5.2 NOAA/NWS TSUNAMETER OPERATIONS SUPPORTING REAL-TIME TSUNAMI WARNINGS AND TSUNAMI RESEARCH

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1. INTRODUCTION

In March 2008, the National Oceanic and Atmospheric Administration's (NOAA)/ National Weather Service's (NWS) National Data Buoy Center (NDBC) completed the planned 39-station U.S. tsunameter network (Fig. 1). The network provides coastal communities in the Pacific, Atlantic, Caribbean and the Gulf of Mexico with faster and more accurate tsunami warnings (NOAA, 2005a).

The NWS is responsible for the overall execution of NOAA's Tsunami Program and supports observations and data management through NDBC (NOAA, 2005b).

1.1 The National Data Buoy Center

NDBC's mission is to provide comprehensive, reliable systems and marine observations to support the missions of the National Weather Service and NOAA, promote public safety, and satisfy the future needs of its customers.

Since 1970, NDBC has operated buoys that provide critical meteorological and oceanographic data, such as wind, wave, air pressure and temperature, and sea surface temperature, in remote maritime environments. Leveraging NDBC's expertise in buoy deployment and data management, NOAA transitioned the first tsunameters from its research office to the operational realm of NDBC in 2003 (Taft *et al.*, 2003). NOAA defines operations as:

> *Sustained, systematic, reliable, and robust mission activities with an institutional commitment to deliver appropriate, cost-effective products and services.*
>
> \- NOAA (2005c)

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Initially consisting of six stations in the North Pacific Ocean, the tsunameters employed the first generation Deep-ocean Assessment and Reporting of Tsunamis (DART® I) technology.

This was followed by the successful transition of the second generation tsunameters (DART® II) technology (Green, 2006). The most significant of the improvements to the second generation tsunameters was the capability for two-way communications between the DART® and shore sites. The two-way communications capability allows NDBC to interrogate the system and retrieve one-hour of the full-resolution data at a time. NOAA's Pacific Marine Environmental Laboratory (PMEL) developed the award-winning (NOAA, 2004), patented (Meinig *et al.*, 2007) DART® technology.

1.2 The Tsunameter Technology

The tsunameters consist of a Bottom Pressure Recorder (BPR), a surface buoy, and the shore side communications infrastructure (Fig. 2). Every 15 seconds, the BPR records pressure and temperature at the seafloor and converts the measurements to an estimated water-column height by multiplying the resultant pressure by 670 mm per pound per square inch of pressure. The BPR contains a Tsunami Detection Algorithm. The algorithm makes predictions of the water-column height and when the difference between the predicted and measured water-column heights exceeds a configurable threshold (usually 30 mm) then the BPR goes into a rapid reporting or Event Mode. This unexpected deviation in water-column height indicates the passage of an open-ocean tsunami, which may be a threat to coastal communities. The first four minutes of the Event Mode provides data at 15-s intervals and then follows with four hours of one-minute averages (four 15-s). It takes less than three minutes for the data to leave the BPR and make it to the shore side processing.

When not in Event Mode, the BPR sub-samples the 15-s data at 15-minute intervals and transmits four (or a one-hour span) measurements to the surface buoy. The surface buoy transmits these data shore side every six hours. Known as Standard Mode data, they provide the health status of the tsunameter and have application in tsunami warnings.

1.3 Data Management Concept of Operations

The Concept of Operations for the management of tsunameter data consists of real-time and retrospective data management processes.

The real-time process provides data from the BPR to the national and international tsunami warning community in three minutes or less. The BPR makes a single acoustic transmission to the surface buoy that has two independent and redundant communications systems (two acoustic modem transceivers and two satellite communications transceivers). The buoy transmits the data via Iridium Router-based Unrestricted Digital Internetworking Connectivity Solution (RUDICS) to an NDBC server that pre-fixes and post-fixes telecommunications header information and transfers the resulting bulletins to the co-located National Weather Service Tele-communications Gateway (NWSTG) in Silver Spring, MD.

The NWSTG then routes the bulletins to the Global Telecommunication System (GTS) via the Washington DC Regional Telecommunications Hub (RTH). The GTS then broadcasts the bulletins to other RTHs around the world, which in turn, distribute the bulletins within their respective regions.

NDBC distributes the data on the GTS under following bulletin headers:

North Pacific Ocean: SZPN01 KWNB
South Pacific Ocean: SZPS01 KWNB
North Atlantic (including the Caribbean and Gulf of Mexico): SZNT01 KWNB

NDBC provides information about the establishment and disestablishment of stations via the *Data Management Notices* distributed under the NOXX10 KWBC bulletin header.

