Report on workshop

SMART Submarine Cable Applications in Earthquake and Tsunami Science and Early Warning

Held at: Deutsches GeoForschungsZentrum (GFZ), Helmholtzzentrum Potsdam, Potsdam, Germany

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Executive Summary

Hundreds of submarine communication cables cross the world's oceans. Today, these cables are unaware of their environment. However, repeaters spaced at ~50 km intervals along them offer access to power and bandwidth, providing the opportunity to add sensor capability to future SMART cables (Science Monitoring And Reliable Telecommunications), a concept advanced by a Joint Task Force of the International Telecommunication Union, the World Meteorological Organization and the Intergovernmental Oceanographic Commission of UNESCO[1]. Two NASA workshops focused on applications in climate research and oceanography[2]. In the workshop described here, research scientists, practitioners from earthquake observatories and tsunami warning centers, and engineers discussed potential applications of SMART cables for earthquake and tsunami early warning and reviewed existing approaches and how they can benefit from SMART cables. They also considered what possibilities exist in research on Earth structure, the physics of earthquakes, and tsunami excitation and propagation.

According to current planning, a first generation of SMART cables will be equipped with a simple instrumentation package containing accelerometers, pressure gauges and temperature sensors in order to make the sensor package simple and able to withstand the rough deployment conditions in standard cable-laying operations.

Most destructive tsunamis are triggered by great earthquakes along the plate boundary faults in subduction zones. Their offshore location makes quick detection and assessment of their tsunamigenic potential a real challenge using land-based networks. The DART system of ocean bottom pressure detectors can detect ocean-crossing tsunamis but sensors are too sparse and too far from shore to be much help in local warning. Dedicated submarine cables present another real-time solution but come with a hefty price tag. Thus a comprehensive coverage of all endangered subduction zones is out of reach, particularly in the developing world.

Already a few cables crossing the Pacific can reduce the time-to-detection of potentially tsunamigenic earthquakes along the Ring of Fire by ~20%, and the detection of the actual tsunami wave would be reduced by a similar fraction. With trench-parallel cables even larger improvements are possible. The continuous high sampling rates possible in a cable allow separation of tsunami and seismic wavefields, allowing reliable tsunami measurements in the near field.

Wide science benefits are expected from the faithful recordings of offshore earthquakes as well as from the vastly improved coverage of the ocean basins from even a small number of SMART cables.

Recommendations:

- The SMART cable concept deserves broad support from the geoscience community and government sponsors.
- SMART cables can significantly cut down early warning delays for tsunami early warning and improve the accuracy of forecast, saving lives and reducing economic damage (also through the avoidance of false alerts). A tangible improvement can also be achieved for earthquake early warning.

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[1] http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

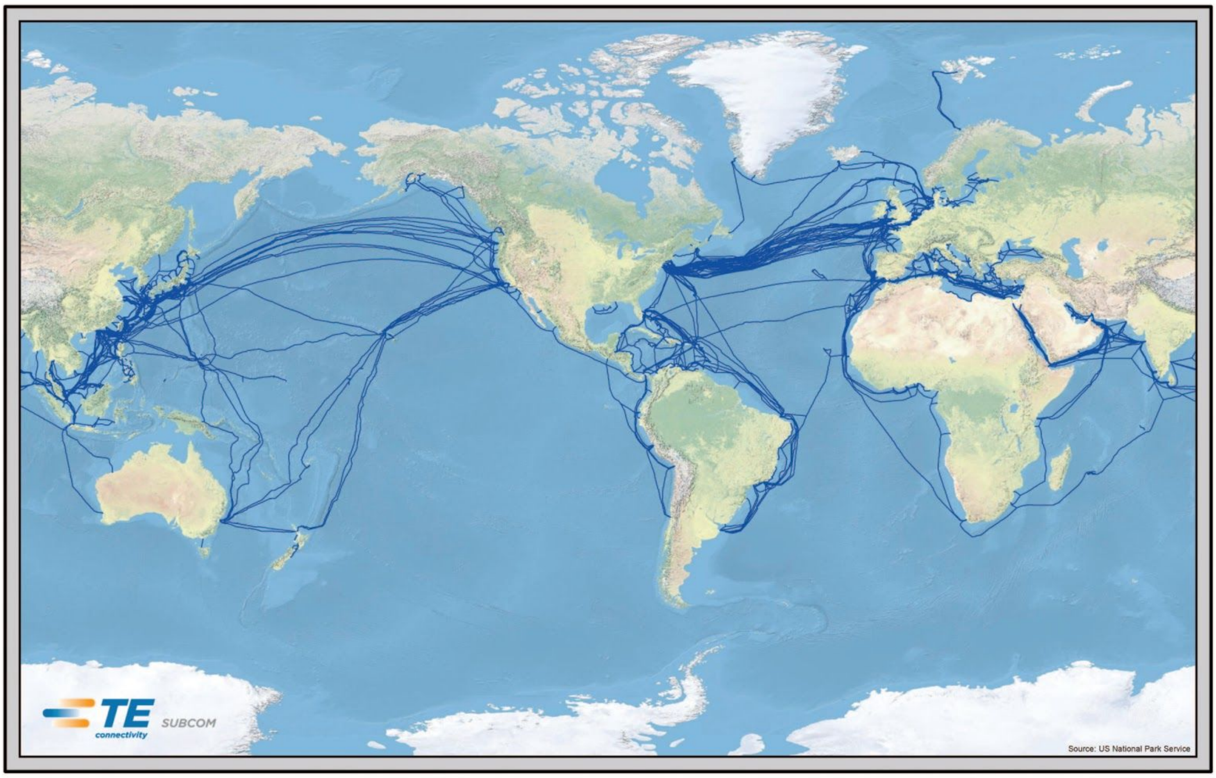
[2] http://www.soest.hawaii.edu/NASA_SMART_Cables/

- Cable routes parallel to major subduction trenches would be of most interest to tsunami and large earthquake researchers. The early warning benefits might provide additional funding avenues, as there is much interest among countries threatened by megathrust earthquakes (e.g. Indonesia, Chile). Ocean-crossing SMART cables would be of great interest for studies of global Earth structure, but also allow detailed analysis of far-field tsunamis and still provide early-warning benefits.
- Sensor spacing in the deep ocean would be enough to sample the tsunami wavefield, allowing detailed characterisation of source and propagation effects even for non-seismic sources, such as landslides.
- Scientific uses in global tomography and tectonics (local earthquake studies) would benefit strongly from high-sensitivity accelerometers operating at longer periods, beyond the current specifications. The JTF should therefore consider revising specifications.
- Long term stability of pressure sensors is of no concern for early warning applications, but would be very beneficial for geodetic applications (search for transient slip events, interseismic strain accumulation).
- Potential sites for a small demonstration system could be existing cabled seafloor observatories. Such a `wet demonstrator' should consist of at least three sensor/repeater packages deployed in a manner equivalent to commercial cable-laying operations to demonstrate the viability of the SMART cable vision and to deliver valuable science data. In Europe a suitable location could be in Greece due to its subduction zone related high seismic activity. In the Pacific, it could be either the Ocean Observatories Initiative Cabled Array or Ocean Networks Canada NEPTUNE observatory, both of which cross the Cascadia subduction zone, or the ALOHA observatory off Hawaii.

Table of Contents

Introduction

In this section the status quo of the engineering design and specifications based on earlier workshops are summarised. An overview of current cable routes based on public databases is shown in Fig. 1.



Source: US National Park Service

Fig. 1 Overview of current cable routes in public databases (e.g. Submarine Cable Almanac, published by Submarine Telecoms Forum, www.subtelforum.com) .

Technical specifications

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 (maximum spacing in current state-of-the-art systems), the signal needs to be boosted using "repeaters", which contain optical amplifiers (Fig. 2, 3). They obtain ~20 W from the single copper high voltage conductor in the cable (up to 15 kV) . 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.

The sensor package needs to fulfil the following requirements:

- Deployment procedures must follow standard industry cable laying procedures without causing noticeable delay.
- Sensors need to be able to withstand the harsh deployment conditions, which can involve exposure to accelerations of several *g.*

- Sensors should have a design lifetime of up to ~25 years. Failed sensors will not be replaced.
- Under any credible failure mode, the sensors must never compromise the main repeater functionality

The recommendation of previous workshops was to limit initial instrumentation to temperature, pressure and acceleration sensors. We summarise here the current engineering specifications for the pressure and acceleration sensors, the sensors most relevant to the topic of the workshop:

Pressure (absolute)
Range: 0-73 MPa (equiv. approx 0-7000 m):
Accuracy ±1 mm
Drift: < 2 kPa / year (equiv 0.02 m) (after settling)
Noise floor: 0.14 Pa^2 /Hz
Sampling rate 20 Hz

Acceleration (3-axis)
Response: 0.1-200 Hz
Noise: < 4 $(ng)^2$/Hz
Sampling rate: 200 Hz

Whereas accelerometers do not need contact with the environment and can thus easily be included in any package, the pressure and temperature sensors need to be able to sense the conditions imposed by the seawater directly.

For the purposes of earthquake detection and analysis, the upper frequency band for accelerometric measurements could be higher (say 20 Hz for local event recordings), whereas teleseismic applications would benefit tremendously from a longer period lower bound (down to 0.01 Hz if this can be achieved).

Following feedback obtained at the JTF workshop in Dubai (Howe et al., 2016), the latest engineering concept (Lentz et al., 2016b) envisages a separate sensor package attached by a power and communications cable to the main repeater at a short distance (5-25 m), with the coupling achieved via a switch within the main repeater housing (Fig. 4).

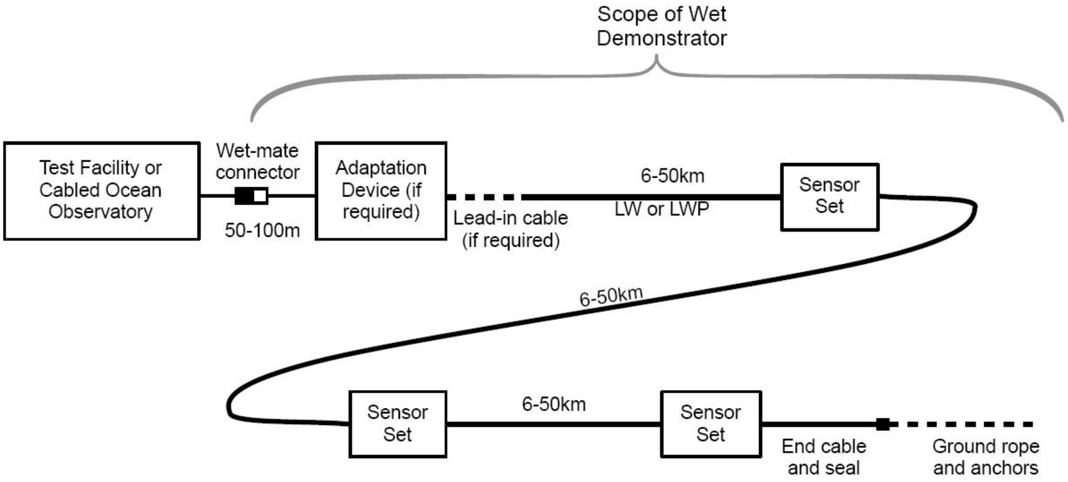


Fig. 2 Conceptual diagram of a cabled system (from Lentz, 2016a)

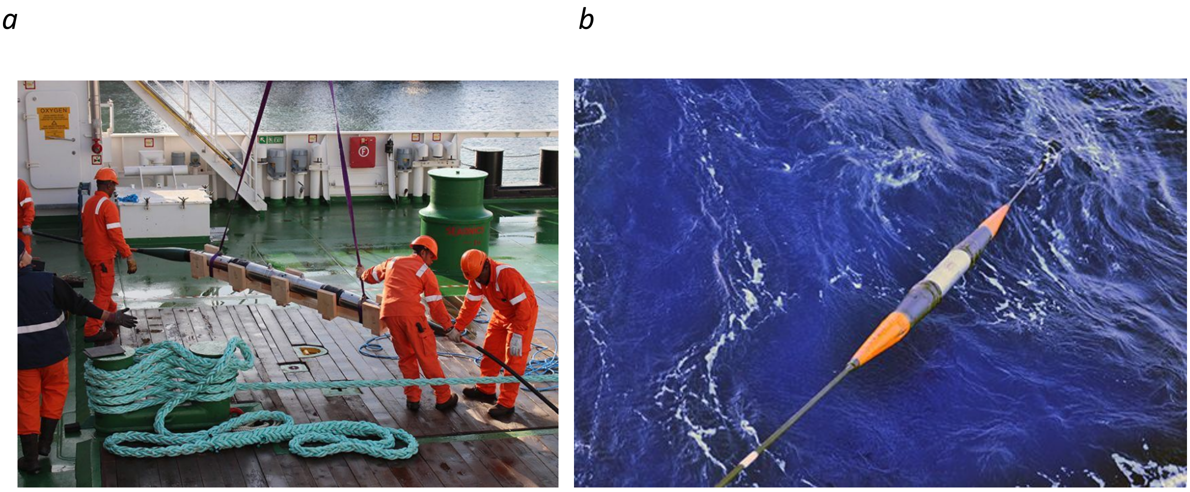
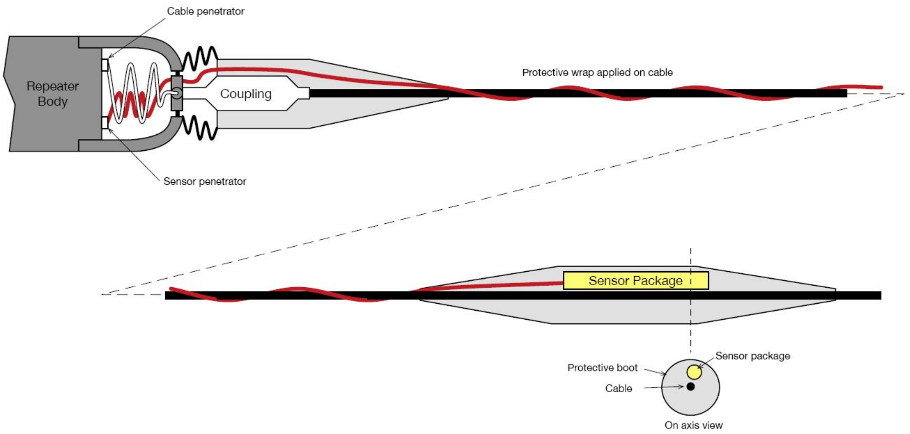


Fig. 3 (a) Crew members load an optical repeater (in wooden cradle) on the deck of Orange Marine's Pierre de Fermat cable ship near Brest, France, during the deployment of an Xtera submarine telecommunications cable system. (b) An optical repeater slips beneath the waves as the cable it is attached to is deployed along the ocean floor. Credit for both photos: Bertrand Clesca, Xtera.



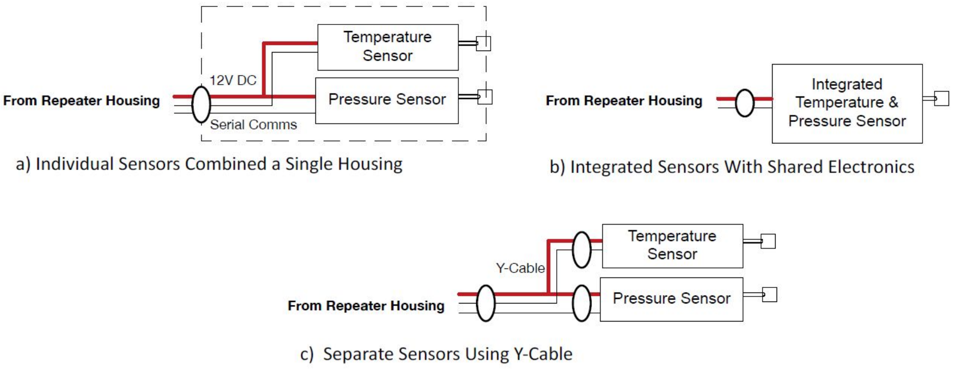


Fig. 4 Sensor attachment (from Lentz, 2016). Top: Attachment and coupling to main repeater. Bottom: Different options for science module.

Wet demonstrator

The purpose of a *Wet Demonstrator,* i.e., a pilot deployment, is to prove the viability of sensor monitoring within a commercial system. The envisioned approach is a sea trial deployment with multiple-vendor wet hardware solutions to acquire sensor data continuously along a commercial system. The sensor/system interfacing will vary and reflect appropriate vendor specific approaches. During the workshop possible sites were discussed. In order to minimise cost, the trial site could possibly be organised as a piggy-back to an existing scientific cabled observatory.

Alternatively, SMART capability could be included from the start inmodest sized commercial systems as a pilot (e.g., inter-island but long enough to require repeaters, or with a dedicated scientific cable run in parallel). For example, the Office of Post and Telecommunications (OPT) New Caledonia has issued an RFP to do this.

Ideally, the location of the wet demonstrator would offer an interesting target, i.e., be near a subduction trench, or otherwise tectonically active area. Sites/Observatories that were discussed at the workshop include: the Ocean Observatories Initiative Cabled Array of central Oregon, the Ocean Networks Canada NEPTUNE cabled observatory, the ALOHA observatory in Hawaii, the South Pacific Islands, and the Hellenic trench.

Cable costs

The NASA workshop report (Howe et al., 2015) made an estimate of the costs: ”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.”

The actual additional maintenance costs for the cable after deployment are negligible, although some significant costs will be incurred for the additional infrastructure on cable landing sites and for the data management systems.

The costs of a wet demonstrator are estimated to be of the order of $10M ($2M design costs + $4 M development + $4 M deployment), but can vary significantly depending to what extent piggybacking on other activities in existing cabled observatories is possible and whether some components, such as short unused cable segments, could be donated to the project.

