Report on two NASA Workshops

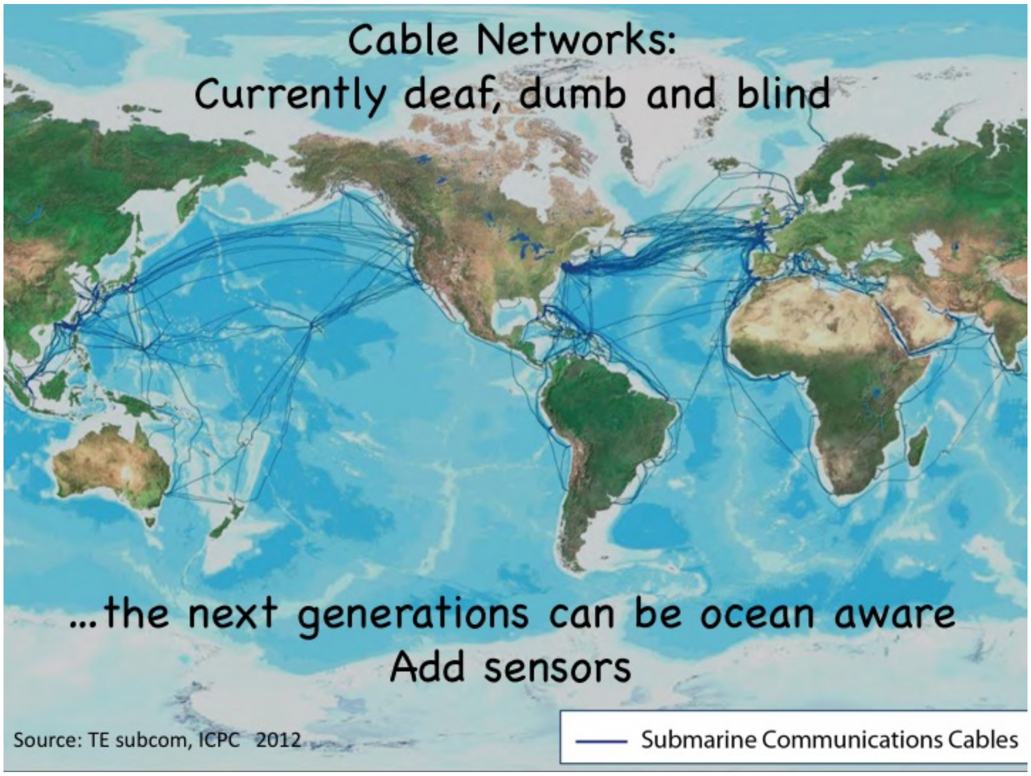
From space to the deep seafloor: Using SMART submarine cable systems in the ocean observing system

9–10 October 2014
Keck Center, California Institute of Technology (CalTech)
Pasadena, California USA

26–28 May 2015
East-West Center, University of Hawaii at Manoa
Honolulu, Hawaii USA

10 December 2015

Bruce Howe and Workshop Participants



SMART: Science Monitoring And Reliable Telecommunications
Climate Monitoring and Disaster Mitigation

Context

The ITU/WMO/UNESCO IOC Joint Task Force (JTF) was established in 2012 to investigate the use of submarine telecommunications cables for ocean and climate monitoring and disaster warning. These workshops reported on herein were an outgrowth of the JTF effort, the first in-depth scientific meetings to consider the topic.

Acknowledgments

Recognizing the potential connections between widespread cable-based measurements and space-based satellite measurements, NASA awarded grant NNX14AO89G to the University of Hawaii at Manoa, principal investigator Bruce Howe, to conduct and report on the workshops. The support and guidance of NASA program manager Eric Lindstrom is much appreciated. This report is a collective effort of all participants.

Web page

The web page www.soest.hawaii.edu/NASA_SMART_Cables reproduces the executive summary and provides links to the workshop report, summary presentation, and presentations by individual participants (collected into one file).

- www.soest.hawaii.edu/NASA_SMART_Cables/NASA_SMART_Cables_Workshop_Report_2015.pdf
- www.soest.hawaii.edu/NASA_SMART_Cables/NASA_SMART_Cables_Workshop_Summary_Presentation_2015.pdf
- www.soest.hawaii.edu/NASA_SMART_Cables/NASA_SMART_Cables_Workshop_Participant_Presentations_2015.pdf
- www.soest.hawaii.edu/NASA_SMART_Cables/NASA_SMART_Cables_Workshop_Poster_AGU_Fall_Meeting_2015.pdf

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Abstract

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.

In these two 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; http://www.itu.int/en/ITU-T/climatechange/task-force-sc).

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Executive Summary

Planning is underway to integrate ocean sensors into SMART subsea cable systems providing basin and, ultimately, global array coverage within the next decade (SMART: Scientific Monitoring And Reliable Telecommunications). In this report on two NASA-sponsored workshops, we explore the scientific benefits of the associated measurements in the ocean observing system linking with satellite and other ocean observations.

SMART cables will:

- Contribute to the understanding of ocean dynamics and climate.
- Improve knowledge of earthquakes and forecasting of tsunamis.
- 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 that will strengthen and complement satellite and* 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 (1 gigameter, 1 million kilometers, 40 times around the earth) with ~23,000 repeaters (to boost optical signals); the overall system is refreshed and expanded on time scales less than 10 years and individual systems have lifetimes in excess of 25 years. Initial instrumentation of the cables with bottom temperature, pressure, and acceleration sensors will provide unique information for monitoring and studying climate change and improved tsunami and earthquake warning. These systems will be a ***new*** highly reliable, long-lived component of the ocean observing system that will complement satellite, float, and other *in situ* platforms and measurements.

The addition of SMART sensors leverages $40M onto the $250M base cost of a present day trans-Pacific 10,000 km cable system with 152 repeaters. Ten such systems cost about $400M, about the same as for a five-year satellite mission, but the cables will last 25 years. If two systems per year are deployed in this time frame, 7,600 SMART sensors will be operating on the seafloor.

Several UN agencies have come together to facilitate this incorporation of science sensors for climate and ocean observing and disaster mitigation into commercial submarine telecommunications cable systems. The International Telecommunication Union, the World Meteorological Organization, and the UNESCO Intergovernmental Oceanographic Commission have formed the Joint Task Force to move this concept to fruition (ITU/WMO/IOC JTF; http://www.itu.int/en/ITU-T/climatechange/task-force-sc).

SMART cable measurements will be relevant to the understanding of climate and its variability. They will greatly improve our knowledge of deep-ocean variability (e.g., temperature) and impose constraints on important depth-integrated quantities (e.g., pressure, and in subsequent phases, depth averaged heat content and velocity), all with high frequency temporal and spatial sampling on a global scale for the first time.

Specific ocean measurements enabled by SMART subsea cables using the initial sensor suite include: spatial and temporal variability of deep-ocean temperatures; propagation of heat anomalies through ocean basins and along ocean boundaries; temporal variability of barotropic tides that impact tidal corrections for satellite missions; ocean response to atmospheric pressure forcing on fast (hours to days) time scales; and impact of infragravity waves on high-precision altimetry and gravity missions.

With subsequent sensors, additional measurements are possible. Active and passive acoustics and cable voltages can provide depth averaged temperature (heat content) and along cable and cross cable depth averaged velocity, transports of heat and mass, and internal wave and tide variability. The simultaneous determination of mass loading and earthquake hazard response effects can be used to evaluate satellite altimetry and gravity missions. Robust bio-optical sensors can characterize carbon export to the seafloor; conductivity for salinity can better determine bottom density and water mass. Passive hydrophones can measure wind, rain, ultragravity waves, marine mammals, and shipping, and can also serve as receivers in an acoustic thermometry network.

The initial sensor suite will improve tsunami and earthquake early warning systems. The acceleration data will speed up the determination of earthquake source parameters, now poorly constrained, that are used as input for tsunami propagation models and earthquake hazard response. The bottom pressure will constrain tsunami amplitudes much faster than the sparse DART array (latencies of seconds vs. ~hour, respectively); further, pressure measurements allow detection of tsunamis that are not caused by large earthquakes, e.g., landslide generated tsunamis.

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

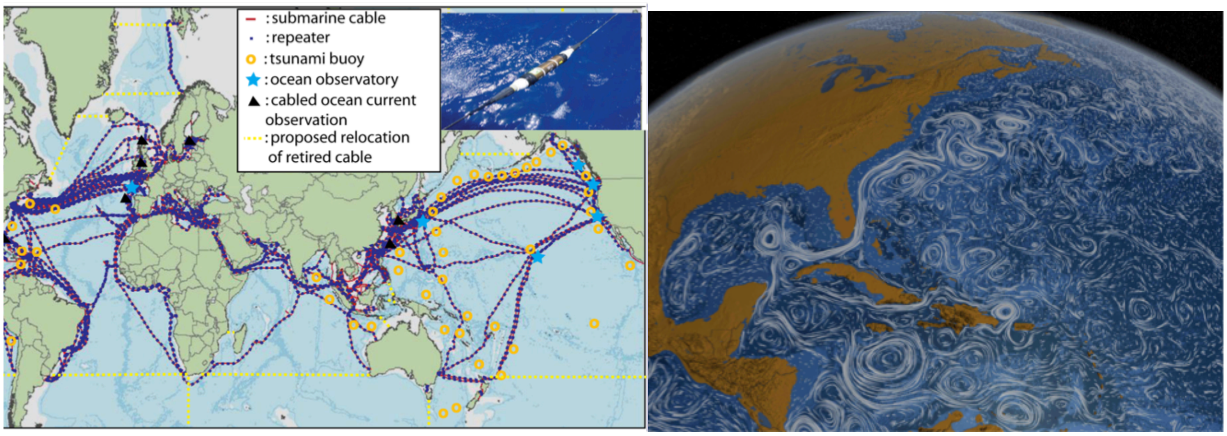
- SMART sensors provide an orthogonal space/time coverage with respect to other observing system components with data from ~20,000 nodes along ocean basin spanning paths that resolve mesoscales (~50 km) with high frequency (seconds to minutes) sampling. Temporal aliasing will be effectively eliminated compared to satellite and other *in situ* systems.
- 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.
- 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.
- 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.
- 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).

- 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.
- 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.

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 telecommunications industrial 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 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?



(left) Map showing existing submarine telecommunications cables with repeaters schematically highlighted; a repeater is shown (top right). (right) Sample output of a high resolution ocean model.

1 Introduction and Background

In 2010, John Yuzhu You wrote a *Nature* opinion article on the possibility of incorporating science sensors into commercial submarine telecommunications cable systems (You, 2010). Sensors integrated into cable repeaters every 65 km and spanning the ocean basins (Fig. 1) could provide observations for (i) ground truthing and adjusting satellite retrieval algorithms, (ii) climate variability and change studies, and (iii) seismic and tsunami hazards.

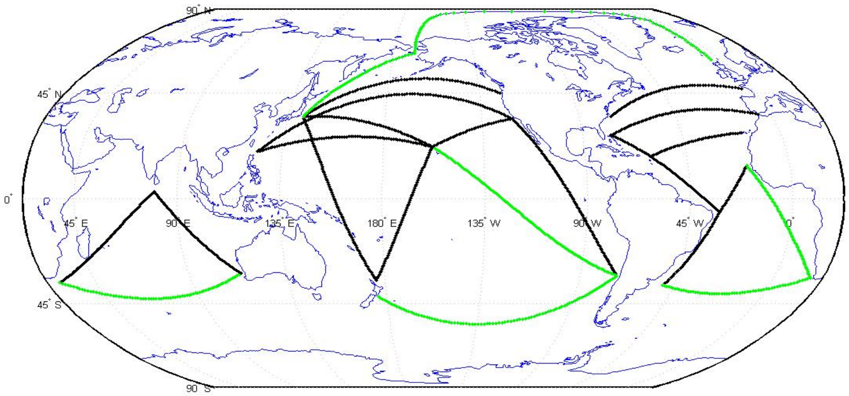


Figure 1. Map shows some of the (notional) present (black) and possible future (green) telecommunication cables with repeaters.

Submarine cables are a critical world infrastructure carrying essentially all Internet traffic—financial, business, and social. Sensors can now be attached to or integrated with the repeaters every ~65 km along the cables. As cable systems are replaced, upgraded, and expanded (e.g., in the Arctic) over a typical ~10-year technology refresh cycle, we can obtain basin scale, high-resolution measurements of (initially) bottom pressure, temperature and acceleration, and possibly other types of data as the system expands. With approximately 1.5 million kilometers of seafloor cable, and ~20,000 repeaters/nodes, this system would contribute substantially to the ocean observing system.

The You (2010) article prompted the International Telecommunication Union (ITU), the United Nations specialized agency for information and communication technologies, to include this concept in subsequent "Green Week" Workshops and commission three reports: Strategy and Roadmap; Engineering Feasibility; and Opportunities and Legal Considerations (Butler, 2012; Lentz and Phibbs, 2012; Bessie, 2012). The ITU, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO/IOC), and the World Meteorological Organization (WMO) established the Joint Task Force (JTF) in 2012 to further develop and carry the concept to fruition (JTF, 2012). A subsequent Science and Society white paper was published in Butler et al., (2014) and two engineering studies in 2015 (JTFa, JTFb, 2015). This concept was initially referred to as "Green" or dual-use cable systems, but is now being called Science Monitoring And Reliable Telecommunication (SMART) Subsea Cable Systems. The current efforts of the JTF are focused on facilitating a "wet demonstrator" project to prove the concept in practice; these have been developed through workshops in Paris (2012), Madrid (2013) and Singapore (2014) with details available on the website,

NASA recognized that such measurements could very significantly improve and indeed enable the scientific utilization of increasingly precise space-based satellite measures of the global ocean and earth. As a specific example, satellite measured global sea surface height altimetry and gravity fields are inextricably and intimately tied to the estimation of the steric (temperature expansion) and mass components of the sea surface height—and consequently ocean circulation, heat content and ocean warming, and climate change—with direct estimates of bottom pressure in the middle. A major positive attribute of satellite measurements is their truly global extent; however, that global extent is achieved every 10 days or so, and processes occurring on shorter times scales (e.g., tides) can confound the interpretation because of temporal aliasing. *In situ* ocean bottom measurements using SMART cables can go a long way to rectifying this problem.

