Real-Time Deep-Ocean Tsunami Measuring, Monitoring, and Reporting System:

The NOAA DART II Description and Disclosure

Christian Meinig, Scott E. Stalin, Alex I. Nakamura
NOAA, Pacific Marine Environmental Laboratory (PMEL)

Hugh B. Milburn
Oceanographic Engineer

1. Introduction

This paper describes the system components that make up the second-generation Deep-Ocean Assessment and Reporting of Tsunamis system, known as DART II[1]. The technical level of this document is appropriate for engineers and scientists who are skilled and knowledgeable in the fields of marine systems and ocean instrumentation. The purpose of this paper is to disclose and describe the existing DART II system characteristics in enough detail for others to begin construction of additional deep-ocean tsunami detection and assessment systems, which comprise a critical portion of a tsunami forecast, warning, and mitigation system.

Tsunami data from the DART system can be combined with seismic data ingested into a forecast model to generate accurate tsunami forecasts for coastal areas[2]. Neither the forecast modeling technology, nor the infrastructure needed to prepare and distribute warnings is addressed in this document.

The motivation for developing a transportable, real-time, deep ocean tsunami measurement system was to forecast the impact of tsunamis on coastal areas in time to save lives and protect property. Over the past 20 years, PMEL has identified the requirements of the tsunami measurement system through evolution in both technology and knowledge of deep ocean tsunami dynamics. The requirement for transportability was a conservative approach to a phenomenon that had little data to guide strategies for choosing deployment sites. The requirement for real time was to provide data in time to create a forecast. The first-generation DART design featured an automatic detection and reporting algorithm triggered by a threshold wave-height value. The DART II design incorporates two-way communications that enables tsunami data transmission on demand, independent of the automatic algorithm; this capability ensures the measurement and reporting of tsunamis with amplitude below the auto-reporting threshold. For more accurate forecast modeling and subsequent, more reliable decision-making, this capability is very important because (a) a very large, destructive tsunami may, in fact, have a very small amplitude at any particular DART station position, and (b) small, deep-ocean tsunami amplitudes can reach destructive values, due to large, localized, shallow-water amplification factors. This latter concern was dramatically affirmed and demonstrated after measurement of a 2cm wave of a tsunami generated in Alaska was amplified to become a 40cm tsunami on the north shore of Oahu, Hawaii.

2. Overview and Background

2.1. Reaction to the Indian Ocean Tsunami of December 26, 2004.

The 9.0 earthquake of December 26, 2004 and the resulting tsunami killed more than 300,000 people – more casualties than any other tsunami ever recorded. It was the largest trans-oceanic tsunami in over 40 years. A second earthquake only three months later of magnitude 8.7 has instilled more fear in the survivors of the first disaster, and has everyone wondering when the next tsunami will occur[3], and how their coastal community can be made tsunami-resilient[4,5].

