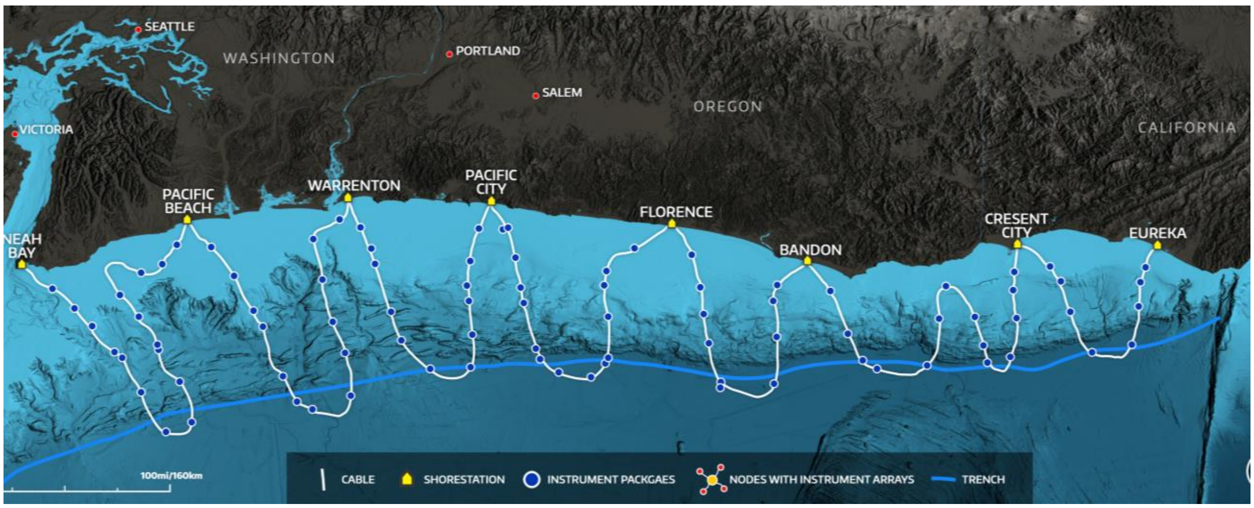
Seafloor Systems for Detecting Earthquakes and Tsunamis: An Engineering Trade Study



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1.0 Executive Summary

A review of mature platform systems and instruments that are relevant to an offshore Cascadia earthquake and tsunami early warning system is presented. Other mature instrumentation technologies that could be adapted or are currently in development and which show promise to be sufficiently mature for this purpose within five years are also discussed.

In order to meet the low data latency, instrument spacing, and other stated requirements for an effective earthquake and tsunami early warning system, a cabled seafloor array of seismometers and bottom pressure recorders is recommended. As currently envisioned, such as system is projected to have an installed cost of \$245M-\$486M, depending on configuration. The addition of a small number of DART buoys should be considered to enhance tsunami coverage in the hours following the arrival of a tsunami. Incorporating some degree of modularity to the cabled system is also recommended in order to minimize servicing costs and to allow efficient instrument upgrades and in-kind replacement of damaged instruments and cables.

2.0 Introduction

In 2016, the Gordon and Betty Moore Foundation provided funding to the University of Washington to explore the development of a real-time, offshore earthquake and tsunami early warning system for Oregon, Washington State and Northern California. Since the subject region is the Cascadia Subduction Zone, this work is also relevant to British Columbia as well as to other regions around the world with similar geophysical characteristics.

This document presents a trade study[1] of existing early warning technologies that are potentially applicable to the envisioned future system. Positive and negative attributes of each technology relative to the needs of the envisioned system are discussed and compared. This document constitutes a basis for follow-on work: specifically, discussions with potential technology providers, and design and cost-benefit analysis of potential alternate configurations for instrumenting the Cascadia Subduction Zone.

3.0 Background

An offshore Early Warning System[2] (EWS) may be considered to be composed of the following three major subsystems.

1) Instrumentation packages at specific offshore locations, that each monitor one or more parameters of interest.
2) A power and communications subsystem that powers the instrumentation packages and relays data back to shore.

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[1] A trade study examines potential solutions to a technical problem, with the goal of selecting the most desirable and practical alternative(s).

[2] For brevity, the term 'early warning system' and the acronym EWS will be used in place of 'real-time, offshore earthquake and tsunami early warning system' in this study.

3) A data processing subsystem that autonomously determines whether an event is significant enough to require notification, and which then forwards this information to the public, first responders, and other stakeholders via a notification system such as ShakeAlert[3] or the U.S. Tsunami Warning System[4].

Each of these subsystems may be implemented in more than one configuration. For example, a power and communications subsystem may be a permanent, cabled network on the seafloor with the cable connected to the shore infrastructure, or it may be an uncabled, distributed network of independently powered stations that communicate with the shore infrastructure by radio. These alternatives are further developed in Section 4.0.

A conceptual diagram of a cabled Cascadia EWS is shown in Figure 1.

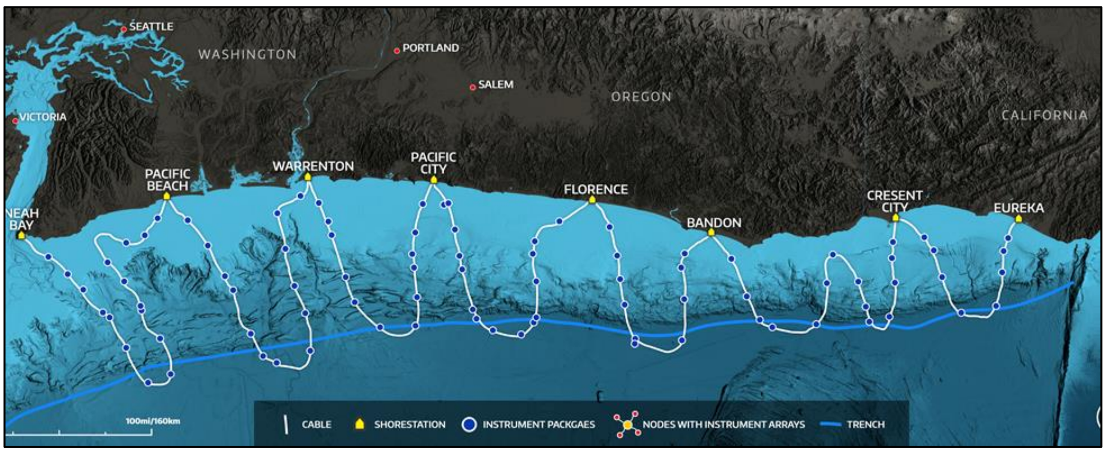

Figure 1. Conceptual configuration of a cabled Cascadia EWS

4.0 EWS Requirements

The white paper *Earthquake and Tsunami Early Warning on the Cascadia Subduction Zone*[5] lists the following earthquake detection requirements for an offshore EWS.

- The detection, classification and location of all offshore earthquakes likely to be "strongly felt" (MMI≥V) from locations onshore.
- An initial event detection within 10 seconds of nucleation, requiring a nominal station spacing of 50 km.
- A delay in data transmission (latency) of less than 2 seconds from the sensors to the analysis center.
- Continuous observations as the earthquake evolves so that the source parameters (magnitude and rupture extent) can be updated.

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[3] https://www.shakealert.org.

[4] https://tsunami.gov

[5] Schmidt et al., *Earthquake and Tsunami Early Warning on the Cascadia Subduction Zone: A Feasibility Study for an Offshore Geophysical Monitoring Network.* Seattle: University of Washington, 2019, 81 pp.

- System resilience such that at least part of the system remains operational after the main shock and can issue alerts for the aftershocks.
- A geographic distribution of stations that is widespread along the coast and offshore, both to "surround" an epicenter if possible and to facilitate tracking of a propagating large rupture.

The following tsunami detection requirements for an offshore EWS are also listed in the white paper.

- In 5 minutes or less, provide coastal impact predictions on a length scale of tens of kilometers, and then
- Every 10-30 minutes provide coastal impact predictions at decreasing length scales, down to 10 m resolution, focused on population centers and critical infrastructure sites, until the end of the tsunami threat.

5.0 Undersea Telecommunications Technology

The underlying technology for all current cabled ocean observatories and cabled offshore early warning systems derives largely from the undersea fiber optic telecommunications industry[6]. This section summarizes the history and key features of these fiber optic systems that are applicable to the design of an offshore EWS.

5.1 Fiber Optic Transmission Development and Transoceanic Systems

The first commercial terrestrial fiber optic communication systems, based on multimode fibers, were installed in 1977 by three organizations in competition with each other: GTE and AT&T in the US, and the British Post Office (BPO) in the UK[7].