With this recognition, NASA funded these first face-to-face science workshops to expand upon earlier white papers. The objectives were to determine how this type of data can be best used to answer scientific questions, validate satellite data and ocean models, complement and supplement satellite altimetry and gravity, and other data (including Argo float data) as it evolves into a permanent, major component of the ocean observing system.

From the start it was suggested that a number of sensors/measurements and infrastructure elements be included: temperature; salinity; pressure; hydrophones; seismometers; acoustic modems; and plug-in “node” capability. However, in keeping with the KISS (keep it simple, stupid) principle, it was decided to emphasize temperature, pressure, and acceleration as the very simplest and basic measurements to begin with in the initial discussions and implementations, and this remains the case today.

The engineering feasibility of incorporating science instruments into submarine cable systems is discussed in detail in the Engineering Feasibility Study (Lentz and Phibbs, 2012) and two subsequent documents (JTFa, JTFb, 2015). Modern submarine communication cables use laser light transmission over optical fibers. Every 65 km or so (the most recent spacing), the signal needs to be boosted using “repeaters”, which contain erbium-doped optical amplifiers (Fig. 2). They obtain ~20 W from the single copper high voltage (up to 15 kV) conductor in the cable. The engineering essence of the SMART cable concept is to extract about 1 W for instrumentation and to tap into the communications system for transfer of science commands and data. At this time, there are several possible implementation methods: thermistors are incorporated into the cable sheathing some distance from the pressure case; a sensor is mounted inside a flooded volume at the end of the case; “blister” packs are another possibility. Currently, however, no method has been singled out as the best. A significant constraint is that the system must be deployable using existing cable ship technology and instrumentation must survive the associated rigors; no maintenance is envisaged once deployed; sensor data is transmitted via the supervisory channel without impacting the telecommunications traffic.

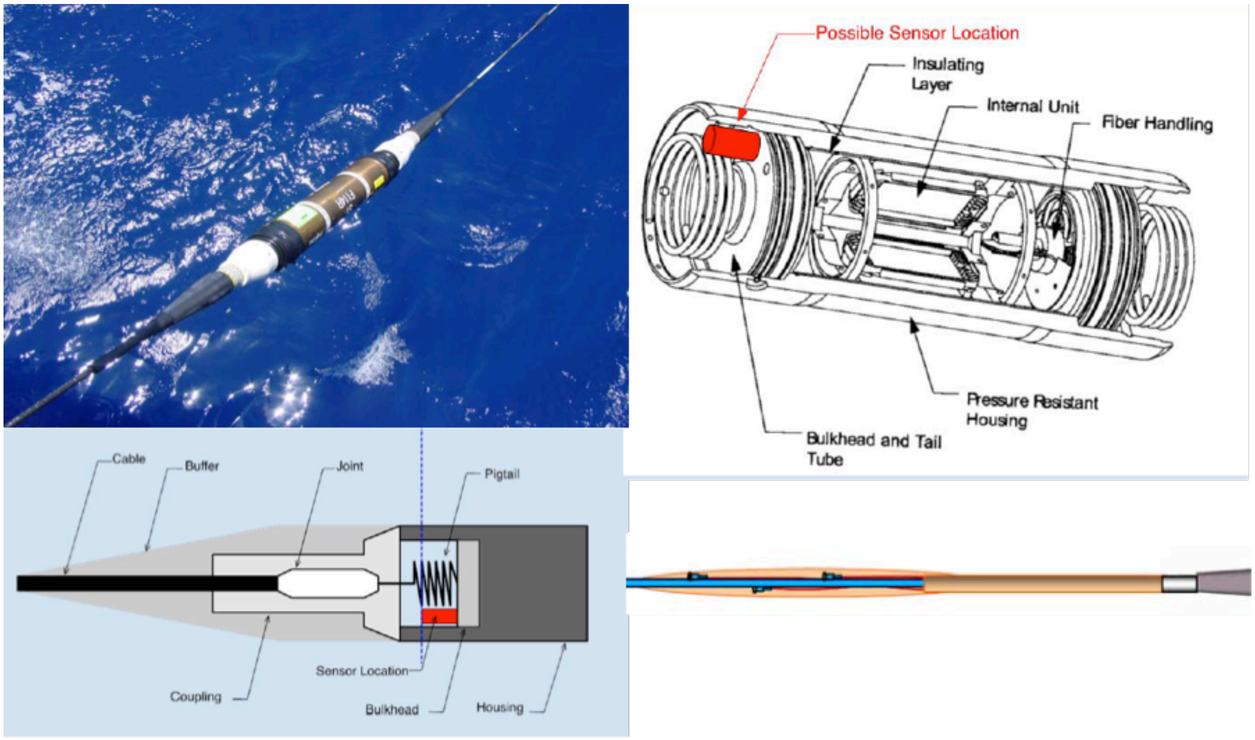


Figure 2. Fujitsu Flashwave S100 Submarine Repeater being laid in the ocean and sensor mounting options in a repeater (courtesy of P. Phibbs and TE Subcom).

The baseline cost of a trans-Pacific 10,000 km system with 152 repeaters is about $250M. The estimated incremental cost for the addition of SMART sensors to the baseline system is $40M, $4k/km, or 16 percent. The cost for ten such systems is $400M, about the same as for a five-year altimetry or gravity satellite mission, but the cables will last 25 years. Deploying two systems per year over 25 years will result in 7,600 SMART sensors operating on the seafloor.

For further comparison, the US NOAA DART program budget is $27M/year, which is comparable to the incremental cost for one SMART trans-Pacific cable, where most of the US DART buoys are located. The Argo program with 4000 expendable floats costs about $32M to maintain. The NSF funded Ocean Observatories Initiative (OOI) cost ~$400M for the fabrication phase with operating costs of ~$50M per year. NOAA estimates it spends approximately $430M annually to operate and maintain its ocean, coastal, and Great Lakes observing systems.

During the two workshops, the various scientific presentations and discussions of the scientific value of the SMART cable effort led to three overarching themes. First, SMART cables will significantly contribute to further observing and understanding the dynamics of oceanic systems, and thus are of relevance for the study of the climate system and for sea level change. Second, as a societal benefit and direct application of the new knowledge gained, SMART cable measurements will provide crucial information to help research the dynamics of earthquakes and tsunamis, thus contributing to tsunami warning systems. Third, SMART cable measurements will complement and enhance satellite observation systems.

2 Scientific Value and Climate Relevance of SMART Cable Measurements

The deployment of SMART cables, which complement other components of the global observing system (satellites, moorings, floats, etc.), will improve the quantification of surface-to-bottom oceanic variability and its resulting impact on climate change. Globally, the variability of the ocean at depth and on its boundaries is poorly known. Along the entire length of SMART cables lying on the seafloor across ocean basins, temperature and pressure—fundamental oceanic quantities—as well as acceleration, will be resolved on an unprecedented range of time (seconds to decades) and space scales (from kilometer to trans-basin scales). In this way, SMART cables will contribute to the investigation of the global wavenumber-frequency spectrum of oceanic variability, encompassing many oceanic processes of climatic relevance. While interannual and decadal time scales are obviously of importance for climate studies, short-time variability of pressure and temperature (as an example induced by barotropic tides) are modulated on longer time scales so that their impact on climate processes may vary.

2.1 Initial sensors: temperature, pressure and acceleration

SMART cable measurements will help the scientific community address a number of outstanding scientific questions.

- In broad terms, what is the spatial and temporal temperature variability below ~2000 dbar? This level is the current limit of the Argo array. Even the proposed "deep Argo" program, which will sample to 6000 dbar with an implementation date of 2017, will have sparse spatial and temporal sampling compared to the resolution of temperature measurements along a SMART cable.
- What are the processes linking the deep ocean to coastal regions? As an example, regions shallower than 2000 dbar at the boundaries are not accessible by Argo but will be sampled by the SMART cables as they depart from the coast and reach the deep ocean via the continental shelf and slope.
- What are the abyssal processes on sub-regional, regional, and global scales? How are heat and water masses redistributed between deep ocean basins, from the surface to the deep, on decadal time scales down to very short time scales (e.g., temperature changes of the order of 20 mK on daily time scales, as seen at Station ALOHA, Fig. 3)? Sampling from SMART cables will combine with other observing systems (e.g., moorings, GO-SHIP hydrographic profiles, satellite, Argo array, etc.) to improve the accuracy of closing budgets. Vertical and horizontal fluxes of heat and mass inferred from SMART cables will provide insight into: deep water mass formation linked to overturning that occurred in the past (typically decades before); water mass flowing over topographic features; mixing associated with topographic sills or bottom topography; surface formation processes of deep water masses; geothermal fluxes at the seafloor; and the steric (thermal expansion) contribution of the deep ocean to sea level change.

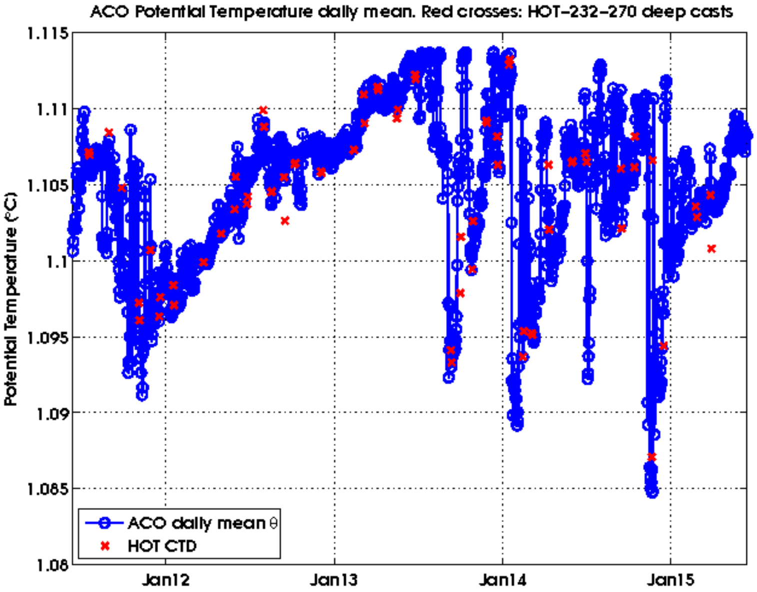


Figure 3. Four years of bottom potential temperature at Station ALOHA (22 45N, 158W, 4728 m) using the ALOHA Cabled Observatory (ACO). Red 'x' indicates the quasi-monthly temperature measured by the HOT project.

A specific example of a poorly known deep process is the association of abyssal temperature trends with climate change. The current signal from decadal hydrographic surveys (Purkey and Johnson, 2010) indicates broad warming trends, ranging from ~50 mK/decade in the Southern Ocean to ~5 mK/decade in the deep basins of the Northern Hemisphere. These decadal bottom temperature trends will be detectable in most regions of the world with improved spatial coverage and temporal resolution using SMART cables temperature sensors.

- What is the temporal variability of barotropic and internal tides? Specifically, what are the spatial patterns of: high-frequency constituents such as overtides; seasonality and secular trends in tides; internal tide non-stationarity at the mm to cm levels; generation of internal tides and their nonlinear interactions; impact on the global mixing of the ocean; impact in the Arctic? The tides energize other energy bands of oceanic variability (e.g., barotropic wave trains) and studying nonlinear wave interactions at the boundaries and their spatial distribution will identify the source of this energy. Having multiple cables will further refine the determination of energy sources. The secular change in tides is in some locations comparable to the change in mean sea level.
- What is the ocean's response to atmospheric forcing, as seen in ocean bottom pressure? At relatively short time scales, what is the form of the ocean's response, which is not expected to be inverse barometer? At longer time scales, what are the mechanisms associated with notable correlation patterns between ocean bottom pressure and climate atmospheric indices? On continental shelves and in coastal regions, what are the ocean dynamics that need to be elucidated to improve predictions of storm surges and meteorological tsunamis?
- What is the impact of infragravity waves on the capacity of future satellite altimetry missions to monitor the surface ocean? Infragravity waves are long surface waves (2-20 minute

period) that can be mistaken for other surface ocean processes when measured from space. Seafloor pressure measurements from SMART cables will allow us to monitor and improve the modeling of infragravity waves, thereby improving the ocean observing capability of future satellite altimetry missions.

- What is the compliance (elastic response) of the sea floor? Combined measurements of bottom pressure, which provides information on the water mass above the seafloor, and accelerometer measurements, which provide information on the vertical displacement of the seafloor, may provide insight on seafloor dynamics.

2.2 Future sensors

In addition to pressure, temperature, and acceleration we envisage that additional sensors will complement the scientific value of SMART cables. For instance, point current meters or Acoustic Doppler Current Profilers can be added to measure velocity, conductivity sensors to measure salinity, voltage measurements to measure mass transports, and active and passive acoustic systems to measure heat content and velocity, biogenic, or rain and wind acoustic signals, and other oceanographic quantities.

- Temperature, salinity and velocity measurements on ocean basin boundaries can be used to estimate the pressure gradients that drive the variability of the meridional overturning circulation (MOC, the large scale ocean circulation connecting the ocean basins) and, which is proportional to pressure gradient differences between east and west boundaries (Hughes et al., 2013; Elipot et al., 2014).
- An array of inverted echo sounders along cables would allow computation of the frequency-horizontal wavenumber spectra of internal gravity waves, thus providing a comparison with numerical model results showing that such spectra follow linear dispersion curves (Müller et al., 2015). The echo sounders would also provide global-scale, high-frequency measurements of internal tide non-stationarity, which impacts tidal corrections for the upcoming wide-swath satellite altimeter mission. To prepare for this possibility, echo sounding measurements could be simulated by computing vertical acoustic travel times at hourly intervals in synthetic water columns taken from the output of high-resolution models forced by both atmospheric fields and tides (Arbic et al., 2010, 2012; Müller et al., 2012, 2014; Dimitris Menemenlis paper in preparation).
- Combined measurements of velocity and pressure will allow us to resolve boundary/Ekman layer processes.
- If measurements of velocity and temperature are obtained above the bottom boundary layer on ocean boundaries this could resolve (coastally-trapped) topographic waves.
- Measuring induced voltage between repeaters will enable estimates of mass transport perpendicular to the cable. Conductive seawater moving through the Earth's magnetic field generates horizontal electric fields proportional to depth-averaged velocity (Sanford, 1971; Chave and Luther, 1990), which are integrated along cables to give a voltage that is closely related to the volume transport across the cable. With sufficiently precise voltage measurements, it is possible to obtain averages and fluctuations in ocean circulation by applying present-day techniques to interpret oceanic electric fields. These measurements will complement and extend other variables that infer ocean circulation indirectly. The sources of noise and bias are well defined (Szuts, 2012), from high-frequency atmospheric noise to constant but laterally homogeneous sedimentary factors (Flosadottir et al., 1997),

and can be accounted for with an expected accuracy of 10% in the open ocean. The 50 km distance between repeaters will resolve oceanic decorrelation scales and maximize the oceanic signal-to-noise ratio. Full-depth ocean circulation is very rarely measured, and continuous cable voltage measurements would greatly improve our observational knowledge of this fundamental property.

