Appendix F

Abstracts

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How Time-Variable Contributions to Bottom Pressure by the Water Column can be Accurately Measured and Removed

D. Randolph Watts, Kathleen A. Donohue, and Meng (Matt) Wei
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To measure tectonic deformation at the sea floor using bottom pressure sensors, two other sources of variability must be removed – sensor drift and contributions by physical processes within the water column. This talk will focus upon the water column processes. Illustrating typical pressure signal amplitude (1hPa ~ 1 cm height) and time and length scales, the variations in bottom pressure are strong even in deep water:

Process	Amplitude (hPa~cm)	Time scales	Length scales
Tides	30-150 hPa	hours	basin scales
Topographic waves	5 – 25 hPa	a few days	10 – 100 km
Mesoscale eddies	5 - 60 hPa	weeks-months	10's – 100's km
Long barotropic	3 - 20 hPa	days	100's – 1000's km

Excepting tides, these bottom processes are not well determined by measurements just at the sea surface, nor can they be accurately modeled in real time. The Current and Pressure Recording Inverted Echo Sounder (CPIES) can be used to constrain these bottom processes. The CPIES, a bottom-mounted instrument, measures hourly bottom pressure, surface-to-bottom round-trip acoustic-travel-time and near-bottom horizontal currents. Combining these measurements, one can separately determine the water signal by accounting for the geostrophic balance between slowly evolving large-scale ocean currents and pressures.

Figure 1 illustrates one daily snapshot of the pressure and currents under the Kuroshio Extension. The Optimal Interpolation (OI) mapping procedure for each time step has close analogy to Krigging; in analogy to geophysical studies the mapping stringently demands laterally correlated measurements. The currents can be seen in this figure to flow along isobars with magnitude proportional to the lateral pressure gradient: $\Delta p = vf(\Delta X)$, where v is current velocity, f is the Coriolis parameter, and ΔX is the horizontal distance. The current and pressure measurements each respond to the same oceanic pressure field. Our methods level an array of pressure sensors and detect and remove sensor drift at the 1 cm level of accuracy. Additionally, if the pressure measurements are at different depths across the continental slope, such as offshore Cascadia, the time-varying vertical structure of the currents must be measured. We determine this vertical structure using inverted echo sounder measurements. Alternatively, coherently-spaced acoustic Doppler current profilers could measure that structure across the continental slope.

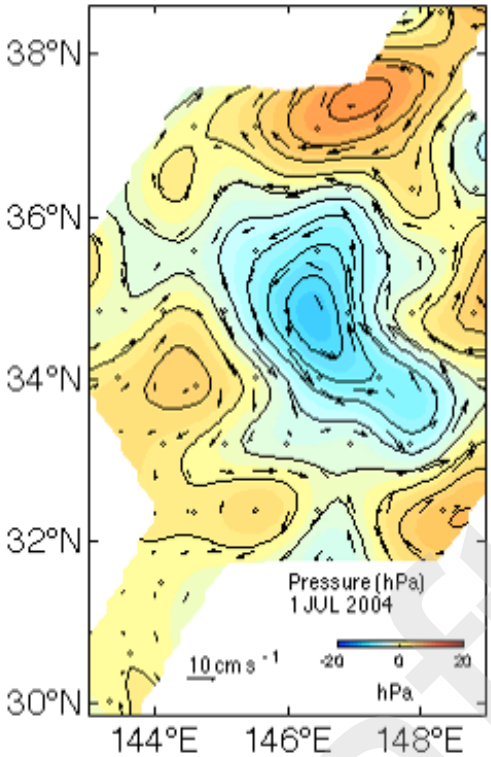

Figure 1. Typical example of one daily snapshot of bottom pressure and current fields mapped from measurements under the Kuroshio Extension, in ~6000m depths east of Japan. The currents flow counterclockwise/ clockwise respectively around the low and high pressure centers in geostrophic balance. These deep eddies have pressure amplitudes ranging ± 20 hPa, equivalent to ± 20 cm water height. The lateral scales are 100-200 km, and typical time scales are 5- 30 days.

Cascading, multiple-fault ruptures: a challenge for earthquake early warning

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The viability of earthquake early warning systems depends in part upon rapid estimation of moment magnitude. Here, I highlight challenges posed by a new class of earthquake in which seismic rupture bridges fault segment boundaries tens-of-kilometers wide to grow into larger, composite events. Such events, which have been identified only recently through improved geodetic and seismic imaging capabilities, break the long-standing assumption that segment boundaries of >5 km will always arrest rupture (Wesnousky, 2006). To illustrate, I describe two multi-fault earthquakes including the earliest well-documented instance and the most recent and perhaps most spectacular example. (1) In the February 27th 1997 Harnai, Pakistan (M_w 7.2) earthquake doublet, dynamic stresses generated by seismic waves from an initial thrust faulting event caused slip to initiate ~50 km away and ~19 seconds later on a colinear but structurally-distinct reverse fault (Nissen *et al.,* 2016). The second event increased the cumulative seismic moment by ~50% and likely doubled the duration of strong local ground-shaking from ~15 to ~30 seconds. However, this complexity was only revealed through InSAR analysis and teleseismic back-projections, measurements that were unavailable in real-time. (2) The November 14th 2016 Kaikoura, New Zealand (M_w 7.8) earthquake commenced with meter-scale slip on the Humps and Hundalee faults, but eventually ruptured a network of at least fourteen distinct faults with up to ~10 m of slip and at least one jump of ~15 km (Hamling *et al.,* 2017). Had a conventional early warning system been in place, the initial appraisal of moment magnitude may have been M_w <7. Slip on one offshore thrust fault, only determined weeks after the earthquake, is the likely cause of ~3 m-high tsunami waves observed at Kaikoura (Clark *et al.,* in review). The rapidly growing list of large, composite ruptures now includes subduction zone, fore-arc, ocean transform, continental, and intraplate examples, implying that they are a common and global phenomenon (Fan and Shearer, 2016). Earthquake early warning systems should ideally be attuned to the possibility of small-to-intermediate events growing into much larger ruptures by jumping across fault segment boundaries.

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The Chilean Seismic Observation Network and Earthquake Early Warning

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Chile is frequently affected by very large earthquakes (up to magnitude 9.5) resulting from the fast convergence (approx. 7 cm/yr) 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, as it is shown in Fig. 1. Further south, it is the Antarctic plate which subducts beneath the South American plate at a rate of approximately 2 cm/yr. In austral Chile and Argentina it is the interaction of the Scotia and South American plates that give rise to a strike-slip boundary.

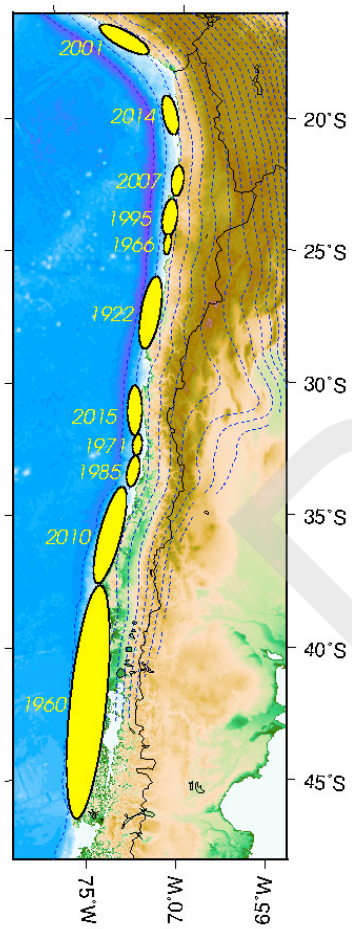

Fig. 1. Rupture areas of selected large thrust earthquakes in Chile –and their year of occurrence- since the beginning of the 20th Century. The size of the ellipses is proportional to the magnitude of the event, being the 1960 the largest (M=9.5) to 1966 and 1971 with 7.8.

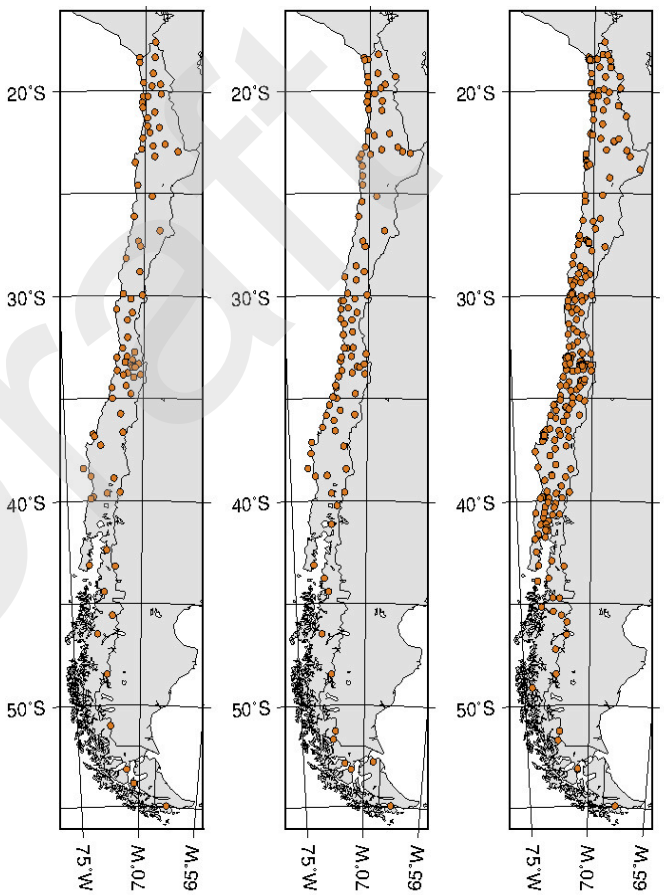

Fig. 2. Distribution of 98 multi-parametric (broadband + accelerographic) stations (left panel), 130 GNSS stations with installation to be completed during 2017 (central panel), and 297 strong ground motion devices (right panel). An important role in this network is played by 10 IRIS and 20 Integrated Plate Boundary Observatory (IPOC) stations, an effort between GFZ (Potsdam) and IPGPO (Paris).

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 (CSN) of the University of Chile. The network (Fig. 2) 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 are 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

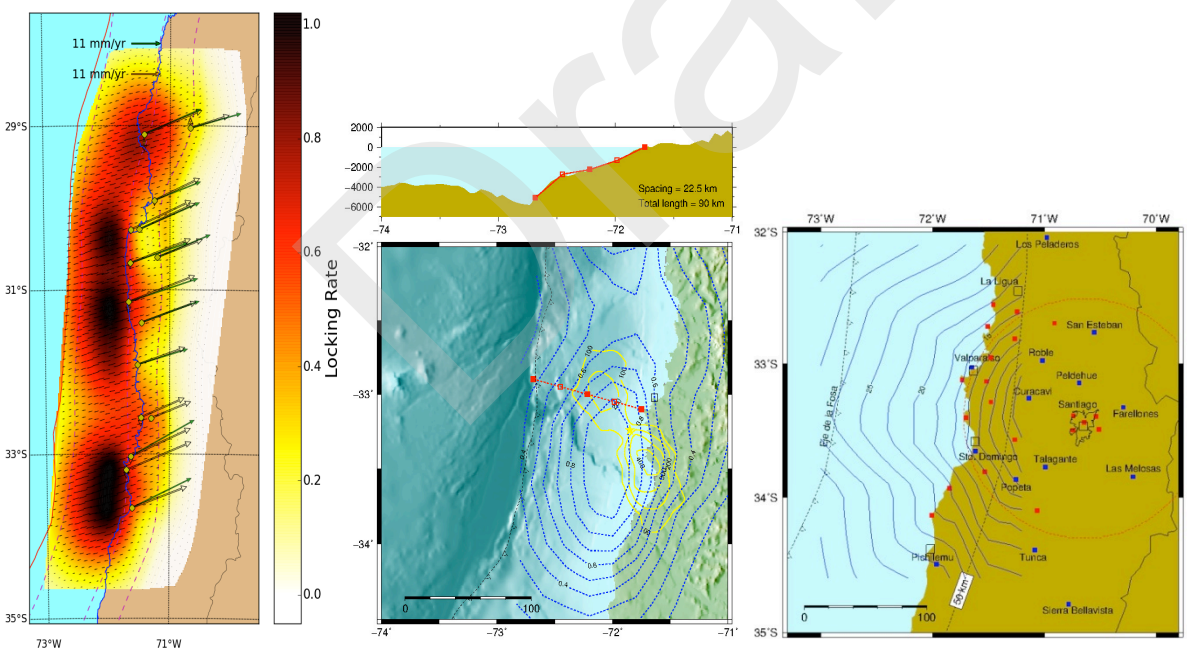

Fig. 3. **Left**: Locking rate between the Nazca and South American plates prior to year 2010; maximum values are reached between the coast and the trench. The locked patch south of 33°S is depicted in the central panel as blue dashed lines. **Central:** Slip distribution associated with the 1985 Mw=8.0 earthquake (yellow continuous lines, in cm) is surrounding the locked path, 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, bathymetric profile along the length of the cable; maximum depths are of the order of 5000 m. **Right:** Estimated time lapse before arrival of the S waves to Santiago depending on the location of the hypocenter with 4 s of record at any of four stations recording the P wave arrival.