Lower loss, single-mode fibers were subsequently developed, and were used together with multimode fibers in the first undersea cable trial in 1980 by Standard Telecommunications Laboratories and the BPO in the UK[8].

Fiber optic cables and supporting systems continued to be developed for underwater service, with the first fiber-based transoceanic system (TAT-8) being installed by a multinational consortium across the Atlantic Ocean from Tuckerton, New Jersey to Widemouth Bay, UK, and Penmarch, France in 1988. This system had two working fiber pairs with a third pair as a spare. It delivered a throughput of 280 Mb/s per fiber pair over a primary cable length of greater than 5800 km[9], and included the first commercial implementation of a branching unit (see Section 5.1.3) in a seafloor cable.

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[6] Except where explicitly noted, information about the undersea telecommunications industry and technology is derived from Chesnoy, Jose, ed. *Undersea Fiber Communication Systems, 2nd Edition*. Amsterdam, Elsevier 2016.

[7] Hecht, Jeff, *City of Light*, Oxford University Press, 1999.

[8] Ibid.

[9] *The Voyage that Changed the World*, ICPC Press Release, 01 December, 2008 https://www.iscpc.org/documents/?id=8

This technology continues to evolve, with transoceanic cables incorporating bundles of single mode fibers that currently deliver up to 20 Tb/s per fiber pair at a competitive cost. The recently installed Marea cable[10], a joint venture between Microsoft and Facebook, is an example of the state-of-the-art, spanning 6600 km from Virginia Beach, Virginia to Bilbao, Spain with a capacity of 160 Tb/s through eight fiber pairs.

Modern transoceanic cable systems have benefited from a number of design iterations over the last 30 years that enable them to economically provide high data rates and high reliability in an extremely hostile environment with a design life of 25 years, without routine servicing. These systems are composed of the following components, all of which are applicable to a cabled EWS.

5.1.1 Undersea Cables

In common with high bandwidth terrestrial telecommunications cables, current undersea versions are based on optical fibers, which consist of a silica core surrounded by a high-refractive index glass cladding that contains the light signal within the core. Single mode fibers have a greater data carrying capacity than multimode fibers and are the preferred choice for long telecommunications cables. A typical single mode fiber has an 8 µm core diameter, a 125 µm outside diameter, and is covered by a thin plastic sheath for protection which is colored to uniquely identify specific fibers within a bundle.

The following elements are commonly integrated in the construction of undersea fiber cables (see Figure 2 for an example), listed in order from the center of the cable outward.

- Pairs of optical fibers, typically single mode for maximum data rate/minimum attenuation. One fiber in each pair transmits in one direction, the other transmits in the reverse direction. To maximize throughput per fiber, it is common for several channels, each at a different wavelength, to be combined at the fiber input and separated at the output.
- A continuous plastic, copper or stainless steel, gel-filled buffer tube surrounds the fibers and is located along the central axis of the cable. The buffer tube protects the fibers from crush damage and is flexible enough to accommodate movement of the cable from manufacture through deployment.
- A strength member made up of one or more layers of high-tensile steel wires is helically laid around the buffer tube to withstand the tension loads encountered during deployment.
- A continuous copper or aluminum sheath surrounds the strength member to provide a low-resistance electrical path for powering repeaters (described in Section 5.1.2), and to protect the fibers from hydrogen-induced degradation.[11]

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[10] Bach, Deborah, *Microsoft, Facebook and Telxius complete the highest-capacity subsea cable to cross the Atlantic*. https://news.microsoft.com/features/microsoft-facebook-telxius-complete-highest-capacity-subsea-cable-cross-atlantic/

[11] Hydrogen can be generated by some plastics, by seafloor bacteria, and by the corrosion of metallic elements (e.g. steel armor wires) through exposure to seawater that can be

- A polymer insulating layer surrounds the copper sheath.
- Helically wound steel wires or tapes are generally used to armor those sections of cable that are near shore, and which are consequently at risk of damage from commercial fishing and anchoring activities.
- Polymer or tar-soaked nylon yarn jackets are added to the outside of seafloor cables as a protective layer. Since the outer jacket mainly functions to shield the interior elements from incidental physical damage, these jackets tend to be thinner than the inner polymer insulating layer.

Figure 2. Typical undersea telecommunications cable (image from TE Connectivity[12])

5.1.2 Repeaters

Optical signals become attenuated with increasing fiber length. Higher quality fibers suffer less from this effect, but still experience losses. The undersea telecommunications industry manages this issue with repeaters, which are corrosion- and pressure-resistant metal housings in line with the cable that contain optical amplifiers to boost the signal. These amplifiers commonly incorporate short lengths of erbium-doped single-mode fiber with one or two laser diodes coupled to the fiber as shown in Figure 3, and are termed erbium-doped fiber amplifiers (EDFAs). The lasers are tuned to 980 nm, which excites the erbium ions into energy states that amplify optical signals in the 1550 nm range (commonly used for long distance cables) via stimulated emission. A single EDFA can simultaneously amplify many data channels at different wavelengths[13].

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exacerbated by accidental current leakage from the cable power conductor. Optical fibers are sensitive to hydrogen, which increases fiber losses over time. Modern subsea telecommunications cable construction is effective at minimizing this issue.

[12] http://www.te.com/content/dam/te-com/documents/subcom/global/subcom-brochure.pdf

[13] R. Paschotta, https://www.rp-photonics.com/erbium_doped_fiber_amplifiers.html

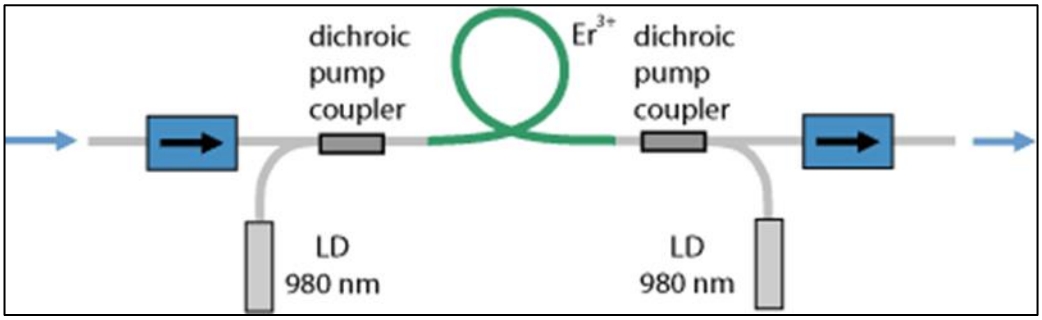

Figure 3. Basic optical amplifier (image from rp-photonics.com[14])

Repeaters are typically spaced 70-100 km apart and are powered from shore using the cable's internal metal sheath as the supply conductor, with a seawater electrical return path. In order to power the repeater electronics, a Zener diode[15] is placed in line with the primary conductor (which, as previously noted, can be at 10 kV or higher) as indicated conceptually in Figure 4. The voltage drop across the diode powers the electronics.

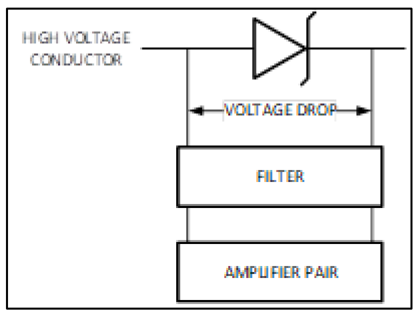

Figure 4. Basic optical amplifier (image from rp-photonics.com[16])

In addition to optical amplification, repeaters can contain components to support optical time domain reflectometry (OTDR), which is used to establish the location of potential fiber damage, as well as line monitoring functions for system maintenance.

An example of a repeater for the OOI Cabled Array (see Section 6.1.1) being loaded onto the TE Connectivity Cable Ship Dependable is shown in Figure 5. The black conical elements are stiff rubber bend restrictors that prevent the cable from violating their minimum bend radius at the junctions with the housing.

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[14] Ibid.

[15] https://en.wikipedia.org/wiki/Zener_diode

[16] Ibid.

Figure 5. Repeater being loaded onto C/S Dependable in preparation for deployment onto OOI Cabled Array[17]

5.1.3 Branching Units

A branching unit (BU) is a metal housing similar in size to a repeater that can be installed to distribute power and signal between three cables. One cable is connected to one end of the BU and two cables are connected to the other is shown in Figure 6.

Figure 6. Seafloor cable branching unit (image from NEC[18])

BUs are configured to provide full connectivity between the three cables and may be wholly passive or allow active power and signal switching from shore. The first commercial instance of a BU was implemented in the TAT-8 cable mentioned in

[17] http://www.interactiveoceans.washington.edu/files/slide04_med.jpg

[18] http://tr.nec.com/en_TR/global/prod/nw/submarine/product/ns-series.html

Section 5.1, which allowed the cable that originated in the US to branch out to terminate in both Britain and France.