An Observation System Simulation Experiment (OSSE) framework can quantify proof of concept for converting voltage measurements to mass transport. High resolution simulations (a few km resolution, e.g., MIT GCM run llc2160; Menemenlis, personal communication, see Fig. 6) are key to providing a near-realistic spectrum of variability including tides, barotropic waves, eddies, and low-frequency signals. The model output would be synthetically sampled with a reduced-order electromagnetic model to calculate electric field and include noise sources (sediment, atmospheric noise, parameterized higher-order theory). This approach will determine the voltage accuracy needed to obtain scientifically useful results.

- Many ocean processes can be observed and studied using acoustics (Howe and Miller, 2004; Duda et al., 2006; Dushaw et al., 2010). The most obvious acoustic sensor to add in phase 2 of SMART cables project is a passive hydrophone to address wind and rain, surface wave phenomena including infragravity waves, marine animals, ocean circulation and climate, and more (volcanoes, seismic activity, glaciers and ice, and anthropogenic sources such as shipping and oil and gas activities). *In situ* measurement of rainfall on scales of minutes and averaged over a surface area with diameter 5 times the water depth would be invaluable to validate satellite derived rainfall estimates and improve understanding of the oceanic hydrological cycle (Yang et al., 2015). With an active pinger more can be done with respect to ocean circulation and climate while also serving the infrastructure role of wireless communication, as an acoustic modem to nearby vehicles and instrumentation, and providing navigation beacon signals over ~30 km ranges. Mounting active transducer(s) requiring vertical orientation will be challenging but is deemed feasible.
- Ocean circulation and climate can be addressed in passive forms using noise interferometry (proof of concept and development needed; Godin et al., 2014) and as receivers in a long-range acoustic thermometry system (assuming sources provided independently, as done with the Acoustics Thermometry of Ocean Climate (ATOC) project, Dushaw et al., 2009). In the active case, inverted echo sounders (IES, typically 12 kHz) provide the top-to-bottom average temperature sampled every ~minute (round trip travel time gives sound speed, almost directly proportional to temperature). Inverted echo sounders are usually combined with pressure (PIES) and current (CPIES). The latter uses either a point sensor or an acoustic Doppler current profiler to provide a velocity reference as well as bottom boundary layer information. The bottom pressure and travel time measurements can be used to estimate the mass-loading and steric height variations in sea surface height (SSH), respectively. (Steric height changes result from expansion of sea water due to temperature and salinity changes. Temperature usually dominates; it can be inferred from sound speed (~temperature) changes observed by measuring changes in round trip acoustic travel time, between the bottom instrument and the surface.) The simultaneous measurements of mass-loading and steric SSH provide opportunities to evaluate satellite altimetry and gravity measurements. These units have been extensively used in dense bottom arrays over the last decades, e.g., in the Kuroshio Extension (Park et al., 2012). The scientific benefits anticipated by installing PIES or CPIES on SMART cables include: 1) accumulation of *in situ* data for evaluation of satellite altimetry and gravimetry; 2) monitoring long-term heat content

changes for the total water column; 3) monitoring long-term sea-ice extension and thickness changes in the Arctic Ocean; 4) measuring long-term meridional overturning circulation in the Atlantic Ocean; 5) measuring internal wave energy changes; and 6) measuring deep ocean current variability.

- Inverted echo sounders in adjacent cable repeaters (separated by ~50 km) could “talk” to one another to provide depth averaged temperature and absolute water velocity along the cable (10 km separation has been demonstrated; Tomoyoshi and Taira, 1993; demonstration at ~50 km needed, likely at ~4 kHz). The combination of temperature and velocity (and cross-cable velocity from cable voltage) will provide estimates of barotropic momentum and heat fluxes on time (minutes) and space (50 km to basin) scales that were previously unattainable
- What is the ocean carbon export to the sea floor? Transmissometers would allow quantification of particle fluxes and marine biogeochemical cycles at the ocean’s floor. Many other measurements will be possible when appropriately robust and long-duration sensors become available.

2.3 The special connections between deep seafloor and satellite measurements

Sea level is globally remotely sensed with satellite altimetry (e.g., Jason-II), typically with a 10-day repeat period. Gravity is globally measured by GRACE on ~1000 km scales with a 30-day repeat period and can be interpreted as ocean bottom pressure (in equivalent cm of water). Ocean bottom pressure and gradients thereof give the absolute depth averaged flow and circulation (water runs from high to low pressure). Conversely the altimetry data yields information on the surface or relative currents. Together they can give the depth dependent (two mode) absolute velocity. With additional analysis, changes in sea level height can be separated into contributions from thermal expansion (heat content) and added mass (ice melting from land).

These global-spanning satellite measurements are technological triumphs, with precisions on the order of a few centimeters to millimeters of water. Climate and ocean circulation signals are on the order of millimeters to 10 or 20 cm (the Gulf Stream has a 1 m signal). However, they are not simultaneous along their ground tracks. In both cases these measurements are strongly affected by ocean processes with time scales shorter than twice their repeat period, i.e., aliasing occurs. Any ocean sea level or pressure variation with time scales shorter than 20 or 60 days, respectively, is aliased unless corrected.

The most significant correction is for tidal effects. Typically, all the satellite data to date are used to extract tidal “constants” from which tidal elevation can be predicted for any time and subtracted from the measured signal to obtain a corrected signal. As will be shown below, this has been found to no longer be valid because the constants are in fact not so: there are seasonal variations on the order of 5 mm, and secular trends as well. SMART measurements are uniquely suited as independent *in situ* data to constrain time evolving tide models needed to correct satellite products.

Similarly, 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).

With an improved estimate of gravity in the ocean domain, the gravity estimates over land as well as estimates of glacial and ice sheet loss and changes in ground water volumes will also improve.

3 Tsunamis, Earthquakes, and Early Warning Systems

3.1 Tsunamis

Tsunami warnings should give affected communities the maximum possible time to prepare. The need for speed means that tsunami warnings, initially, are made purely from seismic data. Direct measurements of the tsunami, while intrinsically slower, are still essential because the tsunami is strongly affected by the shallowest rupture, which is often poorly constrained by seismic or GPS data. Once direct observations are available, the warning is appropriately modified. At present, direct tsunami measurements are provided by the DART instruments' deep ocean pressure gauges (Mofjeld, 2009). The DARTs trigger when they sense a tsunami (short-term pressures fluctuates by more than 3 mbar), and begin transmitting 1-minute data, although there is a latency of several minutes. The instruments must be deployed significantly seaward of expected source earthquakes (typically 400 km, or about 30 minutes of tsunami travel time) both to avoid constantly being triggered by small events, and thereby running down their batteries, and also to keep the seismic and tsunami signals temporally separated. That large distance makes the current DARTs inappropriate for local warnings. A promising new design with more rapid sampling and smarter on-board processing will allow the next generation of DARTs to be deployed closer to anticipated subduction sources. However, in order to provide adequate coverage there will have to be at least triple the number of DARTs. There are 60 instruments currently in the DART global network and keeping them all going is already a challenge, especially since their failure rate is high. Installing and maintaining more DARTs is currently not feasible within current budgets.

Pressure gauges on SMART cables could completely supplant the DART network in much of the ocean and would offer huge advantages. With instruments at every repeater (~50 km spacing), the tsunami would be far better defined than with the current DART spacing of 500 km or more. Furthermore, the higher sampling rate and real-time transmission from the gauges would allow separation of seismic and tsunami signals by simple filtering and would eliminate the 3-5-minute latency currently imposed by communications via the Iridium satellite constellation. In areas where the proposed cables pass very close to trench axes (e.g., the Aleutians) it would be possible to see the tsunami form during the earthquake and therefore provide very fast warnings.

The one potentially serious problem with the current DART network is the prospect of unilateral rupture (Fryer et al*.,* 2014). The three largest earthquakes ever recorded all exhibited this form of rupture with the break starting at one end of the fault and growing in one direction over the entire five- to ten-minute duration of the earthquake. Each tsunami radiated away from one end of the fault earlier than from the other with the result that the entire tsunami radiation pattern was rotated as much as 12° away from the trench normal. The current DART network is too sparse to detect such behavior so the data are interpreted as if the entire earthquake ruptures instantaneously, which would project the tsunami normally from the trench. If a really large earthquake occurs the current system is likely to assume the tsunami went in the wrong direction and will overwarn some areas and underwarn others. The denser network possible with cables would eliminate this problem.

To quantify the improvements possible with pressure sensors on SMART cables we simply need to run tsunami forecast models. For a hypothetical earthquake (e.g., with instantaneous rupture or sequential rupture), we could run a tsunami modeling code to produce synthetic DART records then explore the range of different earthquakes that produce DART records that are a passable match to the "true" record. If we repeat this procedure using the proposed denser network of cabled pressure gauges, we should be able to quantify the improvements (to both speed and forecasts) that could be accomplished with the cabled instruments.

3.2 Earthquakes

The accelerometers proposed for the SMART cables will significantly speed up the determination of fundamental earthquake parameters, which would benefit tsunami warning systems as well as emergency response to damaging earthquakes. The seismometers currently used to locate earthquakes are nearly all on dry land, which means that the location and depth of offshore earthquakes are too poorly constrained to assess tsunami hazard or provide rapid assessment of where severe shaking has occurred until seismic waves reach a distant island seismometer or a seismometer on the far side of the ocean. Accelerometers on the SMART cables will be on the seaward side of the earthquake but (potentially) at very close range. Accelerometers can withstand very high accelerations (well in excess of 1 g) before clipping, so they will return useful information even from within the epicentral region. The record from one or two cabled accelerometers, combined with currently available seismic data, would provide a tightly constrained solution of the earthquake several minutes faster than can currently be accomplished. For a local earthquake where the tsunami might reach the nearest coast within 20 minutes, this improvement would be very significant.

A simple simulation test is all that would be required to quantify the speed improvements possible with cabled accelerometers. For a given distribution of seismometers, it is straightforward to work out how quickly the epicenter, depth, and origin time of an earthquake can be determined for an earthquake at a given location. The time savings can be determined simply by adding the additional accelerometer locations and running the simulation again.

4 Contributions to Existing Earth Observing Systems

SMART cables will act as a new earth observing system that will sample at a range of time and length scales not provided by other sampling networks (Fig. 4). It will be a valuable future component of global earth observing systems such as the Global Geodetic Observing System (GGOS), Global Ocean Observing System (GOOS), or 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.

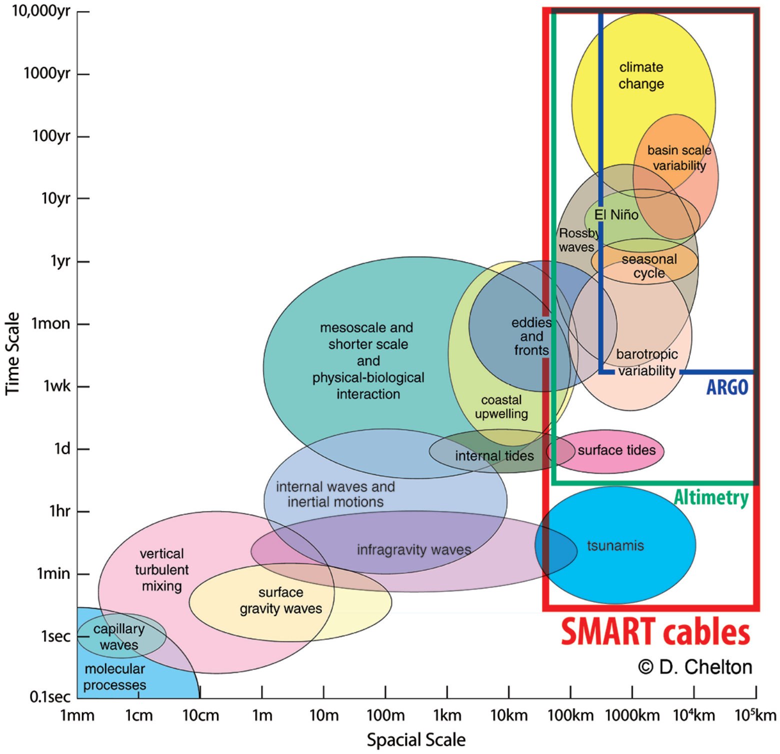


Figure 4. A representation of processes based on their time and space scales, with schematic space-time coverage provided by existing observations networks (Argo global network of profiling floats, satellite altimetry) and for the proposed SMART cable design.

4.1 Sea level

Sea level is a key parameter of the climate system. It has been extracted from satellite altimetry data from successive missions since 1993. Raw satellite altimetry data undergoes various corrections to account for tidal and atmospheric effects. SMART cables would provide bottom pressure data that can be used to improve de-aliasing tidal models. This tidal de-aliasing will in turn improve past satellite altimetry products and facilitate the identification of drift or biases. SMART cable pressure data will also allow a realistic representation of the ocean's response to atmospheric pressure variations and dispense with oversimplified inverse-barometric model assumptions, especially on short time scales.

4.2 Gravity

Ocean mass changes and redistribution and associated variations in the mass component of sea level and the Earth's gravity field are important key parameters of the climate system and have been observed by the satellite gravity mission GRACE since 2002. However, due to limitations of resolution in time and space, short-term processes aliasing into the satellite data have to be removed within the data processing procedure (Dobslaw et al., 2013). Further complications arise from land-signal-leakage and episodic events, such as undersea earthquakes affecting the spatial distribution of ocean mass. The quality of the resulting de-aliasing and correction products has turned out to be one of the main limitations of current and future gravity field missions (e.g., Panet et al., 2013). Complementary continuous ocean bottom pressure measurements from SMART cable systems will provide valuable information on sub-monthly variability that is presently not resolved by GRACE and can be used as independent constraints for the oceanic component of the background modelling system, e.g., by applying a Kalman filter. Thus, the observations of short-term ocean bottom pressure variability will not only be an important ground-truth of remotely sensed gravity fields, but are also expected to substantially improve de-aliasing and correction products, separation of non-ocean gravity signals, and, thus, final global gravity fields derived from ongoing and future gravity field missions.

