Transition of the Deep-ocean Assessment and Reporting of Tsunamis Network – A Technology Transfer from NOAA Research to NOAA Operations

B. Taft[1], C. Meinig[2], L. Bernard[1], C. Teng[1], S. Stalin[2], K O'Neil[1], M. Eble[2], C. Demers[1]

1. NOAA/NDBC Stennis Space Center Stennis, MS 39426
2. NOAA/PMEL 7600 Sand Point Way NE Seattle, WA 98115

Abstract - The Deep-ocean Assessment and Reporting of Tsunamis (DART) network was established for the early detection and real time reporting of tsunamis in support of the National Tsunami Hazard Mitigation Program (NTHMP). Each DART station is occupied by a surface buoy and a bottom pressure recorder (BPR) anchored on the seafloor that monitors and reports water column height. An acoustic modem transfers BPR measured heights to the surface buoy which in turn relays the data to ground receivers via a NOAA Geostationary Operational Environmental Satellite (GOES). Data are then disseminated to NDBC for processing, quality control, and data display, to PMEL for diagnostics and research applications, and to the National Weather Services (NWS) two Tsunami Warning Centers in Alaska and Hawaii for providing warning guidance to coastal communities. Data are displayed and made available for download from the NDBC web site URL: *www.ndbc.noaa.gov/dart.shtml*. Operational responsibility for the DART system is being transferred from a research lab (PMEL) to the appropriate operational center (NDBC). This paper gives a brief overview of the DART system followed by details of the transition process.

I. INTRODUCTION

The Deep-ocean Assessment and Reporting of Tsunamis (DART) system was developed in support of the National Tsunami Hazard Mitigation Program (NTHMP). The primary goal of the program is to reduce the loss of life and property resulting from Tsunami innundation. For example, the 1993 Hokkaido, Japan tsunami claimed 200 lives on Okushiri Island and caused $1.5 billion in property damage. A secondary goal of the program is to eliminate false alarms, which potentially cost millions of dollars in lost revenue, endanger lives, and erode the credibility of the warning network [1].

The DART system was developed and tested as a prototype in 1995 by the NOAA Pacific Marine Environmental Laboratory (PMEL). Currently, the network is in an operational configuration and has expanded to an array of six stations. This includes three DART stations south of the Aleutian Islands, two off the United States Oregon and Washington Coasts, and one Equatorial station (Fig. 1) [2].

Operational responsibility for the DART system is being transferred from a research lab (PMEL) to the appropriate operational center (NDBC) because the system is robust, reliable, and cost-effective. The transition process that was begun in the late summer of 2001 is on track for completion in the fall of 2003. PMEL will continue to provide engineering support as needed and will continue with development of future generation DART systems to take advantage of technological advancements. NDBC will be responsible for system troubleshooting, routine maintenance, documentation, testing, deployment procedures, and data quality control, display and dissemination to the public. The partnership of NDBC and PMEL is committed to ensuring the long-term success of the DART system.