It must be pointed out that all cost estimates given are extremely rough estimates, which can only be refined once the engineering concepts are fleshed out further.

Early warning targets

Most tsunamis are triggered by sudden uplift or subsidence of the seafloor resulting from large and great earthquakes. Tsunamis have been responsible for a significant proportion of earthquake-related deaths. Earthquakes with magnitudes larger than ~7 can cause tsunamis threatening nearby seashores, and earthquakes with magnitude > 8-8.5 have the potential of triggering tsunamis capable of causing devastation even across ocean basins. Notably, the 2004 Sumatra-Andaman earthquake caused more than 220,000 deaths from the tsunami, the majority of which occurred in the Aceh province in the near field of the tsunami, but also in other countries further afield (Thailand, Sri Lanka, India, and even Eastern Africa). The Tohoku earthquake in March 2011 is another example where the tsunami caused nearly all of the ~19000 fatalities.

The challenge of tsunami early warning can be broken down into (1) quick detection, location and magnitude determination of potentially tsunamigenic earthquakes, and (2) direct detection of the tsunami. In both taks, SMART cables would provide substantial benefits in providing faster warnings and more detailed constraints, thus reducing losses but avoiding unnecessary evacuations.

Earthquake Detection

The first evidence for triggering a tsunami warning usually comes from seismometer and accelerometer networks, which detect the triggering earthquake, as elastic waves travel much faster (6-8 km/s for P waves at local to regional distances of a few 100 km) than tsunami waves (200-250 m/s in the deep ocean, slower near the continental margin). In some countries the seismological data are supplemented by the analysis of GPS data, which faithfully records the near field static displacement for large earthquakes. The most important pieces of information are the magnitude of the earthquake and its location, which is often the only information available when the decision has to be taken to trigger a tsunami warning or advisory for the near field. With a few exceptions, where dedicated cabled ocean bottom observatories have been installed (Japan, Cascadia), the seismic network is limited to land-based observations. As tsunamigenic earthquakes have most of their rupture offshore, and earthquakes near the trench are of particular concern, and the limitation to land-based instruments delays both detection and location. Also, the one sided view of the earthquake source results in much larger uncertainties, particularly with respect to depth.

Furthermore, events with similar magnitude and epicentre can differ dramatically in their tsunamigenic potential. The main factors are:

1. *Length of the rupture and source directionality.* Source length is an important parameter in determining a tsunami's destructiveness in the far field, and determining the affected part of the coast line in the near field. The same is true for source directionality, which measures where most the earthquake energy is released

with respect to the hypocentre, the nucleation point of the rupture. Where the seafloor topography varies along the strike of the subduction zone or where there are islands present, the direction in which the earthquake ruptures can make the difference between a catastrophic tsunami and one whose runup is measured in tens of centimetres. The 2005 Mw 8.6 Nias Island (Indonesia) earthquake did not generate a tsunami that was destructive away from Sumatra because the presence of Nias Island reduced the amount of water displaced by the earthquake.

2. *Slip distribution*. Great earthquakes do not have homogeneous slip distributions. In many cases most of the energy release is well away from the epicentre, affecting the strength of the tsunami at nearby coastlines. Examples include the Aceh-Andaman earthquake (Sumatra, Indonesia, 26 December 2004 Mw=9.3) or the Arequipa, Peru 23 June 2001 (Mw=8.4). The slip distribution can also significantly affect the estimated arrival time of the tsunami, even in the far field to a limited extent.
3. *Rupture speed*. Whereas the ground deformation imposed by the earthquake rupture can be treated, to first order, as instantaneous, low rupture speed is an effective diagnostic indicative of low shear rigidity (weak material) in the very shallow subduction megathrust. Earthquakes, whose rupture zone lies predominantly within weak low rigidity material are so-called tsunami quakes because the tsunami generated is much larger than expected based on the seismic moment. This is due to the greater displacement resulting from the earthquake in weaker materials. Tsunami quakes also generate much less ground shaking than expected. Populations in the near field will often not perceive a tsunami threat and thus not self-evacuate. The tsunami quake is perhaps the greatest challenge to tsunami warning systems, yet at the same time the type of event where the warning system can really make a big difference in the near field.
4. *Focal mechanism*. The largest events in subduction zones generally occur as low-angle thrusts on the subduction megathrust and accommodate large-scale plate convergence. Nevertheless, great earthquakes can also occur as intraplate events. For example, normal faulting events in the outer rise, i.e the oceanic plate just seaward of the trench, have generated deadly tsunamis in the past (e.g. Sumba, Indonesia, 19 August 1977, Mw=8.4, Samoa, 29 Sep 2009, Mw=8.0). Steeper angle thrusts in the overriding plate, so-called splays, could also lead to an increased tsunami hazard - slip on a splay fault has been hypothesized to have enhance the tsunami of the 2004 Sumatra earthquake. The steeper dips of the fault planes of interplate events potentially increases the vertical movement of the seafloor and thus their tsunamigenic potential.

The fast determination of these properties with land-based sensors is very difficult due to the one-sided view. Hence, sensors on the continental margin and on the oceanic plate are crucial for obtaining fast and reliable results. A few dedicated systems are operating or are under construction at selected margins (Cascadia, Japan) but SMART cables would allow a much wider coverage (see presentation by R. Wang).

Accurate magnitude determination for great earthquakes relies on measurements at long periods. For this, the established practice is to utilise the so-called W-phase. The W-phase is a combination of Rayleigh wave overtones that travel with a group velocity between that of P and S waves. Centroid Moment Tensor (CMT) inversions performed with the W-phase yield an authoritative magnitude and focal mechanism without the need to wait for the arrival of the slower travelling fundamental mode surface waves. The pressure sensors planned for SMART cables are expected to be sensitive enough to accurately record the W-phase. SMART cables could thus allow the computation of the W-phase CMT within 5-10 minutes for both trans-oceanic and margin-parallel cable routes.

Direct tsunami detection through seafloor pressure fluctuations

In the *near field* the density of cable networks will allow more timely warnings (see summary of presentation by S. Weinstein). Understanding tsunami size from near-field pressure recordings requires separation of the pressure fluctuations induced by elastic waves and acoustic modes in the water from the tsunami wave, which is possible using frequency filtering but requires much higher sampling rates than provided by standard DART buoys (see presentation by M. Nosov and A. Babeyko). The denser sampling provided by SMART cables also allows a much better estimate of the along-strike extent of tsunami generation. With these more accurate measurements of tsunami amplitudes and along-strike extent, more targeted warnings are possible.

In the *far field*, similar arguments apply. Here ocean-crossing SMART-cables would provide a reasonable sampling of the tsunami wavefield (see presentation by N Rakowsky). Information from cabled networks could be used to either generate a forecast or validate an existing forecast based on source characteristics. In particular, this is a good way to ascertain the radiation pattern of the tsunami, i.e., the variation of tsunami strength as a function of the source azimuth. Evacuations on distant coastlines outside the main lobes can thus be avoided while still providing adequate warning for more strongly affected areas.

A dense network would also meet the challenge of detection of tsunamis triggered by non-tectonic sources, typically land or submarine slides, and even meteorological phenomena. Submarine slope failures on the continental margin are also known to trigger cable breaks, so multiple cable breaches could be a diagnostic for a massive submarine sliding in their own right. For example, the slope failures triggered by the 2011 Tohoku earthquake resulted in 15 cable breaks. However, there is only a poor correlation between the cable breakage rate and the size of the triggering earthquake (Pope et al., 2017).

Solid Earth research

In addition to their use in early warning networks, SMART cables would provide a boost to the research into Earth processes. Here, we discuss a few sample applications to Earth structure and earthquakes source studies but really there is a large number of studies, which could be carried out with these new sensor networks.

The number of openly available broadband stations has increased dramatically in the last few years, such that most continents have a reasonable coverage with seismometers and detailed images of the lithosphere and deeper mantle can be derived for the continents. However, operation of ocean bottom instruments is costly, in particular where distances between stations are large and islands are sparsely distributed such that the global coverage of the ocean basins with permanent stations has hardly improved at all compared to the situation 10 years ago. In addition, large swaths of the ocean are plates with little internal deformation and thus hardly any seismicity. Having a limited number of sources and receivers in large parts of the ocean by necessity limits the global coverage. Here, we briefly consider exemplary classical seismological analysis approaches and how they might benefit from ocean-crossing SMART cables.

Global Earth Structure from body waves

Body waves are of particular importance for measuring mid- and lower mantle structure and the mantle transition zone. A dramatic improvement of ray coverage could be achieved with a few SMART cables, which could extend well into the mid-mantle below the large ocean basins (see presentation by C. Rowe). Most tomographic studies make use of secondary phases such as PP and SS, which are reflected at the seafloor or Earth's surface at the midpoint between earthquake and receiver. Although these secondary phases help to fill out the gap in station coverage below the ocean basins, there are often substantially lower frequency, have complicated sensitivity regions and therefore are more limited in resolution compared to higher frequency direct arrivals. Again, waveform tomography techniques mitigate against this to some degree, but computational resources limits the total number of earthquakes which can be included in these studies, and the demands on signal-to-noise ratios are stronger.

In addition to providing enhanced coverage for global tomographic models, two-dimensional transects along the cable can be constructed, allowing in principle horizontal resolution close to the order of one or two station spacings, i.e. ~100 km. Vertical resolution of body wave travel time tomography will be poorer, but if coupled with surface wave approaches, at least in the upper mantle, similar or better vertical resolution might be achievable.

Another body wave technique capable of high vertical resolution is the receiver function technique, which uses conversions of wave types (P-to-S and S-to-P). While this has been used with free-fall ocean bottom instruments its application on the ocean floor is tricky because (a) high quality horizontal component seismograms are required and (b) water layer reverberations need to be taken into account in many situations. Tilting of the cable by currents and possibly asymmetric horizontal response imposed by the sensor housing geometry and cable direction may potentially degrade the quality of the horizontal components..

Surface wave tomography and ambient noise techniques

Surface waves travel parallel to the surface of the Earth and their sensitivity to structure decays with depth (for fundamental modes; higher modes have a more complicated relationship but ultimately also lose sensitivity). Longer period surface waves penetrate more deeply into the Earth and are thus sensing the elastic velocities there, resulting in dispersion.

Because of the horizontal propagation of surface waves it is already possible to get good coverage of the large ocean basins (Schaeffer et al., 2016, Maggi et al. 2006), even though most stations and sources are placed around it. State-of-the-art models resolve the cooling of lithospheric plates and the larger scale pattern of anisotropy, which generally aligns with the fossil spreading direction in the lithosphere and the current plate motion direction in the asthenosphere. However, resolving smaller scale variations of azimuthal anisotropy and structure as might be caused by minor hotspots, important for a full understanding of the geodynamics will require additional long term observations of the seafloor.

There are two energy sources available. Traditionally, earthquakes are being used, and these are still the first choice, when it comes to observations at long periods (> ~30s). For the last 10 years or so, ambient noise has been used as an alternative way to get structural information. Here the long term average of the cross-correlation of the records of a sensor pair will give approximately the same record as would be obtained with the source at one station and the receiver at the other one.

Whereas it remains to be seen whether the accelerometers have sufficient sensitivity for the longer period ground velocities needed in surface wave analysis to be reconstructed, past studies have shown that Rayleigh waves from earthquakes are well recorded on ocean bottom pressure gauges and can be used for source inversions (e.g. Laske et al., 1999). The ambient noise field does not only contain seismic contributions but also contributions from water layer gravity waves but at least in deep water ambient noise correlations have been derived successfully from pressure records (Yao et al., 2011; Harmon et al., 2012).

Sample science question which might be answered by tomographic models utilizing SMART cable data include

- What is the variability of oceanic crustal and mantle lithospheric thickness and elastic properties at 100 km resolution and is it related to the stability of the mantle temperature field or chemistry, and the frequency of sources of off-axis melt.
- What is the variation of horizontal anisotropy on the scale of prospective mantle convection cells?
- Can we see evidence for minor plumes along cable routes in upper mantle velocities?

Local structure (compliance)

The transfer function between pressure and the vertical motion of the seafloor contains information on the shallow structure below it (see presentation by W. Crawford). Applicability of this technique to SMART cable systems will depend on improvements in the long period response of the accelerometer.

Earthquake source studies

The different measurements described above in the early warning section for characterising earthquakes are also important scientifically for understanding the earthquake process and its interaction with interface structure and rheological properties (see presentation by R. Wang).

In addition SMART cable sensors would drastically improve the location accuracy of many smaller local offshore earthquakes, thus providing scientifically valuable information on margin structure and seismotectonics. Such studies will also benefit from more accurate focal mechanisms and the possibility to determine focal mechanisms or small events.

Seafloor deformation

An important recent development is the potential to study silent slip events, i.e., transient episodes of plate interface slip that are too small to excite seismic waves, but which can be detected geodetically. There are many measurements available for such events at the downdip edge of the plate interface, as these occur close enough to land to be picked up by coastal GPS stations but it is very difficult to detect whether such slip episodes also occur on the shallow updip end near the trench.

Episodic vertical uplift of the seafloor can be detected in the form of pressure transients, as demonstrated for example, along the Japan Trench (Ito et al., 2013) and on the Hikurangi margin of New Zealand by Wallace et al. (2016). With recent improvements in sensor technology that ensures long term stability by in-situ recalibration, even recordings of the much slower interseismic deformation is in the realm of feasibility.

If acoustic transponders were added to the sensor package at a future date then A-GPS measurements (acoustic GPS) might be possible but require additional surface instrumentation operating in the area (e.g., autonomous waveglider), and - for the current state-of-the art methodology - additional autonomous seafloor instrumentation.

If the sensor package included an inductively coupled power and data communications capability, then in regions where the cable is not buried additional seismic and geodetic sensors that are too bulky to be included in the sensor package or which are not developed at the time the cable is deployed could be placed next to the repeater at sites of particular interest.

Data management

There is consensus that the data provided by a future SMART cable network must be open and available at minimum latency to both early warning centres and the scientific community. Established file standards and distribution mechanisms are already established in the seismological and tsunami communities.

Acknowledgements

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Abstracts of presentations

CTBTO cabled hydroacoustic monitoring system overview

Georgios Haralabus (Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Vienna, Austria)

The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) operates a global network of 321 stations and 16 radionuclide laboratories, knows as the International Monitoring System (IMS), to monitor the globe for evidence of nuclear explosions. The IMS incorporates four complimentary technologies: seismic, infrasound, radionuclide and hydroacoustics. The hydroacoustic component of the IMS includes 11 stations, five of which are T-phase stations using seismometers to pick up waterborne signals coupled in the crust of coastal areas. The other six are cabled stations with underwater hydrophones suspended in the ocean deep-sound-channel (SOFAR). Hydrophones are deployed in triangular configurations in the horizontal plane with an inter-phone separation of two kilometres. Figure 1 shows all the hydroacoustic stations in the IMS. All cable stations have two triplets of hydrophones with the exception of the station at Cape Leeuwin, Australia, which has only one triplet.

While the CTBTO uses its hydroacoustic network to ensure that no underwater nuclear test goes undetected, it is clear that the data offer a wealth of scientific information. Data from the IMS are used in studies for marine mammal vocalizations, seismic monitoring, iceberg calving, underwater volcanoes, undersea soundscaping and long-term ambient noise monitoring. Finally, the IMS also plays an important role in emergency response and disaster risk reduction. Data from IMS hydroacoustic and seismic stations are transmitted in near real time to tsunami warning centres around the world established under the auspices of the UNESCO Intergovernmental Oceanographic Commission (IOC) and contribute to tsunami emergency response plans. Tsunami warning centres in 14 countries currently participate and receive data from around 100 IMS stations.

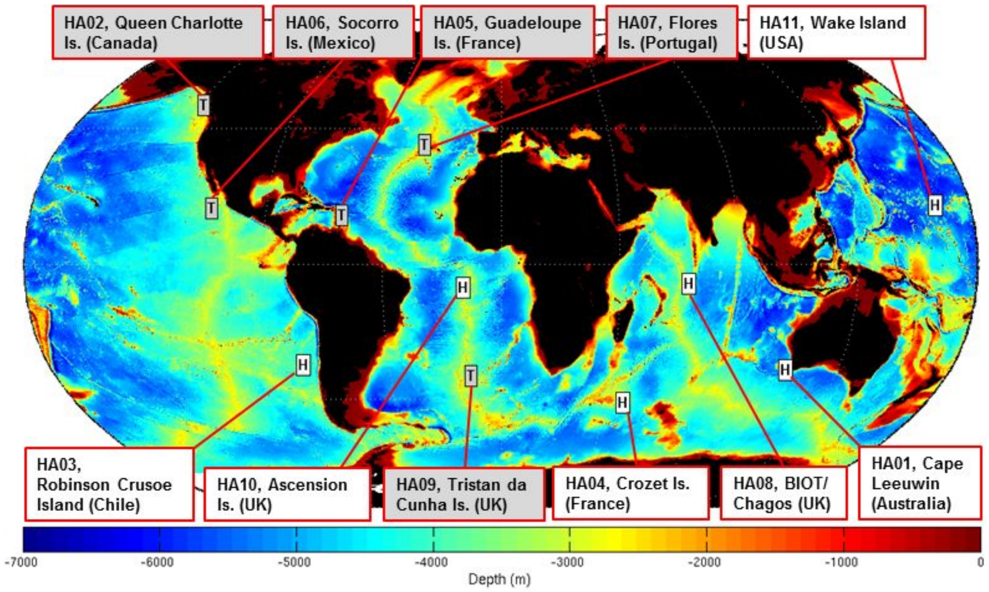


***Figure 1** The hydroacoustic component of the International Monitoring System (IMS) at CTBTO. Cabled hydrophone stations are represented by the letter "H" while T-stations are represented by the letter "T".*

A Not Too Technical Description of PTWC Operations and How Smart Cables Can Improve Them

Stuart Weinstein (Pacific Tsunami Warning Center, NOAA, Honolulu, Hawaii, USA)

PTWC functions as the basin-wide warning center for the Pacific Ocean and Caribbean Sea Basins. PTWC was the Interim Tsunami Advisory Service for the Indian Ocean basin following the 2004 Sumatra tsunami until April 2013. The growth of seismic and sea-level networks that occurred in the aftermath of the Sumatra 2004 Tsunami coupled with scientific advances has greatly benefitted the operations of the PTWC. The growth of seismic and sea-level networks has enabled PTWC to greatly speed up its determination of earthquake parameters and assess the potential destructiveness of tsunamis. PTWC uses the Mwp magnitude method to provide a robust estimate of earthquake magnitude. PTWC also calculates the MB, Ms, Mm, Me magnitudes which provide additional estimates of earthquake size and source characteristics. The Theta method (Newman and Okal, 1998, Weinstein and Okal, 2005) is used to assess potential earthquake slowness (Tsunami Quakes).

