History and Future of Deep-Ocean Tsunami Measurements

Eddie N. Bernard, Scientist Emeritus
National Oceanic and Atmospheric Administration /
Pacific Marine Environmental Laboratory
Seattle, WA USA
Eddie.Bernard@comcast.net

Christian Meinig
National Oceanic and Atmospheric Administration /
Pacific Marine Environmental Laboratory
Seattle, WA USA
Christian.Meinig@noaa.gov

Abstract—**The history of the development of real-time measurements of tsunamis in the deep ocean for the purpose of forecasting coastal tsunami impacts will be presented, with early history to include the various instruments tested to determine IF tsunamis could be measured in the deep ocean. The measurement of pressure changes induced by the tsunami required a high resolution pressure sensor installed on the seafloor, to provide a motionless environment that allowed the ocean to filter out higher frequency ocean waves. Instruments included bourdon tubes and vibrating crystals that rested on the seafloor and used the depth of the ocean as a pressure reference. Once deep ocean measurements were deemed possible, testing and evaluation was used to identify which technology was accurate, affordable, and reliable enough to be used for tsunami forecasting under tsunami warning conditions. National Oceanic and Atmospheric Administration (NOAA) had completed the research and development, including an operational prototype, by October of 2003, when the technology was transferred to NOAA operations. The first generation Deep-ocean Assessment and Reporting of Tsunamis (DART I) array consisted of six stations strategically located off Alaska, Oregon, and near the equator to detect tsunamis originating in the Chile/Peru area. The original DART array demonstrated its value within four months by measuring a small tsunami originating in Alaska and relaying these data to NOAA's Pacific Tsunami Warning Center in real time. The tsunami data indicated a nondestructive tsunami had been generated and evacuation of Hawaii's coastline was unnecessary, saving the cost of a nonessential evacuation.**

The December 2004 Indian Ocean tsunami, which killed over 235,000 people, led to the development of the second generation system, named DART II because of the two-way communication link from seafloor to desktop. Another impact of this horrific tsunami was the appearance of many technologies that were touted as being able to detect tsunamis in the deep ocean. Satellite-based technologies, radar-based technologies, and acoustic-based technologies were identified as tsunami detection technologies. However, these technologies could not measure tsunamis as accurately, reliably, and within time constraints required to forecast tsunamis in real time. The pressure-measurement-based DART technology prevailed as the most affordable and accurate technology to measure tsunamis for real-time forecasting. By 2008, NOAA had expanded the original DART array from 6 to 39 stations in the Pacific and Atlantic oceans. Because the U.S. wanted to make this technology available to all nations, NOAA licensed the patents for the technology and a commercial DART was manufactured by a U.S. private company that currently provides DART technology to foreign countries. Meanwhile, NOAA continued to make improvements to the original design, reducing operating costs and improving reliability. By 2010, over 40 tsunamis had been measured using DART technology and the third generation DART system had become a part of the operational global array. The DART ETD (Easy to Deploy) is more affordable and does not require large ships or highly specialized crew to deploy and maintain the operational arrays. These new developments in DART technology hold promise for a global network of DART stations supporting a standardized global tsunami warning system.

Keywords- tsunami detection; tsunameter; real-time tsunami measurements; tsunami detection history; DART.

Early History of Tsunami Detection

The rationale for placing bottom pressure stations in the open ocean for observing tsunamis and reporting these data in real time to tsunami warning centers was put forward by [1] and [2]. Such stations could be placed near potential tsunami sources and thereby report direct tsunami measurements, often hours before the tsunamis impacted major coastal communities. Bottom pressure sensors could be used to measure tsunamis because tsunamis are barotropic gravity waves with wavelengths much longer than the ocean depth. As such, these waves have bottom pressure fluctuations directly proportional to the time-varying sea surface elevation induced by the tsunamis as they propagate over the station. Observing tsunamis in the open ocean has the added advantage that measurements are made before tsunamis encounter the complicating effects of the continental shelf and the coastal region, as well as the resonance effects in bays and harbors. Deep-ocean measurements permit a more straightforward interpretation of tsunamis to accurately forecast coastal impacts of the tsunami [3], [4].