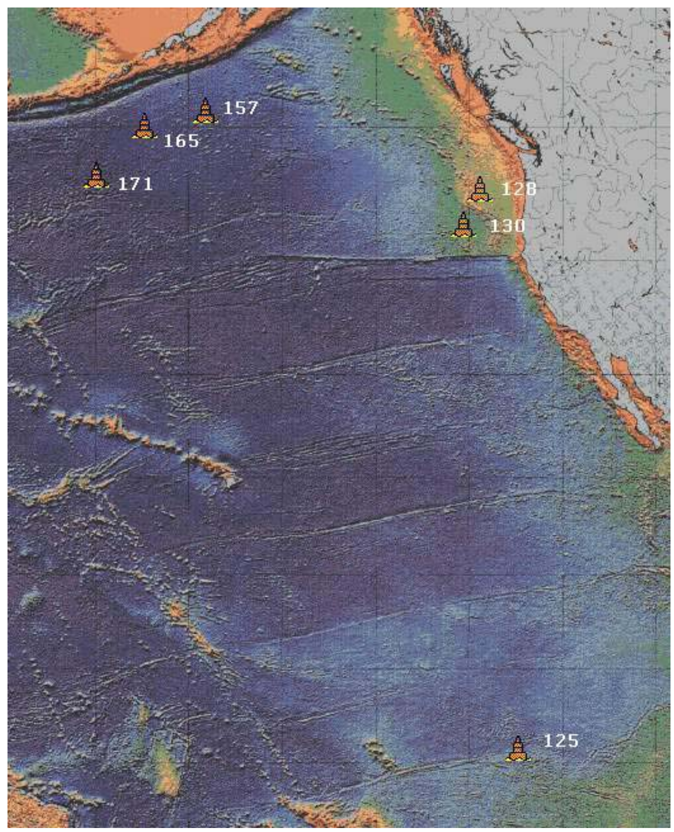

Figure 1. Pacific Ocean map of existing DART stations

II. SYSTEM OVERVIEW

Each DART station (Fig. 2) is comprised a Bottom Pressure Recorder (BPR) and a surface buoy. The BPR measures and records the pressure of the overlying water column using a Paroscientific model 410K-017 digi-quartz pressure transducer and a PMEL designed counting circuit [3]. A tsunami detection algorithm developed by PMEL [4] compares real-time measured pressure values to those expected. Data are converted from pressure to seawater height in millimeters and are then relayed to the surface buoy via a Benthos ATM-870 acoustic modem. The DART system is capable of measuring tsunamis as small as 1 cm with a resolution of 1 mm of measured pressure at the ocean floor.

During normal operation, the BPR continually samples and processes the pressure measurements at the seafloor. These measurements are then stored into four 15 minute blocks, which are an accurate representation of the tidal level at the node. These values along with system engineering parameters are transmitted hourly to the surface buoy via an onboard acoustic modem. Two consecutive deviations in height from BPR predicted values cause the system to trip into event reporting mode. During this mode, the averaging period is decreased and the reporting frequency is increased. These reports are transmitted without delay to the buoy.

The BPR platform is comprised of a mounting platform, acoustic transducer, electronics canister, battery canisters, pressure transducer, acoustic release, mooring and anchor. The BPR is deployed in areas in which the ocean floor bathymetry is relatively flat to ensure that the 55 degree conical beam of the acoustic modem transducer completely envelops the watch circle of the surface buoy. The system is powered with sufficient batteries to allow for a two year unattended deployment with a planned activity of ~10 tsunami events per year. The mounting platform is latched onto a disposable anchor via a hard mounted acoustic release. The acoustic release is attached to a subsurface mooring consisting of glass ball floatation and mooring line.

The purpose of the surface buoy is to provide a communications link from the BPR to the NWS Tsunami Warning Centers in Hawaii and Alaska. The buoy acts as a relay by receiving the acoustic message from the BPR from its own acoustic modem transducer and sending the pressure values and engineering data to shore via the GOES system. The buoy engineering data consists of parameters related to the quality of the acoustic modem transmission including signal to noise ratio, number of attempts to transmit the data, and Doppler shift. This message is transmitted across the GOES system through the National Environmental Satellite and Data Information Service (NESDIS) and the NWS Telecommunications Gateway (NWSTG) and distributed to user sites, including PMEL, NDBC, and the NWS Tsunami Warning Centers, and to the public via the NDBC webpage.

The 2.5m diameter buoy is constructed of a foam filled fiberglass shell with an internal stainless steel frame. It has a stainless steel bridle and an aluminum tower superstructure and electronics well. Each buoy houses a complete redundant system to boost overall system reliability, which has exceeded 95% reliability from 1997-2001 for the array [5]. The system includes a GPS receiver, internal processor for formatting data messages, GOES transmitter, acoustic modem and a power distribution system. The power system of the buoy is comprised of eight battery assemblies, consisting of standard D-cell alkaline batteries. This battery capacity is designed to power the buoy for over 1 year with ~10 tsunami events. Each buoy is equipped with a short range RF modem that allows field engineers to monitor the system immediately following deployment. The buoy is moored in place by a taut mooring with a design scope of 0.985. The tight scope and deploying the buoy as close to the BPR as possible helps ensure that the buoy remains with in the 55 degree transmission cone of the BPR acoustic modem.