From our standpoint, the development of the W-phase CMT may be the most important scientific advance since 2004. The true size of the Sumatra Earthquake was not known prior to the assessment of the Earth's free oscillations it generated. Those estimates weren't published until weeks after (Stein and Okal, 2005, Lay et al., 2005) the great earthquake occurred and 260,000 lives lost due to the tsunami. The W-phase CMT has greatly reduced the time needed to provide an authoritative assessment of an earthquake's magnitude and focal geometry. PTWC has been utilizing the W-phase CMT since late 2010 and obtains the seismic moment and focal geometry in approximately 20 minutes. Obtaining an authoritative magnitude and focal geometry quickly enables the generation of reliable tsunami forecasts in near real-time. PTWC uses two forecast methods, RIFT (developed at PTWC, Wang et al., 2009), a shallow water finite difference method that employs Green's law for coastal forecasts, and SIFT (developed at PMEL) which relies on a database of pre-computed scenarios and uses a multi-gridded numerical method (MOST) for computing inundation of select coastlines. With RIFT, PTWC can now compute a Pacific basin-wide tsunami forecast in approximately 10 minutes (we expect this to decrease markedly with faster CPUs in the future), and a quick forecast for areas within three hours tsunami travel-time of the epicenter in ~10s.

PTWC began issuing "Enhanced Products" based on the PTWC tsunami forecast in Sept. 2014 to tsunami focal points appointed by the host countries in PTWC's areas of responsibility. These enhanced products include deep-ocean and coastal tsunami amplitude forecast maps and polygon maps which indicate the threat levels (based on forecasted tsunami amplitude) expected along the different coastlines in PTWC's areas of responsibility. KML files are also provided (forecast information can be viewed in

GoogleEarth) as well as text files containing the raw results of the coastal tsunami amplitude forecasts.

I will present calculations conducted at PTWC which show that even a few “Smart Cables” with sensors 500km apart, can appreciably speed-up both earthquake location and tsunami detection within the Pacific Basin. Many such cables with shorter intervals between sensors would greatly enhance the capabilities of the world’s tsunami warning systems.

The New Chilean Seismographic Network

Sergio Barrientos (National Seismological Center, University of Chile)

Chile is frequently affected by very large earthquakes (up to magnitude 9.5) resulting from the convergence and subduction of the Nazca plate beneath the South American plate along 3000 km of its 4200 km long coast. These megathrust earthquakes exhibit long rupture regions reaching several hundreds of km with fault displacements of several tens of meters.

Fast characterization of these giant events to establish their rupture extent and slip distribution is of the utmost importance for rapid estimates of the shaking area and their tsunamigenic potential, particularly when there are only few minutes to warn the coastal population for immediate actions.

The task of a rapid evaluation of large earthquakes is accomplished in Chile through a network of sensors being implemented, and consolidated, by the National Seismological Center of the University of Chile. The network includes about one hundred broad-band and strong motion instruments and 130 GNSS devices, all connected in real time. Forty units present an optional RTX capability, where precise satellite orbits and clock corrections are sent to the field device producing a 1-Hz stream of ground displacements with 4-cm precision. In the other units, raw data will be sent in real-time to be processed later at the central facility. Hypocentral locations and magnitudes are estimated after a few minutes by automatic processing software. For magnitudes less than 7.0 the rapid estimation works within acceptable bounds. For larger events, automatic detectors and amplitude estimators of displacement are being developed from the real time GNSS streams. This software has been tested for several cases showing that, for plate interface events, the minimum magnitude threshold detectability reaches values of the order of 6.5 (1-2 cm coastal horizontal displacement), providing an excellent tool for earthquake early characterization for tsunamigenic potential. In addition to the real-time system described above, 297 strong motion off-line instruments complement the network for engineering purposes

Broadband data in real time are publicly available through IRIS/DMC under networks C and C1. Strong motion data for recorded accelerations larger than 5% g are available through the CSN webpage (http://evtdb.csn.uchile.cl/).

Additionally, locking rate between along the subduction of the Nazca beneath the South American plate can be estimated using GNSS observations with some assumptions on the fault geometry. This is presented in Fig. 2, where the locking rate borders regions of maximum slip during the 1985 M=8.0 earthquake in Central Chile.

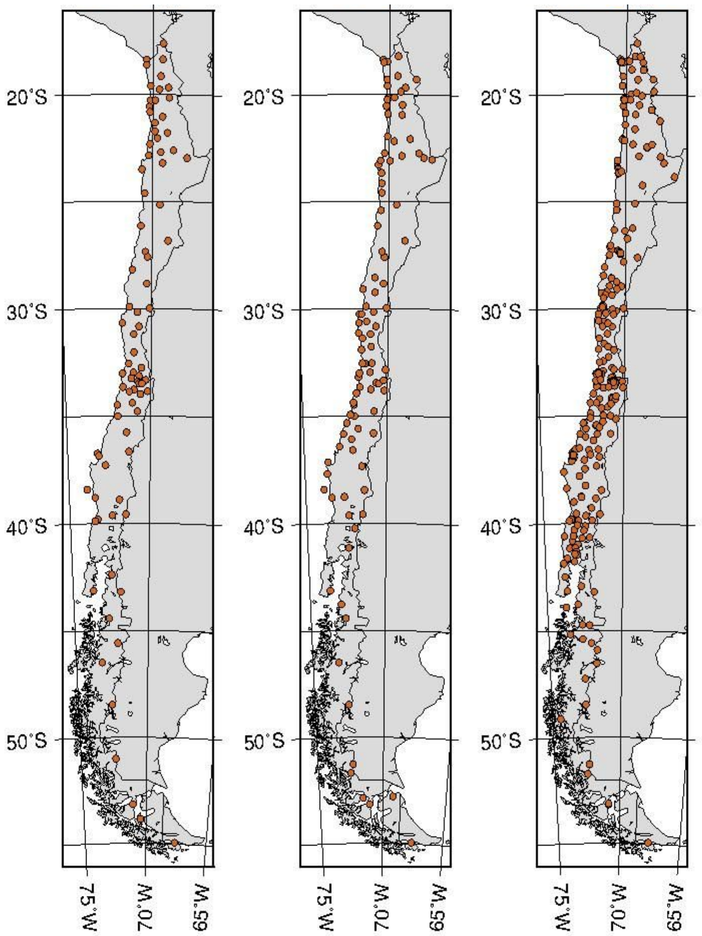


Fig. 1. Distribution of 98 multi-parametric (broadband + accelerographic) stations (left panel), 130 GNSS stations with installation to be completed by the end of 2016 (centre panel), and 297 strong ground motion devices (right panel). An important role in this network is played by 20 Integrated Plate Boundary Observatory (IPOC), an effort between GeoForschungZentrum Potsdam and Institut de Physique du Globe de Paris.

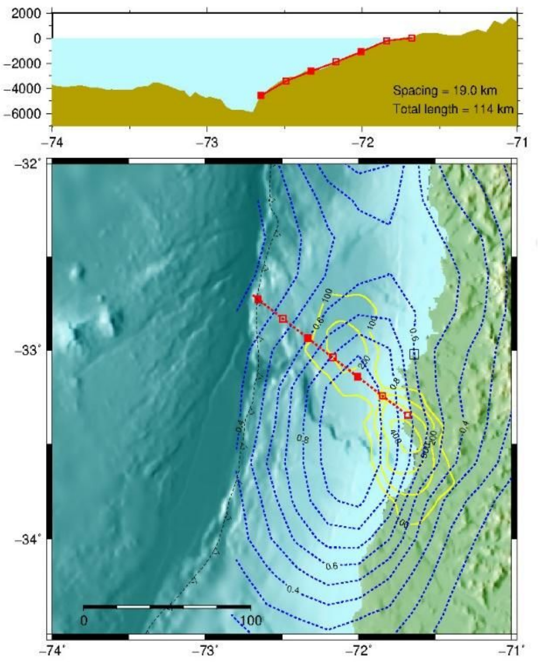
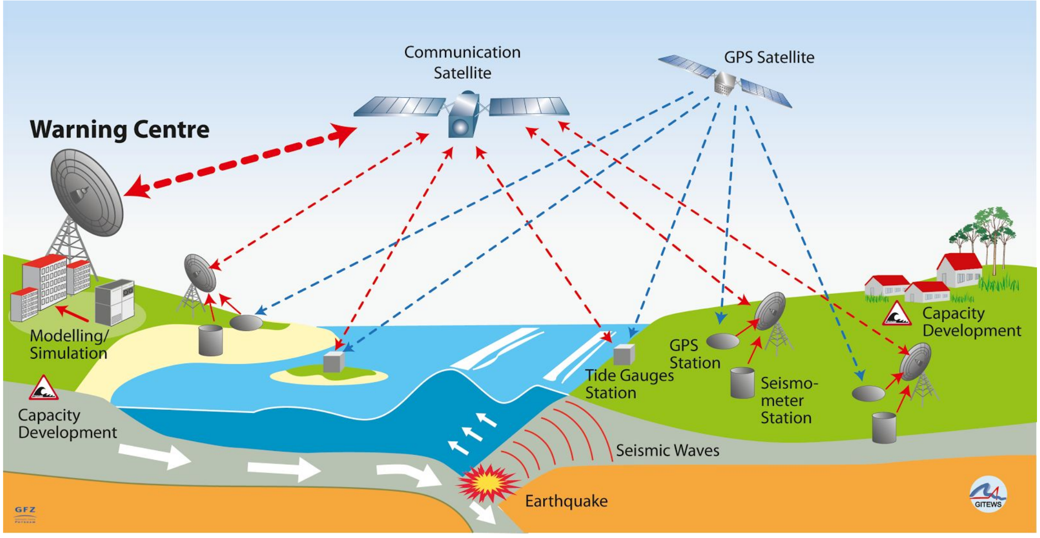


Fig. 2. Locking rate (blue dashed lines, bottom panel) between the Nazca and South American plates; maximum values are reach between the coast and the trench south of Valparaíso (small square). The slip distribution associated with the 1985 Mw=8.0 earthquake (yellow continuous lines, in cm) is located down-dip, and to the north of, the locked patch. As an example, seismic sensors as well as pressure gages place along a submarine cable (red straight line) could help detect the generation of a tsunami, providing faster early warning. Top panel, batymetric profile along the length of the cable, maximum depth are of the order of 5000 m.

Tsunami Warning in Indonesia

Joern Lauterjung and Angelo Strollo (GFZ German Research Centre for Geosciences, Potsdam, Germany)

The InaTEWS (Indonesian Tsunami Early Warning System)[3] started to operate in November 2008 and the German contribution to it, GITEWS (German Indonesian Tsunami Warning System)[4], was handed over formally to the BMKG (Meteorological Climatological and Geophysical Agency)[5] in March 2011. An intensive capacity building program carried out between 2011 and 2014, the so called PROTECTS[6] project, ensured the successful handover not only of the hardware and software components but also of the necessary know-how to successfully operate this complex system. New scientific processes and innovative technologies distinguish this system from the previous tsunami warning systems. Due to the specific geological situation in Indonesia, the previously used, established tsunami warning systems were not optimal for Indonesia. The earthquakes in the Indian Ocean at Indonesia originate along the Sunda Trench, a subduction zone which extends in an arch from the northwest tip of Sumatra to Flores in eastern Indonesia. If a tsunami originates here, in an extreme case, the waves reach the coast within 20 minutes, so that only very little time remains for an early warning. Therefore, the concept of the entire system was based on this prevailing condition and the warning must be disseminated within 5 minutes from the origin time of tsunamigenic event. More than 300 sensors including seismic, GPS and tide gauge stations have been deployed across all of Indonesia and supply their data to the warning centre in real time (Figure 1: Technical concept of GITEWS)



The basic requirement for the early warning system in Indonesia were the fast and reliable earthquake location and magnitude determination of the earthquakes. The SeisComp3[7]

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[3] https://inatews.bmkg.go.id/new/

[4] http://www.gitews.org/1/homepage/

[5] http://www.bmkg.go.id/

[6] http://www.gitews.org/1/protects/

[7] http://www.seiscomp3.org/

software package was specifically developed for this challenge by the GEOFON[8] working group of the GFZ[9] and can reliably determine earthquake strength and location within around four minutes, even with strong earthquakes. This makes SeisComp3 unique worldwide. GFZ provided this system to the community free of charge, so that all countries bordering the Indian Ocean have implemented this system quasi as standard. From the technical point of view the system, today fully operated by BMKG, has proved its capacity. The latest improvement has been the implementation of an automated Moment Tensor analysis module based on W-Phases capable to provide reliable Moment Magnitude in a very short time. Submarine sensors like what is proposed in the SMART cables Whet demonstrator initiative can further speed up earthquake locations and magnitude determinations in particular may allow to have reliable Moment Tensor solutions within the 5 minutes warning time.

NEAMTWS – Accreditation of Candidate Tsunami Service Providers and Updates 2016

Alexander Rudloff (GFZ German Research Centre for Geosciences, Potsdam, Germany)

The presentation reflects the German engagement in the accreditation process of Candidate Tsunami Service Providers (CTSP) within the Tsunami Early Warning System for the North-Eastern Atlantic, Mediterranean and connected seas (NEAMTWS). During the summer 2016 the centres from France (CENALT), Greece (HL-NTWC), Italy (CAT/INGV), and Turkey (RETMC/KOERI) were successfully evaluated by two accreditation teams under German leadership in a table top exercise.

At the 13th Session of the Intergovernmental Coordination Group (ICG) of the NEAMTWS (ICG/NEAMTWS-XIII) in Bucharest/Romania in September 2016, the four CTSP's were upgraded to TSP's. Two further CTSP's for future accreditation in 2017 or 2018 could be Portugal and Romania.

On 5th November 2016 the first World Tsunami Awareness Day (WTAD) will be held.

The Hellenic National Tsunami Warning Center (Greece): current status and future prospects as Tsunami Service Provider in the frame of NEAMTWS (IOC-UNESCO)

G. A. Papadopoulos (Institute of Geodynamics, Hellenic National Tsunami Warning Center, National Observatory of Athens, Greece)

The mandate of a Tsunami Warning Center (TWC) is to collect, record, and process earthquake data for the rapid initial warning; compute the arrival time of the tsunami in pre-selected forecasting points and collect, record, and process sea level data for confirming or cancelling the warning. For the later a dense and reliable tide gauge network is necessary. The Hellenic National Tsunami Warning Center (HL-NTWC) acts as a tsunami warning center

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[8] http://geofon.gfz-potsdam.de/

[9] http://www.gfz-potsdam.de/startseite/

for Greece and Tsunami Service Provider for the North-Eastern Atlantic, Mediterranean and connected seas Tsunami Warning System (NEAMTWS/IOC/UNESCO).

The Hellenic Arc subduction zone along with its associated South Aegean volcanic arc is the most seismically active geotectonic structure in the European-Mediterranean region producing large earthquakes measuring magnitudes up to about 8.5. Such earthquakes generated large tsunamis that affected the entire eastern Mediterranean basin in AD 365 and 1303. Regional tsunamis were also produced by earthquakes in AD 1481 and 1956, while large volcanic tsunamis were caused in AD 1650 as well as around 1613 BC.

For the monitoring of sea level changes, the HL-NTWC is supported by its own tide gauge network currently consisting of 17 stations, all being equipped with radar sensors, while three of them are also hosting pressure sensors. The sampling rate is in the order of 1/30 sec or less, which is suitable to record tsunami waves and to support tsunami operations. Four of the stations are collaborative and are operated jointly with JRC-EC, while another two are operated in collaboration with national earthquake institutes (EPPO, ITSAK). The communication with the tide gauge stations in real-time is based on the same topology of a star network system. All tide-gauge stations are equipped with GSM, 4G modems for transmitting the data. Few of them have also ADSL links that serve as the primary communication method, while GSM is used as a backup. Data from all these stations are available in real-time to the HL-NTWC control room, with their waveforms being immediately accessible by the operators for inspection and evaluation through a dedicated software (Tsunami Analysis Tool-TAT, provided by JRC). The sea level data are also available to IOC and JRC, thus being openly accessible by other warning centers. Apart from these 17 stations, tide gauge stations operated by the Hellenic Navy Hydrographic Service (HNHS) are accessible via ftp communication procedure, when they are available. Currently most of them are in the stage of upgrade. In addition, the HL-NTWC receives also directly tide gauges records, when available, belonging to other organizations in Italy and Egypt, as well as to the National Technical University of Athens. The list of HL-NTWC tide gauge stations and their general specifications can be seen in http://bbnet.gein.noa.gr/tide-gauge/.