As mentioned in Section 2, satellite altimetry and gravity with the *in situ*, basin spanning SMART measurements is an extremely powerful combination for observing the ocean.

4.3 Surface waves

Future satellite missions, such as the NASA/CNES SWOT mission, will include wide-swath altimetry to sample meso- and submesoscale ocean surface features. Infragravity (IG) wave amplitudes have been shown to be large enough in some regions to significantly contribute to the error budget of these future altimetry missions (Aucan and Ardhuin, 2013). SMART cable pressure data combined with IG modeling (Ardhuin et al., 2014; Rawat et al., 2014) will improve our ability to remove this IG wave signal from altimetry data.

Opposing swell or wave trains that can be of different origins causes microseism-generating pressure signals. These high frequency signals undergo little attenuation with depth and can be recorded by seafloor pressure sensors. In the future, the pressure data from SMART cable systems may be inverted into individual swell or wave trains and assimilated into operational wave models.

4.4 Tides

Although tidal forcing is precisely known, there is still much to learn even about the variability of barotropic tides. Recent results show that barotropic tides vary on seasonal and secular timescales. SMART cable measurements of pressure would allow unique quantification of barotropic tidal variability over a wide range of timescales, thus yielding ground truth for seasonal and secular changes to tidal correction models used in altimetry applications.

To determine expected improvements from SMART cables, bottom pressure can be sampled at hourly intervals along cable paths using high-resolution global ocean models that are forced simultaneously by atmospheric fields and astronomical tidal potential (Arbic et al., 2010, 2012; Müller et al., 2012, 2014; Menemenlis et al., in preparation). From these simulations we can quantify the seasonal variability of barotropic tides to demonstrate the signals that the SMART cables will be uniquely capable of measuring. For example, the amplitude of the seasonal variability of the principal lunar semi-diurnal tide M2, in cm, is given in Fig. 5. The range is from 0 to 5 mm, very significant in this context.

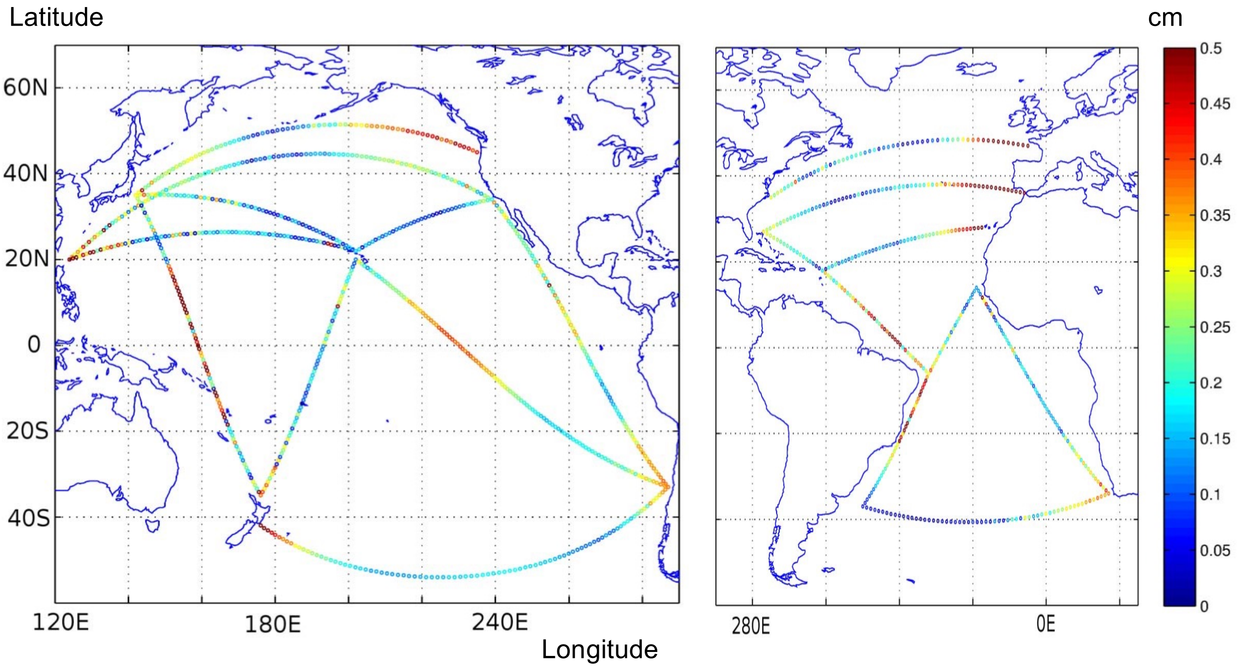


Figure 5. Seasonal amplitude (cm) of the principal lunar semi-diurnal tide M_2 *along cable routes, sampled along cable routes in the Pacific and Atlantic from the STORMTIDE model forced by both atmospheric fields and the astronomical tidal potential (Müller et al., 2014). Courtesy Malte Müller.*

4.5 Ocean surface vector wind stress

Ocean surface wind stress is a key driver of large-scale ocean circulation. For this reason, several satellite-borne instruments have been developed and deployed that are capable of inferring ocean wind stress using passive (microwave) and active (scatterometer) instruments. Because direct observations of ocean wind stress are sparse, however, the satellite observations of wind stress are calibrated using vector wind observations and atmospheric weather model analyses. Ocean bottom observations could provide an alternative methodology for evaluating and improving measurement functions for microwave and scatterometer observations of surface wind stress. For example, Petrick et al. (2014) show that low-frequency ocean bottom pressure variability observed by GRACE in the North Pacific is approximately explained by a local Sverdrup balance, relating the time-variable mass transport to changes of the vertical component of the wind stress curl. At periods away from the seasonal cycle, such signals are particularly prominent at moderate latitudes as, for example, in the western subtropical North Pacific. Petrick et al. (2014) conclude that GRACE-based ocean bottom pressure observations provide integrated information about atmospheric surface pressure and wind stress. A basin-scale array of bottom pressure sensors combined with a suitable inversion system, such as the Estimating the Circulation and Climate of the Ocean (ECCO) consortium, may contain useful information for evaluating and calibrating satellite-borne observations of surface wind stress.

4.6 Ocean temperature observations

Deep ocean temperature observations are currently extremely limited in space and time. From the limited ship based repeat hydrography we know that the global deep ocean is currently warming at an average rate of ~5 m °C per decade, with the strongest (order 50 decade) magnitudes found in the Southern Ocean. After 5-10 years, the deep SMART cable temperature sensors should be able to detect any decadal temperature changes in the deep ocean, supplementing the other deep observing systems with the only long-term high temporal resolution deep ocean temperature record and contribute to more accurate estimates of deep ocean heat content and steric sea level rise.

In addition to the long-term climate trends, the deep observations will offer a unique look at local deep temporal variability. At a given location in the ocean, local fluctuations in temperature are dominated by vertically homogenous isotherm heave from passing eddies, tides, and shifting fronts. Therefore, temperature measurements at the single depth at the bottom can provide accurate information about horizontal and temporal variability throughout much of the deep ocean. Using the high temporal sampling of ocean bottom temperature collected along transocean bottom cables throughout the world, it will now be possible to evaluate high to low frequency variability at many locations throughout the global ocean.

4.7 Ocean circulation

4.7.1 Large-scale ocean volume transport

Through the topics discussed above, bottom pressure and temperature from SMART cables will advance our understanding of large-scale ocean circulation. The bottom measurements will provide estimates of barotropic flow and deep advective-diffusive balance, related to overturning circulation, temperature content, and mass redistribution in the ocean. The cables will also sample along continental slope boundaries and provide insight into intensified boundary currents, mixing, and boundary processes. Indirectly, improvements in altimetric and gravimetric satellite products through better tidal and high-frequency corrections will translate into more accurate low-frequency circulation from surface geostrophic velocities and horizontal pressure gradients. Thus, even though they are point measurements along a line, SMART cable measurements will improve our understanding of global circulation.

4.7.2 Ocean state estimation

The ECCO project makes available simulations and inversions of global ocean circulation, as well as modeling and data assimilation infrastructure, that can be used to explore and articulate the impact of cabled ocean-bottom observations on physical and biogeochemical oceanography. The most recent ECCO inversion is the so-called version 4 (v4), which is on a grid with 40-110 km horizontal spacing for the period 1992-2011 (Forget et al., 2015). A slightly older solution, GECCO2, is also obtained on a grid with 40-110 km horizontal spacing but spans a longer 1948-2013 period (Köhl, 2015). A third inversion is currently underway on a grid with 14-36 km horizontal grid spacing for the period 2001-present with a focus on polar regions (Fenty et al., submitted). These three ECCO inversions are obtained using the adjoint method to constrain the model with a wide variety of satellite (e.g., altimetry and sea surface temperature) and *in situ* (e.g., Argo profiling floats and Conductivity, Temperature, and Depth sensors) observations. A distinguishing feature of ECCO inversions is that water properties are conserved for the complete period of data assimilation, which makes them suitable for climate science and other studies that require closed budgets, e.g., ocean biogeochemistry. The ECCO solutions have previously been used to study thermal changes in the abyssal ocean (Wunsch and Heimbach, 2014) and bottom pressure variability (Piecuch et al., 2015).

The ECCO project also makes available high-resolution (1-2 km, 2-4 km, and 3-9 km horizontal spacing and 90 vertical levels) simulations that include tides and atmospheric pressure forcing.

These simulations, although not constrained by ocean observations, are particularly well suited to study the role of tides in large-scale ocean circulation (e.g., Flexas et al., 2015). Full 3-dimensional model fields have been saved at hourly intervals, which make these simulations a remarkable resource for studying ocean processes and simulating satellite and *in situ* observing systems. Preliminary results are extracted from this model for a hypothetical cable in the western Pacific (Fig. 6) and for comparison with DART bottom temperature off of the Aleutians (Fig. 7). Shown in Fig. 6 are changes from November to December 2011 of (top) bottom pressure, (upper middle) sea surface height, (lower middle) bottom temperature, and (bottom) depth-averaged temperature. The change in bottom pressure (top) are large scale, indicative of atmospheric causes. The sea surface height and depth averaged temperature are correlated. Though the low-frequency temperature range is comparable (5 mK for DART data, 3 mK for model, Fig. 7), the model variability is much too low at tidal frequencies. This is thought to be caused by mismatched representation of bottom slopes and topographic roughness.

The above ECCO inversions and simulations can be used as ocean truth for a cable mission simulator and to carry out Observation System Simulation Experiments (OSSE). Additionally, the ECCO modeling and estimation infrastructure can be used to evaluate the impact of simulated ocean bottom observations on the estimation of large-scale ocean circulation. In a first step to evaluate the impact of cable observations (bottom pressure and temperature, etc.), we could use one year of the llc2160 simulation as ocean truth, sample it at the locations and times of existing ocean observations for that year, and carry out an inversion using the ECCO v4 ocean state estimation system. In a second step we would add notional cable observations and repeat the ECCO v4 inversion. We could then evaluate the impact of adding the cabled ocean bottom observations on this inversion against the known ocean "truth". In this way we would be able to quantify the impact of these proposed observations on ECCO v4 ocean state estimates. We expect that the main impact would be in the accuracy of the abyssal solution, below the 2000-m threshold of the Argo profiling floats. We also expect some improvement in the high-frequency barotropic response of the solution from the bottom pressure observations.

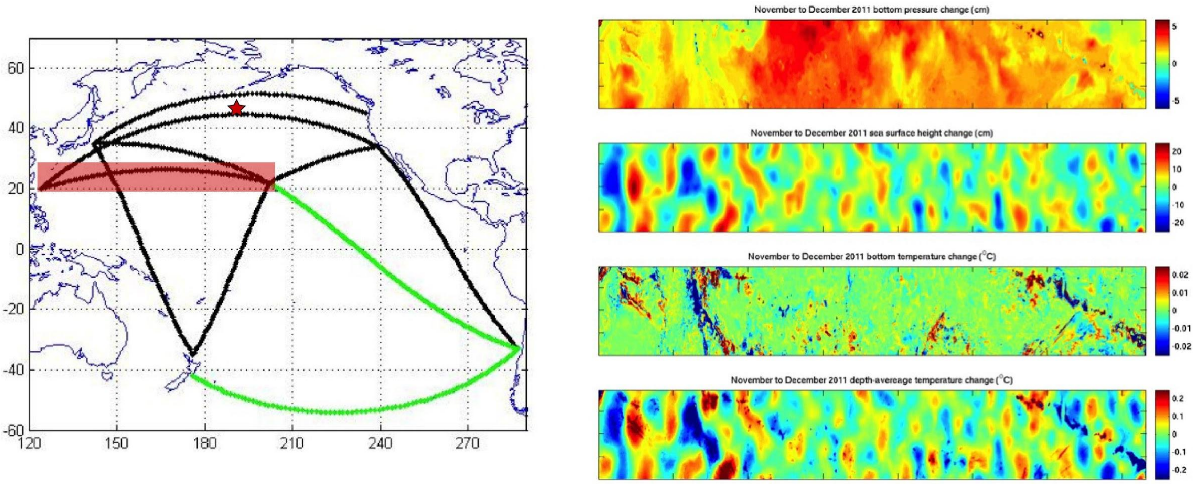


Figure 6. (left) A cable route in the western Pacific. The red box indicates the region extracted in the right, while the star indicates the location of the DART data shown in Fig. 7. (right) Output from the llc4320 run of the MITGCM.

