From space to the deep seafloor: Using SMART subsea cables in the ocean observing system

SMART:

Science Monitoring And Reliable Telecommunications

Climate Monitoring and Disaster Mitigation

Report on two NASA workshops

CalTech 9-10 October 2014 and University of Hawaii 26-28 May 2015

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10 December 2015

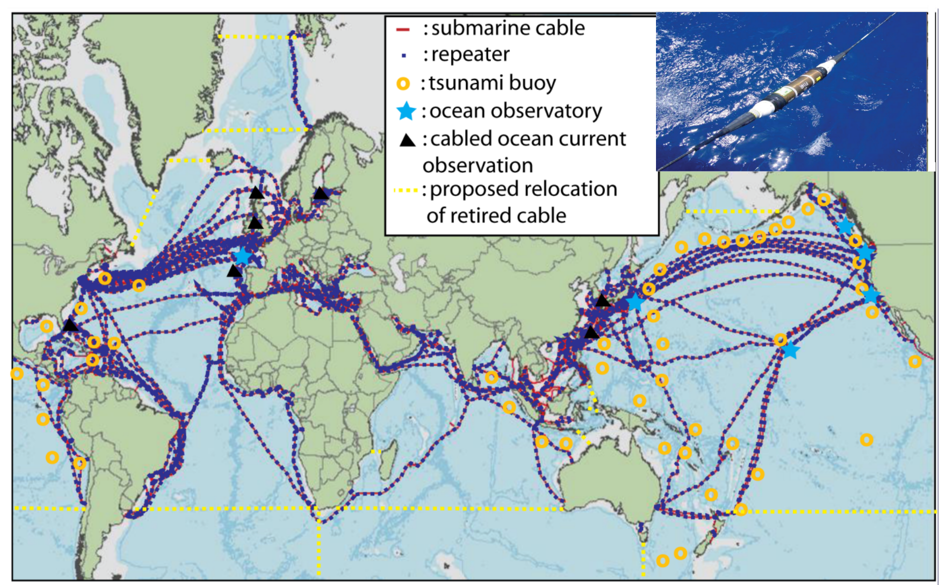
SMART subsea cables in the ocean observing system

- Cable repeaters host sensors
- 20,000 repeaters, 1 Gm, 10-20 year refresh cycle
- UN ITU/WMO/IOC effort

SMART cables will:

- Contribute to understanding of ocean dynamics and climate
- Improve knowledge of earthquakes and forecasting of tsunamis
- Complement and enhance existing and future satellite and in-situ observing systems

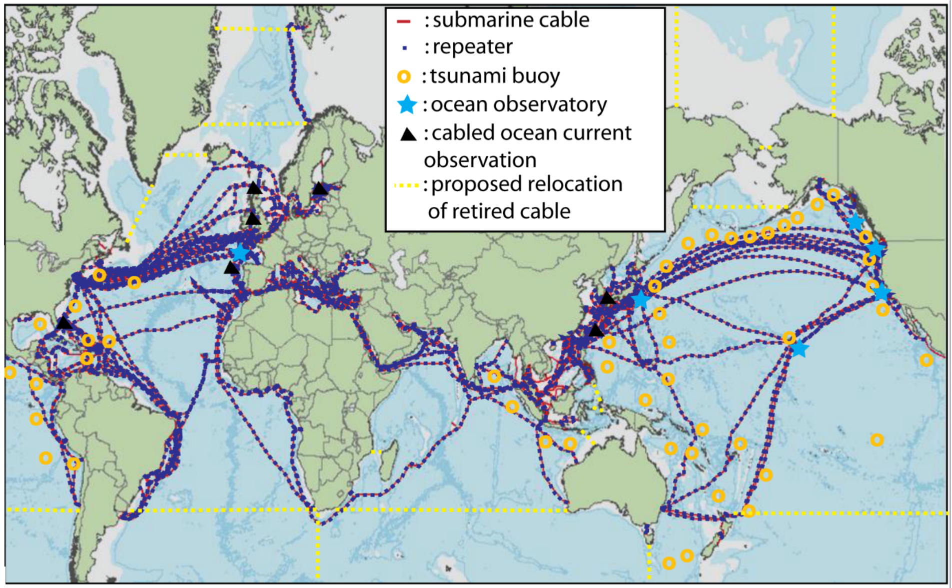
SMART cables – first order addition to the ocean observing system, with unique contributions that will strengthen and complement satellite and in-situ systems.



