The scientific and societal case for the integration of environmental sensors into new submarine telecommunication cables

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Acknowledgments

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Additional information and materials relating to this report can be found at: itu.int/go/ITU-T/greencable

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Scope and vision

The United Nations Convention on the Law of the Sea - which, in Article 112, recognizes the right that *"All States are entitled to lay submarine cables and pipelines on the bed of the high seas beyond the continental shelf"* - asserts, in its Preamble, the principles embodied in Resolution 2749 (XXV) of 17 December 1970 in which the General Assembly of the United Nations declared: *"1. The sea-bed and ocean floor, and subsoil thereof, beyond the limits of national jurisdiction (hereinafter referred to as the area), as well as the resources of the area, are the common heritage of mankind."*

Executive summary

The global infrastructure of submarine telecommunication cables is the backbone of our connected world, essential to business, finance, social media, entertainment, political expression and science. Internationally, these cables *are* the bottom, physical layer of the Internet. The dependability of this infrastructure is so important that, when problems arise, whole national economies are affected. And problems do arise, with cables sometimes damaged from external forces.

However, none of the world's telecommunication cable systems possess even the simplest sensory instrumentation to monitor anything other than their own internal state-of-health. They are deaf, dumb and blind to their external environment and natural hazards. This situation does not meet expectations of the due diligence required for critical infrastructure serving humanity.

Humanity faces environmental threats, both immediate and long-term, which require access to the deep ocean. Tsunamis have the potential to threaten many of the world's coastal communities within minutes or hours of a large seismic event. Reliable, robust tsunami-warning systems will save lives and property. Our ocean and climate are experiencing global changes that will affect us and our descendants. Without access to the seafloor for fundamental oceanographic measurements, scientists cannot quantify and respond to the dilemma facing humanity. As we begin to make submarine telecommunication cables environmentally aware "*green cables*", we look to a future where cables serve a dual purpose, both as communications infrastructure and a scientific backbone for monitoring tsunamis, earthquakes and the world's seafloor temperatures and circulation.

The scientific and societal reasons for the project are compelling. A relatively straightforward complement of instrumentation - accelerometers, high-resolution pressure gauges, thermometers - will answer many of the basic science and societal needs as well as provide for the monitoring of the physical state-of-health of the cable system itself. Technological advances have made it possible to integrate basic sensors with repeaters on submarine telecommunication cables at intervals of about 50-70 km, at an estimated installation cost of 5-10% of the total cost of system deployment[1]. Ideally, future cable systems will

[1] Lecroart, A., Alcatel Lucent Submarine Networks, *Green Cable: Any idea of how much it would cost?,* 3rd ITU/WMO/UNESCO IOC Workshop on Propelling a Pilot Project on Green Cables, Madrid 2013, http://www.itu.int/en/ITU-T/Workshops-and-Seminars/gsw/201309/Pages/programme-19-20-Sep.aspx

incorporate ports for a broader variety of sensing systems for genomics, carbon, water velocity and whole-water-column heat content.

This effort has been promulgated since 2011 by a Joint Task Force (JTF) of three United Nations agencies - the International Telecommunication Union (ITU), the World Meteorological Organization (WMO), and the Intergovernmental Oceanographic Commission of UNESCO (UNESCO-IOC) - in collaboration with the telecommunications industry, governments and the international scientific community. Industry is already beginning to progress towards the JTF's goal, with press releases announcing the potential integration of sensor systems into new commercial cable systems in their planning stages. The JTF strongly endorses the *green cable* concept and welcomes participation to ensure that humanity benefits from its realization.

1 The business case for green cables

The *global* Internet is based on the network of submarine telecommunication cables that traverses the Earth's seafloor. These remarkable fibre-optic cables serve as the international link between the Internet's 2.7 billion users[2], carrying more than 97% of data traffic between continents at a rate of more than 30,000,000,000,000+ bits per second[3,4]. Our civilization has become increasingly dependent on this infrastructure - for finance, commerce, entertainment, the traditional telephone and many more services - making the reliability of these systems a concern to all of humanity. The special, privileged nature of submarine cables - from the telegraph, through the analogue telephone, to digital telecommunications - is enshrined in the UN Convention on the Law of the Sea[5].

Traversing the seas, these submarine cables are vulnerable to earthquakes and their concomitant submarine landslides and turbidity flows, which can break them without notice, cutting communications and requiring expensive repairs. At ocean depths of more than 1000 m, earthquakes are the dominant cause of damage to submarine cables[6]. This occurred first in 1929 when the Grand Banks earthquake broke at least eight submarine telegraph cables[7], and such occurrences continue to affect even today's most modern systems. For example, in 2003 and 2006, earthquakes of a relatively modest magnitude (~M7) caused cable outages off the coast of Algeria (five cables; $100 million to repair) and Taiwan (Province of China) (nine cables), respectively[8]. In both cases, damage was exacerbated by massive submarine landslides and turbidity currents (in the latter case, over 20 km/h extending to 4000 m water depth) triggered by the earthquake and its aftershocks[7]. In 2011, the great M9 Japan earthquake broke or damaged six cable systems, and temporarily knocked out approximately 30 % of Japan's international communications capacity[9]. In 2013 and 2014, earthquakes[10] of M7.5 and M5.9 magnitude, respectively, broke submarine cables off the coast of Southeast Alaska. Communications losses are mitigated in part by the recent practice of deploying "ring" systems that incorporate a back-up path to carry traffic, but the costs of cable repairs are still enormous for telecommunications companies. However, compared to the potential indirect losses incurred by national economies, these direct losses are relatively small[11].

1.1 Due diligence

Despite the world's dependence on submarine telecommunication cables, those responsible for overseeing their institution's exposure to operational risk cannot perform *due diligence* because there is insufficient

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2 https://www.itu.int/net/pressoffice/press_releases/2013/05.aspx

3 Karl Frederick Rauscher, The Reliability of Global Undersea Communications Cable Infrastructure (ROGUCCI), The Report, Issue 1, rev. 1, IEEE Communications Society, p.18, 2010.

4 https://www.itu.int/net/pressoffice/press_releases/2013/05.aspx

5 Articles 21, 51, 58, 79, 87.1c, 112-115, 297.

6 http://www.iscpc.org/publications/About_SubTel_Cables_2011.pdf

7 Lionel Carter, Submarine cables and natural hazards, Chapter 10, in *Submarine Cables: The Handbook of Law and Policy*, Edited by Douglas R. Burnett, Robert C. Beckman, and Tara M. Davenport, Martinus Nijhoff Publishers, The Netherlands, DOI 10.1163/9789004260337, 2013. B.C. Heezen and M. Ewing, Turbidity Currents and Submarine Slumps, and the 1929 Grand banks Earthquake. *American Journal of Science*, 250, 849-873 1952.

8 Rauscher, op. cit., p. 172.

9 http://www.telegeography.com/press/press-releases/2011/04/11/earthquakes-and-red-tape-challenge-carriers/ and http://gigaom.com/2011/03/14/in-japan-many-under-sea-cables-are-damaged/

10 http://www.capitalcityweekly.com/stories/013013/ae_1093833840.shtml; http://www.ktoo.org/2013/01/05/breaking-tsunami-warning-for-southeast-alaska/

11 Economic Impact of Submarine Cable Disruptions, APEC Policy Support Unit, 87 pp., December 2012. Currency trading over submarine cables exceeds $1 trillion/day. Rauscher, op. cit., p. 172.

information available[12]. The global system of submarine telecommunication cables is *deaf, dumb, and blind* to its external ocean environment[13]. Cables possess no sensory information[14] that could detect, measure or mitigate the hazards that lead to cable outage. This lack of information essential to risk analysis is a significant barrier to proper due diligence, as it prevents advanced analysis of outages and trend information and the formulation of a coordinated response to resilience issues. For example, accelerometers in the cable repeaters could warn of earthquakes, submarine landslides and turbidity flows, quantifying the potential extent of resulting damage and thereby providing data of fundamental value to building resilient cable systems. Another example would be a ship's anchor catching and dragging a cable out of position, an occurrence which is *not sensed* until the damage is done. Knowledge of the cable's motion from an embedded accelerometer could alert operations personnel to the need for action, potentially saving a cable from damage. The status of submarine cables as critical infrastructure necessitates the incorporation of basic sensors to monitor that infrastructure. Without this basic data, the design of cable systems remains uninformed with regard to the natural and manmade hazards that must be mitigated.

The world tallest building, the Burj Khalifa, towers over Dubai at 2,717-ft tall (828 m) and is equipped with accelerometers to monitor its dynamic response to winds and seismic vibration[15]. The world's longest bridge, the 32.5-km Donghai Bridge between Shanghai and Yangshan Island in China, has more than 500 accelerometers spread across each segment of the bridge to acquire the frequency response from environmental stimuli[16]. Accelerometers are also essential in monitoring the health of satellite systems[17]. These extraordinary feats of engineering - and numerous other, more commonplace examples - consider embedded sensors as essential to the monitoring of their environmental response[18]. That the global undersea communications cable infrastructure does *not* monitor its ocean environment is itself extraordinary. As a matter of both scientific prudence and societal necessity, addressing this flaw is a matter

12 Rauscher, op. cit., p. 124.

13 Butler, R., Strategy and roadmap: Using submarine cables for climate monitoring and disaster warning, International Telecommunication Union, Geneva, 30 pp., (July 2012). While no internal sensors are aware of the external oceanic environment, the voltage signal in a submarine cable is affected by a motionally induced signal due to oceanic transport variations and by fluctuations of the magnetic field of the Earth. These signals are also affected by the dielectric properties of the sediments on which the cables lay. In principle, the oceanic transport can be derived with sufficient knowledge of the other variables. However, the NOAA Atlantic Oceanographic and Meteorological Laboratory notes that a combination of magnetometers and careful in-situ calibration of the ocean transport and sediment properties are necessary to resolve the ocean transport signal from the cable voltage. As much as the necessary ship time for calibrating each repeater is large, the measurement of ocean transport between repeaters appears to be initially impractical.

14 All telecom systems (repeatered or unrepeatered) internally monitor both the electrical and optical power flowing through the cable itself. Coherent-optical or electronic time-domain reflectometers allow the System Owner to have a pretty good idea of the optical power profile along the fiber. Fiber breaks or large spot attenuation increases can be detected this way. All repeatered systems also monitor Power Feeding Equipment current and voltage variations allowing detection of shunt faults on the system. The combined use of both techniques described above allows the System Owner to detect and locate major optical or electrical problems on their system, in most cases before the system actually stops functioning, whatever might have initiated the defect (internal or external cause). Some repeatered systems also have in each repeater inner sensing capabilities with indications of input optical power level, output optical power level and pump current variation, providing an increased level of information on the internal state-of-health of the system. It is true though that telecom systems do not monitor their external environment, deemed to be pretty stable in normal conditions.

15 Ahmad Abdelrazaq, Validating the Structural Behavior and Response of Burj Khalifa: Synopsis of the Full Scale Structural Health Monitoring Programs, http://www.ctbuh.org/LinkClick.aspx?fileticket=DUN2DTspi%2Fs%3D&tabid=468&language=en-US

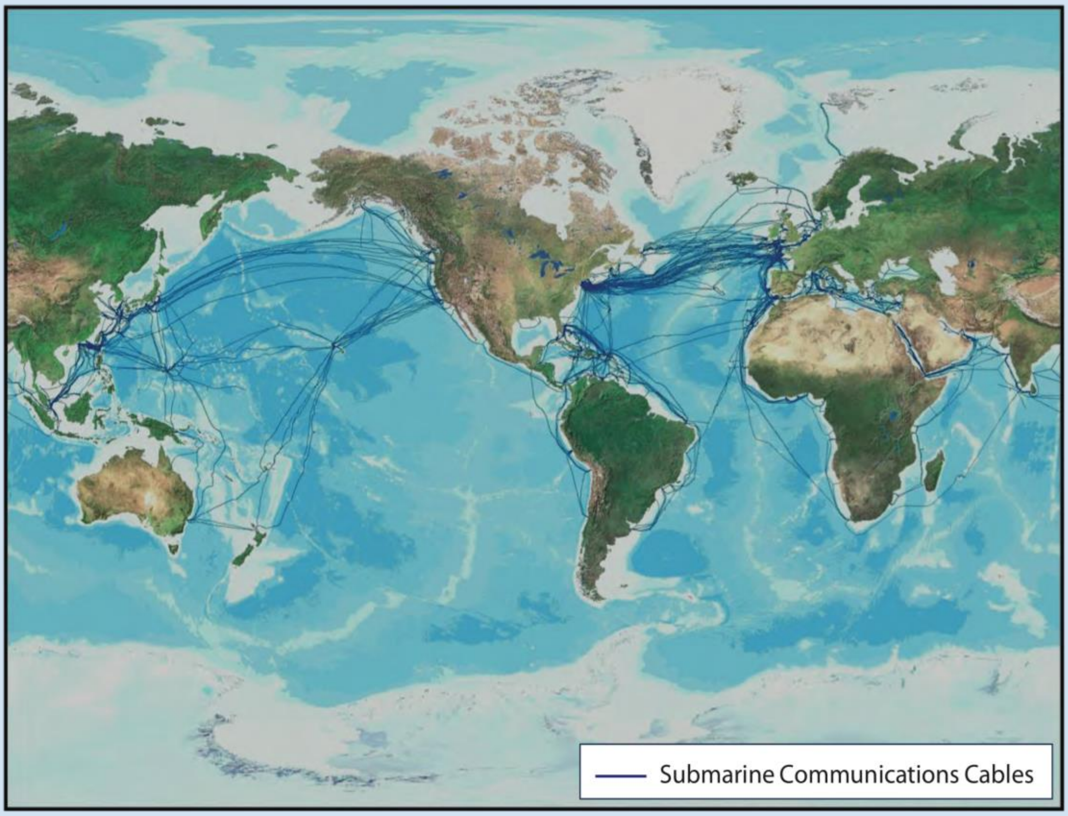
16 Kurt Veggeberg and Nanxiong Zhang, Integrated On-line Structural Health Monitoring Architecture of the Donghai Bridge, Proceedings of the IMAC-XXVII, Society for Experimental Mechanics Inc. 2009.

