MSM OCEAN

Sonardyne

Overview of the Tsunami Early Warning System

Application Guide

Table of contents

Introduction

In January 2022, Mediterráneo Señales Maritimas (MSM Ocean) and Sonardyne International Ltd (Sonardyne) formalised over a decade of working together by announcing a teaming agreement to supply a complete Tsunami Early Warning System (TEWS) for at-risk coastal communities. The agreement combines MSM Ocean's expertise in oceanographic measurement buoys, on-board data processing and telecommunications and Sonardyne's highly precise deep water pressure measurement and acoustic through-water telemetry capabilities.

This guide gives an overview of the system and outlines the technical considerations for its deployment. The systems track record is outlined and illustrated by a number of case studies.

Don't forget to visit our respective web pages:

https://www.sonardyne.com/products/tsunami-detection-system/

https://msmocean.com/en/tsunami-buoys/

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Definitions

Abbreviation	Definition
AI	Artificial Intelligence
AIS	Automatic Identification System
AtoN	Aids to Navigation
AZA	Ambient-Zero-Ambient
BPR	Bottom Pressure Recorder
CPU	Central Processing Unit
DART	Deep-ocean Assessment and Reporting of Tsunamis
DAS	Data Acquisition System
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
LED	Light Emitting Diode
LMF	Low Medium Frequency band (14-19 kHz)
NCTR	NOAA Center for Tsunami Research
NDBC	National Data Buoy Center (USA)
NOAA	US National Oceanic & Atmospheric Administration
RCS	Radar Cross Section
SCC	Shore Control Centre
ShiPRAS	Ship Proximity Remote Report and Surveillance
SMS	Sonardyne Messaging Service
SMT	Surface Modem Transceiver
TEWS	Tsunami Early Warning System
TDS	Tsunami Detection System
USV	Uncrewed Surface Vessel

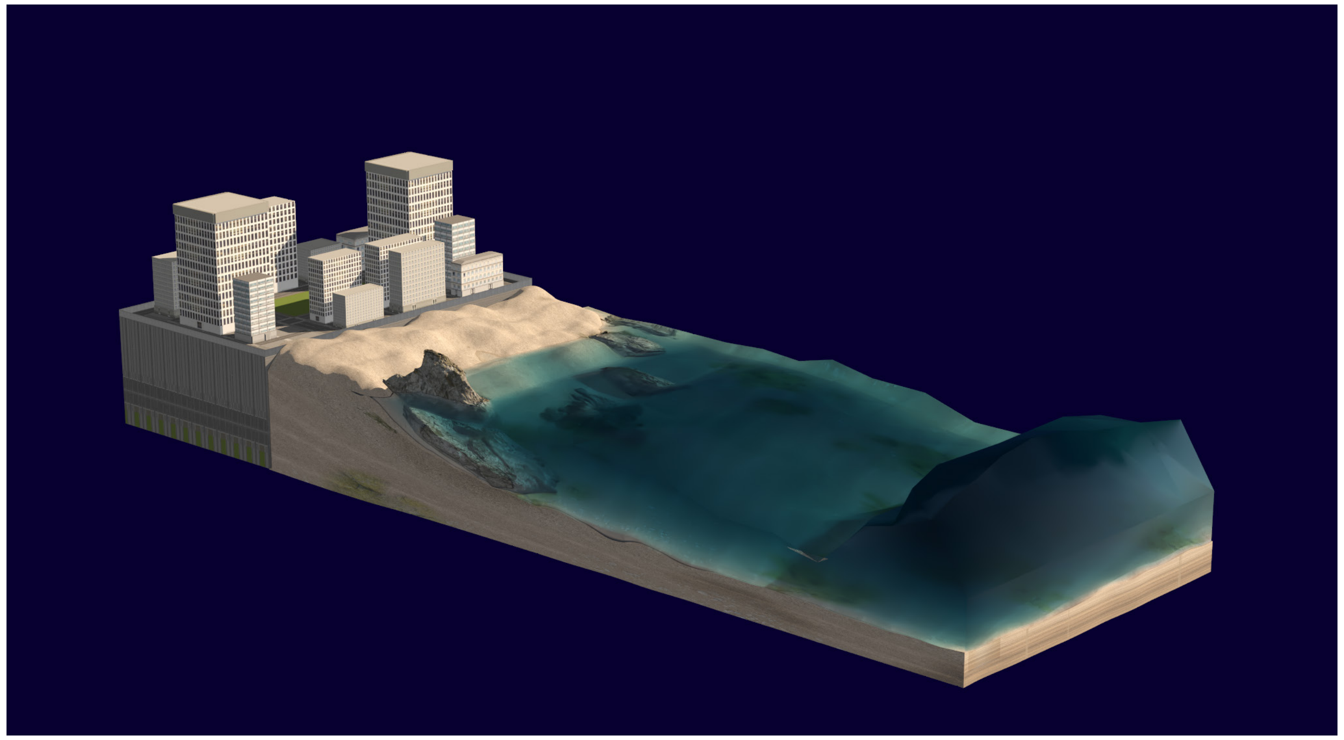
What causes a tsunami?

Tsunamis are generated by bodily displacement of a large mass of water, usually associated with a rapid change in seabed or adjacent coastal topography. While a few tsunamis are caused by the rapid barometric pressure changes associated with the passing of a front (known as a meteotsunami), and the causes of some submarine slope failure induced ones remain unclear, the vast majority are triggered by seismicity.

Nevertheless, seismicity is associated with two different types of events that cause tsunamis. These are significantly different in their characteristics:

- Landslides – These can occur both above and below sea level and occur when earthquakes destabilise unstable slopes. As such they have been associated with the highest recorded tsunamis (the 1958 Lituya Bay megatsunami was 524 m high), although none have been recorded as crossing an ocean. Self-evidently, these tsunamis are generated at the coast, albeit this could be an offshore island. **In such cases, detection of the passage of the tsunami by TEWS typically provides little warning time.** Consequently, a better approach is to identify and monitor potentially unstable slopes. Technology for monitoring unstable submarine slopes is available but is not further discussed in this guide.

- Submarine earthquake at a subduction zone – At a typical subduction zone, an oceanic plate is forced under an overriding continental plate and sinks into the earth's mantle. Elastic strain builds up along thrust faults at this margin, which is periodically released in the form of earthquakes that displace the seabed vertically. 80% of tsunamis occur around the Pacific Ocean's 'Ring of Fire' which is ringed by a network of subduction zones. Consequently, the source of these tsunamis is offshore, which affords an opportunity for remote detection before they reach the shore. **TEWS is most appropriately used in these situations.**



How does TEWS detect a tsunami?

A tsunami in deep water creates a small (usually less than a metre) but measurable change in water height that will be maintained for as long as an hour. Detection of this change is the fundamental basis of the TEWS. To do this, a bottom pressure recorder (BPR) uses a high accuracy pressure sensor to distinguish the increased pressure caused by the tsunami from the background pressure signal of the water column above. This is not straightforward as the background pressure signal changes due to tides, which are largely predictable, and meteorological conditions, which are much less predictable.

The BPR therefore runs an algorithm developed by the US National Oceanic and Atmospheric Administration (NOAA), which uses the previous 3-hour history of the background pressure measurement to take account of weather conditions and temperature to produce a predicted measurement. The measured pressure is continuously compared to this prediction and should the difference exceed a programmable threshold, a detection is flagged.

Figure 1 illustrates operation of the algorithm, using a simulated tsunami in a water tank: The predicted pressure is continuously compared to the measured pressure in order to calculate the difference. In this case, the detection is made when the difference exceeds the default threshold of 3 cm) for two consecutive samples. The algorithm also includes a spike filter that rejects any single measurement that exceeds the predicted by >10 cm.