Outline

- Introduction
- Climate relevance of SMART cable measurements
- Tsunamis, earthquakes, and early warning systems
- Contributions to existing earth observing systems
- Recommendations
- Concluding remarks

Cable repeaters host sensors



1 gigameter 20,000 repeaters 10-20 year cycle

Introduction

- Plans to integrate ocean sensors into ***Science Monitoring And Reliable Telecommunication (SMART) Subsea Cable Systems*** – UN agencies ITU/WMO/IOC
- Initial measurements will include bottom pressure, temperature and acceleration every 50 km along cables—could be supplemented with more sensors later
- Workshop presentations led to 3 overarching themes. SMART cables will:
  – Contribute to our understanding of ocean dynamics and climate
  – Improve knowledge of earthquakes and forecasting of tsunamis
  – Complement and enhance existing and future satellite and in-situ observing systems

Climate relevance of SMART cable measurements

- SMART cables can
  - Greatly improve our knowledge of deep-ocean variability, which is currently poorly documented
  - Provide constraints on important depth-integrated quantities
  - Provide high frequency measurements on a global scale for the first time

Specific measurements enabled by SMART subsea cables

Initial sensors

- Spatial and temporal variability of deep-ocean temperatures
- Evolution/Propagation/Spread of heat anomalies between ocean basins and along ocean boundaries
- Temporal variability of barotropic tides, which impact tidal corrections for satellite missions
- Ocean response to atmospheric pressure forcing on fast (< 2 day) time scales
- Impact of infragravity waves on high-precision altimetry missions

Specific measurements enabled by SMART subsea cables

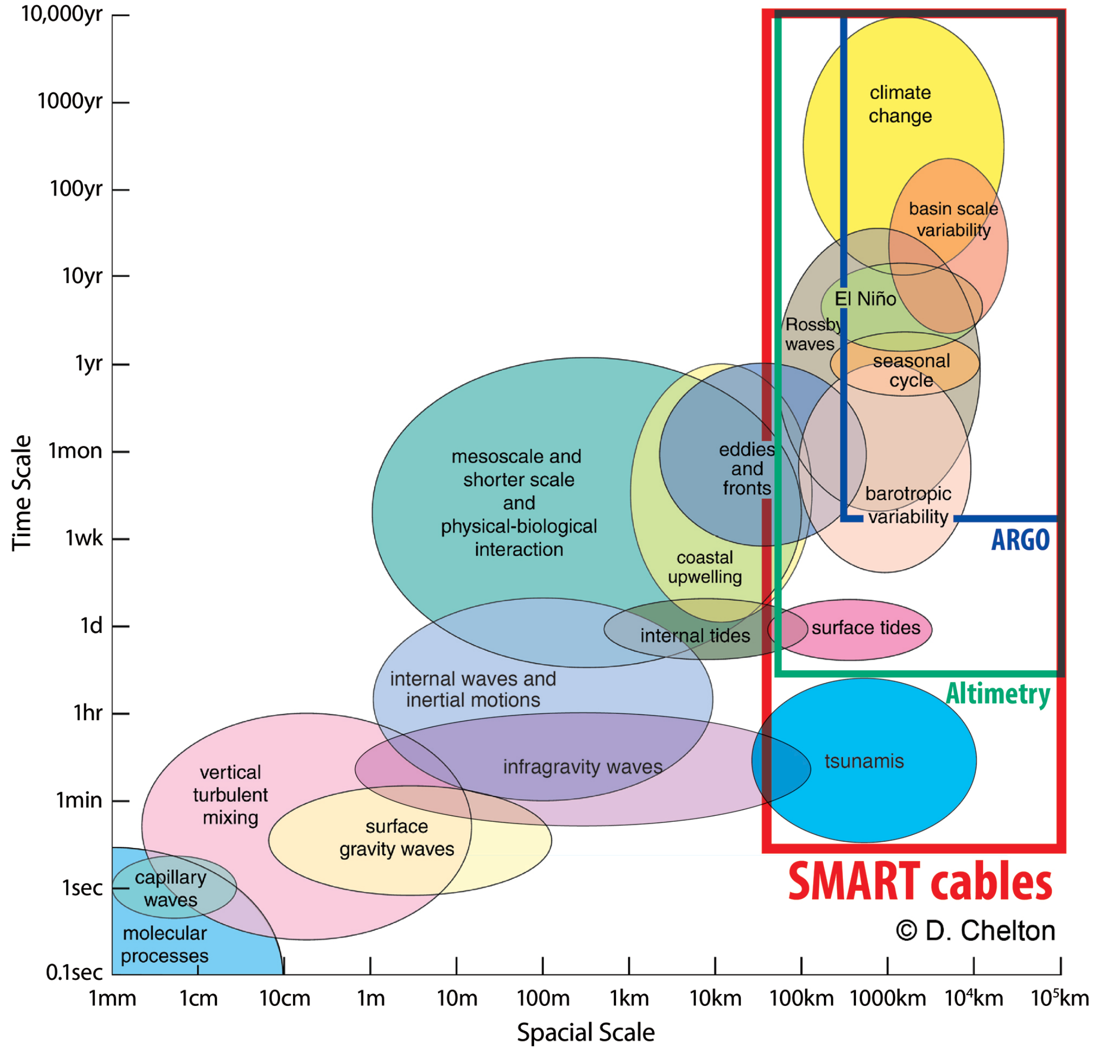
Sensors considered for later deployment

- ADCPs and conductivity to measure velocities, salinities, mass transports, and bottom boundary layer processes
- Inverted echo sounders, and variants thereof, to measure internal waves and internal tide stationarity, which impacts tidal corrections for satellite missions, and simultaneous mass loading and steric effects to evaluate satellite altimetry and gravity missions
- Voltage measurements for transport across the cables
- Bio-optical sensors to measure carbon export to the seafloor
- Passive hydrophones to measure wind, rain, infragravity waves, marine mammals, shipping.

