster and more accurate tsunami warnings.

3. MANAGING DEPLOYMENTS OF DART BUOYS

One of the many issues surrounding the DART network was the management of deployment requirements in order to complete the development of the DART network. This management detail included finding a deployment vessel, determining the transport modes domestically and internationally, arranging port services, ensuring exportation compliance, submitting both administrative and operational paperwork and finally ensuring travel arrangements were in place.

The biggest key to deployment success was determining the proper deployment vessel. A key element for vessel utilization was to have a good operational working deck capable of moving heavy anchors, buoy hulls and mooring material easily. A large A-frame with a heavy lift winch, a capstan and a crane capable of a 10,000 lift were usually desired. Additionally, a vessel having position-keeping capability, single beam or multi beam sounding equipment, at-sea Internet capability and a good working crew was always desired.

During the DART network expansion, the DART team deployed on many different vessels. The largest was the research vessel *Melville* from the Scripps Institute of Oceanography at 279 feet and a gross tonnage of 2,516 tons. The smallest deployment platform was the UNOLS research vessel *Pelican* from the Louisiana Universities Marine Consortium (LUMCON) at 116 feet. The most utilized vessel was the Motor Vessel *Bluefin* operated by Northlake Shipyard and contracted through C-Port Marine Services.

The *Bluefin* was the workhorse for three major deployments to the Pacific theater. First, it supported a deployment to the Alaska waters in the summer of 2006. It then supported a deployment to the western Pacific in the summer of 2007 that began in Seattle, traveled to Guam, then to the waters off the coast of Japan before turning northward along the Kuril Islands, the Aleutian Islands, into the Gulf of Alaska and finally back to Seattle. Finally, it supported the southwestern Pacific station establishments in March 2008 and continued to circumnavigate the Pacific basin for an additional three months before pulling into Seattle after nearly six months at sea. This vessel is 180 feet long, has a 24-foot A-frame and a protected working deck that makes deploying and recovering buoys easier in all sorts of weather conditions (See Fig. 3)



Fig. 3: Motor Vessel Bluefin
(Courtesy of Northlake Shipyard)

Once the vessel was selected, then the management objective became to move the deployment equipment into position for loading. The location of the deployment vessel would dictate whether a normal flatbed truck could be utilized or an International Organization for Standardization (ISO) 20-foot container would have to be used. Most domestic deployments, starting and beginning from a U.S. port, allowed for the free loading of deployment material onto a 52-foot flatbed truck and trailer. Deployments originating from port facilities outside of the continental United States and international ports required deployment material to be containerized and shipped far enough in advance to meet the deployment vessel.

Domestic transportation allowed for arranging trucks to transport deployment material from the DART production facility located at Stennis Space Center, Mississippi, to the departure port far enough in advance to meet deployment requirements. This advance period was usually a week to 10 days prior to sailing. Trucks would arrive at Stennis Space Center and be loaded using a combination of a heavy lift crane and forklifts. The loading process normally took 4-8 hours, depending on the size of the outgoing shipment. A normal one-buoy deployment would have the material in Table 1 associated with it. The associated weight for this material is nearly 20,000 pounds.

TABLE I
DART DEPLOYMENT MATERIAL

DART Deployment Weights and Sizes				
Description	Size	Weight (lbs)	Total Pieces	Total Weight (lbs)
Buoy Hull	5'H x 8'Dia	2500	1	2500
Buoy Mast	3.5'H x 6'Dia	100	1	100
Buoy Bridal	3'x3'x4'	750	1	750
Buoy Anchors	4'x4'x4'	3600	2	7200
BPR Platform and Anchor	4'x3'x4'	1000	1	1000
Spare Anchor	4'x3'x4'	750	1	750
Wire Basket w/ Floats	4'x4'x4'	650	1	650
3/4" Nylon Spool	3'x3'x3'	250	5	1250
Mooring Line Box (12,000 FT)	4'x4'x6'	2000	1	2000
Acoustic Release	3'x1'x1'	100	2	200
Reel Stand - 3' dia	5'x7'x4'	175	1	175
Gray Shipping Boxes	3'x3'x2'	250	8	2000
White Shipping Tote	4'x4'x4'	700	1	700

International transportation and ports outside the continental United States called for a more compact transportation concept. To meet this compact concept, an ISO 20-foot container was utilized. After some experimentation on weight distribution and material placement, a nominal plan was developed to be able to place one complete DART system in a Conex box. This containerized utilization ensured all material associated with one DART system would stay together during transport and also arrive at the deployment point intact. Over the course of the last three years, most international and outside the continental United States deployments called for only one or two DART systems.