The technology to make precise observations of bottom pressure in the deep ocean was developed in the 1960s and 1970s. Much of this early development focused on overcoming a host of instrumental problem associated with making precise pressure observations at the bottom of the deep ocean (e.g., high pressure, temperature influence, instrumental drift, frequency instability, power supply, data storage, aliasing, instrument retrieval, etc.). A host of scientists contributed to the development of the deep-sea capability using a variety of different pressure sensors and instrument platforms (e.g., [5], [6]). After retrieving an autonomous pressure recorder deployed in deep water near the entrance to the Gulf of California, Filloux ([7], [8]) discovered that the instrument had recorded a small tsunami generated by the March 14, 1979 Petatlan earthquake off the nearby Pacific coast of Mexico. By analyzing the tsunami time series in the bottom pressure record, he obtained more detailed information about the tsunami and found that a simple shelf resonance of the continental shelf was not consistent with the observed characteristics of the tsunami. He also correctly identified background noise as apparent pressure fluctuations caused by seismic surface (Rayleigh) waves from the earthquake source area.

I. From Tsunami Detection to Operational Prototype

Through the 1980s, the development of autonomous tsunami instruments for the open ocean accelerated. This effort was carried out by NOAA's Pacific Marine Environmental Laboratory (PMEL) with the goal of creating a network of real-time reporting bottom pressure systems to improve tsunami forecasting [9], [3]. Pilot projects were carried out in the Gulf of Alaska using internally recording bottom pressure recorders (BPR) and several tsunamis were recorded in the late 1980s. This was also the first time that high-resolution tsunami models were used together with bottom pressure measurements to study the potential for forecasting tsunami effects [10].

Once the use of deep-ocean tsunami measurements to forecast tsunami coastal impacts was established, PMEL took the first important step with the development and field testing of the first generation of real-time tsunami detection systems, named "tsunameters" (Fig. 1), and the successful establishment of a Pacific network [11], [12]. Development of an operational tsunameter was an extraordinary accomplishment, and a real-time operational network was a powerful catalyst for the paradigm shift in tsunami research and forecasting, away from indirect observations and toward direct, high-quality measurements and analyses of the tsunami itself.

The task was to design, develop, test, and deploy real-time reporting, deep-ocean tsunameters capable of surviving a hostile ocean environment while performing with the quality and reliability demanded of an operational tsunami warning system on which so many lives depend. The PMEL tsunameter project was initiated to meet this challenge, using a set of criteria to accurately measure and then report these data in near real time to assimilate into forecast models. No such system had ever been developed [3].

The overall effort, which began in 1996, was remarkable in scope. The tsunameter system (Fig. 1) termed Deep-ocean Assessment and Reporting of Tsunamis (DART) was composed of four integrated subsystems. The first subsystem was the BPR. The sensor in the BPR was a Paroscientific, Inc. model 4, 10K, 0–10 000 psia piezoelectric Bourdon tube sensor that showed very stable characteristics and high signal-to-noise ratios. The sensor, along with a very low power frequency counting circuit board, had been used in PMEL self-recording BPRs for years with a least-bit resolution of 0.00035 psi or 0.25 mm of water [13].

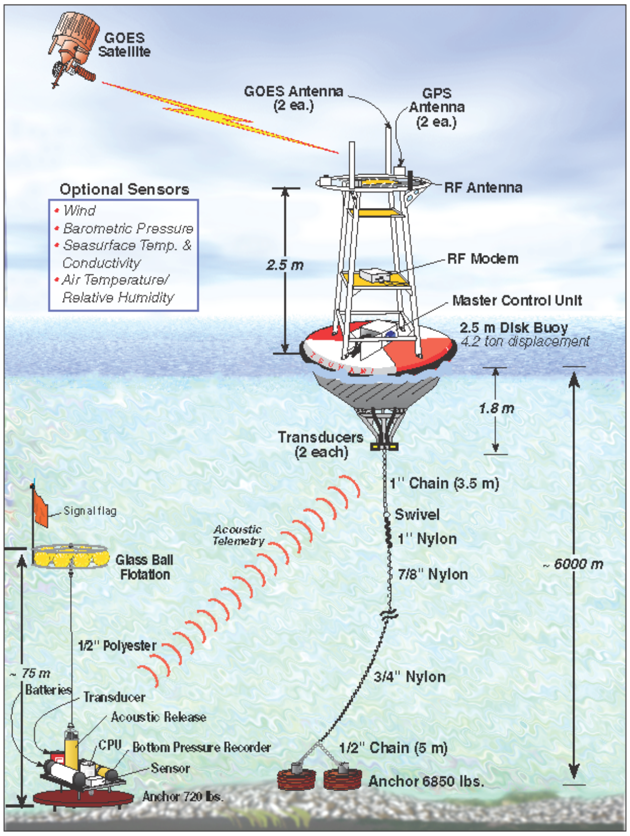

Figure 1. The first generation NOAA tsunameter, Deep-ocean Assessment and Reporting of Tsunamis (DART), illustrating the four major components that had to be integrated into a single system.