5.1.4 Shore Stations

Transoceanic cables have two or more shore stations, which are buildings at the terminus of each cable, and which house the dry plant. The dry plant comprises the submarine line terminal equipment (SLTE), power feed equipment (PFE), an element management system (EMS) and a cable termination box (CTB).

The cable exits the shore station through the CTB (a concrete vault inside the main shore station building) from which it is routed underground, rising to the seabed surface at a safe distance offshore of the surf zone. In the shore station, the cable optical signal is integrated into a terrestrial fiber network via the SLTE hardware under the control of the EMS (a software command and control system), and the cable is powered by the PFE, also controlled by the EMS. The EMS usually operates autonomously but has a user interface to allow human intervention when needed.

3-phase AC power from the local utility is supplied to the PFE, which converts it to DC for the cable. In the event of a utility power outage, a large uninterruptable power supply in the shore station is automatically switched in to maintain service. If the outage persists beyond a predetermined time, a backup generator at the shore station is automatically started and takes over the supply of power to the PFE until utility power is restored, thus maintaining continuity of service.

Modern PFEs are generally designed to supply 10 kV DC or higher to the cable. Systems with more than one shore station typically have the capability to power the cable from one PFE and can switch to another PFE at another cable terminus to allow maintenance of the first PFE.

The power architecture used for undersea telecommunications cables is termed constant current, meaning that the voltage decreases from the supply PFE to the destination PFE due to resistance loss in the cable and to the voltage drop within each repeater (each repeater operates at approximately 60 VDC). A typical PFE supply current is in the range of 0.5-1.5 A.

An anode bed is connected to each PFE and consists of a number of long metal rods driven into the soil near the shore station. Return current flows through the earth and ocean between the anode beds of the shore stations.

5.1.5 Cable Installation

Following the manufacture and testing of a complete cable assembly (which includes repeaters and, in some cases, BUs and branch cables), the assembly is coiled up in one or more dedicated holds in a cable ship. The ship then steams to the vicinity of the starting shore station, where a trench has been dug in the beach between the water's edge and a dedicated underground conduit that ends at the shore station CTB.

One end of the cable is passed from the ship through the trench and conduit and is connected to the CTB panel. The ship then steams to the destination(s), paying out the cable in a controlled manner along a route that has been plotted to minimize seafloor hazards.

If there is more than one destination, the ship lays the first cable as far as the location of the branching point, then secures the end of that cable to a temporary buoy. The ship subsequently steams to the second shore station and lays the second cable from there to the buoy. After recovering the first cable, all three cables are connected to the BU, which is lowered to the seafloor. The ship then steams to the third shore station, where the third cable is connected to the CTB of that shore station. A similar process would be repeated for additional branches.

5.1.6 Cable Repair

Despite nautical chart updates and notices to mariners that are issued to warn the maritime industry of the locations of seafloor cables, these cables are sometimes damaged, usually from accidental bottom trawling by fishermen. The undersea telecom cable industry has developed reliable methods for making repairs, which generally involve using a grapnel to recover the cable to the ship's deck where a new section of cable is spliced in. These splices are designed to introduce minimal optical losses and to function reliably for the life of the cable. The repaired section of cable is lowered to the seafloor in a similar manner to that of the original deployment.

6.0 Cabled Seafloor Observatories and Existing Offshore Early Warning Systems

6.1 Cabled Ocean Observatories

Cabled ocean observatories are designed in two different formats. General purpose observatories are multipurpose seafloor networks that are designed to host a wide variety of oceanographic instruments and devices. They typically rely heavily on the undersea telecom technology described in Section 4.0 with the addition of nodes with wet-mate connectors for modularity.

Nodes, also referred to as junction boxes, are fundamental building blocks of modular cabled ocean observatories, functioning as sophisticated multiplexing devices. An example of an OOI Cabled Array[19] (OOI-CA; see Section 6.1.1 for details) junction box is shown in Figure 7. In contrast to telecom repeaters or BUs, which are hard-wired to an undersea cable, an observatory node is inherently modular, being generally configured with a number of wet-mate connectors that are designed to be mated and unmated underwater by an ROV, as shown in Figure 8. Node functionality can vary from primarily acting as a network branching device to acting solely as an interface to multiple oceanographic instruments and devices.

Additionally, while a telecommunications cable will have a constant current power system, in which repeaters are in series along the cable such that each repeater operates on an identical, fixed voltage drop as described in Section 5.1.2, a modular observatory is generally based on a constant voltage power system, in which the nodes are effectively in parallel. Although a constant voltage system

[19] Except where noted, all references to and images of the OOI Cabled Array are from the authors of this study and from internal program files.

has a more complex power topology, it offers significantly greater power and flexibility for instrumentation than a constant current system.