17 Robert H. Chen, Hok K. Ng, Jason L. Speyer, Lokeshkumar S. Guntur, and Russell Carpenter. *Health Monitoring of a Satellite System*, Journal of Guidance, Control, and Dynamics, Vol. 29, No. 3 (2006), pp. 593-605. doi: 10.2514/1.15012.

18 Even submarine power cables now include temperature monitoring of power conditions, *e.g.*, http://www.nexans.com/eservice/Corporate-en/navigate_22410/Optical_sensing_cables.html, Kluth et al. 2007, Application of temperature sensing and dynamic strain monitoring to subsea cable technology, www.jicable.org/2007/Actes/Session_A9/JIC07_A96.pdf

of satisfying the *due diligence* requirements associated with the mitigation of future outages in global Internet traffic.

Figure 1: Map of the distribution of global undersea communications cable infrastructure[19].



Map used with permission of Tyco Electronics Subsea Communications LLC. Copyright, all rights reserved.

1.2 Cables and natural hazards

Comparing the global distribution of submarine communications cables[19] (Figure 1) and a century of seismicity[20] (Figure 2) makes it evident that there will always be a potential threat of cable damage from earthquakes (and related natural phenomena). Even for the relatively non-seismic region of North America's east coast, the Grand Banks earthquake clearly demonstrates that earthquakes have the potential to cause cable damage anywhere in the world. A recent report of the Asia-Pacific Economic Cooperation states that, with respect to hazards to cables[11]: "The overall minimum-approach should be to build up the capacities to monitor the situation, obtain as much information about the status as possible, and prevent undesirable developments as soon as possible. In addition the provision of basic protection measures against the common, likely hazards on the one hand, and the less likely but especially devastating ones on the other, must be made." Therefore, sensor data are needed routinely throughout the ocean telecommunications systems as cables are upgraded and new systems installed.

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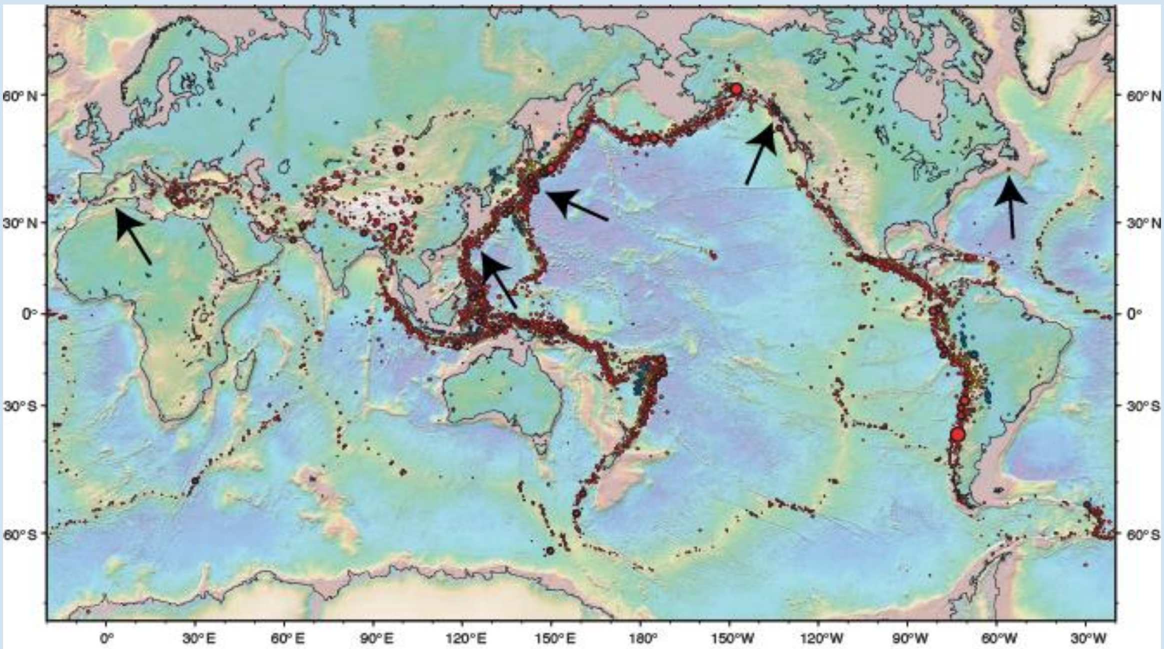
19 Source: Tyco Electronics Subsea Communications LLC. Copyrighted and all rights reserved.

20 E. R. Engdahl and A. Villaseñor (2002). Global seismicity - 1900-1999, chap. 41 of Lee, W.H.K., Kanamori, H., Jennings, P.C., and Kisslinger, C., eds., International handbook of earthquake and engineering seismology, Part A: Amsterdam, Academic Press, pp. 665-690.

Figure 2: Map of all earthquakes with a magnitude greater than or equal to M6 during the twentieth century. Symbol size is in relation to magnitude. Note earthquakes' distribution throughout the world's oceans. The black arrows show the location of the aforementioned earthquakes responsible for damage to cables. Left to right: Algeria 2003, Taiwan (Province of China) 2006, Japan 2011, Southeast Alaska 2013 and 2014, and Grand Banks 1929.



Map adapted with the permission of the International Association of Seismology and Physics of Earth's Interior (IASPEI)[20].

Accelerometers (3-axis) are the minimum complement of sensors under consideration. They are small, rugged and low-power. Additional sensors, such as those taking measurements of pressure and temperature, can also help to assess the environmental situation prior to and during a cable-fault event. High-resolution pressure data provides additional dynamic constraints[21], and temperature measurements are sensitive to turbidity-flow events[22]. The volume of sensor data transmitted is negligible (<20 kb/s) when considered in the context of cable capacity.

To be effective in entraining resilience and robustness into future systems, the sensor data must be shared. Private-sector companies that own and operate undersea communications infrastructure should collaborate to establish a shared, trusted environment for the exchange of sensor data, contributing to the common good by improving the monitoring and protection of submarine telecommunications systems. The ITU/WMO/UNESCO-IOC Joint Task Force offers a framework in which to begin sharing sensor data within and between the private sector, governments and the scientific community.

1.3 Dual-use green cables

Realizing the necessity for equipping the global undersea communications cables infrastructure with environmental sensors in order to improve the resilience of these systems in circumstances of natural hazards and disasters, the societal benefits in viewing the dual uses of this approach are manifest. Sensors

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21 Paros, J., P. Migliacio, and T. Schaad. "Nano-resolution sensors for disaster warning systems." In OCEANS, 2012-Yeosu, pp. 1-5. IEEE, 2012.

22 http://www.mbari.org/benthic/Turbidity_Event_2002/canyon_events.html

monitoring the structural health of cable systems, attuned to the ocean environment around them, may also serve to monitor ocean/climate changes affecting all of humanity as well as tsunamis affecting coastal communities and infrastructure. In this role, submarine telecommunication cables become a principal vantage point for keeping active watch over Earth's ocean environment. The scientific needs are compelling, and this momentum towards engaging the private sector in this essential monitoring role is a natural complement to governments' leadership in scientific networks.

2 Monitoring tsunamis and earthquakes using submarine telecommunication cables

2.1 Introduction

Earthquakes can cause tsunamis able to devastate coastal communities. Since 2004, there have been eleven deadly tsunamis in the Pacific and Indian Oceans. The 2011 Great East Japan Earthquake generated tsunami waves that left nearly 19,000 people dead or missing in Japan[23], where infrastructure and property costs were estimated to have exceeded $300 billion[24]. In 2004, the Sumatra-Andaman earthquake and subsequent tsunami impacted fourteen countries in South Asia and East Africa, with nearly a quarter-million people killed or going missing and about 1.7 million people displaced[25]. Tsunamis are uniquely dangerous as a natural disaster, able to cause deaths at great distances from their source. For the Great 1960 Chilean earthquake, the resultant tsunami traveled over 15,000 km across the Pacific, causing 61 deaths in Hawai'i. Striking northern Honshu and the Philippines about one day after the earthquake, the tsunami left 185 and 32 people dead or missing, respectively[26]. Ample warning is essential to save lives. The dual-use of sensor technology to monitor submarine cable systems and their environment offers a unique opportunity to meet the due diligence requirements of both industry and humanity.

Tsunamis have been recognized as a potentially significant hazard to coastal communities and national economies worldwide. However, large-scale ocean-based detection systems have only been in place since the 2004 Indian Ocean tragedy, which raised societal awareness of the need for efficient tsunami-warning systems to be implemented on a global scale. The basic functions of these warning systems include tsunami detection - the rapid confirmation or cancellation of the tsunami-generation alert - and the characterization of the tsunami wave to forecast coastal impacts.

Prior to the development and widespread deployment of seafloor pressure-sensing technology, a global network of seismometers identified locations and magnitudes of possible tsunamigenic earthquakes, which would lead to the dissemination of a tsunami warning in certain circumstances. Augmenting this network with seafloor sensors deployed in the open ocean enables the monitoring of the pressure of a tsunami as it passes over the sea floor, allowing the measurement of the actual tsunami generated to assess its potential coastal threat and corroborate the necessity of a warning. From earthquake and tsunami theory, it is known that only a small fraction of an earthquake's energy is transferred to the water column[27]. Seafloor pressure-

[23] http://www.ngdc.noaa.gov/hazard/tsunami/pdf/2011_0311.pdf

[24] Miyamoto, H . Kit (2011). *2011 Tohoku earthquake and Tsunami | Field Investigation Report*, p.5, www.miyamotointernational.com

[25] http://earthquake.usgs.gov/earthquakes/eqinthenews/2004/us2004slav/

[26] http://earthquake.usgs.gov/earthquakes/world/events/1960_05_22.php

[27] This was recently confirmed by recent investigations using the rich observation database acquired during the March 2011 Japan Tohoku tsunami and over the days that followed. See: Tang, L., V.V. Titov, E. Bernard, Y. Wei, C. Chamberlin, J.C. Newman, H. Mofjeld, D. Arcas, M. Eble, C. Moore, B. Uslu, C. Pells, M.C. Spillane, L.M. Wright, and E. Gica (2012) Direct energy estimation of the 2011 Japan tsunami using deep-ocean pressure measurements. Journal of Geophysical Research, 117, C08008, doi: 10.1029/2011JC007635.

sensor technology effectively enables the measurement of both tsunami and seismic waves in the open ocean, making it possible to integrate ocean physics with that of the solid-earth to form a comprehensive, dynamic assessment. Both the ocean-pressure and seismic data must be available in near real time to provide for tsunami early warning and alert[28].

Moored offshore and linked by surface buoy to satellite telemetry, tsunami instrumentation is both expensive and difficult to maintain. Reliable, sustainable systems must be deployed. In this context, this paper explores the tsunami-warning applications of a dual-use cable partnership between commercial and societal interests in the interest of saving lives in coastal communities threatened by tsunamis. Furthermore, the same sensor technology will also be shown to be essential in monitoring ocean/climate change.

2.2 Current limitations of tsunami-detection technology and associated challenges

Tsunami waves can be detected through measurements of pressure taken by an Absolute Pressure Gauge (APG) at a fixed point on the seafloor[29]. Deep-ocean sensing technology, and software such as that used in the Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy systems[30] (Figure 3) and other near-shore cabled systems[31,32], take advantage of this fact to provide real-time observations of tsunami waves as they propagate across an ocean. The technology can detect tsunami wave amplitudes of less than 1 cm in the open ocean (at depths of up to 6 km). Data are sampled from 10 Hz (in real time in the case of cabled networks) to 15-second integration periods for the DART system, where most data are transmitted in near real time during an event (during approximately the first 3 hours) as 1-minute averages of the 15-second samples. This current data-sampling and return scheme was developed to maintain a minimum resolution while at the same time conserving power.

The resulting trade-off is one of system proximity to the source versus the ability to separate the tsunami from the seismic signal. When deployed far enough from the seismic faulting zones, the tsunami and seismic waves - which travel with different velocities - are naturally separated by arrival time. However, the signals overlap significantly for DART and other tsunami-monitoring technologies when sited in close proximity to tsunamigenic source regions. As a consequence, the tsunami signal is often ‘contaminated’ by a highly aliased (*i.e.*, under-sampled) seismic signal. The difficulties present in extracting the tsunami signal from observations in close proximity to a tsunami source are shown graphically in Figures 4 and 5.

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28 Another advantage of tsunami detection based on offshore pressure sensors is the potential capability of detecting non-seismic tsunamis, such as the ones generated by submarine landslides and meteorological disturbances (the latter “tsunami like” waves are called meteo-tsunamis or “rissagas” in the Mediterranean and “abiki” in Japan).