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 2% 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. 3, where the locking rate borders regions of maximum slip during the 1985 M=8.0 earthquake in Central Chile.

The CSN is proposing national authorities an EEW system that contemplates two (weak/moderate and strong) or three levels of ground shaking:

A system like the one proposed should give an alert before the arrival of the S wave to Santiago of the order of 10 seconds or more for earthquakes that take place in the contact between the Nazca and South American plate (the further away the epicenter from Santiago, the greater the time of warning), of the order of 3 to 4 seconds for those earthquakes that take place 90 km deep under the city and would not generate an alert if a shallow earthquake takes place in the ouskirts of the city, for example, in the San Ramón Fault.

Additionally, the CSN is collaborating with USGS in an earthquake and tsunami early warning experiment based on a deployment of low-cost smartphones (Brooks et al, 2016). The new instruments deployed up to March 2017, are shown on the figure to the right (Fig.4).

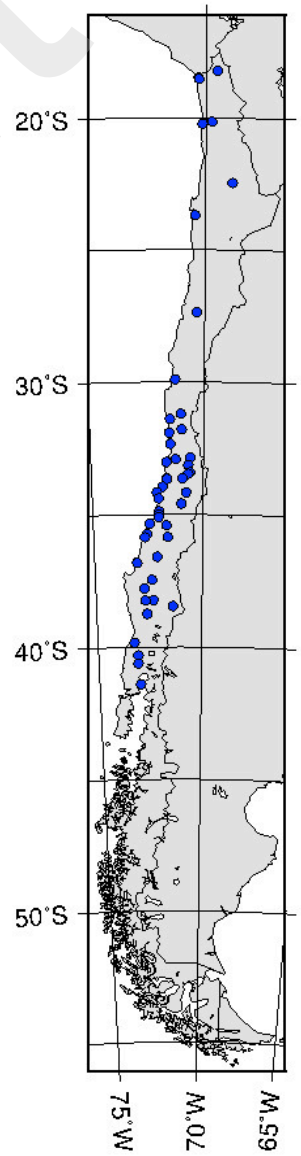

Fig. 4. Locations in Chile where low-cost smartphone-devices have been installed and currently operational.

SMART submarine telecommunication cables for climate monitoring and earthquake and tsunami early warning.

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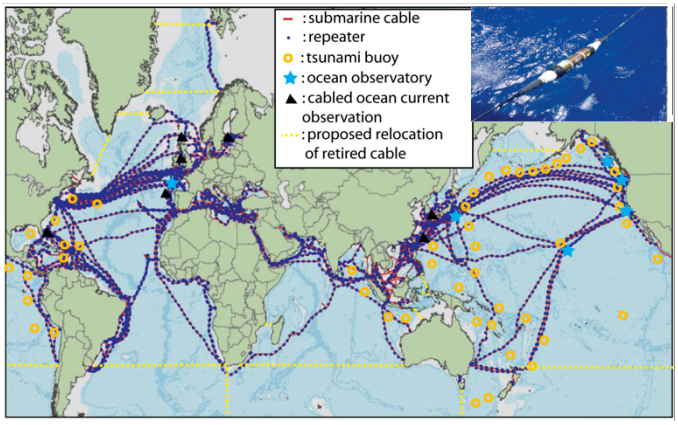
Representing the Joint Task Force (JTF) SMART Subsea Cable Initiative: Science Monitoring And Reliable Telecommunications, Climate Monitoring and Disaster Mitigation

A Joint Task Force (JTF) sponsored by three U.N. agencies --International Telecommunication Union (ITU), the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO-- is leading an effort for integrating environmental monitoring sensors into transoceanic commercial submarine telecommunication cables. These are called SMART Cables – Science Monitoring And Reliable Communications. The initiative addresses two main issues of importance to science and society: a) the need for sustained climate-quality data from the sparsely observed deep oceans onto continental slopes and b) the desire to increase the reliability, integrity, and scope of the global earthquake and tsunami warning networks. The Joint Task Force of scientists, the telecommunication industry, governments, and UN agencies is initially focusing upon integrating sensors for temperature, pressure, and acceleration.

Several science workshops have recently reviewed and endorsed the SMART cable concept, specifically covering ocean climate and circulation monitoring (at CalTech and UHawaii), and tsunami and earthquake measurements (at Geosciences Research Center, Potsdam). In one of the studies presented at these meetings, models showed that a few cables crossing the Pacific could reduce the time-to-detection of tsunamis by approximately 20 percent. Furthermore, the linear sensor (~50 km spacing) arrays enabled by SMART cables would allow direct measurements of the tsunami wave field. Such dense sampling would allow improved warning against tsunamis triggered by submarine landslides or other non-tectonic sources.

To help move this initiative from concept to pilot, a request for information has been issued in late 2016 for a “wet demonstration” project, which may involve testing within existing science cable observatory systems or be installed in a relatively short communications cable. There could be direct synergies between JTF goals and technology and possible solutions for a Cascadia early warning system.

These SMART cable systems would be a new highly reliable, long-lived component of the ocean observing system, complementing satellite, float and other in situ platforms and measurements. International participation and interest parties are welcomed. Further information is at http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx.



Telecom companies continually add new submarine cable system installations to satisfy Internet demand. A new global-spanning component of the ocean observing system can be established over the next decades in these systems by adding environmental sensors to repeaters (blue dots, every fourth repeater shown). This new component would focus on the societal issues of climate and sea level change and earthquake and tsunami risk mitigation.

Credit: ITU/WMO/UNESCO IOC Joint Task Force. Cable distribution data from Global Marine Systems, Ltd.

Evaluating the Geodetic Alarm System (G-larmS) Performance using Synthetic Earthquakes

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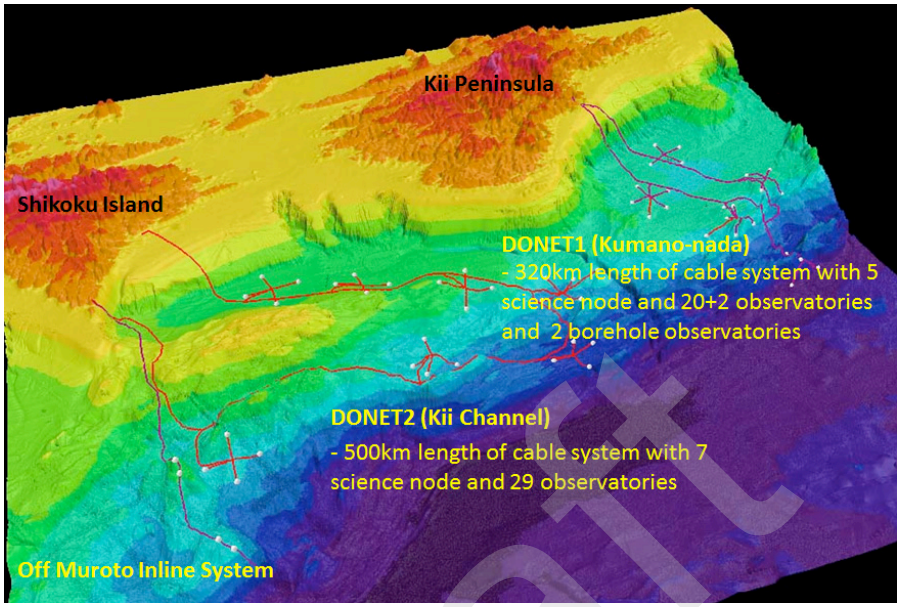
The Geodetic Alarm System (G-larmS) is a collaboration between the Berkeley Seismological Laboratory and New Mexico Tech to integrate real-time GNSS into Earthquake Early Warning (EEW). G-larmS has been in continuous operation since 2014 using event triggers from the ShakeAlert EEW system and real-time position time series from a triangulated network of GPS stations along the west coast. G-larmS has been extended to include southern California and Cascadia, providing continuous west-coast wide coverage since 2016. G-larmS currently uses high rate (1 Hz), low latency (<~5 s), accurate positioning (cm level) time series data from a regional GPS network and P-wave event triggers from the ShakeAlert EEW system. It extracts static offsets from real-time GPS time series upon S-wave arrival and performs a least squares inversion on these offsets to determine slip on a finite fault. A key issue with geodetic EEW approaches is that unlike seismology-based algorithms that are routinely tested using frequent small-magnitude events, geodetic systems are not regularly exercised. Scenario ruptures are therefore important for testing the performance of G-larmS. Synthetic long-period 1Hz displacement waveforms were obtained from a new stochastic kinematic slip distribution generation method (Fakequakes). Waveforms are validated by direct comparison to peak P-wave displacement scaling laws, peak ground displacement GMPEs obtained from high-rate GPS observations of large events worldwide, and NGA-West2 spectral acceleration GMPEs at 10s period. We develop a catalog of 1300 Cascadia megathrust scenarios as well as ~4000 individual ruptures on 25 large faults (capable of M>6.5) in California built from realistic 3D geometries. We use simulated real-time displacement streams to systematically test the recovery of slip, fault length, and magnitude by G-larmS. We characterize the overall performance of G-larmS and discuss recommendations and implementations for improving the algorithm and geodetic EEW on the west coast in general.

Submarine cabled real-time seafloor surveillance system "DONET"

Katsuyoshi Kawaguchi
Japan Agency for Marine-earth Science and Technology (JAMSTEC)



DONET (Dense Ocean-floor Network system for Earthquakes and Tsunamis) is a submarine cabled seafloor observatory network for seismogenic zone monitoring in western Japan. Development of DONET has been begun in 2006 and the original system "DONET1" entered operation status from August 2011. Construction of second generation system "DONET2" has been begun in 2010 and complete March 2016. A total of 51 locations of observatory is deployed in the seafloor. To maintain this large scale system for more than 20 years, observatory network consists of three separable components of backbone cable, seafloor concentration (named node), and observation instrument package (called observatory). Each component is connected through an underwater mateable connector (UMC) to realize the expandability, replaceability and maintainability in operation life time. Backbone cable has been developed using telecommunication submarine cable technology to get the more than 20 years of lifetime without maintenance. Node is a kind of hub system for power feeding and data transmission between landing station and observatories, and key device of DONET development. Twelve nodes are equipped on the DONET1 and 2 network, and each node has eight UMC interfaces for observatories. Total 96 interfaces are prepared for observation, 51/96 interfaces are reserved for DONET standard observatory, two interfaces are reserved for borehole observatories maintained by IODP program and 43 interfaces can be used for future expansion. DONET standard observatory consists of ground motion sensing system and pressure sensing system and each sensing system consist of more than single sensor. The subsea construction of DONET is carried out by cable laying ship, research ship and work class ROV for science research. Approximately 5monthes of cable laying ship operation and 700 days of research cruise ship time (including 250 ROV dive) are spent for preliminary survey and observatory construction. Data from these observatory network is delivered to the Japan Meteorological Agency and is utilized for earthquake early warning system and tsunami forecasting system.

Wave Gliders for Seafloor Geodesy

Dave Chadwell
Scripps Inst. Oceanography

The state of faulting along the shallowest portion of the subduction zone megathrust nearest the trench is often the least constrained part of the megathrust fault. For most subduction zones, e.g. Cascadia and Aleutian, it is unknown whether this offshore portion of the megathrust is locked or creeping aseismically. Efforts to measure locking out to the trench require seafloor observations, given that terrestrial observations along the coastline are typically too far and largely insensitive to shallow locking at the trench.

A proven technique to measure seafloor motion is the GPS-Acoustic (GPS-A, or GNSS-A) method, which transfers GPS measurements of crustal motion from land to the seafloor. However, each site requires a minimum 4-5 days of shiptime in each year to track motions at the centimeter-level. The high cost of this shiptime has stalled GPS-A measurements within the US community following the initial successes of the approach.