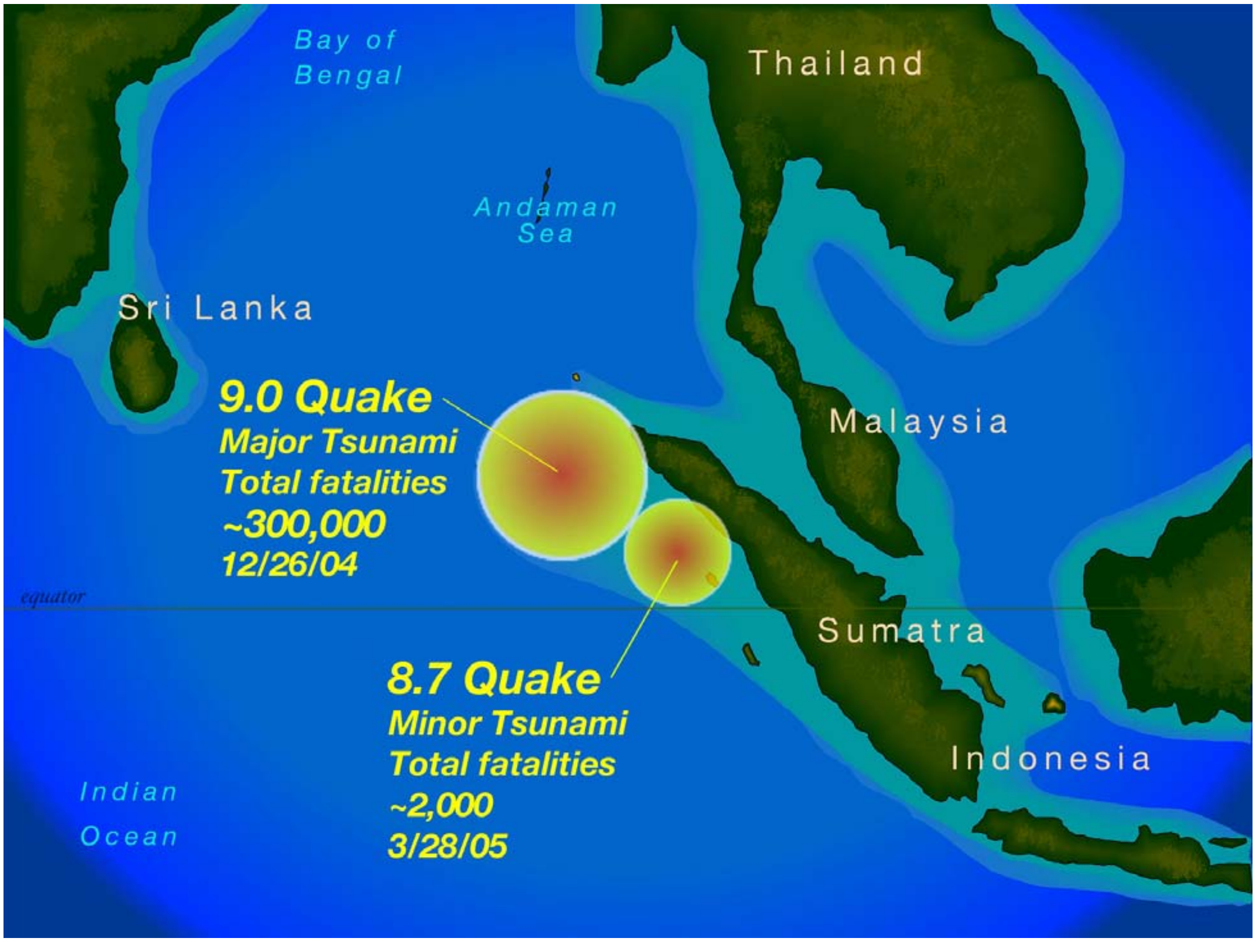

Figure 1: Location of two earthquakes in the Indian Ocean: the first caused massive casualties; the second created panic.

As a result of this tragedy, there is strong interest in installing a global tsunami warning system as soon as possible. Additionally, the Bush Administration has provided funds to expand the current tsunami warning system by deploying 37 additional DART systems in the Pacific, the Atlantic, and the Caribbean[6]. Thus inquires have come to NOAA's PMEL about the technology and methodology that has been developed for tsunami warning and hazard mitigation; especially the DART technology.

2.2. DART System Evolution

DART systems, developed by NOAA's Pacific Marine Environmental Laboratory (PMEL), have proven to be robust and reliable. A six-buoy array has been transitioned to operational status and is monitoring and reporting water column heights in the Pacific Ocean at relevant locations for tsunami propagation. The cumulative data return ratio for the array from 1997 – 2003 exceeded 91%. The data return ratio is computed by dividing the total data received on shore by the total expected data. The DART systems have reacted to and reported six seismic-induced wave events that contributed to operational decisions, avoiding false alarms and the resultant costs associated with them[7]. One incident, a magnitude 7.5 earthquake in the Aleutian Islands that occurred on November 17, 2003, triggered a tsunami 'watch' in Hawaii and Alaska. Data from three tsunameters showed the wave was not significant, and no warning was issued, thus saving Hawaii >$68M in evacuation costs. However, the November 17, 2003 2 cm tsunami observed at a DART buoy (less than the 3 cm self-trip threshold) resulted in a surprisingly large 40 cm wave recorded on the north shore of Oahu, Hawaii, as depicted in Figure 2. A small tsunami that could potentially be dangerous clearly demonstrated the need for bi-directional communications with the DART system.