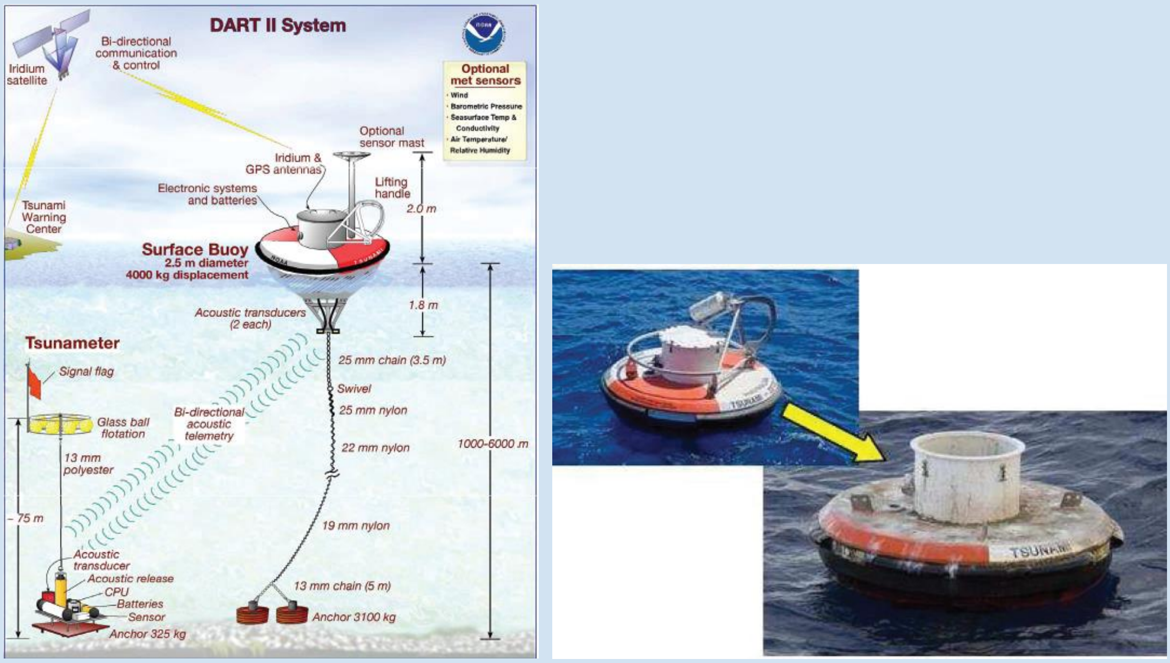
29 Meinig, C., S.E. Stalin, A.I. Nakamura, F. González, and H.G. Milburn (2005): Technology Developments in Real-Time Tsunami Measuring, Monitoring and Forecasting. In Oceans 2005 MTS/IEEE, 19-23 September 2005, Washington, D.C.

30 Bernard, E., and C. Meinig (2011). History and future of deep-ocean tsunami measurements. In Proceedings of Oceans' 11 MTS/IEEE, Kona, IEEE, Piscataway, NJ, 19-22 September 2011, No. 6106894, 7 pp.

31 Other systems of international tsunameters networks include the real-time cabled networks DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis, https://www.jamstec.go.jp/donet/e/) in Japanese waters, NEPTUNE (North East Pacific Time-series Underwater Networked Experiment, http://www.oceannetworks.ca/) in Canada, and Aloha Cabled Observatory (ACO) near Hawai‘i (http://aco-ssds.soest.hawaii.edu).

32 The Eastern Sicily NEMO-SN1 EMSO node (European Multidisciplinary Seafloor and water column Observatory, www.emso-eu.org) discusssed in Favali, P., et al. (2012). NEMO-SN1 Abyssal Cabled Observatory in the Western Ionian Sea, IEEE J. Oceanic Engineering, doi: 10.1109/joe.2012.222.4536. Chierici, F., P. et al. (2012). NEMO-SN1 (Western Ionian Sea, off Eastern Sicily): a cabled abyssal observatory with tsunami early warning capability, ISOPE-Int. Soc. Offshore and Polar Engineers, Proc. 22nd Int. Offshore and Polar Engineering Conf., Rhodes, July 17-22, ISBN:978-1-880653-94-4, ISSN:1098-6189.

Figure 3: The deployed configuration of a tsunami DART buoy system is shown at the left and centre (courtesy of NOAA PMEL). To the right is an example of vandalism that frustrates the robustness of buoyed tsunami warning systems.



(Figure[33] used with the permission of IOC/WMO).

Figure 4: Plot of deep-ocean bottom pressure record during the November 15, 2006 Kuril Island tsunami recorded by a Japanese cabled station (blue line, time in hours). Data sampling rate of 1 Hz shows the need for high-frequency data to extract the tsunami signal (forecasted, long-wavelength tsunami signal is shown in red). These high-frequency records allow the separation of the tsunami and seismic signals, essential for tsunami analysis. If only 1-minute-sampled data were available, the tsunami wave would be very difficult to separate from the aliased seismic signal.

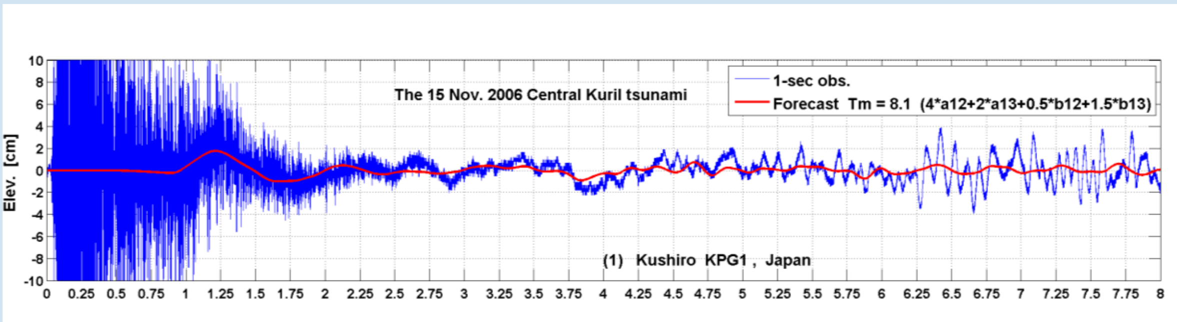


Figure from NOAA PMEL.

33 Jarrott, K., Ocean data buoy vandalism – incidence, impact and responses (2011) *Data Buoy Cooperation Panel: International Tsunameter Partnership*, DBCP Technical Document No. 41. Intergovernmental Organization Commission of UNESCO and World Meteorological Organization.

Figure 5: DART 1-minute pressure data transmitted during an event (black, time in hours) shows an aliased seismic signal near the earthquake origin time and tsunami signal 1 hour later. However, recognizing the latter buried within the aliased data record (black) is difficult at best; in this case, it is only possible given the after-the-fact prediction (red). Altering the tsunami signal is inevitable in trying to retrieve it on such an aliased record, therefore compromising its use for accurate forecasts.

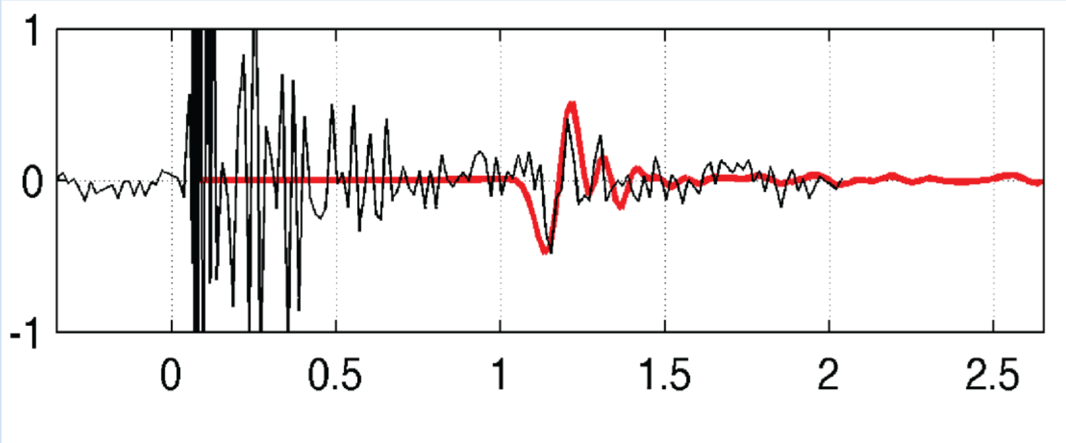


Figure from NOAA PMEL.

Despite the associated difficulties, placing systems closer to the tsunami source provides for faster tsunami detection and, therefore, faster characterization of the wave threat. Near-shore cabled systems use higher sampling rates and deploy pressure gauges alongside accelerometers or seismometers, which enables the seismic signal in the pressure sensors to be distinguished from the tsunami signal[34]. Thus, this joint sensor-deployment configuration has the potential to permit even earlier warnings of catastrophic tsunamis. This is particularly important for earthquake source regions near populated coastal areas. Recent developments in high-resolution, wideband pressure-observation technology[35] permit an APG to be sampled at 100 Hz, significantly extending its capability to record unaliased seismic signals. Were it not for power and telemetry limitations in DART buoy systems, this sensory regimen could be adopted. Fortunately, submarine telecommunication cables offer the potential to achieve tsunami-detection best practice across the broad ocean basins and near the earthquake tectonic zones.

DART tsunami buoys suffer environmental and maintenance issues, beyond the technical issues of enhancing sensor sample rates, telemetry bandwidth and co-location of pressure and seismic acceleration to improve real-time tsunami detection and characterization. Tsunami buoys in operation in the Indian Ocean have experienced many problems resulting from vandalism (Figure 3). To mitigate such issues, Indonesia is considering using submarine fiber-optic cables instead of surface buoys. DART systems are often installed in the remote ocean, and annual servicing by ships is both difficult and costly. Severe weather conditions and storm damage bring down many DART systems for much of the winter-spring season as they await summer repair (see Figure 6). For example, along the Aleutian arc from Kamchatka to the Alaska coast, two-to-four DARTs have been down for each of the preceding four years, leaving dangerous gaps in coverage for coastal communities affected by Aleutian tsunamis. Hawaiʻi is one such community, surrounded by tsunamigenic source regions.

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[34] Tolkova, E. and T. Schaad (2013). Comparing the nano-resolution depth sensor to the co-located ocean bottom seismometer at MARS, http://arxiv.org/pdf/1401.0096.pdf

[35] Paros, J., C. Meinig, M. Spillane, P. Migliacio, L. Tang, W. Chadwick, T. Schaad, and S. Stalin (2012). Nano-resolution technology demonstrates promise for improved local tsunami warnings on the MARS project, In Oceans 2012 MTS/IEEE, Yeosu, Korea, 21-24 May 2012 (2012).

Figure 6: Map shows the location of tsunami DART buoys deployed. Sites in red are not currently operational (May 2014), leaving gaps in coverage. The buoy network is deployed near the earthquake source regions (see Figure 2), but does not provide coverage of the tsunami waves crossing the broad ocean basins. Note also that no tsunami buoys are currently deployed around Europe, even though Lisbon, Portugal was destroyed in 1755 by an earthquake and tsunami[36], and over 450 tsunamis have occurred in Mediterranean Sea[37] since 2000 BC.

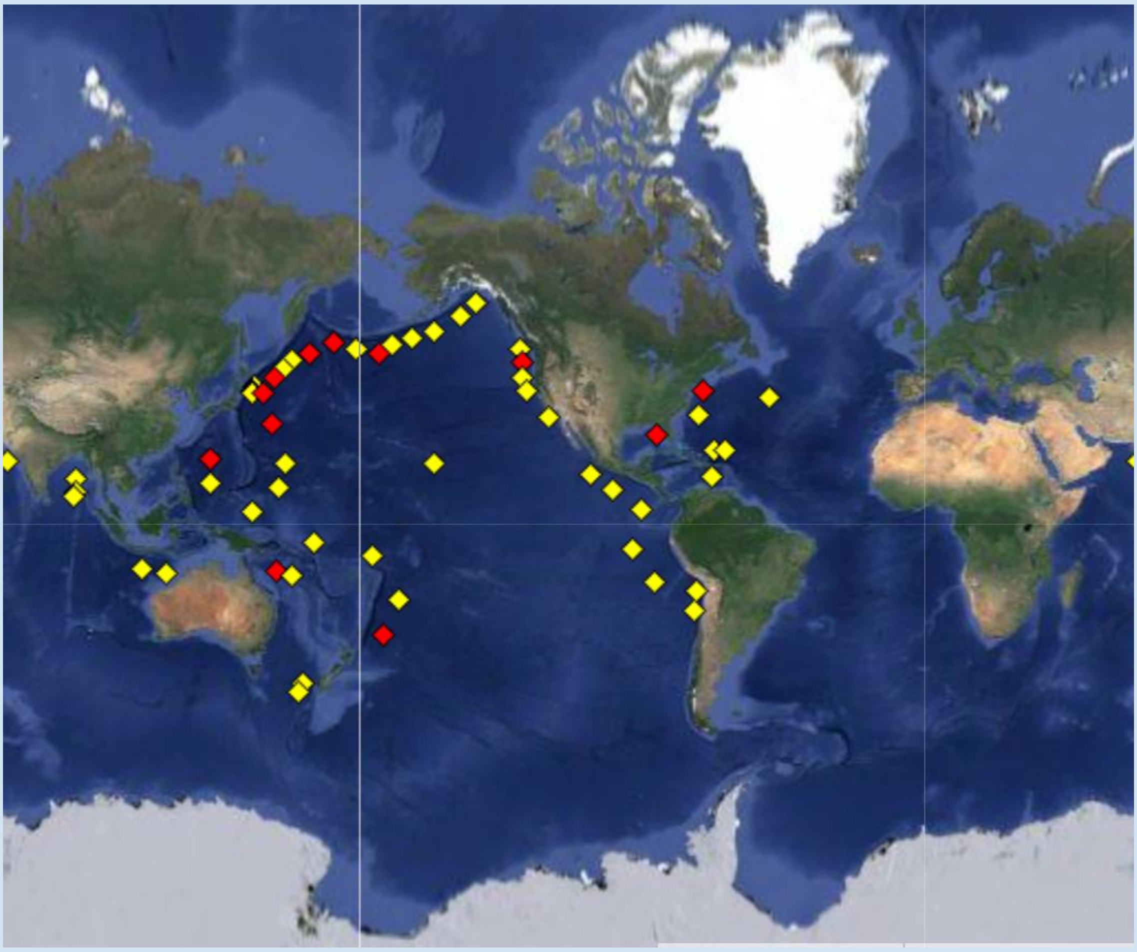

Figure from PacIOOS, SOEST, University of Hawai'i at Manoa.