TWCs strive to be rapid, by providing warnings as soon as possible after a potential tsunami generation; accurate, by issuing warnings that minimize false warnings and reliable, by making sure they operate continuously, and that their messages are sent and received promptly and understood by the users of the system. Therefore, continuous real-time access to sea level data, without data gaps, with minimum reception latency is of great importance for successful operational procedures. HL-NTWC looks forward to improve tsunami recording capabilities by installing seafloor sensors. Therefore, cable network technology is of great interest to HL-NTWC which is available to host a wet demonstration project.

Near real-time earthquake source imaging - a potential use of SMART cables

Rongjiang Wang (GFZ German Research Centre for Geosciences, Potsdam, Germany) and
Yong Zhang (School of Earth and Space Science, Peking University, Beijing, China)

In recent decades, earthquake early warning systems have shown their increasing importance in the mitigations of earthquake and its related disasters. More and more efforts have been made to improve methods used in real time seismology for EEW. At present, a rapid inversion of near-field strong-motion and/or high-rate GNSS records for the earthquake rupture process is the most important issue in real time seismology. By using the newly developed Iterative Deconvolution and Stacking (IDS) method for automatic source imaging, we demonstrate an offline test for the real-time analysis of the near-field seismograms of the 2008 Wenchuan and 2011 Tohoku earthquakes, aiming to estimate how fast and reliably the rupture process can be imaged. For this purpose, we compared the results from the real-time imaging with those from the retrospective reconstruction. Through the retrospective reconstruction ‘where, when and how much the fault is ruptured’ will be revealed, while through the real-time imaging the rupture evolution can only be estimated with time delay depending on the distance of the network to the source because only the data that becomes available can be used. It is shown that, using the existing strong-motion and/or high-rate GPS networks in these two cases, we are theoretically able to image the complex rupture process of the two large earthquakes automatically soon after or even during the rupture process. In the case of the Wenchuan earthquake, the rupture process can be imaged reliably with a time delay of about 30 s due to the good network coverage around the earthquake fault. In comparison, the source imaging for the Tohoku earthquake show a significantly larger time delay of about 70 s. Also the spatial distribution of the fault slip, which is of the most importance for tsunami modelling, is less stable compared to that of the Wenchuan earthquake because of the one-side coverage and father distance of the network to the source. Therefore, our test results indicate that additional off-shore networks using the SMART cables concept will improve the real-time source imaging considerably.

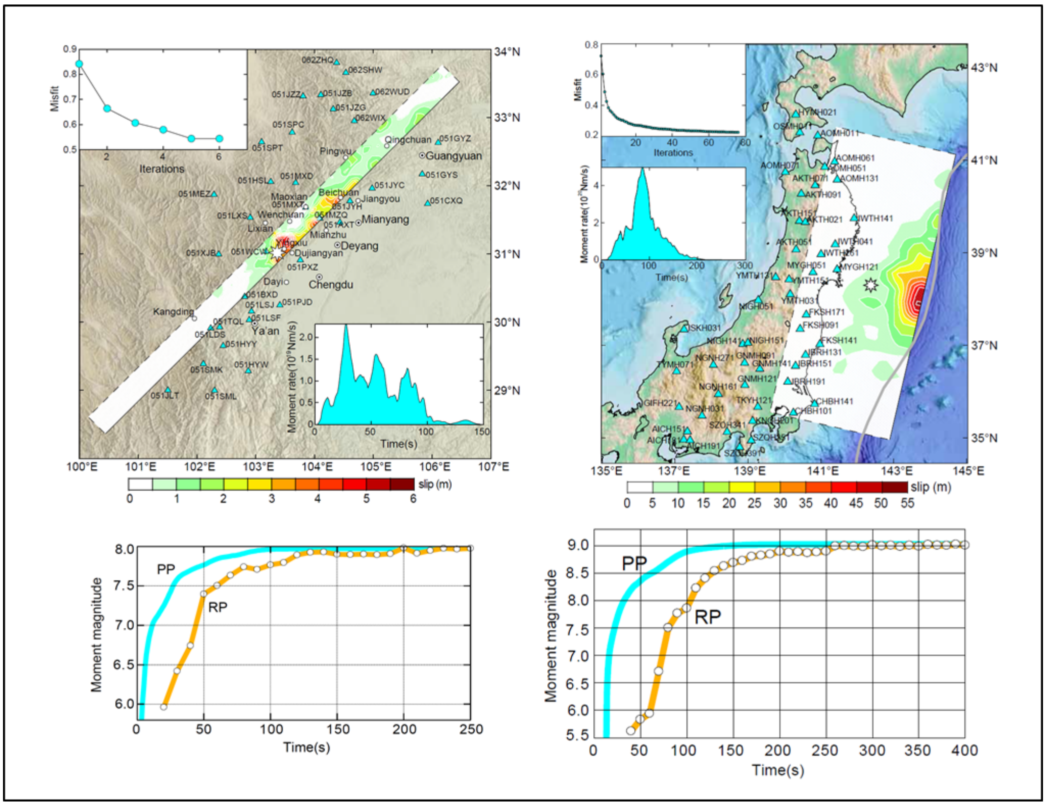

Figure 1. IDS source imaging results for the 2008 Mw7.9 Wenchuan earthquake (left) using the strong-motion data and the 2011 Mw9.0 Tokoku earthquake (right) using the high-rate GPS data. The inset figures are the misfit curve of the iterations (top left) and the source time function (bottom right), strong-motion (Wenchuan) or GPS (Tohoku) stations (cyan triangles), the surface projection of fault slip distribution, and the magnitude curve from the real-time processing (RP) in comparison with that from the post processing (PP).

The role of the tsunami modeling component in the early warning framework

N. Rakowsky, S. Harig, A. Immerz, A. Androsov, W. Hiller (Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany)

The tsunami modeling group at Alfred Wegener Institute was established as part of GITEWS (German-Indonesian Tsunami Early Warning System, BMBF-project 2005-2011). The tsunami simulation code TsunAWI, based on the shallow water equations (SWE), was developed and used to compute a tsunami scenario database with ≈4,500 scenarios and warning data products for the Sunda Arc. Furthermore, an interface was set up to manage the database and select the best matching scenarios in case of a tsunamigenic earthquake. A set of scenarios is chosen according to the earthquake magnitude and epicenter, taking a confidence interval into account. GPS data is used to refine the selection.

After InaTEWS was handed over to Indonesia, the area of coverage has been extended to a total of ≈10,000 scenarios covering all major rupture zones in the Indonesian archipelago. As TsunAWI includes inundation and operates on an unstructured mesh, all Indonesian coastal areas are represented with a resolution of 50m - 200m. This allows to use the database for risk assessment, too.

In addition to the TsunAWI database, the very fast real time model EasyWave was developed by A. Babeyko (GFZ). It comes into play if an earthquake happens outside the region covered by the database, or if more information on the source becomes available. The speed of EasyWave comes at the cost of simplified model physics and a coarse resolution. However, the resulting warning levels (none, yellow 0.1-0.5m, orange 0.5-3m, red >3m) are comparable to TsunAWI simulations.

When using simulation for tsunami warning, one should have the limitations and the uncertainties in mind. In the early warning context, the tsunami source is by far the most dominant unknown, while the limitations of the SWE at the coast can be neglected. However, if one is interested in inundation simulation for risk maps, the topography data must be of high quality and bottom roughness should be well estimated. Furthermore, simulations based on SWE can estimate the extent of the inundation reasonably well, but e.g., a realistic velocity field requires a 3D model with more model physics incorporated.

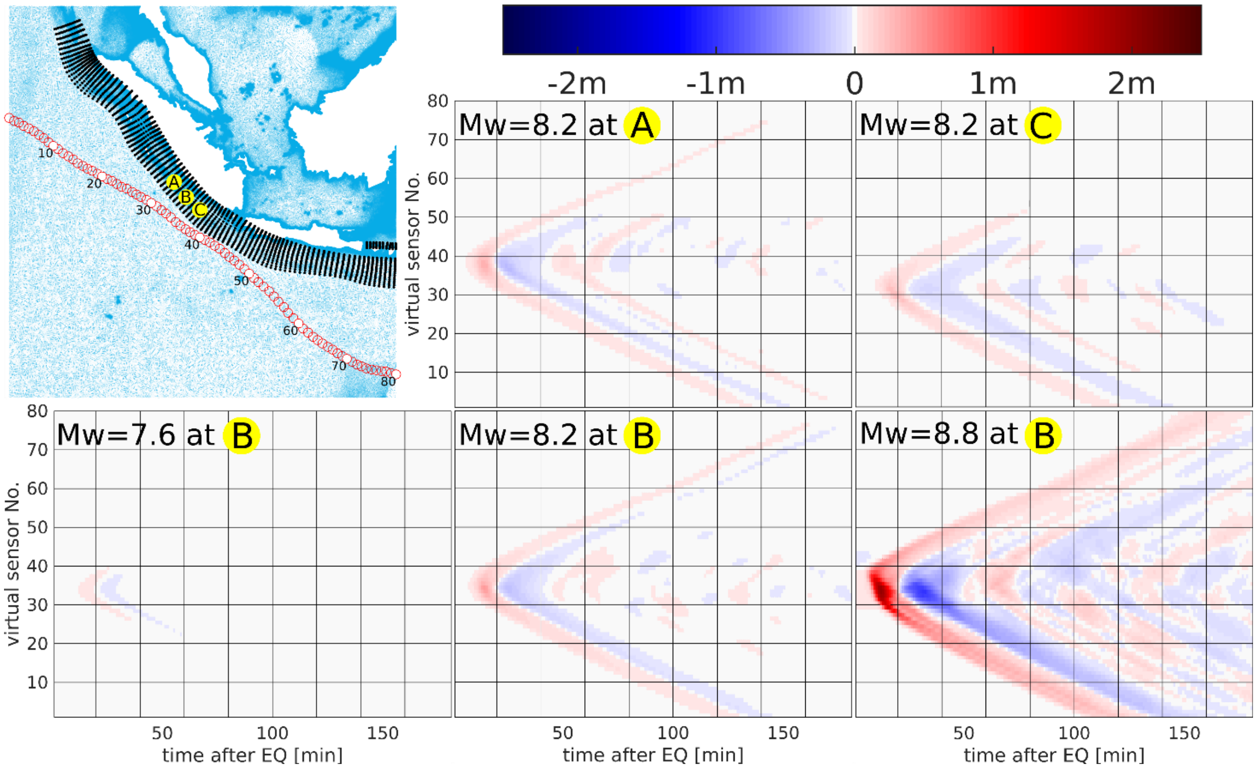

Figure 1: For five scenarios Southwest of Sumatra from the operational database, the sea level measurements at virtual sensor locations along a SMART cable are shown. Upper left: zoom into the model domain (blue dots: grid points, black larger dots: scenario epicenters, red circles: virtual cable sensor locations); upper middle: result for scenario with westernmost epicenter; upper right: easternmost epicenter; lower row: middle epicenter with varying Mw=7.6, 8.2, 8.8.

The most important contribution of SMART cables to the early warning will be to improve the source information in the first minutes after the event (Fig. 1). Regarding the sea level derived from the bottom pressure, we expect two problems in the warning for the near field. First of all, the pressure signals from the earthquake and the tsunami overlap close to the epicenter, which makes it difficult or impossible to extract the sea level. Second, when a clear tsunami signal reaches the cable location, the tsunami has most probably already arrived at the coast. However, the SMART cable will improve the far field warning and the general assessment of the situation, and it will provide vital information on tsunamis originating from other sources, e.g., landslides. The figure shows the sea level at cable sensor locations for scenarios in the database. The magnitude and the location parallel to the trench are clearly visible in the signal.

We want to thank our project partners at BMKG, DM Innovations, Geoscience Australia, GFZ, and DLR for the fruitful collaboration, and DFAT Australia and BMBF for funding.

Interpretation of the signals recorded by ocean-bottom pressure gauges

Mikhail Nosov (Department of Physics, Moscow State University, Moscow, Russia)

The idea of tsunami detecting far from the coast by ocean bottom pressure gauges was put forward back in the 60s of the past century by Sergey Soloviev [Soloviev, 1968]. But broad practical implementation of this idea in such systems as DART, DONET/JAMSTEC etc. was made possible by technological developments only at the beginning of the twenty-first century [Bernard *et al*, 2011, Matsumoto *et al*, 2013].

Signals registered by ocean-bottom pressure gauges represent a superposition of manifestations of seismic, hydroacoustic, and gravitational waves. For adequate interpretation of the signals it is extremely important to understand the character of the response of a water layer to bottom oscillations in a broad frequency range peculiar to seismic bottom movements (~ 10^{-2}–10^{2} Hz).

A compressible water layer that is limited from below by an absolutely rigid bottom and from above by a free surface, represents a waveguide, characterized by a cutoff frequency,

$$f_{ac} = c/4H \ , \qquad (1)$$

where c is the velocity of sound in water and H is thickness of the layer. Hydroacoustic waves are capable of propagating along such a waveguide only if their frequency exceeds the cutoff frequency: $f > f_{ac}$. Thus, the cutoff frequency, determined by formula (1), represents a critical frequency that imposes a lower limit on the frequency range for the existence of hydroacoustic waves. Under condition $f < f_{ac}$ water layer can be considered as incompressible liquid.

From the analytical solution of the problem of surface gravity wave generation in a layer of incompressible liquid by small dynamic bottom deformations [Levin and Nosov, 2016], it follows that the spectrum of these waves is always modulated by the rapidly decaying function, $1/\cosh(kH)$, where k is the wavenumber related to cyclic frequency ω (

$\omega = 2\pi f$) with the dispersion relation for surface gravity waves, $\omega^2 = gk\tanh(kH)$. The result of such modulation is an exponentially rapid decrease in the amplitude of waves, excited by bottom movements, as the frequency f (or wavenumber k) increases. So, surface gravity waves can be caused by bottom oscillations only of sufficiently low frequencies.

Exactly the same rapidly decaying function relates displacement of the free surface in a monochromatic wave, ξ , and the variations in pressure p, created by this wave at the bottom of the basin [Locombe, 1965]

$$\frac{p}{\rho g \xi} = \frac{1}{\cosh(kH)} \, . \qquad (2)$$

From formula (2) it follows that only waves of sufficiently low-frequency manifest themselves in variations of the bottom pressure. The above reasoning permits to introduce critical frequency for gravitational waves [Levin and Nosov, 2016]:

$$f_g \approx 0.366\sqrt{g/H} \, . \qquad (3)$$

Numerical coefficient in (3) corresponds to a hundred-fold attenuation of the wave compared to the amplitude of bottom oscillations and, at the same time, to a hundred-fold attenuation of pressure variations compared to hydrostatic law (i.e. $1/\cosh(kH) = 0.01$).

Within the “gravity-wave” frequency range of $f < f_g$ it is expedient to single out a subrange of long waves, $f < f_{lw} < f_g$:

$$f_{lw} \approx 0.0718\sqrt{g/H} \, . \qquad (4)$$

The numerical coefficient in (4) implies the deviation from the law of hydrostatics less than 10% (i.e. $1/\cosh(kH) \geq 0.9$).

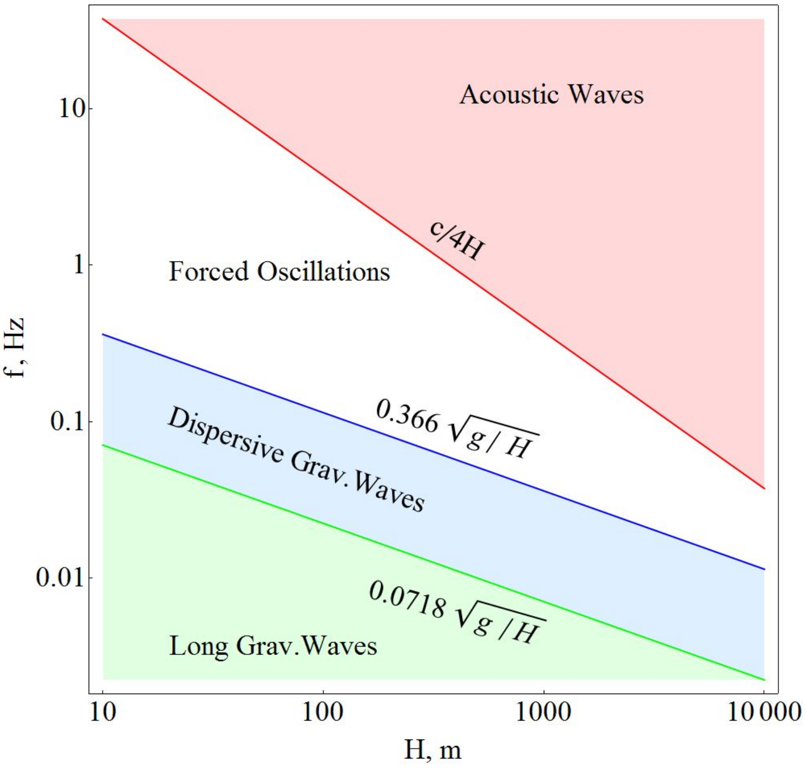

Fig. 1. Critical frequencies for gravitational and acoustic waves in a water layer versus depth H.

The dependences (1), (3) and (4) are presented in Fig. 1. In the "depth-frequency" plane these three curves identify regions, in which the excitation is possible of gravitational waves ($f < f_g$), or of long gravitational waves ($f < f_{lw}$) and of hydroacoustic waves ($f > f_{ac}$). The intermediate frequency range $f_g < f_{lw} < f_{ac}$ corresponds to the mode of forced oscillations. If the frequency of bottom oscillations is within the range of "forced oscillations", then neither gravitational nor hydroacoustic waves arise, and the water layer will follow movements of the bottom like a single whole. In the mode of forced oscillations, when the ocean bottom is flat and horizontal, variations of the bottom pressure p are related to the vertical component of acceleration a of bottom movements, in accordance with Newton's second law, $p = \rho H a$, where ρ is density of water. It is also seen from Fig. 1 that gravitational and hydroacoustic waves excited by seismic movements of the bottom are always related to different (not intersecting) frequency ranges.