The second subsystem was an acoustic link to a third subsystem, a surface buoy, equipped with a fourth subsystem, a micro-computer with satellite telecommunications capability (Fig. 1). In September of 1997, the first successful deployment of an integrated tsunameter system provided a three-month record off the Oregon coast, and by 1999, a three-station array was transmitting data from seafloor to desktop with a return rate of 97%, significantly higher than the original goal of 80% [11].

The research and development effort for implementing the prototype array in 2001 used eight different ships on 18 different expeditions totaling about 100 days at sea, and included more than 25 PMEL engineers, technicians, and scientists. The total R&D effort included individuals from more than 85 partner firms and suppliers at a cost of approximately $6 M over five years [3].

Due to the importance of tsunami data in responding to destructive tsunamis, these data had to be available in real time to the NOAA tsunami warning centers. In addition, it was essential to share these data globally so other nations could take appropriate actions. An emerging technology that met the real time and global distribution requirements was the internet. A web-based data sharing system was developed for public and scientific distribution as part of the prototype DART system. In "standard mode," each DART system reports every 6 hr a set of pressure values spaced every 15 min [12]. When attached to previous values and plotted in sequence over a few days, the result is a time series of pressure (Fig. 2) that is dominated by the tides. These data, and those obtained during tsunami events (Fig. 2), are processed and made publicly available by the NOAA/National Data Buoy Center (NDBC) as preliminary data; the Center also has the responsibility of deployment and maintenance of the U.S. DART Network (see Section 3). Such plots (Fig. 2) provide an operator and staff at tsunami warning centers throughout the world, with an immediate check on a system to verify if it is operating within specifications, based on a comparison with predicted tides for that station. The "event mode" provides plots of the tsunami at 1-min data rates to rapidly evaluate the amplitude of the tsunami in the deep ocean.

II. DOMESTIC APPLICATIONS: TRANSITION DART TO NOAA OPERATIONS

A two-year transition period was required to transfer responsibility of the array from research (NOAA/PMEL) to operations at NOAA's NDBC, including the network maintenance and real-time data distribution. 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 at-sea experience, and a final operational phase in which the NDBC conducted deployment and recovery activities while PMEL specialists were present for technical support [14]. The operational field activities met a successful culmination in June of 2003 when NDBC and PMEL personnel completed a 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. By 2008, NOAA had received a Presidential supplement that expanded the original DART buoy array from 6 to 39 stations in the Pacific and Atlantic oceans (Fig. 3).

III. FIRST REAL-TIME TEST: ALASKA 2003

The NOAA tsunameter was developed in response to the high priority assigned by the Pacific states to "...quickly confirm potentially destructive tsunamis and reduce false alarms." A single false alarm was estimated by the state of Hawaii to cost $60 M in economic impact, in addition to untold costs in the loss of warning system credibility [12].To this end, even without sophisticated forecasting tools, the immediate value of the network is clear—tsunameter records, especially those acquired directly seaward of the source, can help verify the existence or absence of destructive tsunami energy propagating toward communities. The first test came on November 17, 2003, approximately four months after the network was established. A Ms 7.5 magnitude earthquake occurred on November 17, 2003 at 06:43 UTC. In this case, a warning was issued for Alaska at 07:07 then cancelled at 08:12, shortly after a tsunameter registered maximum deep-ocean tsunami amplitude of 2 cm [15]. Costly and potentially hazardous evacuations of Alaskan and Hawaiian coastal communities were averted. Additionally, this test showed that tsunamis < 3 cm in the deep ocean (a typical threshold for self triggering) caused some damage on the north shore of Oahu, Hawaii. The first generation DART system needed to be modified to provide two-way communications to and from the BPR and the warning centers.

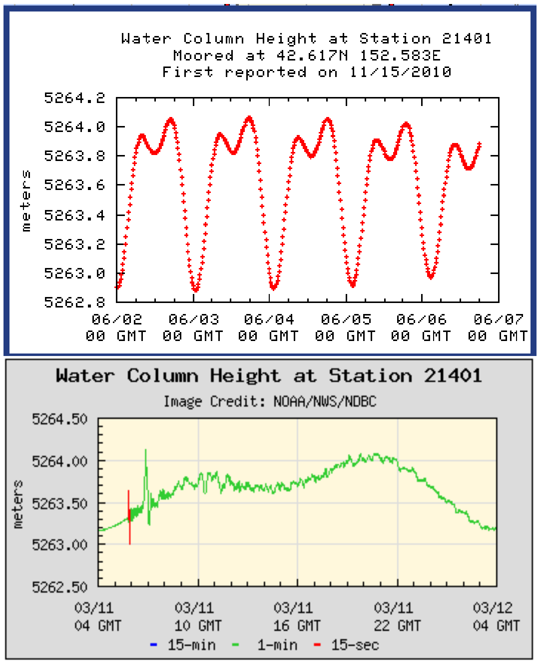

Figure 2. Typical bottom pressure (converted to equivalent water depth) time series of a DART system in standard mode (top panel) and event mode for the March 11, 2011 Japanese tsunami (bottom panel). Data are transmitted via the Iridium satellite system to shore for processing and displayed at http://www.ndbc.noaa.gov/dart.shtml.