As an alternative, we have adapted the GPS-Acoustic method to a Liquid Robotics Wave Glider, a remotely piloted sea surface platform. The Wave Glider uses mechanical wave motion of the ocean surface for propulsion, solar arrays for electrical power and Iridium satellite communications for command/control from shore. Given both the sea-surface wave action and solar energy are renewable, the vehicle can operate for extended periods (months). The cost of operating and collecting GPS-A data is ~$500/day with the Wave Glider compared to ~$50,000 /day for a dynamically-positioned UNOLS vessel – a factor of 100 times less expensive.

In July/Aug. 2016, we operated our Wave Glider on a 40-day-long mission collecting GPS-Acoustic data at three sites ranging from offshore Newport, Oregon to offshore Grays Harbor, Washington. The Wave Glider was deployed July 13th from a small boat ~10 miles out of Newport Oregon and travelled at ~1.6 kts to each site, collecting 4-6 days GPS-A data before proceeding to the next site. It returned to ~10 miles offshore Newport and was recovered on Aug. 22nd. We will review this mission and future plans in a talk and poster. Wave Gliders are likely to work in other subduction zones, particularly along the US Coast. Their low operating costs and freedom to cover wide regions opens new avenues to collect seafloor geodetic data.

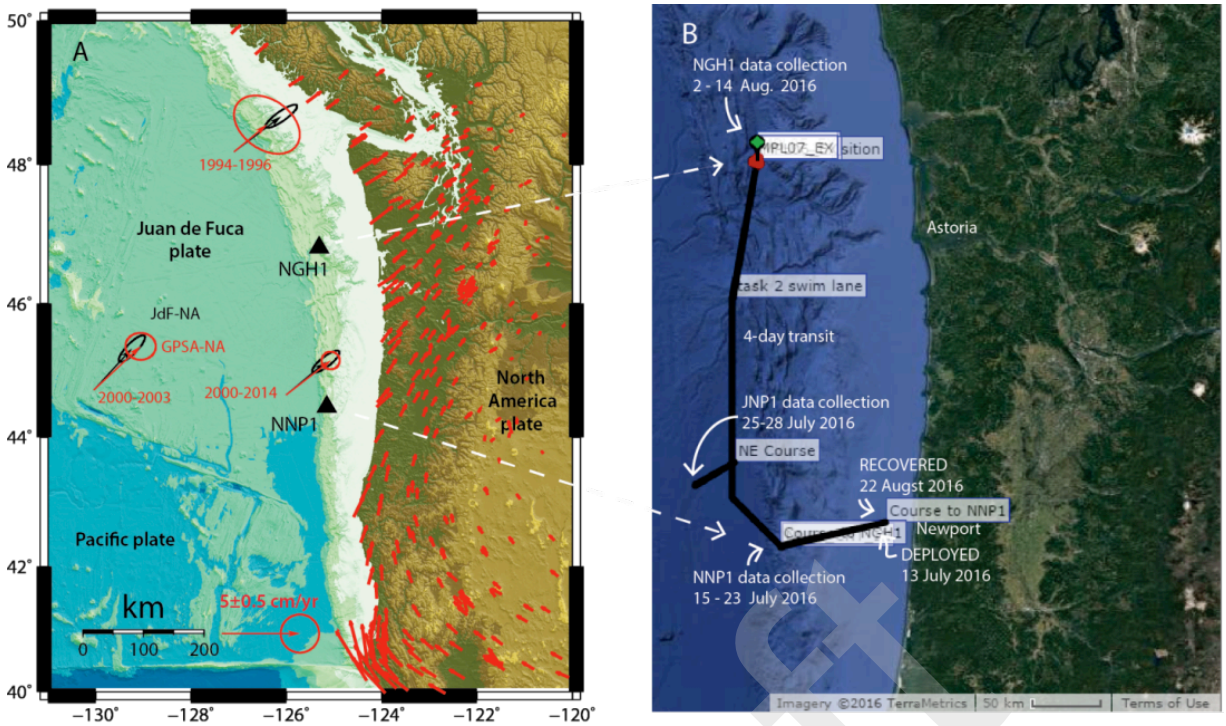


Figure (**A**) Map showing location of NNP1 and NGH1. (**B**) Track of the GPS-A Wave Glider (SFG1) during a 40-day mission to collect GPS-A data at sites NNP1, JNP1 and NGH1 during July/ August 2016.

The use of hydrophones for detection and analysis of submarine landslides

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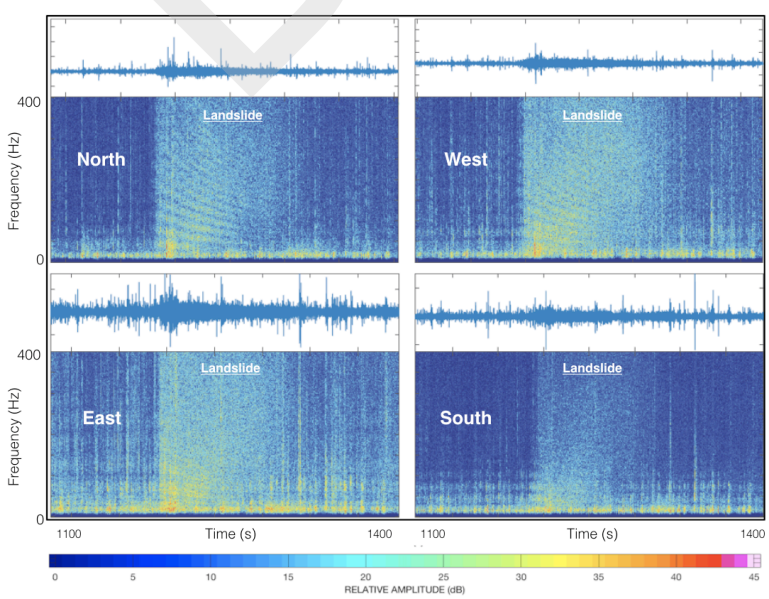
Submarine landslides have the potential to be tsunamigenic, yet they are not easily detected and thus represent a hidden hazard to coastal communities. If deployed at the right location and depth, hydrophones can be used to detect submarine landslides and estimate their location and propagation velocity. Hydroacoustic recordings of submarine landslides on Kilauea and West Mata volcanoes suggest that these events have a characteristic appearance in spectral data: they have broadband (0-200 Hz) frequencies and last from 10s of seconds to 10s of minutes. Acoustic energy may undergo multipathing between source and receiver, generating a characteristic interference pattern known as a Lloyd's mirror (see Figure). Surface-reflected waves travel a slightly longer path to the hydrophone than do direct waves, causing integer multiples of specific frequencies to cancel out and others to amplify. These frequencies are related to the difference in travel time between the direct and reflected waves, and thus are solely a function of source-receiver geometry. Acoustic signals recorded in association with the eruption of West Mata have a strong Lloyd's mirror effect, with summit explosions generating strong interference patters with at integer multiples of ~36 Hz. Some signals, however, have interference patterns at frequencies that change with time (see Figure). Because the Lloyd's mirror depends on source receiver distance, and because we know the receiver is fixed, this requires a moving source, which we interpret as a submarine landslide. In all cases the spectral content shows a decrease in interference frequencies, consistent with a source moving downhill; in contrast, a Doppler shift would be expected to rise for landslides moving toward the hydrophone and fall for slides moving away from the receiver. Analysis of hundreds of West Mata landslides indicates that they initiate near the summit at 1500 m depth, and propagate to depths of 1900-2100 m at speeds of 2-11 m/s.



Development of seafloor cabled seismic and tsunami observation system using ICT and installation in source region of the 2011 Tohoku-oki earthquake

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[2] *National Research Institute for Earth Science and Disaster Prevention*

We have been developed the new compact Ocean Bottom Cabled Seismometer (OBCS) system using Information and Communication Technology (ICT) from 2005. Our system is characterized by securement of reliability by using TCP/IP technology and control by mainly software with up-to-date electronics technology. In 2010, the first OBCS was installed in the Japan Sea. After the 2011 Tohoku-oki earthquake, we decide to install newly developed Ocean Bottom Cabled Seismic and Tsunami (OBCST) observation system for additional observation and/or replacement of the existing system in the source region. The new OBCST system is placed as the second generation of our system, and uses standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control and system monitoring. The Wavelength Division Multiplexing (WDM) is also introduced to reduce number of optical fibers. There are two types of observation nodes. Both types have accelerometers as seismic sensors. One type of observation nodes equips a crystal oscillator type pressure gauge as tsunami sensor. Another type has an external port for additional observation sensor by using Power over Ethernet technology. Clock is delivered to all observation nodes from the GPS receiver on a landing station using simple dedicated lines. In addition, clock can be synchronized through TCP/IP protocol with an accuracy of 300 ns (IEEE 1588). A simple canister for tele-communication seafloor cable is adopted for the observation node, and has diameter of 26 cm and length of about 1.3 m.

A route for the new OBCST was selected in consideration of those of the existing cable and plans for another new cable system (S-net), and results form a route survey in 2013. According to the route plan, the system has a total cable length of 105 km and 3 observation nodes with 30 or 40 km spacing. Two observation nodes have a built-in tsunami meter, and the furthest observation node has the PoE port. At the deployment of the cable system, we attached a precise pressure gauge with digital output to the PoE port.

Deployment of the OBCST system was carried out in September 2015 by using a commercial telecommunication cable ship. First, the cable ship swept the seafloor along the cable route to remove obstacles on the seafloor. An end of cable was landed to the landing station and the cable ship started deployment of the cable system offshore. In the region where the water depth is less than 1,000 meters, the submarine cable and the observation node closest to the coast were simultaneously buried with using a plough-type burial machine. Burial depth is 1 meter below the seafloor. Finally, a remote operated vehicle buried the submarine cable around the landing point. After finishing of the deployment, data recording was immediately started. From the seismic data from the new system, it is found that the noise levels are comparable to those at the existing cabled system off Sanriku. In addition, it is confirmed that burial of the sensor package is effective noise reduction. For water pressure data, pressure gauges have a resolution of less than 1 hPa. Tsunami-waves in November 2016, which were generated by an earthquake with magnitude of 7.4 off Fukushima were clearly observed by all pressure gauges in the system.

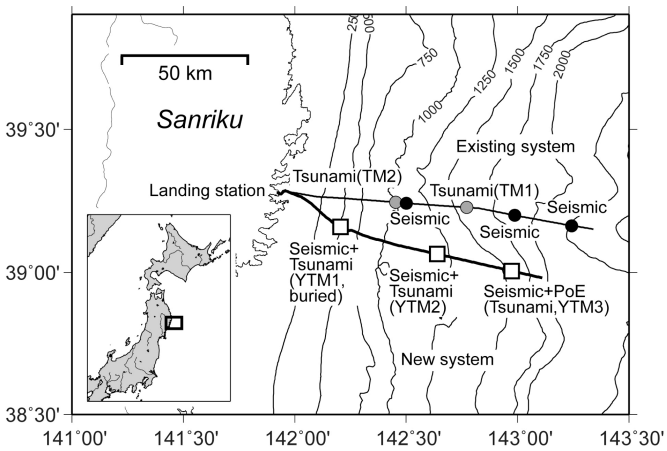

Fig.1 Positions of the OBCST system

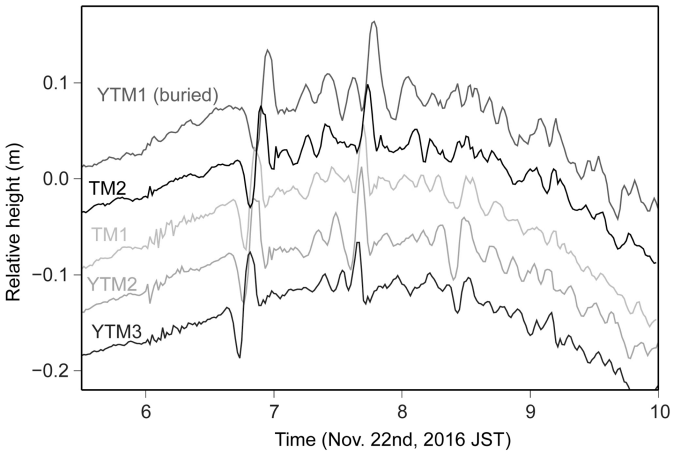

Fig.2 Tsunami records from pressure gauges

Rapid tsunami forecasting in Salish Sea and Puget Sound, with an emphasis on a Cascadia mega-event

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This presentation describes a new way of using sea level measurements for tsunami forecasting. With the suggested technology, the tsunami source reconstruction - an ambiguous component of the today's forecasting - is bypassed. Instead, this technology provides an instant solution to a boundary value problem of numerically propagating the wave directly from the detector(s). The predictions are generated as a response or a combination of responses to one or more tsunameters, with each response obtained as a convolution of the tsunameter real-time measurements and a pre-computed Pulse Response Function (PRF). Each PRF depends on the tsunameter location, location of the forecasted site, and (not always) on a general EQ (earthquake) area. The PRF does not depend on the details of the sea surface deformation in the tsunami origin. Response forecasting method demonstrated high accuracy with forecasting historic trans-Pacic tsunamis (2010 Chile and 2011 Tohoku-oki), comparable to or exceeding an accuracy of conventional techniques.