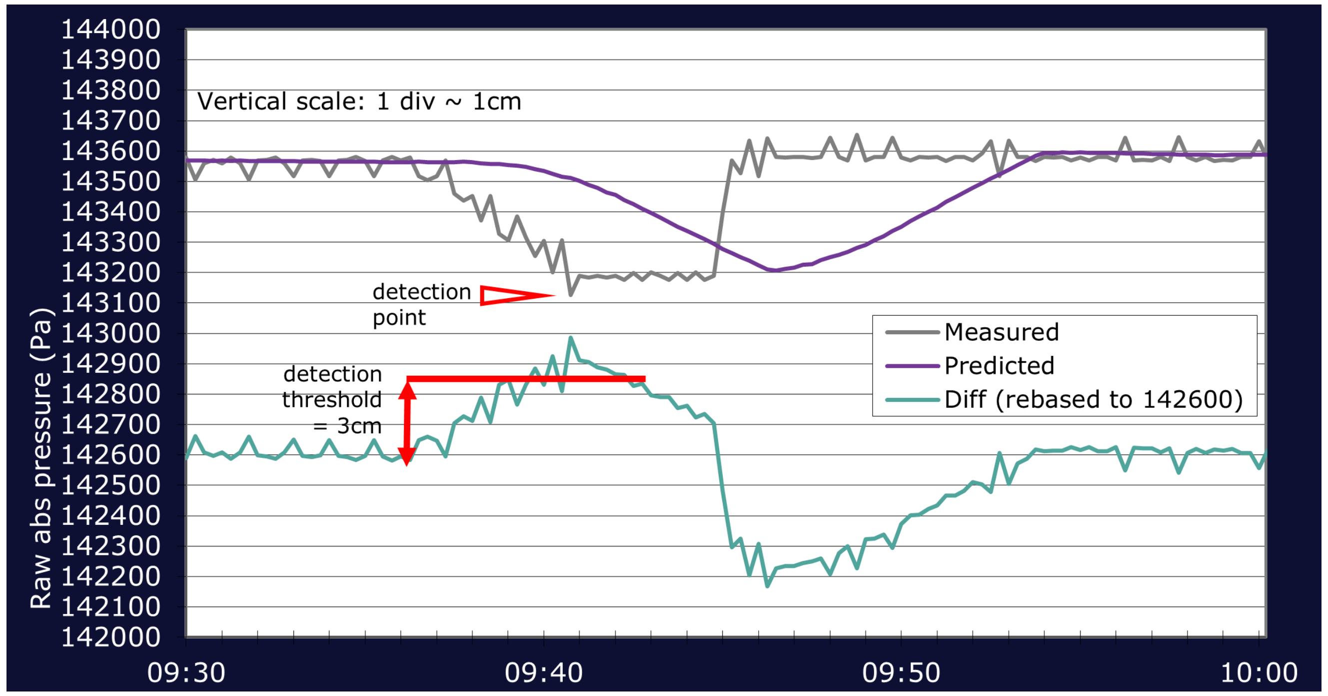


Figure 1 – Simulated tsunami event (10,000 psi Digiquartz sensor)

How much warning time does TEWS provide?

The warning time provided by a detection using this method is dependent on both the depth and distance of the BPR from shore.

A tsunami wave travels at a speed (in ms-¹) roughly equal to the square root of the depth of the water in metres multiplied by the acceleration due to gravity (9.81 ms-¹) – in short, it travels faster in deeper water - see Figure 2.

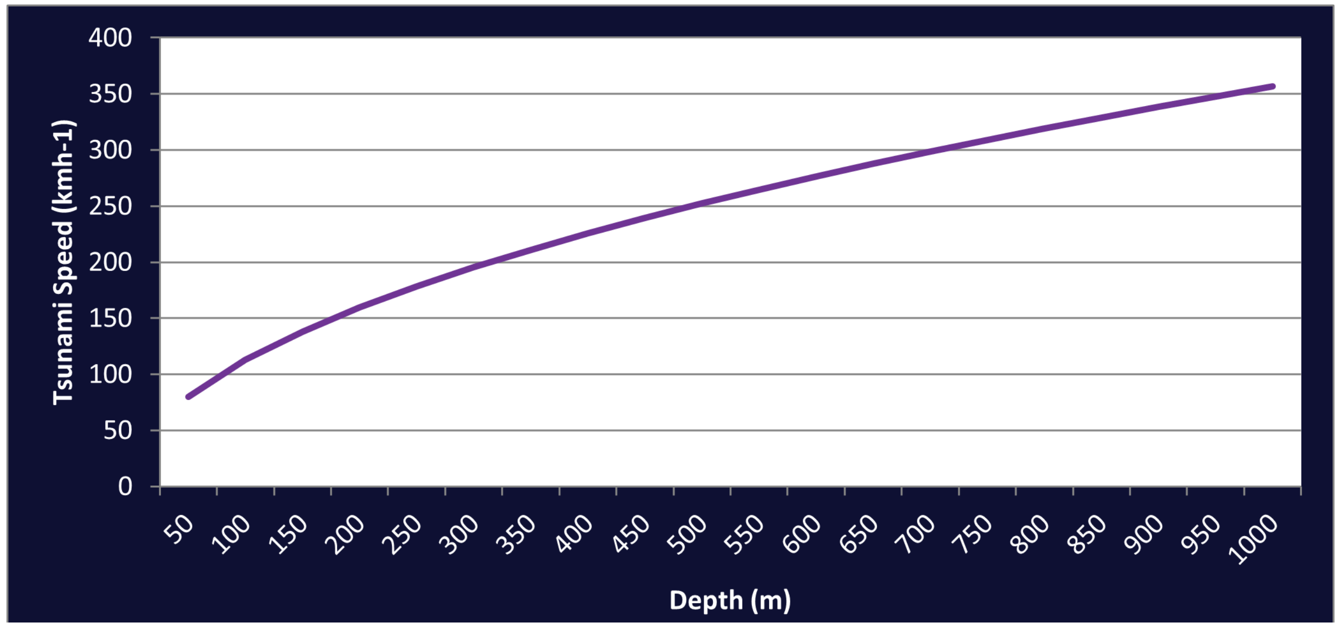


Figure 2 – Tsunami speed in different depthsDigiquartz sensor)

While depth is the controlling factor in terms of tsunami speed, this has to be combined with distance offshore to calculate time of arrival at the coast. Obviously, this assessment is not straightforward as bathymetry varies; however, it is reasonable to assume that a tsunami crossing a wide continental shelf will slow and arrive later than a tsunami crossing an equivalent distance where the shelf break is close to the coast.

Nevertheless, the depth will in all cases decrease towards the shore, meaning that the tsunami will slow significantly as it approaches the coast. As it does so though, its height (amplitude) increases – this is the reason why a tsunami that passes almost imperceptibly in open ocean, can arrive at the coast many metres high.

Referring to Figure 3, a station in 800 m depth, 200 km offshore would give a warning time of at least 38 minutes, while a station the same distance offshore, but in only 200 m of water, would give a longer warning time of at least 75 minutes.

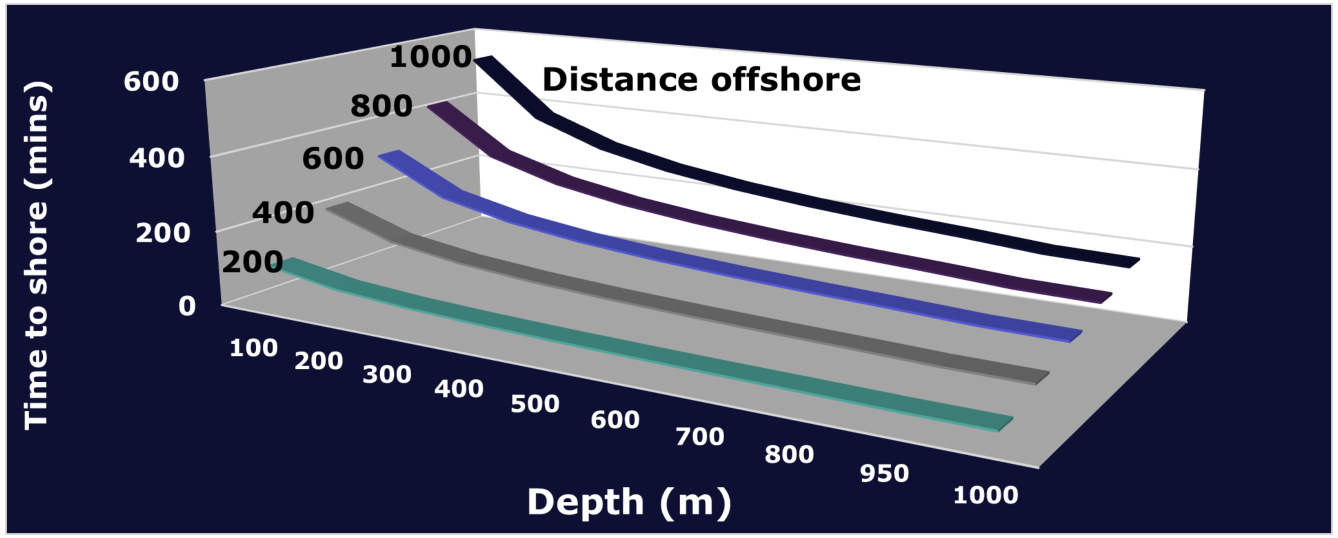


Figure 3 – Tsunami time to shore by depth and distance offshore

TEWS Overview

Detection is just one component of the TEWS – to be useful, the detection of the tsunami offshore has to be transmitted ashore. The TEWS therefore comprises three main components (detailed descriptions are given later in this guide):