IV. 2004 INDIAN OCEAN TSUNAMI LEADS TO SECOND GENERATION DART AND EVALUATION OF ALTERNATE TECHNOLOGIES

Following the deaths of over 235,000 people in the December 2004 Indian Ocean tsunami, NOAA/PMEL accelerated the development of two-way communications between the BPR and the warning center. DART II incorporated several features to improve the system:

1) *Data and trigger request.* Enhancements enabled the tsunami warning centers to request high frequency data at any time during the tsunami event, giving operations flexibility in tracking the evolution of the hazard. Historical data could also be requested via command.

2) *Remote problem diagnosis.* DART II operators could reboot the computer system on the seafloor, change threshold triggering height, and request engineering values by remote command. These remote diagnostic features have been used many times in the maintenance

of the DART II array and saved significant ship servicing costs.

3) *Iridium satellite.* By switching from GOES to Iridium satellite communications, this system was able to be globally deployed on a common set of communication standards.

4) *Endurance.* The upgraded electronics doubled the endurance of deployed systems to two years for the surface buoys and four years for the BPRs.

After the December 2004 Indian Ocean tsunami, many technologies were touted as being able to detect tsunamis in the deep ocean. Satellite-based technologies (including altimeters, scatterometers, and differential GPS), radar-based technologies (including over the horizon radars and CODAR), and acoustic-based technologies (including hydrophones and seismometers) were identified as tsunami detection technologies. By applying the following requirements for real-time tsunami forecasting:

1) Measurement type: amplitude over time
2) Accuracy: 0.5 cm
3) Sample rate: <1 min
4) Processing speed: within 2 min
5) Availability: within 5 min, globally

Only one technology could measure tsunamis accurately, reliably, and within time constraints required to forecast tsunamis in real time. Table 1 illustrates that DART technology is able to meet all five requirements and identifies the limitations of other tsunami measurement technologies.

TABLE I. COMPARISON OF REQUIREMENTS FOR TSUNAMI FORECASTING WITH TECHNOLOGIES. BLUE CHECK INDICATES MEETING REQUIREMENT, WHILE X INDICATES NOT MEETING REQUIREMENT

Tech / Criter	**Type**	**Accuracy**	**Rate**	**Processing**	**Availability**
DART	✓	✓	✓	✓	✓
GPS Buoy	✓	×	✓	✓	×
CODAR	×	×	×	×	×
Sat. Altimeter	✓	×	✓	×	×
Sat.Scatt.	×	×	×	×	×
ADCP	×	×	×	×	×
E/M voltage	×	×	×	×	×
Acoustic	×	×	✓	×	×
Cabled BPR	✓	✓	✓	✓	×

Joseph [16] assessed the challenges of measuring tsunamis in the deep ocean and reporting these data in real time. He concluded on page 252 that "these and the preceding challenges indicated are met by the real-time DART system implemented by NOAA."

The DART II technology has prevailed as the most affordable and accurate technology to measure tsunamis for real-time forecasting. By 2008, NOAA had expanded the original DART array to 39 DART II stations in the Pacific and Atlantic oceans [17]. Also, the international community was encouraged to share tsunami data and to share the costs of maintaining a global array of standardized stations capable of detecting tsunamis in the deep ocean (Fig. 3). Eight countries have deployed and maintained DART technology to date in the Pacific, Atlantic, and Indian oceans.

V. INTERNATIONAL APPLICATIONS: PATENT, STANDARDS, AND COMMERCIALIZATION

Following the 2004 Indian Ocean tsunami, NOAA/PMEL decided to protect the DART II technology by patenting the invention. A patent ensures that the U.S. government would not be subjected to restrictions, should someone else patent the technology. A patent also allow licenses to be issued to industry by NOAA/PMEL. Licensees are subject to annual review on several criteria, including production quality and system performance, which are vital for integrity of a warning system. A patent was filed on May 20, 2005 and was granted on October 30, 2007 (U.S. Patent 7,289,907). A trademark was also registered to the "DART Tsunami Technology"® mark. To allow any company to apply for a DART patent license, the DART II systems characteristics [18] and application forms are posted on the internet, available at http://nctr.pmel.noaa.gov/Dart/index.html. Based in large part to this posting, the DART II design or other similar commercial versions, has become standardized through the adoption of this description/performance by the United Nations' International Tsunameter Partnership [19].