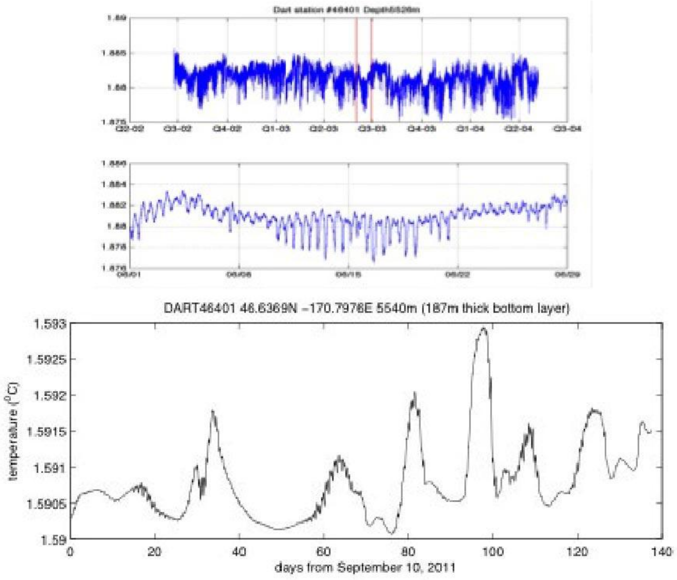


Figure 7. Record from a DART bottom temperature sensor located south of the Aleutians at a depth of 5500 m (see star in Fig. 6, left), over an interval of (top) 2 years and (middle) 4 weeks. (bottom) Bottom temperature from the llc4320 run of the MITGCM at the same location over a 3.5-month period.

5 Concluding Remarks and Recommendations

SMART cables will act as a new cost-effective component of the earth observing system that sample at a range of time and length scales not currently provided by other sampling networks (Fig. 4). 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 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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7 Appendices

7.1 Workshop Agendas

7.1.1 Workshop 1, 9-10 October 2014

NASA Workshop
From space to the deep seafloor:
Using “Green” submarine cable systems in the ocean observing system
9 – 10 October 2014
Keck Center, California Institute of Technology (CalTech)
Pasadena, California USA

Agenda

Thursday 9 October

0800 – 0845	Check in and breakfast
0845 – 0915	Welcome JPL – Ichiro Fukumori NASA – Eric Lindstrom Introductions – Bruce Howe
0915 – 0945	Overview of the Green cable system concept, and charge to workshop – Bruce Howe
0945 – 1020	Ocean science with green cables – Doug Luther
1020 – 1055	Break
1055 – 1130	Deep ocean dynamics, pressure, tides and sea level – Chris Hughes
1130 – 1205	Deep temperature and salinity – Greg Johnson
1205 – 1305	Lunch
1305 – 1340	Time-variable gravity signals over the ocean and connection to ocean dynamics – Felix Landerer and Carman Boening
1340 – 1415	Ocean mass redistribution – Maik Thomas
1415 – 1450	Modeling and data assimilation – Patrick Heimbach
1450 – 1520	Break

Workshop tasks

1520 – 1530	Review Tasks – Bruce Howe (moderator, rapporteur)
1530 – 1600	Task 1 – Janet Sprintall, Shane Elipot – What is the overall scientific value of the measurements (baseline and future) as reflected in the oceanographic and other quantities that can be estimated? Recommend system modifications if appropriate. Recommend future sensors and system elements, with priorities.
1600 – 1630	Task 2 – Steve Jayne, Brian Dushaw – How can such observations and quantities derived therefrom be best used in a “forward problem” sense to validate conceptual models, expected patterns, ocean models and satellite/other data, from initial sparse spatial sampling to an ultimately dense, continuing coverage. Recommend specific short (6-month, i.e., accomplish before next meeting) and long term analyses as appropriate.
1630 – 1700	Task 3 – Dimitris Mememenlis, Ben Loveday – What observing system simulation/sensitivity experiments in an “inverse problem” sense can best guide system development, and demonstrate the value of the data. Recommend specific short (6-month) and long term experiments, e.g., to work toward a “cable mission simulator”.
1830	Drinks and Dinner

Friday, 10 October

0800 – 0830	Breakfast
0830 – 0930	Task 1 – Janet Sprintall, Shane Elipot – summarize, continue discussion
0930 – 1030	Task 2 – Steve Jayne, Brian Dushaw – summarize, continue discussion
1030 – 1100	Break
1100 – 1200	Task 3 – Dimitris Mememenlis, Ben Loveday – summarize, continue discussion
1200 – 1300	Lunch
1300 – 1445	Writing
1445 – 1530	Brief presentations on each task Plan reports, tasks, next workshop meeting in Honolulu, May/June
1530	Close the meeting, snacks Write meeting summary and presentation for Singapore Drinks and dinner

7.1.2 Workshop 2, 26-28 May 2015

NASA Workshop
From space to the deep seafloor:
Using “Green” submarine cable systems in the ocean observing system
26 – 28 May 2015
East–West Center, University of Hawaii at Manoa
Honolulu, Hawaii USA

Agenda

Tuesday 26 May

0830 – 0900	Check in, coffee
0900 – 0915	Welcome Introductions – Bruce Howe
0915 – 0945	Review of the Green cable system concept, charge to workshop – Bruce Howe
0945 – 1015	Deep ocean warming trends and ocean observing – Sarah Purkey
1015 – 1045	Ocean mass transport from cable voltage – Zoli Szuts
1045 – 1115	Break
1115 – 1145	Probing the ocean from the bottom using acoustic signals – Jae-Hun Park
1145 – 1215	Ocean remote sensing using acoustics – Bruce Howe
1215 – 1315	Lunch
1315 – 1345	Possibilities for using new Pacific Island cables – Jerome Aucan
1345 – 1415	Tsunami observing, generation and probabilistic assessment – Gerard Fryer
1415 – 1445	Temperature, pressure, infragravity waves and microseisms – Jerome Aucan
1445 – 1515	Break
1515 – 1545	Long-term and seasonal changes of ocean tides, and internal wave frequency-wavenumber spectra – Brian Arbic with Malte Muller
1545 – 1615	Model temperature and pressure along cable routes – Dimitris Memenlis
1615 – 1700	General discussion, wrap-up, preview tomorrow
1830	Drinks and Dinner

Wednesday, 27 May

0830 – 0900	Coffee
0900 – 0930	Review yesterday, Groups’ previous findings, renew charge – Bruce Howe
0930 – 1000	Task 1 – Shane Elipot – What is the overall scientific value of the measurements (baseline and future) as reflected in the oceanographic and other quantities that can be estimated? Recommend system modifications if appropriate. Recommend future sensors and system elements, with priorities. Review and

	update from October workshop, e.g., including new science, additional measurements.
1030 – 1100	Break
1100 – 1130	Task 2 – Steve Jayne – How can such observations and quantities derived therefrom be best used in a “forward problem” sense to validate conceptual models, expected patterns, ocean models and satellite/other data, from initial sparse spatial sampling to an ultimately dense, continuing coverage. Recommend specific short- and long-term analyses as appropriate. Review and update from October workshop, and incorporate results presented here.
1130 – 1200	Task 3 – Dimitris Memementlis – What observing system simulation/sensitivity experiments can best guide system development, and demonstrate the value of the data. Recommend specific short (6-month) and long term experiments, e.g., to work toward a “cable mission simulator”. Review and update from October workshop, and incorporate results presented here.
1200 – 1300	Lunch
1300 – 1500	Breakout groups for each task meet, write and summarize
1500 – 1530	Break
1530 – 1630	Presentations and discussion on each task
1630 – 1700	Outline workshop report and papers/articles – Bruce Howe
1700	Close the full meeting
1830	Drinks and dinner

Thursday, 28 May

For those staying on, writing all day.
Finalize Workshop 1 Report; produce similar for Workshop 2
Synthesize results from both workshops to produce one combined report for broader distribution

Products:
“Standard” workshop report
Eos project update article (1100 words, 1 figure) report
Viewgraph presentation ~ SMART Seafloor cable systems supporting NASA earth observing
Nature or Science 1 page news article

1200 – 1300	Lunch
Continue	
1600	Close

7.2 List of Workshop Participants

Name and E-mail	**Affiliation**	**Expertise**
Brian Arbic <arbic@umich.edu>	University of Michigan, USA	Ocean modeling all scales, compare with *in situ*
Jerome Aucan <jerome.aucan@ird.fr>	IRD-LEGOS, France	Physical oceanography, tides, bottom pressure, tsunamis
Carmen Boening <Carmen.Boening@jpl.nasa.gov>	JPL, USA	Ocean/climate interactions, sea level, GRACE
Rhett Butler <rhett@soest.hawaii.edu>	University of Hawaii, USA	Cable systems for science
Glenn Carter <gscarter@hawaii.edu>	University of Hawaii, USA	Ocean mixing, internal tides
Bruce Cornuelle <bdc@ucsd.edu>	SIO-UCSD, USA	Ocean modeling and data assimilation
Fred Duennebier <fred@soest.hawaii.edu>	University of Hawaii, USA	Geophysics and cable systems
Brian Dushaw <dushaw@apl.washington.edu>	APL-UW, USA	Ocean tides, acoustical oceanography
Shane Elipot <selipot@rsmas.miami.edu>	RSMAS, USA	Meridional overturning circulation, RAPID
Gerard Fryer <gerard.fryer@noaa.gov>	NOAA_PTWC, USA	Tsunami monitoring and modeling
Ichiro Fukumori <fukumori@jpl.nasa.gov>	JPL, USA	Ocean modeling and data assimilation
Patrick Heimbach <heimbach@mit.edu>	MIT, USA	Ocean modeling
Bruce M. Howe <bhowe@hawaii.edu>	University of Hawaii, USA	Physical oceanography, cabled ocean observatories
Christopher W. Hughes <cwh@noc.ac.uk>	National Oceanography Center, UK	Sea level, deep-ocean dynamics, gravity
Steve Jayne <sjayne@whoi.edu>	WHOI, USA	Ocean modeling and data assimilation
Greg Johnson <gregory.c.johnson@noaa.gov>	PMEL, NOAA, USA	Ocean circulation
Young Ho Kim <yhkim@kiost.ac>	KIOST, South Korea	ocean circulation modeling and data assimilation
Felix Landerer <landerer@jpl.nasa.gov>	JPL, USA	Time-variable gravity, dynamic sea level

Eric Lindstrom <eric.j.lindstrom@nasa.gov>	NASA	Oceanography
Ben Loveday <ben@saeon.ac.za>	SAEON, South Africa	Numerical modeling, regional to basin-scale oceanography,
Doug Luther <dluther@hawaii.edu>	University of Hawaii, USA	Physical oceanography, tides, bottom pressure
Dimitris Menemenlis <menemenlis@jpl.nasa.gov>	JPL, USA	Ocean modeling and data assimilation
Karynne Morgan <karynnem@hawaii.edu>	University of Hawaii, USA	Project support
Malte Muller <maltem@met.no>	Norwegian Meteorological Institute	Ocean modeling; participated remotely and provided data for Fig. 5
Jae-Hun Park <jhpark@kiost.ac>	KIOST, Korea	Physical oceanography, bottom pressure,
Brian Powell <powellb@hawaii.edu>	University of Hawaii, USA	Ocean modeling and data assimilation
Sarah Purkey <purkeysg@uw.edu>	University of Washington, USA	Abyssal ocean circulation
Hanne Sagen <hanne.sagen@nersc.no>	Nansen Center, Norway	Polar oceanography and observing systems
Janet Sprintall <jsprintall@ucsd.edu>	SIO, UCSD	Physical oceanography and observing network design
Tony Song <yuhe.t.song@jpl.nasa.gov>	JPL, USA	Ocean modeling and tsunamis
Zoli Szuts <zszuts@apl.washington.edu>	APL-UW, USA	Ocean transport, electromagnetic measurements
Maik Thomas <maik.thomas@gfz-potsdam.de>	GFZ Potsdam, Germany	Earth System Modeling, gravity, ocean circulation
Andrew Thompson <andrewt@caltech.edu>	CalTech, USA	Ocean observations and modeling
Victor Zlotnicki <Victor.Zlotnicki@jpl.nasa.gov>	JPL, USA	Satellite altimetry and gravity

Workshop attendees, 9 – 10 October 2014, Keck Center, California Institute of Technology

7.3 Presentation abstracts

7.3.1 Review of the green cable system concept, and charge to workshops

Bruce Howe*, School of Ocean and Earth Science and Technology, University of Hawaii, USA*

Improving our understanding and estimation of ocean circulation and climate and earthquake and tsunami warning are the motivation for using commercial submarine telecom cable systems to host science instrumentation. In this workshop, the primary focus of this workshop is ocean circulation and climate; a secondary focus is tsunamis. At the most basic level and in the nearer-term, pressure, temperature, and acceleration sensors would be integrated into new cable systems (likely in the optical amplifier repeater housings spaced every ~50 km). The global ocean-spanning telecommunications infrastructure continues to be upgraded and expanded, driven by the ever-increasing demand for connectivity. New systems are being installed on new routes, e.g., in the Arctic connecting Tokyo and London, and in the Pacific connecting Hawaii with Panama and the west coast of South America. There is general recognition that more geographical diversity is required in the global system to assure a robust, resilient system. As new systems are installed on 10-20 years cycles (> 1 Gm, 20,000 repeaters) a substantial coverage over the globe can be achieved. In the farther future, additional instruments including active and passive acoustics (wind, rain, mammals, heat content, along-cable velocity) and cable voltage (cross-cable velocity) could play a role. The UN ITU/WMO/IOC Joint Task Force (JTF) charged with promoting this concept is described. The charge of the workshop is to explore and make recommendations on the science and the quantification of benefits.