- Bottom Pressure Recorder (BPR) – this is deployed on the seabed and continuously monitors the pressure of the water above it. The BPR is linked to the surface by an acoustic telemetry link.
- Tsunami Buoy – this is a specially designed buoy that operates as an interface between the BPR and the shore control centre (SCC). The buoy is fitted with a Surface Modem Transceiver (SMT) for communication with the BPR, a smart datalogger (CPU) to control the SMT, other operational peripherals and satellite communications between the buoy and SCC.
- Shore Control Centre (SCC) – software hosted either locally or the web is used to remotely control and monitor the TEWS. Alerts received from the system can be assessed and used to alert coastal populations at risk.

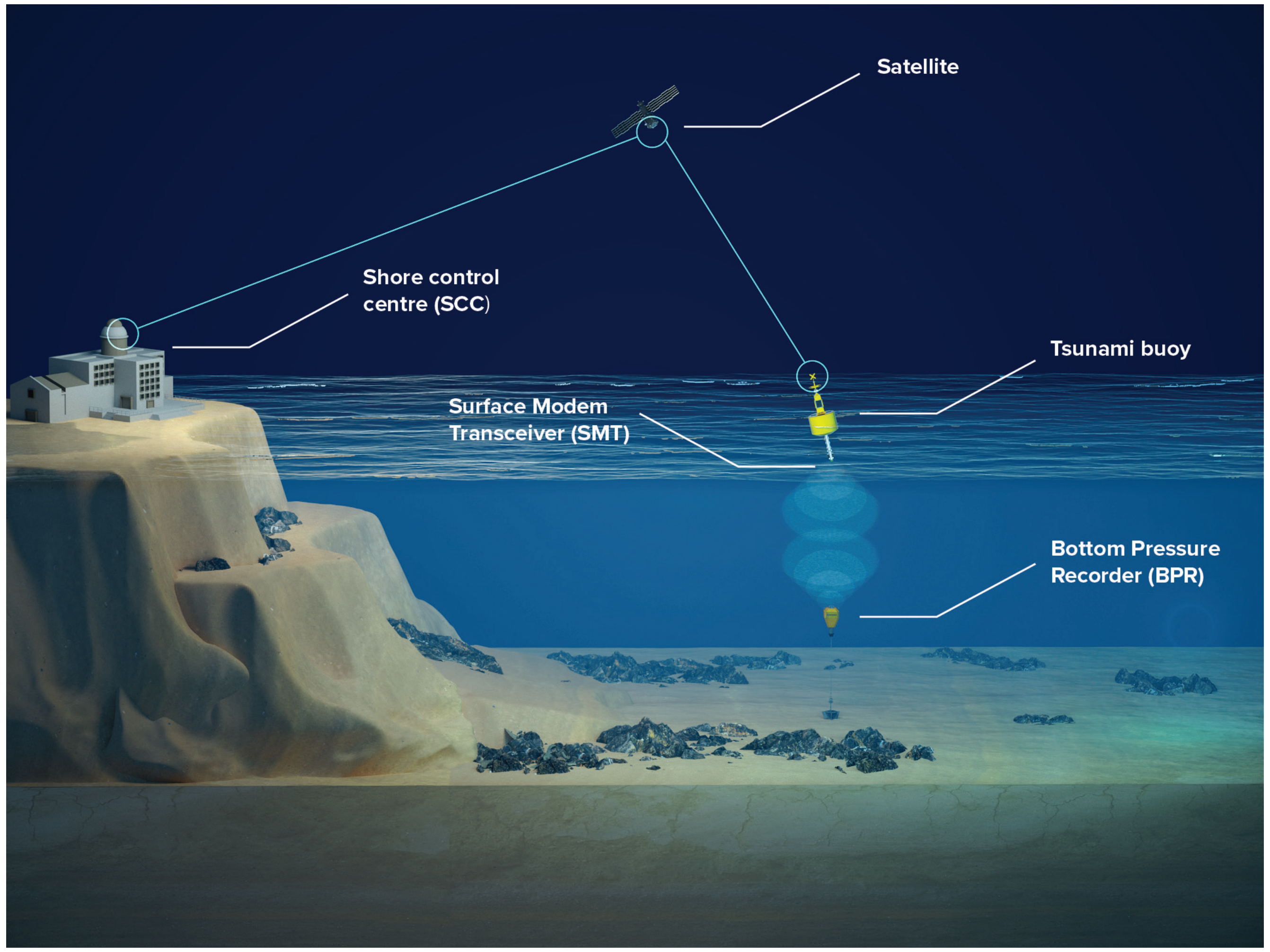


Figure 4 – Tsunami early warning system (TEWS) overview

Communications & DART Messaging

The components of the TEWS are linked by two communications paths:

- Acoustic Telemetry – This uses Sonardyne's latest 6th Generation (6G®) Wideband®2 digital acoustic technology to provide robust bi-directional through water communications between 100 – 9,000 bits per second, even in difficult acoustic conditions. The lower medium frequency (LMF) band, 14–19 kHz, provides longer communication ranges, enabling operation in extreme depths (>4,000 m), even when the surface buoy is displaced laterally by weather conditions. TEWS uses Sonardyne's SMS text messages, which supports the transfer of small human-readable ASCII messages and commands.
- Satellite Telemetry – This uses the Iridium low earth orbit (780 km) constellation of polar orbiting satellites, which provide worldwide coverage and use the L-band (1 -2 GHz). Iridium offers advantages in both redundancy and power requirements.

TEWS supports NOAA's Deep-ocean Assessment and Reporting of Tsunami (DART®) message formats (Table 1.) This means that these messages can easily be ingested into NOAA's National Data Buoy Centre (NDBC) portal.

Message type	Description	Content	Periodicity

D$1	Standard hourly	• Date/time
		• BPR battery status
		• Buoy battery status (added in the buoy)
		• Water level height
		• Flags for:
		  • low battery
		  • override of low battery
		  • tilt (>30° from vertical)
		• BPR temperature
			Normally sent hourly by BPR but D$1 messages can be accumulated in the buoy to reduce satellite airtime.

D$2	Tsunami report	• Event trigger time • Measurement time • Water level height • Deviation from trigger water level measurement. Each message has an incremental ID from the initial report which has ID 00.	The first message is sent as soon as a tsunami is flagged. Subsequent messages are sent as per the schedule shown in Figure 5.
D$3	Hourly Tsunami	• Event trigger time • 120 water level heights – 60 previously reported and 60 new. Each message is indexed from 01.	Replaces hourly D$1 messages when BPR is in alert mode. These exceed the SMS limitation of 128 characters, so are divided into several shorter messages that are recombined in the buoy or SCC.

Table 1 – DART Message Overview

In routine operation, TEWS sends hourly D$1 messages. Once a tsunami is identified by the algorithm, the system goes into alert mode and sends more frequent D$2 messages, while the D$1 hourly messages are replaced by D$3 messages. Transmission of D$3 message continues for six hours; however, if the system is still flagging a tsunami after this, a further hourly D$3 message will be sent.

This continues until a tsunami is no longer being flagged (see Figure 5).