Tsunamis, earthquakes, and early warning systems

- Accelerometers along SMART cables will significantly decrease warning response time of marine earthquakes, which are poorly constrained by land-bound seismic networks
- Bottom pressure measurements on SMART cables will constrain tsunami amplitudes much faster than the sparse DART array
- Will allow detection of tsunamis that are not caused by large earthquakes, e.g., submarine landslide generated tsunamis

Contributions to existing earth observing systems
space/time coverage



Contributions to existing earth observing systems
Sea level

- Sea level, a fundamental property of the ocean, is measured by satellite altimetry
- Bottom pressure measurements along cables provide ground truth for models of tides and other high-frequency motions that must be subtracted accurately from altimeter records before lower-frequency motions can be examined

Contributions to existing earth observing systems
Gravity

- Bottom pressure observations
  - Proportional to total water mass above
  - Will be valuable ground truth for remotely sensed gravity missions
  - Are expected to substantially improve de-aliasing and correction products, and hence the final gravity fields derived from gravity field missions

Contributions to existing earth observing systems
Surface waves

- Infragravity waves are expected to be a significant source of error in the planned NASA/CNES SWOT mission
  - SMART cable bottom pressure data combined with modeling will improve our ability to remove errors due to infragravity waves.
- SMART cable bottom pressure data can be inverted for information on surface waves for assimilation into operational wave models