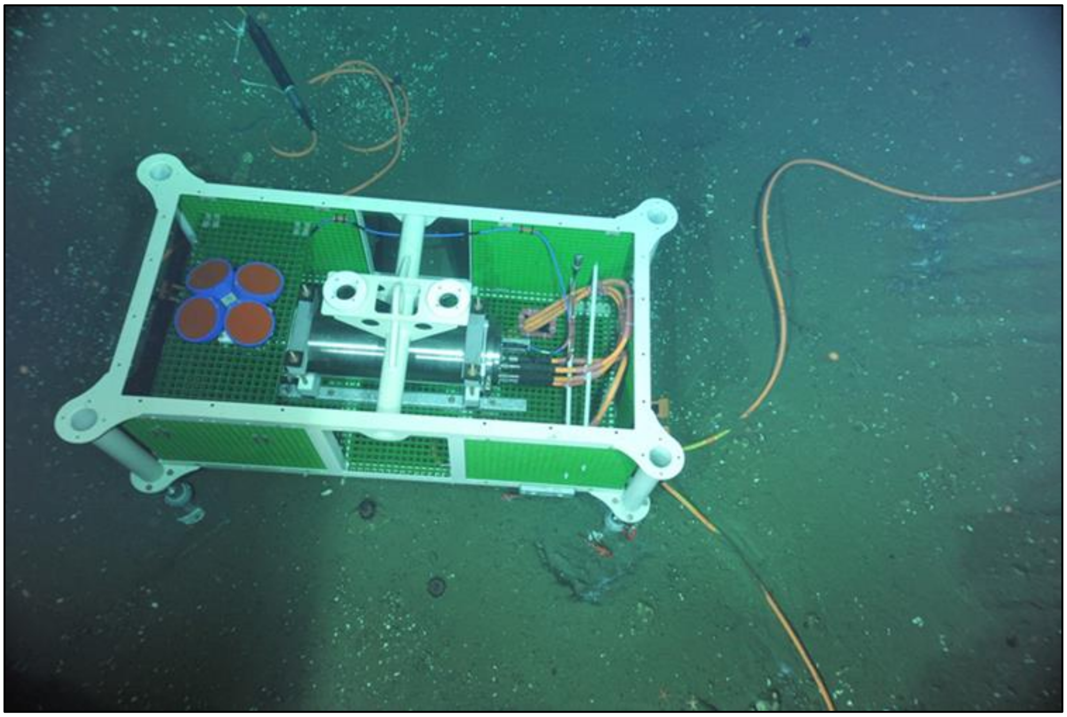

Figure 7. OOI-CA junction box on the seafloor

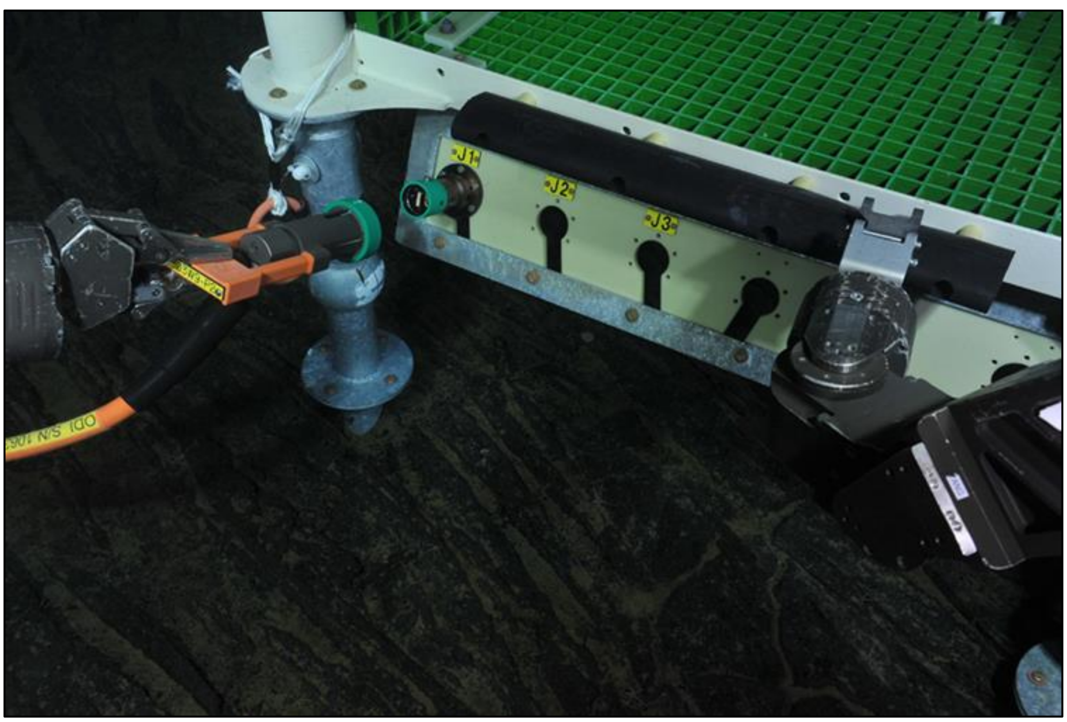

Figure 8. ROV connecting a wet-mate connector to an OOI-CA junction box

Installation of a modular observatory is initially similar to the installation of an undersea telecom cable. Starting from a shore station, a telecom-grade primary cable is laid to create the backbone of the seafloor network. As with subsea telecommunications cables, this backbone or trunk cable incorporates repeaters at suitable intervals. One or more primary nodes are subsequently installed on that cable to step down the cable voltage (usually 10 kV or higher) to a level that is suitable for the secondary nodes and/or instruments of the observatory, and to provide connectivity in the form of wet-mate connector receptacles for those secondary nodes. Backbone cables and primary nodes are deployed from a cable ship.

For observatories with more than one primary node, a secondary infrastructure is installed by ROV, consisting of a number of junction boxes (see Figure 9) and wet-mate-connector-terminated cables (see Figure 10). Instruments and devices are also deployed and connected to junction boxes by ROV.

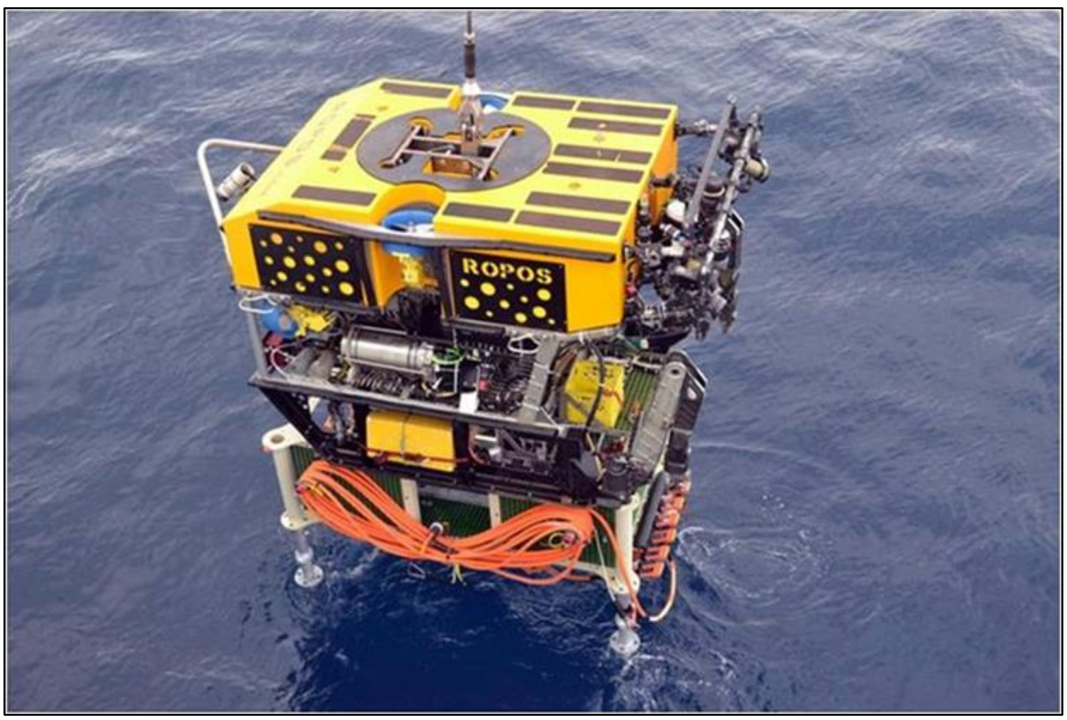

Figure 9. ROV with junction box being lowered for installation on the OOI-CA

In addition to the architectural differences between ocean observatories and undersea telecom cable systems, the EMS of an observatory is more sophisticated than that of a telecom system in order to provide a high level of communication and control for the various devices on the network.

From the EWS perspective, there are three key advantages of a cabled architecture. First, power is ample and essentially continuous, which eliminates the need for batteries and consequently the need for servicing missions to replace expired batteries. Second, data latency to shore is generally well under one second, which is substantially lower than that of any uncabled offshore system. Third, cabled observatories have high reliability and availability.

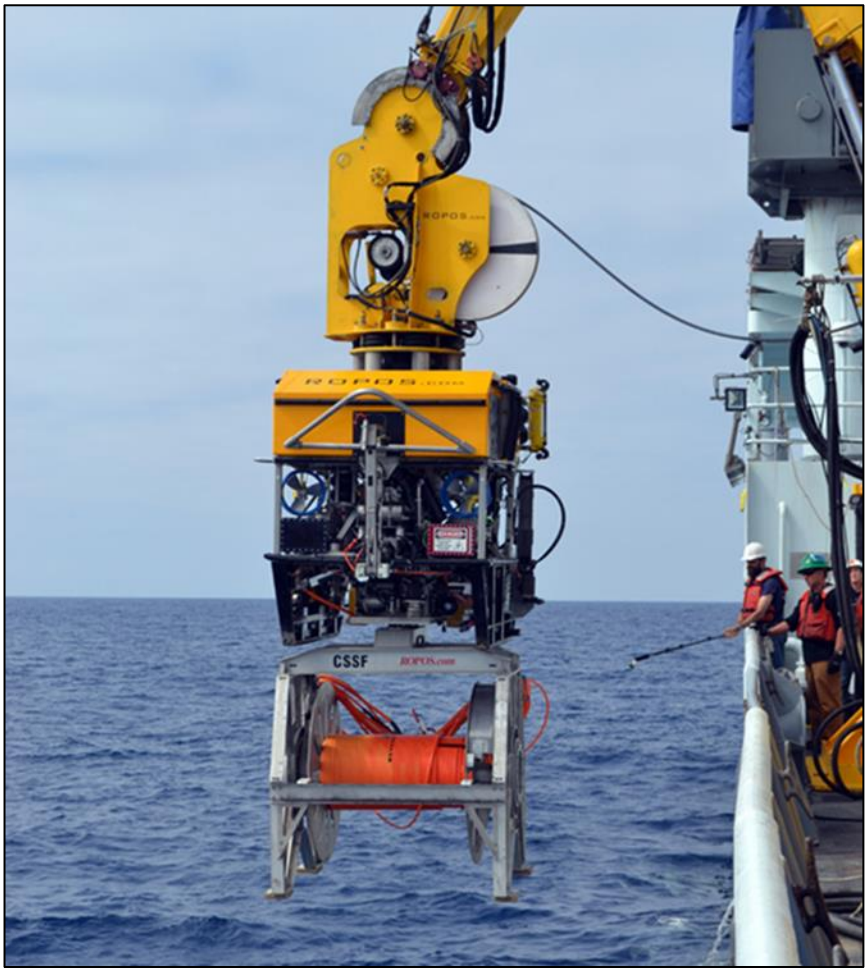

Figure 10. ROV preparing to deploy a secondary cable on the OOI-CA

6.1.1 Ocean Observatories Initiative Cabled Array (OOI-CA)

The OOI-CA (previously named Regional Scale Nodes or RSN) was installed in 2014 by the University of Washington for a 25-year service life. It has a star topology with two primary cables and seven primary nodes as shown in Figure 11, and supports 18 junction boxes and approximately 140 oceanographic instruments as well as cabled profilers at three sites. System installation was by cable ship for the primary cables, primary nodes and two extension cables, and by oceanographic research vessel with ROV for the junction boxes, the remaining extension cables and all instruments.

The University of Washington conducts annual servicing cruises with an oceanographic research vessel and ROV in order to replace profilers, junction boxes and instruments, and to install new junction boxes, cables and instruments.

The OOI-CA was developed to support the broadest possible range of oceanographic research and currently hosts a limited number of geophysical instruments. Deployed instruments of relevance to an EWS include long- and short-period seismometers, bottom pressure recorders and tiltmeters. The OOI-CA is currently at approximately 5% of capacity with respect to available power and data bandwidth. Located within the proposed area of the EWS, it has the potential to support EWS testing and infrastructure.

