PAPER

SMART Cables Observing the Oceans and Earth

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ABSTRACT

The Joint Task Force, Science Monitoring And Reliable Telecommunications (SMART) Subsea Cables is working to integrate environmental sensors (temperature, pressure, seismic acceleration) into submarine telecommunications cables. This will support climate and ocean observation, sea-level monitoring, observations of Earth structure, tsunami and earthquake early warning, and disaster risk reduction. Recent advances include regional SMART pilot systems that are the initial steps to trans-ocean and global implementation. Building on the OceanObs'19 conference and community white paper (https://doi.org/10.3389/fmars.2019.00424), this paper presents an overview of the initiative and a description of ongoing projects including: InSea wet demonstration project off Sicily; Vanuatu and New Caledonia; Indonesia; CAM-2 ring system connecting the Portuguese mainland, Azores, and Madeira; New Zealand; and Antarctica. In addition to the diverse scientific and societal benefits, the telecommunications industry's mission of societal connectivity will also benefit because environmental awareness improves both individual cable system integrity and the resilience of the overall global communications network.

Keywords: telecommunication cables, SMART sensors, seafloor sensing, earthquake early warning, tsunami detection

Introduction

The vision of the Joint Task Force (JTF) for Science Monitoring And Reliable Telecommunications (SMART) Subsea Cables is to observe the oceans and Earth with a planetary scale network of sensor-enabled submarine telecommunications cables, delivering tangible societal benefits (Angove et al., 2019; Howe et al., 2019, 2022; Levin et al., 2019). The JTF is sponsored by three United Nations (UN) agencies: International Telecommunications Union (ITU); World Meteorological Organization; and U.N. Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission (IOC). About 170 JTF members from over 30 countries are working to bring the SMART cable concept to fruition (https://www.itu.int/en/ITU-T/climatechange/task-force-sc).

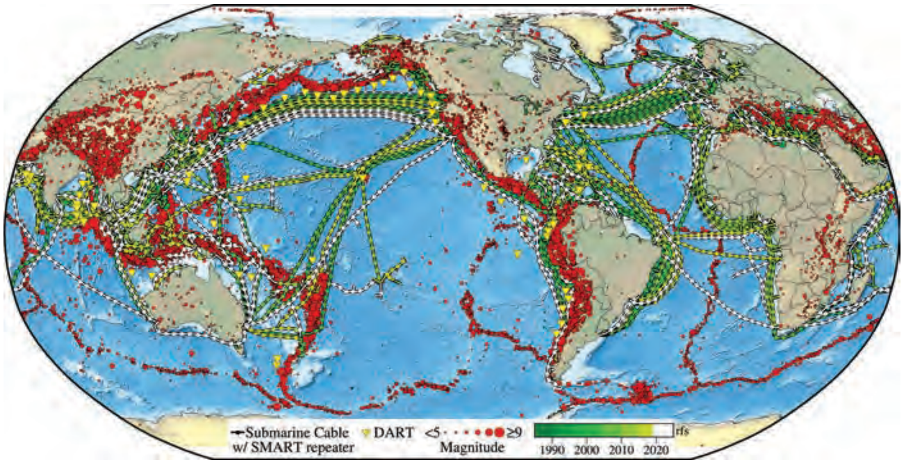
From the OceanObs19 conference, the SMART mission is to implement telecom plus sensing SMART subsea cable systems on a global scale, to support climate, ocean circulation, sea-level monitoring, and tsunami and earthquake early warning and disaster risk reduction (Figure 1). In achieving this goal, we will realize a first order addition to the ocean and Earth observing system. We will share the submarine telecommunications network that links countries and continents together, enabling our civilization. We will leverage this extraordinary, real-time network consisting of over 1.4 million km of cable with ~20,000 repeaters located approximately every 70 km on each cable. This infrastructure is constantly being replaced; by adding sensors to new cable deployments, widespread coverage can be achieved within 10–15 years. The initial sensors will be ocean bottom temperature and pressure, and seismic acceleration. The first major SMART project is being undertaken by Portugal and is underway in the Northeast Atlantic; others are in various stages of planning and implementation.

Societal Relevance

Climate change is humanity's greatest existential threat. With SMART real-time observations, we will contribute to the Sustainable Development Goals (SDGs) of the UN

FIGURE 1

The global submarine telecommunication network as of early 2021, comprising over 1 million km of cable, refreshed and expanded on a 10- to 25-year time scale. Hypothetical SMART repeaters are indicated as dots, depicted every 300 km (actual spacing is 50–120 km), to emphasize the potential of their inclusion as cables are refreshed. Color (green-white) indicates year cable was ready for service. Red dots show historical earthquakes > M 5, scaled by magnitude. Yellow triangles denote DART tsunami warning buoys.



2030 Agenda and the Sendai Framework for Disaster Risk Reduction. We will advance knowledge of climate change, including ocean circulation, heat content, and regionally variable sea-level rise (SDG 13 Climate and SDG 14 Oceans), as well as help mitigate the threats of tsunamis and earthquakes (SDG 14 and SDG 9 Infrastructure, Sendai), while, at the same time, improving societal connectivity—the primary mission of the cables—through improved cable integrity and network resilience (SDG 9 and SDG 11 Sustainable Communities).

The Observables

There continues to be a dearth of sustained, real-time, globally distributed, deep ocean measurements of any type; there are fewer than 100 long time series, deep ocean sites. The lack of global deep ocean sensing capability globally must be addressed if we are to reduce the uncertainties on our ocean models, climate models, sea-level rise predictions, real-time tsunami tracking, and both tsunami and earthquake early warning. The Global Ocean Observing System (GOOS) has identified a suite of Essential Ocean Variables (EOVs), which are defined by GOOS Experts Panels based upon 1) relevance to overall GOOS themes of Climate, Operational Ocean Services, and Ocean Health; 2) feasibility of observing or deriving the variable on a global scale using proven, scientifically understood methods; and 3) cost-effectiveness for generating and archiving data on the variable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

Three simple, robust, and precise sensors—temperature, pressure, and seismic acceleration—will provide a wealth of new and unique insights and pave the way for more.