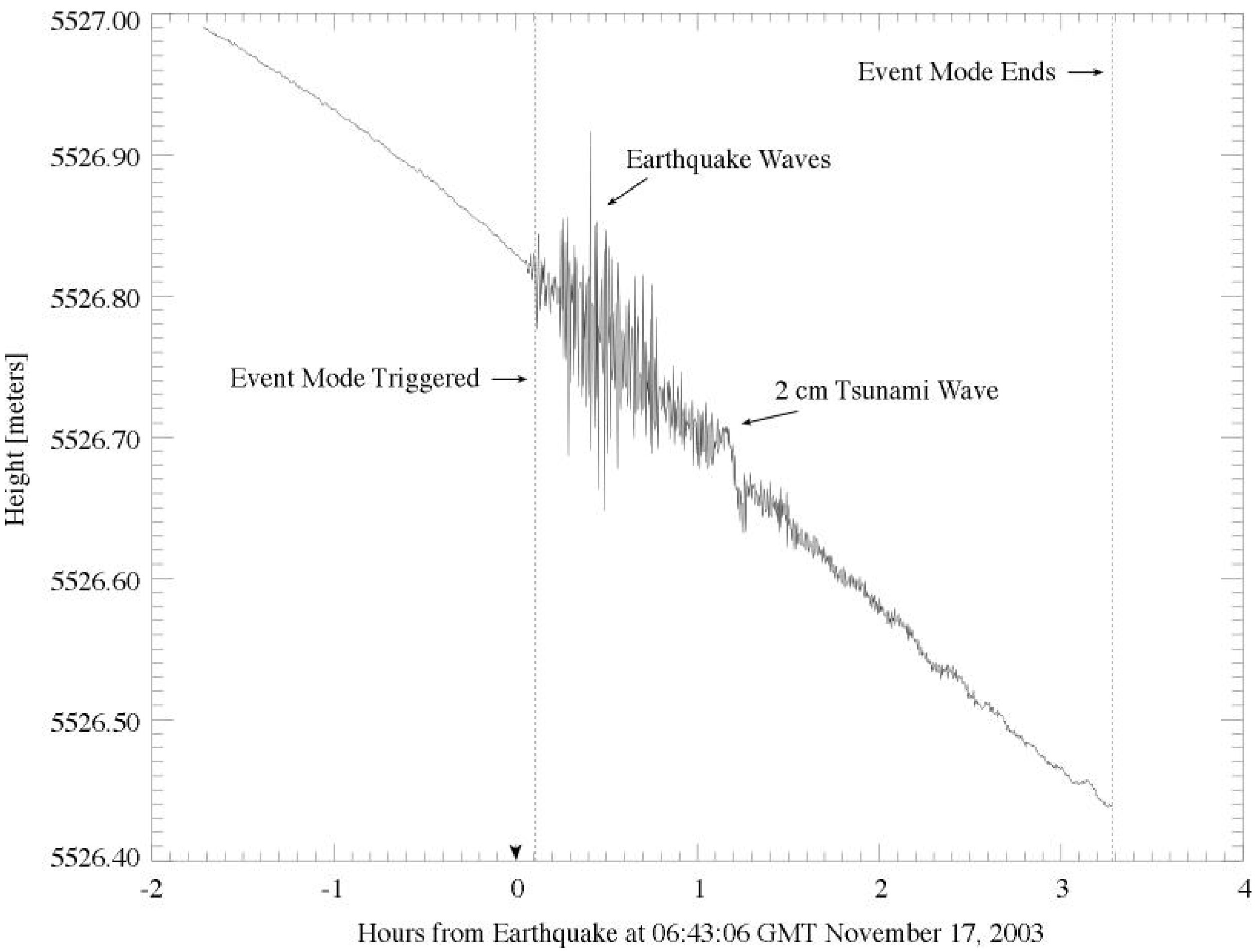

Figure 2: Tsunami of November 17, 2003, as measured at the tsunameter located at 50 N 171 W.

Post-event data from DART systems have been combined with forecast models and compared with coastal tide gage records to show a high correlation in amplitude and arrival times, validating the system parameters. Additionally, the timeliness of DART reporting has proven to be highly valuable to the warning centers.

The success of DART can be attributed to steady progress in the development of four main components: deep-ocean pressure measurements, acoustic data transmission from the tsunameter to the buoy, buoy and mooring technology, and imbedded software. The DART II systems, which incorporate the latest technologies and advances, have longer maintenance intervals, and feature two-way communication.

2.2.1. Deep-Ocean Pressure Measurements

During the past 25 years PMEL has been designing and deploying bottom-sensor platforms with Paroscientific pressure sensors for the purpose of tsunami and climate research The early efforts used internal recording systems that were deployed and recovered at one -year intervals, and were invaluable in refining and validating the measurement process in deep water.

Tsunamis have wave lengths of hundreds of kilometers, and are considered shallow water waves. They 'feel' the bottom in deep water, and increase in height only as they shoal in areas of decreasing depth. Wind waves are called 'deep water waves' where they have negligible impact below half of their wave length. This well-studied exponential decay of orbital motion with depth was derived and presented by George Stokes in 1847. This phenomenon makes the deep ocean an ideal low-pass filter, and allows tsunamis, tides, and other long-period events to be detected by simply measuring the pressure at a fixed point on the seafloor.

The earthquake waves shown in Figure 2 are an interesting feature of tsunami monitoring with bottom pressure sensors. Earthquake waves travel significantly faster than tsunami waves, and frequently trip the tsunameter into 'Event Mode' before the tsunami arrives. The vertical shifting of the seafloor from the earthquake acts to lift or compress the water column above, showing an increase in pressure as the seafloor rises, or decrease in pressure as the seafloor falls.

The relative quiet environment on the seafloor in deep water can be used to validate the performance of pressure measuring systems. Observed vs. predicted tidal variations can be used to validate the gross measurement, and the finest resolution can be seen by the sample - to - sample variation at periods of high and low tide. The low noise and high resolution in the tsunameters have precluded false alarms from occurring on the deployed DART systems.

For our purposes in this paper, when we refer to measured 'sea level height', it is inferred from the seafloor pressure measurements by assuming a constant 1 psi = 670 mm of water height. The errors resulting from neglecting variations in acceleration and density terms are not significant for tsunami detection, where only the relatively small changes are used in the analysis of wave characteristics.

2.2.2. Acoustic Data Transmission

PMEL began testing Datasonics acoustic modems in 1994 for telemetering data from the seafloor to a surface buoy. PMEL engineers worked closely with industry on the development and refinement of the technology that has led to the systems now available from Benthos, Inc. These systems are reliable and robust, and are commercially available in a usable form. A significant effort has gone into developing a transmission protocol that is used on the DART II systems. The scheme was tailored to the specific acoustic telemetry requirements of the task and is described in section 3.5.2.1.

2.2.3. Buoy Development and Deployment

PMEL has designed, fabricated and deployed hundreds of buoys in support of oceanographic and meteorological research since the early 1970s. The first prototype DART buoy was deployed off the Oregon coast in 1995, and following that prototype effort PMEL has deployed and maintained a six-buoy array in the Pacific. Since 2004 NOAA's National Data Buoy Center has assumed operational responsibility for the array.

2.2.4. Software Development

One of the key advances in software has been in the Tsunami Detection Algorithm, which runs inside the tsunameter[ix]. This software monitors the pressure readings, and can detect a tsunami from anomalous values to send data through the system to provide warning guidance. Additionally, extensive software routines in the tsunameter and the buoy are used to format and control the flow of data between the seafloor and the desktop. An important goal in the development of all the software tools and tasks has been to keep the total power requirements low.

3. DART II System Components and Characteristics

3.1. Overview

A DART II system, shown inside the dashed lines of Figure 3, consists of two physical components: a tsunameter on the ocean floor and a surface buoy with satellite telecommunications capability. The DART II systems have bi-directional communication links and are thus able to send and receive data from the Tsunami Warning Center and others via the Internet. The web site for the DART data is supported by the National Data Buoy Center and can be seen at: http://www.ndbc.noaa.gov/dart.shtml.