Contributions to existing earth observing systems

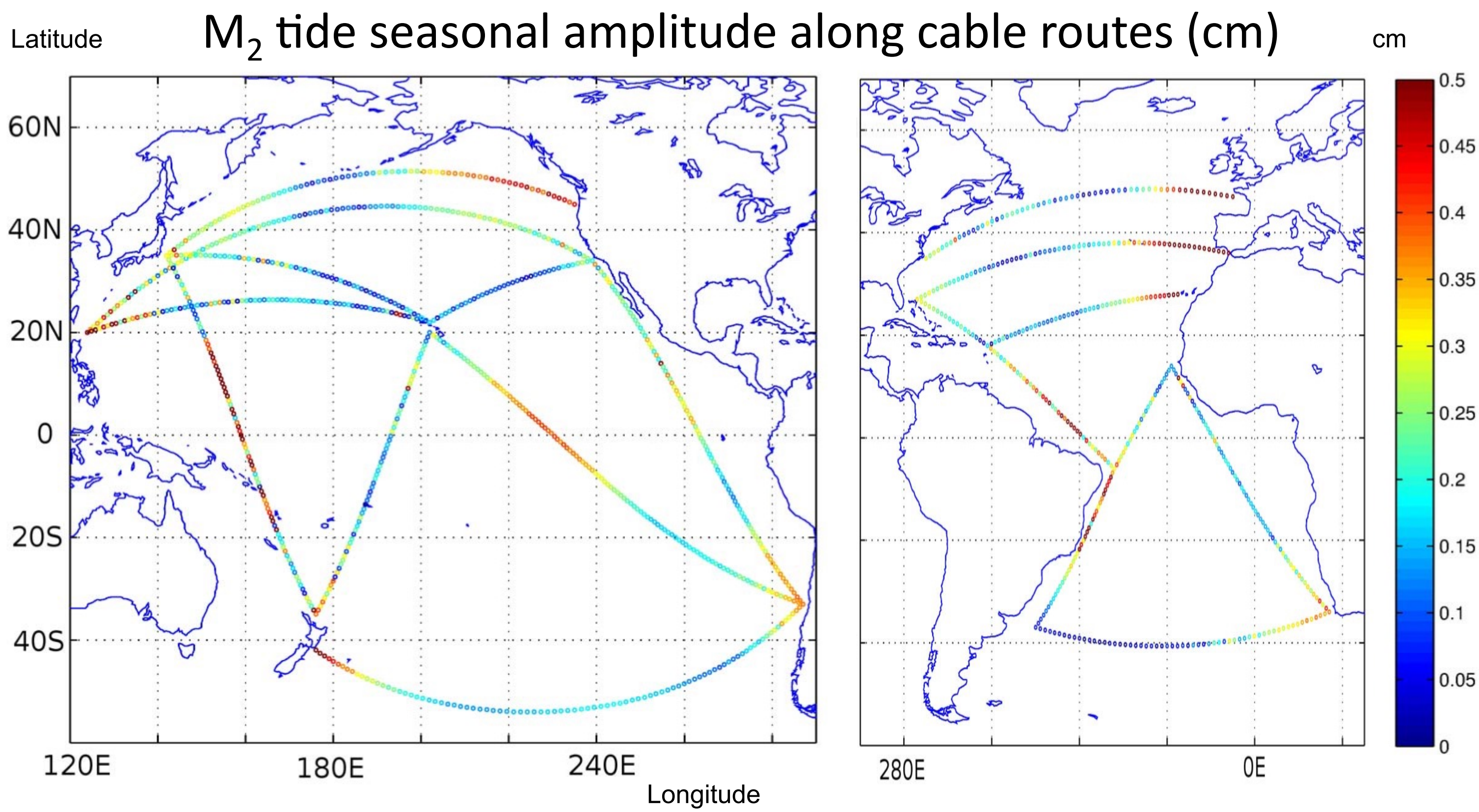
Tides

- Evidence is accumulating that barotropic tides undergo significant seasonal to centennial variability
- Bottom pressure measurements on SMART cables will help to quantify this variability, which will yield improved tidal correction models for satellite altimetry missions

Contributions to existing earth observing systems

Tides - 2

Seasonal variability of principal lunar semi-diurnal tide M_2—sampled from Müller et al. 2014 model by Malte Müller reveals basin-scale patterns of order 5 mm signals (~10% of month-to-month bottom pressure variability)



Contributions to existing earth observing systems

Ocean surface wind stress

- SMART bottom pressure measurements could possibly provide an alternative ground truth method for wind-stress measurements (Petrick et al. 2014)

Contributions to existing earth observing systems
Deep ocean temperatures