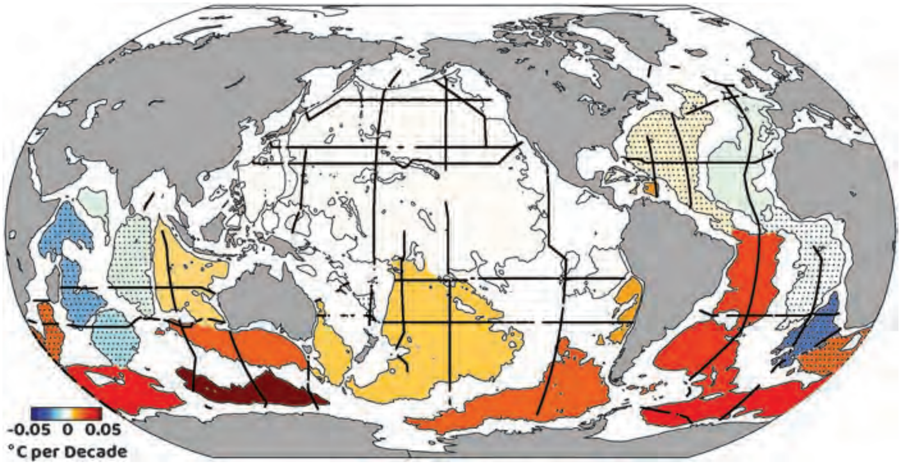
Subsurface temperature is an EOV because of its role in contributing to better estimates of heat content and thermal expansion of sea water leading to sea-level rise, which is regionally variable. It reveals processes that affect ocean circulation on all scales and depths and, thus, climate. In Figure 2, we present warming rates computed by Purkey and Johnson (2010) from seafloor temperature data acquired along 28 seafloor transects revisited two or three times in the 1990s and 2000s. The dark red regions near Antarctica in Figure 2 are warming at an estimated .05°C per decade, which contributes additional thermal expansion beyond that modeled for shallow warming.

Ocean bottom pressure is an emerging EOV, which directly speaks to sea surface height, an existing EOV. There are extremely few time series of bottom pressure, and none provide continuous time series over years or decades. By sensing the increase in ocean mass due to land melt water, pressure measurements will contribute to deciphering the mechanisms of sea-level rise. Pressure gradients across the basins and across varying bathymetry will constrain ocean circulation on multiple time and space scales. Bottom pressure observations of secular and seasonal changes incorporated into tidal correction models will reduce aliasing in altimetry and gravimetry.

Ocean bottom pressure and seismic acceleration will significantly improve earthquake and tsunami early warning (Kamigaichi, 2004; Tanioka, 2018). Because initial tsunami warnings based on land seismic data have large uncertainty, in-situ pressure and seismic measurements are needed to generate reliable tsunami height forecasts. Where near-field risk is

FIGURE 2

Deep basin average warming rates (enclosed shapes) from the 1990s to the 2000s (°C decade^{-1}, color bar) below 4,000 m based on data from Purkey & Johnson (2010). Estimates are based on data from decadal repeats of hydrographic sections (thick solid lines) first occupied during the World Ocean Circulation Experiment (King, 2001) and subsequently by the Global Ocean Ship-based Hydrographic Investigations Program (Talley et al., 2016). Stippled basins have average warming rates that are not statistically significantly different from zero at 95% confidence.



high, governments can influence cable routes to improve coverage.

This new, broadscale seismic network will fill the large ocean area observing gaps, providing unprecedented density of seafloor seismic observation for both local and distant seismic sources, significantly enhancing our ability to illuminate geophysical characteristics of the Earth's interior. Opportunities will present themselves for reducing uncertainties in full-globe 3-D tomographic seismic models, deep sounding reflection or refraction profiles leveraging large earthquakes near a cable, exploiting array processing methods for boosting seismic detection capability on the deep (and often seismically noisy) seafloor, and capturing seismicity occurring at spreading centers and deep sea transform fault systems, among other potential uses. Ocean bottom pressure is also becoming widely used as a seafloor geodetic technique to measure centimeter-level vertical movement of the seafloor during earthquakes and "slow motion" earthquakes at tectonic plate boundaries, whose aseismic slip contributes as much understanding of the rheologic and strain regimes at these boundaries as their seismic movements. Such data are improving our assessment of the geodynamic behaviors of these important plate margins and lead to updated estimates of the hazards regarding rare but catastrophic Great earthquakes (M > 8) that occur there.

UN Decade of Ocean Science for Sustainable Development 2021–2030

The UN has proclaimed a Decade of Ocean Science for Sustainable Development (2021–2030) to support improvement in ocean health and to gather ocean stakeholders worldwide in a common framework to ensure ocean science supports countries in facilitating sustainable development of the Ocean.

SMART Cables align well with UN Decade of Ocean Science challenges and outcomes, and is an endorsed Decade action under the IOC-UNESCO. Our innovation is the leveraging of this robust global telecommunications network for societal benefit. SMART Cables, as a part of the GOOS, will provide benefits for a range of stakeholders, including 1) society through improved early warning of geologic hazards and improved models to predict impactful sea level and climate changes; 2) science, through unprecedented density and distribution of sensing capabilities whose data can validate models and improve observational capabilities, as well as reveal new phenomena previously unobserved; 3) our stewardship of the environment, through real-time observations and feedback on parameter changes that will impact undersea ecosystems, ocean currents, and global weather patterns; and 4) the cable network itself, by providing real-time information on geologic and oceanographic events that may impact its integrity and operation.