Response method provides an unmatched opportunity for forecasting a near-eld tsunami, when the conventional source inversion cannot resolve a complex structure and dynamics of a near-eld tsunami generating function, nor there is time for live hydrodynamic modeling. Using a few hypothetical Cascadia mega-events, we demonstrate how sea level measurements at the entrance of Juan De Fuca strait can be instantly converted into a tsunami prediction by Tacoma 2+ h later, as well as into the wave time histories at other WA and BC locations in the Salish sea. For this application, the response method was modied to allow the detector be located in the tail of the deformation. Response method naturally scales to any number of detectors. Using more detectors across the strait would improve the prediction accuracy by resolving more variance along the wavefront.

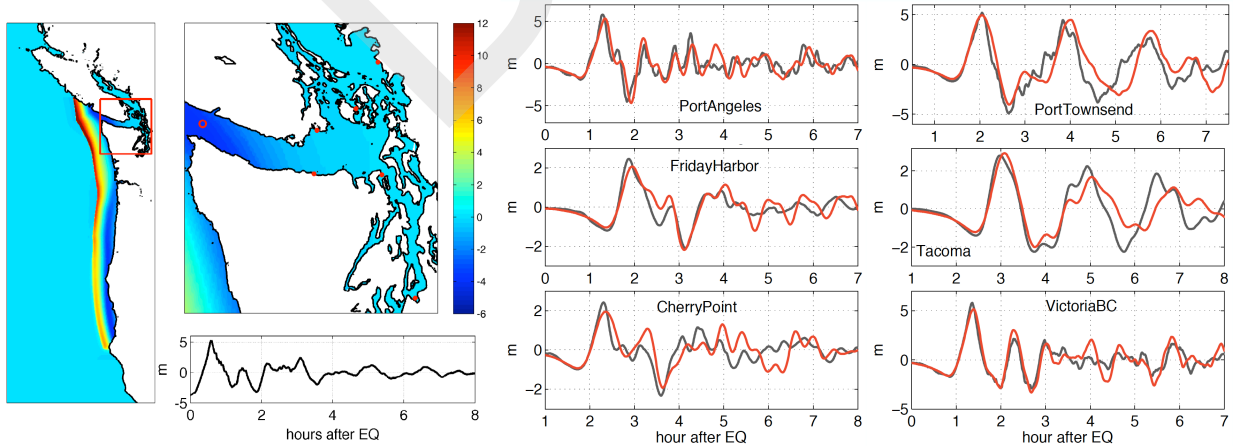

Figure 1: Left: Initial co-seismic deformation (L1 source) oshore WA-OR coast and in the Juan de Fuca strait; locations of the virtual detector at the strait entrance (red o) and forecasted sites (red dots); water level time history at the detector. Right: response-generated predictions (red) vs simulated observations (black) at the forecasted sites.

Seismotectonic characteristics of the Nootka fault zone: results from SeaJade 1 and 2

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The Nootka fault zone (NFZ) is a complex region dominated by strike-slip behavior which divides the Explorer plate from the Juan de Fuca plate. Two phases of SeaJade (Seafloor Earthquake Array – Japan Canada Cascadia Experiment), in which ocean bottom seismometers (OBS) were deployed off the west-coast of Vancouver Island, have allowed us to better understand the NFZ and its associated hazards. From the first phase of SeaJade, we learned that the Nootka fault zone is comprised of northern and southern primary bounding faults, and what appear to be several en echelon faults, which widen toward the Cascadia subduction zone. Focal mechanisms reveal the common modes of failure in this region, while seismic tomography was used to constrain the depth to the Moho. During the second phase of SeaJade, a M_W 6.5 earthquake ruptured along the subducted portion of the Explorer plate, which joins with the NFZ. Preliminary analysis of this data suggests that the M_W 6.5 and proceeding aftershocks can be associated with breakup of the Explorer plate, and may have resulted from the failure of a wider en echelon fault within the subducted portion of the NFZ.

The Ocean Networks Canada Tsunami program: overview of detection and modeling efforts

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Ocean Networks Canada (ONC) is an international science facility hosted at the University of Victoria. ONC operates world-leading ocean observatories, innovative cabled infrastructure that supply continuous power and Internet connectivity to a broad suite of subsea instruments from coastal to deep-ocean environments including those used to measure earthquakes and tsunamis. The ONC Tsunami program targets tsunami modeling for tsunami preparedness and tsunami detection for real-time warning.

As part of this program we leverage the available infrastructure at ONC observatories to detect tsunami waves and currents with different sensors. A new HF WERA radar installed in Tofino detected for the first time an event believed to be meteorological tsunami on October 14th, 2016. This event was caused by the remnants of the Songda typhoon that traveled through the Pacific. This event, detected also in multiple instruments, triggered the tsunami alert system in the radar and is currently helping to test two new tsunami detection algorithms for the Tofino area based on the radial velocities measured.

In order to help with preparedness, this program has also developed inundation models and maps and analyzed maximum currents for the Port Alberni and Barkley sound area. These models used Digital Elevation Models for the area of Barkley and Port Alberni developed by NCEI-NOAA as part of an international collaboration with major Canadian agencies including Emergency Management BC, GeoBC, Alberni-Clayoquot Regional District, Canadian Hydrographic Service and Ocean Networks Canada. Several rupture scenarios of the Cascadia Subduction Zone have been considered, including a buried rupture, trench breaching scenario and splay faulting rupture. FUNWAVE-TVD, a long-wave propagation model that solves fully non-linear and dispersive Boussinesq equations, has been used to calculate inundation, time of arrival and tsunami currents.

Distributed Acoustic Sensing for Earthquake Early Warning Applications

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[2]*Stanford University*

Distributed acoustic sensing (DAS) uses optical fiber to sense strain that is transducted from the environment onto the optical fiber. During the last several years the sensitivity of DAS systems has increased to the point where it can be used fluid flow, seismic and microseismic measurement in a variety of borehole applications with purpose installed fibers.
In contrast, many infrastructure components, such as such as train tracks, pipelines, have fiber optic cable installed for telecommunication purposes. Although not designed for specific DAS sensing purposes, such fiber can be used to obtain useful strain measurements. We show several basic examples and also report on a fiber-optic cable installation on the Stanford campus recording continuously since September 2016 strain measurements in the frequency range of 0-50 Hz. Although the primary purpose is local subsurface analysis using ambient noise recordings, local, regional and distant earthquake signatures have been detected and identified. This indicates significant potential for using fiber-optic cables on existing infrastructure as part of earthquake sensing and early warning.

A low-power tool for measuring acceleration, pressure, and temperature (APT) with wide dynamic range and bandwidth

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[2]*Pacific Geoscience Centre, Sidney, BC, Canada*
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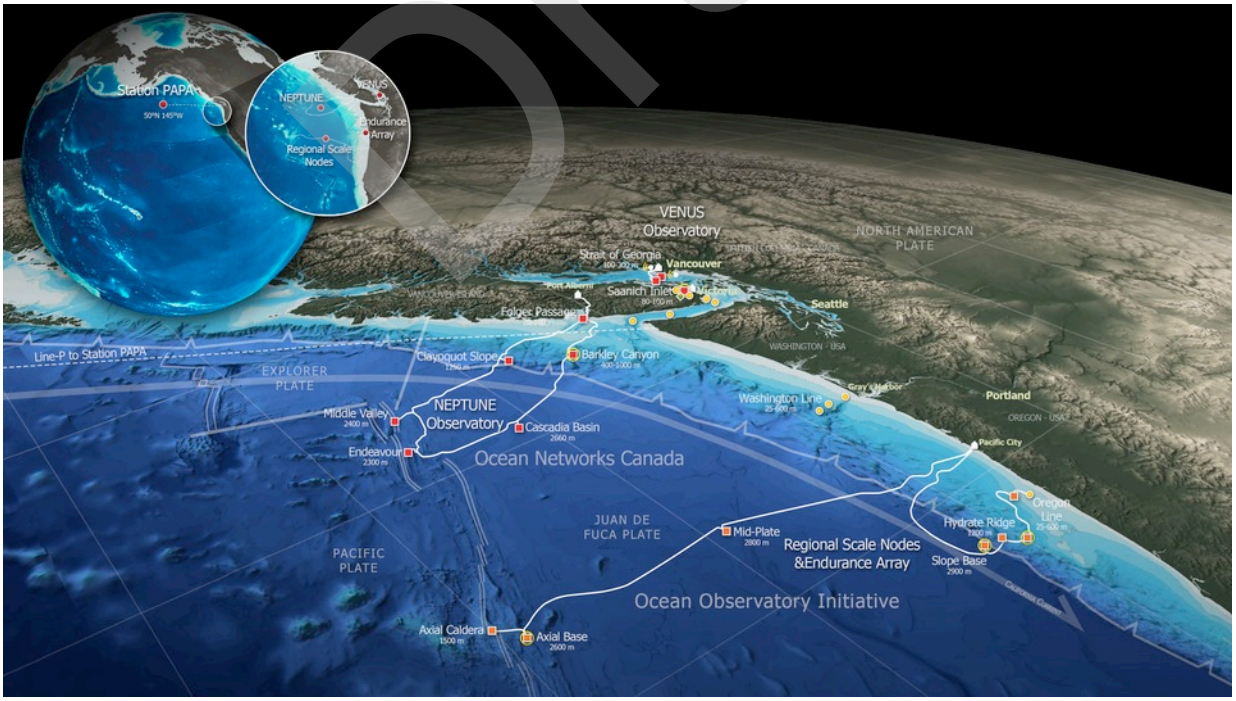
Abstract
We present a new tool that facilitates the study of inter-related geodetic, geodynamic, seismic, and oceanographic phenomena. It incorporates a temperature compensated tri-axial accelerometer developed by Quartz Seismic Sensors, Inc., a pressure sensor built by Paroscientific Inc., and a low-power, high-precision frequency counter developed by Bennest Enterprises Ltd. and built by RBR, Ltd. The sensors are housed in a 7 cm o.d. titanium pressure case designed for use to full ocean depths (withstands more than 20 km of water pressure). Sampling intervals are programmable from 0.08 s to 1 hr; standard memory can store up to 130 million samples; total power consumption is roughly 115 mW when operating continuously and proportionately lower when operating intermittently (e.g., 2 mW average at 1 sample per min). Serial and USB communications protocols allow a variety of autonomous and cable-connection options. Measurement precision of the order of 10^{-8} of full scale (e.g., pressure equivalent to 4000 m water depth, acceleration = +/- 3 g) allows observations of pressure and acceleration variations of 0.4 Pa and 0.3 μm s^{-2}. Long-term variations in vertical acceleration are sensitive to displacement through the gravity gradient down to a level of roughly 2 cm, and variations in horizontal acceleration are sensitive to tilt down to a level of 0.03 μrad. With the large dynamic ranges, high sensitivities and broad bandwidth (6 Hz to DC), ground motion associated with microseisms, strong and weak seismic ground motion, tidal loading, and slow and rapid geodynamic deformation - all normally studied using disparate instruments - can be observed with a single tool. Installation in the marine environment is accomplished by pushing the tool roughly 1 m vertically below the seafloor with a submersible or remotely operated vehicle, with no profile remaining above the seafloor to cause current-induced noise. The weight of the tool is designed to match the sediment it displaces to optimize coupling. An initial deployment of the first instrument constructed began in September, 2015, with a connection to the Ocean Networks Canada NEPTUNE observatory cable to study interseismic deformation of the Cascadia subduction zone. Examples of oceanographic, seismic, and geodynamic signals are presented from the first six months of monitoring. New instruments are under construction for earthquake and geodynamic monitoring using the ONC/NEPTUNE cable system, and for multi-year autonomous operation to study episodic slow slip at the Hikurangi subduction zone. Additionally, we will highlight a new technique to determine long period seafloor deformation from broadband seismometer mass-position measurements.