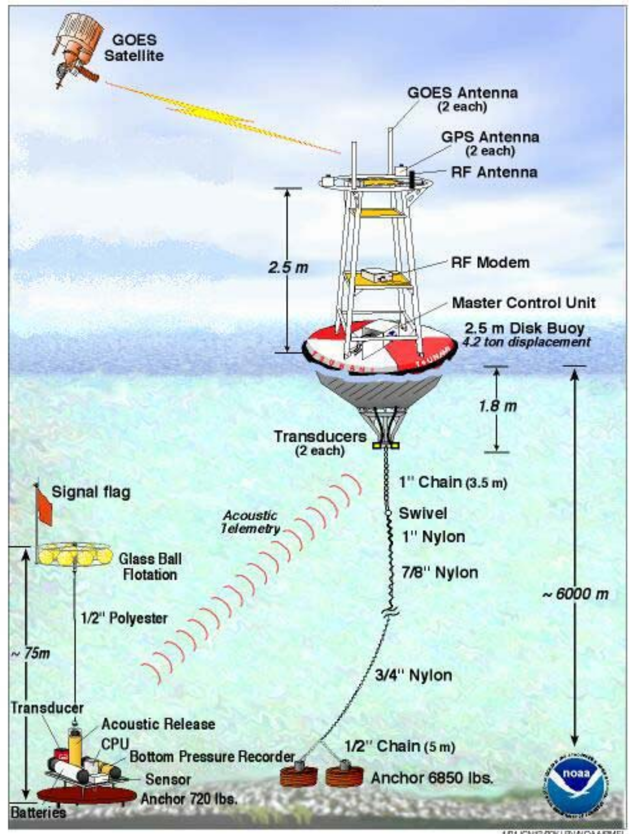

Fig. 2 DART station diagram

III. DATA REPORTING AND DISSEMINATION

The system has two data reporting modes, standard and event. The system operates routinely in standard mode, in which four 15-minute average values of sea surface height are reported at a NESDIS allotted transmission time each hour. This information along with engineering parameters is received across the GOES network. When the internal detection software [4] identifies an event, the system ceases standard mode reporting and begins event mode transmissions utilizing the GOES random channel. This is initiated with the immediate transmission of the first detection message with critical average water height information and time of detection. The first message is followed by three additional messages in the first 15 minutes.

Eight more messages are transmitted in 8 minute intervals followed by an additional 7 messages at 15 minute intervals. These follow up messages contain similar information to the first. The system returns to standard transmission after 4 hours of 1-minute real-time transmissions if no further events are detected. In addition to the random channel transmissions, the buoy system continues to transmit using its designated time slot on the assigned GOES channel. These messages will also indicate an event. When there is no acoustic message received from the BPR during the course of an hour the buoy transmits an alternative message indicating its GPS position. This data can be used to troubleshoot if the watch circle of the buoy has drifted outside the transmission cone of the BPR acoustic modem transducer. This same message is transmitted three times a day over the random channel as means in which to test the random channel function and to provide position tracking in the event of a mooring failure.

IV. TRANSITION

A. MOTIVATION

The purpose of transitioning the operation and maintenance of the DART network within NOAA is to maintain, operate and improve the system in a cost effective manner. As a branch of the National Weather Service Office of Operational Systems (NWS-OOS), NDBC has a clear mission of collecting and delivering operational data to make warning and guidance decisions. This is well beyond the scope of PMEL's mission. Additional benefits are:

- Improve Warnings – NDBC will maintain the DART network and provide the necessary 24/7 support for the Tsunami Warning Centers. This level of support is inappropriate for a research laboratory such as PMEL.
- Infuse Technology– This action will transfer a prototype system from a research laboratory to an operational center, enhancing public safety.
- Increase Efficiency – NDBC can assimilate the DART array into its operations and NOAA will gain efficiencies by consolidating platforms, cruises, and technicians.

