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Using SMART submarine cable systems in the ocean observing system for science and society

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www.itu.int/en/ITU-T/climatechange/task-force-sc/
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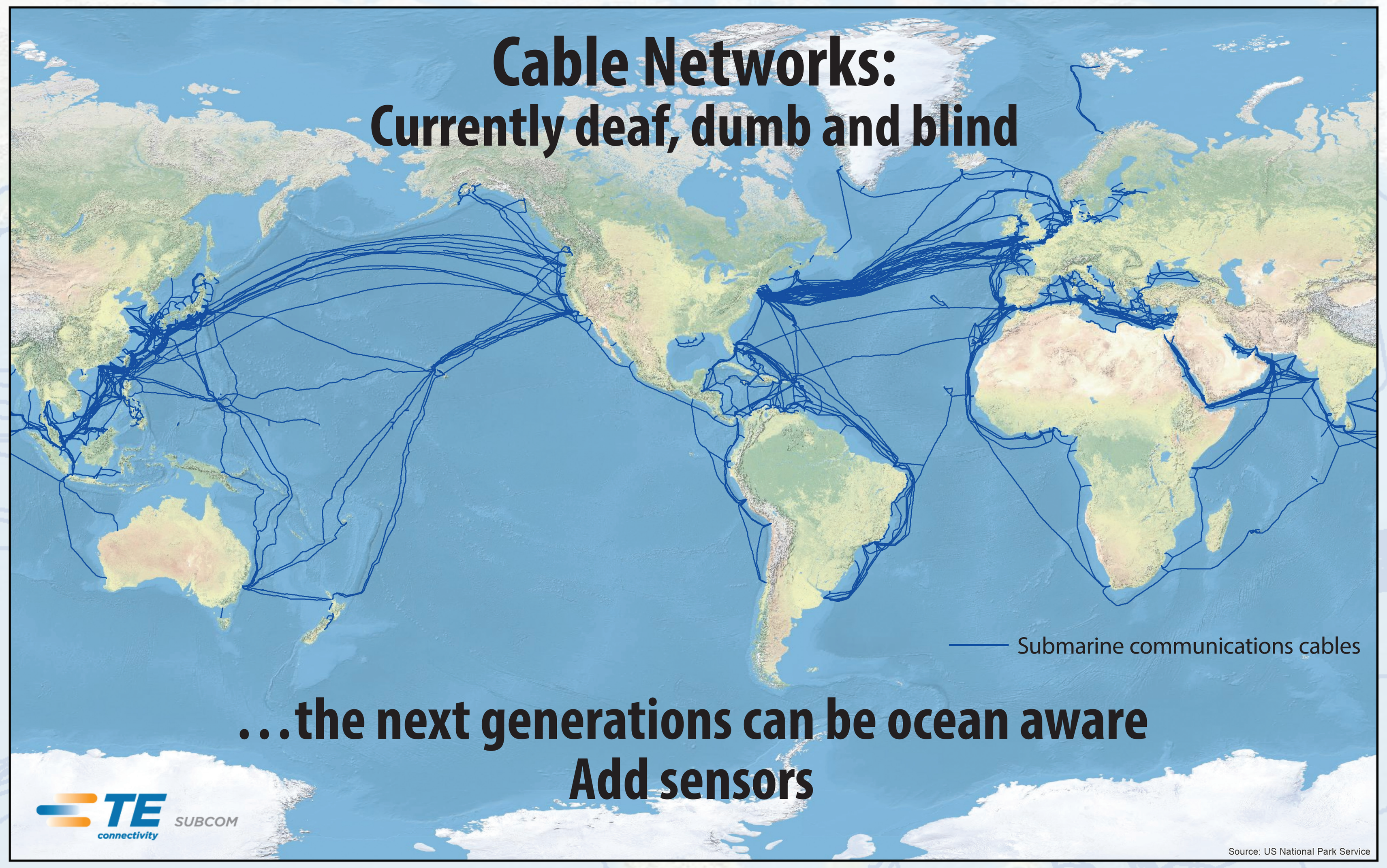
Overview