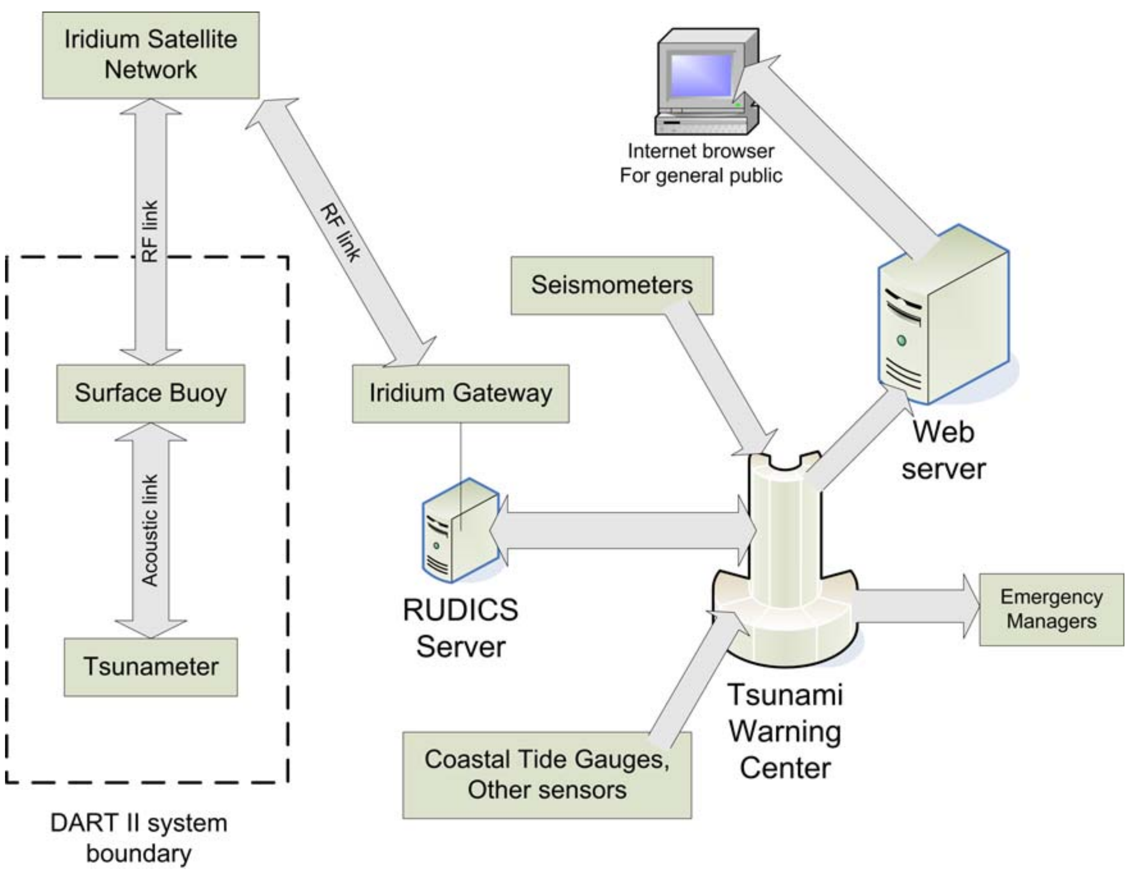

Figure 3: Context diagram showing a DART II system and the related telecommunication nodes.

3.2. DART II Characteristics

DART II performance characteristics are summarized in Table 1. These performance characteristics helped to drive the research and development of the DART II system. Specific engineering details about the tsunameter and the buoy follow.

Table 1: DART II performance characteristics

Characteristic	Specification
Reliability and data return ratio:	Greater than 80%
Maximum deployment depth:	6000 meters
Minimum deployment duration:	Greater than 1 year
Operating Conditions	Beaufort 9 (survive Beaufort 11)
Maintenance interval, buoy	Greater than 2 years
Maintenance interval, tsunameter	Greater than 4 years
Sampling interval, internal record:	15 seconds
Sampling interval, event reports:	15 and 60 seconds
Sampling interval, tidal reports:	15 minutes
Measurement sensitivity:	Less than 1 millimeter in 6000 meters; 2×10^{-7}
Tsunami data report trigger	Automatically by tsunami detection algorithm
	On-demand, by warning center request
Reporting delay:	Less than 3 minutes
Maximum status report interval:	Less than 6 hours

3.3. Tsunameter

The block diagram in Figure 4 shows how the components of a tsunameter function together. The computer reads pressure readings, runs a tsunami detection algorithm, and sends and receives commands and data to and from the buoy via an acoustic modem.

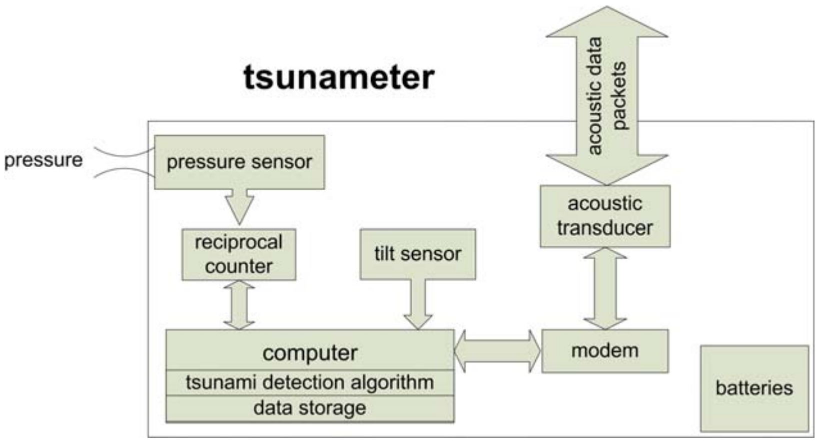

Figure 4: Tsunameter block diagram showing how the components interact.