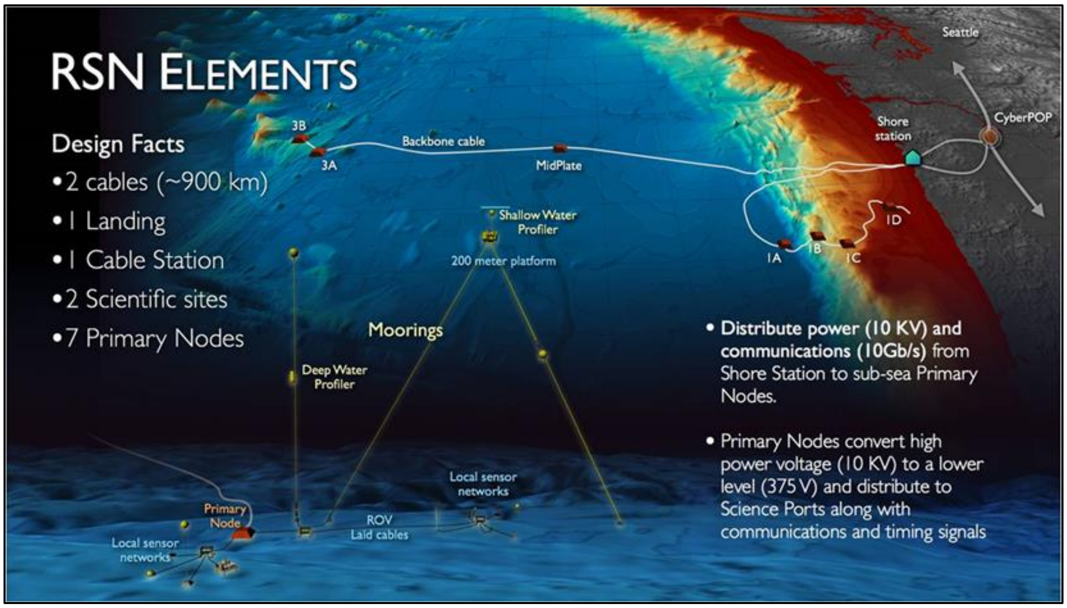

Figure 11. OOI-CA observatory

6.1.2 Ocean Networks Canada (ONC)

The ONC cabled observatories[20] include two seafloor networks, NEPTUNE and VENUS, installed and are operated by the University of Victoria, Canada. An overview of both observatories is shown in Figure 12.

VENUS is a single-cable observatory that includes three primary nodes, and which has been operating in the Strait of Georgia since 2006.

NEPTUNE is a larger observatory off the west coast of Vancouver Island that has been in operation since 2009. It is configured with a ring topology with six primary nodes and is generally comparable in size and functionality to the OOI-CA. Installation was similar to that of the OOI-CA.

In addition to its primary mission to support a wide range of oceanographic sensors on its observatory systems, the NEPTUNE array is hosting the first seismic instruments of a new offshore-focused earthquake early warning network, installed as close to the Cascadia Subduction Zone as possible. ONC has installed a total of eight seismic sensors above the megathrust off coastal British Columbia that will directly inform an earthquake early warning system. These sensors consist of five strong-motion accelerometers and three tilt meters connected to existing nodes on the NEPTUNE cabled observatory. These offshore EEW sensors are complemented by a land-based network of geoseismic instruments (strong

[20] http://www.oceannetworks.ca/Observatories.

motion accelerometers and GNSS) located across Vancouver Island as shown in Figure 13.

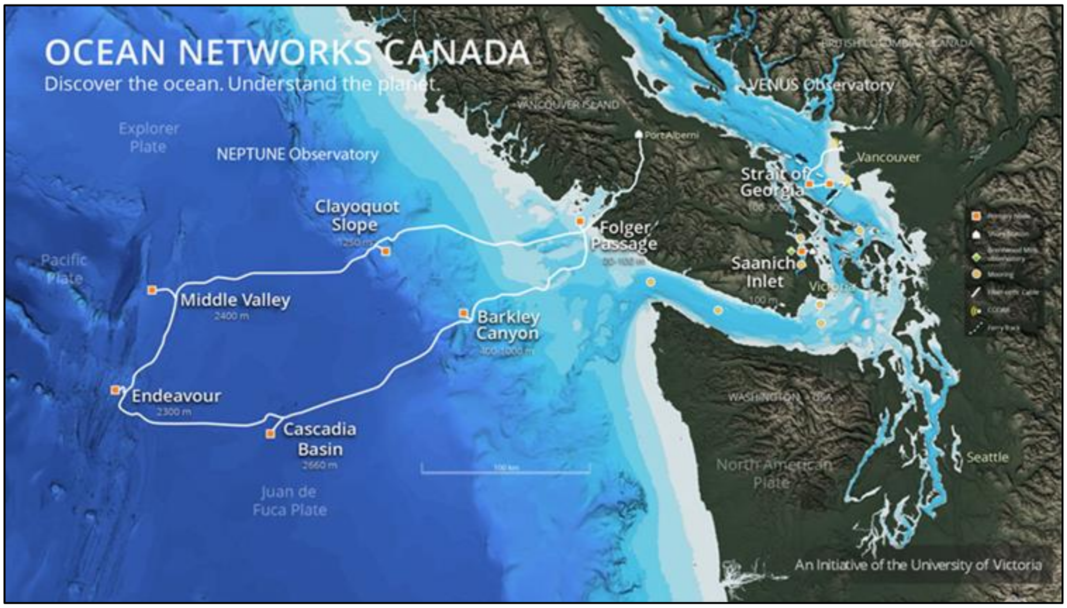

Figure 12. ONC NEPTUNE and VENUS Observatories[21]

Figure 13. British Columbia EWS sites (image courtesy of ONC)

In British Columbia, EEW activities span a number of academic, government and industry organizations and collaboration between these groups is facilitated through an EEW-focused subcommittee of the BC Seismic Safety Council. Ocean Networks Canada is also an associate member on the USGS Joint Committee on

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[21] http://www.oceannetworks.ca/sites/default/files/images/pages/maps/ONCMap_simplelabled.jpg.

Communications, Education, and Outreach and has executed a Memorandum of Understanding with the Pacific Northwest Seismic Network that allows for EEW data to be shared across the border with the U.S.

6.1.3 Applicability of Cabled Ocean Observatories to the Proposed EWS

Large ocean observatories such as the OOI-CA and ONC NEPTUNE demonstrate that undersea telecom technology can be successfully adapted to support long term seafloor instrument networks on the scale of the proposed Cascadia EWS. A key advantage of ocean observatories of this type is their extremely low data latency. They are also highly modular, allowing efficient instrument upgrades and targeted component servicing. Additionally, existing observatories may be used as test beds for prototype EWS elements and could potentially serve as links for a permanent EWS system.

6.2 Japanese Early Warning Systems

Japan is in a particularly seismically active region and has invested substantially in earthquake and tsunami early warning systems. Their offshore early warning systems include modular and non-modular versions described in Sections 6.2.1 and 6.2.2. As with the ocean observatories described in Sections 6.1.1and 6.1.2, the Japanese EWSs rely extensively on the undersea telecommunications technology presented in Section 5.0.

6.2.1 DONET and DONET2

The DONET[22] (Dense Oceanfloor Network System for Earthquakes and Tsunamis) observatory was developed by JAMSTEC[23] (Japan Agency for Marine-Earth Science and Technology). Having a 300 km primary cable, it was installed in 2011 in the Nankai Trough off the south coast of Honshu, Japan. Unlike the OOI Cabled Array and the ONC observatories, DONET is focused exclusively on earthquake, geodetic and tsunami observations, with the main purpose of monitoring the hypocentral region of the Tonankai earthquake, which is predicted to have high probability of an earthquake occurring within the next 30 years. DONET2 is an extended version of DONET with a 450 km long primary cable, installed in 2015 to the southwest of the original observatory. Both observatories feature modular construction[24] similar to that of the OOI-CA and ONC observatories, and have multiple clusters of four or five instruments (seismometers and bottom pressure sensors) distributed around nodes as shown in Figure 14, where nodes are represented by stars and instruments by circles.

Installation of the DONET observatories was by a combination of cable ship for laying the primary cables, and ROV for installing nodes, cables and instruments.

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[22] https://www.jamstec.go.jp/donet/e/.