To select tsunami signal from ocean-bottom pressure records, original data should be subject to low-pass filtration with cut-off frequency of f_{lw} determined by formula (4). For typical ocean depths of 5000 m the value of f_{lw} amounts to 0.003 Hz. Note that filtration with such a cut-off frequency automatically eliminates manifestations of low-frequency surface seismic waves virtually in all cases.

SMART cables provide a unique opportunity to change the “philosophy” of tsunami simulation for the sake of early warning. Nowadays one has first to determine location of an earthquake, then to calculate slip distribution and related co-seismic deformations, after that to calculate initial water surface elevation in tsunami source and, ultimately, to simulate tsunami waves. Making use of data from a set of pressure sensors located along of a SMART cable one can omit all stages mentioned above except the last, i.e. tsunami simulation. Tsunami waves can be calculated directly from sea-level data measured along the external boundary of the calculating area, i.e. along SMART cable. Spacing of pressure gauges required for this purpose, d, can be easily estimated from the Nyquist–Shannon–Kotelnikov theorem. In accordance with the theorem, the spacing should be $d \le \lambda_{\min}/2$, where $\lambda_{\min}$ is the minimal wavelength. Finally we arrive at the following condition [Nosov and Grigorierva, 2015]: $d \le \sqrt{gH}/2f_{lw} \approx 7H$. For the ocean of 5 km depth the distance between the closest pressure sensors amounts to 35 km. Larger spacing of pressure gauges is also possible, however it results in restriction on frequency of waves under consideration: $f \le \sqrt{gH}/2d$.

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Cabled systems for near-field tsunami early warning: An observation system simulation experiment (OSSE) offshore Portugal

A. Babeyko (GFZ German Research Centre for Geosciences, Potsdam, Germany), M. Nosov and S. Kolesov (Department of Physics, Moscow State University, Moscow, Russia)

The problem of far-field (distant) tsunami early warning is nowadays effectively solved by means of a prediction-correction technique based on combination of teleseismic and deep ocean observations (e.g., Titov et al., 2005). The methodology relies on the ability of sensors located at the ocean bottom to measure extremely small variations of bottom pressure caused by the passage of long tsunami waves.

This technique, however, becomes seriously challenged in case of near-field (local) tsunami. Thus, observations of local earthquakes in Japan demonstrate extremely high level of seismic and acoustic noise recorded by bottom pressure sensors. The ‘noise’ amplitude strongly dominates over the tsunami signal making detection of a tsunami wave as a challenging task (Nosov and Kolesov, 2007).

In the present study we employ advanced numerical modeling technique to conduct an observation system simulation experiment (OSSE) offshore Portugal. The experiment aims to simulate bottom pressure records at virtual DART-like sensors ‘deployed’ in the source region close to possible ruptures. At the first step, ocean bottom shaking was computed for a M8.0 thrust earthquake using the kinematic rupture modeling using code QSGRN/QSCMP (Wang, 1999). At the next step, the bottom shaking scenario was implied as a boundary condition into the full 3D compressible ocean simulation. Other than ‘classical’ shallow-water codes limited to simulate long gravitational waves, the numerical code of Nosov and Kolesov (2007) is able to additionally reproduce effects of acoustic and driven oscillations.

Figure 1 shows variation of differential bottom pressure at the virtual sensor located ~100 km apart from the earthquake epicenter. Acoustic and seismic signals (‘noise’) at this distance (black curve) totally dominate over the tsunami signal (red). Note, pressure variations with amplitude of $2x10^6$ Pa correspond (if re-computed in long-wave approximation) to the effective tsunami wave height of 200 m! That means noise amplitude in the near-field can be as much as two orders of magnitude larger that the tsunami signal itself. Despite this fact, tsunami wave can still be effectively filtered out of the noisy record due to the clear separation of ‘noise’ and tsunamis in frequency domain (Nosov and Kolesov, 2007). However, this filtering can only be applied to bottom pressure records with high sampling rate (~1Hz and more). In case of low sampling rates (e.g., 15 sec for DART I-III systems), aliasing problem will prevent successful filtering.

Thus, we conclude that the tsunami early warning in the near-filed can only be assisted by OBU’s supporting high-rate sampling and transmission (or on-site processing) of pressure measurements. The two present-day candidates are (1) cabled systems or (2) last-generation DART 4G. To our knowledgement, the latter was not yet demonstrated operationally in the near-field.

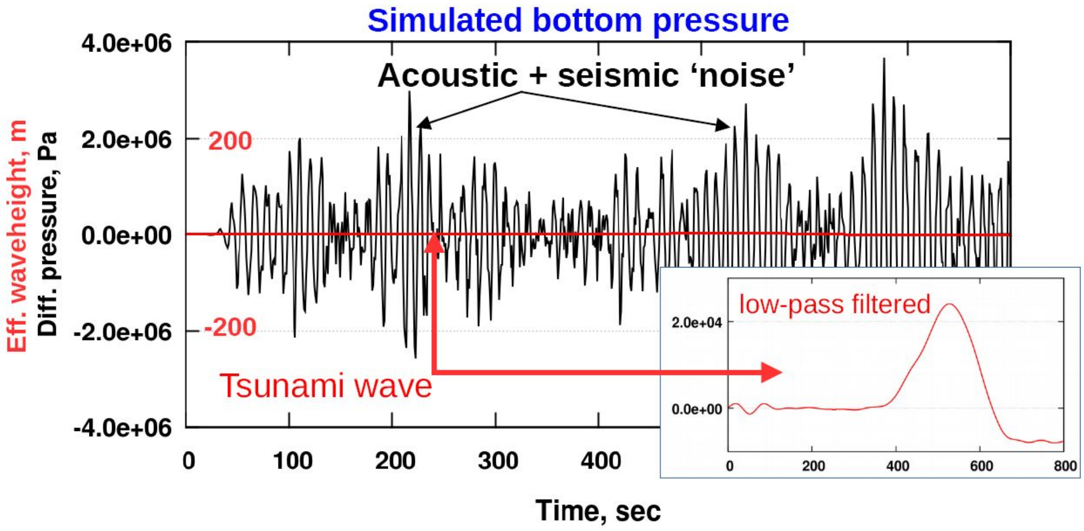

Fig. 1 Simulated variation of differential bottom pressure at the virtual sensor located ~100 km apart from the earthquake epicenter

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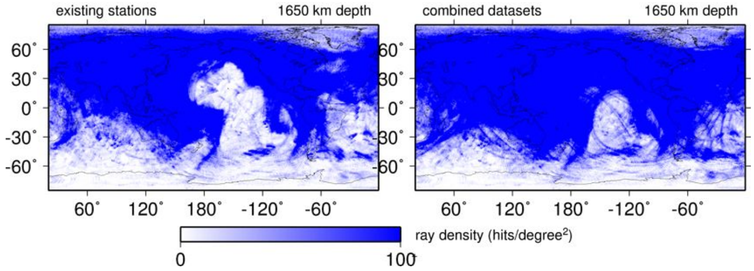
SMART Cable Sensors and Global Seismology

Charlotte Rowe[1], Ellen Syracuse[1], Carene Larmat[1], Michael Begnaud (Los Alamos National Laboratory), and Nishath Ranasinghe (New Mexico State University)

Fundamentals of seismic research require high-confidence seismic source locations which both depend upon, and allow us to build, improved geophysical Earth models. Earthquakes are unevenly distributed around the globe, however, as are seismic stations. The oceans in particular are vast regions where we not only lack sensors, but are also largely aseismic, leaving large gaps in our seismic sampling of the Earth.

We have obtained a preliminary picture of the degree to which global seismic sampling would be improved by the presence of the SMART cables and their sensors. This will allow us to see how they could improve Earth models through body wave tomography, which can lead to improved confidence in our estimates of seismic source locations. We present preliminary results for forward ray tracing through the Earth reference model AK135 for first-arriving P-waves for seismic sources between 0 and 90° from receivers. We have used as sources earthquakes of magnitude 6 and larger, recorded by current and former seismic receivers around the globe. We divide the Earth into a grid of roughly cubic cells of 1° x 1° laterally and 100 km in depth. To reduce raypath redundancy and computational burden we have used only one source and one receiver per cell. Results are presented as a function of ray density, saturating at 100 rays per cell. We compare ray density obtained for current global seismic station distribution to that afforded by the addition of seismic sensors along the first generation of SMART cables.

In future work we will also consider secondary and core phases, and examine diversity of ray direction. We plan to re-evaluate rays through a 3D Earth model, and calculate finite frequency kernels for selected paths using SPECFEM3D on one of the available LANL parallel computing clusters. 3D attenuation parameters will permit us to generate synthetic waveform for the cable receivers, which can provide insights into the seismic event detection and magnitude estimation improvements afforded by the existence of SMART cables.



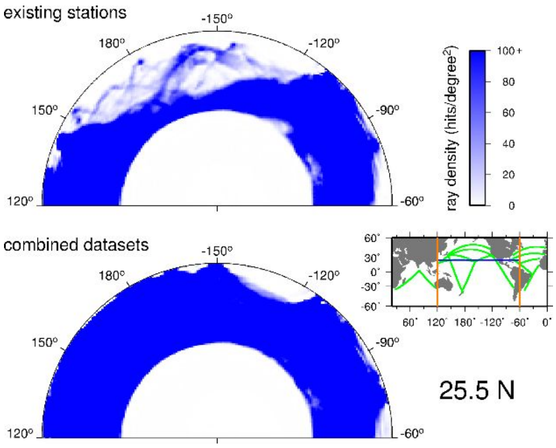


Figure: Comparison of seismic coverage without, and with, SMART cable sensors.

Seafloor compliance on smart cables

Wayne Crawford (Institut de Physique du Globe de Paris (IPGP), France)

Seafloor compliance — seafloor motion under linear ocean surface waves — is sensitive to the subsurface shear modulus beneath the measurement site. Compliance is calculated from pressure and acceleration time series at a single site and has been used to study mid-ocean ridge magma chambers (e.g., Crawford and Webb, 2002), sediment properties and gas hydrate deposits (e.g., Willoughby et al., 2008). As the compliance “source” (ocean waves) is always active, seafloor cables with pressure and acceleration sensors offer a great opportunity to observe variations in sediment and magma chamber properties over time, but the measurements must be sensitive enough at the relatively low frequencies of the seafloor linear ocean wave signal. The frequency and signal range depend on the water depth. I will present the compliance method, some of its past and present applications and the instrument noise levels necessary to measure compliance as a function of the water depth.

References:

Crawford W. C. and S. C. Webb (2002), Variations in the distribution of magma in the lower crust and at the Moho beneath the East Pacific Rise at 9–10°N, Earth Plan. Sci. Lett., 203(1), *117-130*

Willoughby E. C., K. Latychev, R. N. Edwards, K. Schwalenberg and R. D. Hyndman (2008), Seafloor compliance imaging of marine gas hydrate deposits and cold vent structures, J. Geophys. Res., 113, B07107, doi:10.1029/2005JB004136.

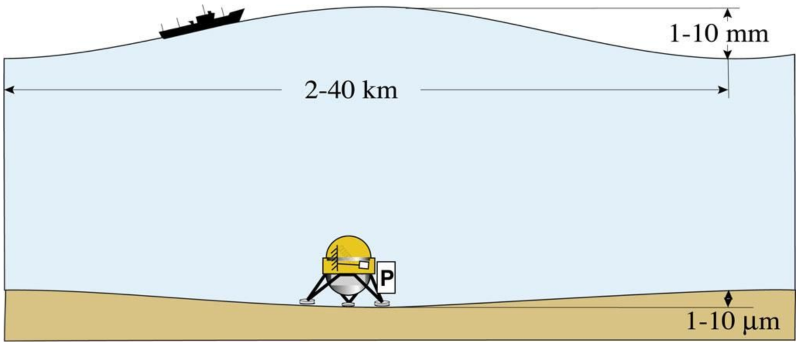


Figure 1: Cartoon of the forces and dimensions for seafloor compliance at 2 km water depth. The lower limit on the wavelength corresponds approximately to the water depth, and the overall wave amplitude may also be higher in shallow water.

Marine geophysical sensors and technology: Opportunities for integration into SMART cable systems

Heidrun Kopp (GEOMAR, Helmholtz centre for ocean research, Kiel Germany

Technical advances in deep-sea instrumentation over the past two decades have led to a new generation of sensors that oftentimes are smaller in size with reduced energy consumption. A wide suite of sensors offers scientific opportunities in very diverse marine research fields, including geophysical studies. Earthquake studies, for example, have long been in the focus of marine geophysical measurements because the majority of earthquakes are generated below the seafloor. The strongest – and potentially destructive – earthquakes are generated in subduction zones close to continental shorelines. Their investigation is of high societal relevance, because subduction zone earthquakes often occur at shallow depth close to coastal communities and potentially evolve into multi-cascade events by triggering tsunami waves (e.g. Aceh-Andaman earthquake offshore northern Sumatra in 2004, Tohoku-Oki earthquake offshore northern Japan in 2011). A persisting difficulty in these investigations is the fact that the distribution of seismic stations is highly lopsided, with the majority of seismic stations being installed onshore (Figure 1).

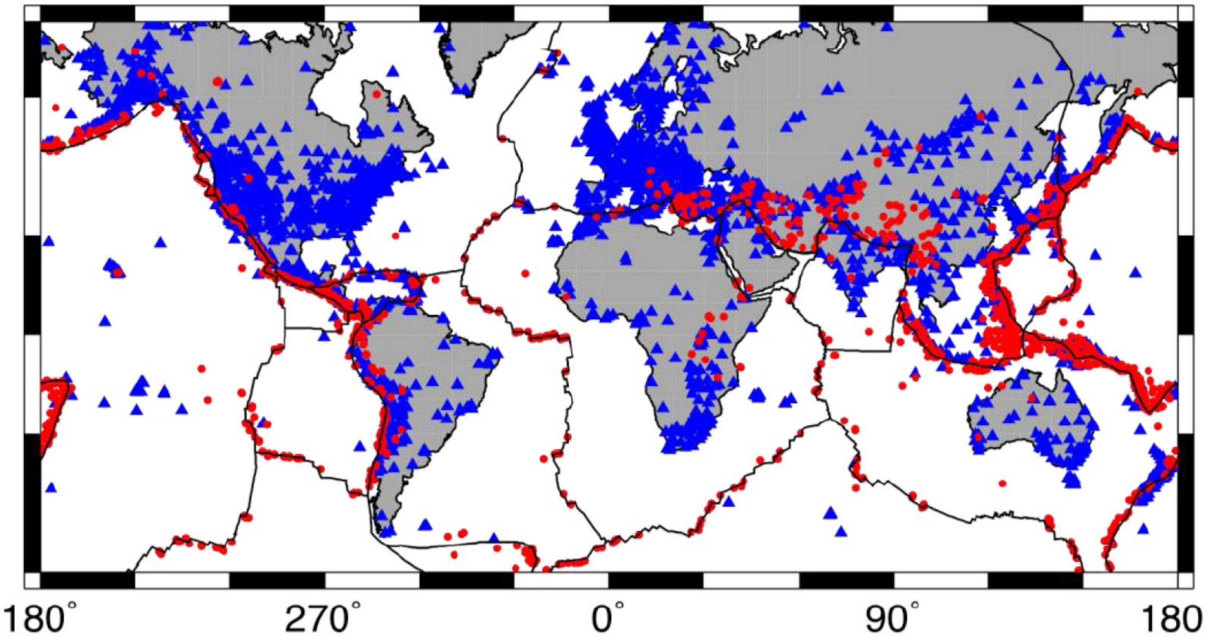


Figure 1: Global distribution of earthquakes (red dots) and seismic stations (blue triangles) (from J. McGuire, WHOI).

This heterogeneity in the station distribution results in an asymmetry of observations and hence difficulties in precise earthquake hypocenter determination. Ocean bottom seismometers commonly are free-fall instruments whose location on the seafloor is uncertain (deployment by ROV is the exception rather than the rule). More importantly, sensor coupling to the seafloor is often not optimal. Battery power for the latest generation of ocean bottom seismometers will last up to 15 month; the data however will only become available after instrument recovery. Real-time data transmission is difficult to achieve without a surface buoy. Integration of seismic sensors in a SMART cable system would allow installation of instruments at mid-ocean locations, rendering a highly improved recording coverage of global seismicity in real-time. In particular, integration of accelerometers is technically feasible. This instrumentation could potentially also serve to monitor continental slopes prone to failure (Figure 2), resulting in mass movement, in particular along passive continental margins, where slope failure may affect vast areas covering tens of square kilometers (e.g. West African continental slope).

Marine instruments are a crucial component in tsunami early warning systems, where a string of buoys tethered to bottom pressure recorders along the circum-Pacific coastlines form the backbone of the Pacific Tsunami Warning Center (Figure 3).