First wet-test of APT proto-type at ONC test facility.

Cabling a Tectonic Plate—Continuous Live Data from the Cascadia Subduction Zone is enabled through Ocean Networks Canada's NEPTUNE Observatory

Martin Heesemann, Tania L. Insua, Kate Moran
Ocean Networks Canada, University of Victoria, Victoria, BC
(with support from and collaboration with G. Rogers, E. Davis, K. Wang, J. McGuire, and others)

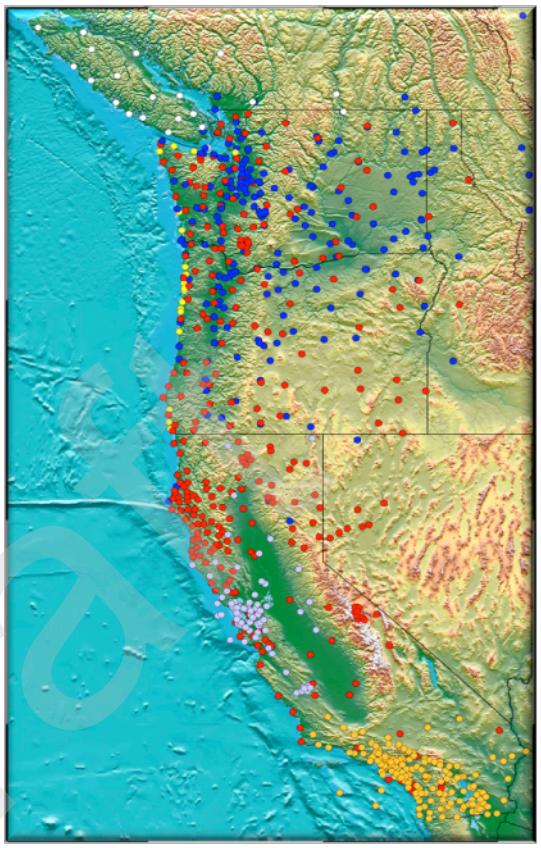
Ocean Networks Canada (ONC) has established the NEPTUNE cabled observatories that spans the Juan de Fuca plate, from the North-American west coast, across the Cascadia subduction zone, to the Juan de Fuca Ridge. NEPTUNE provides power and high bandwidth internet connectivity to the seafloor, enabling continuous and high-resolution real-time data acquisition. This combination serves several important purposes for seismology, geodesy and tectonics: Seismograph data from the top of the subduction zone are available in real time to significantly improve the localization in particular of small to intermediate subduction zone earthquakes, typically the precursors of large megathrust events, whose detection was traditionally limited by the sensitivity of land seismographs. In addition, bottom pressure recorders (BPR) are detecting tsunamis in real-time which helps live updating of tsunami models before far field tsunamis fall on land. Finally, long-term seafloor geodesy experiments can be installed without the need to recover or replace them with fresh batteries but instead bury them deeply such as in boreholes. ONC's NEPTUE observatory and the Ocean Observatory Initiate's (OOI) Cabled Array, are operational and have been streaming years of live data to shore, readily available to monitoring agencies and researchers (seismometer data is available from IRIS, the Incorporated Research Institute for Seismology).



Cascadia real-time GNSS earthquake and tsunami characterization

Timothy I. Melbourne
Pacific Northwest Geodetic Array, Central Washington University

We have completed the first phase of a real-time GPS-based earthquake and tsunami rapid characterization system for large Cascadia earthquakes that includes location, magnitude, faulting spatial distribution, and tsunami excitation due to seafloor uplift. This system currently uses data from ~200 of the ~600 available Cascadia GPS stations, but has been stress-tested to real-time analysis of 800 of the ~1100 West Coast GPS stations. We expect to reach routine handling of ~600 stations this year.



Real-time GNSS on the West Coast of the United States

An intrinsic limit in resolving offshore slip from on-shore geodetic measurements would benefit by deployment of offshore real-time geodetic (including pressure) measurements.

In CWU's system, raw data are processed into station positions with CWU's FastLane GNSS positioning software and made available to downstream geophysical estimation routines using REDIS-backed application servers. We are phasing out GIPSY-based processing and currently working to integrate the FastLane streams into existing Earthworm-based seismic systems operated by the USGS and NOAA as a foundation for on-going expansion throughout West Coast and, eventually, circum-Pacific and globally. Currently, only Japan conducts routine offshore geodetic monitoring.

In addition to CWU's system, NASA and NOAA have formed an applied research and operational Tsunami GNSS Collaborative (TGC) with members from multiple institutions including Central Washington University, University of Washington, Scripps Institution of Oceanography, NASA, UC Berkeley, USGS, and the National and Pacific Tsunami Warning Centers. All of these groups would stand to benefit from offshore instrument deployments.

TGC institutions have also developed and implemented a prototype architecture to collect, process, merge, and disseminate GNSS-based position data from representative real-time stations on the Pacific coast, with quasi-operational reliability and backup using disparate processing algorithms. At the operational centers the data is ingested into the USGS' EarthWorm environment using modules also developed by the USGS. Current TGC activities also include testing algorithms and modules with operations, identifying and promoting access to extend

geographical data coverage, engaging additional warning centers, and evaluating the utility of GNSS-based augmentation of earthquake location and magnitude estimation in the operational environment. Incorporation of offshore measurements from Cascadia into this system would be straightforward.

Fast Identification of Potentially Destructive Earthquakes Using Slowness Parameter

Nooshin Saloor and Emile Okal
Northwestern University

Energy-to-moment ratio or slowness parameter, Θ, introduced by Newman and Okal (1998), can quickly provide information on the distribution of seismic source spectrum between high and low frequencies, and thus identify anomalous events (either "snappy" or "slow") whose sources violate seismic scaling laws. As in snappy earthquakes sources are rich in high-frequency wave energy, they can make large apparent stress drops and sharp rise times which will lead to enhanced ground acceleration and devastating earthquakes (e.g., Christchurch, 2011). Therefore, we can use the concept of Θ to identify such destructive earthquakes in real time, especially since exact depth and accurate focal geometry of these events are not needed in the process and also calculation of Θ is possible using only one station. The main challenge, however, is obtaining good estimates for the seismic moment, M_0, which is not possible in real time. To remedy this, here we substitute M_0 in the algorithm with another parameter, $\tau_{-1/3}$, a good measure of source duration which is proportional to moment and is obtainable in real time (Okal, 2011). We use the methodology introduced by Talandier and Okal (2001) to calculate the time $\tau_{-1/3}$ and then calculate the ratio of energy to $\tau_{1/3}$ for a dataset of earthquakes.

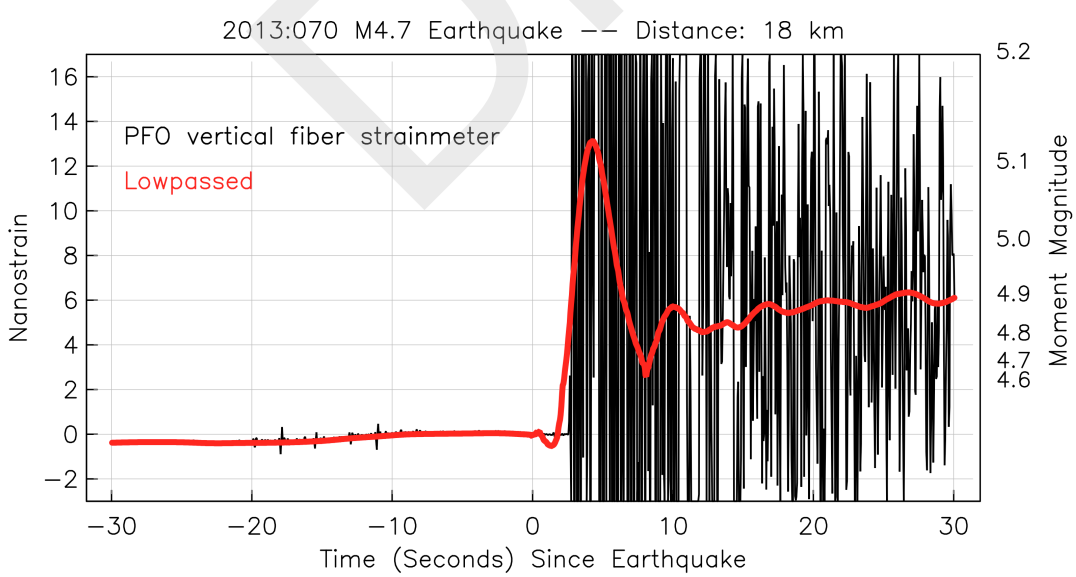
Optical Fiber Sensors for Earthquake Early Warning

Mark Zumberge, Duncan Agnew, William Hatfield, and Frank Wyatt
Scripps Institution of Oceanography, University of California, San Diego

Optical fibers are being used for a wide variety of sensing applications across many disciplines in the physical sciences. While new technologies and methods are being developed rapidly, existing techniques for sensing geophysical phenomena such as strain, pressure and seismic oscillations could be implemented now for Earthquake Early Warning (EEW).

A number of existing systems are promising. One relies on coherent Rayleigh backscatter in the optical fiber. In normal single-mode telecommunication optical fibers, the ever-present scattering centers that reflect small amounts of light back toward the source can be formed into multiple interferometers to sense strain along the fiber. Seismic signals that perturb the fiber are readily detected – literally thousands of 10-meter-long strainmeters can be interrogated from one end of a buried telecommunication fiber, forming a seismometer array with 10 m spacing stretching along a 50 km line.

Long baseline optical fiber strainmeters (OFSs) also hold promise for EEW. Having very wide dynamic range and high sensitivity, these detect both the P-waves that seismometer-based EEW systems rely on and the static strain offsets that GPS-based EEW systems capture. As an example, the record from a 250-m borehole OFS in California 12 km from the epicenter of a magnitude 4.7 earthquake is plotted in the figure below. The P and S arrivals can be seen in the unfiltered data, while the lowpassed record shows the static offset, indicating (with the right-hand vertical scale) an estimate of the magnitude – within about 15 seconds after event.



Given the wide dynamic range, long standoff capability (the optical signal loss is only 0.2 dB per km), robustness, and low cost of optical fiber cables, sensors based on them should be given serious consideration in designing an offshore EEW system.

Near Surface Site Characterization with 3-D Time Domain Full Waveform Tomography

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A new three dimensional full waveform inversion (3-D FWI) method is presented for subsurface site characterization at engineering scales (less than 30 m in depth). The method is based on a solution of 3-D elastic wave equations for forward modeling, and a cross-adjoint gradient approach for model updating. The staggered-grid finite-difference technique is used to solve the wave equations, together with implementation of the perfectly matched layer condition for boundary truncation. The gradient is calculated from the forward and backward wavefields. Reversed-in-time displacement residuals are induced as multiple sources at all receiver locations for the backward wavefield. The capability of the presented FWI method is tested on both synthetic and field experimental datasets. The inversion results from synthetic data show the ability of characterizing laterally variable low- and high-velocity layers (Figs 1-3). Field data were collected using 96 receivers and a propelled energy generator (PEG) to induce seismic wave energy. The field data result shows that the waveform analysis was able to delineate variable subsurface soil layers (Figs 4). The seismic inversion results are generally consistent with invasive tests (SPT N-values).