[23] https://www.jamstec.go.jp/e/

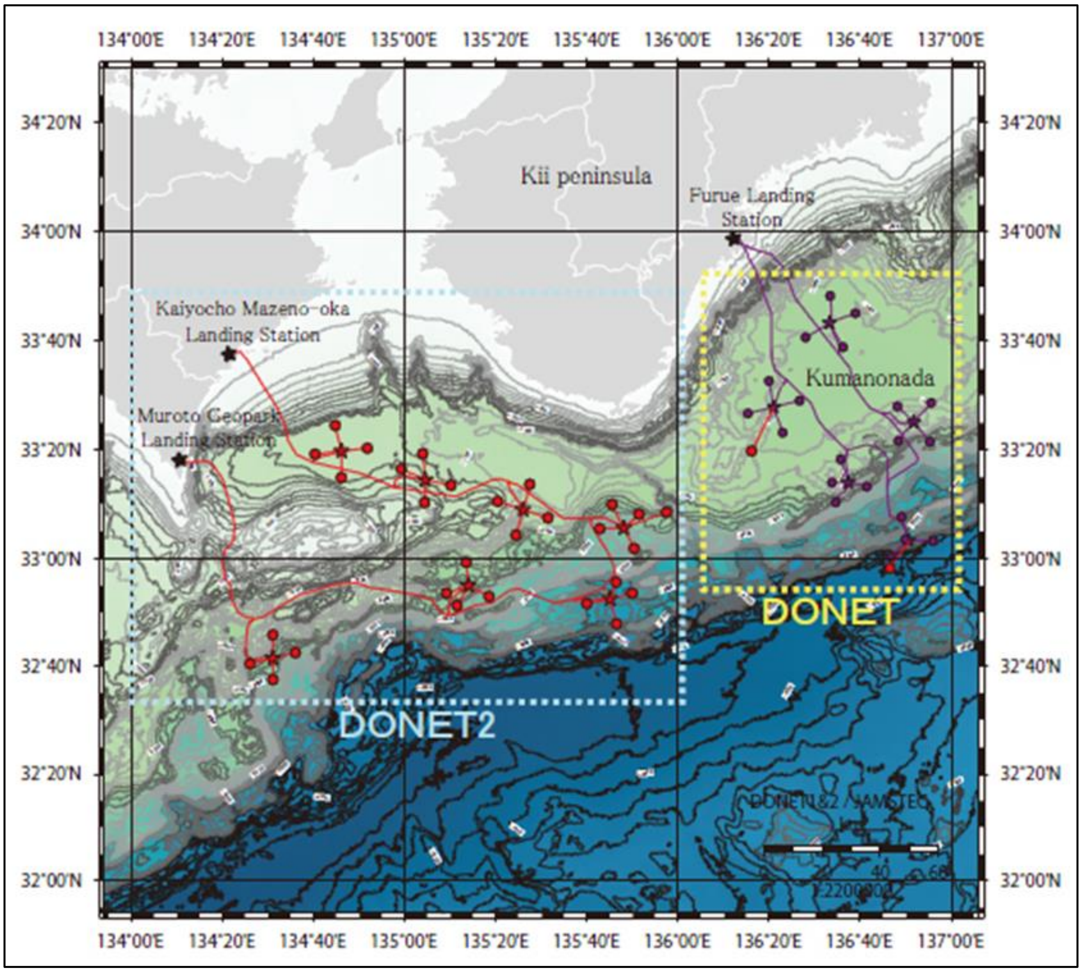

Figure 14. DONET and DONET2 observatories[25]

6.2.2 S-net

The S-net (Seafloor observation Network for Earthquakes and Tsunamis along the Japan Trench) observatory[26] was developed by the National Research Institute for Earth Science and Disaster Prevention (NIED) and installed in 2018[27]. The array is located offshore of northeast Honshu and east of Hokkaido, and incorporates 5800 km of seafloor cable with 150 hard-wired, repeater-like instrument housings spaced at 30 km intervals, as well as six cable landings as shown in Figure 15.

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[25] https://www.jamstec.go.jp/donet/e/donet/donet2.html.

[26] Kanazawa, T., Japan Trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to earth disaster science, Underwater Technology Symposium, 2013 IEEE International.

[27] Tanioka, Y., Gusman, A, Near-field tsunami inundation forecast method assimilating ocean bottom pressure data: A synthetic test for the 2011 Tohoku-oki tsunami, Physics of the Earth and Planetary Interiors, 2018.

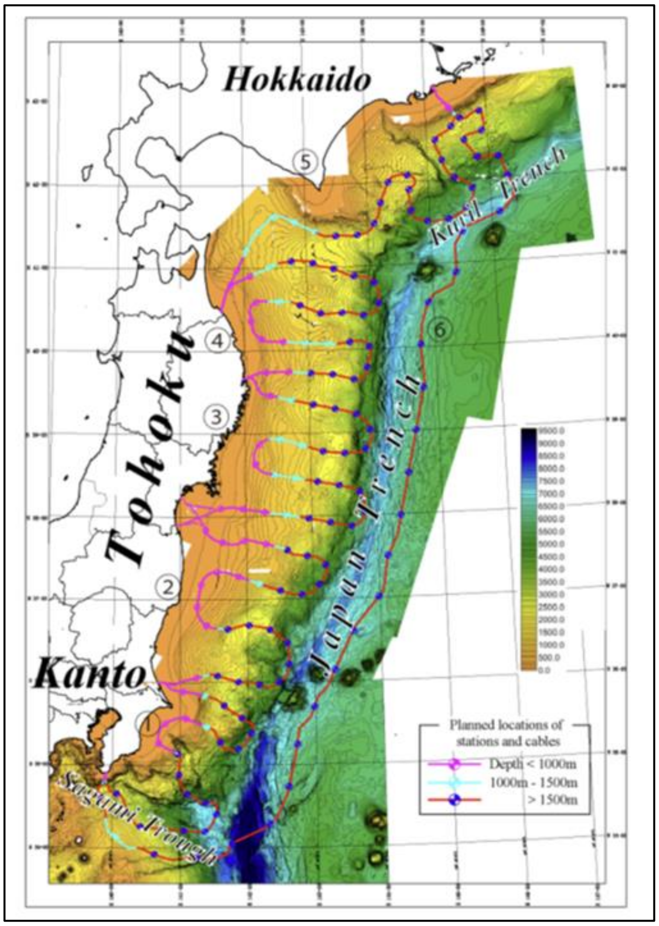

Figure 15. S-net observatory

Each S-net instrument housing contains four accelerometers for long and short period seismic measurements, and two pressure sensors for tsunami detection and seafloor level monitoring. System deployment was by cable ship.

6.2.3 Applicability of Japanese Early Warning Observatories to the Proposed EWS

The DONET and S-net observatories present two different approaches to an EWS, both capable of long-term earthquake and tsunami/seafloor level monitoring.

As with the OOI-CA and NEPTUNE observatories, the DONET observatories are highly modular, allowing efficient, *in situ* upgrades and repairs by ROV with a ship of opportunity. Further, DONET nodes allow power to an individual instrument to be turned on and off from shore. This means that the replacement of a failed instrument, which must always be conducted with it unpowered, can be safely accomplished by an ROV in a single dive of a few hours' duration (weather permitting) without affecting the operation of other instruments on the observatory.

In contrast, the S-net observatory is less easily repaired, being a continuous string of instruments that are hardwired (without connectors) to the trunk cable. In this case repairs would most likely require the services of a cable ship, generally less readily available and more costly than a ship of opportunity, to recover the affected section of cable by grapnel, after which the failed instrument would be cut out, a new instrument would be spliced in, and the repaired section would be lowered back to the seafloor. All this would require at least 24-48 hours in favorable weather, during which the entire affected run of trunk cable would need to be shut down.

Despite these drawbacks, the S-net observatory design has one key advantage in that, for a given number of sensors, it is a more economical system to build and deploy than a modular observatory such as DONET.

6.2.4 Estimated Cost to Install an Offshore Cabled EWS for Cascadia

Two cabled EWS alternatives have been considered for this feasibility study: one based largely on the DONET observatories of Section 6.2.1 and the other on the S-net observatory of Section 6.2.2. Both alternatives would be based on segments of undersea telecommunications cable laid between shore stations from Neah Bay, Washington, to Eureka, California and would meet the requirements listed in the White Paper for an offshore EWS with station spacing approaching 50 km. As analyzed in a 2018 report by Ocean Specialists Inc.[28], the installed cost in current dollars of Option 1, an S-net-type system with 67 inline instrument housings containing accelerometers and pressure sensors is projected to be in the range of $244M to $309M. OSI projects that the cost of Option 2, a connectorized DONET-type system with 20 nodes and 80 seismometer/pressure sensor packages would be in the range of $382M to $486M.

7.0 Key EWS Enabling Technologies

7.1 Ocean Bottom Seismometers

Seismometers are extremely sensitive instruments that detect and measure local ground acceleration in three-dimensional space by means of accelerometers. The signals from three or more seismometers can be processed to establish the location as well as the magnitude of an event such as an earthquake or explosion.