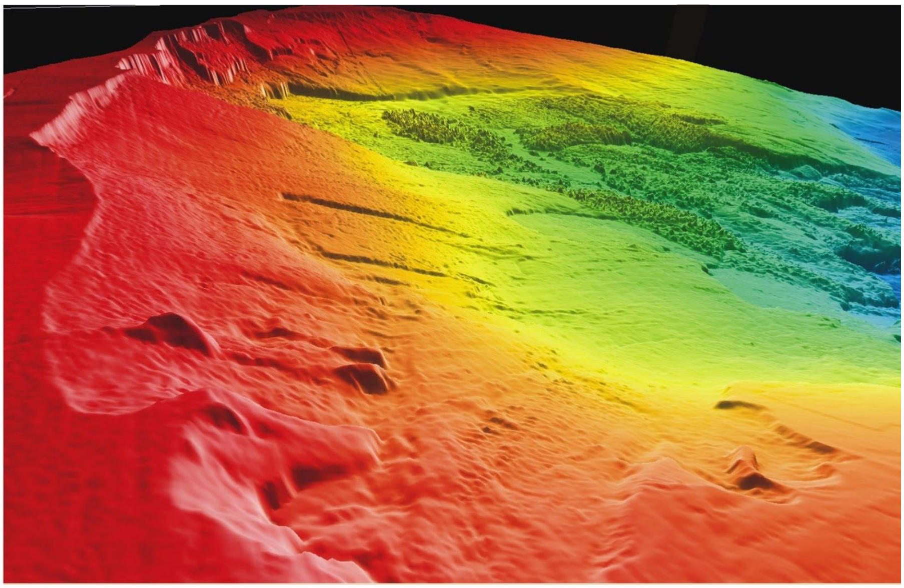


Figure 2:

High-resolution bathymetric seafloor map showing the head scarp of a large submarine slope failure. Seafloor sensors could detect motion of the seafloor as it becomes instable, contributing to hazard forecasting (from GEOMAR).

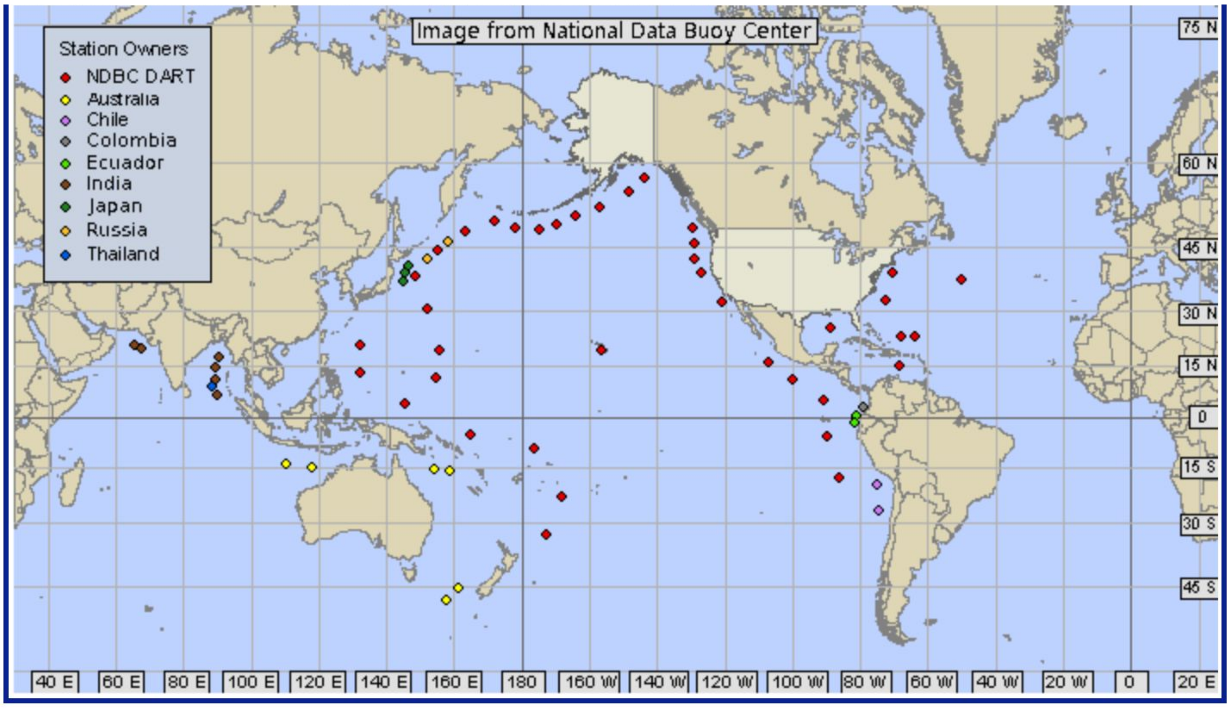


Figure 3: Global distribution of DART Buoys; national station owners indicated by color (from NOAA National Data Buoy Center Website).

These buoys transmit data in real-time, however, they are difficult to service and a number of buoys at any given time are likely not fully functioning. A more uniform distribution of sensors would result in an improved understanding of tsunami wave propagation and contribute to early warning of tsunami waves.

In addition to tsunami wave detection, bottom pressure recorders are also used to detect tectonic vertical motion in seafloor geodesy experiments. Furthermore, they provide information on the short-term variability of pressure to yield ground truthing for e.g. remotely sensed gravity fields. Data from autonomous pressure sensors installed on the seafloor may only be retrieved using a modem deployed either from a vessel of opportunity or from an autonomous surface vehicle, e.g. a wave glider.

Sea bottom instruments are required in oceanographic studies to cover the ocean below the Argo or deep Argo array (Figure 4). At these water depths (>2000 m), measurements of salinity or bottom temperature yield information on the spatial and temporal variability of seawater physical parameters (salinity, vp sensor, current meters).

Figure 4: Deployment of an ARGO float to measure temperature and salinity in water depth up to 2000 m (from KDM).

In summary, the integration of geophysical/oceanographic sensor in SMART cables opens the possibility to monitor locations, which are commonly not covered by campaign style studies. Furthermore, SMART cables off the opportunity for data transmission in real –time, which is of particular interest in geohazard forecasting.

Modular Approach to Subsea Monitoring

Jake Sobin (Kongsberg Underwater Technology, Inc., Kongsberg Maritime Contros GmbH)

The demand for comprehensive subsea monitoring solutions in the marine scientific and industrial sectors is growing. Its interacting drivers are increasing environmental awareness, legislative changes and scientific projects, as well as improvement in process efficiency. Reliable and continuous data collection of multiple parameters is required for applications in offshore decommissioning and aquaculture, as well as CCS (carbon capture and storage) and methane hydrate field monitoring. State-of-the-art sensor and platform technologies are key components in designing contemporary monitoring solutions. The available sensor toolbox comprises physical (i.e., for CTD, currents) and chemical sensors with dissolved gas sensors (i.e., for O2, CO2, CH4) playing a key role in the context of the above mentioned applications (Figure 1).

Within the community, a trend towards a wider usage of autonomous and mobile platforms is visible. In addition, a trend towards sensor interconnection, in the sense of both combined sensor suites on single platforms and the formation of larger measuring networks, can be identified. Measuring networks enable efficient data collection through a more automated and remotely accessed way of working. They utilise synergies from multiparameter measurements, with respect to the combination of stationary and mobile platforms, as well as measured parameters.

Moreover, there is a need in the academic and research community to explore technologies for Disaster Warning via Geodesy Systems. Kongsberg has invested in these studies by partnering with Paroscientific. Intense work is underway to integrate the GODS module into the Kongsberg cNODEs (transponders for underwater acoustic positioning and datalink). This includes the integration of oceanic & seismic sensors which comprises of: 2 Digiquartz® Absolute Pressure Gauges (APG); 1 Triaxial Accelerometer; 1 Digiquartz® Barometer; 3 Nano-resolution Processing Electronics; 1 Three-way Ball Valve for A-0-A Calibration. Field test are already underwater, with the hopes of the application being ready in early 2017 (Figure 2).

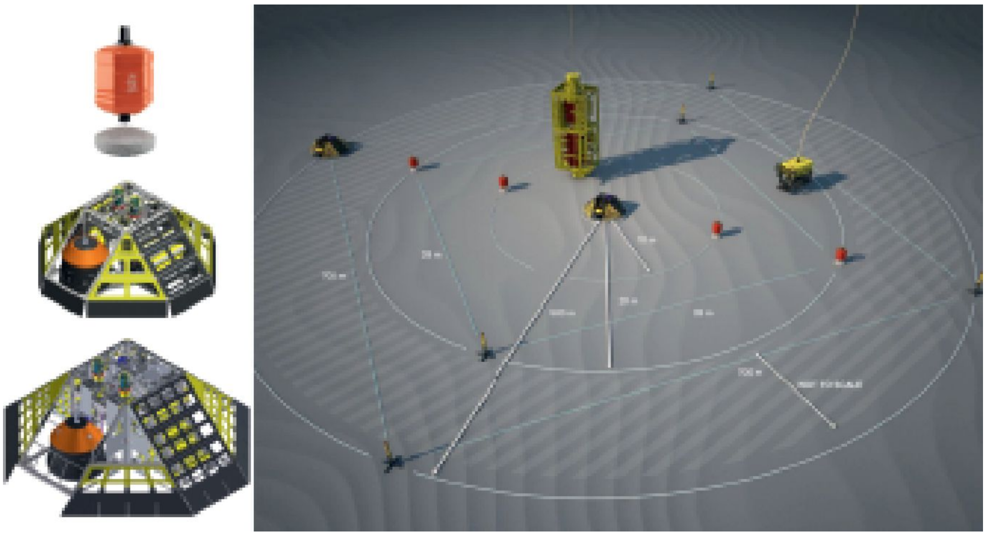


Figure 1: Different types of long-term lander seabed monitoring solutions are shown on the left (from top to bottom, the K-Lander 1, K-Lander 12 and K-Lander 30) and a schematic of a complete subsea monitoring installation centred around a wellhead featuring different lander types as well as acoustic beacons for precise acoustic positioning.

Disaster Warning & Geodesy System

Oceanic & Seismic Sensors

- 2 Digiquartz® Absolute Pressure Gauges (APG)
- 1 Triaxial Accelerometer
- 1 Digiquartz® Barometer
- 3 Nano-resolution Processing Electronics
- 1 Three-way Ball Valve for A-0-A Calibration

Figure 2: Integration will provide: Improved disaster warning times for tsunamis and earthquakes; Improved geodetic measurements for scientific research and predictions of natural disasters.

From a single science node to a dedicated warning system: ALOHA, DONET, and S-Net

Bruce Howe (University of Hawaii at Manoa, Honolulu, Hawaii, USA)

A brief review of cabled ocean observatories is given to provide context for the JTF SMART cable effort, emphasizing the evolving technology. One class of observatory is a closed system with no connectors, built for a specific purpose. Examples include SOSUS (sound surveillance system) arrays, Acoustic Thermometry of Ocean Climate (ATOC) cabled acoustic sources, the Comprehensive Test Ban Treaty Organization hydroacoustic stations, the S-net Tohoku seafloor seismic and tsunami-observation network along the Japan Trench, and more recently the proposed SMART (science monitoring and reliable telecommunications) cable systems. Another class of observatory uses connectors and nodes for flexible use, typically for science, though increasingly for oil and gas. The HUGO system (Hawaii Undersea Geo Observatory) deployed in 1997 demonstrated the combination of multi-port nodes, underwater mateable connectors, extended cable reach, high power, fiber optic communications, high power, servicing using undersea vehicles, and a hydrophone streaming real time data. More recent systems include MARS, DONET, NEPTUNE-Canada, the ALOHA Cabled Observatory (ACO), and the US OOI Cabled Array.

More detail about several of these systems is given. The ACO is a single science node operating with instruments 100 km north of Oahu. At 4728 m water depth, it is the deepest plug-and-play power and internet connection on the planet. The DONET system off central Japan monitors the Nakai Trough; it is a modest-power plug and play system; its primary mission is earthquake and tsunami early warning and secondarily science. The S-net system off Tohoku. It is a multi-segment, closed system (no changes after installation) meant just for early warning. Last is the proposed international effort for SMART subsea cables (http://www.itu.int/en/ITU-T/climatechange/task-force-sc). The basic idea is to routinely install science sensors in the repeaters of trans-ocean commercial telecom systems. As the 1 million kilometers or so of cable systems are replaced and extended over 10 – 20 years, one could potentially obtain 20,000 sensor nodes on the seafloor. The sensors (initially temperature, pressure and acceleration) will be uniquely suited for climate and tsunami and earthquake disaster mitigation. It is similar to the S-net system but its primary mission is telecom and secondarily science and early warning; it is expected to be less expensive for science/early warning than S-net.

Earthquake and Tsunami Applied Science at Ocean Networks Canada

Garry Rogers (Geological Survey of Canada / NRCan) On behalf of Ocean Networks Canada

Ocean Networks Canada (ONC) is a not-for-profit society created in 2007 by the University of Victoria to develop and manage the NEPTUNE and VENUS cabled observatories. ONC operates ocean observatories for the advancement of science and benefit Canada. The observatories collect data on physical, chemical, biological, and geological aspects of the ocean over long time periods, supporting research on complex Earth processes in ways not previously possible. The 800 km offshore NEPTUNE observatory and the nearly 50 km VENUS coastal observatory - which are the main ONC observatories - stream live data from instruments at key sites off coastal British Columbia via the Internet to scientists, policy-makers, educators and the public around the world. ONC also operates a cabled observatory in the Canadian Arctic at Cambridge Bay, Nunavut and other instruments in coastal regions. All ONC data is provided free of charge.

The NEPTUNE seismograph network has both a regional focus, with four widely spaced broadband seismographs and their ancillary instruments, and a ridge focus with closely spaced short period seismographs on the Juan de Fuca ridge. The NEPTUNE tsunami network consists of pressure gauges in the deep ocean and on the continental slope. These networks continue to evolve and have not yet achieved all the original deployment objectives.

More recently ONC has been investigating the challenges of enhancing near field tsunami warning and ONC has been funded by the Province of British Columbia to deliver an earthquake early warning (EEW) system that integrates offshore and land-based sensors to provide alerts of incoming ground shaking from Cascadia Subduction Zone megaquakes. This involves installing new offshore and onshore instruments.

Existing deep ocean telecommunications routes that parallel active margins have a high potential for SMART cable systems to provide data to advance earthquake and tsunami science and contribute to earthquake and tsunami warning systems. The Cascadia margin of western North America is one such region and one with many potential users of the data already established and supporting infrastructure already deployed.

A “wet test” of a proposed SMART cable system would be a very powerful experiment to demonstrate the feasibility and scientific and operational potential of this new deep ocean infrastructure. Ocean Networks Canada would be prepared to host such a ”wet test” and a possible scenario deployment is shown here.

A potential “wet test” of a SMART cable system connecting to the cabled infrastructure and data archiving and data distribution capabilities of Ocean Networks Canada. The SMART cable would traverse the seismically active offshore region – indicated by the rough bathymetry at the landward part of the proposed cable route – and extend to Station Papa, a long lived ship-based weather and oceanographic data gathering site.

Synergies of SMART Cables and Offshore Geophysical Monitoring in Cascadia

William S. D. Wilcock and Michael J. Harrington (University of Washington) [10]

The Cascadia subduction zone is a convergent plate boundary that lies off the coast of the Pacific Northwest, extending over 1000 km from Cape Mendocino to northern Vancouver Island. Every few hundred years, this plate boundary hosts catastrophic earthquakes similar to those that have occurred recently offshore of Japan, Chile and Sumatra. On land, there are extensive seismic and geodetic networks available to monitor the subduction zone; but since the locked portion of the plate boundary lies nearly entirely offshore, these networks need to be complemented by seafloor observations. Such considerations helped motivate the development of the Ocean Networks Canada (ONC) and NSF Ocean Observatories Initiative (OOI), multidisciplinary cabled observatories that cross the subduction zone at two sites off Vancouver Island and one off central Oregon, respectively. However, these scientific observatories have a limited spatial footprint along the strike of the subduction zone. At most locations, observations are still limited to infrequent oceanographic expeditions and to sparse and discontinuous deployments of autonomous seafloor instruments. A real time seafloor observatory extending along the entire subduction zone would allow both improved earthquake and tsunami warning, and an enhanced scientific understanding of subduction processes in Cascadia. The development of such a system if potentially synergistic with SMART cables.

Earthquake Early Warning (EEW) systems provide warning of impending strong shaking from a nearby earthquake. The Pacific Northwest Seismic Network is currently implementing an EEW system, in collaboration with the U.S. Geological Survey and regional partners, using data streams from seismic and geodetic networks on land as well as from the few instruments available on the cabled networks. It will provide seconds-to-minutes warning of the strongest ground shaking, depending on an individual’s proximity to the epicenter. For earthquakes that initiate offshore in the subduction zone, the existing network will provide a warning. However, the availability of real time offshore instrumentation along the entire subduction zone would improve its reliability and accuracy, add up to 15 s to the warning time, and ensure an early warning for coastal communities nearest the epicenter. Furthermore, real-time offshore networks of seafloor pressure sensors above the subduction zone would enable monitoring and accurate predictions of the incoming tsunami - NOAA’s existing buoy system is sparse, and designed only to facilitate warnings of tsunamis from distant earthquakes.