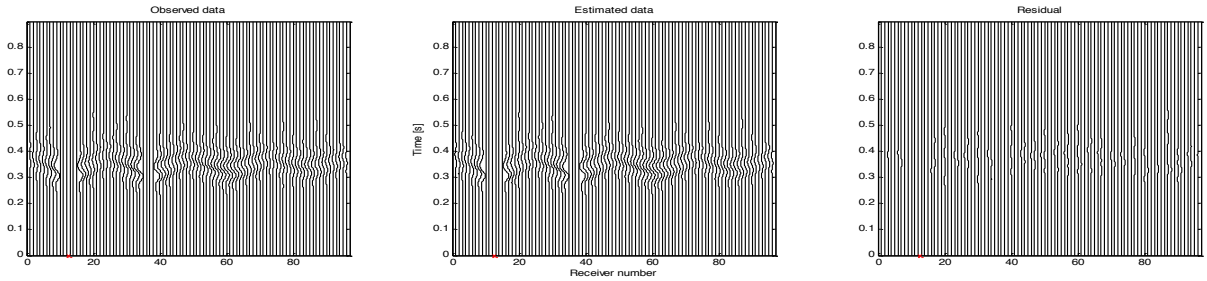

Figure 1: Waveform comparison for a source location (cross)

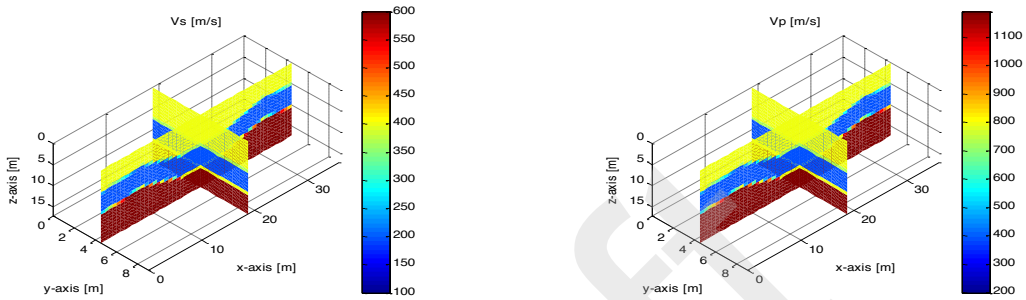

Figure 2: True model

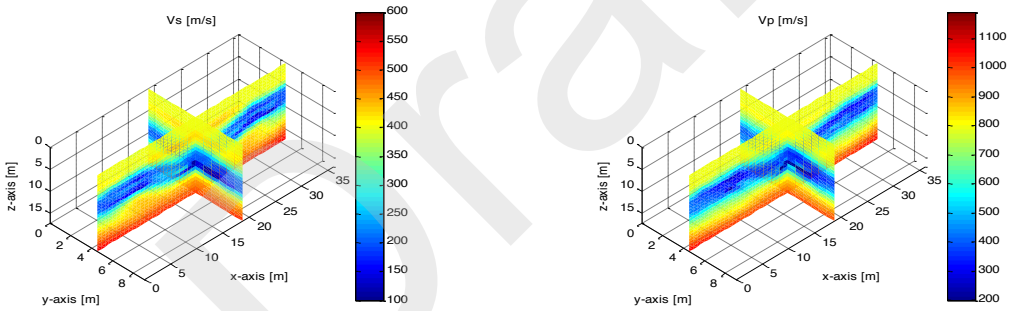

Figure 3: Synthetic study: inverted model

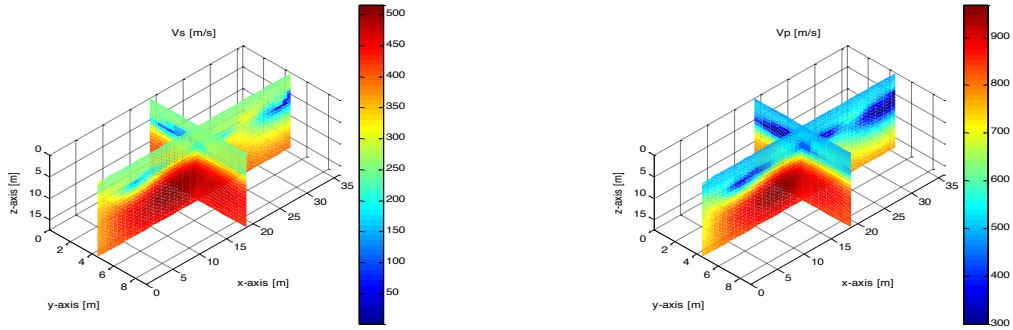

Figure 4: Real data analysis: inverted model

Including NEPTUNE seismic data for processing local earthquakes offshore Vancouver Island

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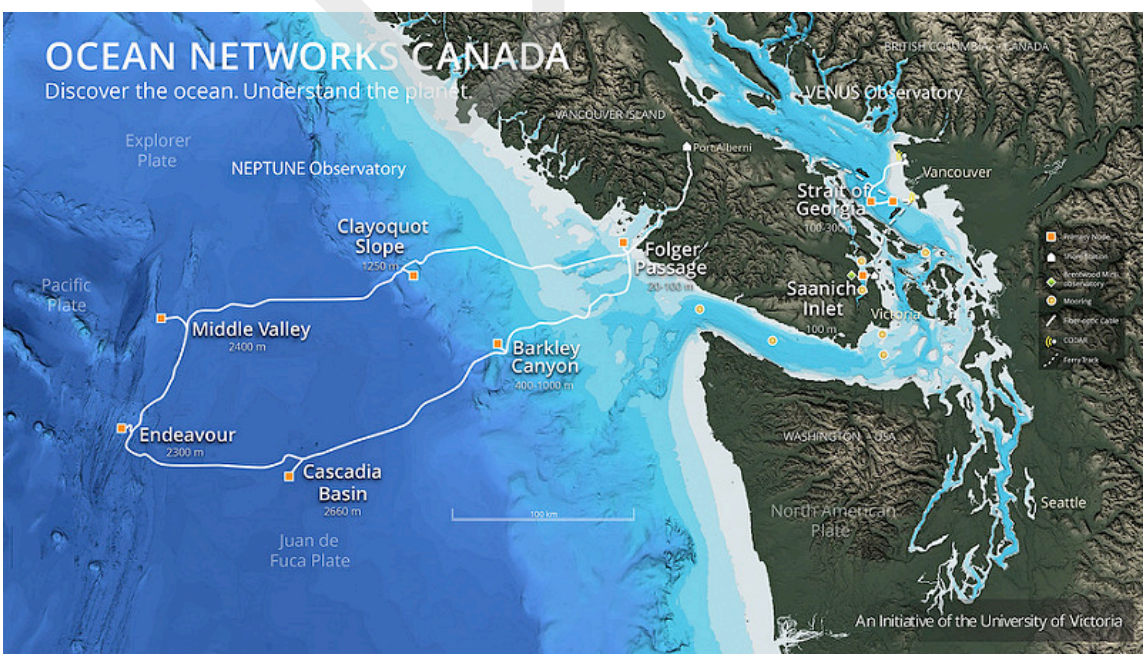
Canada has routinely located earthquakes offshore Vancouver Island since the 1950s. Since the mid-1980s the seismograph network on Vancouver Island used to locate offshore earthquakes has been relatively stable. Since October 13, 2010 data from the NEPTUNE seismograph network has been flowing to the Geological Survey of Canada and IRIS in a routine manner. All data at the Geological Survey of Canada's Pacific Geoscience Centre is processed with the Antelope software suite using the same crustal models that have been used since the 1980s. During the processing, NEPTUNE data is displayed on the analyst's picking screen along with land based stations and treated in the same way.

The effect of including NEPTUNE data when computing offshore epicenters varies with location. For earthquakes near the Juan de Fuca ridge and nearby portions of the Nootka Fault Zone and Sovanco Fracture Zone, including data from NEPTUNE Endeavour sites on the Juan de Fuca Ridge and the mid-plate Cascadia Basin site move the epicenters to the southwest, typically about 10km or so. This is similar to the shifts determined by other OBS studies off Vancouver Island. For earthquakes along the Cascadia subduction zone region, including data from NEPTUNE seismic stations does not move epicenters much, and not in a consistent way, but depth uncertainty is reduced for earthquakes that are close to the NEPTUNE seismographs. The high noise levels at Barkley Canyon (NCBC), the shallowest site (~400m depth), mean that the NEPTUNE data from NCBC only contributed to a minority of the solutions. NCBC has also suffered two long outages due to fishing trawler strikes on NEPTUNE infrastructure, emphasizing the potential vulnerability of shallow sites.



S-net project (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench)

K. Uehira[1], M. Mochizuki[1], T. Kanazawa[1], T. Shinbo[1], T. Kunugi[1], K. Shiomi[1], S. Aoi[1], T. Matsumoto[1], S. Sekiguchi[1], M. Shinohara[2], and T. Yamada[2]
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Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) has 150 real-time monitoring observatories that cover the area about 1000km x 300 km from off-Hokkaido to off-Kanto. NIED (National Research Institute for Earth Science and Disaster Resilience) takes in charge of the S-net project which is supported by MEXT (the Ministry of Education, Culture, Sports, Science and Technology) financially. The purpose of the S-net is to provide the in-situ and real-time earthquake and tsunami data that will be used for disaster prevention.

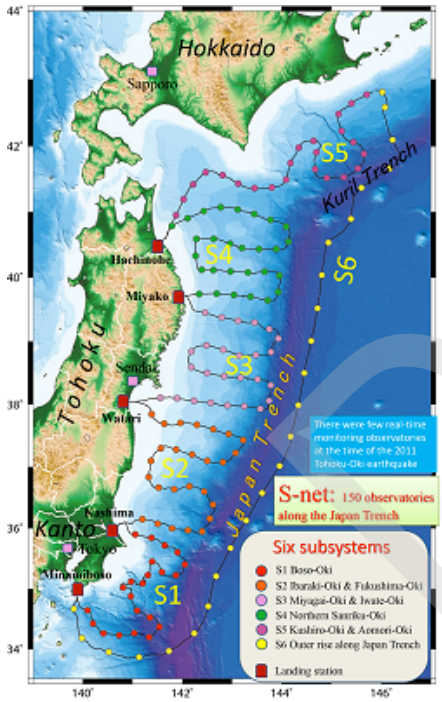

Fig. Map view of S-net. Closed circles and black lines denote positions of seafloor observatories and submarine optical cables, respectively.

The 2011 off the Pacific coast of Tohoku earthquake (Tohoku-Oki Earthquake), the Mw 9.0 interplate earthquake associated with the subducting Pacific Plate along the Japan Trench, occurred off the Pacific coast of Tohoku district, the northeastern part of Japan, on 11th of March in 2011. The gigantic tsunami over 10 m in height, which was generated by Tohoku-oki Earthquake, attacked the coastal areas in the north-eastern Japan and gave severe casualties (about 20,000 people) and property damages in the areas. The present tsunami warning system by the Japan Meteorological Agency (JMA) was a method based on land seismic observation data, and did not work effectively in the case of the M9 earthquake. Concepts of this network are: 1) Cover the area of about 1000 km x 300 km from off-Hokkaido to off-Kanto by the 150 observatories with seismometers and tsunami meters. 2) Locate one observatory in the focal region of M7.5 earthquake which may trigger a remarkable tsunami. By this network, early tsunami and earthquake warnings and earthquake researches are expected to be enhanced.

S-net project started in 2011. Installation of five subsystems (S1 to S5) has already finished, and other subsystem (S6) will be finished in April 2017.

Near-real-time seismology and Geodesy at sea

John Orcutt, Jeff Babcock, Jonathan Berger, and Gabi Laske
Scripps Institution of Oceanography

While seafloor seismometry has advanced significantly over the past decades, access to near-real-time telemetry has not been possible. However, during the past five years, with support from the NSF, Scripps and Liquid Robotics, Inc., we have demonstrated near-real-time telemetry for a remote ocean seafloor observatory concept by modifying an Ocean Bottom Seismograph (OBS) from the SIO Ocean Bottom Seismograph Instrument Pool (OBSIP) and a Liquid Robotics wave glider, which acted as an ocean surface communications gateway (Berger et al, 2016). These developments included:

- Design and build of a towed acoustic modem
- Modification of an SIO BB-OBS to accommodate acoustic telemetry between the seafloor and shore
- Extensive sub-system lab tests and at-sea tests of the entire system

We have proposed, again to the NSF, a transition from a successful prototype to an operational system capable of operating for two+ years between servicing rotations. We will deploy this system at a remote ocean site and operate for at least two years. We will adopt a new Liquid robotics SV3 Wave Glider with an auxiliary thruster and a keel-mounted acoustic modem. The new version will include the continuous transmission of data at 1 sps for each of four channels and enable transmission at 40sps for each of the four channels on-demand or when the four components detect large events. Timing drift will be largely eliminated as first described by Spindel, et al. 1984. An accurate crystal oscillator from Seascan, Inc. (SISMTB) will be disciplined every two days by a rubidium atomic clock to achieve annual drift rates on the order of several ms. The latency in receiving data ashore depends upon delays in accumulating a data frame at the sensor, the delay in the water column and the time required to attach an Iridium satellite connection. In a 68-day prototype deployment we observed a median overall latency of 260s.