Tsunameter station characteristics include:

1) Required Sampling:

- 15-min samples with 6 hr or less reporting frequency in standard mode
- < or = 1-min averages with < 5 min reporting frequency in event mode, once triggered
- Trigger thresholds and activation protocols need agreement between regional and national tsunami service providers and tsunameter operators

2) Communication:

- Standard mode/event mode reporting
- Data shared in real time on Global Telecommunication System (GTS)
- Two-way communications for manual triggering and system status checks
- Reporting delay from seafloor to warning center < 3 min

3) Formats:

- Standard format for transmission to GTS

4) Data Quality and Analysis:

- Real-time quality control procedures
- Procedures for capturing tsunameter data, analyzing processing and evaluating the tsunami signal in an appropriate modeling environment

5) Redundancies:

- Power, processing, and communication in surface buoy

Although several companies have applied for licenses, only Science Applications International Corporation (SAIC) has been licensed to date to produce a commercial tsunami assessment system built to a set of DART-published standards. In 2007, the SAIC tsunami team successfully completed a one year at-sea test, and data were independently evaluated by NOAA as meeting or exceeding operational performance criteria established for DART II system [20]. SAIC has supplied DART systems and components to Australia, Thailand, India, China, Chile, and Russia, and is recognized as a global provider of reliable tsunami deep-water detection systems.

VI. THIRD GENERATION DART TECHNOLOGY: REDUCES TOTAL COSTS

Over the last five years, PMEL has continued to invest in the development of a third-generation tsunameter, called the DART Easy-to-Deploy (ETD) buoy (http://www.pmel.noaa.gov/pico/). The DART ETD incorporates a number of technical improvements to increase endurance, decrease production costs, and greatly decrease deployment costs (Fig. 4). Technical innovations in the mooring line resulted in an additional patent (U.S. Patent 7,244,155). The detection technology, data format, and communication protocols are completely backward compatible, to allow full integration into the warning centers and forecast models. PMEL has made over 15 test deployments over the last several years, including deployments in the challenging conditions of the Gulf of Alaska and the Tasman Sea. Additionally, DART ETD systems have been deployed for extended durations in the Tasman Sea and the Fiji Basin in a joint test with the Australian Bureau of Meteorology (AUS-BOM). AUS-BOM has been a key partner in this development effort, providing deployment opportunities, data sharing, and operational feedback during the prototype stage of the development.

During a two-year endurance test in 2007, PMEL performed a side-by-side test with an operational DART II buoy system off the coast of Hawaii The DART ETD was put through the same operational tests and held to the same performance criteria that the DART II buoy system was subjected to during its independent test. The DART ETD was found to meet or exceed DART II operational performance criteria under all conditions, including measuring a small tsunami [20].

Given SAIC's success in providing and deploying tsunameters for the international community, PMEL agreed to work with SAIC to accelerate the development of the ETD from a research and development project into a fully operational commercial system. Through licensing and a special studies agreement, PMEL worked with the SAIC team in San Diego, California, and completed a multiphase transition program that took over one year to complete. In 2010, SAIC produced the first three commercial SAIC ETD DART systems.

The first system was deployed in the Coral Sea by AUS-BOM on August 27, 2010, and was declared operational by AUS-BOM several days later. The Coral Sea DART ETD has performed exceptionally since then, including surviving a direct strike by super-cyclone Yasi and detecting the Honshu tsunami wave on March 11, 2011 [21]. The second SAIC DART ETD systems were deployed in the Tasman Sea in April of 2011, and the third system is scheduled for an Indian Ocean deployment later in 2011.

VII. SUMMARY AND FUTURE

From initial funding in 1996 to the present, a $10 M research and development effort has led to the invention of three generations of real-time deep-ocean tsunameters that have provided deep-ocean data from over 40 tsunamis. Fig. 5 shows a timeline of DART technology over 15 years. These tsunami data have been used to accelerate the verification and validation of tsunami forecast models that are now capable of forecasting tsunami time series and flooding at coastal communities with 80% accuracy. Accurate tsunami forecasts have improved public response to tsunamis by avoiding false alarms (i.e., 2009 Samoan tsunami) and advising appropriate evacuations (i.e., 2011 Japan tsunami).The economic benefit to Hawaii from more accurate tsunami forecasts has been the avoidance of at least three unnecessary evacuations (estimated cost avoidance of $200 M) and the saving of lives during the 2011 Japan tsunami evacuation. During this same time period, two generations of DART technology has been transitioned to NOAA operations and has been made available to the international community through a NOAA license agreement with a Fortune 500 company. This international partnership is working. For example, real-time tsunami data from a commercial DART II, purchased by Russia in 2010, was used in the U.S. tsunami forecast for the 2011 Japan tsunami (Station 21401 in Fig. 2 is Russian-owned).