SMART Cables offer a technological advance that will support the Blue Economy, defined by the World Bank as, "sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems, through near-ubiquitous sensing of parameters to track the health of the oceans and potentially impactful consequences of climate change." A modest investment on our part will leverage all the resources and expertise of the 170-year-old, $5B per year telecom cable industry, including the experience with dedicated science and early warning systems. SMART and other sensors will improve cable security by providing real-time information of conditions that may affect their integrity and, therefore, protect their primary telecommunications mission of societal connectivity.

The Technology

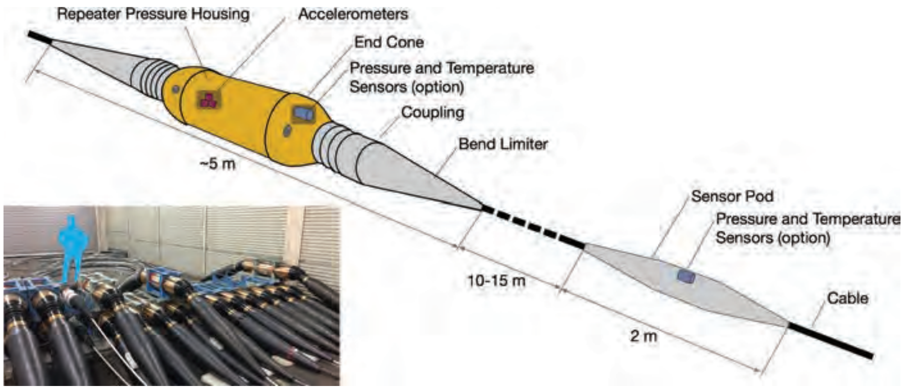
The fundamental technical goal of the SMART initiative is to develop a SMART repeater. This would replace the currently standard repeaters along telecommunications cables, whose purpose is to provide a boost to the telecommunications traffic signal strength. The SMART repeater would retain this critical function but at the same time would house a suite of sensors, whose observables would be constantly transmitted to a data acquisition system onshore through the cable. This initiative strives to make the SMART repeater a ubiquitous, off-the-shelf component of the submarine cable industry, routinely available to incorporate into any new system—and ideally most systems—for a modest ~10% incremental cost. We outline these below.

Technology Overview

There are several possible ways to mount sensors, including on the end of repeater housing under the bell housing, in an external pod, and inside the pressure housing (Figure 3). Engineering issues include determining the best communication path, isolating power, minimizing sensor power and volume, design of a highly reliable penetrator, quantifying the distance over which the sensors may

FIGURE 3

Illustration of a standard repeater housing showing two possible pressure and temperature sensor mounting locations to facilitate SMART capability: (a) on the end of repeater housing under the bell housing or (b) in an external pod. Accelerometers are mounted inside the pressure housing (a). Inset (c) shows standard repeaters awaiting deployment (human silhouette for scale).



alter the temperature in the immediate vicinity of the repeaters (the heat island effect), and more. The penetrator allows power and signals to pass between the interior of the repeater housing and the sensors mounted outside the housing. A failure of the penetrator could allow seawater to enter the housing, thereby causing the telecommunications functions of the repeater to fail. For this reason, the penetrator must be designed with the same 25-year service life as the housing, along with the SMART repeater and its component sensors. The engineering issues are succinctly itemized in the general requirements white paper (JTF Engineering Team, 2016).

Current Development Efforts

Alcatel Submarine Networks, a major system supplier, publicly acknowledged the great importance of climate change and their commitment to including it as a central element in the company strategy, including providing SMART repeaters.

Subsea Data Systems (SDS), a partnership between Samara/Data and Ocean Specialists, Inc., has recently been awarded a Small Business Innovation Research grant from the U.S. National Science Foundation to join forces in developing a SMART repeater sensor prototype. The project includes the integration of pressure, temperature, and seismic sensors in a single system. Key development elements include the necessary software and firmware to support sensor data ingest, along with precision timing, data preparation, and data transmission capabilities using standardized protocols utilized by the scientific community. The system also includes the first of two phases of electronics to isolate power for the pressure and temperature sensors to protect against sensor failures leading to repeater shunt faults, which arise when damage to the repeater housing causes its metallic core to short circuit to the seawater. In a related effort, SDS is developing data flow protocols, delivery infrastructure, and data products to support SMART Cable deployments, including the Vanuatu–New Caledonia project (discussed in the Vanuatu–New Caledonia—and the Moore SMART Cable Project section below) in partnership with the University of Hawai'i at Manoa.

Discussions are ongoing as to the possibility of incorporating distributed acoustic sensing (DAS) (Cartlidge, 2021) into the SMART Cable systems. Such capability could provide unprecedented high-resolution observations of strains arising from temperature, pressure, and seismic signals, although challenges such as the need for dedicated fiber, the ~100-km distance limitations, and the high data volume of such systems are currently unresolved for routine cable usage. Some proposed dedicated pilot experiments (next section) anticipate leveraging this technology.

SMART Projects

SMART projects are underway at various stages, ranging from funded to proposed to early discussions. Some employ variants on the SDS prototype as described above, while others also include additional sensors, tailored to the needs of the specific deployment. These initial deployments are meant as a testbed for the SMART concept, and, in some cases, leverage experiments that are driven by different objectives.