Planning is underway to integrate ocean sensors into Scientific Monitoring And Reliable Telecommunications (SMART) subsea cable systems to provide basin and, ultimately, global array coverage within the next decades. We envision that SMART cables will provide the following: contribute to the understanding of ocean dynamics and climate; improve knowledge of earthquakes and forecasting of tsunamis; and complement and enhance existing satellite and *in situ* observing systems. SMART cables will be a first order addition to the ocean observing system, with unique contributions, strengthening and complementing satellite and other *in situ* systems. Cables spanning the ocean basins with repeaters every ~65 km will host sensors/mini-observatories, providing power and real-time communications. The current global infrastructure of commercial submarine telecommunications cable systems consists of 1.5 Gm of cable with ~23,000 repeaters; the overall system is refreshed and expanded on a time scale less than 10 years whereas individual systems have lifetimes in excess of 25 years. **Figures 1 & 2**

In two NASA workshops, the scientific utility of the initial measurement suite (bottom temperature, pressure, and acceleration) is explored. We focus primarily on information for monitoring and studying climate change but also improved tsunami and earthquake warning. The ocean-basin-spanning, high temporal sampling, and resolution of the mesoscale will be unique.

The bottom temperature and pressure measurements, in concert with satellite altimetry and gravity, form a powerful complementary combination to resolve sea level, heat content, and ocean circulation with climate ramifications. The *in situ* data are essential to correct ever-more precise (millimeters of water) satellite results on the effect of tides and short-term motion, with concomitant benefits on land, including better estimation of ground water and ice sheet volumes. The pressure and acceleration measurements will be extremely effective for reliable tsunami and earthquake detection with improved hazard forecasts. Observing System Simulation Experiments (OSSEs) are necessary to quantify the value of SMART measurements in the context of the existing satellite and *in situ* ocean observing system. A follow-on workshop should study the tsunami and earthquake aspects in greater detail. Planning, technical development, and implementation should also continue.

These new SMART cable systems will be a highly reliable, long-lived component of the ocean observing system. They will complement satellite, float, and other *in situ* platforms and measurements. Several UN agencies including the International Telecommunications Union, World Meteorological Organization, and UNESCO International Ocean Commission have formed a Joint Task Force to move this concept to fruition (ITU/WMO/IOC JTF).



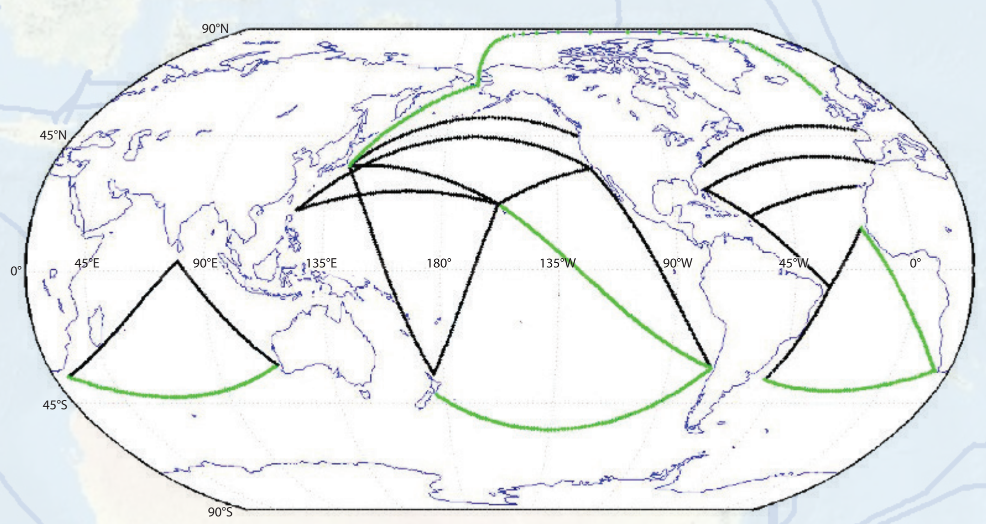


Figure 1. Map shows notional locations of repeaters along present (black) and possible future (green) telecommunication cables. Note the trans-Arctic route.