3.3.1. Pressure Sensor[8]

The DART II pressure sensor is a 0-10,000 psi model 410K Digiquartz® unit manufactured by Paroscientific, Inc.[9] The transducers use a very thin quartz crystal beam, electrically induced to vibrate at its lowest resonant mode. The oscillator is attached to a Bourdon tube that is open on one end to the ocean environment[10]. The pressure sensor outputs two frequency-modulated square waves, proportional to the ambient pressure and temperature. The temperature data is used to compensate for the thermal effects on the pressure-sensing element.

3.3.2. Reciprocal Counter

The high resolution precision reciprocal counting circuit continuously measures the pressure and temperature signals simultaneously, integrating them over the entire sampling window, nominally set to 15 seconds. There is no dead period between the sampling windows. The circuit has a sub-millimeter pressure and sub-millidegree temperature least-count resolution. The reference frequency for the reciprocal counter is derived from a low power, very stable, 2.097152 MHz, temperature-compensated crystal oscillator. A real time calendar-clock in the computer also uses this reference for a time base. At the end of each sampling window, the computer reads the pressure and temperature data and stores the data in a flash memory card. A 15-second sampling period generates about 18 megabytes of data per year.

3.3.3. Computer

The embedded computer system in both the buoy and the tsunameter was designed around the 32-bit, 3.3 volt Motorola 68332 microcontroller, and was programmed in C. It was built to be energy efficient for long-term battery powered deployment. The computer has 4 Mb of flash memory, a 12-bit A/D converter with 8 input channels, two RS232 channels, a hardware watchdog timer, a real-time clock, and 512 bytes of RAM. The embedded computer implements and regulates the primary functions of the surface and seafloor units: transmitting data communications, running the tsunami detection algorithm, storing and retrieving water column heights, generating checksums, and conducting automatic mode switching.

3.3.4. Acoustic Modem and Transducer

A Benthos[11] ATM-880 Telesonar acoustic modem with an AT-421LF directional transducer has a 40° conical beam which is used to transmit data between the tsunameter and the surface buoy. Modems transmit digital data via MFSK modulated sound signals with options for redundancy and convolutional coding. Transducers are baffled to minimize ambient noise from entering the receiver.

3.3.5. Tilt Sensor

Each tsunameter has a Geometrics 900-45 tilt sensor mounted in the base of one of the housings. This is used to determine the orientation of the acoustic transducer when the system has settled on the seafloor. If the tilt is greater than 10 degrees the tsunameter can be recovered and redeployed. The watch circle of the surface buoy could carry it out of the acoustic projection cone from the tsunameter if the angle from the vertical is too great.

3.3.6. Batteries

The tsunameter computer and pressure measurement system uses an Alkaline D-Cell battery pack with a capacity of 1560 watt-hours. The acoustic modem in the tsunameter is powered by similar battery packs that can deliver over 2,000 watt-hours of energy. These batteries are designed to last for four years on the seafloor; however, this is based on assumptions about the number of events that may occur and the volume of data request from the shore. Battery monitoring is required to maximize the life of the system.

3.3.7. Tsunami Detection Algorithm

Each DART II tsunameter is designed to detect and report tsunamis autonomously[12]. The Tsunami Detection Algorithm works by first estimating the amplitudes of the pressure fluctuations within the tsunami frequency band, and then testing these amplitudes against a threshold value. The amplitudes are computed by subtracting predicted pressures from the observations, in which the predictions closely match the tides and lower frequency fluctuations. If the amplitudes exceed the threshold, the tsunameter goes into Event Mode to provide detailed information about the tsunami.

3.3.8. Reporting Modes

Tsunameters operate in one of two data reporting modes: A low power, scheduled transmission mode called “Standard Mode” and a triggered event mode simply called “Event Mode”.

> **Standard Mode** reports once every six hours. Information reported includes the average water column height, battery voltages, status indicator, and a time stamp. These continuous measurements provide assurance that the system is working correctly.
>
> **Event Mode** reports events such as earthquakes and /or tsunamis when a detection threshold is exceeded. The Tsunami Detection Algorithm triggers when measured and predicted values differ by more than the threshold value. Waveform data are transmitted immediately (less than a three-minute delay).

Tsunami waveform data continue to be transmitted every hour until the Tsunami Detection Algorithm is in a non-triggered status. At this point the system returns to the Standard Mode.

3.4. Surface Buoy

The DART II surface buoy, shown in Figure 5, relays information and commands from the tsunameter and the satellite network. The buoy contains two identical electronic systems to provide redundancy in case one of the units fails. The Standard Mode transmissions are handled by both electronic systems on a preset schedule. The Event Mode transmissions, due to their importance and urgency, are immediately transmitted by both systems simultaneously.

The surface mooring uses a 2.5 m diameter fiberglass over foam disk buoy with a displacement of 4000 kg. The mooring line is 19 millimeter eight-strand plaited nylon line with a rated breaking strength of 7100 kg, and is deployed to maintain a tight watch circle, keeping the buoy positioned within the cone of the acoustic transmission. In temperate areas where fish tend to aggregate and bite lines, wire rope is use on the upper few hundred meters of the mooring.