B. PARTNERS

The Pacific Marine Environmental Laboratory (*www.pmel.noaa.gov*) mission is to conduct interdisciplinary scientific investigations in oceanography and atmospheric science. The Laboratory's strength lies in the experience and knowledge of its scientific and engineering staff and their ability to obtain, process, analyze, and distribute high-quality oceanographic measurements. Current PMEL programs focus on open ocean observations in support of long-term monitoring and prediction of the ocean environment on time scales from hours to decades. Studies are conducted to improve our understanding of the complex physical and geochemical processes operating in the world oceans, to define the forcing functions and the processes driving ocean circulation and the global climate system, and to improve environmental forecasting capabilities and other supporting services for marine commerce and fisheries. Results from PMEL research activities contribute to NOAA's strategic goals of implementing seasonal-to-interannual climate forecasts, assessing and predicting decadal to centennial climate change, advancing short-term warning and forecast services, and building sustainable fisheries. Major programs include:

- TAO Project-Real-time data from moored ocean buoys for improved detection, understanding and prediction of El Niño and La Niña. (*http://www.pmel.noaa.gov/tao/*)
- FOCI Program-(Fisheries-Oceanography Coordinated Investigations)- a joint research program of NOAA's National Marine Fisheries Service to understand the recruitment of Walleye Pollock in the Gulf of Alaska and Bering Sea. (*http://www.pmel.noaa.gov/foci/*)
- VENTS Program- Conducts research on the impacts and consequences of submarine volcanoes and hydrothermal venting on the global ocean. (*http://www.pmel.noaa.gov/vents/home.html*)
- Tsunami Program- seeks to mitigate tsunami hazards to Hawaii, California, Oregon, Washington and Alaska. Research and development activities focus on an integrated approach to improving tsunami warning and mitigation. (*http://www.pmel.noaa.gov/tsunami/*)

The National Data Buoy Center (*www.ndbc.noaa.gov*) originated as the National Data Buoy Development Program within the organization of the United States Coast Guard (USCG) in 1967. This was the result of a consolidation of approximately 50 individual buoy programs. Three years later the National Oceanographic and Atmospheric Administration (NOAA) was formed the organization was renamed to the National Data Buoy Office and placed within the National Ocean Service (NOS). In 1982 the NDBO was moved to the National Weather Service and renamed to the National Data Buoy Center (NDBC). The office is located at NASA's Stennis Space Center (SSC) in Bay St. Louis, Mississippi. During the past three and a half decades, NDBC has maintained a strong operations oriented ocean observation program. Through rigorous data quality control and configuration management practices, NDBC has developed a longstanding reputation for providing dependable and accurate meteorological and oceanographic observations to the public. This reputation has led to other organizations to form partnerships with NDBC to provide marine observations for specialty projects in the past and present. These organizations have included the Mineral Management Services, United States Army Corp of Engineers and the Federal Aviation Administration. Through USCG marine and air support, the National Data Buoy Center presently maintains a fleet of 77 moored buoys and 56 fixed Coastal Marine Automated Network (C-MAN) stations. NDBC has a staff of 169 full time personnel including permanent government staff, rotational Coast Guard billets, and technical services contract personnel. The NDBC facility at SSC includes a complete fabrication and integration shop, electronic testing facility, extensive sensor testing and calibration facilities, quality control infrastructure for data and hardware, and integrated logistics support.

C. TRANSITION PROCESS

The goal of the transition process is to share technology, practices, procedures and lessons learned from the PMEL DART prototyping effort. The transition process was separated into three phases. These are loosely described as a technology familiarization phase, a secondary operational phase in which the PMEL conducted the deployment and recovery activities and the NDBC provided support to gain hands-on experience, and a final operational phase in which the NDBC conducted the deployment and recovery activities and the PMEL was present for technical support.