The future looks bright as the third generation DART ETD systems are more affordable and do not require large ships or highly specialized crew to deploy and maintain the operational arrays. These new developments in DART technology hold promise for a global network of standard DART stations supporting standardized global tsunami warning systems. The global array currently consists of two generations of commercial and U.S. government-built systems that are built to a set of communication standards for ease of data integration into tsunami forecast systems. This global array will record more tsunamis allowing tsunami research to progress rapidly. As described by [19], a forecasting framework for research will preserve discoveries in forecast operations so that "reinventing the wheel" in research will be minimized. If research joins the forecasting framework concept, future improvements will be possible using improved and different technologies that are tested in a standardized forecasting environment. A measure of success would be to hear a debate on the statement "My technology improved the tsunami forecast!" rather than the present statement: "My technology is better than your technology!"

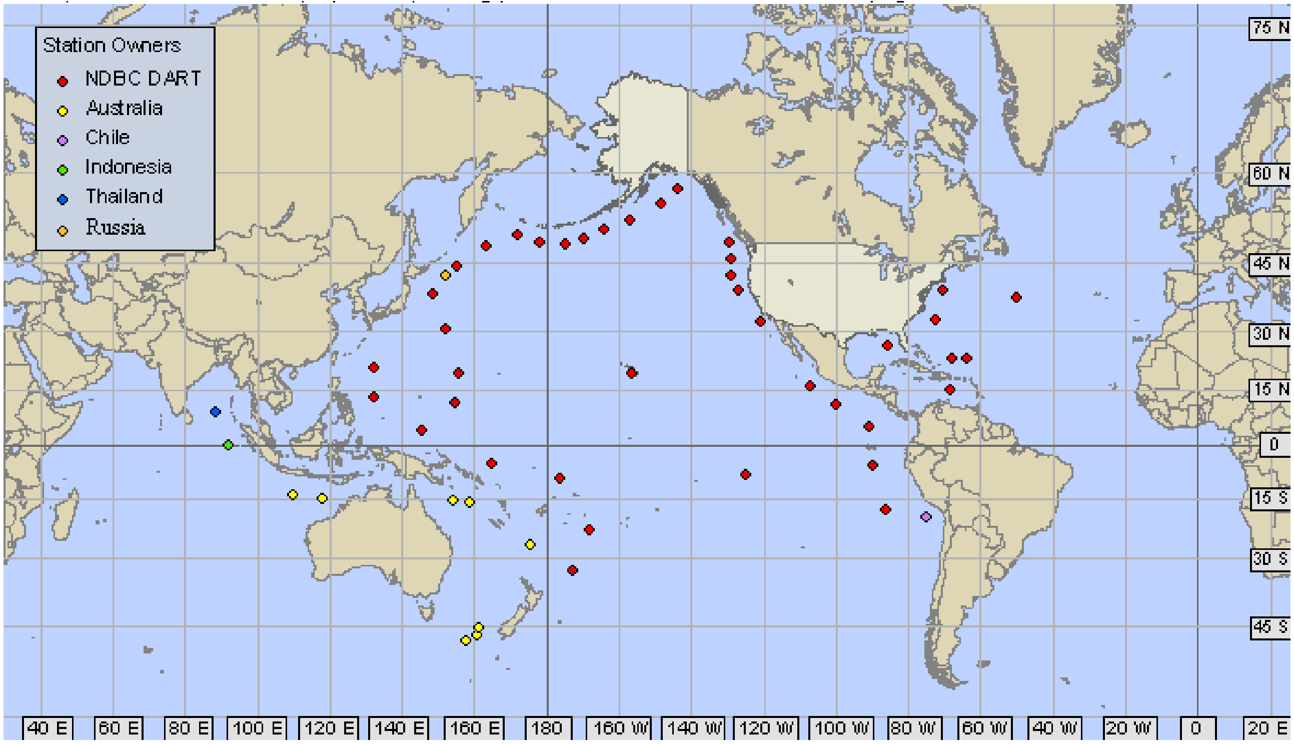

Figure 3. The present global DART network providing bottom pressure observations of tsunamis in the open ocean to tsunami warning centers and the research community.