In all cases, the BPR checks that the message has been acknowledged at the buoy. The BPR will resend the message up to two times if no acknowledgement is received.

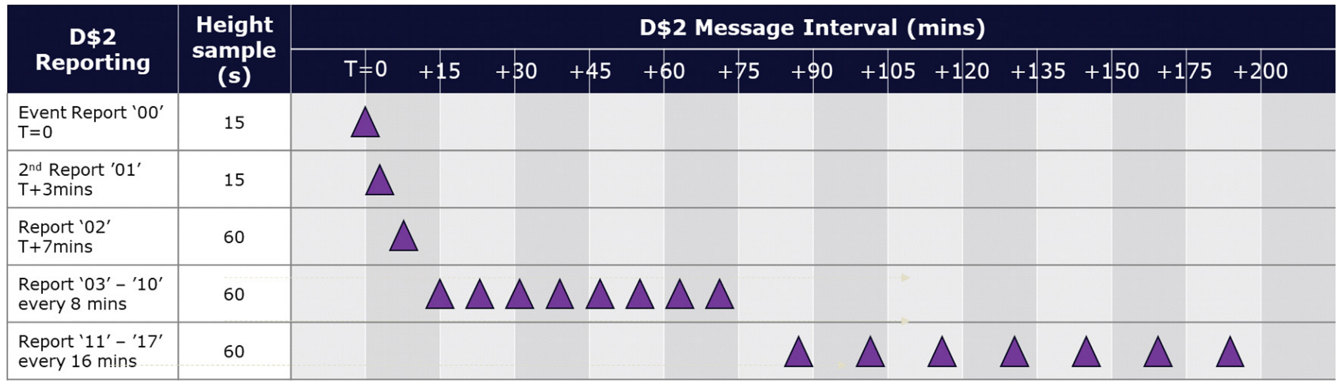


Figure 5 – D$2 reporting schedule

Bottom Pressure Recorder

Sonardyne's BPR is at the heart of the TEWS and is based on the company's successful Compatt 6 seabed acoustic transponder and is available in a variety of versions suitable for deployment in water depth down to 7,000 metres. The BPR comprises the following main components:

- Paroscientific Digiquartz® pressure sensor – This is accurate to 0.01% of range scale (usually 6,000 psi [4,100 m] or 10,000 psi [6,800 m]), and is temperature compensated, using a platinum resistance thermometer to provide highly repeatable measurements. Each pressure measurement is the average of 15 one second samples.
- Data Acquisition System (DAS) – Every 15 s, this converts the pressure sensor outputs into pressure which is logged to SD card. In routine operation, every hour a DART string is passed to the Digital Signal Processor (DSP). The DAS also runs the NOAA tsunami detection algorithm and will switch the instrument into alert mode if a detection is made. This initiates continuous transmission of pressure data for the next few hours.
- DSP and Acoustic Transducer – The BPR uses a directional transducer with ±40° beam shape, which together with five transmit source levels between 202 – 169 dB re 1 µPa @ 1 m, delivers optimum transmission to the surface. The transducer also has 6 levels of receive sensitivity between 80 – 120 dB re 1 µPa, in order to receive commands from the surface.
- Battery Pack - The 6G BPR can be configured in three battery variants (Table 2). The standard and maxi variants are both tube housings, whereas Fetch is a glass sphere housing. The BPR can be programmed to auto-disable when the battery depletion reaches a pre-set reserve level, typically 15 Ah, which preserves enough power for acoustic command and release on recovery. This equates to 85% on a standard variant.

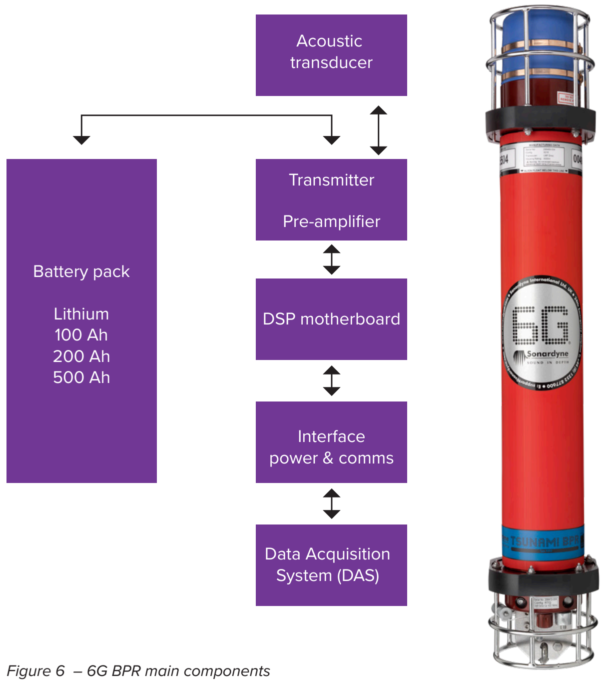


Figure 6 – 6G BPR main components

Variant	Battery capacity (Ah)	Nominal life	Life with reserve
Standard	100	725 days	616 days
Maxi	200	1450 days	1341 days
Fetch	500	9 years	8.75 years

Table 2 – 6G BPR Battery Life

The standard and maxi variants (see figure 7) are deployed using an anchor and strop. The BPR is moored with a specially designed arrow-shaped steel sinker to ensure optimal descent to the seabed, ensuring it is vertically embedded. The BPR is held in position with a floatation collar (300 N standard, 760 N maxi).

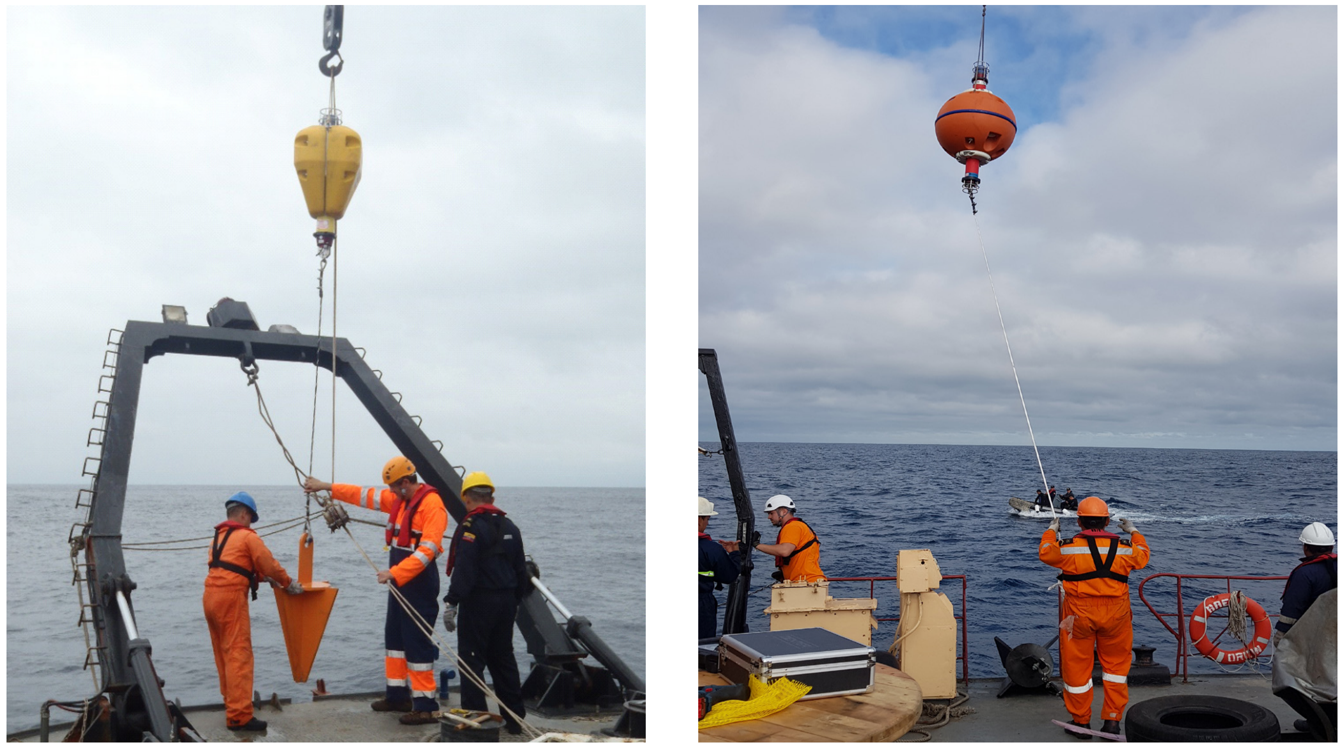


Figure 7 – Standard (left) and maxi (right) 6G BPR with floatation and anchor being deployed

Tsunami buoy

MSM's tsunami buoy fitted with a Sonardyne Surface Modem Transceiver (SMT), acts as a surface gateway for BPR generated DART messages. It communicates with the SCC via a redundant (dual modems and antennas) Iridium satellite communications system. The buoy is moored using a hybrid mooring system, with designs for depths down to 7,000 m.