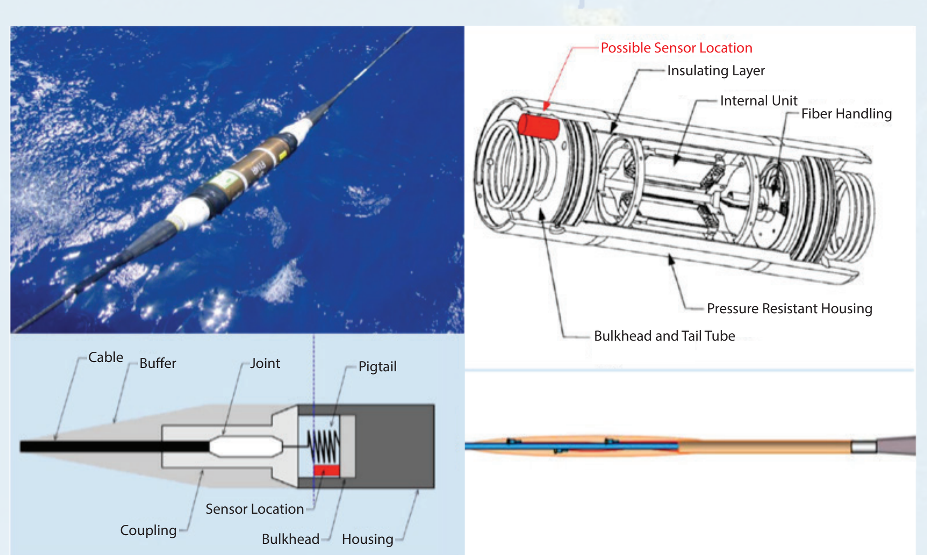


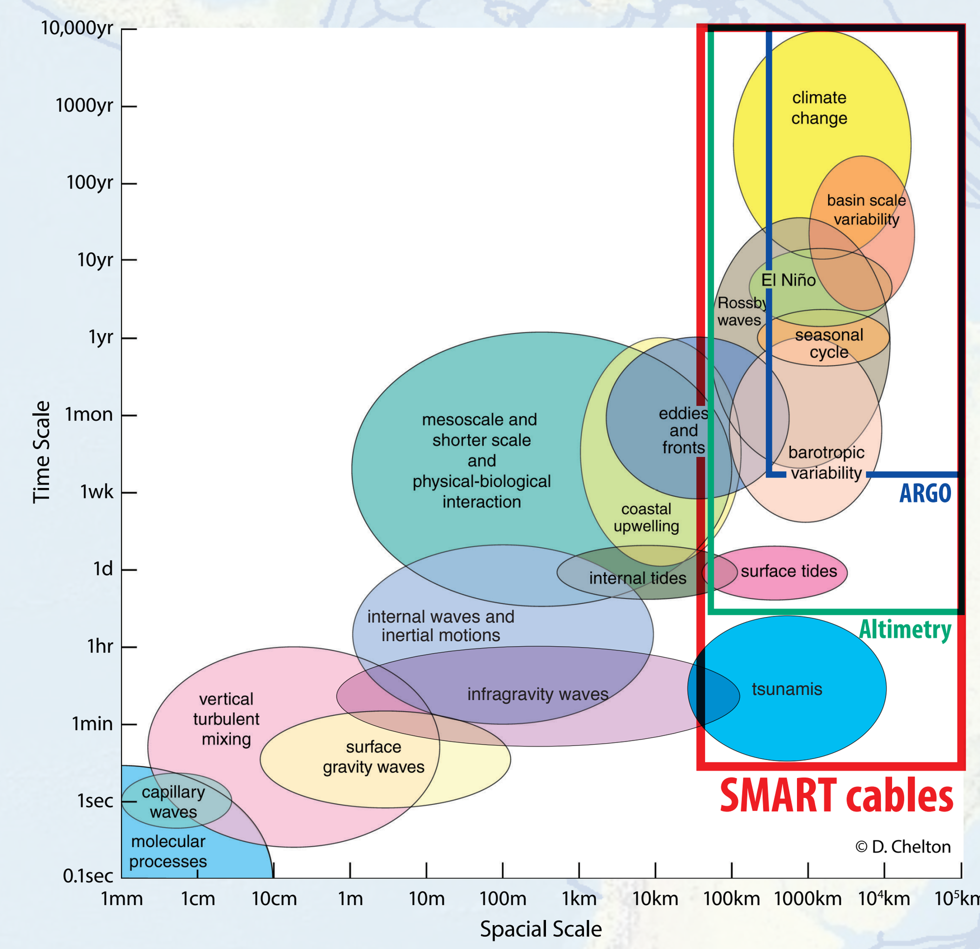
Figure 2. Submarine Repeater being laid in the ocean and sensor mounting options in a repeater.

