SMART Cables Observing the Oceans and Earth

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***Abstract*—The Joint Task Force, Science Monitoring And Reliable Telecommunications (JTF SMART) Subsea Cables are 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 (doi: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 triangle system connecting Lisbon, Azores and Madeira; New Zealand; and Antarctica. In addition to the diverse scientific and societal benefits, the telecommunications industry 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*—*ocean observing, ocean observatories, blue economy, disaster risk reduction, climate observing

I. INTRODUCTION

The vision of the Joint Task Force for 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 [1,2,3]. SMART stands for Science Monitoring And Reliable Telecommunications. The Joint Task Force (JTF) is sponsored by three United Nations (UN) agencies: International Telecommunications Union; World Meteorological Organization; and UNESCO Intergovernmental Oceanographic Commission. 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 (Fig. 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 kilometers 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 to 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.

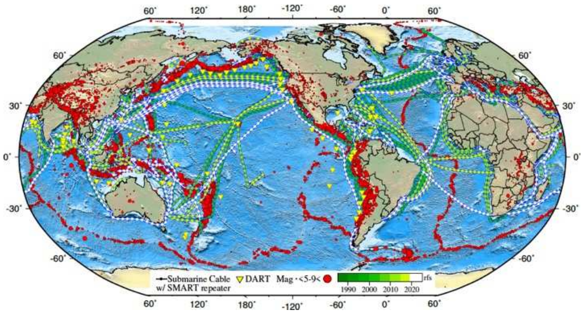

Fig. 1. The global submarine telecommunication network as of early 2021, comprising over one million km of cable, refreshed and expanded on a 10–25-year time scale. Potential SMART repeaters are indicated as dots, depicted every 300 km (actual spacing is 50–120 km). Color (green-white) indicates year ready for service. Red dots show historical earthquakes and magnitude. Yellow triangles denote DART tsunami warning buoys.

II. 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 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).

III. 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. Three simple, robust and precise sensors will provide a wealth of new and unique insights and pave the way for more.

Subsurface temperature is an Essential Ocean Variable (EOV). Ocean bottom temperature will contribute 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. The dark red regions near Antarctica in Fig. 2 are warming at an estimated 50 mK per decade.

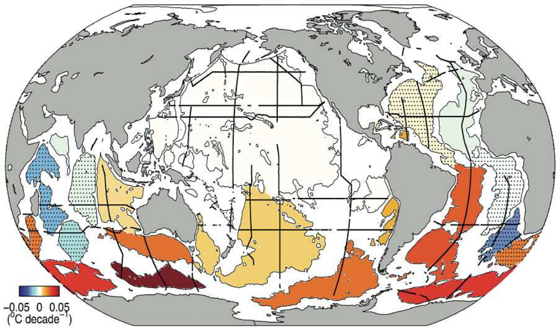

Fig. 2. Deep basin (thin solid lines) average warming rates from the 1990s to the 2000s (°C decade^{-1}, color bar) below 4000 m based on data from Purkey and Johnson (2010). Estimates are based on data from decadal repeats of hydrographic sections (thick solid lines) first occupied during the World Ocean Circulation Experiment (WOCE) (King et al., 2001) and subsequently by the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) (Talley et al., 2016). Stippled basins have average warming rates that are not statistically significantly different from zero at 95% confidence.).

Ocean bottom pressure is an emerging EOV. There are extremely few time series of bottom pressure, and none are long-term. 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 to tidal correction models will reduce aliasing in altimetry and gravimetry.

Ocean bottom pressure and seismic acceleration will significantly improve earthquake and tsunami early warning. 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 high, governments can influence cable routes to improve coverage. This new seismic array will fill the large ocean area observing gaps, enabling a vast improvement in our understanding of Earth's interior. 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.

IV. UN DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT 2021–2030

SMART Cables align well with UN Decade of Ocean Science challenges and outcomes. Our innovation is the leveraging of this robust global telecommunications network for societal benefit. SMART Cables, as a part of the Global Ocean Observing System, will provide benefits for society, science, our stewardship of the environment, and the cable network itself.

SMART Cables are a perfect example of the Blue Economy with mutual benefit to all stakeholders. 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. Alcatel Submarine Networks (ASN), 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.

SMART and other sensors will improve cable integrity and, therefore, the primary telecommunications mission of societal connectivity.

V. THE TECHNOLOGY

The fundamental technical goal of the SMART initiative is 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.