1) PHASE 1 – TECHNOLOGY MIGRATION

The first phase started in August of 2001 and involved a sharing of information and technology between the two organizations with regards to the DART system. This included the present state of all aspects of the system including drawings, integration and testing procedures, and display of data. During the initial meetings the differences and strengths of an operational oriented organization and a research oriented organization became apparent. PMEL's DART team consists of a relatively small group of engineers and technicians that had intimate knowledge of all aspects of the DART system, including design, calibration, data dissemination and field operations. NDBC's task was to capture this information, both written and oral, and develop it into documentation that could be used by a skilled technician who is unfamiliar with the DART system. Although NDBC and PMEL both had well established and successful buoy programs, these programs developed differently over the years. Along these lines, there were several subtle differences including selection of connectors, specification for mooring components, power systems and maintenance philosophy. Additionally, time would show the extent and depth of the corporate knowledge that PMEL personnel possessed with regards to this system that would need to be captured and documented by NDBC. The documentation process would become a continual effort extending through all three phases.

2) PHASE 2 – HANDS ON EXPERIENCE

This phase began in March of 2002 when a group of engineers and field service personnel from NDBC visited PMEL during the laboratory integration period of the DART buoys. The process continued in June of 2002 when a group of four NDBC personnel joined the PMEL DART team in Kodiak Alaska to embark on the service cruise to perform maintenance on the three AASZ (Aleutian) and two CSZ (West Coast) buoys.

During this cruise the NDBC personnel worked hand in hand with the PMEL personnel to transfer system knowledge and to gain experience (Fig. 3). The servicing of these buoys went well throughout the duration of the cruise. This culminated with NDBC personnel taking the lead on the final servicing and exchange evolution with PMEL personnel providing technical support as necessary. NDBC personnel proved to be quick learners and they were able to successfully achieve this objective. The entire cruise was not executed precisely to the detailed plan. There were a handful of events, although increasing the workload of the cruise, were invaluable to NDBC for gaining knowledge and experience. These events included conducting a bathymetry survey for station relocation, and deploying a new DART mooring due to a buoy going adrift just one day before its scheduled service visit.

The overall hands-on experience brought to the forefront many challenges that NDBC would need to overcome to ensure the future operational success of the DART network. One such challenge involves the strict requirements for selection of a deployment location for a new station. This will require special consideration when selecting a vessel to perform the service of the systems. In this respect, the USCG vessels that NDBC presently employs do not have the necessary equipment to provide an accurate bathymetry of the seafloor in the depth of water in which the DART systems are deployed. The management of the work deck during recovery and deployment operations was a relatively new function for the NDBC personnel and will require future training. Additionally, the PMEL philosophy of DART system refurbishment at sea in a 'leap frog' manner is different than present NDBC process and thus require changes in logistics.