From a scientific standpoint, there are a variety of important questions, many related to hazard assessment, which motivate extensive offshore monitoring. Currently we lack a basic knowledge of the plate convergence rate and direction and their variations along

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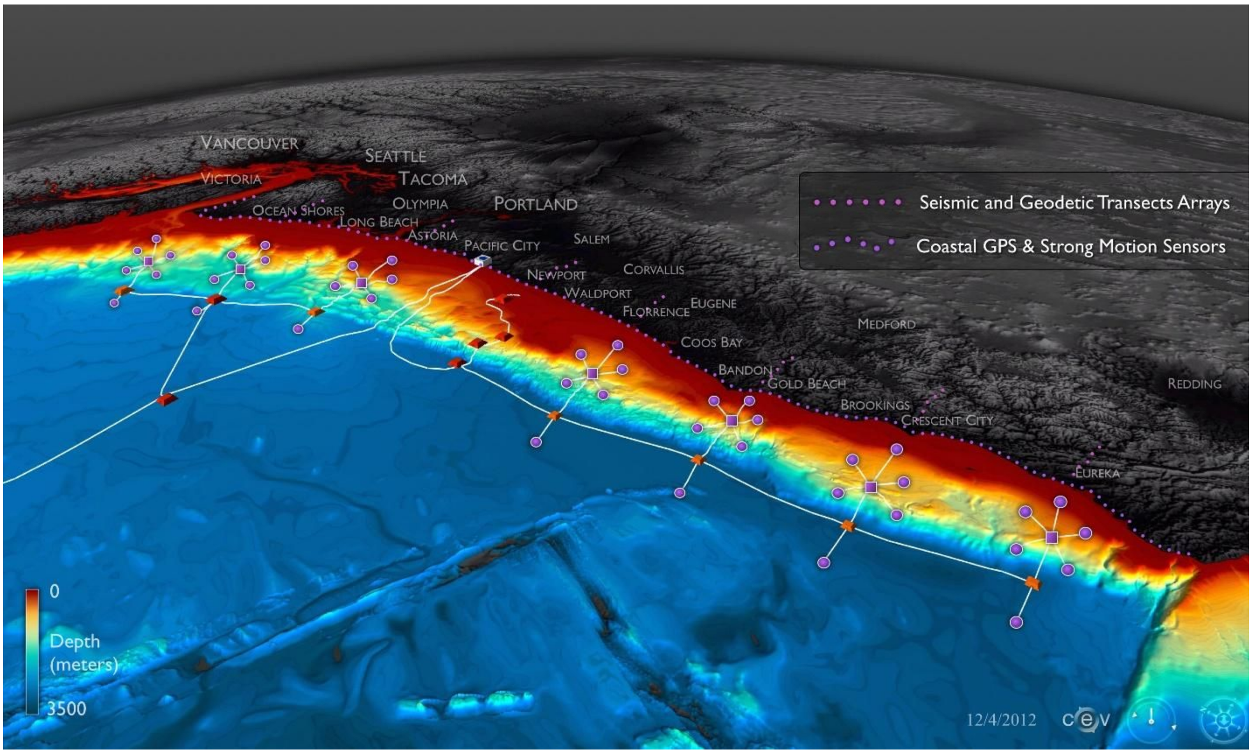
[10] Representing the University of Washington Early Warning Offshore Cascadia (EWOC) Team which also includes David A. Schmidt, John E. Vidale, Paul Bodin, Geoffrey S. Cram, John R. Delaney, Frank I. Gonzalez, Deborah S. Kelley, Randall J. LeVeque, Dana A. Manalang, Chuck McGuire, Emily C. Roland, Mark W. Stoermer, James W. Tilley, Christopher J. Vogl.

strike. Long term measurements of steady deformation and observations of transient processes such as fluid pulsing, microseismic cycles, tremor and slow-slip are necessary for assessing the dimensions of the locked zone and its along-strike segmentation. Such information is critical for improving constraints on the likely size of great earthquakes and assessing how far up-dip and down-dip rupture will extend, which are key parameters for determining a subduction zone's tsunamigenic potential, severity of coastal flooding, and shaking pattern on land. Long-term monitoring will also provide baseline observations that can be used to detect and evaluate changes in the subduction environment. Tantalizing evidence from the most recent great earthquakes in Japan and Chile suggests that these events may have seismically or geodetically observable precursory signals, but improved monitoring is required to understand the degree to which they are predictive.

A real-time offshore network along the entire subduction zone will be costly to install and operate, and its implementation in the US will require support from federal and state governments, private partners and the academic community. The University of Washington (UW) is conducting a preliminary assessment of the US portion of this system that will consider its design, cost and benefits. For a cabled installation, there are two possible endmember designs. First, it could be similar to the existing ONC and OOI observatories in the Pacific Northwest and the DONET observatories in Nankai, Japan, with a trunk cable linking primary junction boxes that are each connected via secondary cables and junction boxes to a flexible and expandable network of instruments. Alternatively, it could follow the approach of the S-net system being installed along the Japan Trench and the SMART cable concept, with a basic set of sensors hardwired into the cable. The system could also be a hybrid of these two cabled approaches and might incorporate emerging technologies such as buoys that are cabled to the seafloor, buoys and surface autonomous vehicles that connected acoustically to the seafloor, and seafloor instruments that are connected acoustically or optically to the network. While less flexible, the advantages of placing sensors within the repeaters on the trunk cable are likely to be a lower lifetime cost for a given spatial coverage and increased reliability. The sensors on a SMART cable can also be easily buried in shallower waters to protect them from trawling.

Whatever the design of the system, the minimal basic sensor package for earthquake and tsunami early warning comprises a seismometer/accelerometer and a bottom pressure sensor, two of the three sensors that are initially envisioned for SMART cables. The UW is currently collaborating with the Scripps Institution of Oceanography (Mark Zumberge and Glenn Sasagawa) on a geodetic experiment off the central Oregon. In this project, long-term bottom pressure records are calibrated to remove sensor drift by making repeated campaign-style observations using the SIO Absolute Self Calibrating Pressure Recorder (ASCPR), an instrument that incorporates a dead-weight tester to calibrate Paroscientific pressure gauges. In 2017, the UW will conduct a test on the MARS cabled observatory in Monterey Bay of the new Paroscientific Geodesy and Ocean Disaster Sensor (GODS). This instrument comprises an accelerometer and a pressure gauge that is calibrated to remove drift by periodically switching from seafloor pressure to the internal pressure of the pressure housing. The UW is also developing a tiltmeter for cabled seafloor deployments that is based on the Paroscientific accelerometer. For this instrument the horizontal components are used to measure tilt with the drift removed by periodically rotating each component into the vertical to measure the acceleration of gravity. The OOI cabled array is a potential site for the SMART cable wet demonstration project. Such a test could utilize the expertise of the UW working with cabled observatories and seafloor sensors, and would be very contribute to efforts currently underway to evaluate systems that would expand real-time offshore infrastructure for early warning and subduction zone research.



Conceptual illustration of the US portion of an offshore geophysical network along the Cascadia subduction zone. For simplicity, this illustration assumes that the existing OOI cabled array will be expanded to extend the length of the subduction zone, but many other approaches, including SMART cables, are possible (Figure created by the UW Center for Environmental Visualization).

Ocean Observatories Initiative – Cabled Array

Michael J. Harrington and William S. D. Wilcock (University of Washington) [11]

The University of Washington Applied Physics Laboratory in conjunction with the University of Washington School of Oceanography designed, built, installed and now operates the Cabled Array component of the National Science Foundation (NSF) funded Ocean Observatories Initiative (OOI). This system brings unprecedented power and real-time bandwidth to the seafloor off the coast of the Pacific Northwest enabling new and novel

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[11] Representing the University of Washington Early Warning Offshore Cascadia (EWOC) Team which also includes David A. Schmidt, John E. Vidale, Paul Bodin, Geoffrey S. Cram, John R. Delaney, Frank I. Gonzalez, Deborah S. Kelley, Randall J. LeVeque, Dana A. Manalang, Chuck McGuire, Emily C. Roland, Mark W. Stoermer, James W. Tilley, Christopher J. Vogl.

scientific instrumentation as well as providing a long term base of continuous core oceanographic measurements on the seafloor and in the water column. It has been designed to have an operational life of 25 years with significant room for expansion beyond is initial configuration.

The Cabled Array system is divided into the Primary and Secondary Infrastructure. The **Primary Infrastructure** was designed, built and installed by L3. It is based on highly reliable telecom cable seafloor distributions systems used for sending data over fiber optic links between continents. It is composed of 890 km of backbone cable running from a Shore Station in Pacific City, Oregon to 7 Primary Nodes at sites of scientific interest across the Juan De Fuca tectonic plate. Each Primary Nodes has 7 ROV Wet Mate connectors and can provide a total of 8 kW of power and 10 Gbps of bandwidth to the attached equipment.

Port Type	Number per Node	Output Port Voltage	Maximum Power per Output Port	Maximum Total Power	Protocols
Normal	5	375VDC	8 kW	8 kW	Optical 1GigE
High Bandwidth	2	375VDC	8 kW	8 kW	Optical 10 GigE

Primary Infrastructure Connections

The **Secondary Infrastructure** was designed, built and installed by the University of Washington Applied Physics Laboratory. It is composed of 18 seafloor nodes, 3 sets of moorings covering the entire water column, the interconnect cables and the scientific instrumentation. The Secondary Infrastructure components are configured to provide the correct power and communication interface needed by each instrument in the system and to aggregate the signals to send back through the Primary Infrastructure to the shore based processing centers and to allow for continuous real time command and control of the instrumentation.

	Number of Instrument Ports	Output Port Voltage	Maximum Power per Output Port	Maximum Total Power	Protocols
Medium Power Junction Box	8	12 VDC 24 VDC 48 VDC	200 W	1.6 kW	10/100 BASE-T EIA-232 EIA-422 EIA-485
Low Power Junction Box	8		50 W	150 W	

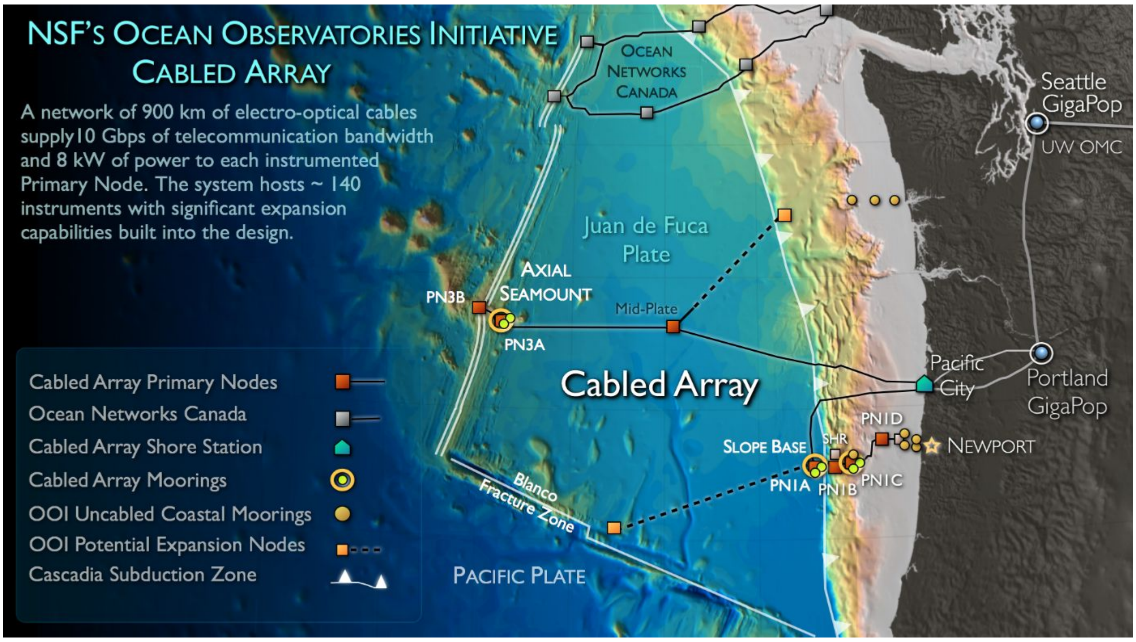
Secondary Junction Box Connection Specification

The Cabled Array was designed as a general purpose oceanographic observatory and includes over 130 instruments of 30 different types. Relevant to earthquake and tsunami early warning there are 5 broadband seismometers with co-located low frequency hydrophones, 8 short period seismometers and 6 high frequency pressure gauges. The seismic data is publicly available in real time from IRIS (www.iris.edu) and the pressure data is available from the OOI data portal (https://ooinet.oceanobservatories.org/)

Many different approaches were used for connecting the cabled equipment on the seafloor depending on the power, communication and distances required. All of the Primary Infrastructure cable was installed with a large cable ship that was able to bury the cable close to shore to protect it from fishing activities. The majority of the secondary cable was installed with a unique deployment system using ROPOS, a Canadian ROV. This allowed cables up to 5km in length to be accurately laid on the seafloor to avoid hazardous areas and to reach very specific locations. Two longer runs of 10km and 19km secondary cable were laid with a cable ship using a specialized two conductor telecom cable.

One novel technology developed by the Applied Physics Lab is the Shallow Profiler. It is important to be able to highly sample the upper water column continuously with a large set of instrumentation. To enable this APL developed a winched profiler with a fixed base 200 meter below the ocean surface. The which has a science pod of instrumentation connected in real time through a slip ring that can be raised and lowered through the water column according to fixed or adaptive schedules. The platform is designed to allow the winch and instrumentation to be replaced each year without having to replace the entire mooring system.

The OOI Cabled array is being used for testing new sensor technologies relevant to early earthquake and tsunami warning system. It also is a good potential side for testing SMART cable technologies as it is in an area of seismic activity, there is an existing suite of relevant instrumentation and it can support adding equipment at a variety of depths and seafloor environments.



Layout of the OOI Cabled Array. (Figure created by the UW Center for Environmental Visualization).

Summary notes from breakout groups

In addition to discussion in the plenum, discussions took place within two breakout groups focussed on the Science requirements and Technology, respectively. Discussions lasted 90 mins, and therefore these topics could of course not be covered comprehensively. The notes from these discussions are summarised here, but note that these should not be considered a succinct recommendation list agreed with all participants.

Science requirements breakout group

- *Sensor spacing*: each repeater should be equipped with a sensor to ensure as high density sampling of tsunami wave as possible. The shortest wavelength which is described by the tsunami wave equation (i.e. where the shallow-water approximation holds and propagation is non-dispersive) is approximately 14 times the water depth, and adequate sampling without aliasing requires sensors spaced at seven times the water depth, i.e. 35 km in the deep ocean. The group recognised that actual repeater spacings are larger which limits the analysis of coherent wavefields to somewhat lower frequencies, or to lower wavenumbers (i.e tsunami wave energy can only be sampled, when obliquely or perpendicularly incident, not when propagating along the cable)
- *Cable routes* parallel to convergent margins intuitively are well suited to measure seismicity and tsunamis in the near field for subduction zone earthquakes. However, both cables parallel to margins or ocean-crossing cables perpendicular to margins are valuable for both understanding of the hazard from and mitigating the hazards
- *Standard sensors:* the ‘standard minimum package’ of pressure, temperature, acceleration sensors already allows many targets to be achieved - new sensor technologies, e.g quartz based pressure and acceleration sensors should be explored, as the achievable science with regard to Earth structure and seismicity depends crucially on the noise levels in the accelerometer in particular, but also that of the pressure sensors. Temperature measured at arbitrary seafloor locations is not an important measurement for earthquake or tsunami research.
- *Additional instrumentation* (for later phase):
    - An acoustic modem and transponder would be of great benefit, as it would allow ocean bottom absolute GPS applications. To what extent motion of the cable represents motion of the seafloor will need to be established, but after a settling phase it is not an unreasonable expectation that sensor motion can be interpreted as seafloor motion.
    - Although the group appreciated that in the initial phase the simple three-sensor package offers the best option due to cost considerations, the group strongly recommends working towards a modular package.
- *Water multiples* are multiple reflections of seismic arrivals (converted to acoustic waves) in the water column, leading to complexity in the seismic waveforms. For near field analysis of large earthquakes the strong motion displacement signal dominates, and water multiples do not need to be considered. For far field seismological techniques (global tomography) water multiples could be an issue. However, using joint analysis of accelerometer and pressure records allows applications of techniques to suppress water multiples
- *Data formats & access* was discussed only briefly. The group appreciated that as far as technical access is concerned, the lead of the cable companies will have to be

followed. The signal will be delivered to the landing site in whatever way the cable company suggests - the scientific community will pick it up from there.

- Possible early warning targets
    - Fast determination of location, magnitude, seismic moment for early warning purposes relies mostly on the accelerometer (early warning for both earthquake and tsunami hazards. W-phase detection on deep-ocean repeaters could offer a faster magnitude estimation, but because of its long period it is difficult to observe on current accelerometers
    - Real time finite source modeling extends the notion of earthquake location by mapping the distribution of seismic slip on the plate interface is very relevant for quick estimates of the affected areas
    - Direct measurement of the tsunami wave as input to tsunami propagation models -> allows faster alarm cancellation, or raising alarm level
    - Sampling along a cable could serve as boundary condition for tsunami modelling and removes the need for an explicit source model for the exciting event(i.e. computing the regional response instead of whole ocean)
    - Detect non-tectonic tsunamis (landslide, volcano,.)
- Possible scientific targets
    - Finite source modelling can be used to understand the physics of large earthquakes and variability of frictional properties of the plate interface
    - Whole Earth tomography would benefit strongly from additional measurement points in the oceans, for both surface wave tomography (on pressure sensors) and body waves (acceleromters, also pressure sensors). The effectiveness of full waveform schemes needs to be tested
    - Detection of microseismicity: small earthquake detection in the upper plate (e.g. splay faults), plate interface or also lower plate. This requires sensors on or just off the continental shelf, but even one sensor has the potential to decrease depth error (detection on accelerometer or pressure sensor)
    - *Measuring tectonic vertical motion/relative sea-level change:* A further potential solid Earth application of pressure sensors is the measurement of local relative sea-evel changes and their interpretation in terms of tectonic uplift or subsidence. Different time scales are relevant for this - for large earthquakes the change in relative sea-level is nearly instantaneous (even for M9 earthquakes not more than a few minutes), but pressure sensors will also show a very strong oscillatory signal from the seismic waves excited by the event. Transient slip events can have different time-scales ranging from a few hours to a few weeks; although sometimes accompanied by tectonic tremor they do not generate an unambiguous seismic signal. Although many episodes of transient slip have been observed at the downdip end there is very little known about their occurrence and properties at the updip end (only known examples are from New Zealand and Japan). Updip transient slip events therefore make an exciting target for SMART cables but might need to be supplemented by additional autonomous sensors to make interpretation robust. For determining interseismic loading effects, i.e. the slow-buildup of elastic stress over decades between major earthquakes, not only a high precision is required but also an exceptional long term stability. The breakout group raised the question whether (automated) recalibration of the sensors at regular intervals could solve this issue but this could not be answered

    within the group. For longer term trends a separation of secular sea-level change and tectonic vertical ground motions is clearly necessary, too.
  - Looking for precursors of mega-events: these could be micro seismicity and slow slip

Technology Breakout

- The orientation of the repeater and/or sensor unit, and therefore the orientation of the accelerometer cannot be controlled directly. It was concluded that this is not expected to be a major obstacle for any suggested analysis because

    a. the cable direction defines one axis, though it is not clear how large the deviations from the main cable directions are

    b. the *g* axis defines the second axis, and the third is simply perpendicular to both

    c. In order to define the uncertainty in the orientation of the horizontal axis, other techniques can be invoked such as ambient noise (which can be used to define the orientation of a sensor relative to its neighbours by carrying out a grid search over azimuth and finding the direction which maximises the correlation between the vertical component and the 90°-phase shifted radial component on the empirical Green's function. The polarisation of P waves could be analysed, but requires good azimuthal averaging. Both techniques have not been tested much with accelerometer data and might stretch the sensitivity of accelerometers at longer periods.

    d. The target should be to know the orientation of the accelerometer to be better than 5°.