ITU References

- Joint Task Force http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx
- Call for Action http://www.itu.int/dms_pub/itu-t/oth/4B/04/T4B0400000D0001PDFE.pdf
- Joint Task Force Members
- http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Documents/JTF_Members.pdf

Workshops as part of ITU Green Weeks:
- “Submarine Cables for Ocean/Climate Monitoring and Disaster Warning: Science,
- Engineering, Business and Law”
- 2011, Rome, http://www.itu.int/ITU-T/climatechange/gsw/201102/programme.html
- 2012, Paris, www.itu.int/ITU-T/climatechange/gsw/201209/programme-009.html
- 2013, Madrid, http://www.itu.int/en/ITU-T/Workshops-and-Seminars/gsw/201309/Pages/programme-19-20-Sep.aspx

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- Engineering, P. Phibbs and S. Lentz, 2012. http://www.itu.int/dms_pub/itut/oth/4B/04/T4B040000170001PDFE.pdf
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- The Scientific and Societal Case for the Integration of Environmental Sensors into New Submarine Telecommunication Cables, Butler et al. 2014. http://www.itu.int/dms_pub/itu-t/opb/tut/T-TUT-ICT-2014-03-PDF-E.pdf
- Scope document and budgetary cost estimate for a wet test to demonstrate the feasibility of installing sensors external to the repeater and to provide data from such sensors for evaluation
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- Functional requirements of "green" submarine cable systems http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Documents/Functional-requirements-2015-05.pdf
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7.3.2 Why telecom cables are good for everything

Doug Luther, *School of Ocean and Earth Science and Technology, University of Hawaii, USA*

Oceanographic sensors and sensor ports integrated into transoceanic telecommunications cables have the potential both to fill important gaps in the current ocean observing system and to establish new paradigms of ocean observing. The deep ocean beneath the directly wind-forced layers of the upper ocean is woefully under-observed, yet it is the flywheel for heat and chemical (e.g., CO2) variability in the climate system. Simple sensors, such as temperature and pressure, integrated into cables will detect important regional changes in the deep waters as well as help discriminate the causes—such as steric versus mass loading—of local sea level rise when combined with satellite observations. Sensor ports at each cable repeater open up the possibility of deploying arrays of proven sensors that can sense the heat content (e.g., Inverted Echo Sounder) and water flow (e.g., Horizontal Electrometer) of the entire water column, enabling unprecedented high-resolution observations of poleward heat and mass fluxes over long periods of time across entire basins. However, these rosy possibilities are tempered with significant geographic and technical caveats. Geographically, the vast majority of telecommunications cables are in the Northern Hemisphere oceans, so, for example, the deepest waters in the Southern Hemisphere, which are warming faster compared to the Northern Hemisphere, will not be well covered by cable-borne sensors. Integrated sensors will also have to be small and self-calibrating, which is well within reach of current technologies but has not yet been achieved.

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7.3.3 Deep ocean dynamics, pressure, tides and sea level

Chris Hughes, *School of Environmental Sciences, University of Liverpool, and National Oceanography Centre, Liverpool, UK*

Observing large spatial scales on long time scales in the ocean is difficult because of the dominance in most regions of eddies and stochastic variability. However, it is important because it is in the slow evolution of integrated properties that the ocean's influence on climate is most important. Satellite observations avoid some of these issues by integrating over the eddy field, but only at the surface. Other observing systems are limited in sampling and resolution. In order to monitor these scales in the deep ocean, we must focus on variables that integrate, such as bottom pressure, and regions where eddy signals do not dominate, such as the tropics and the steep continental slope regions. In the tropics, we find in models that the interannual dynamical variability is so small that pressure measurements are effectively a measure of changing global ocean mass, and in fact we have been able to use bottom pressure time series to measure the annual cycle in ocean mass. On the continental slopes, geostrophic balance integrated zonally across ocean basins means that bottom pressure measurements allow us to determine variations in the meridional overturning circulation. Both of these techniques are limited by the instrumental drift characteristics of bottom pressure recorders, a problem that is mitigated by longer, uninterrupted time series such as could be provided by cable measurements, although a linear trend error is likely to remain. On the continental slope it is possible to avoid this drift problem by indirectly inferring pressure changes from near bottom current and density measurements. Such measurements would also be of great interest for understanding boundary layer processes on the continental slope. By sampling the continental slope, cable measurements have the potential to fill a major gap in the global ocean observing system, which presently includes very few measurements in this dynamically important region. Spatial resolution may be a problem, with the slope region typically being 50-100 km wide, and cable repeater spacing at about 50 km. This may be mitigated where multiple cables cross the same continental slope region, if the repeaters fall at different depths in each case.

7.3.4 Deep ocean temperature and salinity

Gregory C. Johnson, *NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, USA*

Global observations of deep ocean temperature and salinity (T-S) are presently limited to resurveys of a small set of key full-depth coast-to-coast oceanographic sections, most of them at decadal intervals, although some more frequently. There are also localized data from a few long-standing time series (HOT and BATS) and data from many local moored arrays, with most of those only maintained for a year or two. OceanSITES is working to put deep T-S sensors on many of their moorings, which would presumably be maintained for a long time, but that activity is just beginning, and moorings are very widely spaced. Deep Argo is also in pilot stages, but will hopefully become global over the next decade.

The abyssal ocean T-S properties are set by the meridional overturning circulations, involving both North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). Abyssal temperatures and salinities have been changing in both the North Atlantic and Southern Ocean, at rates ranging between 0.1 and 0.03 ºC per decade, with smaller variations at increasing distances from the origins of these water masses. In addition, there are abyssal salinity changes near the source regions for these waters on the order of 0.01 PSS-78 per decade. These changes are potentially important for sea level and global energy budgets, and reflect changes in the global meridional overturning circulations.

While cable measurements would not be global, they would afford abyssal T-S sensors at very high temporal resolution (seconds vs. 10-30 days for Deep Argo floats, and decades for ship-based surveys) and comparatively high spatial resolution (55 km along the cables, about the same spacing as for oceanographic sections, but 10 times better resolved than likely distances between Deep Argo floats). The North Atlantic and Arctic regions would have strong signals, but even the more remote cables would probably see decadal signals that would rise above instrumental accuracies.

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7.3.5 Time-variable gravity signals over ocean and connection to ocean dynamics

Felix Landerer, Carman Boening, Michael Watkins, David Wiese, Ichiro Fukumori, Victor Zlotnicki, *JPL, Pasadena, CA, USA*

Time-variable gravity signals over the ocean are largely reflections of ocean bottom pressure variations, which in turn are primarily connected to barotropic ocean circulation changes, and to a lesser degree baroclinic ocean dynamics. Bottom pressure measurements allow retrievals of, for instance, the Antarctic Circumpolar Current, Meridional Overturning Circulation, and low-latitude planetary waves. Measurements from the Gravity Recovery and Climate Experiment (GRACE) of associated gravity changes thus provide unique observations of these features at monthly time scales. The typical signal amplitudes range from millimeters to several centimeters of water-equivalent-height. A major challenge for GRACE ocean measurements is the lower signal-to-noise ratio compared to land-hydrology signals, and the high-frequency aliasing of sub-monthly variability into the monthly gravity fields. To account for the sub-monthly variability, ocean-atmosphere models are employed to model and remove these signals from the GRACE measurements. While the current GRACE instrument noise is still a dominating error source, future measurement systems (e.g., equipped with a laser ranging instrument and more precise accelerometers) will likely increase this accuracy to an extent that sub-monthly aliasing model errors/uncertainties can become the limiting factor for monthly gravity estimates. Thus, improving estimates of sub-monthly ocean bottom pressure variability over medium-to-large spatial scales (i.e., through 50-100 km sampling at the sea floor) has the potential to improve satellite gravimetry estimates of surface mass changes. However, the sub-monthly bottom pressure improvements will likely have to have near-global reach to significantly improve a global gravity field estimate. As gravity is a potential field, regional improvements over the ocean can positively impact signal retrievals elsewhere such as over land, ice-covered regions by reducing aliasing effects. In addition, continuous ocean bottom pressure measurements are extremely useful for validation of satellite gravimetry measurements (no such analogue exists over land). Of particular value in this regard would be stable long-term (monthly to interannual) bottom pressure measurements, especially in the southern ocean. It would also be useful to compare the gravimetric estimate of the total ocean mass with BPRs deployed in the central tropical Pacific Ocean.

7.3.6 Ocean mass redistribution

Maik Thomas, *Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany*

Recent satellite gravity missions, such as CHAMP, GRACE, and GOCE, provide measurements of vertically integrated global mass redistribution with unprecedented accuracy. However, due to restrictions concerning resolution in time and space, short-term processes aliasing into the satellite data have to be removed within the data processing procedure (Dobslaw et al., 2013). The quality of the resulting de-aliasing products is one of the main limitations of current and future gravity field missions (e.g., Panet et al., 2013). Additional complementary ocean bottom pressure sensors integrated into commercial submarine cable systems will be an important ground-truth of remotely sensed gravity fields. The sensors would also substantially improve de-aliasing products for ongoing and future gravity field missions and provide a valuable future component for the Global Geodetic Observing System (GGOS, Plag and Pearlman, 2009). On the other hand, additional arrays of *in situ* ocean bottom pressure measurements at intervals of

50-70 km will allow reliable quantifications of climate relevant water mass transports (Bergmann and Dobslaw, 2012) and eustatic sea level change (Bergmann-Wolf et al., 2014), the detection of mesoscale ocean mass variability related to, e.g., mesoscale eddies (Kuhlmann et al., 2013), and a consistent integration of various Earth monitoring products.

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7.3.7 Model-data synthesis: an ECCO perspective

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7.3.8 Deep ocean warming trends and ocean observing

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Here, I present the current state of knowledge on the temporal and spatial variability of deep ocean temperature trends since the 1990s and assess possible additions the deep Green Cable observing system will add to our current understanding of the deep warming trend. Deep ocean warming rates between the 1990s and 2000s are estimated using full-depth, high-quality hydrographic sections that have been occupied two or more times between 1980 and the present: usually first by the World Ocean Circulation Experiment (WOCE) Hydrographic Program (mostly after 1990) and more recently by various international repeat hydrographic surveys in support of CLIVAR and carbon cycle science. Regional warming rates and their uncertainty are estimated within 32 deep basins show a strong abyssal warming trend throughout the deep Southern Ocean (below 1000 m), with an abyssal (below 4000 m) warming signal that weakens northward in the central Pacific, western Atlantic, and eastern Indian Oceans. Basins in the eastern Atlantic and western Indian Oceans show cooling trends. We suggest that the deep warming originates from the Southern Ocean as changes in the Antarctic Bottom Water (AABW) propagate around the globe, mostly through isotherm heave (Masuda et al., 2010). The isotherm heave is equivalent to a volume loss of water below 0 °C at a rate of -8.2 (+/-2.6) Sv in the Southern Ocean. Lesser deep losses of AABW are also seen along three of the four northward outflow routes of AABW, suggesting a global scale slowdown of the bottom limb of the Meridional Overturning Circulation (MOC) seen as a deep ocean warming on isobars. At present, limited data allows only for estimates of decadal linear trends in the deep warming rate on basin wide scales. Continued monitoring of the ocean bottom temperature along transocean cables will add to this previous work in three ways. First, it will allow for local studies of deep flow within basins. For example, a recent mooring study as station ALOHA north of Hawaii, showed high temporal variability in deep ocean owing to episodic flow over ridges (Alford et al., 2011). Second, the green cable observing system will allow for better temporal and spatial evaluation of variability for estimates of the spatial and temporal length scales in the deep ocean. Third, on long time scales the array may be able to detect the long-term decadal warming trend observed with the repeat hydrography and better temporal resolution.

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7.3.9 Ocean mass transport from cable voltage

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Conductive seawater moving through the earth's magnetic field generates horizontal electric fields proportional to depth-averaged velocity (Sanford, 1971; Chave and Luther, 1990), which are integrated along cables to give a voltage that is closely related to the volume transport across the cable. Present understanding of interpreting motional induction (Szuts, 2012) and the proposed design of SMART cables (Lentz and Phibbs, 2012) will allow accurate transport measurements at spatial and temporal scales that were previously inaccessible. With voltages measured between repeaters 50 km apart, voltages measure the mean and variable parts of ocean mesoscale circulation including tsunamis (Sugioka et al., 2014), barotropic waves, tides, eddies and low-frequency circulation changes. The measurement requires a highly precise voltmeter (accurate to 1-10 mV) that measures the potential between the inner conductive cable elements (which is powered) and an external electrode (that carries no current). Though there are a number of sources of noise and bias (Szuts, 2012), these uncertainties are clearly identified and can be accounted for with an expected accuracy of 10% in the open ocean. Some past difficulties interpreting historic cable voltages (Larsen and Sanford, 1985; Meinen et al., 2010) are eliminated by the design of SMART cables. First order factors can be estimated from independent data sets, either hydrographic data for the time-varying factor (Chave and Luther, 1990, Szuts and Sanford, 2013a), or from geological databases of sediment thickness (Laske and Masters, 1997) with conductivity models (Flosadottir et al., 1997) for the spatially-variable constant factor. Higher order errors near steep topography (Szuts, 2010b) are isolated to specific segments that can be excluded from analysis. External ionospheric noise can be removed by low-pass filtering. In general, the 50 km distance between repeaters will resolve oceanic decorrelation scales and maximize the oceanic signal-to-noise ratio. Further accuracy is obtained by joint interpretation with other measurements, such as co-located bottom pressure on SMART cables (Butler et al., 2014) or data from other observation networks (SSH, GRACE, or Argo). Such continuous transport measurements from cable voltages spanning ocean basins meet a need for increased sampling of ocean velocity, especially at depth (Garzoli et al., 2010), and will greatly improve our knowledge of full-depth ocean circulation, its variability, and its drivers.

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7.3.10 Probing the ocean from the bottom using acoustic signals

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Arrays of pressure-recording inverted echo sounders (PIESs) have been deployed around the global ocean during the last 30 years. Some of them were located under the ground tracks of satellite altimeters. The PIES measures bottom pressure and round-trip acoustic travel time from the seafloor to the sea surface. The bottom pressure and travel time measurements can be used to estimate the mass-loading and steric height variations in sea surface height (SSH), respectively. The simultaneous measurements of mass-loading and steric SSH provide opportunities to evaluate the satellite altimetry measurements in several areas. The comparisons between satellite-measured SSH and PIES-derived SSH revealed site-to-site feature differences of mesoscale variability that affected the mismatches between the two measurements. Overall good correlations are found between along-track and PIES-derived SSH anomalies with mean correlation coefficient of 0.97 in the Kuroshio Extension System Study region. The correlation drops lower than 0.80 for the comparison in the North Equatorial Current region, which seems to be caused by some issues related with corrections for atmospheric effects on satellite altimeter measurements. The scientific benefits anticipated by installing PIES or current-sensor-equipped PIES (CPIES) on the submarine cable systems are as follows: 1) accumulate *in situ* data for evaluation of satellite altimetry and gravimetry; 2) monitor long-term heat content changes for total water column; 3) monitor long-term sea-ice extension and thickness changes in the Arctic Ocean; 4) measure long-term meridional overturning circulation in the Atlantic Ocean; 5) measure internal wave energy changes; and 6) measure deep ocean current variability.