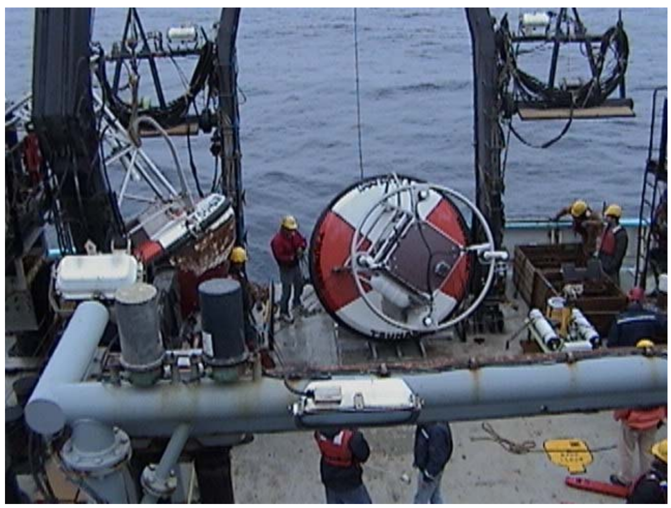

Fig. 3 Joint PMEL/NDBC mooring cruise on R/V EWING

3) PHASE 3 – OPERATIONAL RESPONSIBILITY

This final phase of the transition process involved distilling the information and experience obtained from the first two phases and incorporating them into detailed procedures and drawings. In addition to this, NDBC integrated the real-time data received from the DART stations into its own web site. During this phase, NDBC prepared for the next AASZ and CSZ cruise in May/June of 2003 and PMEL continued to provide expert technical assistance and guidance.

One of the main foci of this phase was for NDBC to be able to capture and document the configuration of the existing DART system. Detailed drawings were developed for all mechanical and structural components, cable assemblies, electronic assemblies, and mooring diagrams. These were produced to NDBC configuration control standards to allow third party quality control verification following fabrication or integration. During this process, PMEL played a critical role in answering questions to complete the details of the drawing and providing additional corporate knowledge to further increase the quality of the documentation.

In conjunction with the above activities, NDBC personnel were drawing from experiences on the past cruise to adapt and develop procedures for testing and integration of the individual components and the system as a whole. This involved working with PMEL technical personnel to adapt their existing procedures and capturing additional corporate knowledge. These procedures were able to receive and initial test in January of 2003 when NDBC supplied the technician to work the Equatorial DART station. With thorough technical support from PMEL, the technician was able to extensively troubleshoot the BPR at this station and ensure that the node remained in an operational status.

In a parallel effort, the NDBC information technology staff incorporated the DART station configuration data and the automated processing of the DART messages into the real-time data processing systems, the NDBC Enterprise Management Information System (NEMIS) and the NDBC web site. NDBC's enterprise system uses the Oracle Relational Database Management System (RDBMS) to store all operational station data, including configuration metadata, processing, parameter control, and equipment and resource management. Through this system, NDBC applies an integrated automated process to station configuration management, inventory control, property tracking, shipping and receiving, work control, and equipment reliability. This database is also a key component of the automated data quality control process developed by NDBC. The DART data was also incorporated into the NDBC web site (*www.ndbc.noaa.gov/dart.shtml*) which provides automatically updated data on a continuous basis to the general public. To ensure that the displayed data would meet the high standards set by the original PMEL web site and to meet the operational requirements of the NWS Tsunami Warning Centers, the NDBC staff worked closely with PMEL and scientific personnel. Historical data back to January 1, 2003 is presently available for viewing and download via the NDBC web site.

Preparations were started for the May 2003 R/V KILO MOANA service cruise, began in September 2002. Discussions took place with the University of Hawaii personnel on deck gear, configurations and cruise logistics. To improve buoy operations, A-frame modifications and the fabrication of a roller chalk were recommended. NDBC, with PMEL guidance assembled and tested two complete DART systems and fabricated and procured necessary spare components.

The final tasks involved with assuming operational responsibility of the DART network were adapting existing NDBC logistical and quality control support process to include the DART buoys. The first step was to identify a set of components in the DART system to be designated as Line Replaceable Units (LRU). These LRUs are comprised of individual components and assemblies of components. With these designations, the performance of the LRUs will be tracked in an NDBC reliability database. This should add significant value to the DART program in the future years by identifying components prone to failure and providing a solid basis for requesting an engineering and configuration changes. Once the type of LRU was established, then minimum and maximum stock levels for these components were determined and incorporated into the automated tracking and ordering capability of the enterprise database. In addition, similar stock levels were established for consumable components such as connectors, mooring line, etc. By establishing these stocking limits, NDBC will be able to react more efficiently to the availability of vessels of opportunity in the event of a system failure or a maintenance scheduling change.