[36] http://nisee.berkeley.edu/lisbon/

[37] NOAA/WDS Global Historical Tsunami Database at National Geophysical Data Center.

Figure 7: In order to improve the observation capability throughout the region of the 2011 Tohoku earthquake and tsunami, the construction of the seafloor cabled network along the Japan trench is being implemented. The deployment of the Boso (red) and Aomori (green) sub-networks are completed, and upcoming deployment phases are noted. Colored dots in the ocean show the locations of pressure vessels in which a set of seismometers and pressure gauges for tsunami detection are included. The network consists of 150 stations in total with a spacing of about 30km in the East-West direction and in a spacing of 50-60km in the North-South direction with a total cable length of 5,800km[38].

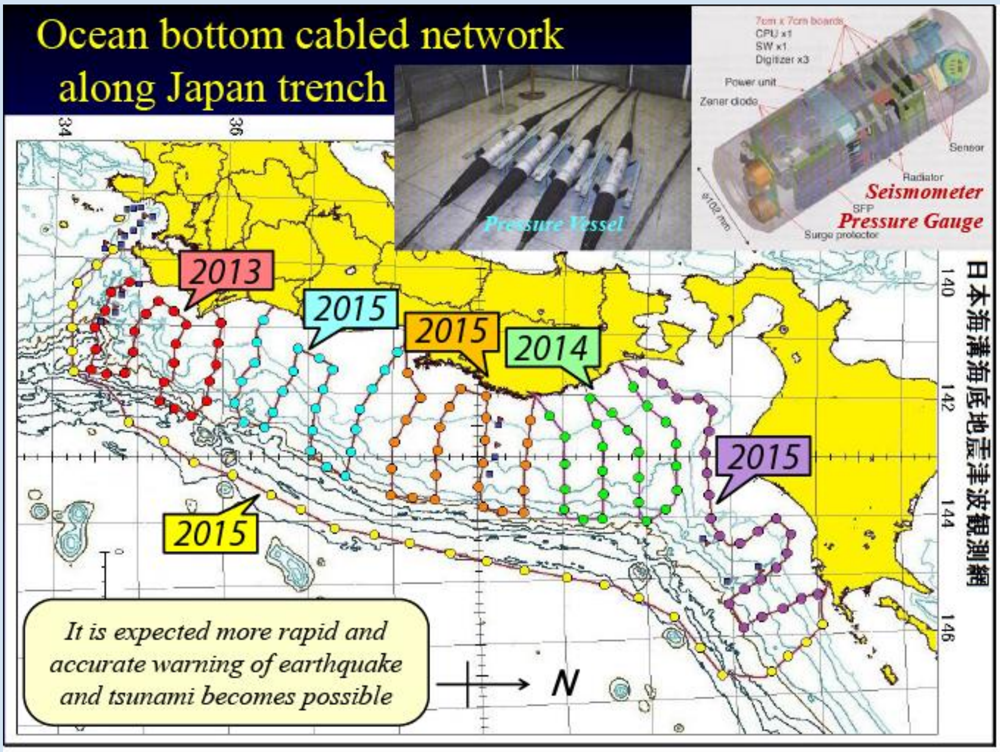

Figure used with permission of Y. Okada, NEID.

2.3 Progress in scientific cable systems

Cables used solely for tsunami and earthquake monitoring have been in operation near the coast of Japan for more than 30 years[39]. Today these cable networks are being expanded through the DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) observatory network[40], as well as the Tohoku seafloor seismic and tsunami-observation network along the Japan Trench[38] (Figure 7).

38 Okada, Y. (2013) Recent Progress of Seismic Observation Networks in Japan, Journal of Physics: Conf. Ser. 433 012039, doi:10.1088/1742-6596/433/1/012039.

39 Meteorological Research Institute (1980). Permanent ocean-bottom seismograph observation system (in Japanese with English abstract), Technical Report 4, 233 pp., Tsukuba, Japan.

40 https://www.jamstec.go.jp/donet/e/

Five scientific cabled observatories[41], on the west coast of North America near Hawai'i and in the Mediterranean Sea, are capable of monitoring tsunamis and deploying and testing a variety of seafloor sensors:

1) the Monterey Accelerated Research System[42] (MARS) testbed 54 km off California;
2) the Axial Volcano cable node of the Ocean Observatory Initiative[43] (OOI) which lies about 450 km from the Oregon coast;
3) the North East Pacific Time-series Underwater Networked Experiment (NEPTUNE), the cabled observatory of Ocean Networks Canada extending 300 km off Vancouver Island;
4) the Aloha Cabled Observatory[44] (ACO) 100 km north of Oahu; and,
5) the NEMO-SN1 observatory[32] 125 km east of Sicily.

Shorter coastal cabled systems are increasingly being installed for science, with examples in the 10-km LEO-15[45] (Long-term Ecosystem Observatory) coastal observatory on the New Jersey coast; the 25-km Ocean Bottom Cabled Seismometer system[46] (OBCS) on the east coast of Japan; and the 15-km Lofoten-Vesterålen Ocean Observatory[47] (LoVe) system on the coast of Norway.

These scientific networks afford the opportunity to deploy and test a variety of tsunami-detection technologies. Over the past two years, the NOAA Pacific Marine Environmental Laboratory (PMEL) has collaborated with the National Science Foundation to deploy real-time cabled APGs as part of an effort to monitor active volcanoes. Prototype tsunami sensors were deployed and tested at the MARS site, where numerous earthquakes and tsunamis were observed with a standard DART APG and a high-resolution wide-bandwidth pressure sensor. The success of these deployments helped to motivate plans for installing these sensors at the OOI Axial Volcano as part of the cabled-node instrumentation. Ongoing instrument testing at the NEMO-SN1 site includes a cabled APG connected to an accelerometer to eliminate the effects induced by the seafloor motion on the bottom-pressure record.

The success of these government-funded scientific observatories has created a valuable resource for the telecommunications industry, with public-sector investments having already solved the questions essential to the scientific monitoring of the oceanfloor. The technical requirements of sensor specifications and real-time data management have been defined and met. Public-private partnerships are now possible for testing sensors and prototypes *in situ*, without developing new test facilities.

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41 A summary of the main cabled observatories in operation or planned is found in: Favali, P., Person, R., Barnes, C.R., Kaneda, Y., Delaney, J.R. and Hsu, S-K. 2010. Seafloor observatory science. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.28.

42 http://www.mbari.org/mars/

43 U.S. National Science Foundation Ocean Observing Initiative http://oceanobservatories.org/infrastructure/ooi-station-map/regional-scale-nodes/

44 http://aco-ssds.soest.hawaii.edu

45 http://marine.rutgers.edu/nurp/leo-15.html

46 Shinohara, M., T. Kanazawa, T. Yamada, Y. Machida, T. Shinbo, and S. Sakai (2013). New compact ocean bottom cabled seismometer system deployed in the Japan Sea, *Marine Geophysical Research*, DOI 10.1007/s11001-013-9197-1.

47 http://love.statoil.com

2.4 Siting opportunities for tsunami-warning systems

The current DART and international tsunameter networks, shown in Figure 6, combine legacy locations with findings from a 2005 siting workshop[29] and tsunami propagation studies. The map of current submarine telecommunication cables (Figure 1) is a proxy for a future network of ocean-aware *green cables*[48]. Comparing the current tsunameter network with cable routes (Figures 1 and 6), it is clear that cables offer extraordinary coverage over the ocean basins not currently monitored. Cabled sites along the continental margins and island arcs can provide a better, more capable and robust alternative to current buoy systems. Nonetheless, some of the existing DART sites have no nearby telecommunication cables (*e.g.*, Kamchatka) and would continue to require buoy systems until cable lays become economically viable or necessary.

Purely in terms of siting for tsunami detection and forecasting as conceived today, positioning pressure sensors at every repeater of a telecommunication cable could be considered excessive. A 'keep-it-simple' approach would rely on studies to identify source regions that pose the greatest potential hazard. This could be accomplished by collecting the results of previously conducted studies reported by a number of investigators. Hazard-assessment studies - event-specific models run by operators and researchers, collations of post-event field surveys and data observed at offshore and near-shore instrument locations during events - can identify specific candidate sites that would meet the principal scientific-monitoring objectives.

[48] Cable systems currently have about a 25-year lifecycle. Hence, as systems are retired, they will be replaced in many of the same locations. This was observed in the transition from analog to optical-fiber systems in the 1990s. New cable routes may also be anticipated as the thirst for additional Internet bandwidth continues to grow (e.g, Japan to UK via the Arctic, www.arcticfibre.com).

Figure 8: The tsunami radiated from the Tohoku earthquake of 2011 is not smooth or uniform[49]. The earthquake geometry directs energy perpendicular to the fault, and the bathymetry focuses and refracts the waves into high and low-amplitude filaments that can be highly variable (red colors are > 20 cm in the open ocean). Current tsunami monitoring networks do not have sufficient resolution to observe these key features and incorporate them into real-time warnings. Dense seafloor measurements from submarine cables would significantly advance the monitoring capabilities.

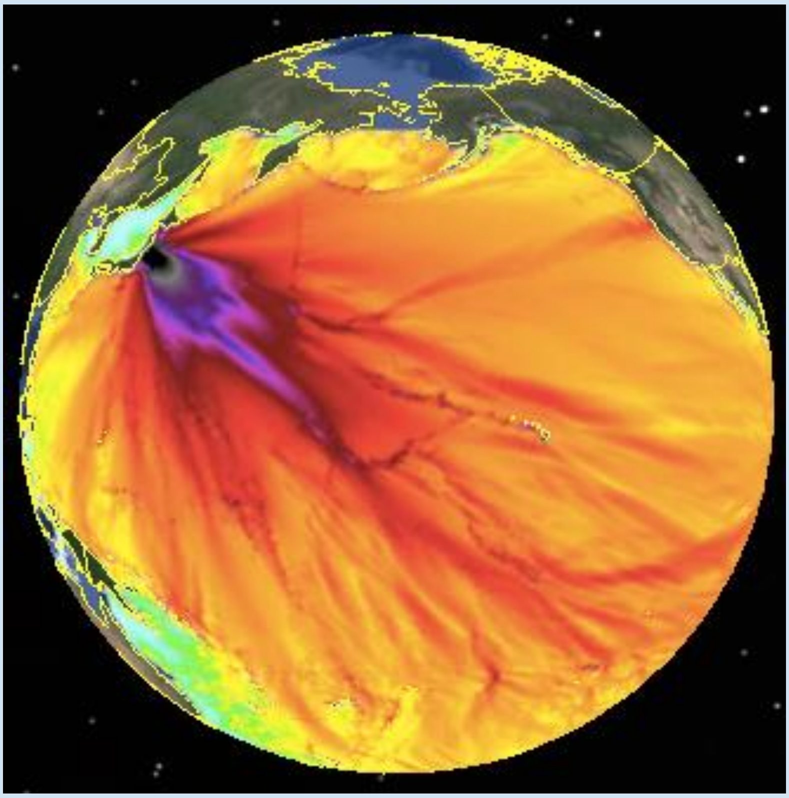

Figure from NOAA PMEL.

A forward-looking approach to tsunami science, however, would justify a greater density of coverage for pressure gauges and accelerometers. The sensors themselves require the redundancy of their nearest neighbours, with their integration and consolidation within the active submarine telecommunication cables limiting or even negating the need for sensor repairs[50]. Secondly, tsunamis are highly directional, caused by spatial geometry of the source and the ocean bathymetry. Sparsely deployed sensors could miss the strongest core region of energy flux[51,52]. In deep water, a tsunami travels at about 0.22 km/s - a tsunami wave with a period of 8 minutes has a wavelength of about 100 km. The necessary spatial-sampling interval

49 http://nctr.pmel.noaa.gov/honshu20110311/

50 Butler, op. cit.

51 This occurred during the Queen Charlotte Island (Haida Gwaii), western Canada, earthquake and tsunami of October 12, 2012, which led to over-prediction of tsunami impact at Hawaiian Islands. http://nctr.pmel.noaa.gov/queencharlotte20121027/

52 The main tsunami energy tends to propagate perpendicular to the strike angle of the fault and less energy propagates along the strike. Tsunami impact will be significantly varied due to its directionality and wavelength (Butler, R., Great Aleutian Earthquakes, Hawai´i Institute of Geophysics and Planetology, Peer-Reviewed Report HIGP-2014-1, 170 pp.). The coastal community within the tsunami main energy path could experience two or three times larger tsunami impact than the one outside of the main energy path. In addition, the tsunami impact will change due to wavelength as well. Clear tsunami signals at three DART buoys for the 2011 Tohoku tsunami between the source and US coasts were certainly valuable information for the US tsunami warning, but these three tsunami signals are not sufficient to indentify the tsunami main energy path and its wavelength.

to resolve such details (Figure 8) corresponds well with the cable repeater spacing, at about 50 km. With a density of coverage encompassing all repeaters and cables, the tsunameter network could resolve a tsunami purely from seafloor data, even without foreknowledge of its source[53] (e.g., an earthquake's location and magnitude).