The EBM24-TS buoy (Figure 8), which is suitable for deployment in depths of up to 4,000 m, comprises an aluminium superstructure with a 2.4 m diameter float and stainless-steel tail. The float is manufactured from closed-cell polyethylene foam rolled up and heat-welded to form a single core, which is then protected by pigmented elastomer polyurethane. This results in a float that is shock-resistant and virtually unsinkable with no water-absorption. The superstructure and float are both coated to ensure high resistance against corrosion and UV radiation.

The buoy complies with all applicable IALA recommendations. This ensures maximum visibility in deep ocean, with a day mark (constituted by the superstructure) providing over 1.3 nautical miles of day visibility and complemented by a top mark and radar reflector. Additionally, the LED lantern integrated in the mast provides a range of over 5 nautical miles for night visibility. An Automatic Identification System (AIS) Aids to Navigation (AtoN) transponder transmits the location of the buoy and its purpose to passing vessels through AIS Message 21.

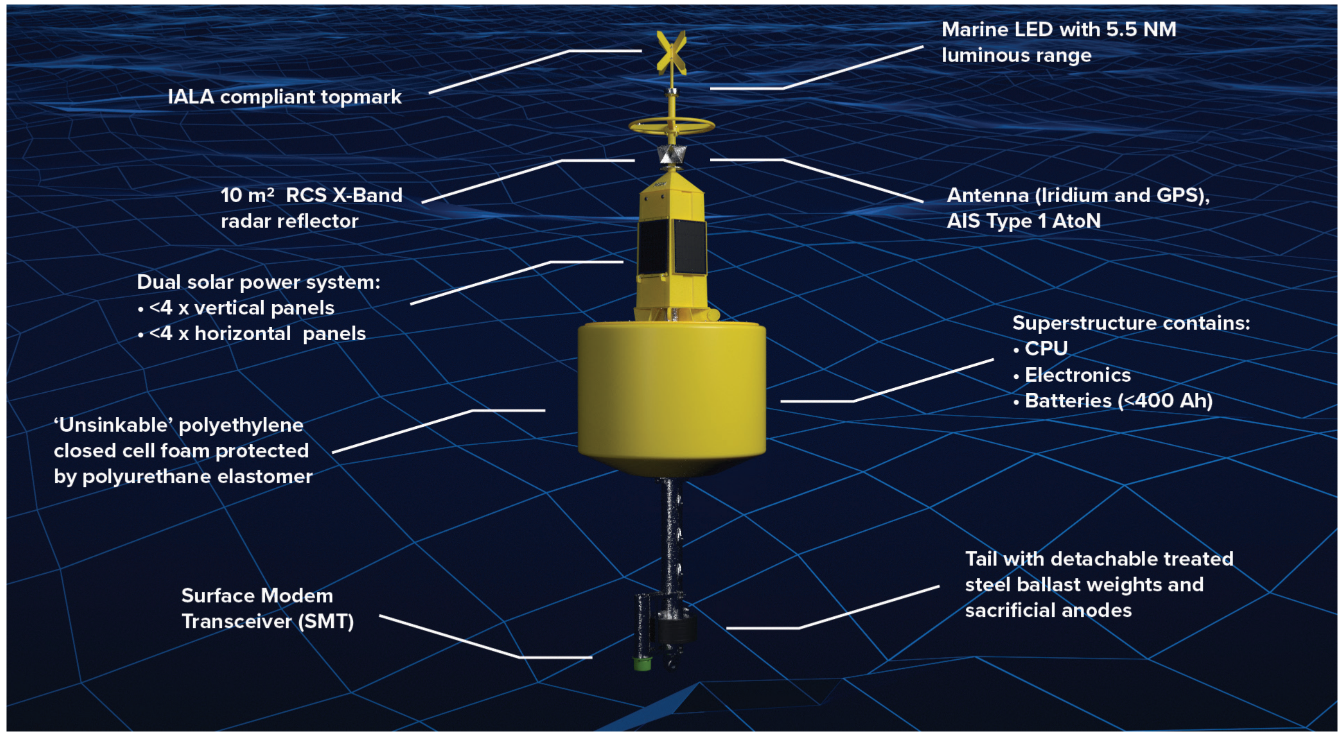


Figure 8 – MSM EBM-24TS tsunami buoy

The buoy is fitted with several field-proven safety and anti-vandalism measures:

- GPS positioning with out-of-position alarm and drift tracking
- Anti-vandalism (unremovable) solar panel frames
- Impact sensor with alarm to SCC
- Safety lock on watertight door of superstructure
- Intrusion sensor with alarm to SCC
- Ship Proximity Remote Report and Surveillance (ShiPRAS) capability for locations with high vessel traffic

The buoy and all peripheral devices are controlled by the CPU with an integrated datalogger. This includes the SMT, positioning, alarm, AtoN systems, and satellite modems. All onboard devices are monitored by AI routines within the specially designed firmware. This detects and repairs malfunctions, including deconfliction of device software routines or freezing. Furthermore, the datalogger has the capability to communicate directly with the BPR in remote mode from the SCC if necessary.

The SMT provides a RS232 command and control interface that enables both receipt of DART messages from the BPR and the ability to send commands to it. It is supplied with an armoured 10m strain cable, which enables it to be mounted well below normal surface wave action, while an acoustic baffle enhances rejection of surface noise. The directional transducer supports three transmit source levels between 196–172 dB re 1 µPa @1 m and has six levels of receive sensitivity between 95–130 dB re 1 µPa.

The buoy's hybrid mooring system is designed for hostile open water deployments of more than two years in depths in excess of 5,000 metres. It comprises a combination of steel chain and shackles with high-resistance nylon rope suspended with intermediary floats, anchored to a steel sinker. This combination makes it robust to high sea states and vandalism.

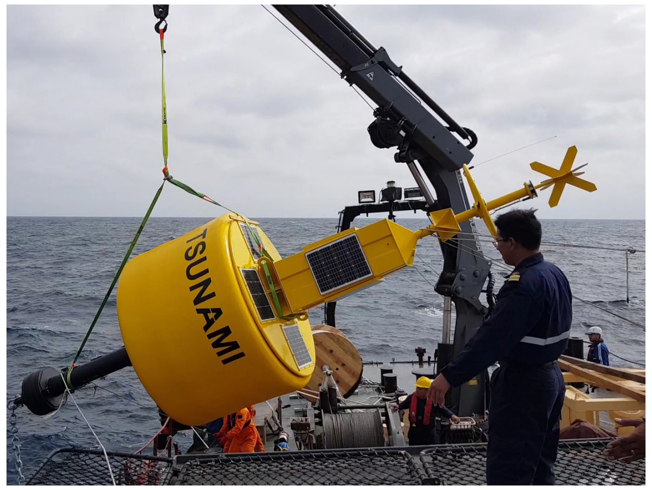


Figure 9 – SMT (left) and part of the mooring system mounted on buoy tail (right)

SCC

Central to the operation of the SCC is MSM's NETCOM-TS software web application, which enables remote management of the tsunami buoy and BPR (Figure 10), as well as display and management of TEWS data (see Figure 11). The web-based application is usually installed on two dedicated servers to provide redundancy and can be backed up by MSM's cloud server.

NETCOM-TS' software ensures the early detection of any issue, enabling maintenance to be programmed in a timely manner, thus guaranteeing continuous availability of the system. The status of and alarms from the BPR and buoy systems are displayed as outlined in Table 3.