The JTF has published (and will likely update) lists of smart sensors requirements (JTF Engineering Team, 2016). To expand SMART capability to global scale this list must be short and must include robust, low power, long life sensors without major calibration issues. Whether different private entities choose to use identical sensors will depend on the individual requirements from the system proponent in their Request for Proposals, to which suppliers can respond appropriately. In the end, standardization is essential to achieve the envisioned global scope. The early systems are expected to set precedents in this regard.

Free and open access to all data, for all nations, following findable, accessible, interoperable, reusable principles in line with the efforts of UNESCO-IOC and other international bodies, is anticipated. The JTF expects to work more closely in the future with the latter organizations to clarify.

Specific parties to a particular cable system (especially the governments of the countries in which the cable lands) may, however, apply their own data policies. Not all cables can be SMART because of funding and other considerations; hence, the JTF and the larger community must consider which systems to support/facilitate and prioritize. Early systems may be unique, and some, such as SMART CAM Portugal (outlined below), are expected to set valuable precedents in this regard. In all cases, it is important that real-time feeds for early warning will be available. The SMART initiative has adopted the general advice to start simple (domestic system, "friendly bi-lateral situations," etc.). Over time, "normal" will become defined.

It is important to note that the projects described herein are a mixture of technology tests (Sicily); national hazard mitigation efforts (Indonesia, Portugal); exploitation of planned telecommunication cable deployments, which may also provide critical observables for hazard mitigation (i.e., early warning) (Vanuatu–New Caledonia, New Zealand); and full-scale joint implementation for both critical scientific observation and critical telecommunications (National Science Foundation's Antarctic plans). We anticipate that successful implementation of the SMART ideas in these pilot studies will advance the aim of SMART technology becoming ubiquitous in major telecom cable operations in the future.

Sicily Wet Demo—Deployment Planned 2023

The Western Ionian Sea hosts one of the European Multidisciplinary Seafloor and water column Observatory (EMSO) Regional Facilities, about 25 km off the coast of Eastern Sicily at 2,100-m water depth. An underwater electro-optical-mechanical cable runs on the seafloor from Catania harbor and splits into two branches that currently host non-SMART-system geophysical, environmental, and oceanographic and physics/neutrino seafloor platforms, managed by Istituto Nazionale di Geofisica e Vulcanologia and Istituto Nazionale di Fisica Nucleare, respectively.

The observation area is vulnerable to numerous natural hazards due to the high level of seismicity and frequent eruptions of nearby Mount Etna volcano. For example, a major earthquake/tsunami in this area in 1693 caused 60,000 casualties in and around Catania, and another event in 1908 in nearby Messina killed about 75,000 people.

In 2019, the project InSEA, funded by the Italian Ministry of Research, began enhancing the Western Ionian Sea infrastructure capabilities. One of the main goals of InSEA is to provide a wet demonstration for a SMART cable system. A map of the areas with the cables is shown in Figure 4.

This project is underway; initial delays due to COVID have led to a new installation schedule in 2023. Sensors will be integrated into three telecom repeaters (Figure 3) and deployed attached to the existing cable infrastructure. Nearby non-SMART EMSO geophysical and oceanographic instrumentation, as well as broadband seismometers also integrated in the deployment, will serve to validate

FIGURE 4

Sketch of EMSO Western Ionian Sea Facility where the InSEA wet demo SMART cable will be laid in 2023. SMART demo cable is indicated in red. The junction box connecting the SMART cable to the primary InSEA branch is shown in magenta. SN1 and ONDE triangles represent instrumentation nodes for other InSEA experiments. Inset location map in lower right hand corner.

the basic SMART sensor data, offering an opportunity to compare data recorded by known, vetted hardware recording alongside the new SMART sensor-repeater assemblies.

Portugal—CAM Ring–Deployment 2025

The first major SMART project will link Continental Portugal to the Azores and Madeira (CAM) in a 3,700-km ring in an explicitly SMART system (with other sensing as well; Figure 5, from Matias et al., 2021). A primary goal is geohazards monitoring motivated by the memory of the very destructive Great Lisbon earthquake and tsunami of 1755. The installation is planned for 2025.

A preliminary evaluation of the added value of the SMART component of the CAM network has been conducted considering seismic sources in the region. Considering only loss of life, the preliminary results indicate if there is a single major event in the 25-year life, the improvement in early warning in economic terms more than pays for the cost of the entire system, including telecommunications; simulations are underway that take into account infrastructure damage and tsunami inundation (V. Silva, pers. comm.), which will further increase the benefit-to-cost ratio.

Vanuatu–New Caledonia—and the Moore SMART Cable Project

Vanuatu is the world's most at-risk country for natural disasters (United Nations World Risk Report, 2016, https://weltrisikobericht.de/wp-content/uploads/2016/08/WorldRiskReport2016.pdf). Its proximity to the seismically active "Ring of Fire" around the Pacific Ocean basin frequently exposes Vanuatu to large, sometimes tsunamigenic earthquakes. Although Vanuatu and New Caledonia themselves have not experienced high death tolls from tsunamis or earthquakes, their tsunamis have historically caused devastation elsewhere in the region. Vanuatu and New Caledonia recognize that better earthquake and tsunami monitoring is necessary. Sea-level rise also continues to threaten the coastal communities of all Pacific Island nations, including Vanuatu. Higher sea levels will increase both the frequency of coastal damage and the size of typhoon and tsunami inundation areas. Better data on ocean circulation and warming are critical for projecting the specific impacts of these threats to the local ecosystem and economy.

Planning is underway for a cable crossing the trench/subduction zone between these two Pacific islands to improve the international connectivity of Vanuatu and New Caledonia, provide valuable early warning tsunami capabilities for both countries as well as the broader region, and to better understand the geophysics of this subduction zone (Figure 6).