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7.3.11 SMART seafloor cable systems: Acoustical oceanography possibilities

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Many ocean processes can be observed and studied using acoustics (Howe and Miller, 2004; Duda et al., 2006, Dushaw et al., 2010). The most obvious acoustic sensor to add in phase 2 of SMART cables is a passive hydrophone to address wind and rain, surface wave phenomena including infragravity waves, marine animals, ocean circulation and climate, and more (volcanoes, seismic activity, glaciers and ice, and anthropogenic sources such as shipping and oil and gas activities). *In situ* measurement of rainfall on these scales (minutes, averaged over a surface area with diameter five times the water depth) would be invaluable to validate satellite derived rainfall estimates and improving understanding of the ocean hydrological cycle, e.g., Yang et al., 2015. With an active pinger, more can be done with respect to ocean circulation and climate while also serving the infrastructure role of wireless communication, as an acoustic modem to nearby vehicles and instrumentation, and providing navigation beacon signals over ~30 km ranges. Mounting active transducer(s) requiring vertical orientation is possible but will be challenging.

Ocean circulation and climate can be addressed in passive forms using noise interferometry (proof of concept and development needed; Godin et al., 2014) and as receivers in a long-range acoustic thermometry system (assuming sources provided independently, a la ATOC, Dushaw et al., 2009). In the active case, inverted echosounders (IES, typically 12 kHz) provide the top-to-bottom average temperature sampled every ~minute (round trip travel time gives sound speed, almost directly proportional to temperature). The IESs are usually combined with pressure (PIES) and current (CPIES). The latter has either a point sensor or an acoustic Doppler current profiler to provide a velocity reference as well as bottom boundary layer information. These units have been extensively used in dense bottom arrays over the last decades, e.g., in the Kuroshio Extension (Park et al., 2012).

The IESs in adjacent cable repeaters (separated by ~50 km) could “talk” to one another to provide depth averaged temperature and absolute water velocity along the cable (10 km separation has been demonstrated (Tomoyoshi and Taira, 1993; demonstration at ~50 km needed, likely at ~4 kHz). The combination of temperature and velocity (and cross-cable velocity from cable voltage) will provide unique estimates of barotropic momentum and heat fluxes on the cable time (minutes) and space (50 km to basin) scales.

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7.3.12 Possibilities for using new Pacific Island cables

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The installation of pressure, temperature and acceleration sensors in the repeaters of future SMART cables will provide unprecedented insight into several scientific and societal issues.

Real-time, high-frequency seafloor pressure measurements in repeaters will be a significant improvement over the existing DART network.

Infragravity waves (2-20 min period) will contribute to the error budget of planned wide-swath altimetry mission (Aucan and Ardhuin, 2013; Ardhuin et al., 2014; Rawat et al., 2014). SMART cable pressure data and modeling will improve our ability to remove this IG wave signal from altimetry data.

Microseism-generating pressure signals are caused by opposing swell trains. In the future, these signals may be inverted and be assimilated into wave models.

Temperature data collected by the SMART cables will allow the quantification of high frequency bottom temperature variability (hours to weeks) as well as climate-timescales bottom temperature variations (decades).

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Aucan, J., and F. Ardhuin (2013), Infragravity waves in the deep ocean: An upward revision. Geophys. Res. Lett., 40, 3435-3439, doi:10.1002/grl.50321.

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7.3.13 Data needs for tsunami warning

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Tsunami warnings ideally give affected communities the maximum possible time to prepare. The need for speed means that tsunami warnings, initially, are made purely from seismic data. Direct measurements of the tsunami, while intrinsically slower, are still essential, as the tsunami is strongly affected by the shallowest rupture, which is often poorly constrained by seismic, or GPS data. Once direct observations are available, the warning is appropriately modified. At present, direct tsunami measurements are provided by the DART instruments, deep ocean pressure gauges. The DARTs trigger when they feel strong shaking and begin transmitting 1-minute data, though there is a latency of several minutes. The instruments must be deployed significantly seaward of expected source earthquakes (typically 400 km, or about 30 minutes of tsunami travel time) both to avoid constantly being triggered for small events and so running down their batteries, but also to keep the seismic and tsunami signals temporally separated. That large distance makes the current DARTs useless for local warning. Both problems have been addressed in a new design with more rapid sampling and smarter on-board processing. The new design will allow the instruments to be deployed very close to anticipated subduction sources, but that raises an even more fundamental issue: to provide adequate coverage there will have to be at least triple the number of DARTs. With 60 instruments currently in the DART network, keeping them all going is already a challenge, especially since their failure rate is high. Installing and maintaining still more is not feasible.

Pressure gauges on SMART cables could completely supplant the DART network and would offer huge advantages: with instruments at every repeater (every 50 to 200 km), the tsunami would be far better defined than with the current DART spacing of 500 km or more. Further, the higher sampling rate and real-time transmission from the gauges would allow separation of seismic from tsunami signals by simple filtering and would eliminate the 3-5 minute latency currently imposed by communications via the Iridium satellite constellation. In those many places where proposed cables pass very close to trench axes (e.g., the Aleutians), it would be possible to see the tsunami form during the earthquake and so provide very fast warnings.

There is one potentially disastrous problem with the current DART network. The three largest earthquakes ever recorded all exhibited unilateral rupture: rupture starting at one end of the fault and growing in one direction over the entire five to eight minute duration of the earthquake. Each tsunami radiated away from one end of the fault earlier than the other, with the result that the entire tsunami radiation pattern was rotated as much as 12° away from the trench normal. The current DART network is too sparse to detect such behavior, so if a really large earthquake occurs, the current system is likely to overwarn some areas and underwarn others. The denser network possible with cables would eliminate this problem.

Additional advantage of SMART network not included in talk: earthquake location
The accelerometers proposed for the SMART cables will significantly speed up tsunami warning by allowing a more rapid determination of fundamental earthquake parameters. The seismometers currently used to locate earthquakes are all on dry land, which means that earthquake location and depth are too poorly constrained to assess tsunami hazard until earthquake waves reach a distant island seismometer or a seismometer on the far side of the ocean. Accelerometers on the SMART cables will be on the seaward side of the earthquake but at very close range. Accelerometers do not suffer from clipping, so they will return useful information even from within the epicentral region. The record from one or two cabled accelerometers, combined with currently available seismic data, would provide a tightly constrained solution of the earthquake as much as five minutes faster than can currently be accomplished. For a local earthquake, where the tsunami might reach the nearest coast within 20 minutes, this improvement would be very significant.

How to assess the improvements possible with SMART cables
The claims made above can readily be tested by running a variety of simulations. We already have a simple code to work out how quickly the epicenter, depth, and origin time of an earthquake can be determined for an earthquake at a given location and with a given distribution of seismometers. Simply by adding the additional accelerometers locations, the time savings can be determined.

The claims about pressure gauges can be verified by running tsunami forecast models. We can hypothesize a particular earthquake (e.g., with instantaneous rupture or sequential rupture) to produce synthetic DART records, then explore the range of different earthquakes that produce DART records, which are a passable match to the “true” record. If we repeat this procedure with the denser network of cabled pressure gauges, we shall be able to quantify the improvements (to both speed and forecasts) that could be accomplished with the cabled instruments.

7.3.14 Temperature, pressure, infragravity waves and microseisms

Jerome Aucan, *Institut de Recherche pour le Développement-Laboratoire d'Etude en Géophysique et Océanographie Spatiale, France*

The installation of pressure, temperature and acceleration sensors in the repeaters of future SMART cables will provide unprecedented insight into several scientific and societal issues. Real-time, high-frequency seafloor pressure measurements in repeaters will be a significant improvement over the existing DART network.

Infragravity waves (2-20 min period) will contribute to the error budget of planned wide-swath altimetry mission (Aucan and Ardhuin, 2013; Ardhuin et al., 2014; Rawat et al., 2014). SMART cable pressure data and modeling will improve our ability to remove this IG wave signal from altimetry data.

Microseism-generating pressure signals are caused by opposing swell trains. In the future, these signals may be inverted and be assimilated into wave models.
Temperature data collected by the SMART cables will allow the quantification of high frequency bottom temperature variability (hours to weeks) as well as climate-timescales bottom temperature variations (decades).

Ardhuin, F., A. Rawat, and J. Aucan (2014), A numerical model for free infragravity waves: definition and validation at regional and global scales. Ocean Model., 77, 20-32.
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Rawat, A., F. Ardhuin, V. Ballu, W. Crawford, C. Corela, and J. Aucan (2014), Infragravity waves across the oceans. Geophys. Res. Lett., 41, 7957-7963, doi:10.1002/2014GL061604.

7.3.15 Submarine cables for tsunami early detections

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The global submarine telecommunication cables, transmitting the global Internet today, cover the worldwide tsunami prone regions perfectly with denser routines toward populated coastal communities. At every 50 km, a submarine repeater is available and can house multiple ocean-bottom sensors. The observed information can be transmitted in real-time along with the Internet. This network is ideal for real-time monitoring tsunami hazards worldwide. This study aims to demonstrate a strategy and roadmap for using the submarine cables for observing tsunamis effectively. Based on the global GPS-Aided Tsunami Early Detection (GATED) system [Song, 2007], developed at JPL and funded by NASA, we focus on simulations of the 2011 Japanese tsunami as a test case in order to build confidence and to ensure success. The feasibility study uses the existing GATED system of NASA for the tsunami source, a set of predefined submarine cables for observation, and tsunami data for the validation. Our study demonstrated that the dual-use of the submarine cables would do the following.

- Improve near-field early warnings and save lives. Note that most of the tsunami victims are local. The cable sensors of ocean bottom pressure directly estimate seafloor deformation and initial tsunami height, aiming to predict tsunami scales immediately following the earthquake and enabling an early alert to local communities before the tsunami reaches shore [Song et al., 2012].
- Reduce false alarms and increase reliability. To avoid possible bias from the land-based GPS measurements of the earthquake, nearby submarine cable-sensor measurements of tsunami height will be assimilated into the forecast system for rapid confirmation or cancellation of the alert [Xu and Song, 2013].
- Improve understanding of tsunami genesis. Direct measurements of seafloor deformation and tsunami height could be used to determine how tsunamis form and why some earthquakes trigger tsunamis while others with the same magnitude do not [Song and Han, 2011].

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7.3.16 Long-term and seasonal changes of ocean tides, and internal wave frequency-wavenumber spectra

Brian Arbic, *University of Michigan, Ann Arbor, MI, USA*, and Malte Müller, *Norwegian Meteorological Institute, Oslo*

This is a talk divided into two parts:

Long-term and seasonal changes of ocean tides

Because the forcing of ocean tides is known very precisely, tides are an interesting test case of the response of the ocean to climate change on time scales ranging from seasonal to centennial. Tide gauge observations indicate that long-term trends in M2 and other tidal constituents, of order 2% per century, are seen throughout the global ocean. Tide gauge observations and regional models also demonstrate that the tides exhibit measurable seasonal variability. A global model forced by both atmospheric fields and the astronomical tidal potential (Muller et al. 2014), complemented with an analysis of satellite altimeter data, suggests that seasonal variability of the tides is common in the ocean. The tidal seasonal variability appears to be driven by more than one mechanism. In seasonally ice-covered regions, such as Hudson Strait, seasonal variability is associated with larger friction in winter due to frictional damping from ice onto the surface ocean. In other coastal regions, the seasonal variability appears to be driven by intensified stratification in the summer leading to a suppression of eddy viscosity, and a consequent increase in upper ocean tidal velocities leading to an altered tidal elevation signature. The global model also suggests that the open-ocean tides have a seasonal signature. Potential mechanisms for open-ocean tidal variability include a "back-effect" of coastal seasonal signals onto the open-ocean, and changes in open-ocean stratification. Green cable measurements of bottom pressure could help to determine whether this pelagic seasonal tidal variability is present in the real ocean, and provide ground truth for both models and empirical tidal correction models for satellite altimetry. The altimeter tidal correction models currently do not account for seasonal (or secular) variability, but as the altimeter community moves towards more sophisticated instruments such as the wide-swath satellite altimeter, empirical tide models will need to account for such effects. Finally, we note that internal tides exhibit measurable non-stationarity, which reduces their predictability and hence impacts the ability of the wide-swath altimeter to remove tidal "noise" before examination of lower-frequency motions is performed. Inverted echo sounders placed onto green cables would provide ground truth for modeled estimates of internal tide non-stationarity.

Internal wave frequency-wavenumber spectra

Although internal gravity waves (IGW) are the primary mixing agents for the subsurface ocean, modeling of IGWs on a global scale is still a relatively new endeavor. The first global internal tide models, performed without wind forcing and with a simplified uniform background stratification, were published just a decade ago (Arbic et al., 2004; Simmons et al., 2004). With the advent of high-resolution global models that are simultaneously forced by atmospheric fields and the astronomical tidal potential (Arbic et al., 2010; Muller et al., 2012; Dimitris Menemenlis, paper in preparation), the ingredients for the development of an IGW spectrum—near-inertial waves, tides, and nonlinearity—are now present in global models. We show that frequency-wavenumber spectra of IGW kinetic energy fill out along predicted linear dispersion curves, and fill out more completely when model resolution increases. Increased resolution therefore leads to a closer agreement between modeled kinetic energy frequency spectra and spectra taken from current meter measurements. Green cables instrumented with inverted echo sounders would provide an unprecedented opportunity to examine the oceanic frequency-wavenumber spectrum at high frequencies, thus serving as valuable ground truth for models of IGW and other high-frequency motions.

7.3.17 Model temperature and pressure along cable routes

Dimitris Menemenlis, *Jet Propulsion Laboratory, Pasadena, CA, USA*

The Estimating the Circulation and Climate of the Ocean (ECCO) project makes available simulations and inversions of global ocean circulation, as well as modeling and data assimilation infrastructure, that can be used to explore and articulate the impact of cabled ocean-bottom observations on physical and biogeochemical oceanography.

The most recent ECCO inversion is the so-called version 4 (v4), which is obtained on a grid with 40-110 km horizontal spacing for the period 1992-2011 (Forget et al., 2015). A slightly older solution, called GECCO2, is also obtained on a grid with 40-110 km horizontal spacing but spans a longer 1948-2013 period (Köhl, 2015). A third inversion is underway on a grid with 14-36 km horizontal grid spacing for the period 2001-present with focus on polar regions (Fenty et al., submitted). These three ECCO inversions are obtained using the adjoint method to constrain the model with a wide variety of satellite (e.g., altimetry and sea surface temperature) and *in situ* (e.g., Argo profiling floats and Conductivity, Temperature, and Depth sensors) observations. A distinguishing feature of ECCO inversions is that water properties are conserved for the complete period of data assimilation, making them suitable for climate science and other studies that require closed budgets, e.g., ocean biogeochemistry. ECCO solutions have previously been used to study thermal changes in the abyssal ocean (Wunsch and Heimbach, 2014) and bottom pressure variability (Piecuch et al., 2015).