Additionally, remote commands, such as status requests, some configuration changes and a system reset, can be sent to the buoy as well as the BPR.

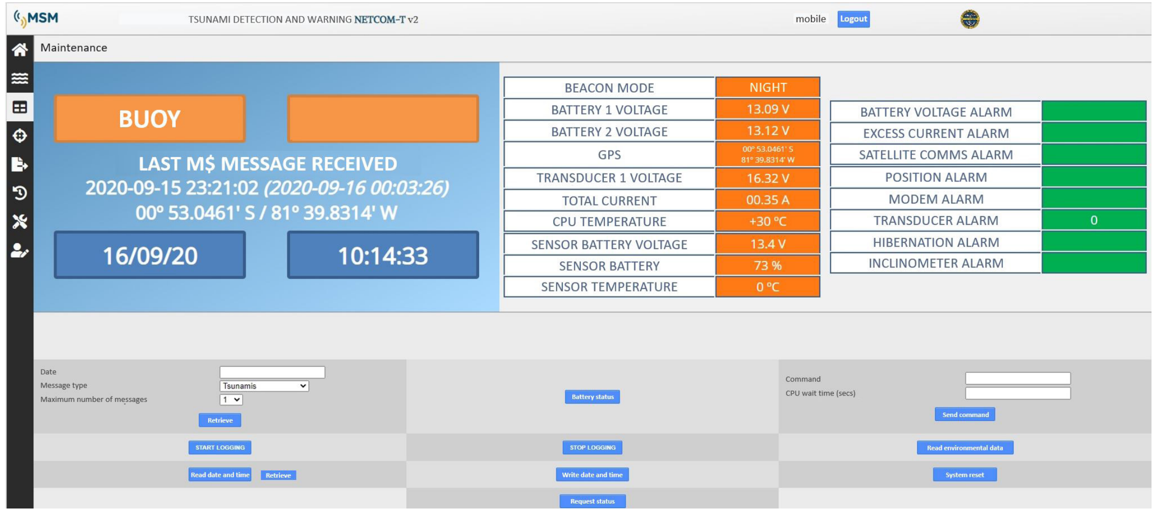


Figure 10 – NETCOM-T web application showing TEWS status

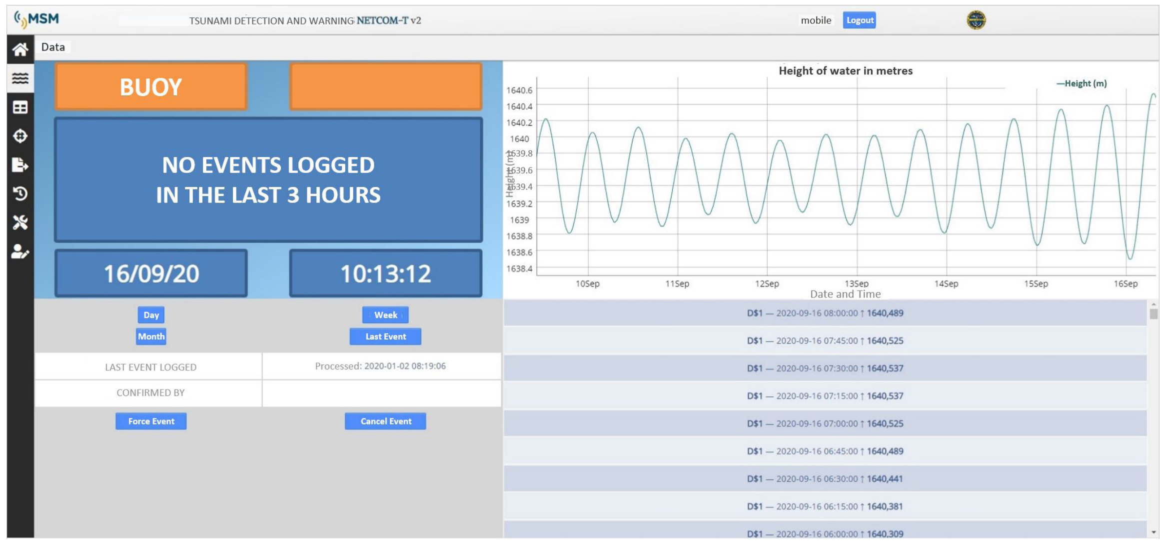


Figure 11 – NETCOM-T web application showing D$1 messages.

System	Sub-system	Status	Alarms
Buoy	Lantern	Operating mode	
	Solar power system	Battery voltages	• Battery voltage • Overconsumption
	SMT	Voltage	Failure
	Datalogger	• Total voltage • Temperature	
	GPS	Position	Out of position
	Satelitle comms link		Fault
BPR	200	• Battery voltage • Remaining battery capacity • Temperature	• Hibernation • Inclination

Table 3 - NETCOM-TS status and alarms

If NOAA is set up to access the SCC server by FTP, the DART messages will automatically be shown on the NOAA National Data Buoy Center (NDBC) website (see Figure 12).

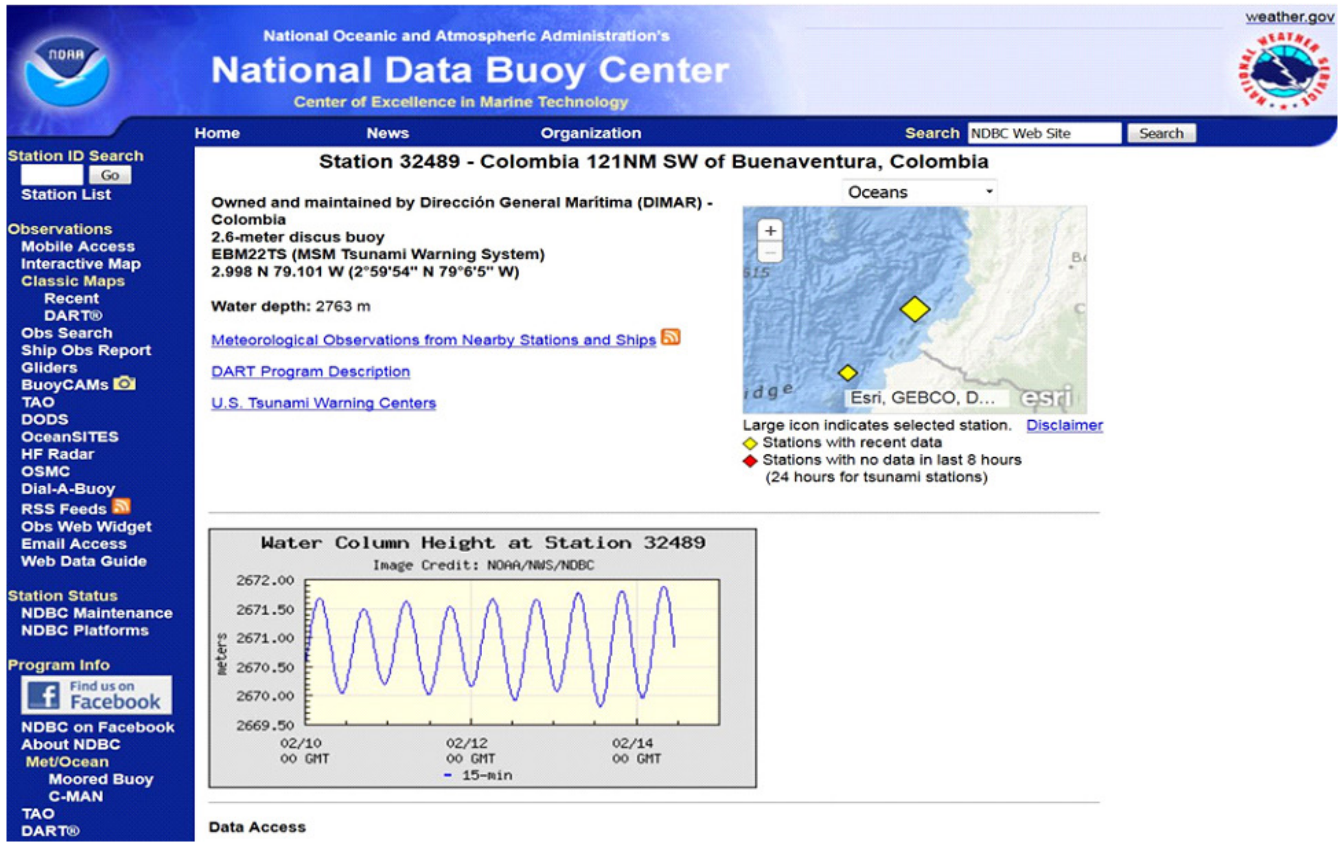


Figure 12 – NOAA NDBC website showing data from Colombia TEWS

Track record

MSM Ocean and Sonardyne have supplied TEWS to a range of customers

- Colombia - Dirección General Marítima (DIMAR)
- Ecuador - Instituto Oceanografico de la Armada (INOCAR)

Separately, Sonardyne have supplied tsunami detection systems (without buoy or SCC) to the following customers:

- India – National Institute of Ocean Technology (NIOT)
- Greece – CSNet/Oceanography Centre of Cyprus
- China - Institute of Oceanographic Instrumentation, Shandong Academy of Sciences

Many of these feed data to NOAA's global network (see Figure 13).