The estimated cost of the SMART (telecom+sensors) cable system for Vanuatu is $20M, and fundraising is currently underway. New Caledonia, through a French research grant, will contribute $2.5M. Vanuatu is in the process of raising funds through donor grants (e.g., from the Asian Development Bank and World Bank). The New Caledonia government's Office of Posts and Telecommunications and Vanuatu will provide the balance based on commercial considerations. Vanuatu and New Caledonia have recently entered into an official agreement to advance the project, for their mutual benefit.

FIGURE 5

Nominal route for the CAM submarine cable with SMART repeaters (black dots), spaced ~70 km. Cables are identified by their endpoints, C for the Portuguese mainland, and M and A for the Madeira and Azores Archipelagos, respectively. Green triangles denote seismic stations currently monitored by the Instituto Português do Mar e da Atmosfera (IPMA). Yellow triangles show coastal tide-gauges monitored by IPMA. Red stars show the location of 3 M > 7.7 earthquakes in the 20th century that caused small tsunamis. The November 1, 1755, earthquake origin is uncertain; tectonic faults shown (red lines) have been hypothesized to be its source. White dots indicate the tsunami scenario database that is part of the Tsunami Warning System in operation at IPMA. Inset map for location reference.

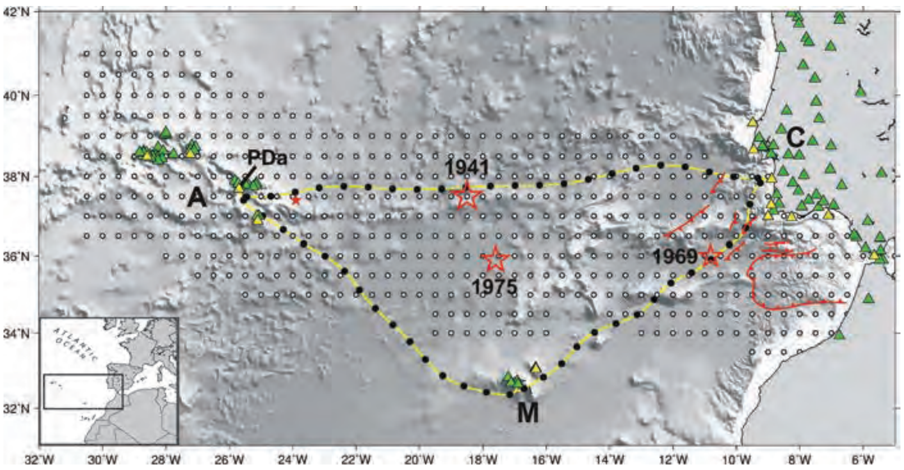
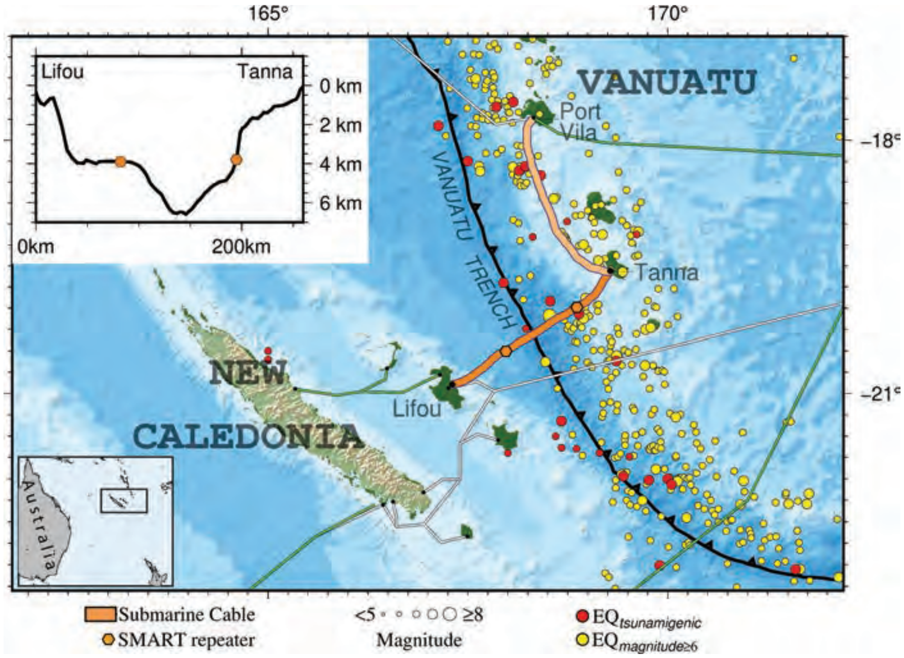


FIGURE 6

Proposed SMART cable connecting Vanuatu and New Caledonia with a SMART repeater on each side of the New Hebrides/Vanuatu Trench. Earthquakes are shown, scaled by magnitude and divided into tsuniamigenic (red) and non-tsunamigenic (yellow). Inset in upper left shows bathymetry of planned cable route across the Vanuatu Trench. Inset map in lower left for location.



A recently awarded 5-year, $7M grant from the Moore Foundation will support implementation of scientific efforts toward tsunami and earthquake early warning, geophysics, and additional oceanographic research in general for the global scale as well as regionally for Vanuatu–New Caledonia. These funds will also support an international JTF SMART project office hosted by the University of Hawaiʻi at Manoa. The Project Office will be the executive office for the JTF, working with the ITU JTF Secretariat in Geneva, facilitating individual cable projects globally to build the envisioned global network, capitalizing on the enormous leveraging potential of the industry. Its activities will include:

- Work through our sponsoring UN agencies for further member state endorsement, facilitating more engagement (e.g., ITU SMART Resolution, Study Group; IOC Assembly; UN Decade of Ocean Science);
- Work within the international Framework for Ocean Observing, i.e., IOC/WMO GOOS, IOC Tsunami Programme, UN Decade, including legal aspects;
- Develop relationships with international and regional telecom regulatory and operator organizations, to trickle down to national levels (e.g., facilitated by Portugal and the Community of Portuguese Language Countries);
- Further develop relationships with multilateral development banks and other funding sources;
- Proactively, within each country and internationally, connect with key stakeholders and educate them so that they will support domestic, regional, and global scale projects when opportunities arise;
- Start a data management activity to coordinate activities across various SMART cable projects; and
- Encourage capacity building.