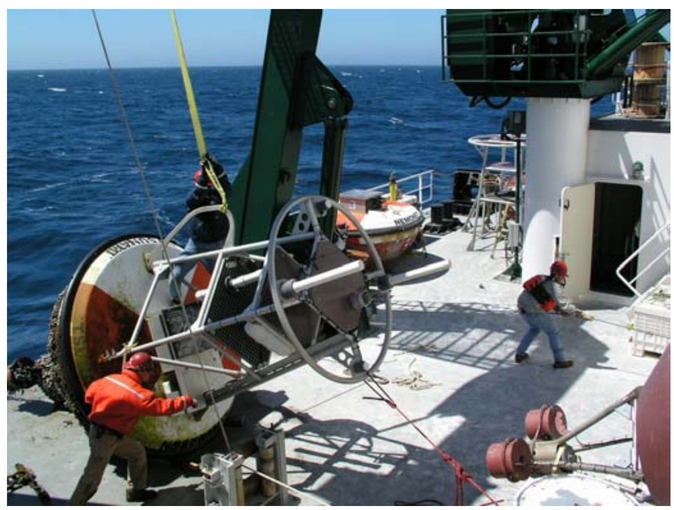

Fig. 4 NDBC working a DART buoy on R/V KILO MOANA

The operational field activities met a successful culmination in June of 2003 when NDBC and PMEL personnel completed the North Pacific DART service cruise aboard the R/V KILO MOANA. NDBC was able to successfully service and refurbish four of the five DART stations in this region with the PMEL personnel providing technical assistance as needed. One buoy could not be serviced due to severe weather. During the initial portion of this cruise NDBC personnel received deck training focusing on recovering and deploying DART buoys in a safe and efficient manner. Following this initial training the NDBC personnel were able to perform these tasks with R/V KILO MOANA Captain and crew to ensure the success of recovery and deployment operations (Fig 4). Additionally, NDBC personnel worked independently to service the recovered buoys that resulted in a successful cruise.

V. FUTURE DEVELOPMENT AND OPERATIONS

The future of the DART network collaboration maintains PMEL as the engineering and developmental lead and NDBC will maintain operational responsibility for the network. Along these lines as new requirements are developed by the Tsunami Warning Centers they will under go a design process at PMEL. This process includes the initial assessment of the technical feasibility of the request followed by laboratory and prototype testing. Through this development period NDBC and other related partners will provide technical feedback and evaluate the extent of operational impact. Once this hardware or software has been proven in prototype format it will be transitioned to an operational status. This will require a similar process as the discussed DART system transfer, with NDBC first gaining some hands-on hands on experience, followed by documenting the configuration and developing procedures, and finally integrating it into the operational system (Fig. 5).

This process will be critical in the near future due to existing technical obsolescence of some of the key components of the system. Most pressing is a next-generation acoustic modem and GOES transmitter. Fortunately, testing and replacing these key components has already been addressed by PMEL with the design of the next-generation DART system. This configuration was recently deployed on the last DART cruise near existing DART station 46404-D128. The next-generation system uses a hybrid high data rate GOES transmitter and an Iridium dial-up connection in lieu of the obsolete 100 baud GOES transmitter. It also uses the next generation Benthos ATM 880 acoustic modem circuitry. Additionally, the internal electronics have been redesigned to a 3.3 volt system that will allow greater capability with reduced power consumption and is expected to extend the time between services to twice the existing level. In addition to critical changes resulting from obsolescence, PMEL and NDBC will investigate the feasibility of integrating NDBC meteorological measurements on DART buoys. This will require a collaborative effort similar to the one described above. Presently, there are two sets of DART and NDBC weather buoys that coexist within a few miles of each other and it is anticipated that significant resources can be saved.