As with any logistical transportation execution, there come emergent and expediting situations. The easiest way to handle these situations was to utilize air freight transportation. In most cases, transportation of highly critical components could be met by using air freight transporters like Federal Express. Most material was packed in a gray shipping box, known as a cruise box, and picked up at the production facility for transport. The biggest restriction for transporting material this way was weight. Air freight transportation restricts the weight to 150 pounds, and the size restriction is driven by the size of the aircraft loading door. This means that some DART deployment material could never be transported by air freight services.

Once deployment equipment reached the port of embarkation, the material had to be off-loaded either from the truck transport or the container. Due to the weight and size of the equipment, management had to ensure there were suitable crane services or forklifts available. Shore cranes were mostly used to lift the DART hulls equipped with their bridals and masts from the shore to the deployment vessel. In some cases, we could utilize the ship cranes if they were capable of conducting the lift. Forklifts were used to position material in place for lifting to the ship, lift bridals and masts into positions for fastening and also to stack and palletize material in preparation for lifting to the deployment vessel.

Exportation of the DART system is relatively painless due to its export classification of EAR99. A determination of the system was conducted by the Department of Commerce's Bureau of Industry and Security office, and it led to an overall classification of EAR99. This meant that the system could be transported to international destinations without very many issues. The bigger issue in exportation was meeting the destination countries' importation requirements. Because, in most cases, the DART system was ultimately going to end up in the ocean, local importation customs were waived. Advance notification, awareness and cooperation allowed for uneventful transport of DART systems to international partners.

Once DART deployment material reaches the domestic or international deployment port of departure, the DART deployment personnel have to arrive for pre-deployment preparations and ultimately deployment. In most cases, their personal transportation to the deployment start point is by air. Travel arrangements were normally made one to two months in advance to ensure their timely arrival. If traveling internationally, additional travel requirements were levied against the traveler to ensure safety. A close watch is also maintained during and after the deployment to ensure travel arrangements ashore meet the DART deployment personnel needs. Hotel accommodations, rental cars and airline travel can and do fluctuate based on the demands of the deployment.

4. DART DATA AVAILABILITY

DART data availability ties directly back to warning capability. If the data from the DART systems was available all of the time, then you would obviously have a higher opportunity to receive accurate and dependable data to make warning decisions. Unfortunately, with systems operating in the ocean environment and also at deep depths, the data is not always available. The original benchmark for the DART network data availability was set at 80%. The following is the statistical data to show the data availability since 2005:

- 2005: Data available = 79% for 10 systems deployed by the end of the year
- 2006: Data available = 88% for 25 systems deployed by the end of the year
- 2007: Data available = 89% for 35 systems deployed by the end of the year
- 2008: Data available = 86% for 39 systems deployed by March 2008 (for six months only)

Along with actual data receipt from the DART systems, the DART project has also tracked the actual deployment reliability statistics for each of the DART systems deployed. Initial analysis was collected for 63 actual touches to the DART system. A “touch” was considered for the actual establishment of the DART station, a return to the station for service or a return to the station for mitigation. The analysis points to two major reasons for new system sudden hardware failure: mooring failure or bottom pressure recorder CPU failure. In Table 2 below is the statistical information concerning DART station deployments through March 2008:

TABLE 2

DART DEPLOYMENT STATISTICS

Number of touches on DART stations	Number of failures in first 30 days	Number of failures first 31-90 days	Number of failures 91-180 days	Number of failures >180 days
63	5	2	2	5
Failure Rate (%)	8%	3%	3%	8%

A closer look at the data indicates that the majority of the first 30-day failures are directly attributed to bottom pressure recorder (BPR) CPU failure, with only one mooring casualty. The second period failures were contributed to mooring failures. Mooring failures can be attributed to strong current flow in the deployment location, a vessel strike to the buoy hull or vandalism. After 90 days, the contributing factor to system failure is even between mooring failure and electronic casualty. One other factor that was also looked at was, in some cases, the vessel that actually established the station was able to return to the site to effect repairs. On three separate occasions, BPR failure was corrected within 10 days of the original deployment.