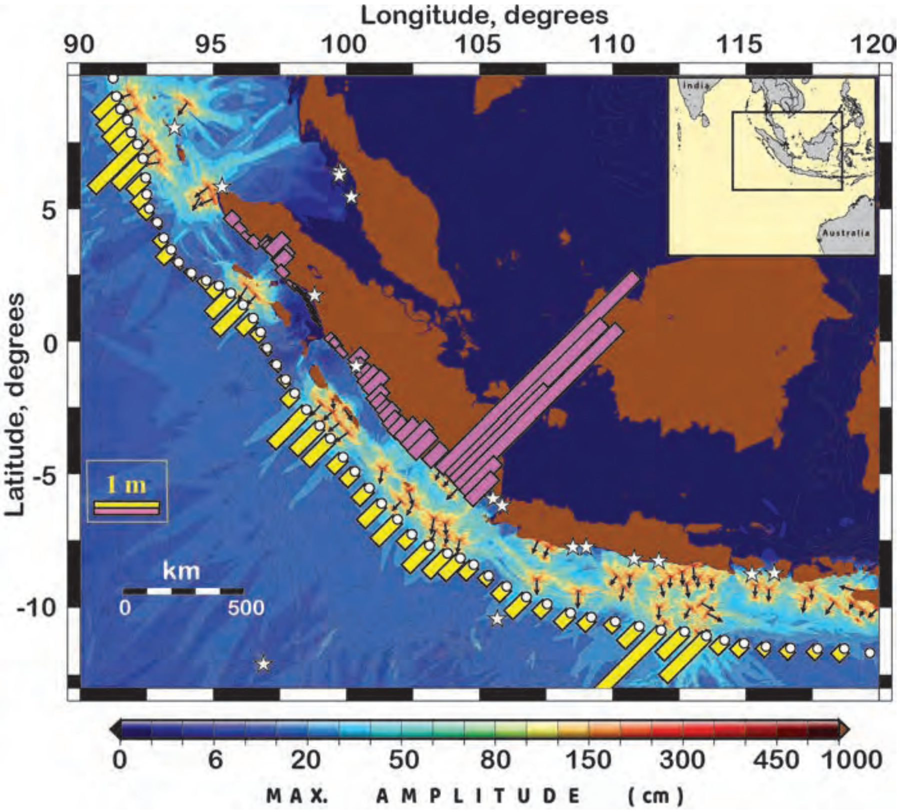
Indonesia—Deployment To Be Determined

Indonesia is one of the most active earthquake regions in the world and lies above three converging continental tectonic plates, namely, Indo-Australia to the west and south; Eurasia from the north; and the Philippines plate from the east. Indonesia is therefore highly vulnerable to tectonic earthquakes, volcanic eruptions, and underwater landslides that could trigger tectonic, nonseismic, or complex tsunamis, and is accordingly threatened by far- and near-field tsunamis.

The importance of landslide-generated tsunamis is becoming more apparent. In Figure 7, we show an example of the estimated cumulative tsunami height due to seismically triggered modeled submarine landslides scenarios. Earthquakes were selected from the Global Centroid Moment Tensor catalog (Dziewonski et al., 1981; Ekström et al., 2012) with depths shallower than 40 km. Fifty-eight dipole sources were used. These results indicate more study of seismically triggered submarine landslides is warranted (Salaree et al., 2022), and the deployment of such a SMART cable in this location would provide invaluable added observations for this sparsely instrumented region, including much faster early warning for waves generated by local landslides than the regional sensor network can provide.

FIGURE 7

Maximum tsunami wave heights are calculated, based on slope of the bathymetry, for 52 landslide scenarios (small black vectors) derived for peak ground acceleration > 0.3 g from local and regional earthquakes. White dots indicate the location of SMART repeaters in a proposed offshore SMART cable installation. Yellow bars show maximum tsunami height that would be recorded at each of the SMART sensors. Pink bars give height near the shore (~ 60-m water depth), at the same scale as the yellow bars. Pink and yellow bar orientations were chosen to avoid overlap. White stars represent existing tide gauges. From Salaree et al. (2022).



The Indonesia Tsunami Early Warning System (InaTEWS) was established following the Aceh/Sumatra tsunami in 2004. InaTEWS is comprised of three sub-systems. The upstream part consists of observational equipment to monitor seismic vibrations and ocean tsunami wave heights. The acquired data are directly transmitted to the Agency for Meteorology Climatology and Geophysics processing center, which produces information on hypocentral location and depth, origin time, magnitude, and the potential for tsunami generation. The resulting early warning information is directly disseminated to potentially affected communities through interface institutions or authorities.

Indonesia's Agency for the Assessment and Application of Technology, now part of the National Research and Innovation Agency, embarked on the development of SMART-CBT (cable-based tsunami) or Advance CBT. The design, conceived in early 2020, will accommodate both tsunami sensors as well as data communication. Early single-ended test systems, which serve to transmit data from sensors to shore, rather than provide two-way telecommunications, are planned for Labuhan Bajo and Rokatenda (Figure 8), and will be expanded with a double-ended system to be deployed across Makassar Strait connecting East Kalimantan and Mamuju in West Sulawesi (Figure 8). This double-ended cable will serve to power the ocean bottom units, as well as transmit their data to shore in much the same way as a SMART repeater assembly would. An evolving network of Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys serve to complement the seafloor sensing network and add redundancy for warning.