Although conventional seismometers are in widespread use at terrestrial sites, ocean-bottom seismometers (OBSs) are less prevalent due to the additional technological development required to enable the systems to withstand deployment and seafloor conditions for long durations, and because of higher system and installation costs.

OBSs are available from commercial providers such as Güralp[29] and Nanometrics[30]. Figure 16 shows a Güralp broadband OBS being installed on the OOI Cabled Array by ROV. Many advanced OBSs are built and fielded by organizations such as the Scripps Institution of Oceanography, Lamont-Doherty Earth Observatory and Woods Hole Oceanographic Institution[31], and are based on

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[28] Lentz, S., Cascadia Early Warning Offshore Budget Analysis, 2018.

[29] http://www.guralp.com/products/instruments/obs

[30] https://www.nanometrics.ca/products/seismometers/trillium-compact-obs

[31] http://www.obsip.org/documents/Babcock_OBSIP_2015.pdf

high-precision terrestrial seismometers, often in conjunction with complementary sensors such as pressure and tilt sensors, collectively packaged in seafloor housings.

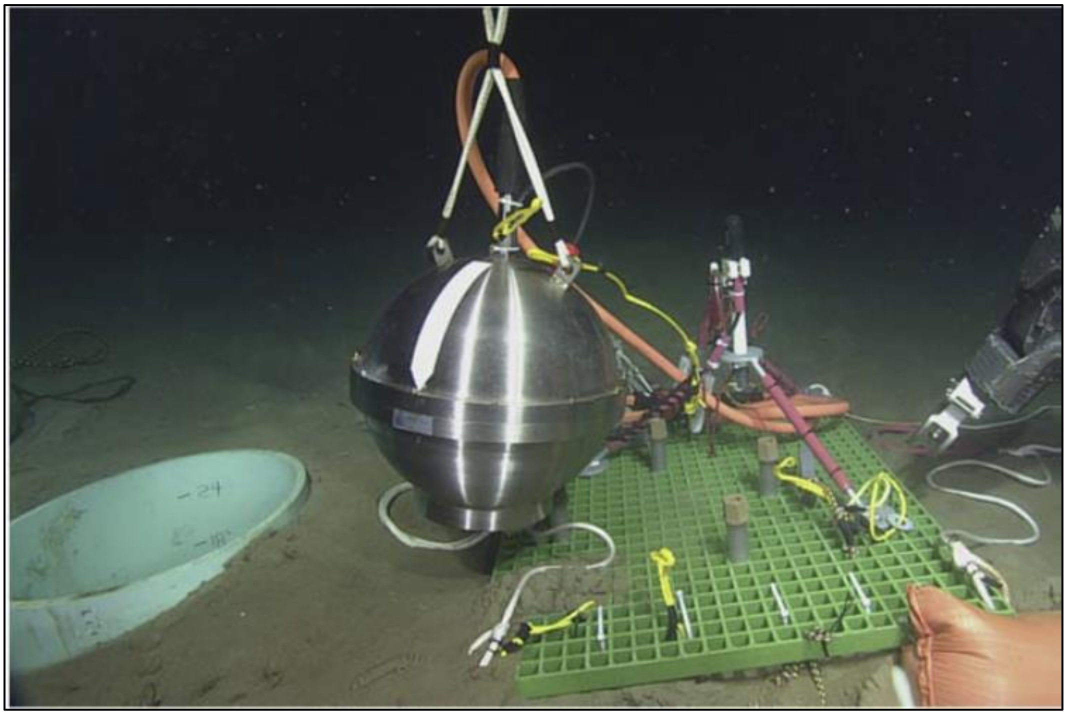

Figure 16. Güralp broadband OBS installation by ROV on the OOI-CA

7.2 Bottom Pressure Recorders

As noted in Section 7.3, bottom pressure recorders (BPRs) are seafloor instruments that incorporate extremely accurate, high-resolution pressure sensors to detect tsunamis and/or to monitor local seafloor depth for geodesy. Commercial versions are manufactured by Paroscientific[32], Presens[33], Sonardyne[34] and RBR[35], and may be battery powered or cabled. If battery powered, they may also be paired with an acoustic modem to enable transmission of event data to a surface buoy as with the DART systems of Section 7.3. Other BPRs with the ability to correct for pressure sensor drift on demand have been developed by the University of Washington Applied Physics Laboratory, both as battery powered systems incorporating radio data upload capabilities, and as cabled systems[36].

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[32] http://www.paroscientific.com/pdf/D50_Series_8000.pdf

[33] http://www.alliantech.com/pdf/capteurs_pression_piezoresistifs/DPX2000_2100.pdf

[34] https://www.sonardyne.com/product/tsunami-detection-system/

[35] http://rbr-global.com/wp-content/uploads/2018/01/0005575revB-RBRduo3-BPR.pdf

[36] http://www.paroscientific.com/pdf/2018_Ocean_Sciences_Poster.pdf

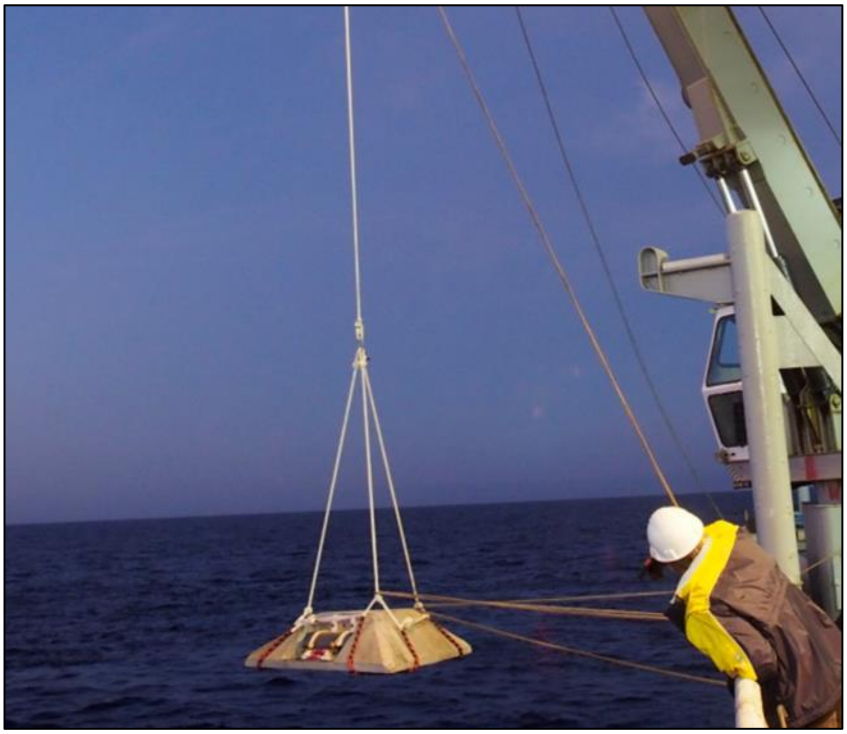

Figure 17. Custom BPR Secured to Concrete Monument Being Installed on the OOI-CA

7.3 NOAA DART System

In 2001, the US National Oceanic and Atmospheric Administration (NOAA) installed six Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys off the Oregon coast. DART buoys have undergone two design cycles since then[37], and have also been deployed by Australia, Chile, Indonesia and Thailand, with a worldwide total of 51 in service[38] as of March 2019.

Unlike cabled observatories, DART buoys do not use a cable for power and communications, relying instead on solar cells and batteries for power and satellite communications to shore. Each buoy is anchored to the seafloor near a bottom pressure recorder[39]. Bottom pressure data are transmitted acoustically from the BPR to the buoy, which retransmits the data using the Iridium satellite network as shown in Figure 18.

[37] https://nctr.pmel.noaa.gov/Dart/about-dart.html.

[38] https://www.ndbc.noaa.gov/dart_metadata/dartmeta_public.php.

[39] A bottom pressure recorder, termed a BPR, is a pressure sensor with supporting power and communication electronics packaged in a one-atmosphere housing on the seafloor.