Tsunami forecasts depend on the calibration of a tsunami model. With continued improvements to computational speed, tsunami forecasts may be re-calibrated and updated (data assimilation) as the tsunami propagates across an entire ocean basin, refracting and diffracting as the tsunami travels. This supports an argument for deploying pressure gauges even well away from anticipated source regions. A corollary to this last point is that seafloor pressure-gauge data are much more useful for validating open-ocean tsunami propagation models than island or coastal sea-level data. A greater density of pressure gauges will help improve these models in hindcast mode, significantly improving our understanding of the physics of tsunami wave dispersion and the effect on tsunami propagation resulting of the Coriolis force (associated with the rotation of Earth)[54,55].

Submarine mass failure (such as landslide and slump) - a major source of damage to undersea cables - is often a consequence of a tsunamigenic earthquake. The additional seafloor deformation caused by the submarine mass failure can amplify the tsunami[56], but with existing measurement technology it is very difficult to identify the presence or absence of the submarine mass failure. Although submarine cables traversing the tectonic region at the coast (in an EEZ) remain at threat, integrated sensors may provide data on seafloor deformation of great value for understanding an event of submarine mass failure and in distinguishing its contribution both to the tsunami and to cable infrastructure damage.

2.5 Monitoring earthquakes on our oceanic planet

Earthquakes are responsible for most tsunamis. The largest tsunamis affecting coastal populations are caused by earthquakes of enormous magnitude[57], Mw 9 and greater, such as the 2011 Japan and 2004 Sumatra-Andaman events. Seismic waves travel much faster that tsunamis (~8 km/s versus 0.2 km/s) and can thus provide early warning of an event. The determination of the location and magnitude of an earthquake is the primary trigger for tsunami-warning vigilance, which in turn awaits corroboration of

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53 Maeda, T., Obara, K., Shinohara, M., Kanazawa, T., and Uehira, K. (2013). Towards Real Time Tsunami Forecasting without Source: A Data Assimilation Approach with Dense Tsunameter Network, American Geophysical Union, Fall Meeting 2013, abstract #NH41B-1713.

54 Dispersion occurs as different tsunami wavelengths travel with differing velocities. An effect of dispersion is to separate a single large wave into a series of successive waves. The Coriolis effect causes the tsunami to the travel in a more westerly direction.

55 Kirby, J.T., Shi, F., Tehranirad, B., Harris, J.C., Grilli, S.T. (2012). Dispersive tsunami waves in the ocean: Model equations and sensitivity to dispersion and Coriolis effects. Ocean Modeling, 62, 39-55, doi:10.1016/j.ocemod.2012.11.009

56 Geist, E.L. (2000). Origin of the 17 July, 1998 Papua New Guinea tsunami: Earthquake or landslides? Seismological Research Letters, 71(1), 344-351. Grilli, S.T., Harris, J.C., Kirby, J.T., Shi, F., and Ma, G., Masterlark, T., Tappin D.R., and Tajali-Bakhsh, T.S. (2013). Modeling of the Tohoku-Oki 2011 tsunami generation, far-field and coastal impact: a mixed co-seismic and SMF source. In Proc. 7th Intl. Conf. on Coastal Dynamics (Arcachon, France, June 2013) (ed. P. Bonneton), 749-758, paper 068. Imamura, F., and Hashi, K. (2003) Re-examination of the source mechanism of the 1998 Papua New Guinea earthquake and tsunami. Pure and Applied Geophysics, 160, 2071-2086. Satake, K., and Tanioka, Y. (2003). The July 1998 Papua New Guinea earthquake: mechanism and quantification of unusual tsunami generation. Pure and Applied Geophysics, 160, 2087-2118.

57 The magnitude is a measure of the size of an earthquake. The magnitude Mw is the current standard for measuring the largest events. Note that Mw is defined such the 1 magnitude unit is about 32 larger, and 0.2 unit is about a factor of 2. Hence, an Mw 8.2 is twice as big as an Mw 8.0, whereas the Mw 9 is about 32 times greater than an Mw 8.0. The relationship between Mw and tsunami height is more complicated, and depends upon many factors including the area of rupture, the extent of deformation beneath the seafloor, and propagation effects. See Butler, R., Re-examination of the potential for great earthquakes along the Aleutian island arc with implication for tsunamis in Hawaii, Seismological Research Letters, 81(1), 30-39, doi: 10.1785/gssrl.83.1.30, (January/February 2012).

water-level data (coastal and DART buoys) to confirm the tsunami wave. Hence, tsunami warning depends on the effectiveness of the real-time seismic networks.

Earthquakes can generate devastating tsunamis but also cause enormous damage in their own right. Recent earthquakes[58] in Haiti (2010), Eastern Sichuan, China (2008) and Pakistan (2005) have caused great loss of life, with 316,000 people lost in Haiti, 87,000 in China and 80,000 in Pakistan. The monitoring and analysis of earthquakes globally depends on the real-time global seismographic network and other regional and national networks[59]. However, despite Earth being 71% ocean, nearly all of its seismic stations are on land (Figure 9). The few exceptions are the scientific cabled observatories[31,32] located on coasts near the seafloor. Yet, the vast majority of earthquakes' rupture faults are located beneath the oceans.

Figure 9: Distribution of earthquake sources (red circles) relative to seismic stations (blue triangles). The vast majority of earthquakes are generated at ruptured faults located beneath the oceans, where there are few permanent observing networks. Oceanic coverage is largely restricted to islands.

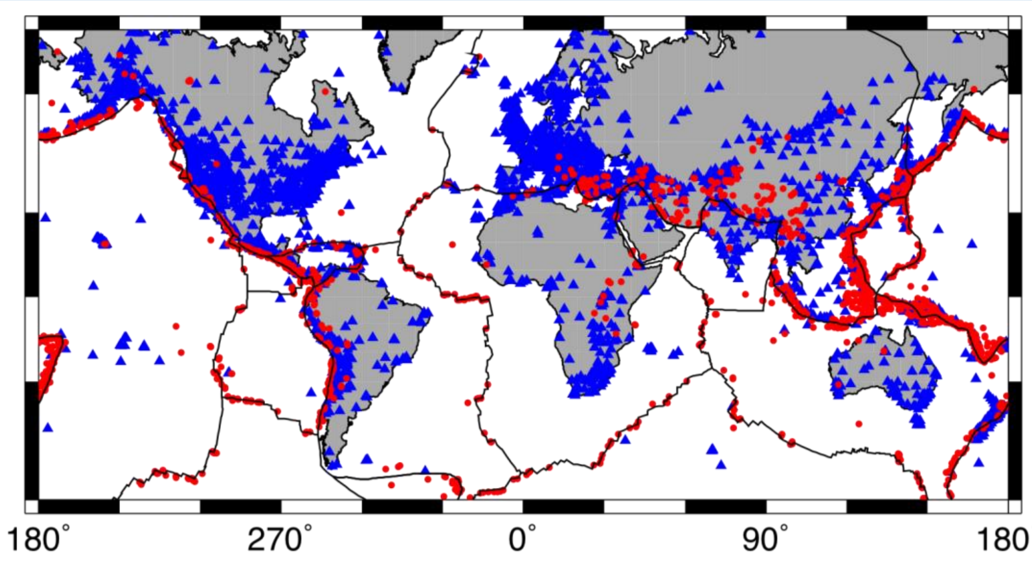

Figure from J. McGuire, WHOI, with permission.

A direct result of this ocean-land disparity in coverage is that the great coastal earthquakes responsible for tsunamis are monitored "from the land side" and a few islands. Although this does not significantly diminish the ability to locate an earthquake, it does substantially limit our resolution of the earthquake process itself. The details of how, where and how much the earthquake moves over its fault surface are fundamental to tsunami generation. High-resolution seismic imaging of the fault surface can only be accomplished with data collected from sensors completely surrounding the earthquake, and nearby seafloor data can reduce the imaging time. With seafloor seismic data at hand, significant improvements in the evaluation of the dynamics of both earthquakes and tsunamis can be achieved using the same sensor technology.

58 http://earthquake.usgs.gov/earthquakes/eqarchives/year/byyear.php

59 Butler, R., K. Creager, P. Earl, K. Fischer, J. Gaherty, G. Laske, W. Leith, J. Park, M. Ritzwoller, J. Tromp, L. Wen. The Global Seismographic Network surpasses its design goal, EOS Trans AGU, 85(23), 225-232, (June 8, 2004). See also www.fdsn.org

2.6 Real-time data for seismic monitoring and hazard response

In addition to their essential societal value in providing tsunami warnings for coastal communities, monitoring networks of seismological stations provide the capability for the rapid identification of and response to hazards emerging from moderate-to-large earthquakes globally.

Many nations take a leading role in monitoring seismic activity in their countries. In addition, the United States Geological Survey National Earthquake Information Center (USGS NEIC[60]) issues global earthquake notifications and evaluates their potential impact on populations worldwide. For all moderate and larger earthquakes worldwide, NEIC determines the magnitude and location of the event within minutes. This basic information is then transformed into an impact estimate by the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) program[61], which provides fatality and economic-loss assessment following significant earthquakes. This publicly available assessment provides a first alert to emergency or hazard response entities, activating relief efforts. The speed and accuracy with which an earthquake can be characterized is directly related to the number and distribution of stations near the event.

Large earthquakes rupture across a fault plane that can be hundreds or thousands of kilometres long. Populations close to this fault rupture are likely to experience the strongest shaking levels and are at high risk of damage to their built infrastructure, even if far from the epicenter where the earthquake was generated. Further, the amount of rupture along this fault plane - and therefore the level of shaking - can vary significantly, complicating impact estimates. NEIC has developed real-time methods to estimate the extent of faulting as well as the rupture distribution along the fault plane in real time. However, the lack of good seismic coverage in the open ocean is an impediment to progress in responding to earthquakes and their concomitant tsunami hazards. Sensors along the dual-use cables would greatly improve the capability and capacity for rapid earthquake-hazard response to affected populations, as well as for imaging of the tsunami source.

Although some continental margins rarely experience seismic activity, the threat is nonetheless present, evidenced by the examples of the 1929 Grand Banks earthquake[7] and the great Stregga landslides on the Norwegian coast[62]. Accelerometers and high-resolution pressure sensors incorporated into submarine telecommunication cables crossing these continental margins (e.g., east coast of North America, west coast of Western Europe, east coast of South America, east coast of Australia) will record low-level seismicity along the margin. Over time, a catalogue of small earthquakes on these margins can be established, and used as a basis for estimating the recurrence rate of larger earthquakes in the 5-6 magnitude range, which are capable of generating submarine landslides along the margin[63].

60 http://earthquake.usgs.gov

61 http://earthquake.usgs.gov/earthquakes/pager/

62 Bryn P, Berg K, Forsberg CF, Solheim A, Kvalstad TJ (2005). Explaining the Storegga Slide. Marine and Petroleum Geology 22: 11-19.

63 Ten Brink, U. S., Lee, H. J., Geist, E. L. and Twichell, D., Assessment of tsunami hazard to the U.S. East Coast using relationships between submarine landslides and earthquakes, Marine Geology, 264, no. 1-2, pp. 65-73, 2009.

Therefore, it is possible to meet requirements for long-range risk assessment of landslides and their potential damage to submarine telecommunication cables through monitoring via the sensors within the cables themselves. High population concentrations at low-level coastal regions along the Atlantic margins, high concentrations of industrial and port facilities and the presence of conventional and nuclear power plants along the coast make this margin highly vulnerable to flooding by tsunamis[64], even if the probability is small.

2.7 Advancing seismology science

Beyond the societal value in warning of, mitigating and responding rapidly to earthquakes, the availability of pressure gauges and accelerometers deployed within submarine telecommunication cables will greatly enhance seismology science.

As the premier tool for understanding the interior of our planet, our ability to map Earth's structure is constrained by the spatial distribution of earthquake sources and seismic stations. Each new seismic measurement on the seafloor represents a sampling of a hitherto unexplored portion of Earth's interior[65]. Increasing our knowledge of Earth's structure improves our ability to model the propagation of seismic-wave energy, and hence increases the clarity of our telescope's view into the interior for the imaging of earthquakes themselves. However, to be truly useful, the data must be accumulated over a span of more than 10 years to acquire a global diversity of earthquakes.

The largest earthquakes and tsunamis occur along the deep trenches where the oceanic crust thrusts beneath the continent or island arc, a movement termed 'subduction'. The shallow regions of a subduction zone's thrust interfaces are difficult to study using land-based seismic networks, as the oceanward coverage is typically nonexistent. However, monitoring events in this region is critical to understanding the mechanics of great subduction earthquakes and tsunami generation. Recent seafloor datasets have documented striking interactions between seismic fault slip (e.g., abrupt motion), aseismic[66] fault slip and fluid flow transients occurring near the trench. In some regions, Very Low Frequency Earthquakes (VLFEs)[67] not recorded by land-based instrumentation have been observed as low-amplitude seismic tremors seen on seafloor instruments. As this is a key region where submarine telecommunication cables cross the tectonic boundary between the ocean basin and the shore station, a better understanding of the dynamics of this region will directly translate into better assessments of cable risk.

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64 Tsunami sources that might affect the Atlantic coasts are fewer than in the Pacific but still significant. These include: 1) submarine landslides along the continental slope and rise; 2) earthquake-generated tsunami sources from the Azores-Gibraltar plate boundary, the Puerto Rico Trench, and possibly from the northern Cuba fold-and-thrust belt; and 3) the collapse of a volcanic flank in the Canary Islands. The latter has generated some concern about a megatsunami threat, however, Hunt et al. (2013) dismiss this as hyperbole. J.E. Hunt, R.B. Wynn, P.J. Talling, & D.G. Masson (2013). Multistage collapse of eight western Canary Island landslides in the last 1.5 Ma: Sedimentological and geochemical evidence from subunits in submarine flow deposits Geochemistry, Geophysics, Geosystems, 14 (7), 2159-2181 DOI: 10.1002/ggge.20138.