Two downward-looking transducers are mounted on the buoy bridle at a depth of 1.5 meters below the sea surface. A multi layered baffle system of steel, lead, and syntactic foam shields the transducers from noise, and cushions them with rubber pads for a soft mount.

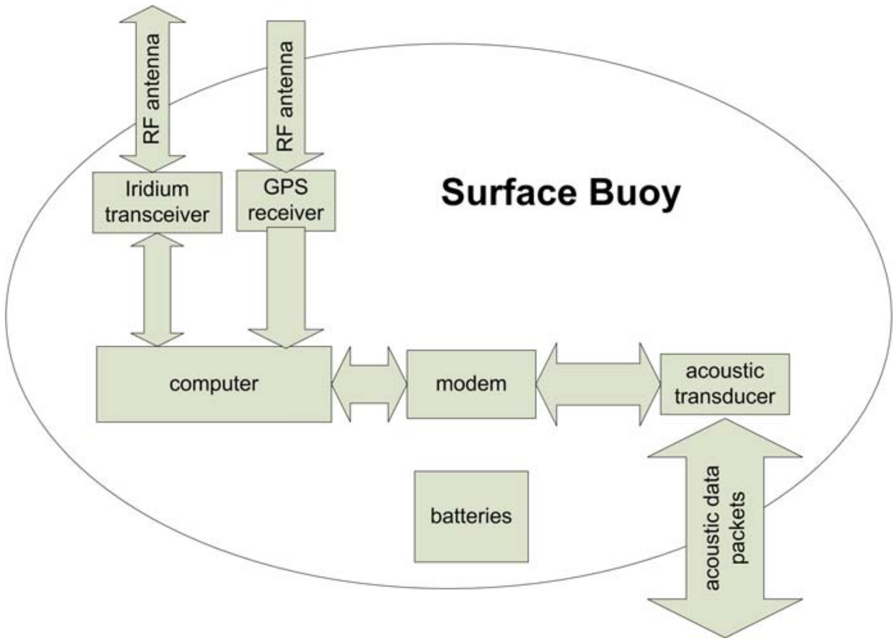

Figure 5: Block diagram of DART II surface buoy.

3.4.1. Modem and Acoustic Transducer

The Benthos Telesonar acoustic modems and transducers are the same as used in the tsunameter. To improve the reliability of data transmission, two identical systems are used on the buoy.

3.4.2. Computer

The computer is the same type used in the tsunameter as described in 3.3.3. It processes messages from both the satellite and the tsunameter.

3.4.3. Iridium Transceiver

A Motorola 9522 L-Band Iridium transceiver from NAL Research provides data connectivity via the Iridium Satellite Network. The buoy computer connects to the transceiver using an RS232 serial port. Data is transferred at 2400 baud similarly to the familiar dial-up modem connections. A typical Standard Mode report takes approximately 30 seconds, including the time it takes to complete the connection, transmit the data, and disconnect.

3.4.4. GPS

A Leadtek model 9546 GPS receiver is used to maintain the buoy's computer clock's accuracy to within ~1 sec of GMT. Additionally, a GPS position is reported once per day to monitor buoy position.

3.4.5. Batteries

The buoy's fiberglass well houses the system electronics and power supply, which is made up of packs of D-cell alkaline batteries. The computer and Iridium transceiver are powered by 2,560 watt-hour batteries; the acoustic modem is powered by 1,800 watt-hour batteries. These batteries will power the buoy for at least two years.

The buoy is designed to mitigate the potentially dangerous build up of hydrogen gas that is naturally vented from alkaline cells. Design features include: 1) hydrogen getters (such as those from HydroCap Corp); 2) pressure relief valves; and 3) spark-free components such as fiberglass or plastic.

3.5. Data Communications

This section describes all the messages that are sent and received to and from the DART II systems. *Telemetry* describes how the data is physically transported over the distance between the hardware components. *Content* refers to the information contained in the messages. *Format* describes how the message is formatted.

3.5.1. Workstation - to - Buoy

A DART II innovation is the ability to send messages from a workstation on land to the buoy and the tsunameter. This bi-directional communication enables commands to be sent to the DART II system.

3.5.1.1. Telemetry

The warning center issues commands that are queued in a server until the DART II buoy is in Listen Mode.

3.5.1.2. Content

Once the connection is established, the following commands can be sent:

- Turn on Deployment Mode for 30 minutes in the tsunameter
- Download one hour of high frequency data (15-second data)
- Trip tsunameter into Event Mode
- Turn acoustic modem on or off
- Turn on Event Mode
- Turn off Event Mode
- Reboot tsunameter computer
- Change tsunami detection threshold (30 to 90 mm range)
- Reboot buoy computer
- Get engineering data from tsunameter

3.5.2. Tsunameter - to - Buoy

3.5.2.1. Telemetry

The Benthos Telesonar acoustic modems use the water itself as the medium for the transmission of acoustic signals. The acoustic modems on the DART II systems are configured to operate in the 9-14kHz frequency band at 600 baud, using MFSK and error-correcting coding. The source level is at 193 dB re 1ɥPa @ 1 m with a 40 VDC supply.

The communication uses a modified x-modem protocol. Entire packets of data with many blocks are sent without requesting an acknowledgement from the receiver after each block. Missing or erroneous blocks are requested to be resent again as individual blocks. If the system is unable to connect, a maximum of two retries are attempted. Most importantly, the modified x-modem protocol greatly reduces power consumption, and efficiently supports high data throughput and integrity.