Further challenges that face NDBC, PMEL and the TWC are data display and archiving. The initial focus of the NDBC information technology staff was on duplicating the web data dissemination capabilities originally available through the PMEL web site. With this in place, additional information and features will be added to the web pages over the next year to provide station operational data and high resolution analytical data to the warning centers, PMEL and NDBC to support maintenance of the stations and analysis of the triggered events. Specifically, the unparsed, raw data message will be made available online for use in validating tsunami events and troubleshooting data stream problems. There is also a need for online access to the buoy housekeeping data that will be translated into engineering units for use in troubleshooting data stream problems. A one-time analysis of time series data for each station to obtain the harmonic constants necessary to remove the tidal factor from the event data will be completed by PMEL. Once the algorithms have been developed that use the harmonic constants derived to predict the tidal elevation, NDBC will apply the algorithms to the event data that is displayed on the web. With the introduction of the Iridium dial-up connection as a replacement of the 100 baud GOES transmitter, the NDBC real-time data processing will also be updated to support the high data rate transmissions.

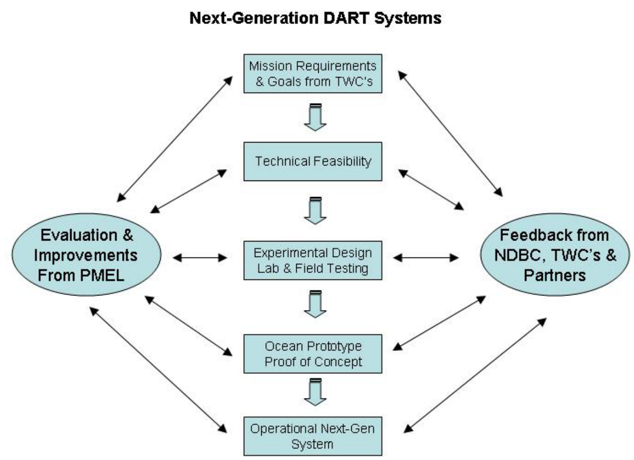

Fig. 5 Future NDBC/PMEL DART System Development

Other tasks involve training additional NDBC personnel on safe and efficient deck operations. This task has been typically performed by the crew of the Coast Guard vessel that was supporting the NDBC operation with the guidance of an NDBC assigned USCG warrant officer. This task coincides with the challenge of finding appropriate serving platforms for the DART stations. NDBC has traditionally utilized USCG vessels while PMEL has employed NOAA, UNOLS and other contract vessels. With these non-Coast Guard vessels comes a greater variety of equipment and capability of crew. These trained personnel will need to make evaluations of vessels when they are contracted to service the DART buoys and from that make determinations as to what additional equipment or modifications will need to be made to ensure a safe and successful cruise. This same evaluation of equipment will also need to be conducted to evaluate the potential of conducting service visits from Coast Guard vessels. The technical interchange between PMEL and NDBC will be essential to the successful future of the DART program.

ACKNOWLEDGMENT

The DART network is sponsored and funded by the National Tsunami Hazard Mitigation Program. The transition process is directed and supported by the directors of PMEL, Dr. Eddie Bernard, and of NDBC, Dr. Paul Moersdorf. The views expressed in this paper are those of the authors and do not necessarily represent those of the National Oceanic and Atmospheric Administration.

REFERENCES

[1] H. Milburn, A. Nakamura, and F. Gonzales, "Real-time Tsunami Reporting from the Deep Ocean", *Oceans 96 MTS/IEEE Proceedings*, Fort Lauderdale, FL, September 1996.

[2] F. Gonzales, H. Milburn, E. Bernard, and J. Newman, "Deep-ocean Assessment and Reporting of Tsunamis (DART): Brief Overview and Status Report", *International Workshop on Tsunami Disaster Mitigation Proceedings*, Tokyo, Japan, January 1998.

[3] M. Eble, F. Gonzales, "Deep-ocean Bottom Pressure Measurements in the Northeast Pacific", *Journal of Atmospheric and Oceanic Technology*, 8(2), 221-233.

[4] H. Mofjeld, "Tsunami Detection Algorithm", unpublished.

[5] C. Meinig, M. Eble, and S. Stalin, "System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997-2001", *ITS 2001 Proceedings*.