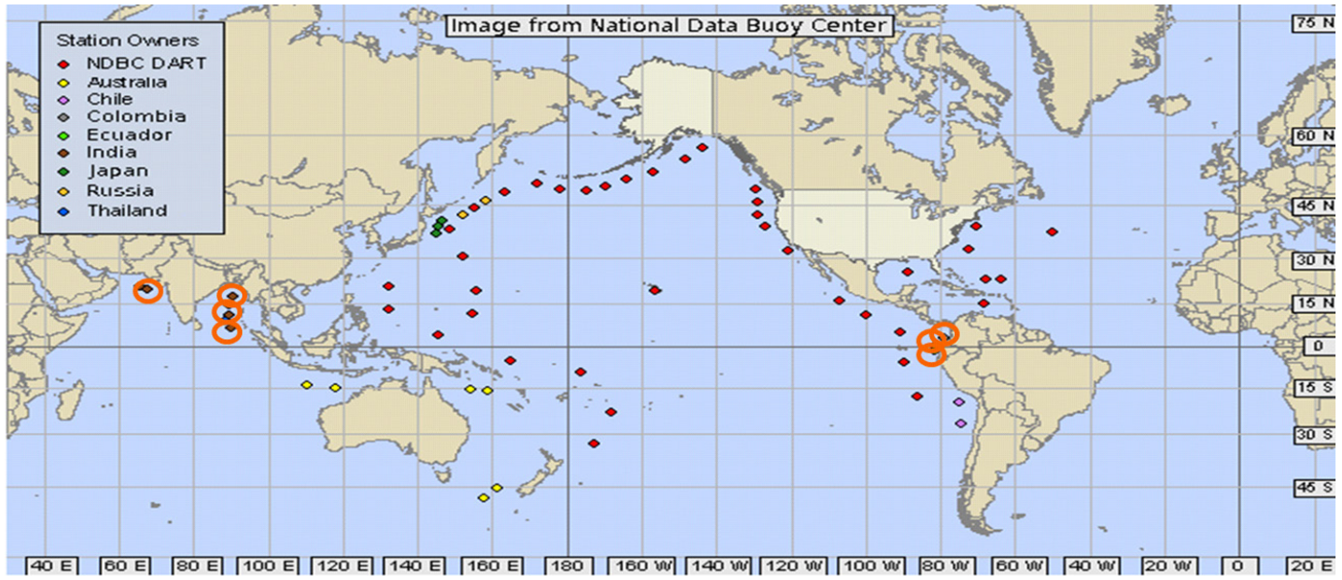


Figure 13 – Tsunami systems in operation (circled)

Case study - Ecuador

Two TEWS buoys were first installed off the Manta and Esmeraldas coast in Ecuador for the Navy's Oceanographic and Antarctic Institute (INOCAR) in 2011. On 15th January 2022, these went into alert mode following the violent eruption of the Hunga-Tonga submarine volcano in the South Pacific.

Originating from more than 10,000 km away, the tsunami was detected by the Manta and Esmeraldas stations at 19:24:30 and 19:39:30 (UTC) respectively. The buoys immediately went into alert mode, with the first alert message arriving at INOCAR's National Tsunami Warning Center of Ecuador less than 35 seconds after the detection. As described above, the systems then transmitted a stream of D$2 and D$3 messages for subsequent real time monitoring. The buoys measured a variation of the water of up to 12 cm over the course of the event, initiated by the 3 cm threshold.

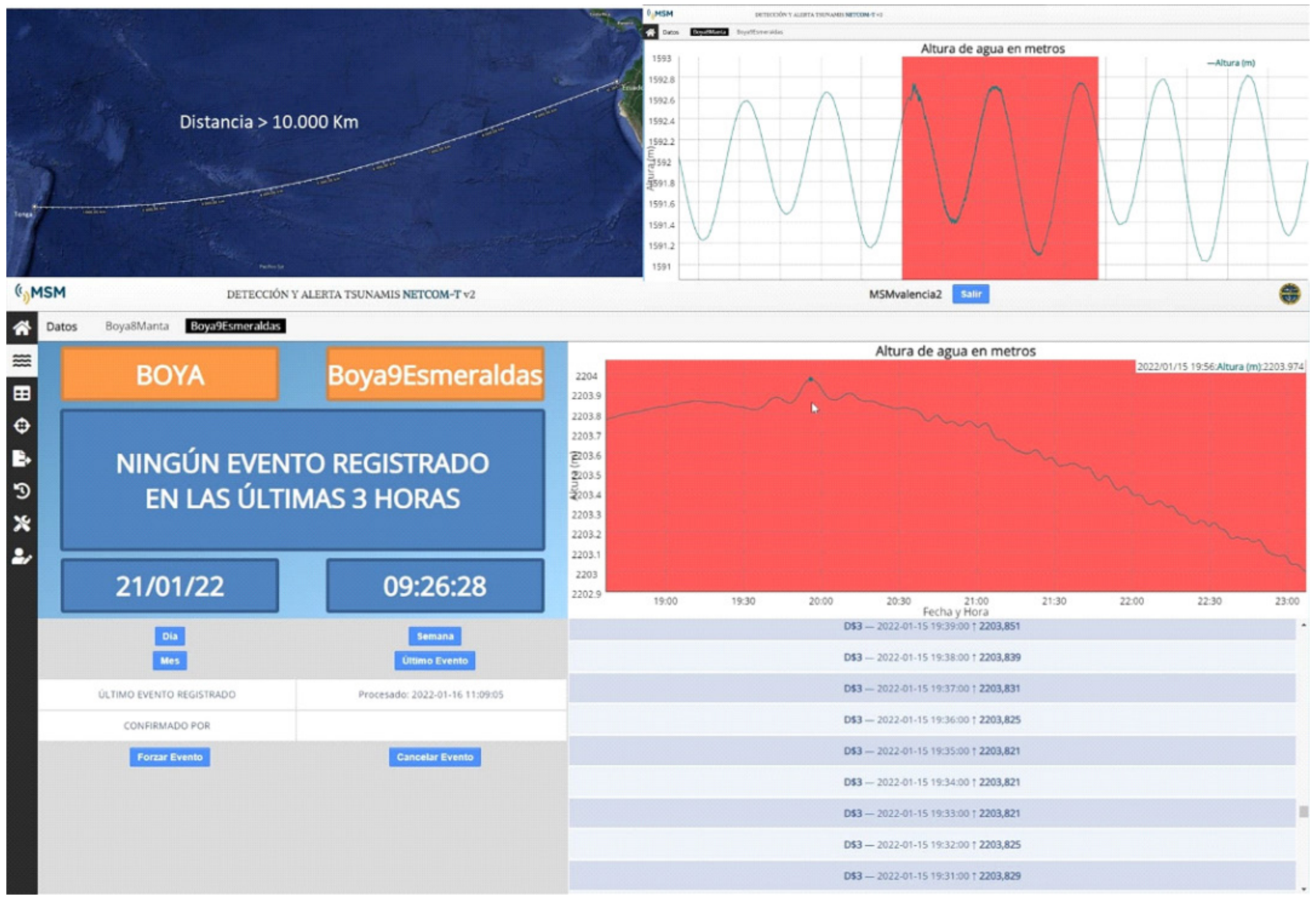


Figure 14 – Tsunami detection following Hunga-Tonga eruption 15th Jan 2022

Frequently asked questions

What are the main factors that affect DART message return?
Tests and operational deployments have shown that 98% of acoustic messages from the BPR are received at the buoy. However, the main reliability issues are generally due to issues at the buoy and have required mitigation:

- Rough Weather - TEWS is designed to be both physically and acoustically robust in rough weather: the transducers on the BPR and SMT have sufficiently wide beam angle (±40°) to ensure an acoustic path in most circumstances, even when the buoy is laid over by wind/wave action. The SMT is also baffled to reject surface noise, while a 10m armoured cable means that the SMT can be mounted below most surface effects.