There are now significant efforts underway to improve greatly on satellite communications. In particular, SpaceX is deploying a 4,425 satellite constellation in MEO orbits with communications with extremely high bandwidths. The largest contribution to latency, above, is the time for the glider to establish a communications link with Iridium. When this system becomes available, the largest delay will be the acoustic link that contributes a bit more than 2s in 3km of water. The available warning time will be competitive with a fiber-optical cable.

This new technology will enable the extension of the continent and island-based Global Seismic Network (GSN) to the oceans. The system is also very well suited for deploying offshore seismic and geodetic stations in large numbers for both seismic and tsunami warning. The system avoids the use of a seafloor tether thereby increasing reliability and lowering costs. We have tested the use of a tow-body for pulling a seafloor OBS over substantial distances and, in the future, we anticipate further experiments for eliminating the use of ships altogether. We have recently developed a new autonomous seafloor burial mechanism and, in the future, propose to extend this to burying the seismometers to reduce noise levels, which have been a significant

problem in the past. This autonomous system is particularly well-suited for early warning, especially since the three components of motion and pressure all contribute useful information about the source.

To enhance reliability, a standby wave glider ashore can transit from shore to the site to take up the gateway responsibility and the original glider can return to shore for maintenance. The software for moving data from the seafloor to shore is based on the Science Observatory Network (SciON) derived from the NSF's original OOI software system that employs message passing for speed and security.

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Toward near-real time monitoring of offshore earthquake energy release

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Generating complete catalogues of earthquakes and other seismic phenomena along major plate boundaries is crucial for calculating aftershock forecasts and monitoring the evolution of slow-slip events (SSE). This is particularly topical in New Zealand in the aftermath of the Te Araroa (Mw7.1) and Kaikoura (Mw7.8) earthquakes and commensurate significantly heightened potential for future large subduction megathrust events. However, catalogues based on traditional sparse arrays (e.g. GeoNet's national network) contain only a fraction, perhaps 25%, of the events that actually occur during these sequences. This is primarily due to the low-amplitude nature of seismic signals and 'real-time' processing limitations of sparse arrays. For example, Figure 1 highlights missing events not captured in routine analysis using sparse onshore network data during the Te Araroa aftershock sequence. The processing that led to the more complete catalogue in the figure cannot currently be accomplished in real-time and was only possible using months of data recorded after the event. This presents a problem for real-time monitoring and the timely communication of earthquake hazard to governments and society. The same problem exists when looking at the seismic phenomena associated with SSE (e.g. tremor and low-frequency earthquakes). We simply do not have the data density to find low-amplitude signals in high-noise environments in real time. We are developing two collateral workflows to overcome these difficulties. 1) We will present catalogues of radiated energy that do not rely on impulsive phases for detection. We suggest that maps of radiated energy can be used in seismic hazard assessment in much the same way that discrete earthquake catalogues are currently used. Energy mapping is based on back projection of continuous velocity squared waveforms and defines the relative likelihood of energy radiation from every element in a 3D earth model in discrete time steps. 2) We can overcome poor signal to noise ratios by using arrays of dense seismic arrays (tiny clusters with ~10-20 seismometers). This approach has been successfully applied in Cascadia, Aleutians and Taiwan. We are testing the sensitivity of such arrays in New Zealand, with the specific goal of optimizing sensitivity to SSE related tremor signals. We believe that this will demonstrate the utility of dense onshore arrays in areas with no means for offshore sensors and provide a pathway to increasing the sensitivity of the GeoNet array far more economically than installing borehole seismometers.

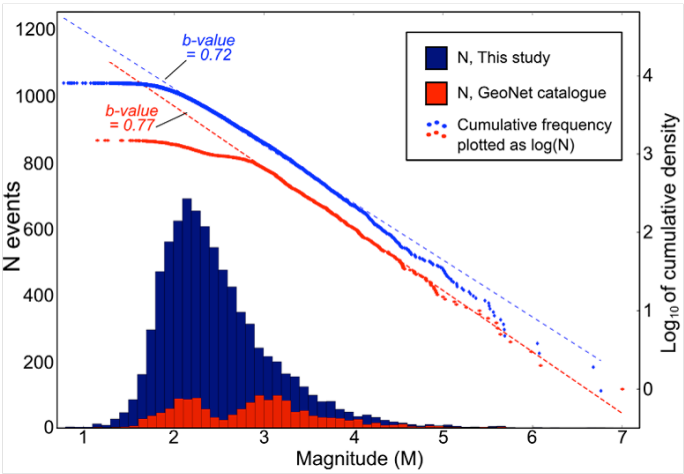

Figure 1: Earthquakes recorded in the 2016 Te Araroa earthquake. Red histogram shows the GeoNet catalogue based on sparse onshore networks. The blue curve shows our results after reprocessing the data a few months into the sequence. This type of reprocessing is NOT possible in near real-time, which is necessary for providing earthquake statistics. **The workflow we are developing with dense arrays and energy mapping may provide a catalogue superior to the one shown in blue, in near real time.**

Scenarios for slip characterization improvement for Cascadia subduction earthquakes by augmenting the existing onshore GNSS network with offshore observations

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The shallowest portion of the subduction interface, from the trench to ~15 km depth, is generally assumed to be creeping due to the low rigidity associated with subducted sediments in the accretionary wedge. However, this subduction region is capable of producing tsunami earthquakes – long duration, moderately-sized earthquakes that produce disproportionally large tsunamis compared to their seismically-determined magnitude. In Cascadia, it is unknown whether the subduction interface is locked to the trench, so near-source tsunami early warning systems targeted for this region need to be capable of rapidly identifying a shallow tsunami earthquake. One approach to near-source tsunami warning is to use a rapid slip inversion of the earthquake as input to a tsunami model, and the results of the simulation are used to guide the warning issued to populations living along the coastlines immediately adjacent to the earthquake. Near-source onshore data such as Global Navigation Satellite Systems (GNSS) displacements are capable of measuring the low-frequency ground motions and coseismic offsets necessary for characterizing large tsunamigenic earthquakes, but onshore data may not be able to uniquely determine the rupture region because the data is located to one side of the rupture. Augmenting this dataset with offshore data closer to the trench will reduce non-uniqueness of the slip inversion and improve rapid characterization of the rupture region. This work examines how different scenarios of offshore station configurations for Cascadia combined with the current real-time GNSS network in the Pacific Northwest improve static slip inversion solutions, particularly in the shallow portion of the megathrust. We use two rupture models with the same slip distribution for this comparison: a shallow rupture simulating a tsunami earthquake, and a deeper rupture in the typical seismogenic region of the subduction interface. We assess the key offshore data locations necessary to determine the region of rupture with sufficient accuracy to be useful for distinguishing tsunamis of different threat levels.

S-net Project

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NIED has launched the project of constructing a seafloor observatory for earthquake and tsunami monitoring in order to enhance reliability of early warnings of tsunami and earthquake after the occurrence of the 2011 off the Pacific coast of Tohoku Earthquake (the 2011 Tohoku Earthquake). The seafloor observation network was named "S-net". "S-net" is acronym standing for Seafloor observation network for earthquakes and tsunamis along the Japan Trench. S-net project has been financially supported by the Ministry of Education, Culture, Sports, Science and Technology .

S-net is the online and real-time seafloor observation network of 150 observatories for earthquakes and tsunamis along the Japan Trench. It consists of six segment networks of about 25 observatories and 800-1,600 km submarine optical cable and covers the focal region of the 2011 Tohoku Earthquake and its vicinity regions.

Each observatory equips two sets of pressure gauge for tsunami observation and 4 sets of three component seismic sensors of different performances to secure wide dynamic range of earthquake observation covering slow slips, small and large earthquakes. The employment of the multiple sensors is resilient against a sensor failure. Sensors, optical amplifiers and a data transmission unit are installed inside a beryllium-copper-alloy-made pressure vessel of 34cm diameter and 226cm long.

The 150 seafloor observatories are connected in line with submarine optical cables. The optical cable connecting between observatories is used one which has 12 fibers forming 6 fiber pairs (there is an exception that the route through the outer rise employs 10 core optical fiber cable.). 5 of 6 fiber pairs are used for data transmission and another fiber pair is used for power supply control. We employ 4 kinds of 12 core optical fiber cables which have different protection structures properly according to the depth of water.

And those optical cables are landed at 5 sites (Minami-Boso-city, Kashima-city, Watari-town, Miyako-city and Hachinohe-city) on the Pacific coast of NW Japan. Observed data are transmitted bi-directionally to the landing stations. Landing station is unmanned control center of the offshore cabled systems of the segment networks. It equip ordinary and emergency power supply, optical transmitter-receivers, workstations (data conversion, data transmission), surveillance systems, receivers, air conditioners, network routers and so on.

The observed data are transmitted from the landing stations at 5 sites to not only S-net data center at NIED, but also Japan Meteorological Agency (JMA) via IP-VPN network (EarthLAN). JMA started to utilize the S-net data for monitoring tsunamis and earthquakes.

Plans and future potential for offshore monitoring at the Hikurangi subduction margin, New Zealand

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The Hikurangi subduction zone, where the Pacific Plate subducts beneath the North Island of New Zealand, is New Zealand's least understood and potentially its largest source of geohazard. We currently rely on the GeoNet network, which is a shore-based GPS, seismic, and tide gauge network to monitor earthquakes, slow slip events, and tsunami. However, relying solely on shore-based data inherently limits our knowledge of earthquake, deformation, and tsunamigenic processes occurring on the offshore Hikurangi subduction zone. The recent U.S. NSF, Japanese, and New Zealand funded HOBITSS experiment offshore the northern Hikurangi margin (2014/2015) very clearly demonstrated the utility of Absolute Pressure Gauges to discern detailed, cm-level vertical deformation of the seafloor during offshore slow slip events. Building on the HOBITSS success, we are expanding our efforts to further develop monitoring capability at the offshore Hikurangi margin. Recent events such as the September 2016 Mw 7.1 Te Araroa earthquake and the November 2016 Mw 7.8 Kaikoura earthquake generated tsunami detected by the onshore tide gauges; large uncertainties about what happened to generate these earthquakes and tsunami underscore the need for continuous monitoring offshore New Zealand.

A number of New Zealand and internationally-funded activities are currently underway to investigate earthquake, slow slip, and interseismic locking processes using seafloor and sub-seafloor instrumentation at the offshore Hikurangi subduction zone. Due to the close proximity of the slow slip source area to the seafloor at the northern Hikurangi margin (<2-15 km), it has become an important international target for a variety of investigations to understand the physical mechanisms that lead to slow slip. IODP drilling and CORK observatory installations with the Joides Resolution in 2018 at the northern Hikurangi margin are at the center of efforts to address this important problem. We have recently been funded by the New Zealand government for rolling deployments of Absolute Pressure Gauges and OBS to further investigate offshore deformation and seismicity related to these shallow slow slip events. This project will also involve deployment and surveys of a GPS-Acoustic transponder array at the deeply locked southern Hikurangi margin to evaluate the trenchward extent of locking there. A variety of international partners are developing plans to join in these efforts to broaden out the seafloor deployments to other parts of the Hikurangi margin. All of these efforts will help to grow much needed New Zealand-based expertise in offshore seismic and geodetic investigations.

One of the main drawbacks of the currently planned experiments is that they are being undertaken with instrumentation that either has to be downloaded on-site with ROV (e.g., the CORKs), or via recovery of the instrument itself. For such data to be useful for tsunami and earthquake early warning, the data need to be continuously flowing to shore in real time.

Developing such a network has been recommended as a future goal of GeoNet, and we are currently in the very early stages of investigating whether or not such a cabled, offshore network is a feasible goal for New Zealand.