5. DEVELOPMENT OF DART DATA MANAGEMENT

When the operation of the DART network was transferred from the research and development efforts of PMEL to the operational purview of NDBC, responsibility for the DART data was migrated as well. Retrieval, storage, and dissemination are all currently done on servers located at the NDBC facility at Stennis Space Center, Miss., and the National Weather Service Headquarters in Silver Spring, Md.

In early 2005, servers were set up at NDBC using software provided by PMEL to receive calls from the DART stations. NDBC began an effort to evaluate the software and incorporate it into the standard operational suite. Visits were made to PMEL as well as the Iridium offices in Tucson, Ariz. Following Hurricane Katrina in August 2005, it was immediately obvious that backup communications servers were required. In 2006, two systems were purchased and placed in Silver Spring and at Stennis. The primary server is located in Silver Spring with the NWS Telecommunications Gateway (NWSTG). The backup server is located at NDBC. Both servers run the exact same software and are able to perform their tasks with no degradation in service.

Communications between the servers and buoys takes place over the Iridium satellite network, using the Router-Based Unrestricted Digital Internetworking Connectivity Solution (RUDICS). The RUDICS protocol allows two-way communications to take place through a direct point-to-point connection. While fairly reliable for mobile-originated calls, a noted increase in missed calls when attempting to contact the station from the shore-side server has been noted since March 2007. Testing is ongoing to determine the cause for these outages.

When data is received by the communications server, it is reformatted into a Global Telecommunications System (GTS) message and transferred via File Transfer Protocol (FTP) to the gateway in Silver Spring for dissemination. In early February 2007, an additional FTP connection was made between the server and the Chilean Oceanographic Agency (SHOA) due to their lack of a GTS connection. In March of that same year, an FTP connection was made with the Australian Bureau of Meteorology. These connections provide an immediate transfer of data to the respective agencies for their own processing. In September 2007, an account was created for the Thailand National Disaster Warning Center on the NDBC server for them to access DART data via FTP as needed.

As previously noted, data received at the NDBC communications servers are sent via FTP to the NWSTG. Plans were initially made in April 2005 to develop the NOAA Network (NOAANet). This is an enterprise network designed to be the backbone which provides secure communications between over 200 NOAA locations. NDBC began operating over NOAANet in August 2006. The Tsunami Warning Centers were connected in 2007.

6. INNOVATIONS AND EFFICIENCIES

As the DART array became larger, it was apparent that there was a need to improve the processes of the program. This improvement process led to some very innovative ideas and created some significant efficiency along the way.

One of the earlier problems seen in the first build of the DART II system was the configuration of the DART II payload. The Build I payload consisted of one large containment box with dual payloads within. It was also equipped with a power monitor that became problematic from the onset. Initial assessments of troubleshooting indicated that the main payload box would have to be removed from the power enclosure in order to troubleshoot either the primary or secondary side of the payload. After some initial concept work, it was conceived that placing the primary payload and the secondary payload into separate container boxes would make it more efficient to service individual boxes versus one large box. Further production on payloads was rapidly transitioned into single payload boxes, and this has proven to be very efficient when servicing the payloads.

These single payload boxes were constructed from a single-hinged fiberglass enclosure that was able to house the central processing unit (CPU)/serial board assembly, the acoustic modem board assembly, the Geo-Positioning System board assembly, the Iridium modem and the Iridium/Global Positioning System antenna mounted on the top of the enclosure. Individual connection portals were mounted on the forward and rear of the payload box to allow for easier access. Each payload box weighs about 10 pounds and is easily transported by the technician. The size of the box is 10 inches by 8 inches by 6 inches compared to a somewhat cumbersome 20 inches by 18 inches by 9 inches.

Transporting the DART II system is costly and was even more costly in the early stages of array transition. The process in place at the time suggested that the DART material be transported via flatbed truck to the port of departure, containerized and then shipped to an international destination. In most cases, the oversized DART hull did not fit into a 20-foot ISO container and was shipped on a special flat rack. This flat rack, in most cases, cost more than a container to ship. Using a concept from another buoy program, the DART team designed a transportation sled to change the transport size of the DART hull. By placing it on a sled, it could easily be placed into a container box (See Fig. 6).