3.5.2.2. Content

Standard Mode

Normally, the tsunameter is in its low-power Standard Mode and transmissions are made only once every six hours. Standard Mode messages contain the following data:

- Message ID, a sequential number
- Message status, C = corrupted, I = intact
- Date= month day year
- Time= hour minute second
- Main battery voltage,or error code
- Acoustic modem DSP battery voltage
- Acoustic modem battery voltage
- Four values for water column height in millimeters corresponding to 15-minute intervals
- Number of tries to deliver tsunameter data
- Checksum delimiter
- Checksum

Event Mode

When the tsunameter first detects an event and enters Event Mode, it immediately transmits an alert to the buoy, which causes it to turn on the Iridium transceivers for immediate transmission of data to the warning centers. The first Event Mode message (message #0) contains the following data:

- The exact time that the event was detected
- A message ID
- The average water column height that triggered the Event Mode, along with three height deviations.
- Check sums and other data verification values that insure the integrity of the data transmission.

Following message #0, the tsunameter sends messages on a predetermined schedule, as shown in Figure 6. Message #0 and message #1 contain 15-second height values. Ensuing messages are similar, but include 15 one-minute average height values, where the one-minute values consist of the average of four 15-second height values.

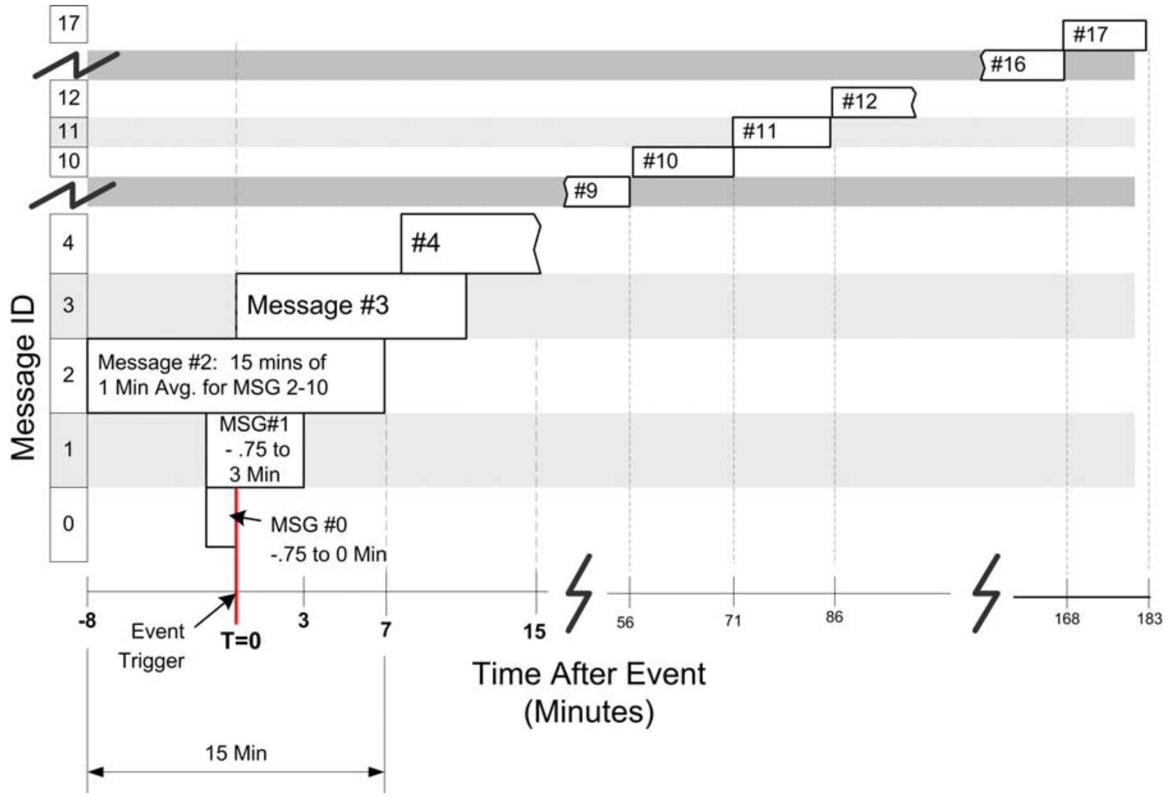

Figure 6: Timing diagram showing messages during Event Mode.

Once in Event Mode, the Standard Mode stops transmitting every six hours, and is replaced with an Extended-Reporting Mode for additional data redundancy. This mode transmits messages that consist of 120 one-minute average values, which are transmitted every hour, as shown in Figure 7. After the Tsunami Detection Algorithm is in non-triggered status, Standard Mode is resumed, and Extended Reporting Mode is stopped.