- Vandalism - Tsunami buoys have been subject to vandalism, so the buoy is fitted with a range of measures to mitigate this (see *Tsunami buoy*)

- Fishing gear entanglement – Net entanglement can affect communications with the SMT; however, use of an IALA compliant buoy mitigates this by ensuring detection/visibility of the buoy in most conditions at a good range. Fishing gear entanglement can also be inferred from some of the values available in the software, which enables a maintenance response to be scheduled in a timely manner.

- Bio-fouling – Heavy biofouling has been observed on the SMT during several deployments, but has not been a source of acoustic comms failure.

What is the power draw of the BPR?
In routine operation, the BPR draws a quiescent power of <80 mW and has a daily usage of 2 Whrs including acoustic status messages. In alert mode, when transmitting a sequence of event data messages, the additional accumulated power drain is only 0.3 Whrs.

How often does TEWS need maintenance?
BPR deployment is purely limited by the battery capacity (see *Bottom Pressure Recorder*). With regards to the buoy, a lot depends on the deployment location and its environment, including susceptibility to biofouling of the SMT, fishing or interference from vandals.

What support for deployment, training and support can MSM Ocean/Sonardyne supply?
MSM Ocean and Sonardyne can provide support for all aspects of training, commissioning and support during TEWS installation, as well as options for through-life maintenance and support.

Is it possible to access raw data on the BPR?
Every 15 second pressure measurement is recorded to SD card for backup and later recovery via a card reader. Short periods of data may be recovered remotely over the acoustic link.

Is TEWS compatible with other Sonardyne Transceivers?
TEWS is compatible with any LMF enabled Sonardyne transceiver. This includes LMF Ranger 2 ultra-short baseline systems, which can be used to accurately position the BPR on the seabed, as well for communicating with it and tracking it during ascent following a release. A LMF acoustic comms module only is also available for USVs, which can be used as a temporary surface gateway if for any reason the buoy is not on station.

What is the 'Near Field Problem'?
TEWS works best when deployed far enough from the coast to produce sufficient warning time; however, tsunamis that can reach the coast within an hour of generation are known as 'near field' events and are problematic for detection by BPR in two ways:

- Such events, by their nature, offer very little warning time

- The seismic event generating a tsunami will also produces seismic waves that will be detected by the BPR – these waves may persist for some time and are liable to mask detection of the tsunami if they coincide with the time of passage of the wave over the BPR.

Consequently, the detection of near field tsunamis is an ongoing subject of research in the academic community. At present, the approach to near-field tsunamis is therefore use of multiple sensors to assess and monitor risk.

Is Digiquartz sensor drift a problem?
All Digiquartz sensors drift; however, because the NOAA algorithm is comparing the measure water height to a predicted water height based on the previous three hours of measured data, drift is not a problem. Sonardyne do produce an instrument with in-situ calibration of the pressure sensor that uses a technique called ambient-zero-ambient (AZA) for situations when the customer requires accurate pressure measurement.

Resources and references

NOAA and DART

DART® (Deep-ocean Assessment and Reporting of Tsunamis)- https://nctr.pmel.noaa.gov/Dart/

NOAA tsunami algorithm: https://nctr.pmel.noaa.gov/tda_documentation.html

DART message formats: https://nctr.pmel.noaa.gov/Dart/Pdf/dartMsgManual3.01.pdf

NDBC: https://www.ndbc.noaa.gov/

BPR and SMT

Sonardyne tsunami detection system datasheet: https://www.sonardyne.com/wp-content/uploads/2021/07/Sonardyne_8303_Tsunami_6G_TDS.pdf

Sonardyne tsunami 6K detection system datasheet: https://www.sonardyne.com/wp-content/uploads/2021/07/Sonardyne_8303_602-0140_Maxi-6k-Tsunami_6G.pdf

Sonardyne Fetch datasheet: https://www.sonardyne.com/wp-content/uploads/2021/06/Sonardyne_8306_Fetch-General.pdf

Sonardyne Fetch AZA datasheet: https://www.sonardyne.com/wp-content/uploads/2021/06/Sonardyne_8306_Fetch_AZA.pdf

Tsunami buoy

MSM EBM24-TS datasheet: https://msmocean.com/en/tsunami-buoys/

Case studies

Detection and Early Warning of Tsunamis in Ecuador: https://msmocean.com/en/successful-case-detection-and-early-warning-of-tsunamis-in-ecuador/

Detection and Early Warning of Tsunamis in Ecuador- Tonga volcano - January 15 2022: https://msmocean.com/en/successful-story-detection-and-early-warning-of-tsunamis-in-ecuador-tonga-volcano-january-15/

Underpinning the Indian Tsunami early warning system: https://www.sonardyne.com/case-studies/underpinning-the-indian-tsunami-early-warning-system/

About the partners

Mediterráneo Señales Maritimas (MSM Ocean)

Mediterraneo Señales Maritimas (MSM Ocean) has been integrating instrumentation in its buoys since 2009, culminating in the creation of a dedicated Oceanographic Division, MSM Ocean, which now leads in the development and implementation of data measurements systems.

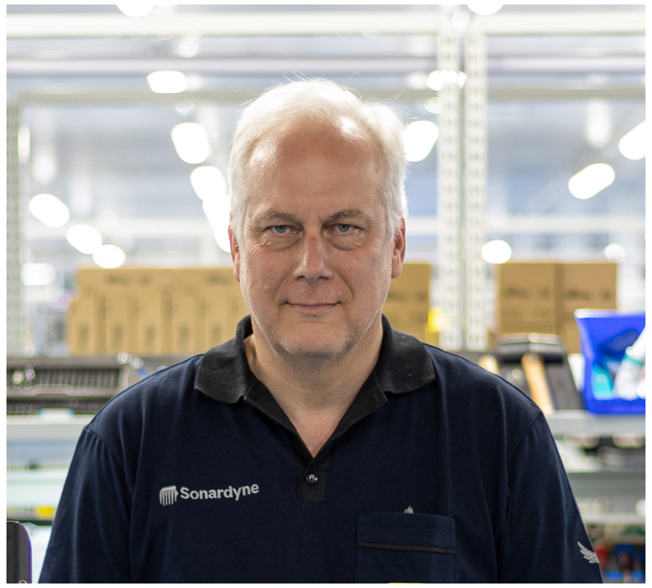
MSM Ocean have collaborated with Sonardyne since 2011 on the development of TEWS , completing the installation of two buoys that same year. As a consequence, it now has over a decade's track record of successful deployment and support of tsunami buoys.

Sonardyne

Sonardyne supplied its first Tsunami Detection System (TDS) the National Institute of Ocean Technology (NIOT) in India in 2007. For this project Sonardyne were not responsible for buoy or SCC provision. Subsequently and since 2012, Sonardyne have worked closely with MSM to provide tsunami systems to a range of customers.

Sonardyne introduced the 6G Compatt in 2010 and it is now field-proven, with many systems operating worldwide; all benefitting from Sonardyne's Wideband® 2 technology, which constitutes the most flexible and reliable acoustic systems available to date.

About the authors



Geraint West is a Chartered Marine Scientist and has managed Sonardyne's ocean science business activity since 2016. His working career in the maritime sector stretches back almost 40 years and includes the Royal Navy, Fugro and the National Oceanography Centre.

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