- SMART cable temperature measurements could detect current deep warming trends within several-10 years
  - Much higher temporal sampling (thus, less aliasing problems) than other arrays
  - Much higher spatial sampling as well (20,000 nodes at 50 km spacing, compared to projected 1,000 deep global ARGO floats)
- SMART temperature measurements will also allow unprecedented exploration of temporal variability of deep ocean temperatures due to tides, eddies, mixing, etc.

Contributions to existing earth observing systems
Ocean circulation

- Next-generation cable voltage measurements would allow estimates of cross-cable absolute transport over the full water column.
- Measuring transport on a continuous basis across ocean basins will greatly improve our knowledge of full-depth ocean circulation.
- Combined with acoustically determined along-cable velocity and temperature, could improve estimates of ocean mass and heat transports.

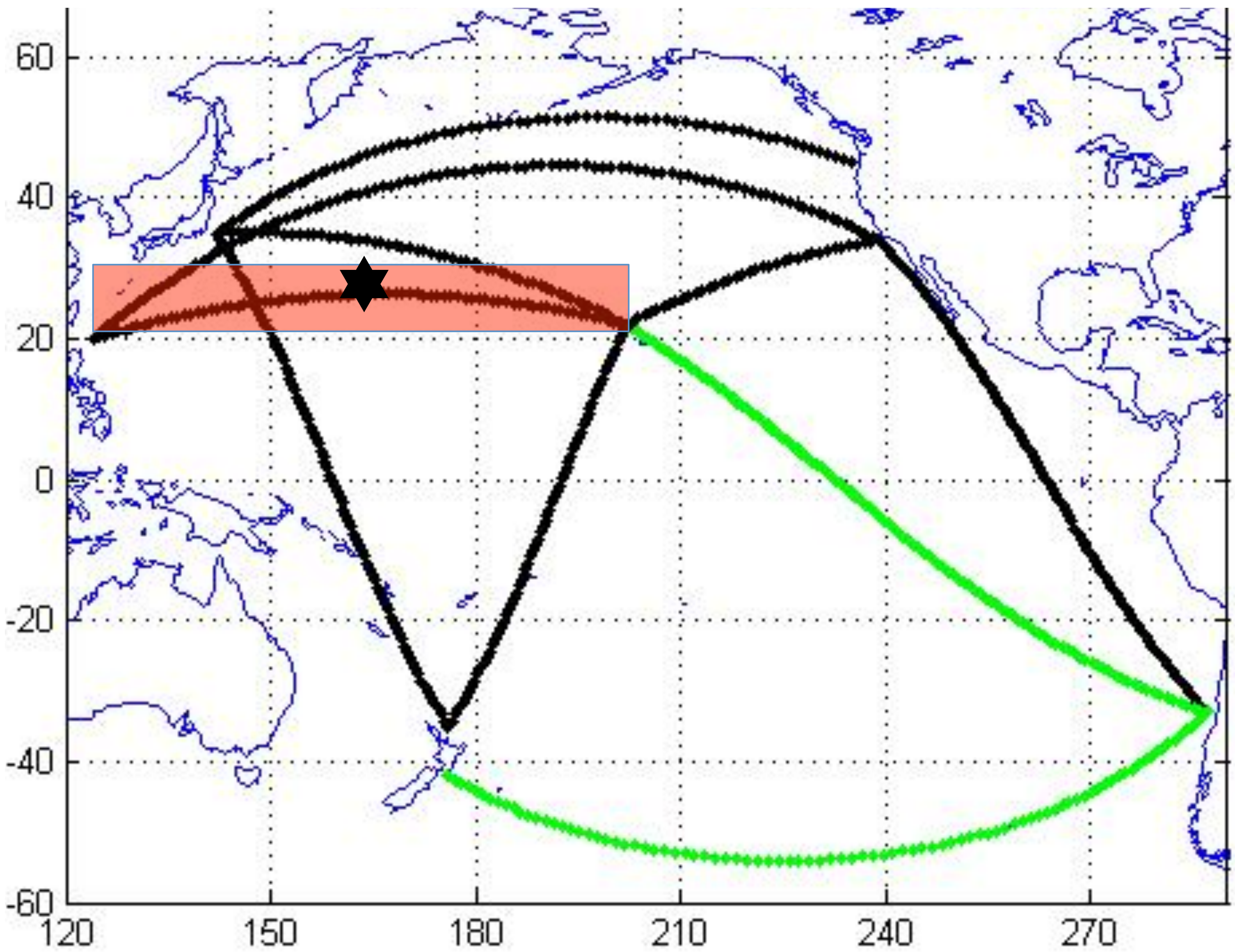
Contributions to existing earth observing systems