65 Seismic profiling is the most useful technique available for imaging Earth's crust and upper mantle. Moreover, by using the sensors deployed in cables as receivers in areas where seismic data are missing or rare, one can carry out active-source seismology with only a seismic source ship. However, such cable systems by themselves will have little resolution for exploration of oil and gas (See Appendix 1). Further, even routine seismic noise data are highly valuable, when using interferometry methods to derive the properties of the oceanic crust and uppermost mantle at a scale comparable to the repeater spacing.

66 Aseismic slip is characterized by slow motions that do not radiate vibrations.

67 Obara, K., and Y. Ito (2005), Very low frequency earthquakes exited by the 2004 off the Kii peninsula earthquakes: A dynamic deformation process in the large accretionary prism, Earth Planets Space, 57, 321-326.

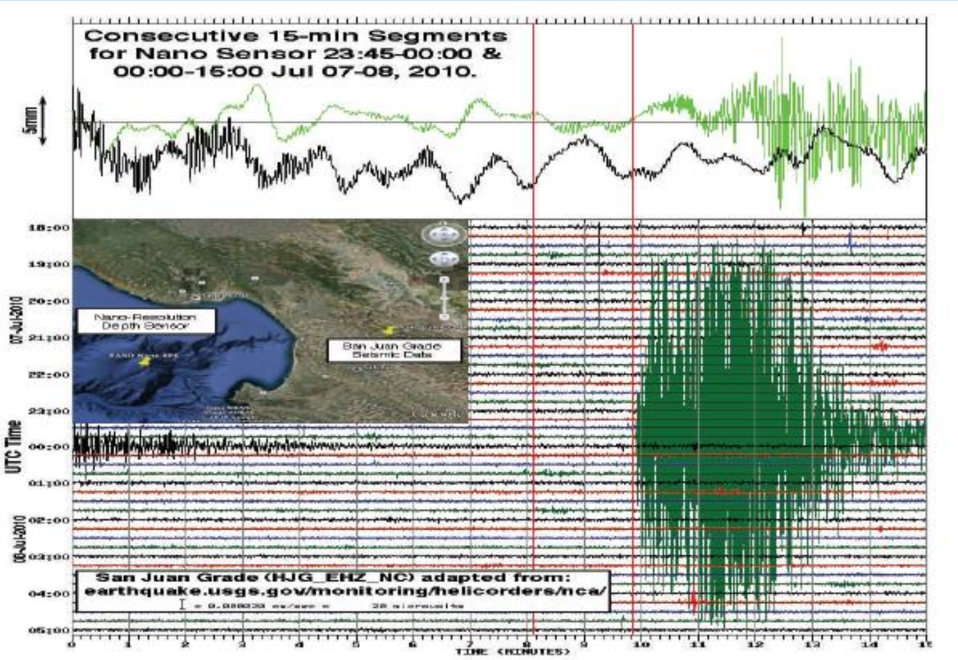
2.8 *Cable sensor requirements for tsunamis and earthquakes*

The minimum complement of sensors required to advance tsunami-warning capabilities are well matched with the monitoring needs of cable systems themselves. Twenty-first century pressure-sensor technology encompasses both high-resolution and wide-bandwidth APGs, enabling the measurement of both the tsunami and its precursory seismic signal. Accelerometers such as those recommended by national seismic networks are sufficiently rugged and low-noise, with sufficient long-period response to overlap and complement the pressure gauge in order to resolve earthquakes' seismic signals from tsunami signals. This combination of sensors is also sufficient to satisfy the demands of earthquake monitoring.

Absolute Pressure Gauge (APG)

The Paroscientific APG has long been used for tsunami detection and characterization. It has already been used successfully as a seafloor geodetic sensor[68], which further recommends its utility in monitoring the cable systems for motions. These inherently digital sensors utilize a quartz resonator bar that changes frequency with pressure. In recent years, a number of groups have greatly improved the resolution at which the frequency output of these sensors can be measured. These high-resolution APGs have been deployed as seismic sensors to record the pressure signals associated with Rayleigh waves. Figure 10 shows examples of an earthquake recorded by APGs.

Figure 10: A high-resolution absolute pressure gauge (Nano-Resolution APG) cabled at MARS in the ocean off the California coast records a magnitude 6.7 earthquake in Alaska. Deploying both an APG and accelerometer within submarine telecommunication cables will provide extraordinary new data source for tsunami warning and earthquake monitoring.



Nano-resolution Depth Sensor & Land-based Seismometer Comparison
Plot courtesy of NOAA-PMEL

68 Nooner, S. L., and W. W. Chadwick Jr. (2009), Volcanic inflation measured in the caldera of Axial Seamount: Implications for magma supply and future eruptions, Geochem. Geophys. Geosyst., 10, Q02002, doi:10.1029/2008GC002315.

Seismic waves on the seafloor are detected and measured with inertial sensors such as seismometers or accelerometers, or with pressure sensors such as hydrophones[69] or APGs. Earthquake-generated seismic waves vary in frequency from less than a milliHz to tens of Hz (periods from about an hour to hundredths of a second), and can have more than 140 dB of dynamic range (the largest signals being larger than the smallest signals by a factor of more than ten million). While individual seismometers with this bandwidth and dynamic range exist and are capable of measuring earth motion across this entire band, and are indeed routinely deployed on land, it is likely impractical to deploy such instruments within cable repeaters at this time given their size, orientation requirements and robustness. However, much of this seismic band can also be monitored in the ocean with a combination of proven, robust sensors suitable for deployment within commercial cable systems. In the future, when they become available, compact, low-power seismic instrumentation without orientation requirements will garner a strong recommendation for use.

Accelerometers

Equipping deep-sea optical cable repeaters with acceleration-monitoring instruments will maximize measurement capabilities for hazardous earthquakes, submarine landslides, turbidity flows or manmade hazards such as an anchor or fishing line dragging a cable out of place. The constraints on the design of the accelerometers incorporated into cable repeaters are that they must remain within a small form-factor, be little affected by sensor orientation, use little power, and be robust enough to survive cable-ships' deployment process and the 25-year expected cable lifetime.

The accelerometer should have a flat response to acceleration and nearly flat phase to well above earthquake frequencies. It should also have good response below 0.1 Hz for earthquake and turbidity monitoring, and should overlap with the APG response. Sensor noise levels should be low enough (≤ 2 nano-g per √Hz) to record the microseism noise on land (due to ocean surface waves, as oceanic ambient noise levels are generally higher than land levels) and resolve natural seismic signals with good fidelity and sensitivity. The sensor should record accelerations up to ±1.5 g, which covers all but the largest proximal earthquakes; therefore, nearly all signals of interest will remain on scale and be well resolved[70].

Timing and Data Sampling

The short-period seismic data from the accelerometers must be timed to an accuracy of at least 1 millisecond and sampled at 100 samples/s. The APGs would need to be sampled at 20 samples/s to avoid vessel-detection/military concerns (Appendix 1), and to be compatible with existing global seismic standards. For sophisticated time-series analysis and for future uses, a timing accuracy and precision of 1 microsecond is recommended.

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69 Hydrophones have been used successfully to monitor earthquakes for many decades, and would prove to be a valuable addition to the absolute pressure gauge and accelerometer. However, there are significant security concerns by navies regarding the deployment of hydrophones, as discussed in Appendix 1, and these concerns may raise barriers by governments in permitting entry of new submarine telecommunication cables. Focusing upon 'keep it simple' in this initial implementation of APG and accelerometers for *green cables* is straightforward and does not substantially diminish the science or value to society. Nonetheless, in the future when national security concerns may abate, the inclusion of a hydrophone into the systems would be valuable for marine mammal research and to serve as receivers in ocean acoustic tomography networks measuring large scale ocean temperature, as well as local sea-surface wind and rain for weather and climate.

70 MEMS (micro-electro-mechanical system) sensors could be potential candidates fitting the needs. A prime example is the Silicon Audio Geolight series of accelerometers. The Geolight is designed for the rigors of petroleum-exploration, and should handle cable deployment conditions well. The power requirement is ~70 mW. Similar sensors are in development by Hewlett Packard and Shell but not presently commercial. Although such sensors are used in petroleum-exploration research, hundreds must be employed together—a single sensor is essentially useless (see Appendix 1).

Real-time Data Access

Without an open data-sharing policy, all of the improvements accrued by installing sensors in *green cables* are forfeited. Both tsunami-warning and seismic networks work together in a spirit of international cooperation, sharing data openly and adopting common frameworks for formatting and transmitting those data. Since its inception as a monitoring science over 100 years ago, global seismology has recognized that earthquakes cannot be located and measured without exchanging international data. Today's tsunami-warning and seismic networks are real-time systems, instantly sharing the data they capture. This is essential when monitoring hazards to save lives.

A broad infrastructure of data centres and standards to manage data captured from the seafloor already exists within the international scientific community. This infrastructure has the potential to distribute and archive the data captured by monitoring instrumentation deployed within cable repeaters, at no cost to the submarine telecommunication cable industry. Proprietary data formats must be avoided in favour of ascii encoding in natural units for temperature (°C), acceleration (m/sec^2) and pressure (Pa) that can be readily interpreted by all. The ITU/WMO/UNESCO-IOC Joint Task Force is prepared to work closely with the scientific community and the submarine telecommunication cable industry to arrange for data-sharing practices able to benefit humanity.

3 Sensors integrated into undersea communications cables: A sea change in the observation of the climate of the oceans

3.1 Introduction

The Earth's hydrosphere - atmosphere, oceans and ice - is warming. This is indisputable. Economic, social and political disruptions, and opportunities, can be expected. Exactly how much of this climate change and its consequences can be attributed to human activities is still a subject of debate. What is not debatable is how little we know about the changes occurring through direct observations. While the sparse observations available have outlined the broad spatial patterns of warming rates in the oceans (for example, that they are strongest around Antarctica in the deepest layers[71]), we have not yet achieved a clear picture of where and by how much the oceans are warming.

The oceans can be viewed as the flywheel of the climate system, absorbing and holding heat and chemicals for up to thousands of years. But how that flywheel works is not well understood, although theories are plentiful. Is heat accumulating faster in certain layers than others, thus altering the fundamental stratification of the deep oceans? Is heat accumulating in certain geographic regions more than others, thus altering the circulation systems that depend on the horizontal stratification differences?

The oceans are also believed to be absorbing as much CO_2, a critical "greenhouse gas", as is being trapped in the atmosphere[72]. How long will this gas remain in the oceans? Will it ever be released and thus accelerate the atmospheric "greenhouse" effect? What effects will it produce on the chemistry, and thus the biology, of the oceans? Acidification of the oceans resulting from the absorption of CO_2 has already been documented and will have negative ramifications for many ecosystems, such as coral reefs[73].

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71 Purkey, S.G., and G.C. Johnson (2010): Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. J. Climate, 23(23), doi: 10.1175/2010JCLI3682.1, 6336-6351. Purkey, S.G., and G.C. Johnson (2012): Global contraction of Antarctic Bottom Water between the 1980s and 2000s. J. Climate, 25(17), doi: 10.1175/JCLI-D-11-00612.1. DOI Purkey and Johnson 2010;2012).

72 Gruber, N. & 13 others, 2006, *Glo. Biogeo. Cyc*., **23**, GB1005, doi:10.1029/2008GB003349.

73 Hoegh-Guldberg et al., 2007, *Science*, **318** (no. 5857), 1737-1742.

These and many, many more unanswered questions about the impact of the oceans in the climate system, as well as the oceans' responses to land- and atmosphere-driven climate changes, are spotlighting the appalling lack of observations of ocean environments, especially beneath the top few hundred metres. While nothing can be done about the lack of observations from the past, much can be done now to implement observation systems that will reveal the detailed character of climate changes in the future. Scientists and government agencies have responded to this need with a number of initiatives over the past two decades: satellite observations of the surface layer[74]; globally drifting instruments that profile the upper two thousand metres[75]; repetitive expeditionary cruises along selected transects[76]; arrays of moored instruments across significant currents[77]; autonomous gliders[78]; and a few small cabled observatories[79]. But these efforts remain grossly inadequate, as they focus primarily on the upper layers of the oceans. Even in the upper thousand metres, their spatial distribution is exceedingly sparse.

3.2 Sensor gateway: the ideal role for communications cables

The modern technology revolution has resulted in an explosion of miniaturization and sensor improvements that will most certainly continue in the coming decades. Previously laboratory-bound instruments, such as mass spectrometers[80] and genome sequencers[81], have been miniaturized and automated for deployment on the seafloor. More common instruments, such as those that measure pressure and temperature, have become simple enough to be mass-produced and deployed in large numbers for long periods of time, communicating acoustically among themselves and with telecommunication devices.

The need for sensor networks and chemical and biological sensors is an urgent one, but the extent of this need depends on the region and, as technology advances and our understanding of ocean environments grows, monitoring objectives will most certainly change. What is considered an important measurement to acquire today may not be the most important measurement in the future. These circumstances argue for a highly flexible observation system, allowing the addition or deletion of sensors as deemed appropriate in the years to come.

One can imagine that such a highly flexible observation system could be an integral part of an undersea communications cable that carries "sensor ports" at each of its repeaters. At a minimum, these ports would allow communications to external sensors and sensor networks, either through subsidiary cables or acoustically. Ideally, these ports would also provide power, although this characteristic may become less important as technological advances continue to miniaturize sensors and reduce their power consumption, permitting long-term autonomous deployments.

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74 Satellite observations of the ocean: http://ioc-goos-oopc.org/obs/surface_sat.php. There is a relatively high risk associated with satellites (http://www.gao.gov/products/gao-13-283) - not just space weather (plasma, magnetic fields, radiation solar wind) and other failures, but funding challenges. Ocean observing is a critical infrastructure and needs independent redundancy and diversity in all respects to create a resilent system.