Goals and priorities for megathrust science in monitoring offshore Cascadia

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The Cascadia subduction zone poses great seismic and tsunami threat to coastal western North America. As a representative end member of warm-slab, sediment-rich, and smooth-interface subduction zone at a late stage of interseismic strain accumulation, it yields important information for understanding earthquake cycles worldwide. However, because land-based geodetic observations provide no resolution near the deformation front, our knowledge of the kinematics of the Cascadia megathrust is rather incomplete, hindering informed studies of the mechanics and dynamics of the system. Resolution of the following kinematic issues urgently requires offshore monitoring. (1) Is the megathrust fully locked? Elastic and viscoelastic locking models can fit land-based geodetic measurements by assuming either a narrow and shallow zone of full locking or a much wider zone of partial locking. Although warm-slab subduction and the present nearly complete lack of interplate seismicity support theoretical arguments for narrow and full locking, the true locking state can be observationally defined only by offshore deformation monitoring. (2) How does the locking state vary along strike? Models of the 1700 AD great Cascadia earthquake based on paleoseismic observations suggest heterogeneous rupture. For understanding fault mechanics and assessing hazards, it is important to know whether the heterogeneity is geologically controlled and hence persistent. It can be shown that land-based geodetic measurements cannot resolve along-strike variations in megathrust locking and creep far offshore. Deformation monitoring near the deformation front can readily answer this question. (3) Are there slow slip or other transient deformation events offshore? Cascadia is a prolific producer of Episodic Tremor and Slip (ETS) around the mantle wedge corner, but it is not known whether slow slip events also occur near the deformation front as observed in some other subduction zones. Because slow slip events are creep pulses, monitoring shallow slow slip also helps to answer the first two questions. (4) How do other faults off the megathrust move in the current stage of the earthquake cycle? Steady or transient creep of the shallow megathrust is expected to cause other faults in the overlying sediment cover and accretionary prism to move. The mechanical behaviour of these faults may play important roles in tsunami generation. Faults within the incoming oceanic plate associated with plate cooling and bending may also move in response to megathrust motion. The small motion of these secondary faults can be detected with seafloor and subseafloor monitoring.

The M9 Project: 3-D Simulations of Magnitude 9 Earthquakes on the Cascadia Megathrust

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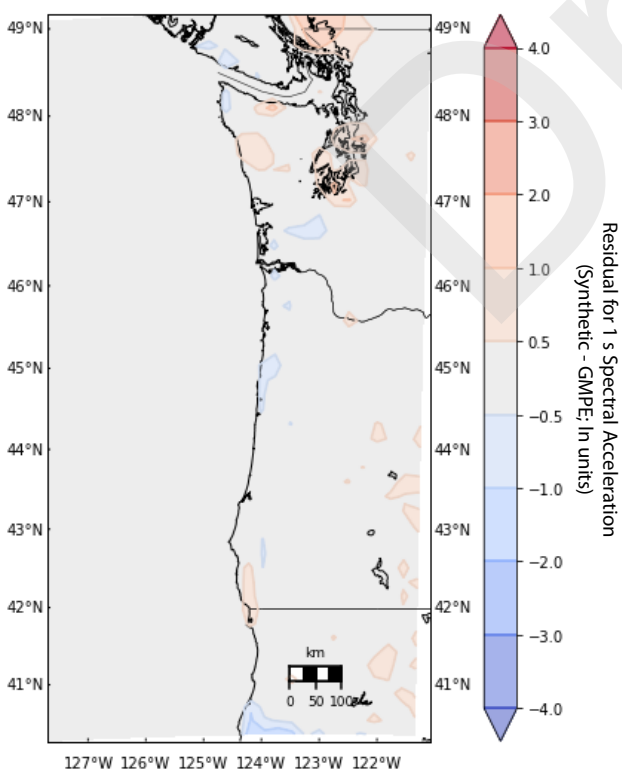
University of Washington

The M9 Project is a collaborative, multi-disciplinary effort currently underway at the University of Washington. The project aims to reduce the catastrophic consequences of Cascadia megathrust earthquakes on the social, built, and natural environments through research advances in methodologies, warnings, design, and community planning. We perform 3-D ground motion simulations for multiple fault rupture scenarios, in order to evaluate the range of potential consequences from a magnitude 9 megathrust earthquake in Cascadia. Our simulations provide a suite of synthetic ground motions that capture the directivity of the rupture, duration of shaking, presence of damaging surface waves, and amplification from deep sedimentary basins. Results indicate significant basin amplification (a factor of 2 to 5) for sites in the Seattle and Tacoma sedimentary basins, relative to sites outside the basins. We also find that key parameters significantly influence the resulting synthetic ground motions, including the down-dip limit of the rupture, the spatial distribution of slip and rupture velocity, the average rupture velocity, the hypocenter location, and the character of high stress drop subevents distributed along-strike. To capture this variability, we have assembled a suite of ~50 proposed M9 earthquake scenarios for Cascadia. The results of our simulations will be used to inform tsunami, liquefaction, and landslide modeling, as well as to understand the effects on built structures, and improve preparedness and resilience in local communities.



(left) Comparison of 1s spectral accelerations for Simulation csz002_sd10 and BC Hydro Ground Motion Prediction Equations (GMPEs). Note that basin sites are amplified relative to nearby hard-rock sites, and the GMPEs. (Figure by Nasser Marafi, UW)
(above) An M9 Project "Coastal Resilience Workshop" took place in Aberdeen, WA in February 2016, with the goal of understanding how stakeholders may better mitigate hazard and build resilience in their communities.

Catalog of near-shore seismicity in the Pacific Northwest from Cascadia Initiative OBS data

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We have developed a catalogue of near-shore seismicity for the coasts of Washington, Oregon, and Northern California using data from the 4-year Cascadia Initiative OBS deployment. Through amplitude based filtration methods, we located 270 earthquakes with epicenters located over the locked portion of the Cascadia megathrust fault (between the trench and shoreline). 74 of the detected events have corresponding records in regional land-based seismic catalogues. These earthquakes represent both known and uncharacterized sources of regional seismicity. Event locations were found using SVD least-squares location methods (Locsat and Hypoinverse), with depths updated from previous work. We attempt to quantify the quality of our search by plotting the spatial and time distribution of stations used during event detection. We plan on further characterizing the observed sources of seismicity through the use of cross-correlation-based detection methods. Our long term goal is to use the updated catalogue to assess regional land-based seismic networks' ability to locate offshore seismicity, as well as to update structural models of the region.

Real-time tsunami prediction system using DONET

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NIED/JAMSTEC

The off Tohoku earthquake tsunami in 2011 brought great damages on the coastal areas along the Northeastern Japan area. Along the areas, there are large breakwaters with the height of over 10 meters, but the huge tsunami with the maximum height of 40 m washed away every house beyond the breakwaters. Therefore, seismogenic monitoring group of JAMSTEC developed a real-time tsunami prediction system using the dense oceanfloor network system for earthquakes and tsunamis (DONET) and started the implement on some local governments. This system predicts arrival time of tsunami, maximum tsunami height and inundation area for coastal target points by extracting proper fault models from a tsunami database. We calculated waveforms of pressure gauges on all DONET stations and of water levels for the target points for the tsunami prediction using 1506 models, changing the magnitudes, depths, and angles of the fault planes. Recently DONET2 installed in 2016 and the DONET covers with not only the Tonankai earthquake rupture zone but also Nankai earthquakes. Important things to realize the tsunami prediction with high accuracy are to focus the fault models in the database based on the directions of the tsunami source, and to select proper DONET stations for each tsunami prediction point. After detection of seismic signals and tsunami on the DONET stations, proper fault models from entire models is selected by estimated direction of the source using seismic and tsunami data based on each different travel-time among the stations. To select proper DONET stations, we introduced dynamic selection of the stations based on the estimation of the tsunami propagation to each tsunami prediction point. Using theoretical tsunami waveforms of the Tonankai and Nankai earthquakes tsunami and huge fault models with magnitude of nine proposed by Japanese Cabinet Office. We can see good correlation between the pressure gauge's values of the DONET stations and the maximum tsunami heights, and we extract fault models as candidates to show the tsunami arrival time, the maximum height and the inundation area. There are worse cases on the correlation, but the correlation becomes good by introducing above selection of fault models and DONET stations. Now we already implemented it on the local governments, and they show the tsunami prediction to the coastal municipality. The local government judges the best scenario of the countermeasures for the recovery from tsunami damages. Here, I show you the logic of the prediction system and the examples of the implementation.

The Future of Geodesy in a Subduction Zone Observatory

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Terrestrial GPS stations along with other geodetic tools like borehole tensor strainmeters are powerful tools to study interseismic, coseismic, and post-seismic surface deformation on the upper plate at subduction zones. Since EarthScope was initiated in 2003, UNAVCO has built, operated, and maintained the Plate Boundary Observatory, which is comprised of ~1100 cGPS, ~80 borehole seismic, strain, and pore pressure instruments, ~26 short-baseline electronic tiltmeters deployed at 10 volcanic targets, and 6 long-baseline laser strainmeters deployed along the San Andreas Fault system. PBO is currently supported through a Cooperative Agreement with the National Science Foundation through the Geodesy Advancing Geosciences and EarthScope (GAGE) Facility. GAGE as well as EarthScope will officially sunset in 2018, but UNAVCO anticipates that much of geodetic instruments that currently comprise PBO will continue to be supported as part of proposed new NSF facility called the National Geophysical Observatory for Geoscience (NGEO). In addition to PBO, and based on its well-established design and best-practices, UNAVCO, with additional funding from the NSF MRI program and our partner Universidad Nacional Autónoma de Mexico (UNAM), has recently completed TLALOCNet, a 37-station cGPS-Met network in Mexico. TLALOCNet now connects PBO with COCONet, the multi-hazard federated, 83-station cGPS-Met network in the Caribbean, which UNAVCO built starting 2011 and now operates for NSF. UNAVCO anticipates that the combined PBO, TLALOCNet, and COCONet would be merged, upgraded to form the Network of the Americas (NOTA) under NGEO. Here we present a summary of these geodetic assets with the idea that these will would form a basis for terrestrial geophysical infrastructure in a future Subduction Zone Observatory.

Research and Monitoring Needs for Tsunami Mitigation in Washington

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The Washington Geological Survey has been participating in the National Tsunami Hazard Mitigation Program since 1995. Among other things, the program aims to mitigate tsunami hazards by identifying and mapping the hazard areas and providing evacuation guidance. For areas where timely evacuation is not feasible due to lack of nearby high ground, we have developed design guidance for construction of vertical evacuation structures, or safe havens, in FEMA 646, using hydrodynamic models of scenario earthquakes and tsunamis. One such structure, Ocosta Elementary School, has been built near Westport, Washington. ASCE 7-16, chapter 6, has extended FEMA 646 using probabilistic hazard analysis, and is being implemented in the design of a berm adjacent to Long Beach Elementary School. There are significant uncertainties in calculating tsunami inundation depths and loads that are accounted for by adding safety factors. The most significant uncertainty, however, is in the generation of the tsunami. Slip distribution and surface deformation are the drivers of the tsunami model and they are poorly known. Seafloor geodetic and seismic monitoring would improve understanding of the seismic source and more closely constrain the initial condition for the tsunami model, which in turn could reduce the magnitude of safety factors. Earthquake early warning could also help facilitate successful tsunami evacuation by adding a few minutes to the short (a few tens of minutes) time available to reach high ground or a vertical evacuation structure.

Near-field tsunami simulation of western Makran hypothetical earthquake scenarios

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The western Makran region is characterized with almost no seismicity and has no large earthquake recorded instrumentally. We considered a hypothetical rupture area (L=450 Km, W=210 Km, Dip= 7° and Strike= 280°) in the western Makran and then used scaled slip distribution models of four recent tsunamigenic earthquakes i.e. 2015 Chile, 2011 Tohoku (two models), 2006 Kuril Islands and 2004 Sumatra earthquakes into the rupture area based on the equality of the seismic moment. To express the theoretical background, we used the finite fault models to investigate near-field effects of those modeled earthquakes. The near-field tsunami hazard was then evaluated based on the numerical modelling of the five scenarios. The computed vertical seafloor deformation with the algorithm of Mansinha and Smylie (1971) was implemented as an initial condition in the tsunami simulations. The deformation field of each scenario was consistent with its slip distribution on the western Makran rupture area. The results of the distribution of maximum amplitudes were used to compare all five scenarios. We concluded that the Tohoku scenarios are the most hazardous and the Kuril scenario produced a minimum risk for the study area. Since the rupture area is constrained by the shores of Iran and Oman, it reduced tsunami waves energy significantly, thus having less effect on the more distant shorelines while the maximum impacts were on the coastlines of Iran and Oman. However, the southeastern shores of Iran were exposed with the more hazard in comparison with Oman shores. Furthermore, we selected seven stations near the major ports in the study area. Chabahar and Muscat stations experienced maximum water heights. The average arrival time of the highest tsunami waves in Chabahar is 28 minutes and 15 minutes in Muscat after the origin time. Sumatra scenario caused the minimum arrival time for the highest water elevation while Chile scenario had the maximum arrival time.