Ocean state estimation

- Ocean modeling can be used to estimate the impact of SMART cable bottom pressure measurements on ocean state estimation, and then to 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.
- Following slides show a North Pacific region sampled by cables, and the changes from November to December 2011 of several variables, in the global 1/48th degree (~2 km) MITGCM simulation

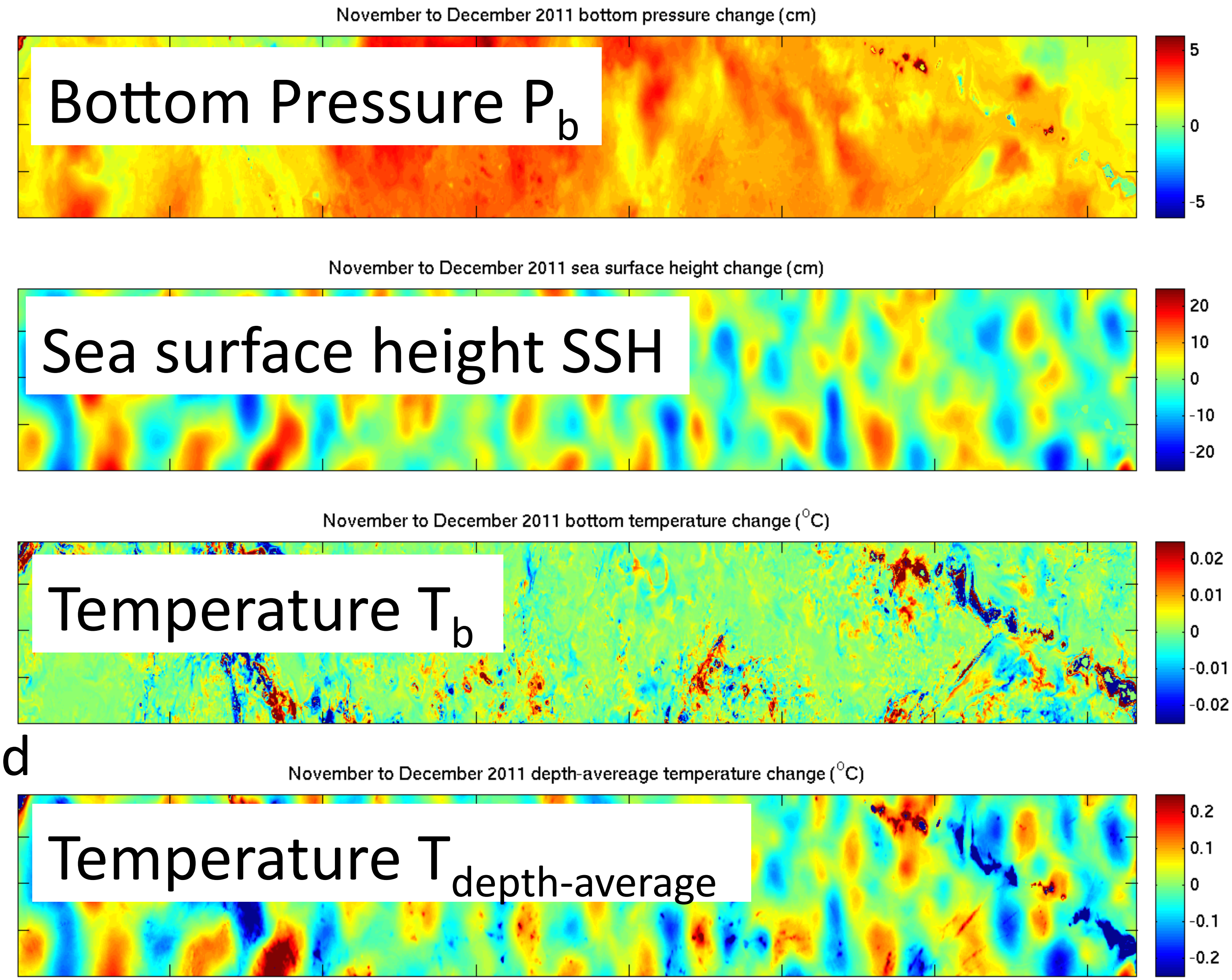
Sample location – red box

- "Generic" cable routes



Example: Nov – Dec 2011 model changes

- P_b 5 cm signals
- SSH 20 cm signals
- SSH and $T_{depth\text{-}average}$ correlated



Recommendations - 1

1. The ***SMART cable concept deserves broad support from the science community.***
2. The ***seismic and tsunami*** communities should refine their scientific support by similar ***workshops***.
3. The scientific community should ***prioritize*** which ***cable routes*** are most scientifically useful.
4. The scientific and subsea community should assist the JTF to ***identify a SMART demonstrator cable system***.

Recommendations - 2

5. 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 model output is sensitive to cable measurements.
7. Perform ***Observation System Simulation Experiments*** (OSSEs) for proposed bottom pressure and temperature sensors to quantify ocean state estimate improvements.
8. Develop a "***SMART cable mission simulator***" that produces realistic data and noise from models, performs data assimilation, compares with truth, estimates uncertainties, with useful products.

Recommendations - 3

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. Investigate the ramifications for the temperature and pressure measurements when cables are buried in shallow water to protect them from external aggression (e.g., fishing and anchoring; <1000 m)?

Cost

- SMART sensors add ~$40M to $250M base cost of a trans-Pacific 10,000 km cable system with 152 repeaters.
- Ten systems ~$400M, ≈ five-year satellite mission, but cables last 25 years. Two systems/year over 25 years, 7,600 SMART sensors on the seafloor.
- For comparison:
  - US NOAA DART program $27M/year, ≈ incremental cost of a SMART trans-Pacific cable, where most buoys located.
  - Argo 4000 expendable floats ~$32M/y
  - NSF Ocean Observatories Initiative (OOI) ~$400M for the fabrication, operating costs of ~$50M per year.
  - NOAA ~$430M annually for ocean, coastal, and Great Lakes observing systems.

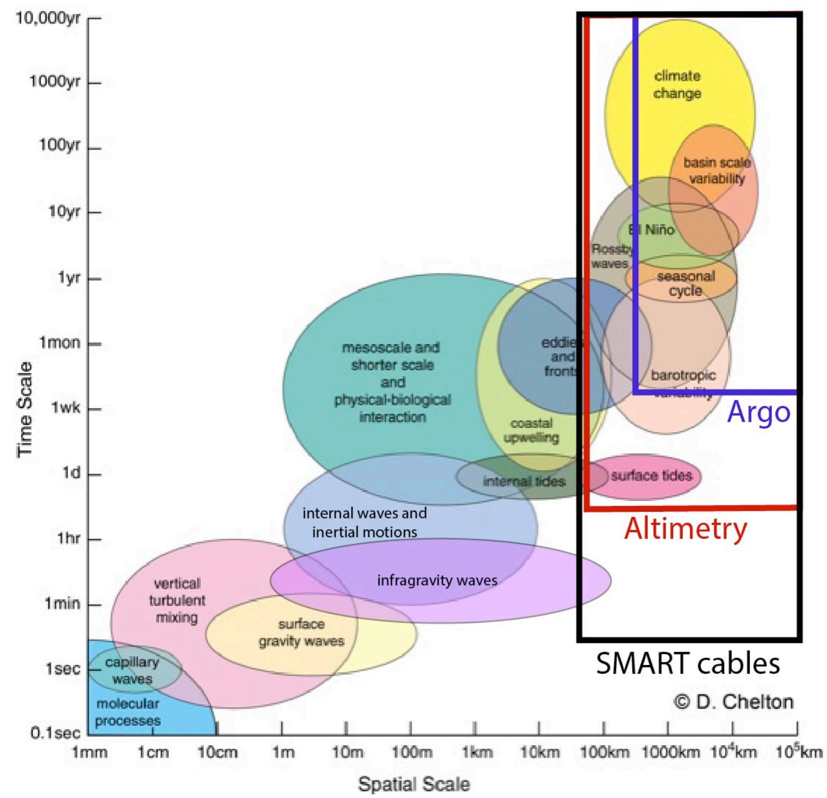
SMART cables in the ocean observing system
Summary 1