There are several possible ways to mount sensors (Fig. 3). There are engineering issues to address, including determining the best communication path, isolating power, minimizing power and volume, design of a highly reliable penetrator, quantifying the heat island effect, and more. The first systems will result in a repeater that is warranted for a 25-year life.

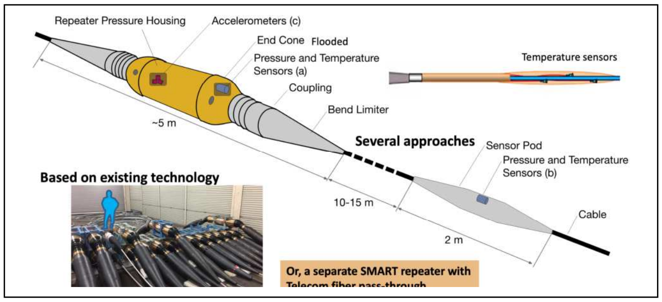

Fig. 3. Illustration of a repeater housing showing two possible sensor mounting locations: (a) on the end of repeater housing under the bell housing; or (b) in an external pod. Accelerometers are mounted inside the pressure housing (c).

VI. SMART PROJECTS

There are several SMART projects at various stages, ranging from funded, to proposed, to early discussions.

A. *Sicily Wet Demo*

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 2100 m water depth. An underwater electro-optical-mechanical cable runs on the seafloor from Catania harbor and splits into two branches that host geophysical, environmental and oceanographic and physics/neutrino seafloor platforms, managed by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Istituto Nazionale di Fisica Nucleare (INFN), respectively.

The observation area is prone to numerous natural hazards due to the high seismicity and nearby Mount Etna. 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 realize the SMART wet demonstrator. A map of the areas with the cables is shown in Fig. 4.

This project is underway, with installation in 2022. Sensors will be integrated into three telecom repeaters and deployed attached to the existing cable infrastructure. Nearby instrumentation, as well as broadband seismometers also integrated in the repeaters, will serve to validate the SMART sensor data.

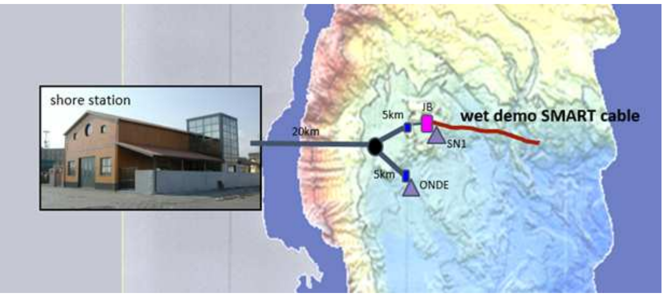

Fig. 4. Sketch of EMSO Western Ionian Sea Facility where the InSEA wet demo SMART cable will be laid in 2022.

B. *Portugal CAM2 Ring*

The first major SMART project will link the European Continent/Lisbon to the Azores and Madeira (CAM) in a 3700-km ring in an explicitly SMART system (with other sensing as well; Fig. 5). 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 2024.

A preliminary evaluation of the added value of the SMART component of the CAM2 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; simulations are underway that take into account infrastructure damage and tsunami inundation (V. Silva, pers. com.), which will further increase the benefit-to-cost ratio.

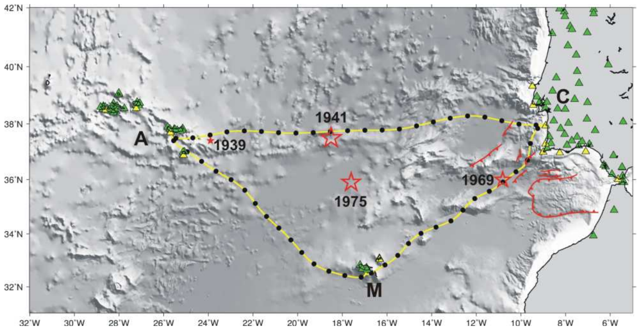

Fig. 5. Nominal route for the CAM-2 submarine cable with SMART repeaters (red dots), spaced ~70 km. The cables are identified by the landing points on both ends, C for the Portuguese mainland, M and A for the Madeira and Azores Archipelagos, respectively. The green triangles denote seismic stations currently monitored by the Instituto Português do Mar e da Atmosfera (IPMA). The yellow triangles show the location of coastal tide-gauges monitored by IPMA. The red stars show the location of 3 M > 7.7 large earthquakes that occurred in the 20th century and caused small tsunamis. The location of the 1 November 1755 earthquake is uncertain, and the tectonic faults shown (red lines) have been hypothesized to be at the source of that event. The grid with dots shows the location of the tsunami scenario database that is part of the Tsunami Warning System in operation at IPMA.