Science

SMART cable systems can make unique and complementary contributions to the existing earth observing systems and provide synergies with satellite observations.

- SMART sensors provide an orthogonal space/time coverage with respect to other observing system components with data from ~20,000 nodes along ocean basin spanning paths that resolve mesoscales (~50 km) with high frequency (seconds to minutes) sampling. Temporal aliasing will be effectively eliminated compared to satellite and other *in situ* systems. **Figure 3**
- Sea level, globally remotely sensed with satellite altimetry, depends on *in situ* measurements (e.g., SMART pressure and temperature) for validation, and tide and other high frequency (e.g., infragravity waves) corrections. **Figures 5 & 6**
- Gravity, globally measured by GRACE on ~1000 km scales, can be interpreted as ocean bottom pressure (in equivalent cm of water); the SMART pressure measurements serve as ground truth and de-aliasing for tidal and other high frequencies. SMART pressure data are necessary for ground truth validation of GRACE data, leading to significantly improved precision and global resolution. **Figures 5 & 6**
- The SMART pressure sensors can detect surface (infragravity) waves useful for correcting future satellite altimetry missions and improving wave models.
- While deterministic astronomical forcing generates the ocean tides, the tides are now known to vary on seasonal to centennial time scales due to changes in the ocean state—currents, stratification, water column thickness, ice cover, etc. SMART measurements are uniquely suited to constrain time evolving tide models needed to correct satellite products. **Figures 5**

Figure 3. A representation of processes based on their time and space scales, with schematic space-time coverage provided by existing observations networks (Argo global network of profiling floats, satellite altimetry) and for the proposed SMART cable design.



- Ocean surface wind stress produces large spatial scale barotropic (top-to-bottom) currents with time scales of 10 days (storm) or less, affecting satellite altimetry and gravity results. Presently atmospheric weather models are used to correct the satellite measurements but SMART measurements have the capability to estimate the wind stress through an inverse process (a research problem). **Figure 6**
- Within a few years of deployment, SMART seafloor temperature sensors will be able to determine climatically significant trends (~5 mK/y) with high temporal and spatial sampling, growing to 20,000 nodes with 50 km spacing, compared to a projected 1,000 deep global ARGO floats. **Figure 4**
- Next-generation acoustically determined along-cable velocity and temperature, combined with cable voltage measurements providing cross-cable absolute transport, could improve estimates of ocean mass and heat transports, greatly improving our knowledge of full-depth ocean circulation.
- Ocean modeling can be used to estimate the impact of SMART cable bottom pressure measurements on ocean state estimation, and then assimilate the SMART data. High-resolution simulations and existing data can characterize the high-frequency variability of the SMART cable bottom pressure and temperature measurements. **Figure 6**