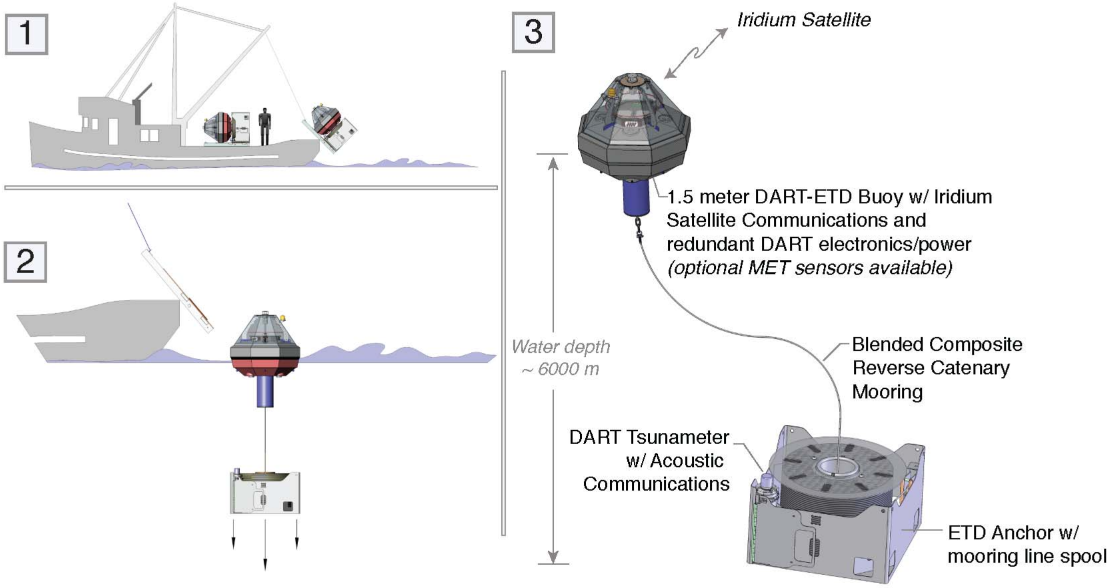

Figure 4. Third generation DART system: easy-to-deploy (ETD) deployment.

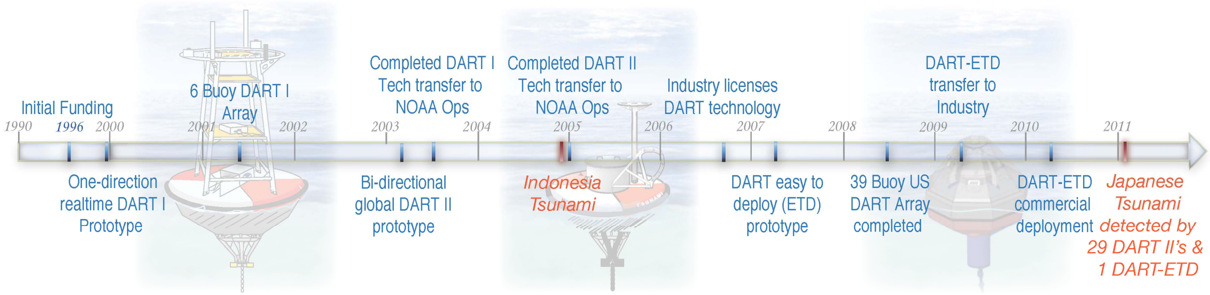

Figure 5. DART technology timeline.

ACKNOWLEDGMENTS

This research was supported by NOAA's Pacific Marine Environmental Laboratory. The authors wish to thank all the personnel that spent long and arduous days at sea developing and operating DART systems. We also acknowledge the engineering excellence of Hugh Milburn who accepted the initial challenge of detecting tsunamis in the deep-ocean.

References

[1] A. Zielinski and N. Saxena,. "Rationale for measurement of midocean tsunami signature. Mar. Geodesy," vol. 6(3-4), pp. 331–337, 1983.

[2] A. Zielinski and N. Saxena, "Tsunami detectability using open-ocean bottom pressure fluctuations," IEEE J. Oceanic Eng., vol. OE-8(4), pp. 272–280, 1983.

[3] E.N. Bernard, F.I. González, C. Meinig, and H.B. Milburn, "Early detection and real-time reporting of deep-ocean tsunamis," in Proceedings of the International Tsunami Symposium 2001, Seattle, WA, 7–10 August 2001, pp. 97–108.

[4] H. O. Mofjeld, "Tsunami measurements," Chapter 7 in The Sea, Volume 15: Tsunamis. Cambridge and London: Harvard University Press, 2009, pp. 201–235.