In addition, NDBC posts the data in real-time to its website as:

- Columnar text data: http://www.ndbc.noaa.gov/dart.shtml

- network Common Data Form (netCDF) via its Distributed Oceanographic Data Systems (DODS) using Open Source Project for a Network Data Access Protocol (OPeNDAP) software under the Thematic Realtime Environmental Distributed Data Services (THREDSS) infrastructure: http://dods.ndbc.noaa.gov/thredds/catalog/data/dart/catalog.html

In the retrospective process, NDBC forwards the full 15-s resolution data recovered from the BPR's flash memory card and the deployment/recovery metadata to the designated long-term archive activity – NOAA's National Geophysical Data Center (NGDC), Boulder, CO. NGDC provides the data via its website at: http://www.ngdc.noaa.gov/hazard/DARTData.shtml

NDBC posts the metadata for current tsunameter deployments in a spreadsheet on the webpage: http://www.ndbc.noaa.gov/dart_metadata.shtml.

2. Support for Tsunami Warning

NOAA's Tsunami Warning Centers (TWC), the West/Coast and Alaska Warning Center (WC/ATWC) in Palmer, AK and the Pacific Tsunami Warning Center (PTWC) at Ewa Beach, HI, use observations of seismic activity and sea height from tidal stations and the deep-sea tsunameters with forecast models to issue Watches and Warnings where appropriate. The TWCs have access to the tsunameter data via the GTS with backup provided by a file transfer protocol (ftp) server at the NWSTG (Bouchard *et al.*, 2007a).

Standard Mode data, in addition to providing the status on the health of the tsunameter, provides the long-term time series record used by the TWCs for analysis to determine the tidal constituents for the removal of the tidal signal from the tsunameter data. The removal of the tidal signal provides for better assessment of the amplitude and timing of the arrival of tsunamis at the tsunameters. Operational availability of the DART® network as a whole has exceeded the goal of 80% (Bouchard *et al.*, 2007b).

The tsunameter Event Mode data are the primary tools for warning and advisories. The tsunameter is set into Event Mode either by the arrival of the seismic signal or a tsunami or by command from the TWCs, therefore the tsunami is found in the one-minute averaged data that follows the initial four-minutes of 15-s data (Fig. 3).

The application of the tsunameters by the TWCs during an event is illustrated by the series of employments of the tsunameters in conjunction with the November 2006 Kuril Island earthquake and tsunami (Table 1). Initially the tsunameters nearest the earthquake are triggered by the arrival of seismic signals (Geophysical Triggering Mechanism). As the TWCs make their assessments, they placed seven successive tsunameters in Event Mode (Manual Triggering Mechanism) to capture the passage of the possible tsunami.

A recent development is capability to ingest the tsunameter Event Mode data to adjust the tsunami source parameters for the NOAA Tsunami Forecast System. This system incorporates real-time tsunami event data with numerical models to provide estimates of tsunami propagation and inundation amplitudes and arrival times for at-risk U.S. coastal communities. (Venturato, *et al.*, 2007).

3. Support for Tsunami Research

NDBC schedules the recovery of the BPRs on a two-year cycle and routinely forwards the data from the on-board flash memory cards and metadata of the deployment to NGDC for long-term archive and to NOAA's Center for Tsunami Research (NCTR). The data consist of hourly time-stamped data blocks of the pressure and temperature counts at 15-s intervals. The counts coupled with the calibration parameters reconstitute the full record of temperature-corrected pressure values during the deployment.

Research applications have employed the real-time data, although of coarser sampling resolution, to validate models (Meinig *et al.*, 2005) and even detect the 2004 Sumatran Tsunami in the Northeast Pacific Ocean (Gower and González, 2006). NDBC can also make limited sets of the full-resolution 15-s data available in near real-time by using the tsunameters' two-way communications to interrogate the BPR to retrieve one-hour blocks of the full-resolution data. Availability of these data is dependent on the health of the system, operational constraints, and the value of the data to further tsunami warning and detection capabilities.

4. SUMMARY

The NOAA/NWS tsunameter network, operated by NDBC, provides data to two mutually supportive tsunami applications – real-time warning/advisories and research. After the technology completed a successful transition from research to operations, the network reached its planned full-operating capability in early 2008.