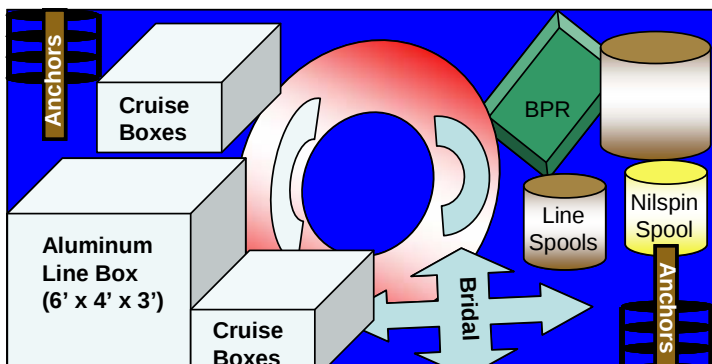


Fig. 6 DART Deployment Material in an ISO 20' Container (Side View)

7. ASSISTING INTERNATIONAL PARTNERS

One of the fallouts from the disastrous tsunami of December 2004 was a response from the United States government to launch an effort to contribute to and help develop an integrated early warning and mitigation system in the Indian Ocean region.

This effort was directed to those countries most directly impacted by the 2004 tsunami. This program also involved close collaboration with the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The IOC had the lead responsibility for developing the Indian Ocean's regional warning capability. [11]

The program that led the DART team to assist in the deployments of the DART system in the Indian Ocean was the U.S. Indian Ocean Tsunami Warning System (IOTWS) Program, which was funded by the United States Agency for International Development (USAID). The program was funded and implemented for the period from August 1, 2005, to March 31, 2008. In addition to USAID, additional support was provided by NOAA, the U.S. Geological Survey (USGS), the U.S. Department of Agriculture/Forest Service (USDA/FS), and the U.S. Trade and Development Agency (USTDA).

The U.S. IOTWS Program focused its efforts on the countries most affected by the devastating tsunami of December 2004, which include Indonesia, Sri Lanka, Thailand, and the Maldives, as well as implementing limited activities in India [12]. The objective of the U.S. IOTWS Program was to provide strategic support to the international effort led by the IOC to develop an operational IOTWS that provides integrated end-to-end capabilities at the regional, national, and local levels within a multi-hazard framework.

In mid-November 2006, the two-man DART team and the NDBC DART program manager deployed to Phuket, Thailand, for the first international support deployment. (See Fig. 4) Three months prior the DART II deployment, equipment had been loaded into a 20-foot ISO container and shipped to Thailand for arrival in the same time period.



Fig. 4: DART® II System at Phuket Port, Thailand

On the morning of December 1, 2006, a dedication ceremony was held on the Cape Panwa pier near the Phuket Marine Biological Center. The DART buoy — the focal point of the celebration — was at the end of the pier, secured on the deck of a large, sturdy research and training vessel, M/V *SEAFDEC*, provided by the Southeast Asian Fisheries Development Center, to take the buoy to its deployment location in the Andaman Sea, at 9 degrees north, 89 degrees east, halfway between Thailand and Sri Lanka. The M/V *SEAFDEC* departed the port of Phuket on the morning of December 1, 2006, and arrived on station on December 3, 2006.



Fig. 5: Commemorating the DART® II Launch in Indonesia
(Courtesy of the National Oceanic and Atmospheric Administration)

Shortly after the return of the DART team from Thailand, plans were begun to deploy a DART II system in Indonesia. The DART team traveled to Jakarta, Indonesia, and worked with the Badan Pengkajian dan Penerapan Teknologi/Agency for the Assessment and Application of Technology (BPPT) to prepare for the station establishment. On September 19, 2007, an official dedication ceremony was held to commemorate the occasion of the launching. (See Fig. 5) The DART team loaded the DART II equipment on the R/V *Baruna Jaya III* and proceeded to the designated deployment location. The U.S. and Indonesia team launched a second DART II system in the Indian Ocean on September 26, 2007, at 0.0N and 92.0E.

These two DART stations contribute to a planned array of 22 stations to support comprehensive detection capability in the Indian Ocean as endorsed by the ICG/IOTWS. Through its technical training on the deployment, maintenance, and operation of DART

stations, NOAA and its partners have demonstrated the implementation of IOC standards and protocols for reliability, accuracy, interoperability, free and open exchange of data, and integration. DART II helped in determining that no damaging tsunami formed from the September 2007 earthquake in Indonesia, thus avoiding unnecessary and costly evacuations. In that case, the non-damaging tsunami was quickly detected, assuring that cancellation of the warning was the appropriate action. This deep-ocean sensor capability improves quality assurance and reliability of the warning system, reduces the risks of false alarms, and provides much longer warning lead times as compared to a network of sea-level gauges alone.