75 Argo profiling floats: http://www.argo.ucsd.edu

76 CLIVAR repeat hydrography and carbon transects with research vessels: http://www.clivar.org/resources/data/hydrographic

77 The Tropical Atmosphere Ocean (TAO) project uses moored instruments to provide real-time observations of upper ocean temperature, salinity and currents in the tropical Pacific (10° latitude): http://www.pmel.noaa.gov/tao/

78 Autonomous gliders are used for climate-related objectives: https://www.nsf.gov/news/news_summ.jsp?cntn_id=114647

79 A few regional cabled observatories already exist and have climate related objectives: http://www.oceannetworks.ca/about-us; http://aco-ssds.soest.hawaii.edu/#; MARS http://www.mbari.org/mars/; http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04231138

80 A mass spectrometer will be deployed on the seafloor and connected to the Ocean Observatories Initiative regional cabled observatory: http://www.interactiveoceans.washington.edu/story/Mass_Spectrometer

81 A robotic microbial gene sequencer, the Environmental Sample Processor (ESP), is being developed for deployment on the MARS observatory: http://www.mbari.org/mars/science/deep_esp.html

With flexible sensor ports spaced every ~50 km along a seafloor cable, instrumentation could be strategically placed where needed. On the one hand, scientists would likely want certain climate-relevant measurements at every repeater, such as temperature, salinity, pressure and water-column heat content (obtained with Inverted Echo Sounders[82]). On the other hand, the flexibility of the sensor port permits an aggregation of sensors in regions of high multi-disciplinary significance, such as beneath the Deep Western Boundary Currents, in mid-ocean ridge fracture zones, beneath circulation frontal zones and across the continental slopes.

3.3 Embedded sensors: the fundamental role of communications cables

Studying the long-term changes of ocean environments requires, at the very least, the establishment of a set of observation systems in many different locations which would be maintained for long periods of time (decades to centuries). This need both complements and overlaps the need described above for flexible systems that enable the adoption of new or updated technologies.

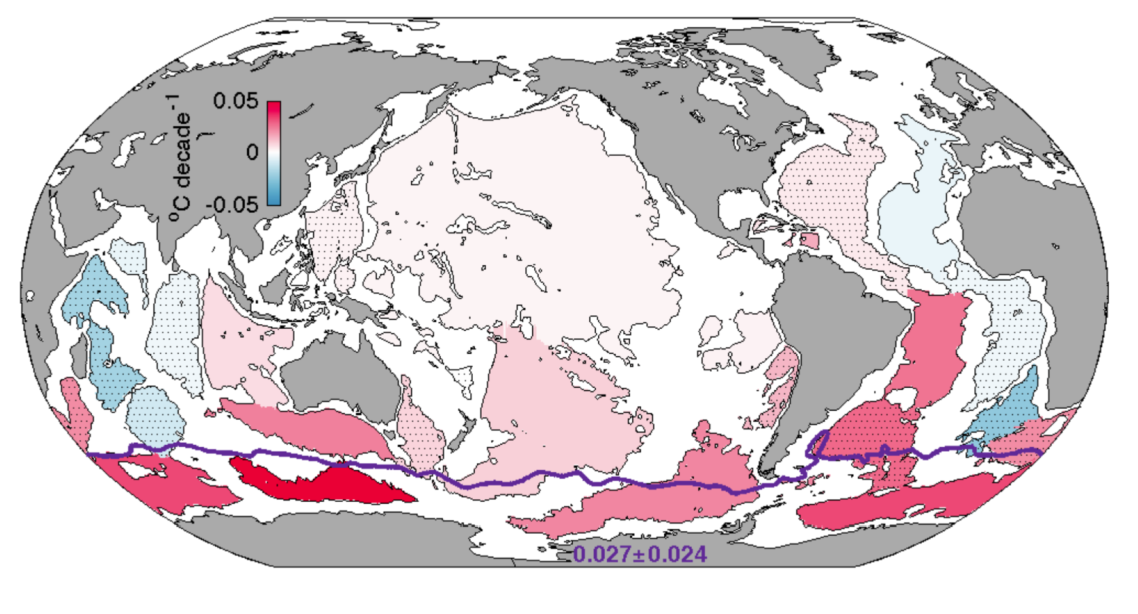
Sensors that measure basic climate-relevant variables, such as temperature and pressure, have now been miniaturized and simplified to the point that their insertion into communication cable repeaters has become eminently feasible. A likely consequence of this integration is that the sensors will not be modified for the lifetime of the cable. Once instrumentation for the measurement of variables like temperature and pressure has been deployed, it is inconceivable that the scientific community would ever want these measurements halted. However, the community would need to be convinced of their continuing accuracy. The sensors will drift and degrade over time. Periodic calibration cruises along the cable routes, perhaps using long-range autonomous undersea vehicles (AUVs), should suffice to ensure the utility of the measurements.

The Value of Water Temperature Observations Made at the Seafloor

Using sparse observations (roughly decadal resolution in time, and several thousands of kilometres resolution horizontally), Figure 11 reproduces a basin-average map of the rate of warming of oceans' deepest waters. Although coarse, this map permits an incipient understanding how the oceans are absorbing heat and moderating the increase of warming in the atmosphere. Rates of warming in different water masses reveal the dynamics of oceanic heat storage. Cable-based temperature observations at the seafloor would provide insights into spatial (cross-basin) and temporal (sub-decadal) variability, thus providing more information on warming dynamics as well as the unseen variability in the trends derived from intermittent hydrographic expeditions such as those used in the construction of Figure 11.

[82] Watts, D. R. and H. T. Rossby, 1977, *J. Phys. Oceanogr*., **7**, 345-358.

Figure 11: Rates of warming at depths exceeding 4000 m (degree C per decade). The primary source of these waters is the sinking of recently cooled surface waters around Antarctica. These waters are showing a clear warming trend. As this Antarctic Bottom Water (AABW) spreads around the globe it takes its warming signature with it. However, for unknown reasons, some basins indicate cooling of the abyssal waters despite being connected to the AABW flows. The data used to create this figure come primarily from the high-quality, but infrequent, WOCE and CLIVAR hydrographic expeditionary surveys[83]. Each transect (of order 10 per basin) has been occupied at least twice since 1980; some over a dozen times. The smaller basins are crossed by only a single hydrographic section every decade or so.



Figure[71] adapted with permission of the American Meteorological Society.

Ocean bottom temperature measurements made at telecommunication cable repeaters will actually provide information on much more of the water column than just the deepest layers displayed in Figure 11. Where cables cross mid-ocean ridges and continental slopes they come into contact with the mid-level water masses. Key components of the so-called Ocean Conveyor Belt[84] of ocean circulation tend to occur in boundary-intensified currents. For instance, the Atlantic's Deep Western Boundary Current, which transports water that has sunk from the surface in the high latitudes of the North Atlantic, flows southward along the eastern side of the North American and South American continents at depths of 1000-4000 m. A recent re-analysis of the heat content of the oceans[85] suggests that, since 2000, the waters between 700 m and 2000 m have been warming at a rate faster than the waters at greater or lesser depths, with the fastest rate occurring in the tropics (within ~30° of latitude about the equator). The mid-depth waters that

83 World Ocean Circulation Experiment (WOCE): http://www.nodc.noaa.gov/woce/
CLIVAR | Climate Variability and Predictability: http://www.clivar.org/

84 Lozier, M. S., 2010, *Science*, **328** (5985), 1507-1511. The term Ocean Conveyor Belt refers to a circulation of waters from high latitudes, where the surface waters sink due to an increase in density from loss of heat to the atmosphere, to lower latitudes of all oceans at depth. At these lower latitudes the waters rise as their density is decreased due to downward mixing of heat. The loop, or Belt, is closed by return flows to high latitudes near the surface. This Conveyor Belt flow is weak in magnitude, and is intertwined with the stronger horizontal circulations of water driven by the winds, but it is believed to have an outsized impact on climate due to the air-sea heat exchanges associated with it.

85 Balmaseda, M. A. et al., 2013, *Geophys. Res. Lett.*, **40**, 1754-1759, doi:10.1002/grl.50382.

have been in recent contact with the atmosphere, carrying imposed signatures of the atmosphere's heat and chemical content, can be observed by cable-borne sensors as the cables follow the seafloor's topography upward into these layers.

The study and monitoring of rising sea levels will benefit from cabled seafloor-temperature observations. A major contributor to sea-level rise is the expansion of ocean waters resulting from warming. Up to one-third of this thermal expansion component is estimated to be the result of warming in the deep oceans[86] (below 700 m). The scarcity of observations of deep waters means that this estimate has a relatively high uncertainty. Continuous and distributed temperature measurements from cabled sensors will improve this estimation[87]. Implementation of Inverted Echo Sounders[82] that can measure the water-column heat content would be an extremely valuable addition to the complement of cable sensors.

Large deposits of methane hydrate, a temperature-sensitive solid consisting of methane and water, exist at the seafloor and within the sediments below, primarily along continental margins[88]. This "fire ice" has the appearance of ice but is flammable as it melts at normal room air temperatures and pressures[89]. Methane hydrate is stable at the high pressures and cold temperatures now found in the ocean below 500 m. It is estimated that, globally, methane hydrate stores approximately twice the amount of carbon than all fossil fuels on Earth. This may represent a significant resource for humanity, but it is also a threat. There is concern that increased ocean temperatures will destabilize the hydrates and enact the release of vast amounts of methane, a powerful greenhouse gas. Temperature sensors along submarine cables would provide data on the stability of methane hydrate as ocean bottom temperatures rise. Sub-seafloor temperature measurements could further refine estimates of the stability of buried methane hydrate.

On shorter time scales of hours to months, cabled seafloor-temperature observations will participate in the march of discovery regarding oceanic variability, revealing and characterizing a variety of phenomena, such as mixing in deep basins (known to occur on time scales as short as minutes and hours) and meandering patterns of sub-surface currents (especially in conjunction with the seafloor-pressure observations discussed below).

The Value of Water Pressure Observations Made at the Seafloor

The movement of the waters in the oceans is determined by, and in turn altered by, the distribution of water properties such as temperature, salinity and density. Accurate models of this intricate interaction require data for both validation and initialization of forecasts, on many timescales, e.g. seasonal, inter-annual and decadal. Ultimately, humanity has to rely on models to understand and prepare for future changes in the Earth's climate. Measurements of seafloor pressure are quite valuable to the validation of ocean-circulation models, and thus for evaluating the causes of the oceans' present and future movements of mass and heat (*i.e.*, in simple terms, flow is from high pressure to low pressure).

Given the balance between the horizontal gradients of pressure and the structure of currents at periods longer than a day, accurate seafloor pressures can provide specific estimates of ocean-bottom current amplitudes and thereby improve the accuracy of numerical models of global ocean circulation. This is such a fundamentally important issue that it was one of the principal arguments for the construction and launch of

86 Church et al., 2011, *Geophys. Res. Lett.*, **38**, L18601, doi: 10.1029/2011GL048794.

87 Extending the network of Argo floats, currently limited to 2,000 m depth, to greater depths will also help to improve the situation. http://wo.jcommops.org/cgi-bin/WebObjects/Argo

88 "Potential for Abrupt Changes in Atmospheric Methane", *The Encyclopedia of Earth*, http://www.eoearth.org/view/article/155322/

89 USGS Gas Hydrates Lab: http://www.youtube.com/watch?v=U46XOoU0DrM&list=TLy3s2YYOFXMxIJAZaqcixju5p9SYIBwmy

the GRACE satellite mission (Gravity Recovery and Climate Experiment[90]) which cost USD 127 million (in 2002 dollars). The value of cabled pressure measurements is very similar to the value of the GRACE mission.

However, the GRACE mission provides a rather coarse horizontal resolution of seafloor pressure, being sensitive only to scales of variability longer than a few hundred kilometres. And, its orbit is non-repeating. The cabled pressure observations will provide observations with high resolution in time, unlike GRACE, in addition providing better horizontal resolution if each repeater contains a pressure sensor. However, this higher spatial resolution is achieved only along the cable route. Outfitting multiple cables with pressure sensors would mitigate this limitation.

A distinct advantage of cabled pressure sensors will be their ability to resolve well in time (and in space, somewhat) the large-scale circulation's variability on time scales of days, weeks and months, especially within ~40^o latitude of the poles where surface and deep flows are most tightly linked. Among other attributes, these fluctuations are the principal conduits of energy from semi-permanent circulation features to small-scale motions where the energy is dissipated. Their dynamics continue to be an important research topic. Understanding the full extent of their geography requires many more observations, such as those which can be provided by cabled seafloor-pressure sensors. How and why this geography evolves over time are key questions that must be answered to understand how ocean circulation is contributing and responding to climate change.

Finally, as for the temperature measurements discussed previously, seafloor-pressure observations contribute to our understanding of the causes of sea-level rise driven by global warming. In combination with observations of sea level, such as those obtained via satellite altimetry, seafloor-pressure observations help to reveal the origins of long-time-scale changes in sea level. Thermal expansion for example, deducible from changes in water temperatures (as measured, for instance, by seafloor-temperature sensors), does not change the mass of the water column and so is not observed in seafloor pressure. However, glacier and ice-cap melting does increase the mass and is observed in seafloor pressure. Pressure sensors distributed across the seafloor will aid in defining how changes in water-column mass are distributed geographically, helping to test models' predictions. Defining the geographical structure of such changes in mass is also an objective of the GRACE mission.