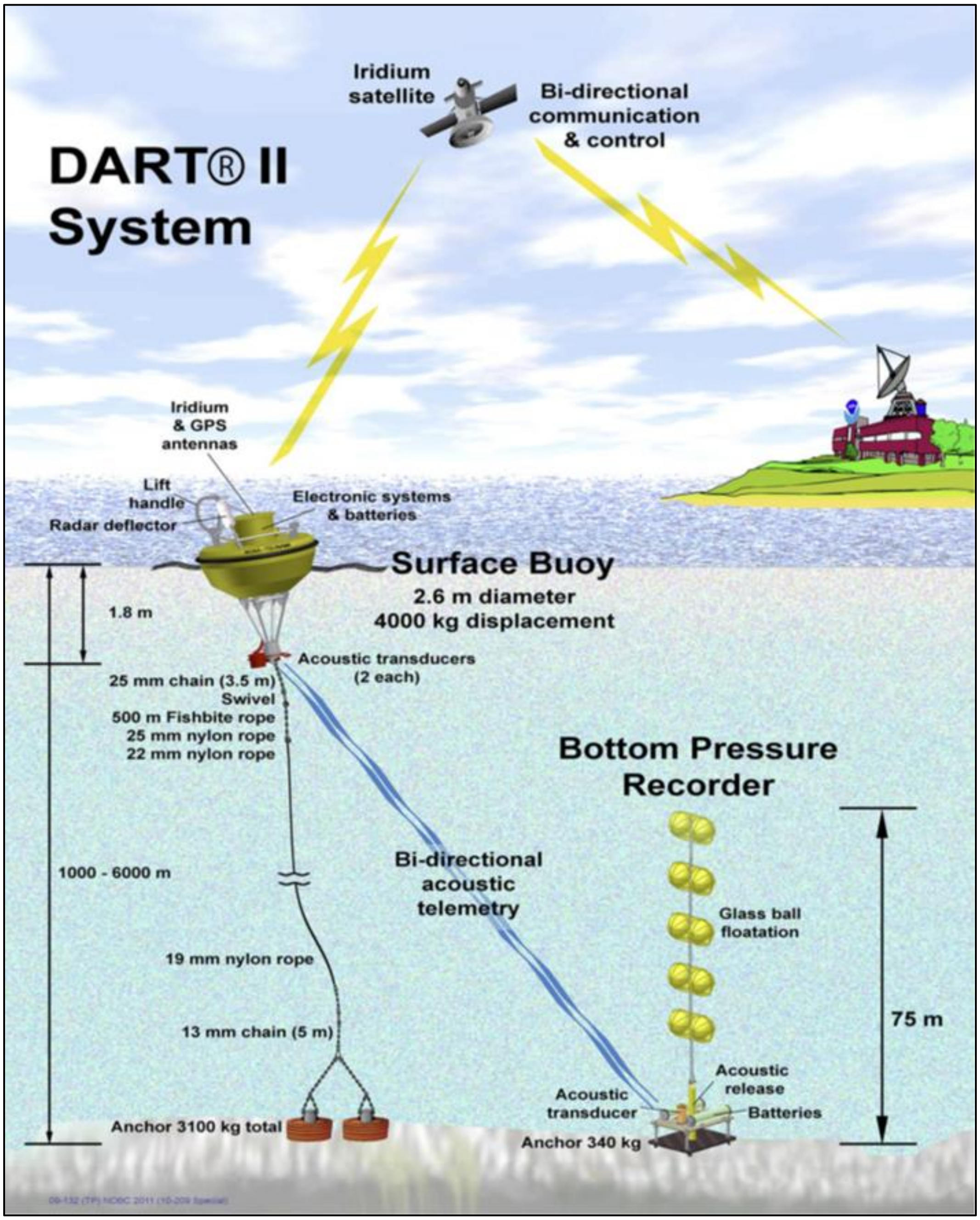

Figure 18. DART II System Overview

Data latency for a DART buoy is approximately three minutes[40], split roughly equally between the time required to acoustically transmit data from the seafloor to the buoy and the time to packetize and retransmit the data to shore via satellite. Relative to a cabled observatory, DART buoys offer the advantage of significantly lower construction and deployment costs. Conversely, they require

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[40] From conversation with Chris Meinig, Director of Engineering Development, NOAA Pacific Marine Environmental Lab on 24 May 2019.

servicing every two years to repair vandalism and animal-generated damage, as well as to replace weathered components such as solar panels.

The approximate purchase price of a commercial DART buoy from SAIC is currently $600k-$650k, depending on site conditions. SAIC currently has a maximum capacity of 10 buoys per year, so this technology is, at most, only suited for a few specific sites within the Cascadia EWS area.

7.4 Additional Instrument Systems for Consideration

The following technologies show promise to augment the more developed instrument systems described above.

Bottom Pressure Recorders, covered in Sections 7.3 and Section 7.2, have been installed **in seafloor boreholes** to measure the formation-fluid pressure of the surrounding seabed. Variations in pressure have been associated with activity recorded by nearby seismometers and may provide valuable clues about the evolution of subduction faults through their earthquake cycles.

Coastal High Frequency Radar is an adaptation of Over-the-Horizon (OTH) radar, which had originally been developed for long distance military surveillance and subsequently applied to the remote sensing of sea surface height (SSH). The severe tsunami resulting from the 9.1M Sumatra earthquake on 26 December 2004 led to German government-sponsored research into the use of existing OTH radars for tsunami detection, which has been since expanded by a number of companies and institutions worldwide[41]. Recent progress in this field include the 2016 installation of a coastal high frequency radar at Tofino, British Columbia as part of the ONC early warning system. Using a technique termed Time Correlation Algorithm, researchers have made significant progress toward real time tsunami detection with coastal HF radar.

Tide Gauges have been in widespread use for over 100 years, initially as aids to shipping. Modern versions are capable of real-time reporting of SSH at sample rates high enough to be useful for tracking tsunamis at the coast for subsequent analysis, although they have limited range and may be destroyed during the event.

GPS Buoys deployed in Japan[42] use Real-Time Kinematic (RTK) positioning to establish SSH to a resolution of approximately 1 cm[43]. This approach has a maximum range of about 20 km[44] and has a relatively noisy signal which would require temporal averaging that may impede real time tsunami detection[45]. An alternative version is under investigation by NOAA Pacific Marine Environmental

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[41] Dzvonkovskaya, A., HF surface wave radar for tsunami alerting: from system concept and simulations to integration into early warning systems. IEEE Aerospace and Electronic Systems Magazine, 33(3), 48–58, 2018.

[42] https://www.unescap.org/sites/default/files/Day%201%207-EWS%20GPS%20Buoy%20in%20the%20Pacific%20UoT.pdf

[43] https://en.wikipedia.org/wiki/Real-time_kinematic#cite_note-Wanninger2008-1

[44] http://www.wasoft.de/e/iagwg451/intro/introduction.html

[45] From conversation with Chris Meinig, Director of Engineering Development, NOAA Pacific Marine Environmental Lab on 24 May 2019.

Laboratories (PMEL) which relies on Global Navigation Satellite System (GNNS) Precision Point Positioning[46] (PPP), a protocol that supports a much greater range, albeit resulting in SSH measurement accuracy on the order of decimeters[47].

Distributed Acoustic Sensing (DAS) is an evolving technology that delivers spatially-distributed acoustic, seismic, pressure and temperature sensing by directing pulses from a highly stable laser into an optical fiber at tens of kHz. Changes in backscattered light (Rayleigh scattering) from small variations in the optical path length and refractive index of the fiber can be related to mechanical strain and temperature along the fiber by means of coherent optical time domain reflectometry (C-OTDR). In effect, this converts an optical fiber up to 50 km long into a series of highly sensitive sensor elements arranged in virtual segments as small as 1 m along its length. Useful sensitivity and bandwidth can be achieved with conventional optical fiber cables in the as-laid condition (i.e. without making an effort to couple the cable to the ground in the case of seismic sensing), and better results are achieved with specially-designed fibers that are tightly coupled to the cable jacket. A recent study[48] at the MBARI MARS node suggests that a seafloor DAS installation has considerable promise for detecting seismic events. DAS has potential as a cost-effective alternative for ocean bottom seismometers in a network such as the proposed EWS.

8.0 Recommendations

In terms of currently available technology, a cabled system that is powered from shore would be the most viable approach for a long-term Cascadia EWS that meets the station spacing and latency requirements stated in Section 4.0. The system could benefit from additional DART buoys for added resiliency in the event that sections of the cable were to be damaged in an earthquake or undersea landslide, but the low production capacity of the principal commercial source, SAIC, would limit this option to a relative few sites or to a multi-year deployment.

A linear S-net-type cabled system is clearly less expensive and more rapidly deployable than the modular DONET-type alternative, but at the cost of complex and expensive repair scenarios. In its purest form, an S-net-type system also has no provision for upgrading or adding instruments after installation. A more flexible cabled solution would be a combined system, being primarily composed of S-net-type segments connected to occasional junction boxes for modularity.

Although not fully mature for this purpose, DAS has promise as a cost-effective alternative to distributed ocean bottom seismometers and will continue to be monitored for this purpose.

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[46] Ibid.

[47] https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/precise-point-positioning-ppp/

[48] Lindsey, N., *Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing*, Science, 29 Nov 2019: Vol. 366, Issue 6469, pp. 1103-1107