- Climate relevance of SMART cable measurements
  - Uniquely sample deep-ocean variability
  - Constrain fundamental depth-integrated quantities
  - Provide new capability for high frequency global measurements
- With initial sensors: temperature (T), bottom pressure (BP), acceleration (A)
  - **T:** spatial and temporal variability of deep-ocean temperatures, propagation of heat anomalies through ocean basins and along boundaries
  - **BP:** Temporal variability of barotropic tides, fast (<2 day) ocean response to atmospheric pressure forcing, aliasing from infragravity waves, constrain tsunami amplitudes
  - **A:** improve sampling in the ocean of earthquake parameters much more than the sparse DART array
- Scientific Benefits of initial sensors:
  - Monitor ocean warming with measurements unattainable on similar time/space scales
  - Increase accuracy of satellite altimetry by improving tidal corrections and aliasing of high frequency ocean signals
  - Improve speed and accuracy of real-time earthquake and tsunami warning systems, including landslide-generated tsunamis
- With subsequent sensors
  - Acoustics and cable voltages: heat content, velocity, and heat and mass transports; internal waves and tides, simultaneous mass loading and steric effects to evaluate satellite altimetry and gravity missions
  - Bio-optical sensors for carbon export to the seafloor; conductivity for salinity
  - Passive hydrophones to measure wind, rain, infragravity waves, marine mammals, ships

SMART cables in the ocean observing system
Summary 2

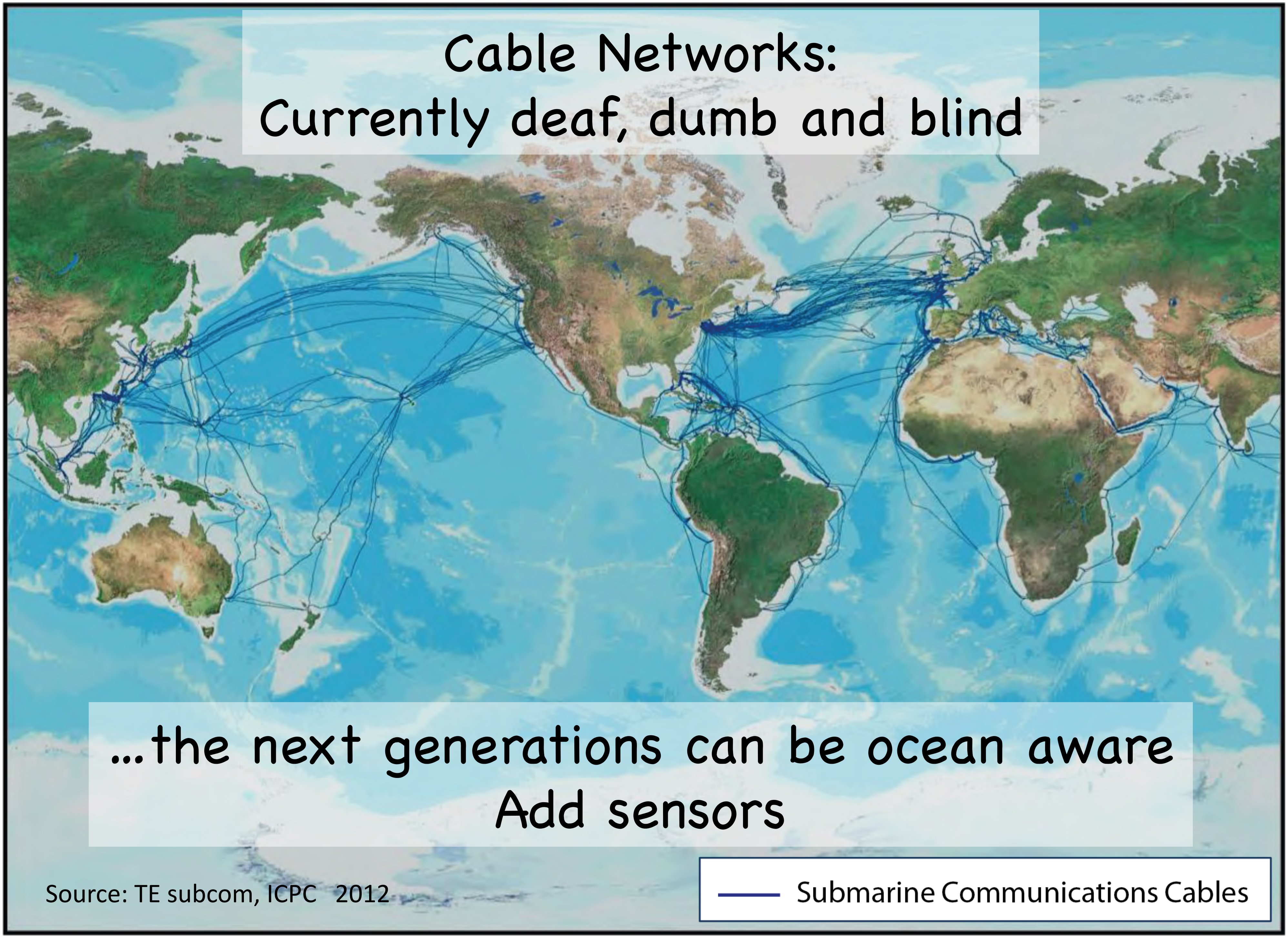
- Synergies with satellite observations. Cables provide **increased space/time coverage** to **improve satellite corrections** for fast and small-scale processes.