- Sufficient power should be available for all sensors suggested in the standard set, and even for the additional sensors (see technical specifications for wet demo). Highly visionary concepts such as acting as charge points for AUVs might require more energy input than available

- Wet demonstrator

    a. Possible sites of interest: Greece (deep close inshore), Cascadia, Indonesia

    b. Demo repeater spacing > 3 x water depth; 50km typical in industry; scientific prefer denser spacings

    c. Purpose: primarily mechanical demo to reassure industry side

    d. Cable industry interested to develop motion-sensing capability?

    e. Likely cost $2-10M, depending on availability of in-kind hardware and ship time

    f. There might be opportunities for funding in EU H2020 programe.

    g. Detailed specification in current Functional Requirement document may be over-generous and should be reviewed. An updated spec might specify seismic noise floor as function of frequency. The Paros scientific sensor capabilities should be weighed against MEMS capabilities

- The main advantages of SMART cables over DART systems are the lower latency, greater reliability and higher sampling rate.

- Societal benefit vs business case

    a. Industry driven by business case

    b. Can effective pressure be brought by funding agencies (governments, World Bank, EU)?

        i. EU interest extends beyond Europe

        ii. Small island projects, e.g. Indonesia, could be an effective way to demonstrate the capability of SMART cables as well as bringing immediate benefit (also note current plans in New Caledonia)

        iii. There are some permitting advantages for in-region (rather than ocean-basin crossing international) activities

- Specific comments on wet demonstrator:

    a. Keep it simple! Failure would kill any hope of building industry confidence.

    b. Select and survey demo site and arrange permitting

    c. The main tasks already well described in wet demo doc

Appendix

Programme

Thursday Nov 3

8:30-9:00	Registration + coffee	
09:00	Welcome and Introduction	Reinhard Hüttl (Scientific Executive Director of GFZ)
	Global networks (chair F. Tilmann)	
09:15	The JTF SMART Cable Initiative: Science Monitoring And Reliable Telecommunications, Climate Monitoring and Disaster Mitigation	Rhett Butler + Bruce Howe
09:40	CTBTO cabled hydroacoustic monitoring system	Georgios Haralabus
10:05	Technical Description of PTWC Operations	Stuart Weinstein
10:40	Coffee break	
	Regional networks (chair B. Howe)	
11:00	Earthquake and tsunami warning in Chile, status and future plans	S. Barrientos
11:30	Tsunami warning in Indonesia	A. Strollo + J. Lauterjung
11:45	MONSOON (MONitoring Subduction by Ocean Observatory Network): A Proposal to Develop Cost-Effective Seafloor Observatory System in Sumatra Java against Earthquake Tsunami Using the New Korean Research Vessel Isabu	Sang-Mook Lee
12:00	NEAMTWS: Evaluation of Candidate Tsunami Service Providers and updates 2016	Alexander Rudloff

12:15	The Hellenic National Tsunami Warning Center (Greece):current status and future prospects as Tsunami Service Provider in the frame of NEAMTWS-IOC-UNESCO	Gerasimos Papadopoulos
12:30	Seismic activity in the Black Sea and the possible effects on the west coast of Black Sea and the infrastructure in the area	Constantin Ionescu
12:45	Lunch	
	Large earthquakes and tsunamis (H. Kopp)	
13:30	Near real-time earthquake source imaging - A potential use of SMART cables	Rongjiang Wang
13:55	The role of the tsunami modeling component in the early warning framework	Natalja Rakowsky
14:20	Interpretation of the signals recorded by ocean-bottom pressure gauges	Mikhail Nosov
14:45	Cabled systems for near-field tsunami early warning: An observation system simulation experiment (OSSE) offshore Portugal	Andrey Babeyko
15:10	Coffee	
	Earth Structure applications (chair R. Butler)	
15:40	SMART Cable Sensors and Global Seismology	Charlotte Rowe
16:05	Seafloor compliance	Wayne Crawford
	Subsea sensors	
16:30	Marine geophysical sensors and technology: opportunities for integration into SMART cable systems	Heidrun Kopp

17:15	Wrap-up discussion: planning of breakout groups
17:45	Close of day
19:30	Workshop dinner in Potsdam centre (Schmiede 9)

Friday Nov 4

Cabled Observatories (chair S. Weinstein)

09:00	The Modular Subsea Monitoring-Network	Jacob Sobin
09:15	From a single science node to a dedicated warning system: ALOHA, DONET, and S-Net.	Bruce Howe
09:45	Earthquake and Tsunami applied science at Ocean Networks Canada	Gary Rogers
10:15	Synergies of SMART cables and offshore geophysical monitoring in Cascadia	William Wilcock
10:35	Ocean Observatory Initiative Cabled Array	Mike Harrington
11:00	Coffee break	
11:30	Discussions in breakout groups	

Possible topics:

1. Define tasks still needed for quantitative demonstration of benefits to tsunami warning, earthquake physics and tomography.
2. Review of current technical concept (sensor types, sensitivities, connection to repeaters); future instrumentation ideas
3. Identify possible funding avenues; link to local

	partners, industry and regulatory bodies
13:00	Lunch
13:30	Short tour of the historical Telegrafenberg campus
14:00	Joint discussion of outcomes of breakout groups
15:00	Coffee
15:30	Initiate putting together written summaries / recommendations
16:30	Final wrap-up session; summarising outcomes; next steps
17:00	Close of workshop

Notes:

Wireless internet will be available through “eduroam” or guest accounts distributed on the day.

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EPOS EUROPEAN PLATE OBSERVING SYSTEM

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Article in EOS summarising the workshop

Citation: Tilmann, F., B. M. Howe, and R. Butler (2017), Commercial underwater cable systems could reduce disaster impact, Eos, 98, https://doi.org/10.1029/2017EO069575. Published on 23 March 2017.

Commercial Underwater Cable Systems Could Reduce Disaster Impact

Workshop on SMART Cable Applications in Earthquake and Tsunami Science and Early Warning; Potsdam, Germany, 3–4 November 2016

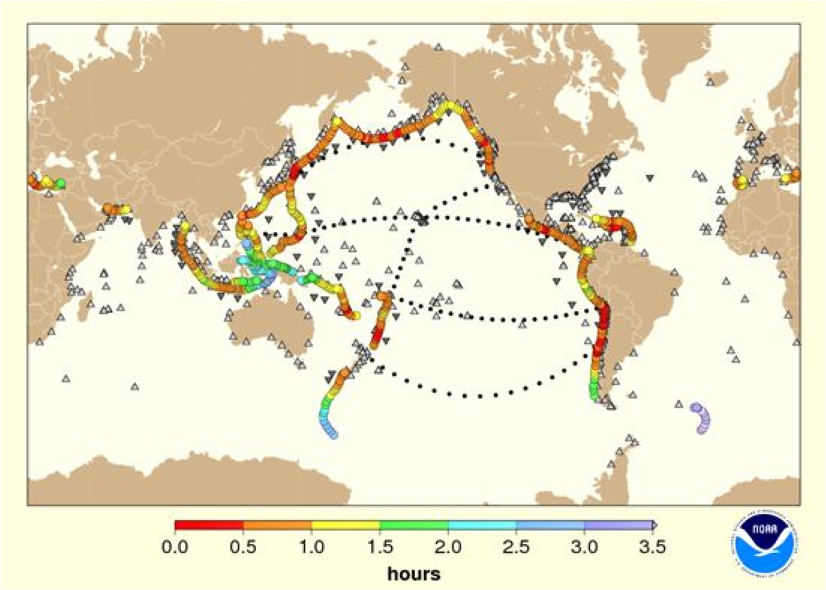
By Frederik Tilmann, Bruce M. Howe, and Rhett Butler 23 March 2017

The cable ship *René Descartes* lays an underwater fiber-optic cable near the Isle of Lewis in the Outer Hebrides. At a November 2016 workshop in Potsdam, Germany, participants discussed the feasibility of developing an early warning system for tsunamis using transoceanic submarine telecommunications cables. Credit: Mark Stainton, CC BY-NC 2.0

Every minute counts in the business of tsunami early warning because tsunami waves often arrive less than 30 minutes after offshore earthquakes. Because most massive subduction zone quakes occur offshore, offshore observations are extremely valuable for quickly detecting and characterizing potential tsunamis. At the same time, unnecessary evacuations are costly and can endanger lives, so false warnings must be minimized.

The current Deep-ocean Assessment and Reporting of Tsunamis (DART) system uses ocean bottom pressure sensors to detect ocean-crossing tsunamis. The DART sensors are too sparse and too distant from shore to provide local warnings, and other real-time solutions like dedicated submarine detection cables come with a hefty price tag. Comprehensive coverage of all endangered subduction zones is out of reach using these systems, particularly in the developing world, but another approach that adds new capabilities to an existing resource could be a significant step in the right direction.

Today, submarine telecommunications cables cross the world's oceans, and many run through or parallel to margins threatened by subduction zone earthquakes. The cables that currently form this network are not sensing their environment; however, these cables are routinely replaced every 10 to 15 years. Installing suitably modified repeaters along future cables, spaced at nominal 50-kilometer (31-mile) intervals, could provide power and bandwidth for sensors along these cables.

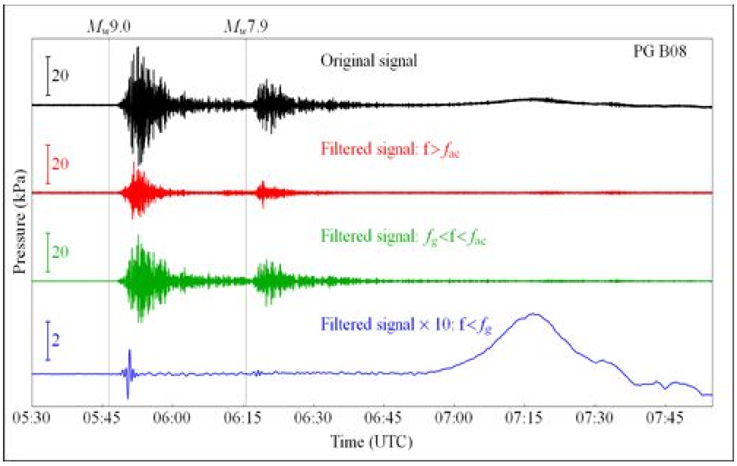


The color scale shows the time lag between tsunami generation and detection for possible earthquake epicenters along subduction zones in the Pacific Ocean that could be achieved by installing sensors on the cable repeaters (black dots are 500 kilometers apart; separation in actual systems is 50 kilometers) along several existing submarine cables. The paths crossing the South Pacific Ocean are notional future paths, whereas the others are existing routes that are renewed every 10 years or so. Dark gray triangles show existing DART tsunameter buoys, and the light gray triangles represent seismic stations and mainland and island stations that measure sea level. Credit: Nathan Becker and Stuart Weinstein, Pacific Tsunami Warning Center, NWS, NOAA

Last November, a group of research scientists, practitioners from earthquake observatories and tsunami warning centers, and engineers gathered for a workshop in Potsdam, Germany, to discuss the viability of a new early warning system that uses enhanced telecommunications cables to create a Science Monitoring and Reliable Telecommunications (SMART) network capable of detecting tsunamis and shaking from great earthquakes. They further discussed how SMART cable sensor arrays would support research into tsunami excitation and propagation, the physics of great earthquakes, and the structure of Earth.

Given the needs of operational earthquake observatories and tsunami warning centers, attendees were excited about the concept of SMART cable systems equipped with accelerometers, pressure gauges, and temperature sensors. This concept is being advanced by a joint task force of the International Telecommunication Union, the World Meteorological Organization, and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization. The Potsdam workshop followed two prior NASA workshops focused on applications in climate research and oceanography.

In one of the studies presented at the meeting, models showed that a few cables crossing the Pacific could reduce the time to detection of potentially tsunami inducing earthquakes by approximately 20%. The time to detection of the actual tsunami wave would be similarly reduced. Furthermore, the linear sensor arrays enabled by the SMART cables allow direct measurements of the tsunami wavefield. Such dense sampling could reduce the dependence on seismological networks and allow researchers to characterize tsunamis triggered by submarine landslides or other nontectonic sources.



The original signal (black) registered by pressure gauges of Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) station B08 during the 2011 Tohoku-Oki earthquake and tsunami barely records the tsunami at 07:00 to 07:30 Coordinated Universal Time (UTC). Band-pass-filtered signals are shown in red and green with the frequency ranges as indicated. High-frequency measurements show acoustic waves (red), whereas water column oscillations following seismic activity are best shown at intermediate time periods (green). The signal from the "gravitational wave" range (blue) is amplified tenfold and clearly shows the tsunami. Times corresponding to the main seismic event of M_w 9.0 and the first strong aftershock of M_w 7.9 are indicated. Sensors on SMART cables would allow the separation of tsunami signals in the ocean bottom pressure record as shown here, whereas the 15-second sampling interval of a standard DART system precludes this. Credit: *Physics of Tsunamis,* Role of the Compressibility of Water and of Nonlinear Effects in the Formation of Tsunami Waves, 2nd ed., 2016, p. 236, Boris W. Levin and Mikhail A. Nosov, © Springer International Publishing Switzerland 2016. Used with permission from Springer.

Workshop participants identified several potential targets for a small demonstration system, including existing cabled seafloor observatories. The participants agreed the demonstration systems should be deployed in a manner equivalent to commercial cable-laying operations to demonstrate the viability of the SMART cable vision and to deliver valuable science data.

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Poster presented at EGU 2017 in Vienna

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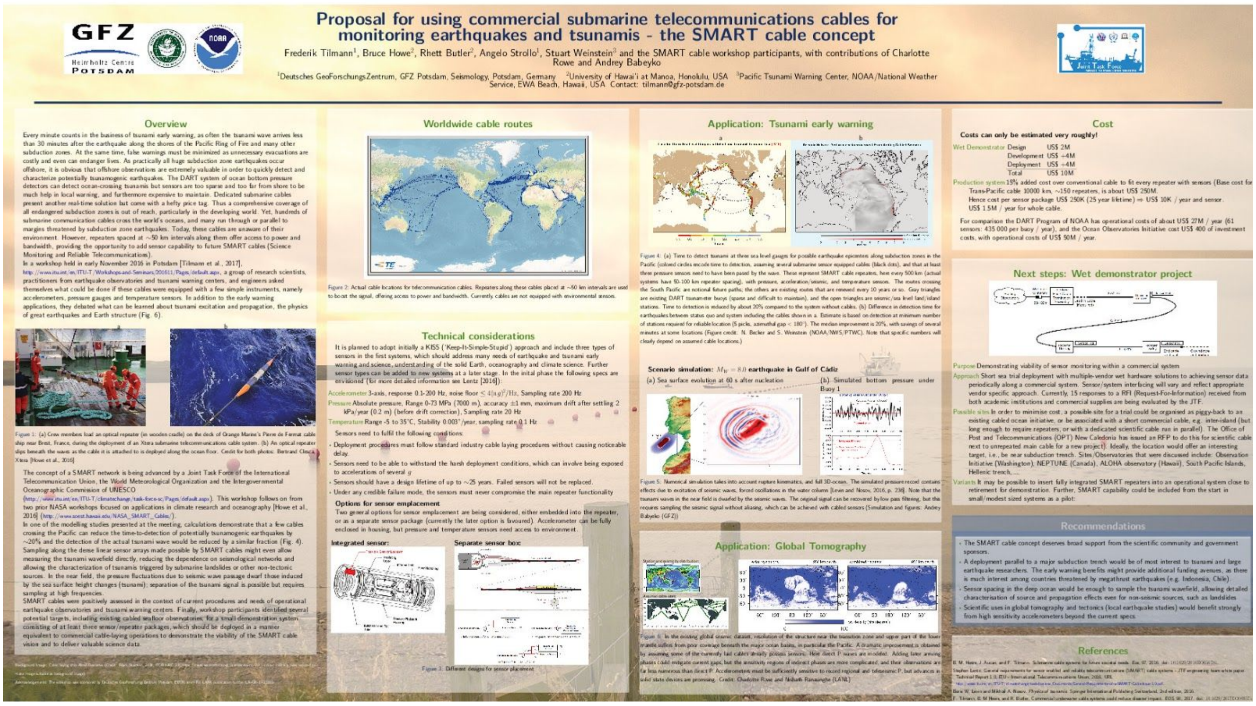

Proposal for using commercial submarine telecommunications cables for monitoring earthquakes and tsunamis - the SMART cable concept

Frederik Tilmann[1], Bruce Howe[2], Rhett Butler[2], Angelo Strollo[1], Stuart Weinstein[3] and the SMART cable workshop participants, with contributions of Charlotte Rowe and Andrey Babeyko

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For a full resolution copy of the poster, please visit http://www.itu.int/en/ITU-T/Workshops-and-Seminars/201611/Pages/default.aspx