The ECCO project also makes available high-resolution (1-2 km, 2-4 km, and 3-9 km horizontal spacing and 90 vertical levels) simulations that include tides and atmospheric pressure forcing. These simulations, although not constrained by ocean observations, are particularly well suited to study the role of tides in large-scale ocean circulation (e.g., Flexas et al., 2015). Full 3-dimensional model fields are saved at hourly intervals, which make these simulations a remarkable resource for studying ocean processes and for simulating satellite and *in situ* observing systems.

The above ECCO inversions and simulations can be used as ocean truth for a cable mission simulator and to carry out observation system simulation experiments. Additionally, the ECCO modeling and estimation infrastructure can be used to evaluate the impact of simulated ocean bottom observations on the estimation of large-scale ocean circulation.

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7.4 Workshop Breakout Group Summaries

7.4.1 Science value of SMART cables as part of the global observing system

What is the overall scientific value of the measurements (baseline and future) as reflected in the oceanographic and other quantities that can be estimated? Recommend system modifications if appropriate. Recommend future sensors and system elements, with priorities.

- Deploying green cables, in combination with the other components of the global observing system (satellites, moorings, floats, etc.) will improve the quantification and understanding of surface-to-bottom oceanic variability related to climate change.
- Fundamental oceanic quantities such as total water mass, heat content and sea level will be resolved on an unprecedented range of time (seconds to decades) and space scales (from kilometer to trans-basin scales).
- Green cables will generate new scientific discoveries about the circulation of the ocean (waves, tides, currents).
- The variability of oceanic **temperature** below 2000 m is poorly known: green cables will improve estimates of heat and water mass exchange between ocean basins. This deep variability reflects heat and freshwater input at the surface in the past decades.
- Oceanic **bottom pressure** integrates a vast range of ocean-atmosphere processes, from surface waves to tides to mass, sea level, and water cycle changes on global scales. Green cables measurements of pressure at high resolution will expand the currently sparse sampling by orders of magnitude, as well as enhance satellite observations.
- Valuable additional measurements are possible for science and engineering (e.g., active and passive acoustics; cable voltage).

7.4.1.1 "Big" themes

- Power of combining components of the global observing systems (including remotely sensed measurements like GRACE) for observing climate variations: from top to bottom including changes in mass (sea level change components).
- Earth-based science could be used in the future science on other planets. Transformative process, New way of observing the ocean.
- Explore Artic/Antarctic processes (e.g., bottom water overflows); values of identifying teleconnections
- Long term observations: will answer questions on long term variability of temperature, and pressure (e.g., nonstationarity of tides).
- Observations on continental slopes i.e. boundaries of ocean basins (e.g., mixing/boundary layer processes, MOC processes).
- Observations of abyssal processes, how variable are they? New processes to be discovered from high frequency (e.g., daily fluctuations of T).
- Even localized, cable measurements will have impact globally (for GRACE correction/validation, for heat/T distribution, for the MOC).
- Short-time variations have an impact on long-term processes, the value of having a long-term real time observing system. This is also useful for predictive purposes (e.g., Hanne mentioned in the Arctic).

7.4.1.2 Temperature

- What is the temperature variability below 2000 db? (Not accessible by Argo until “deep Argo” and also on the boundaries where Argo does not reach.)
- Abyssal processes on sub-regional scales; redistribution of heat and water masses between deep ocean basins (e.g., T changes of order 20 milli Kelvin) on daily/short time scales; implications for water overflows, MOC processes at high latitudes in the North Atlantic. Bottom temperature are an integral measure of past deep water formation processes at the surface.
- What is the impact of T changes in deep water for steric changes? Ability to resolve over various time scales (e.g., Johnson study vs. recent study by Llovel et al. looking at different time periods, so this gets the latency issue of having high frequency measurements and their ability to resolve the scales on top of the longer period resolved by go-ship sections). Combination with ARGO fields to resolve the heat flux from top to bottom.
- Can we measure geothermal processes from bottom temperature? The group thinks this is probably not feasible as this instrument is not the correct one. Currently, the seismic community is making a concerted effort to study this issue.
- Subregion changes possible—a direct measurement of the changes in deep MOC at higher resolution than Go-SHIP.

7.4.1.3 Pressure

- A potential first: wavenumber/frequency spectral analysis of oceanic variability (possible from altimetry but this now able to resolve very very high frequency O(sec), mesoscale/large scale variability, Also useful for de-aliasing of SWOT altimetry, validation of models, infra gravity waves will not be detected using swat - difficult to, better understand the signal from swat altimetry (the sub-grid scale).
- Barotropic tides measurements: study of tidal constituents, non stationarity (sub cm, sub mm level), wave-wave interactions of the spectrum of variability; for global mixing, for aliasing of satellite altimetry going to high resolution/SWOT altimetry, internal tides, stammer (2014) review paper showed importance of understanding and measuring tides in the Arctic.
- Geodesy applications as well: land movement information (e.g., Love number).
- Mass changes over the global ocean, complement to GRACE data; will provide information on submonthly variability to allow for de-aliasing of GRACE data. De-aliasing over the ocean will improve the GRACE estimate globally. Also, measurements near basin boundaries will provide a lot of information on land contamination. Tides energizing other energy bands, e.g., barotropic wave trains. What are the nonlinear wave interactions at the boundaries? All the energy at very high frequency and especially information from spatial distribution will identify the source of this energy. The more cables you have the finer tuning you can determine the source of this energy. We are much more interested in the higher frequency constituents of the tidal forcing - it is no longer sufficient to just understand the dominant constituents. Bottom pressure is low-noise component of mass changes. The change in tides is sometimes comparable to the change in sea level, so secular changes in tides can be comparable to changes in sea level. It is important to continue to understand the long-term drift in pressure sensors so that this does not contaminate the (long-term) tidal signal.

- The non-inverted barometer response to the atmospheric pressure (Ichiro).
- Study of magnetic field? (Steve Jayne). Issues about the accuracy of the magnetometers to be able to resolve this?
- Coastal area - non-hydrostatic response from internal tides.
- Bring back the tsunami relevance paper.
- Pressure and GRACE: Sea level changes and hydrological cycle.
- Atmospheric changes: correlation between OBP and climate/atmospheric indices. Meteo tsunami/waves in the atmosphere.
- Climate of surface waves: pressure will provide information from 1s to 1h: study of infra gravity waves, surface gravity waves. Also useful for de-aliasing of SWOT altimetry.
- Seismic perturbation to gravity and mass field? Ability to detect sea floor displacements that can drive.

7.4.1.4 Others

- T, S and velocity on boundaries will lead to pressure gradient and MOC estimates.
- Broadband active and passive acoustic systems. Passive systems can provide quantitative measures of wind and rain, marine mammals, shipping and other anthropogenic activity; Further, using noise interferometry techniques vertically averaged sound speed can be obtained at a location (a la IES) and possibly between cable repeaters (on 50 km scale). Passive hydrophones can listen to distant acoustic tomography/navigation sources, providing addition paths for long range averages of sound speed (temperature). An active source (with receiver) can serve as an acoustic modem providing communications and navigation infrastructure support for nearby autonomous instruments and vehicles. It can serve as the active component of an IES, also possibly interacting with nearest neighbors to obtain path averaged sound speed and along-path velocity. These combinations can lead to heat flux estimates.
- Velocity and pressure: Boundary/Ekman layer processes; MOC resolution.
- Measurements just above the bottom boundary will resolve the topographic waves (Arbic).
- Salinity? Problematic?
- Voltage measurements? Is this possible? Measuring the voltage between cable conductor and sea water can yield measures of the barotropic flow perpendicular to the cable, thus contributing to momentum and heat flux estimates.
- Additional sensors for resolving geothermal fluxes?
- Recommendation for self-calibrating pressure sensors. If this is not possible, then from a practical point of view, it will be important to continue to understand the long-term drift in pressure sensors so that this does not contaminate the (long-term) tidal signal.
- Recommendations for system modifications.
    - Higher resolution (< 50 km) on boundaries, which might be achieved by multiple coastal cables that are slightly offset.
    - Which cables? Where? How many? Relocation? Repurpose of cables.
    - What if the repeater is buried - are T and P measurements useful? Measurements on the continental shelf for prediction of storm surge.

    - Calibration? How do we do this? Calibration opportunities? Use AUVs as mobile calibration units?

7.4.2 Using the proposed cable data to validating satellite data and ocean models

How can such observations and quantities derived therefrom be best used in a "forward problem" sense to validate conceptual models, expected patterns, ocean models and satellite/other data, from initial sparse spatial sampling to an ultimately dense, continuing coverage. Recommend specific short (6-month, i.e., accomplish before next meeting) and long term analyses as appropriate.

- Basic measurements: Temperature, pressure, acceleration.
- Assumption: Computer models represent a way to accurately synthesize sparse measurements at many length scales.
- With existing ocean models we can simulate observations on green cables.
- These simulations capture local and large scale effects at temporal scales from seconds to decades.
- Modern models are high quality but they lack data (temperature and pressure) from the sea floor.
- Satellite data: To understand the oceanography of the water column we need measurements of both sea-surface height and bottom pressure.
- Design of observing elements can be obtained by analysis of synthetic data derived from ocean models, with comparisons of these synthetic data to observations where possible.
- This analysis identifies "gaps" in our observing system; the deficiency from the lack of deep ocean measurements is widely acknowledged.

7.4.2.1 Temperature

- Station ALOHA has a long time series and there are other bottom data sets for temperature available. One obvious forward problem test is to compare T-ALOHA to the data assimilation models. How similar, or different are the observations and models? Significant differences, which may occur at different time scales, imply data from repeaters adds important constraints.
- Task: Compile available data and compare variances/spectral characteristics of observations to model variances/spectral characteristics.
- A trans-basin cable, with closely spaced T, P provides a test for models at a variety of temporal and spatial scales. One can compare frequency and wavenumber spectral characteristics to equivalent model characteristics.
- The ECCO adjoint can be employed to determine the impact of data on the model. Such a project requires some work in analysis and interpretation. ECCO requests assistance.

7.4.2.2 Pressure

- ECCO has good estimates for pressure from 6-hourly wind forcing. Other models for pressures exist.
- DART has existing pressure time series, but considerable quality control is needed at longer time scales/drifts/etc.
- Preliminary analysis of existing pressure data by R. Ray and C. Hughes. It would be a large effort to distill these data to high quality, independent observations.

- BEMPEX and HOME data are available. Comparisons can be made between these data and model pressure. Pressure differences may more critically test the smaller scale barotropic waves. How important are small scale barotropic phenomena? Models need quality high-resolution topography data; it can never be accurate enough.
- Models for pressure can reproduce bottom pressure at short time scales, 3-15d, but they have trouble with scales longer than 30 days. Hence we seek quality pressure data to constrain barotropic variability at the longer time scales.
- The open ocean may vary at long space scales for pressure, hence we might need only widely spaced instruments there. Coastal ocean/continental slopes may vary at short scales, hence may need closer spacing. We should test this hypothesis.
- Hydrographic sections may have temporal aliasing effects. Can bottom temperature at 50-km spacing be used to determine aliasing effects?
- Bottom thermistors may be on abyssal plain, or in rough regions, or in small basins such as ALOHA. These regions will have different characteristics and variability. For models, these data will have different representation error for models.
- Bottom temperature/pressure in the Arctic is new, unexplored territory. A recent review paper on tides by Stammer et al. highlighted the need for pressure data in the Arctic for constraining tidal models.

7.4.2.3 Other

- Forward problem means Dobs-Dmodel. There are many global or regional models, ECCO, HYCOM, SODA-POP, etc. that may be employed for model testing.
- A philosophical point to contemplate: should we focus on models and data assimilation and set aside "observational analysis" How else to rationally combined bottom thermistor time series with sparse, non-synoptic hydrographic sections or sparse moored data. (But "green"/SMART will not offer comprehensive, global measurements.)
- What time scales for this analysis? hourly, monthly, yearly, decadal, century?
- One approach is to emphasize the accuracy of the model, and therefore one can leverage sparse data for a more exhaustive scientific study.
- Initial measurements are temperature, pressure, and acceleration. We will not discuss acceleration here. IES is a poor man's tomography. It might be possible to transmit signals to adjacent repeaters (with a surface reflection) to form (reciprocal) tomography transmissions. These result in not only the point measurements from the IESs, but also temperature and current averaged between repeaters (with single ray path averaging).

7.4.3 Toward a "cable mission simulator"

What observing system simulation/sensitivity experiments in an "inverse problem" sense can best guide system development, and demonstrate the value of the data. Recommend specific short (6-month) and long term experiments, e.g., to work toward a "cable mission simulator". What computer simulations can demonstrate value of data and guide environmental sensing on the cable network.

7.4.3.1 Key ingredients

- Realistic numerical ocean truth.
- Projected spatial and temporal sampling of observing system.

- Simulated geophysical and instrumental noise and drift; informed by current and projected technologies.
- Observation System Simulation Experiments (OSSEs) for planning cables to resolve oceanographic and climate signals.

7.4.3.2 Short-term objectives

- Choose small number of process studies and satellite calibration problems from Task 1 for initial OSSE and adjoint sensitivity experiments.
- Sample simulated ocean-truth temperature and pressure at projected instrument locations with projected errors and drifts.
- Reconstruction of key processes, e.g., MOC, from synthetic observations.
- Identify useful objective functions for adjoint sensitivity experiments.
- Use adjoint-model to identify bottom observation locations that have largest impact on these objective functions.
- Produce decadal animations of global bottom temperature.

7.4.3.3 Long-term objectives

Inverse/assimilation problem simulations, for example, twin-experiments that include:

- Ocean truth, e.g., from a model at higher resolution;
- Baseline estimate, e.g., from a model at coarser resolution; and
- Assimilation of various simulated data sets to explore impact of data and estimation.

7.4.3.4 Key approaches to consider

- Growing interest in diminishing Arctic ice effects on tidal non-stationarity: formulate OSSEs for improving tidal models.
- Determination of volume of water colder than 1.5° in the global ocean as a function of time as measure of deep ocean heat content.
- Sampling models at high/low frequency, to mimic cable/satellite data, will yield estimates of the aliasing error of seasonally varying tides in satellite data. This is of particular concern in the Arctic, causing significant errors in gravimetry data.