C. *Vanuatu-New Caledonia*

Vanuatu is the world's most at-risk country for natural disasters (United Nations World Risk Report, 2016). Due to its location near the seismically active "Ring of Fire", Vanuatu frequently experiences earthquakes that can generate tsunamis. Although Vanuatu and Caledonia themselves have not experienced high death tolls from tsunamis or earthquakes, their tsunamis have historically caused devastation 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 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 to: improve the international connectivity of Vanuatu and New Caledonia; provide valuable early warning tsunami capabilities for both countries and the region; and better understand geophysics of this subduction zone (Fig. 6). The tentative installation date is 2025.

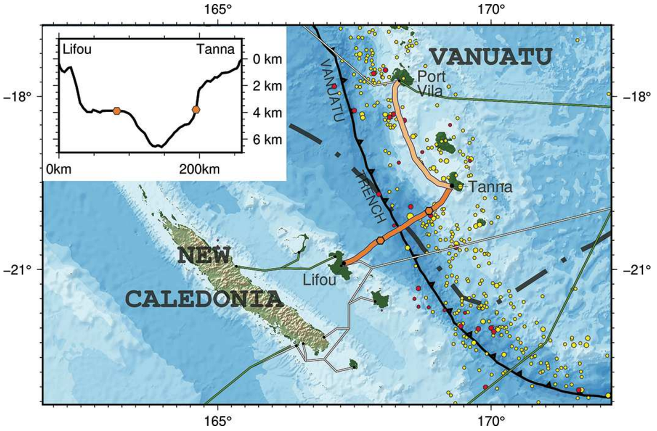

Fig. 6. Proposed SMART cable connecting Vanuatu and New Caledonia with a SMART repeater on each side of the New Hebrides/Vanuatu Trench.

D. *Indonesia*

Indonesia is one of the most active earthquake regions in the world, and lies above three collisions of 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 a "normally" tectonic tsunami or atypical one, and is accordingly threatened by far- and near-field tsunamis.

The importance of landslide-generated tsunamis is becoming more apparent. Here we show an example of the estimated cumulative tsunami height due to seismically triggered submarine landslides scenarios (Fig. 7). Earthquakes were selected from the CMT catalog with depth shallower than 40 km. Fifty-eight dipole sources were used. These results indicate more study of seismically triggered submarine landslides is warranted [4].

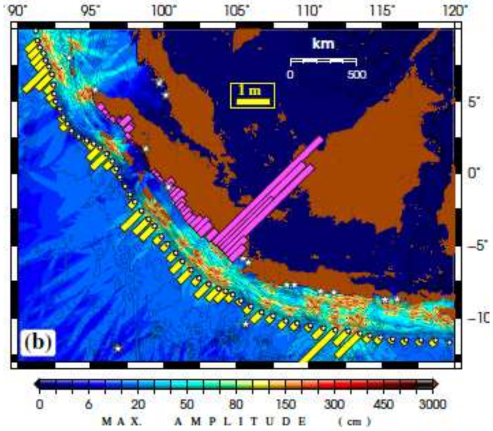

Fig. 7. For a possible SMART cable (yellow dots) scenario, tsunami wave heights are calculated from 52 landslide scenarios designed for peak ground acceleration > 0.3 g based on the bottom slope. Yellow bars show tsunami height at SMART sensor. Pink bars give tsunami height near the shore (~ 60 m water depth). White stars represent existing tide gauges.

The Indonesia Tsunami Early Warning System (InaTEWS) was established right after Aceh's tsunami in 2004. InaTEWS is made up of three sub-systems. The upstream part consists of observational equipment to monitor seismic vibrations and ocean tsunami wave heights. The acquired data is directly transmitted to the BMKG (Agency for Meteorology Climatology and Geophysics) processing center, which produces information on: location of epicenter; depth; time of occurrence; scale of magnitude of the earthquake; and the potential of tsunami occurrence. The resulting early warning information is directly disseminated to potentially affected communities through interface institutions or authorities.