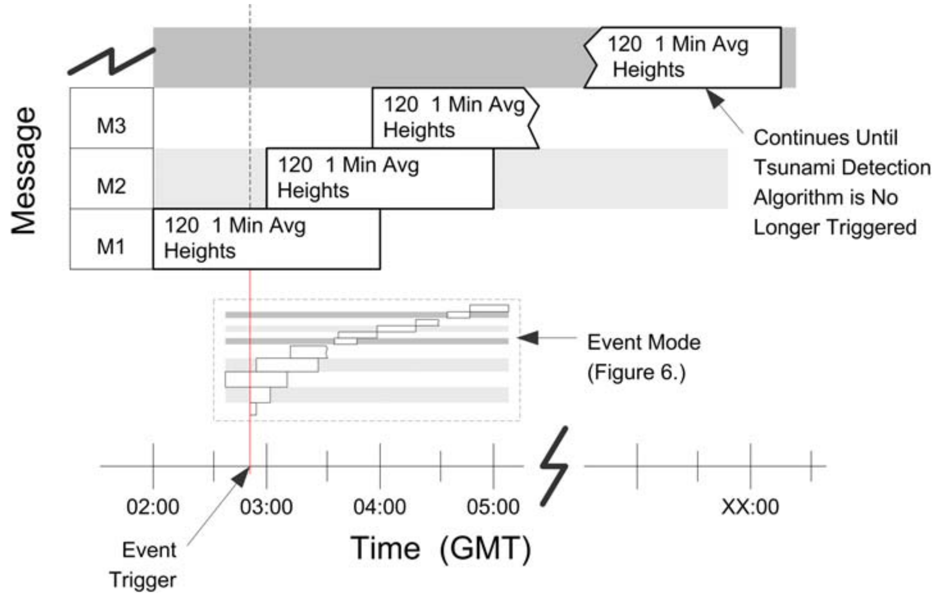

Figure 7: Timing diagram during Extended-Reporting Mode

3.5.2.3. Format

The format of the messages is a space-delimited text string of values, followed by an asterisk, followed by a checksum. The deviation values are coded as four hexadecimal digits.

3.5.3. Buoy to Satellite

3.5.3.1. Telemetry

Each DART II buoy sends its data to the Iridium Satellite Network using an Iridium transceiver[13]. The radio frequency transmission in the 1565 MHz to 1626.5 MHz range and the data transmission rates are at 2.4 kilobits per second.

The satellite communication also uses a modified x-modem protocol as described in section 3.5.2.1.

3.5.3.2. Content

Event Mode

In Event Mode, both communication systems relay the data from the tsunameter. See section 3.5.2 for more information about the content and format of the data.

Standard Mode

In Standard Mode, that is, no tsunami detected, the surface buoy relays the data it receives from the tsunameter using both systems. These timed transmissions occur once every six hours. Receiving these timed water-column height data ensures that each DART II system is functioning properly. If data are not received from the tsunameter, the buoy sends GPS coordinates instead of water column height data. The reported position is checked to ensure that the buoy has not parted from its anchor[14].

Deployment Mode

The tsunameter will enter into Deployment Mode prior to deployment. This mode enables the user to verify that the system is working on the seafloor before leaving the site. Deployment Mode will transmit data to the buoy every other minute for four hours. Once the buoy has received a few messages, it will transmit these messages thru the Iridium system. The data will show the tilt of the tsunameter, a quality parameter of the acoustic modem channel, and four 15-second pressure measurements.

Listen Mode

The buoy listens for an Iridium call with a 20% duty cycle. The redundant systems will turn on their respective Iridium transceivers at alternate times for three minutes out of 15 minutes. This yields a maximum inaccessibility of only six minutes. This scheme is employed to control the buoy power requirements by decreasing the standby power draw of the Iridium transceivers.

3.5.3.3. Format

Data sent from the buoys to the satellite are formatted as text messages sent over a voice-grade telephone connection, just like a normal dialup link.

3.5.4. Satellite to Ground Stations

3.5.4.1. Telemetry

DART II makes use of the Iridium Satellite network. Data from each DART II system is downloaded and stored on a server via the Iridium Gateway and RUDICS server. The warning centers monitor this data stream in real time and are responsible for issuing warnings. In addition, the data is posted to a web server, and can be viewed by anyone with a browser.

3.5.4.2. Content

Normally, sea level or tide data are relayed from the satellite to ground stations, ensuring that the systems are working. Immediately after an event is detected, transmissions increase in frequency, and the data include both averages and deviations along with time stamps, as described in section 3.5.2.2.

Commands can be sent from workstations on the ground to both the buoys and the tsunameter's computer. The commands are summarized in section 3.5.1.2.

3.5.4.3. Format

No messages are stored in the satellite network; rather messages are simply relayed from the buoy to servers or workstations. The format of the messages is text using TCP/IP.

3.6. Site Characteristics

To reliably send and receive the acoustic packets to and from the tsunameter, which might be submerged between 1000 and 6,000 meters below the buoy, the tsunameter must be located on a relatively flat portion of the ocean floor, and the buoy must be moored such that it stays within a 40-degree cone; a cone whose vertex is at the tsunameter, and whose base encompasses the buoy. Outside of this cone, the signal - to - noise ratio deteriorates rapidly, and data integrity will be compromised.

The mooring needs to be strong enough to withstand harsh ocean conditions of wind, waves, currents, fish bites, and vandalism.

4. Summary

The DART system has evolved to become a reliable and robust system. In the years since its initial funding in 1996, many lessons have been learned, and progress has been steady in four areas: tsunameters, moorings, telecommunications, and software algorithms. These scientific and engineering advances at NOAA's Pacific Marine Environmental Laboratory (PMEL) have led to a highly-reliable system that acquires and delivers direct tsunami measurements from deep ocean locations between the tsunami generating event and distant at-risk communities, and transmits these data in near real time to tsunami warning centers and the Internet.

The six DART systems that are deployed in the Pacific Ocean have faithfully monitored tsunamis since their deployment, beginning with the first buoy in 1997. Each year has seen engineering advances in both the reliability and robustness of the deployments, and in the maintenance intervals of both the tsunameters and the buoys[15].

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