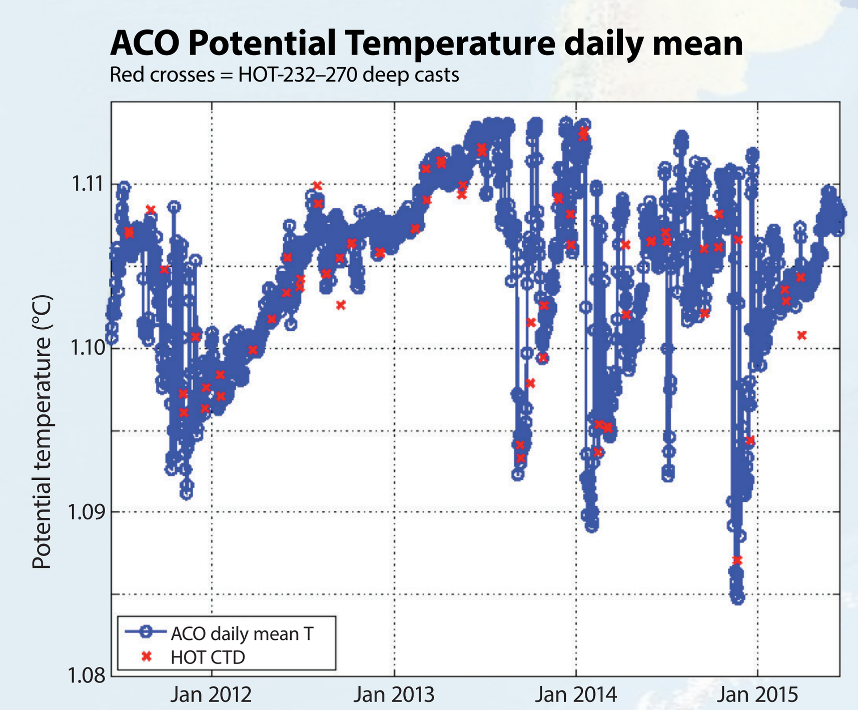


Figure 4. Four years of bottom potential temperature at Station ALOHA (22° 45'N, 158°W, 4728 m) using the ALOHA Cabled Observatory (ACO). Red "x" indicates the quasi-monthly temperature measured by the HOT project.

Cost

SMART sensors add ~$40M to the $250M base cost of a trans-Pacific 10,000 km cable system with 152 repeaters. Ten systems cost ~$400M, roughly the same as a five-year satellite mission, but cables last 25 years. Two systems/year over 25 years result in 7,600 SMART sensors on the seafloor.

For comparison: The US NOAA DART program is $27M/year, roughly the incremental cost of a SMART trans-Pacific cable, where most buoys are located. The NSF Ocean Observatories Initiative (OOI) cost ~$400M for the fabrication, with operating costs of ~$50M per year.

Figure 5. Seasonal amplitude (cm) of the principal lunar semi-diurnal tide M2 along cable routes, sampled along cable routes in the Pacific and Atlantic from the STORMTIDE model forced by both atmospheric fields and the astronomical tidal potential (Müller et al., 2014). Courtesy Malte Müller.

The tides are no longer "constant."

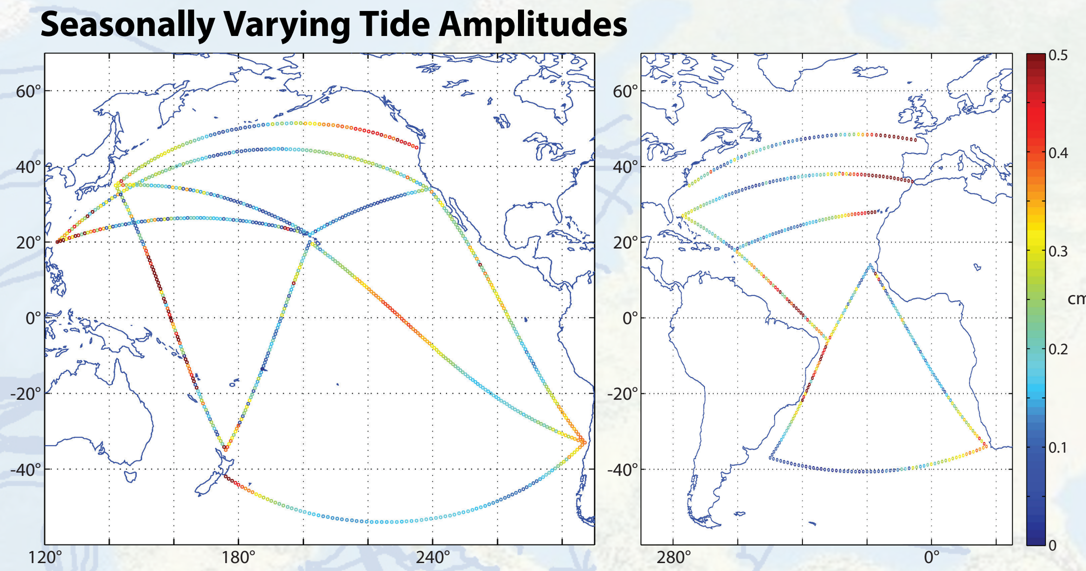
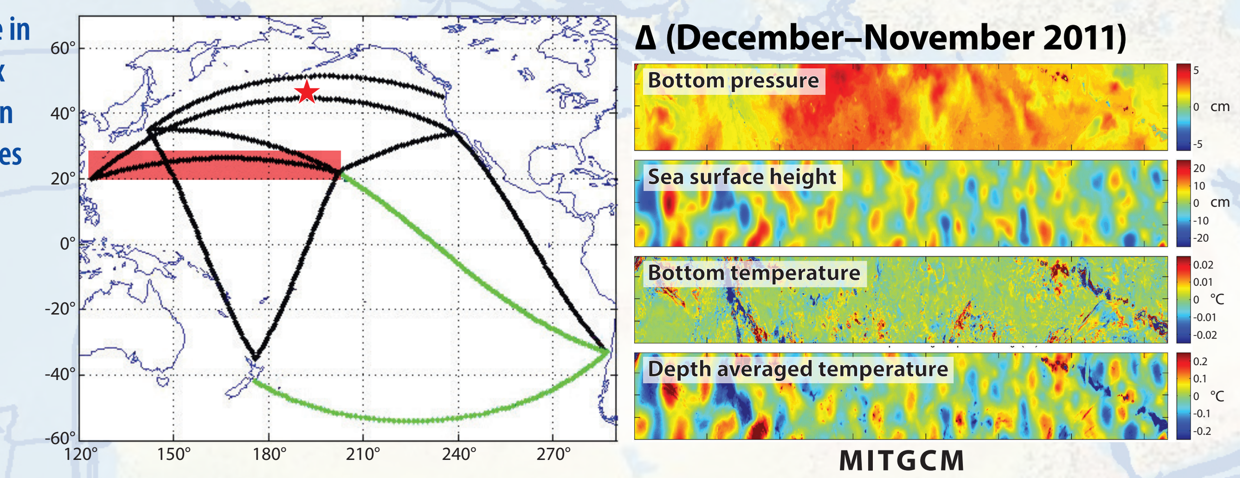