Siting

The optimum distance between sensors may be determined from ocean observing system simulations, both for climate change and tsunami warnings, carefully examining fiscal and regional scientific tradeoffs. As with the considerations relevant to tsunami warning, system redundancy is achieved by deploying sensors in adjacent repeaters as repairs will rarely, if ever, occur during a cable's lifetime. One statistical metric is the distance over which ocean variability becomes uncorrelated. This distance varies as a function of the

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90 GRACE: http://www.csr.utexas.edu/grace/gravity/oceanographic_sciences.html and http://www.jpl.nasa.gov/news/press_kits/gracelaunch.pdf. The primary goal of the GRACE mission is to map accurately the variations in the Earth's gravity field over its lifetime. The system first launched in 2002, continues in operation, and will be updated in 2017 with a GRACE Follow-On mission.

The GRACE mission has two identical spacecrafts flying about 220 kilometres apart in a polar orbit 500 kilometres above the Earth. It maps the Earth's gravity fields by making accurate measurements of the distance between the two satellites, using geodetic quality Global Positioning System (GPS) receivers and a microwave ranging system. This provides scientists from all over the world with an efficient and cost-effective way to map the Earth's gravity fields with unprecedented accuracy. The results from this mission yield crucial information about the distribution and flow of mass within the Earth and it's surroundings.

The gravity variations that GRACE studies include: changes due to surface and deep currents in the ocean; runoff and ground water storage on land masses; exchanges between ice sheets or glaciers and the oceans; and variations of mass within the Earth. The results from GRACE contribute significantly to Earth Observation System and global climate change studies, and make a huge NASA's Earth science goals, Earth Observation System (EOS) and global climate change studies.

variable and period but is commonly on the order of 100 km, which thus dictates a spacing of sensors along the cable at roughly similar intervals. Coincidentally, repeaters are spaced at intervals of 50-75 km.

Instrumentation

Today's oceanographic pressure and temperature sensors meet the sensitivity requirements for monitoring the ocean. In particular, the high-resolution APGs used for tsunami warning and earthquake monitoring can serve the breadth of purposes desired. Inverted Echo Sounders[82], engineered to meet the demanding conditions of deployment within a cable repeater, would be a very valuable augmentation to the temperature sensor. There are several technical issues that will need to be addressed to ensure that embedded sensors are of value to studies of both environmental change (usually small changes over long periods of time) and the dynamics of more energetic, shorter-time-scale variability.

All pressure sensors have substantial drifts, especially in the first six months following deployment. Proper drift diagnosis will initially require semi-annual in-situ calibration. Given the warming rates of bottom waters[71] over approximately 10-year spans, temperature sensors should not drift by more than 0.01° C over 10 years. Existing sensors match or exceed this stability criterion. Initially, annual calibration cruises should suffice to ensure the veracity of temperature measurements. Longer intervals between cruises may suffice as time goes on. Calibration standards, and the required frequency of calibration efforts, are matters for further deliberation by international scientific-monitoring agencies.

Repeaters are powered and hence emit heat into the ocean environment. In principle, the heat generated by the repeater may introduce a bias in temperature measurements. However, this could be mitigated if the sensor is integrated into the cable (as a "blister") at a reasonably short distance from the repeater, rather than within the repeater itself. Another alternative is to have the sensor package attached to the repeater by a short umbilical cable. Further, if the normal operation of the repeater produces temperature fluctuations, the resulting impact on the pressure sensor's operation must also be assessed.

If thermal constraints can be met, a concept worth consideration is the deployment of multiple, independent temperature and pressure sensors within each repeater. This is not an uncommon practice in experimental oceanography, where three independent sensors are typically deployed to gauge reliability and evidence of drift. However, the viability of this approach is dependent on the limits of space available within repeaters, perhaps making it an option only for future envisioned systems with repeater ports for additional instrumentation.

4 Conclusions

Integrating scientific sensors into the repeaters of submarine telecommunication cables is in the best interests of the telecommunications industry, enabling it to perform the *due diligence* demanded by purchasers of fiber capacity - *e.g.,* financial institutions - to understand and mitigate risks from natural hazards. Earthquakes and turbidity flows are known to have damaged at least 20 telecommunication cables in the past decade alone, causing country and regional-scale loss or reduction of service (and revenue), substantial repair costs and delays to repairs resulting from the shortage of cable ships relative to numbers of damaged cables in the affected area.

Critical infrastructure, on which society and business depends, incorporates basic sensors to monitor its state-of-health in real time. Bridges, buildings, submarine *power* cables, airplanes and satellites all possess this capability. Submarine telecommunication cables are the unique exception, currently deaf, dumb and blind to their environment, even as it affects them. Integrating basic scientific sensors - specifically to monitor acceleration, temperature and pressure - into cable system repeaters will provide real-time assessment of cable hazards and basic data for enhancing system robustness.

These direct benefits for the telecommunication cable customer will also serve to protect the populations that live along the coasts of the oceans where cables come ashore. The potentially devastating threats from tsunamis are real today, and our progeny face the impending threat of sea-level rise from global ocean/climate. These same basic sensors in green cable systems will deliver robust, early warning of tsunamis, as well as crucial data fundamental to deep-ocean monitoring of global climate change. This initial triad of sensors - monitoring acceleration, temperature and pressure - will reap benefits for global commerce, science and society.

The current network of tsunami-warning buoys is too vulnerable to surface storms and vandalism, which leads to broken systems, long times-to-repair and dangerous gaps in coverage. Similarly, the earthquake-monitoring networks that trigger tsunami alerts and characterize tsunami potential have almost no coverage over the ocean side of the tectonic zones that cause the tsunamis. Deep-ocean monitoring for tsunamis using accelerometers and pressure sensors would create a robust, real-time framework for tsunami warning. It would also advance tsunami science toward better forecasting coastal inundations as tsunami waves approach the coast - necessary information for emergency mitigation and saving lives.

Traditional ship and buoy-based ocean observations are expensive to sustain and new “smart” ocean-observing methods of sampling the ocean have been introduced, for example in Argo floats, gliders, voluntary ship observations, ferry-box systems, towed continuous plankton recorders from commercial vessels, animal observers or animal tagging. Piggybacking sensors on commercial telecommunication cables accords with this progress.

Our climate and oceans are changing, with potentially catastrophic effects for the planet and humanity. Despite the politics and wavering consensus around humanity’s hand in the cause of this change, which is now limiting our global response, the evidence for humanity’s contribution mounts yearly from measurements from space, the atmosphere and the ocean surface. The deep oceans are an essential part of the picture *not* routinely monitored. Yet the ocean circulation and the exchange of heat through the ocean depths and with the atmosphere all link to the bottom of the ocean. An untapped platform for oceanographic sensors, one that could outstrip all other systems attempting to observe the deep oceans, is the undersea communications cable. Pressure and temperature sensors represent the most minimal needs across the seafloor, installed in *green cable* repeaters with sufficient coverage to see the details of spatial and temporal ocean/climate change. An Inverted Echo Sounder would enable whole-ocean-depth thermal measurements. Integration of a sensor port on the repeaters would enable installation of new sensors with wider capabilities in the future. These data are needed not only to improve and validate forecast models, but also to document what is occurring throughout the whole Earth system. If we don’t begin to collect this data now, it will be forever lost to science and our legacy to our progeny will be a gap in our understanding of the world’s oceans and climate.

Telecommunication cable systems have a lifetime of at least twenty-five years. The map seen in Figure 1 will be regenerated over this timeframe with newer cables, following both the existing pathways (previously followed by analogue cables) and new transit routes. If we start today, in twenty-five years Earth could possess an extraordinary capability for monitoring tsunamis and global ocean/climate change. These *green cables* would serve the Earth’s coastal population not only with the best Internet, but also with the data required to respond to the risks posed by these hazards. Open access to these data in real time and in a non-proprietary format is essential, and can be handled within existing data-management systems.

The ITU/WMO/UNESCO-IOC Joint Task Force strongly endorses the concept of embedding critical climate-relevant, tsunami-warning and cable-hazard sensors in seafloor communications cables. We call upon the private sector, governments, scientists, philanthropic foundations and the Internet-using public to recognize this extraordinary need and opportunity, and to take concerted action to make this system a reality for humanity.

Appendix 1: Regarding concerns by Nations of the potential use of cable systems for unauthorized energy exploration or vessel-detection/military purposes

Question posed by JTF Legal Committee to Engineering and Science and Society Committees:

Address from technical and data-gathering perspectives how dual-purpose telecom-marine data cables will differ in terms of capabilities and characteristics from other sensing technologies that could be used for energy exploration or vessel-detection/military purposes. It would be helpful to compile this information to address two issues that have consistently led governments to assert greater jurisdiction over marine data gathering.

Response to Legal Committee query:

Current scientific seismo-acoustic monitoring on the sea floor of the northeastern Pacific by pressure/seismic/hydroacoustic sensors is subject to prior review by military entities for frequencies between 8 Hz and 3 kHz[91]. At lower frequencies (below 8 samples/s or 4 Hz Nyquist frequency) these data are passed without review. Therefore, band-limiting the seismic and pressure channels at 8 sample/s is appropriate for avoiding known military issues. This situation may be appropriate for dual-use cables situated in the region of naval facilities or transit lanes, but can be relaxed in more distant locations, such as the Southern oceans. For instance, for the OOI cabled observatory off the West coast of North America, there has been less military interest in high-resolution pressure measurements < 50 Hz. Also, the two broadband hydrophones on the ALOHA Cabled Observatory (~150 km from military facilities, at 4728 m depth) are not considered a problem. Furthermore, above 3 kHz acoustic sensors are sensitive to wind, rain and the calls of small marine mammals, and such environmental data would be valuable for monitoring global change and marine mammal migration. Therefore additional, higher-rate sampling at > 3 kHz (if filtered to avoid the 8 Hz-3 kHz band) will be useful. It should also be noted that marine vessel detection often requires extensive, directional arrays beyond the needs or financial capability of the scientific community.

Oil and gas exploration uses the frequency band 5-100 Hz for finding sedimentary structures. However, for pressure/seismic sensors deployed with dual-use *green cables* collocated every 50-100 km with optical repeaters, the spacing of the sensors is far too great to be useful for detecting 3D structures characteristic of oil/gas deposits. Oil/gas exploration typically involves large numbers of deployed, standardized seismic/acoustic sensors densely covering a ~5 km region of the seafloor (spaced ~50 m), and up to 16 streamers of acoustic sensors (each streamer is ~10 km long, with sensors at every 1 m - about 10,000 per streamer - and analyzed in groups of 25) trailed from a ship. An air-gun (10-200 Hz) or vibrator (10-80 Hz) source illuminates the array of sensors at many distances and directions to permit stacking the data as the ship navigates across the array, like a farmer plows a field. These data are processed to create a 3D image of the sediments and crust beneath.

Data from a green cable with only a single sensor collocated at every repeater (~50 km) are not comparable, and cannot be used alone to derive such 3D sedimentary structures. Still, some limited information about the seafloor compliance (elasticity) of the gross sedimentary structure and crust may be determined from measurement of pressure/acceleration data at one site. Such data is of limited utility for oil/gas exploration without a comprehensive marine seismic survey conducted by ship. Even for a shipboard marine seismic source transiting over the *green cable* sensor, the data could be reduced and stacked to yield only a vertical

91 Neptune Canada

reflection profile at the site. Again, this will be of limited utility, since the 2D or 3D structure is absent. Further, the ability to undertake such a survey in an EEZ would require the consent of the country where the cable is laid. If a *green cable* repeater is limited to frequencies necessary to avoid vessel-detection issues - i.e., < 8 Hz - then the information content in this single sensor is limited to seafloor crustal properties, with little resolution of the sediments where oil/gas deposits may or may not exist.

Temperature is a local variable. Although temperature variations are observed due to the variations of tides and currents, temperature does not propagate like a sound wave. Hence, temperature measurements lack remote-sensing capabilities manifest in acoustic pressure or seismic monitoring. Nonetheless, temperature data will be important to plot at specific locations over time to determine the pattern of long-term ocean current/climate change in the deep ocean/slope and for changes in current structure in, for example, the Deep Ocean Conveyer Belt for which there is very limited information. Temperature data will have negligible utility for either vessel-detection or oil/gas exploration.

Glossary

AABW	Antarctic Bottom Water
Accelerometer	Sensor to measure acceleration
ACO	Aloha Cabled Observatory
APG	Absolute Pressure Gauge
ARGO	Array for Real-time Geostrophic Oceanography
AUV	Autonomous Undersea Vehicles
CLIVAR	Climate and Ocean – Variability, Predictability, and Change
CO_2	Carbon Dioxide
Coriolis force	Associated with the rotation of Earth
DART	Deep-ocean Assessment and Reporting of Tsunamis buoy system
DONET	Dense Oceanfloor Network System for Earthquakes and Tsunamis
EEZ	Exclusive Economic Zone
GRACE	Gravity Recovery And Climate Experiment satellite mission
Green Cables	Submarine telecommunication cables incorporating basic environmental sensors (temperature, acceleration, pressure) and sharing data openly
IOC	Intergovernmental Oceanographic Commission of UNESCO
ITU	International Telecommunication Union
JTF	Joint Task Force
LEO-15	Long-term Ecosystem Observatory
LoVe	Lofoten–Vesterålen Ocean Observatory
MARS	Monterey Accelerated Research System
Nano-g	10^{-9}g (1 g = Earth's gravity)
NEIC	National Earthquake Information Center
NEMO-SN1	NEutrino Mediterranean Observatory - Submarine Network 1
NEPTUNE	North East Pacific Time-series Underwater Networked Experiment

NOAA	National Oceans and Atmospheric Administration
Nyquist frequency	½ of the sampling frequency
OBCS	Ocean Bottom Cabled Seismometer system
OOI	Ocean Observatory Initiative of the National Science Foundation
PAGER	Prompt Assessment of Global Earthquakes for Response
PMEL	Pacific Marine Environmental Laboratory
Sub-decadal	Less than 10 years
Tsunameter	APG
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VLFE	Very Low Frequency Earthquakes
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

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