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Table 1. Employment of Tsunameters during the Kuril Islands November 2006 Tsunami Event

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

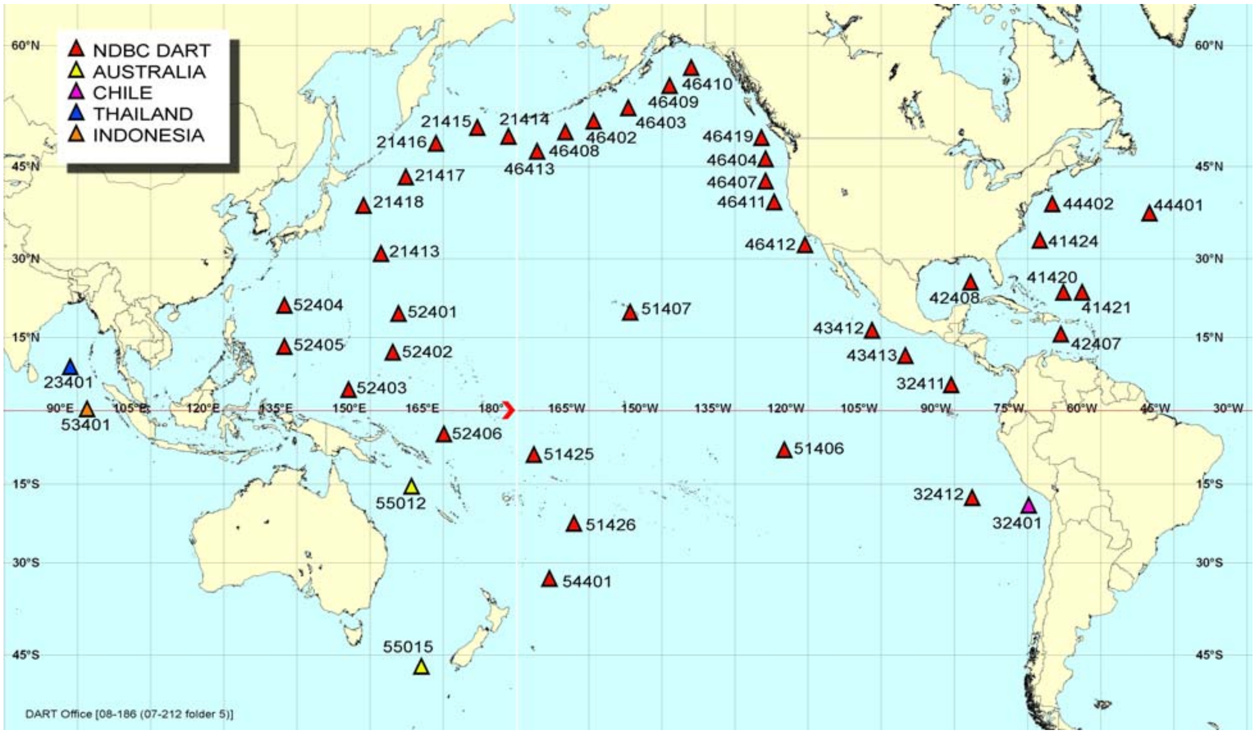

Figure 1. NOAA/NWS Tsunameter Locations (NDBC DART®)