Figure 6. (left) A cable route in the western Pacific. The red box indicates the region extracted in the right, while the star indicates the location of the DART data. (right) Output from the llc4320 run of the MITGCM.



Recommendations

SMART cables will act as a new component of the earth observing system that will sample at a range of time and length scales not provided by other sampling networks (**Figure 3**). It will be a valuable future component of global earth observing systems such as the Global Geodetic Observing System (GGOS), the Global Ocean Observing System (GOOS), or the Global Earth Observing System of Systems (GEOSS). Not only will bottom pressure serve as an important constraint for de-aliasing and correcting models of past and current remote sensing data, but it will also be an important ground-truth of future remotely sensed sea surface heights and gravity fields.

Recommendations and outstanding questions from the two workshops include the following.

1. The SMART cable concept deserves broad support from the scientific community, with support from government sponsors.
2. The seismic and tsunami communities should clarify their strong scientific case for SMART cables through similar workshops.
3. The scientific community should prioritize which cable routes are most useful for this purpose.
4. The scientific and subsea telecommunication communities should assist the JTF to identify a SMART demonstrator cable system.
5. Continue work to extract bottom pressure from high resolution global ocean models to quantify expected seasonal (and longer) variability of tides that SMART cables would be uniquely capable of measuring, with impacts on altimetry and gravity.
6. Perform sensitivity experiments that elucidate the degree to which assimilation ocean models are sensitive to SMART cable measurements (e.g., in the form of volume of water colder than 1.5°C).
7. Perform Observation System Simulation Experiments (OSSEs) for the proposed sensors to quantify ocean state estimate improvements. This will, for instance, provide strong constraints on otherwise unconstrained deep temperature.
8. Build on the sensitivity experiments and OSSEs to develop a "SMART cable mission simulator" that produces realistic data and noise from models, performs the data assimilation, compares with truth, estimates uncertainties, and produces useful products. Data would include measurements from the initial pressure and temperature, as well as, for instance, cable voltage and inverted echosounders.
9. Perform simulations to quantify the improvement in accuracy and speed for tsunami (bottom pressure) and earthquake (accelerometer) warning systems using SMART cable measurements, similar to the ocean observing simulations.
10. Begin development of sensors for following phases, e.g., acoustics and cable voltage, bio-optics and biogeochemical sensors.
11. In many cases, cables are buried in shallow water to protect them from external aggression (e.g., fishing and anchoring; <1000 m). What are the ramifications for the temperature and pressure measurements?

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