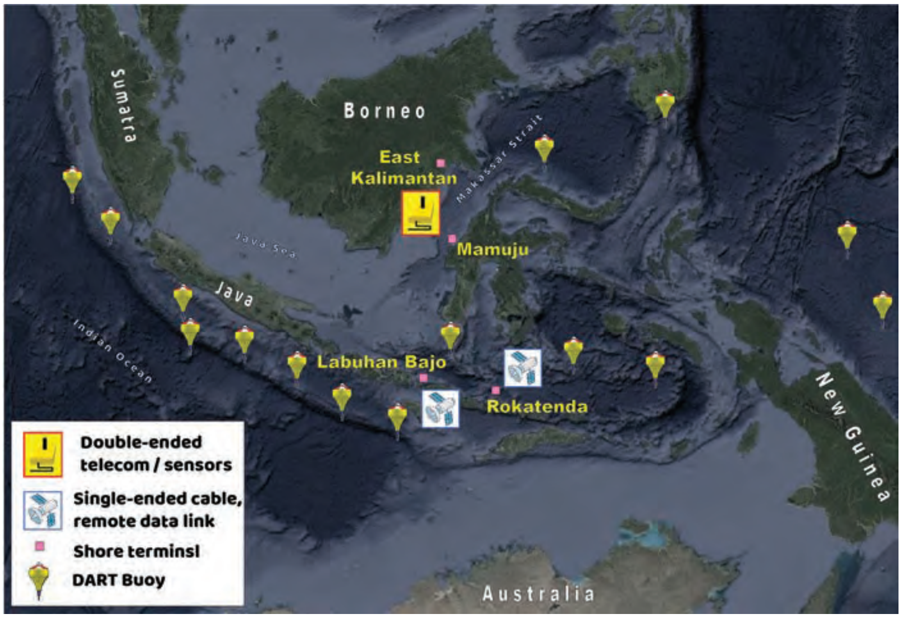
New Zealand–Chatham Islands —Planning Underway

Given the dual needs in New Zealand for telecommunications connectivity to the Chatham Islands as well as improving seismic and tsunami warning with concomitant scientific understanding, a workshop was convened in February 2021 to consider how to satisfy these needs.

The report (Wallace et al., 2021) summarized the main findings and conclusions of the workshop and background information necessary for considering the development of permanent, offshore observing capability in New Zealand. A primary conclusion of the workshop, and a recommendation of the report, is "that a hybrid cable design incorporating both 'in-line' sensors (SMART repeater assemblies) and external sensors connected to branching units, plus fiber strands usable for DAS would provide the best balance between the oceanographic, geophysical, and geohazards monitoring benefits of offshore scientific infrastructure. This approach to the cable design would future-proof the cable and its sensor payloads, maximizing the return on investment as technology improves in decades to come, while ensuring that the scientific components did

FIGURE 8

Evolving tsunami sensing and warning capability for Indonesia. A network of DART buoys is partially installed, with comprehensive coverage anticipated as shown. Seafloor sensors sending data to shore terminals, which is telemetered to data centers, are part of the initial phase, with positions at Rokatenda and Labuhan Bajo. Planned telecommunications cable spanning the Makassar Strait linking East Kalimantan and Mamuju would also provide data transmission and power for SMART-like ocean floor sensing packages.



not compromise the cable's primary mission." Discussions and planning regarding this possible cable system are currently ongoing, spearheaded by the New Zealand Institute of Geological and Nuclear Sciences. The proposed project is shown in Figure 9.

Antarctica—Planning Underway

The U.S. National Science Foundation is interested in a submarine fiber optic telecommunications cable from New Zealand to McMurdo Station, with terabit-scale networking capability that could eliminate current bandwidth constraints faced by researchers, educators, and support functions, while also reducing the high latency of current satellite-based communication. Ab initio, the cable infrastructure is also expected to serve as a scientific platform using SMART Cables with capability to monitor ocean conditions and seismic activity (Figure 10). To document the benefits of such a cable, a workshop (https://www.pgc.umn.edu/workshops/antarctic-cable/) was held on June 29 to July 1, 2021.

The workshop report (Neff et al., 2021) provides the following insights: Observations of temperature and pressure on a new SMART cable to McMurdo will immediately provide important climate change metrics in the Southern Ocean, including Antarctic Bottom Water temperature and volume, Antarctic Circumpolar Current transport, and regional sea-level rise. The cable's enabling characteristics would be real-time, high-frequency sampling, 24/7/365 acquisition, good spatial resolution (~50 km), the spanning of a major inter-ocean chokepoint, and rare observations below 2,000 m. These simple measurements are invaluable for understanding the progression and causes of climate change, and predicting global climate conditions into the future.