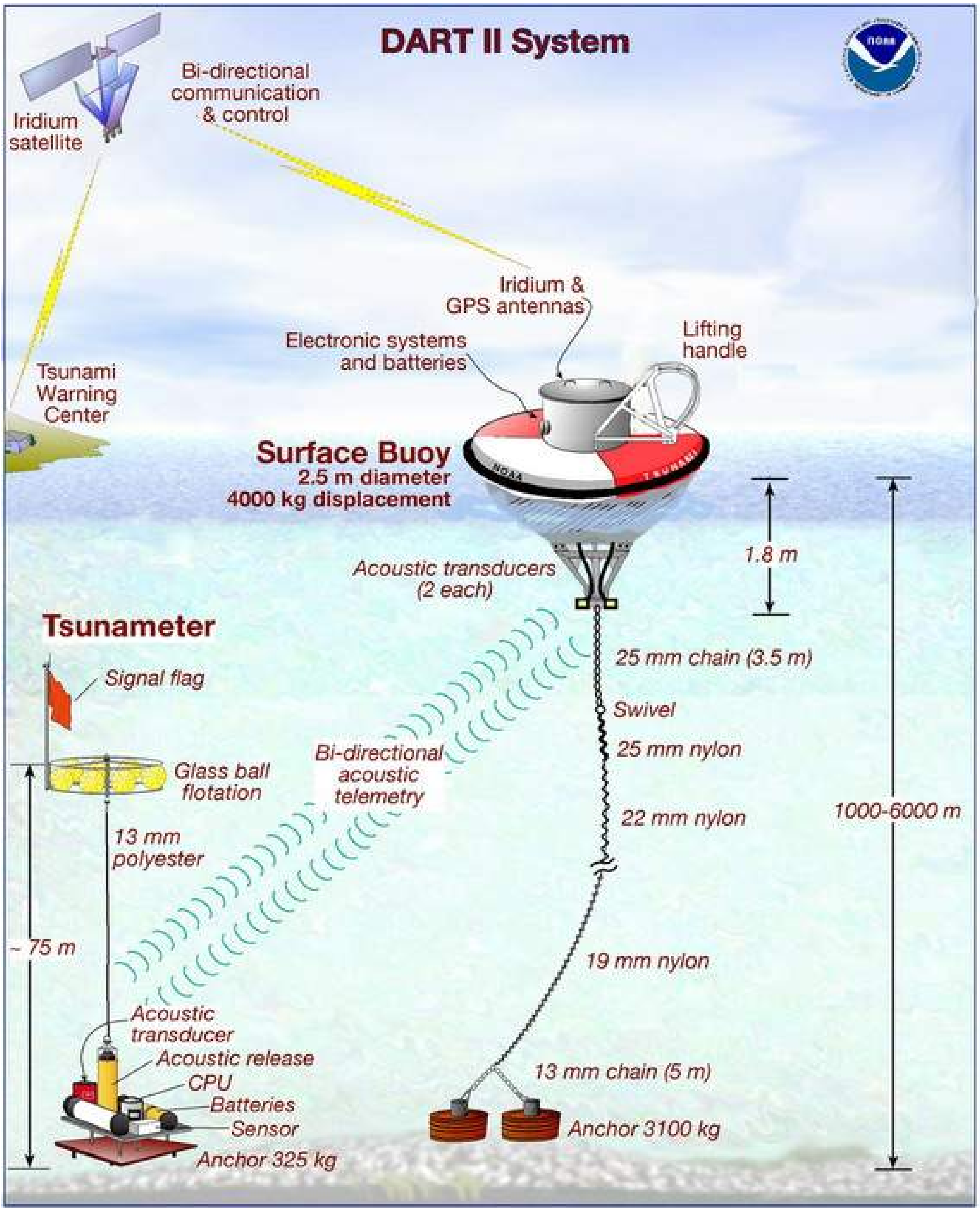

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Figure 2. Tsunameter System using the DART® II Technology

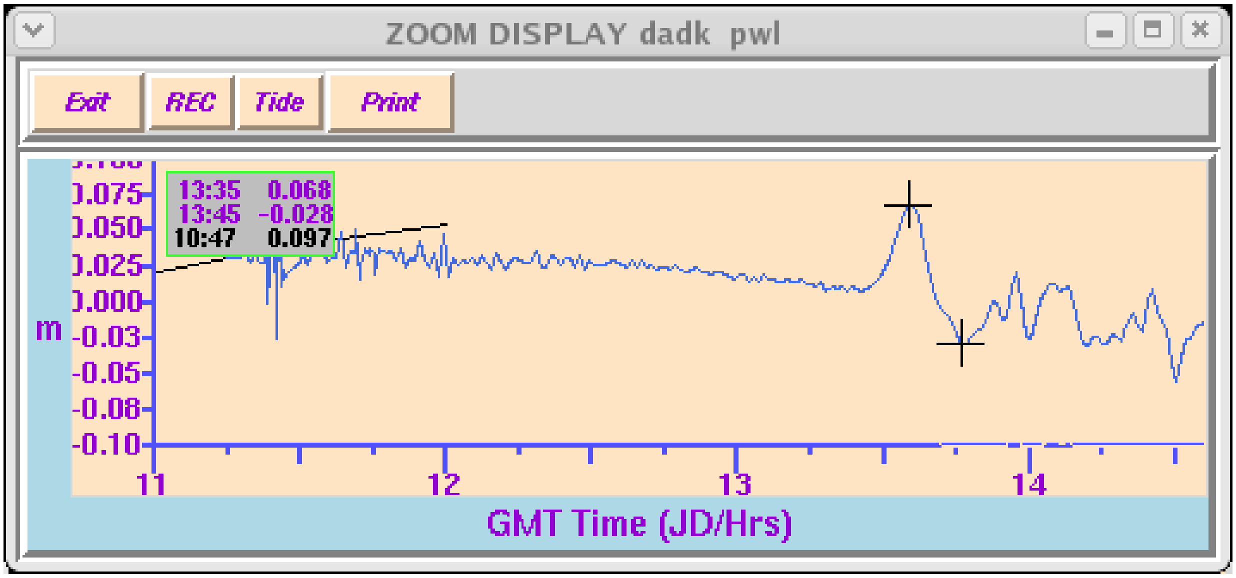

Figure 3. Display at the Pacific Tsunami Warning Center of de-tided tsunameter data associated with Nov 2006, Kuril Islands tsunami. 9.5 minutes after the earthquake, arrival of seismic signal (sawtooth signal between time 11.25 and 11.5 hours) triggers 46413 (south of the western Aleutians) into rapid reporting mode, then 0.10 m tsunami arrives two hours later (indicated by the cross-hairs), and propagates to Crescent City CA where 0.88 m tsunami impacts marina. Image courtesy of Dr. Dailin Wang, PTWC.