[5] M. J. Vitousek, An evolution of the vibrotron pressure transducer as a mid-ocean tsunami gage. Hawaii Inst. Geophys., HIG-65-13, Univ. Hawaii, 1965, 12 pp.

[6] J. H. Filloux, "Bourdon tube deep sea tide gauges," in Tsunamis in the Pacific Ocean. Honolulu: University Press, 1970, pp. 223–238.

[7] J. H. Filloux, "Tsunami recorded on the open ocean floor," Geophys. Res. Lett., vol. 9, pp. 25–28, 1982.

[8] J. H. Filloux, "Pressure fluctuations on the open-ocean floor off the Gulf of California: tides, earthquakes and tsunamis," J. Phys. Oceanogr., vol. 13, pp. 783–796, 1983.

[9] M. C. Eble and F. I. González, "Deep-ocean bottom pressure measurements in the Northeast Pacific," J. Atmos. Ocean. Tech., vol. 8(2), pp. 221–233, 1991.

[10] F. I. González, C. L. Mader, M. C. Eble, and E. N. Bernard, "The 1987–88 Alaskan Bight Tsunamis: Deep ocean data and model comparisons," Special Issue on Tsunami Hazard, E. N. Bernard, Ed., Nat. Hazards, vol. 4(2,3), pp. 119–139, 1991.

[11] C. Meinig, M. C. Eble, and S. E. Stalin, "System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997–2001," in Proceedings of the International Tsunami Symposium 2001 (ITS 2001), NTHMP Review Session, R-24, Seattle, WA, 7–10 August 2001, (on CD-ROM), pp. 235–242.

[12] F. I. González, E. N. Bernard, C. Meinig, M. Eble, H. O. Mofjeld, and S. Stalin, "The NTHMP tsunameter network," Nat. Hazards, vol. 35(1), Special Issue, U.S. National Tsunami Hazard Mitigation Program, pp. 25–39, 2005.

[13] H. B. Milburn, A. I. Nakamura, and F. I. González, "Real-time tsunami reporting from the deep ocean," in Proceedings of the Oceans 96 MTS/IEEE Conference, Fort Lauderdale, FL, 23–26 September 1996, pp. 390–394.

[14] B. Taft, C. Meinig, L. Bernard, C. Teng, S. Stalin, K. O'Neil, M. Eble, and C. Demers, "Transition of the Deep-ocean Assessment and Reporting of Tsunamis network—A technology transfer from NOAA Research to NOAA Operations," in Proceedings of Oceans 2003, San Diego, CA, September 2003, pp. 2582–2588.

[15] V. V. Titov, F. I. González, E. N. Bernard, M. C. Eble, H. O. Mofjeld, J. C. Newman, and A .J. Venturato, Real-time tsunami forecasting: Challenges and solutions. Nat. Hazards, vol. 35(1), Special Issue, U.S. National Tsunami Hazard Mitigation Program, pp. 41–58, 2005.

[16] A. Joseph, Tsunamis: Detection, Monitoring, and Early-warning Technologies. Oxford: Elsevier, 2011, 436 pp., ISBN: 978-0-12-385053-9.

[17] R. Bouchard, C. Kohler, P. Lessing, and K. Kern, "Performance of the first year of the completed US operational deep-sea tsunameter network," in OCEANS 2009, MTS/IEEE Biloxi – Marine Technology for our Future: Global and Local Challenges, 26-29 October 2009.

[18] C. Meinig, S. E. Stalin, A. I. Nakamura, and H. B. Milburn, (2005) Real-time deep-ocean tsunami measuring, monitoring, and reporting system: The NOAA DART II description and disclosure, DART II® References, Available: http://nctr.pmel.noaa.gov/Dart/Pdf/DART_II_Description_6_4_05.pdf.

[19] E. N. Bernard, C. Meinig, V. V. Titov, K. O'Neil, R. Lawson, K. Jarrott, R. Bailey, F. Nelson, S. Tinti, C. von Hillebrandt, and P. Koltermann, "Tsunami resilient communities," in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1), Venice, Italy, 21–25 September 2009, J. Hall, D. E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306, 2010, doi: 10.5270/OceanObs09.pp.04.

[20] NOAA National Data Buoy Center, OPS52 Branch, "Capability Assessment of the SAIC Tsunami Buoy, August 2007," unpublished.

[21] R. A. Lawson, D. Graham, S. Stalin, C. Meinig, D. Tagawa, N. Lawrence-Slavas, R. Hibbins, and B. Ingham, "From research to commercial operations: The next generation easy-to-deploy (ETD) tsunami assessment buoy," in Proceedings of the IEEE Conference Oceans 2011, Santandar, Spain, 6–9 June 2011.