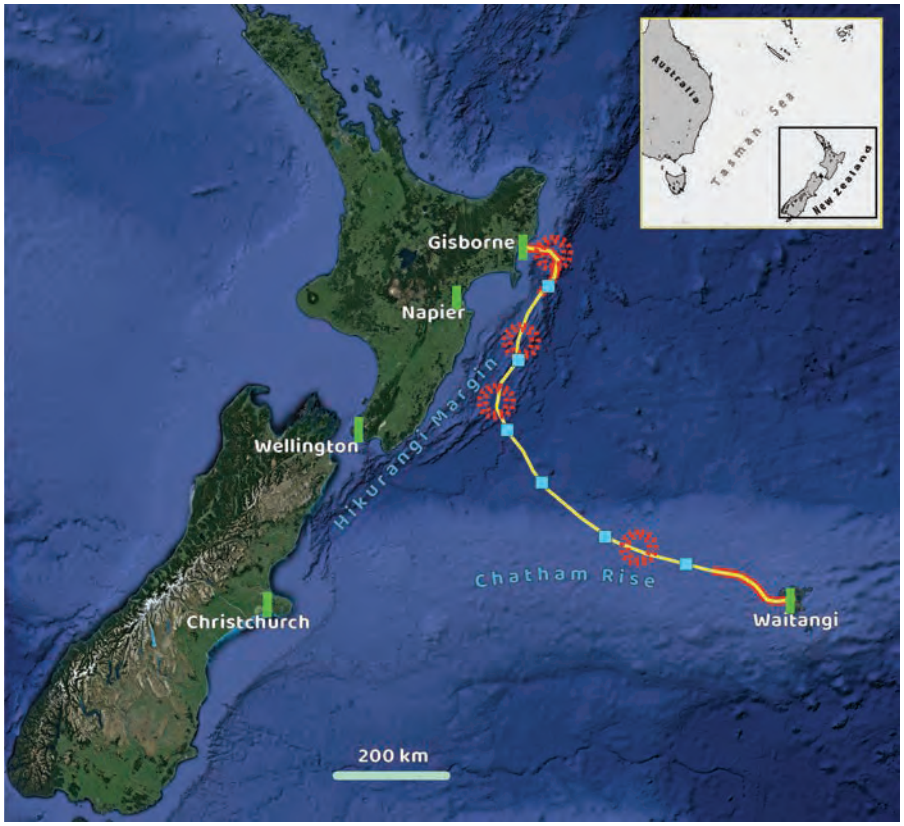
SMART seismic accelerometers can provide important new observations for regional and teleseismic seismic waves traversing the Earth beneath the Southern oceans, where significant paucity of wave propagation data exist due to heterogeneous distribution of seismic sources and land-based sensors (Ranasinghe et al., 2018) that limits the ability to resolve significant features in 3-D Earth geophysical models.

SMART seismic acceleration data, augmented with inexpensive acoustic and optical fiber sensing, enable the monitoring of ice, ice shelf-breaking tsunamis, marine mammals, seismic ocean thermometry, local and regional earthquakes, and plate seismometry and strain. The inclusion of additional branching nodes (a form of future-proofing that could be developed over time) would open up unprecedented opportunities in permanent, broadband seafloor seismometers; Southern Ocean biogeochemical, ecosystem, and water column sensing; autonomous underwater vehicle docking; acoustic communications; and navigation. All of these enhancements to the basic SMART cable are neutral with respect to the fundamental communications mission of the cable, having no impact on its primary operation, and could enable the first step in a future Southern Ocean Observatory.

Chile has also proposed a cable from Puerto Williams in southern Chile to King George Island, which hosts several Antarctic bases. Other systems currently at various stages are located in the Mediterranean,

FIGURE 9

Map of the route to the Chatham Islands that provides optimal coverage of the Hikurangi Margin and eastern Chatham Rise. A 25-km radius for seafloor observatory opportunity/branch nodes is indicated by dashed red lines. Cable landings indicated as green rectangles. Repeaters are shown as blue squares, at approximately 125-km spacing. Preferred cable route is shown in yellow, with red border indicating potential DAS extent. Location map insert is shown in the upper right corner.



French Polynesia, Australia to Malaysia, and India to Oman.

Other Developments

The JTF is following several paths to encourage adoption. Within ITU, several activities are advancing: a SMART Resolution before the World Telecommunications Standardization Assembly; amendments to existing climate and disaster risk reduction resolutions, a Study Group preparing Recommendations; participation in the Global Symposium for Regulators; etc. Within the IOC, the Assembly just approved a Tsunami Program explicitly including SMART for the UN Decade of Ocean Science for Sustainable Development, and the JTF is now an endorsed Project of the UN Decade. All these activities are at a level involving the UN member states.

Concluding Remarks

SMART Cables follow an innovative path outside the classical "oceanography box." The sum of combining cable and sensing technology will be greater than the parts, revolutionizing access to the global deep ocean and enabling unique ocean observations of major importance, while improving cable system performance. The recent Hunga Tonga–Hunga Ha'apai volcano/tsunami is a reminder that Earth is always surprising us with new (or at least unexpected) events that require monitoring at all scales, and at the same time has highlighted the vulnerability of our undersea infrastructure and the importance of improved state-of-health capability as well as system redundancy. To achieve this, the ocean community and the telecom industry must work together in the context of the UN Decade of Ocean Science and the Blue Economy to produce a telecom plus global science network for societal benefit, providing potentially near ubiquitous monitoring of seafloor temperature and pressure (indicators of sea-level rise and changes to weather and climate), seismic sensing, and pressure sensing for earthquake and tsunami early warning as well as global seismic monitoring improvements.

Submarine cables are a critical infrastructure exposed to a variety of risks for damage, manipulation, or disruption. These dangers may include natural causes (such as landslides, turbidity currents, earthquakes or volcanoes), accidental events by ships (anchors and fishing trawling), or even deliberate geopolitical threats. In this regard, resilience and redundancy of undersea cables is critical to ensuring global connectivity. SMART sensors can help to monitor the cables by real-time detection and localization of possible impactful events.

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FIGURE 10

Proposed SMART cable route between McMurdo and New Zealand (green/yellow), illuminating the current telecommunication isolation of Antarctica. This novel, Spilhaus projection provides a different perspective of the world, stressing the oceans and the current coverage of submarine telecommunications cables (red), highlighting the importance of adding an Antarctic route. Geographic labels for land masses have been added to orient the reader.

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