Recently, the BPPT (Agency for the Assessment and Application of Technology) embarked on the development of SMART-CBT (cable based tsunami) or Advance CBT. The design, which began in early 2020, will accommodate both tsunami sensors as well as data communication. Early single-ended test systems are planned for Labuhan Bajo and Rokatenda, evolving to a double-ended system to be deployed across Makassar Strait connecting East Kalimantan and Mamuju in West Sulawesi (Fig. 8). The COVID pandemic is delaying the development.

Fig. 8. Locations of Ina-CBT activity.

E. New Zealand-Chatham Islands

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 [5] 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 and external sensors connected to branching units, plus fibre strands usable for distributed acoustic sensing (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, maximising the return on investment as technology improves in decades to come, while ensuring that the scientific components did not compromise the cable's primary mission." Discussions and planning regarding this possible cable system are currently ongoing (Fig. 9).

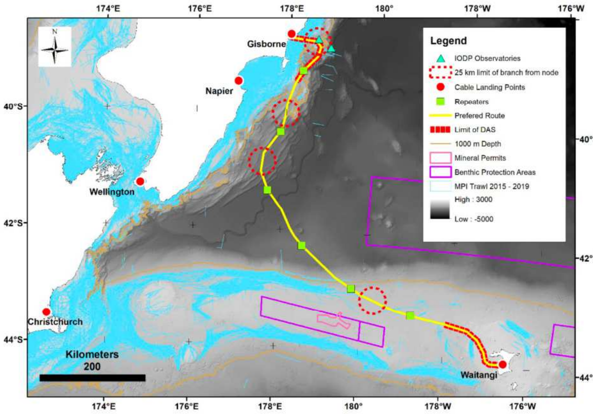

Fig. 9. Map of the route to the Chatham Islands that provides optimal coverage of the Hikurangi Margin and eastern Chatham Rise. The repeaters are located approximately every 125 km along the cable. The closest is 150 km from land and is highlighted to show possible DAS coverage. The location of possible nodes and branch units are illustrated as a 25 km radius circle to indicate the extent of a seafloor monitoring network.

F. Antarctica

The US 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 latency of current satellite-based communication. The cable infrastructure can also serve as a scientific platform using SMART Cables with capability to monitor ocean conditions and seismic activity (Fig. 10). To document the benefits of such a cable, a workshop (https://www.pgc.umn.edu/workshops/antarctic-cable/) was held on 29 June–1 July 2021.

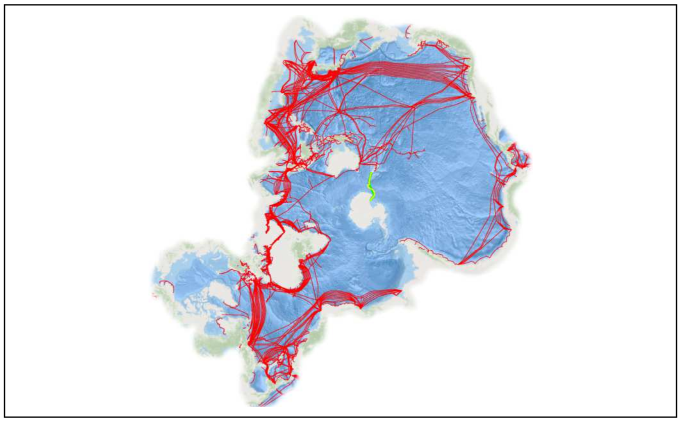

Fig. 10. A possible SMART cable route between McMurdo Bay and New Zealand (green), highlighting the present telecommunication isolation of the Antarctic continent. This Spilhaus projection gives a different perspective of the world and of the current coverage of submarine telecommunications cables (red).

While the workshop report is still in preparation, some of the authors of this paper attended and provide 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 2000 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 [6] limits the ability to resolve global Earth 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, earthquakes, and plate seismometry and strain. The inclusion of additional branching nodes would open up unprecedented opportunities in Southern Ocean biogeochemical, ecosystem, and water column sensing, AUV 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 and could enable the first step in a future Southern Ocean Observatory.

G. *Others*

Other systems currently at various stages are located in the Western Mediterranean, French Polynesia, Australia to Malaysia, and India to Oman.

VII. OTHER DEVELOPMENTS

The JTF is following several paths to encourage adoption. Within ITU several activities are advancing: a SMART Resolution before the World Technical Standards 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 Programme explicitly including SMART for the UN Decade of Ocean Science for Sustainable Development, and the JTF has requested endorsement as a project of the UN Decade. All these activities are at a level involving the UN member states.

VIII. 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. 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.

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