At the same time the Indian Ocean efforts were taking place, the Australian Bureau of Meteorology (BOM) and NOAA were meeting and developing a partnership to help Australia build its tsunami early warning systems. On February 23, 2007, the implementing arrangement was signed and the DART team was ready to provide assistance. [13]

On April 5, 2007, the DART team arrived in Hobart, Tasmania, in preparation for a DART II system deployment. On April 14, 2007, the RV *Southern Surveyor* got underway to travel to a designated deployment location 670 nautical miles to the southeast. On April 16, 2007, DART II station 55401 was established in the Tasman Sea.

In March 2008, the DART team assisted in the second Australian DART station establishment. This time, the Australian-led deployment team did the work while the U.S. DART team assisted in the deployment process. The second DART II system was deployed in the Coral Sea near 15.8 South and 158.8 East.

8. CONCLUSION

During the expansion of the DART network, we have successfully accomplished (1) the establishment of an efficient operational process/procedure for deploying DART buoys, (2) development of the DART data management system, and (3) provided outstanding assistance to our international partners for a global tsunami buoy network.

The DART program, as part of the strengthening of the U.S. tsunami network program, reached full operational capability on March 8, 2008. The DART buoys will significantly improve the capability for the early detection and real-time reporting of tsunamis in the open ocean. DART is essential to fulfilling NOAA's national responsibility for tsunami hazard mitigation and warnings. The DART network complements other parts of the U.S. Tsunami Warning Program, including NOAA's network of tide stations, forecast models for at-risk communities, and its TsunamiReady® education program.

REFERENCES

- [1] NOAA Launches Final Two Buoys to Complete U.S. Tsunami Warning System, March 10, 2008 NOAA Press Release, available on-line at: http://www.noaa.gov/stories/2008/20080310_buoy.html
- [2] Taft, B, Meinig, C.; Bernard, L.; Teng, C.; Stalin, S.; Oapos, Neil, K.; Eble, M.; Demers, C Transition of the Deep-ocean Assessment and Reporting of Tsunamis network - a technology transfer from NOAA research to NOAA operations, *OCEANS 2003, Proceedings*, Volume 5, Issue , 22-26 Sept. 2003 pp. 2582 – 2588.
- [3] Green, D.S., 2006. Transitioning NOAA Moored Buoy Systems From Research to Operations, *OCEANS 2006 Proceedings*, Sept. 2006, pp. 1 – 3.
- [4] G. Smith and D. Green, *Program Charter for Tsunami Program*, NOAA, February 28, 2006.
- [5] H.O. Mofjeld, *Tsunami Detection Algorithm*, unpublished. Available on-line at: <http://www.ndbc.noaa.gov/dart/algorithm.shtml>
- [6] C. Meinig, S.E. Stalin, A.I. Nakamura, and H.B. Milburn, *Real-Time Deep-Ocean Tsunami Measuring, Monitoring, and Reporting System: The NOAA DART™ II Description and Disclosure*, 2005, unpublished. Available on-line at http://nctr.pmel.noaa.gov/Dart/Pdf/DART_II_Description_6_4_05.pdf.
- [7] Bouchard, R., McArthur, S., Hansen, W., Kern, K.J., and Locke, L., 2007. Operational Performance of the Second Generation Deep-ocean Assessment and Reporting of Tsunamis (DART II), *Proceedings Oceans 2007*, Vancouver
- [8] Wayne A. Morrissey, *Tsunamis: Monitoring, Detection, and Early Warning Systems*, Congressional Research Service Report for Congress, Updated March 15, 2005, p. 6
- [9] USAID Announces Launch of Indian Ocean Tsunami Warning System Program”, Press Release 2005-074, August 17, 2005
- [10] Eric Geist, Frank Gonzalez and Uri ten Brink, “Workshop on Optimizing the DART Network for Tsunami Forecasting” US Geological Survey Sound Waves Monthly Newsletter, October 2005
- [11] USAID Announces Launch of Indian Ocean Tsunami Warning System Program”, Press Release 2005-074, August 17, 2005
- [12] US Indian Ocean Tsunami Warning System (IOTWS) Programs and Objectives Available on-line at: <http://apps.develebridge.net/usiotws/pageaahome.html>
- [13] Valentina Lazarevska, Media and Communications, Bureau of Meteorology, “Australia and US secure tsunami partnership”, Media Release, February 23, 2007