- Sea surface height:
  - Low frequency sea level
  - Tidal corrections
  - Temporal aliasing from surface gravity waves and atmospheric forcing
- Gravity
  - Aliasing from surface gravity waves
  - Barotropic velocity/tides
- Ocean surface wind stress
- Ocean state estimation
  - Deep ocean temperatures
  - Ocean Circulation

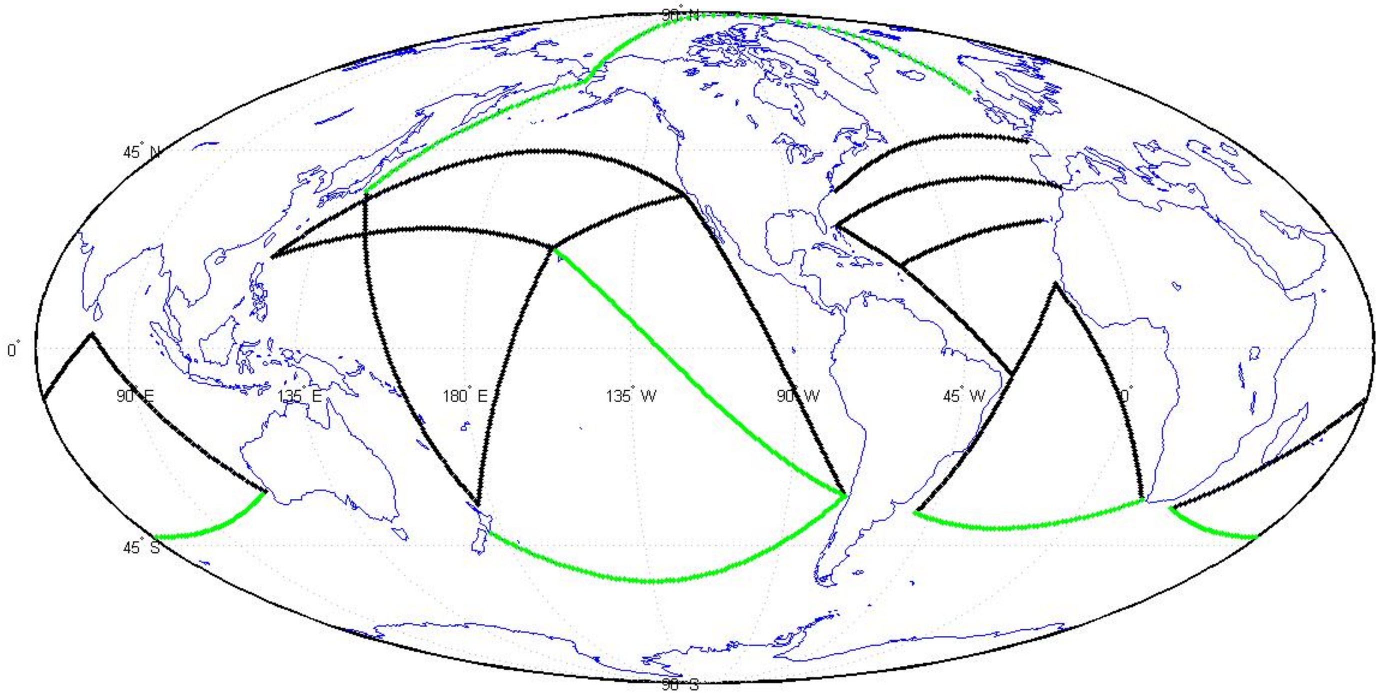


SMART cables in the ocean observing system
Summary 3

- Three overarching themes. SMART cables will:
  - Contribute to our 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 – first order addition to the ocean observing system with unique contributions that will strengthen and complement satellite and in-situ systems.**


Cable Networks:
Currently deaf, dumb and blind
…the next generations can be ocean aware
Add sensors
Source: TE subcom, ICPC 2012
Submarine Communications Cables

NASA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