Geodesy & Ocean Disasters Sensors (GODS)

GODS

Geodesy + Ocean Disasters Sensors (GODS) modules have been developed for both disaster warning and geodetic measurements. The instrumentation package includes deep-sea absolute pressure gauges, a triaxial accelerometer, and nano-resolution processing electronics. An in-situ calibration system eliminates pressure sensor drift. The GODS modules work on cabled systems, in remote ocean bottom recorders, and in underwater vehicles.

DISASTER WARNING SYSTEMS

The GODS modules were developed in response to the need for improved offshore instrumentation as expressed by Dr. Andrew V. Newman in the 23 June 2011 issue of Nature:
(http://geophysics.eas.gatech.edu/people/anewman/research/papers/Newman_Nature_2011.pdf)

"It should be possible to bring instrument manufacturing and deployment costs to under US$50,000 per station within a decade, if research and development is stepped up on available and emerging technologies. It would then cost $5 million to $20 million to equip an environment like the Japan Trench. That's far less than the current spend on national, land-based scientific-grade GPS infrastructure in countries such as the United States, Japan, and New Zealand. (The western US Plate Boundary Observatory, for example, cost $100 million to install, and needs about $10 million per year in upkeep.) Put another way, the figure is less than 0.01% of the projected costs of the Japanese tsunami, which may exceed $300 billion."

The absolute pressure gauges and triaxial accelerometers independently measure dynamic seismic and pressure events such as earthquakes and tsunamis.
(http://www.paroscientific.com/pdf/Nano-resolution_Sensors_for_Disaster_Warning_Systems.pdf).

The GODS module contains 3 accelerometers and 2 depth sensors similar to those used in the Japan Trench Tsunami Warning System.

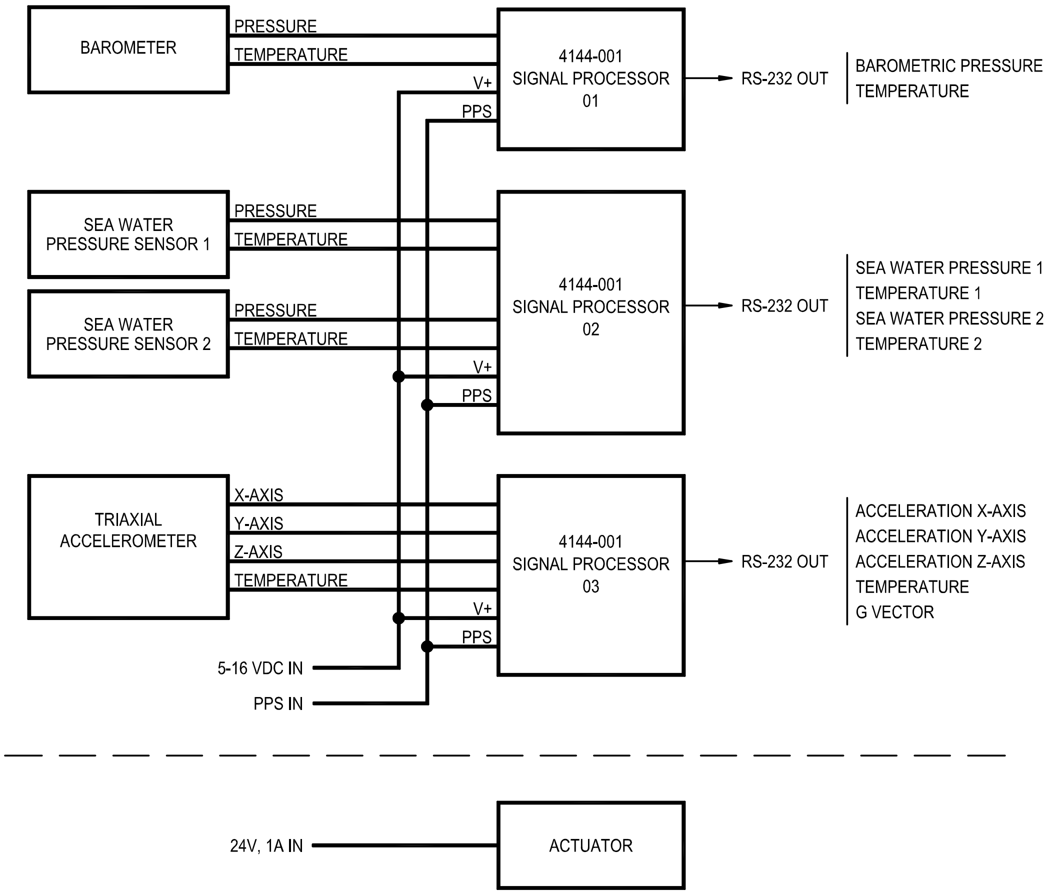
GEODESY

Recent papers describe the need for improved offshore geodetic measurements including slow slip (See Appendix “Excerpts”). The May 6th issue of Science includes the following excerpt by Dr. Anne M. Tréhu on measurements of slow slip at the Hikurangi Trench in New Zealand using Digiquartz® absolute pressure gauges (http://science.sciencemag.org/content/352/6286/654):

“This has led to development of alternative techniques for obtaining seafloor geodetic data such as differencing of swath bathymetric data, seafloor and borehole strain meters, and arrays of absolute pressure gauges (APGs), which measure changes in the mass of overlying ocean, from which seafloor uplift or subsidence can be determined. Because of their relatively low unit cost, APGs can achieve the spatial coverage needed to understand complex environments, **although there are a number of challenges to be overcome, including long-term sensor drift and separation of tectonic signals from oceanographic effects**.”

The Absolute Pressure Gauges and Triaxial Accelerometer separate the seismic and oceanic signals. The in-situ A-0-A calibration system provides long-term measurements to eliminate sensor drift (See http://www.paroscientific.com/pdf/g8097.pdf). A-0-A is a variation of the Scripps Self-Calibrating Pressure Recorder that uses 2 absolute pressure gauges, a barometer, nano-resolution processing electronics, and a valving arrangement. Oil-filling and configuring the A-0-A system are described at: http://www.paroscientific.com/pdf/G8085.pdf.

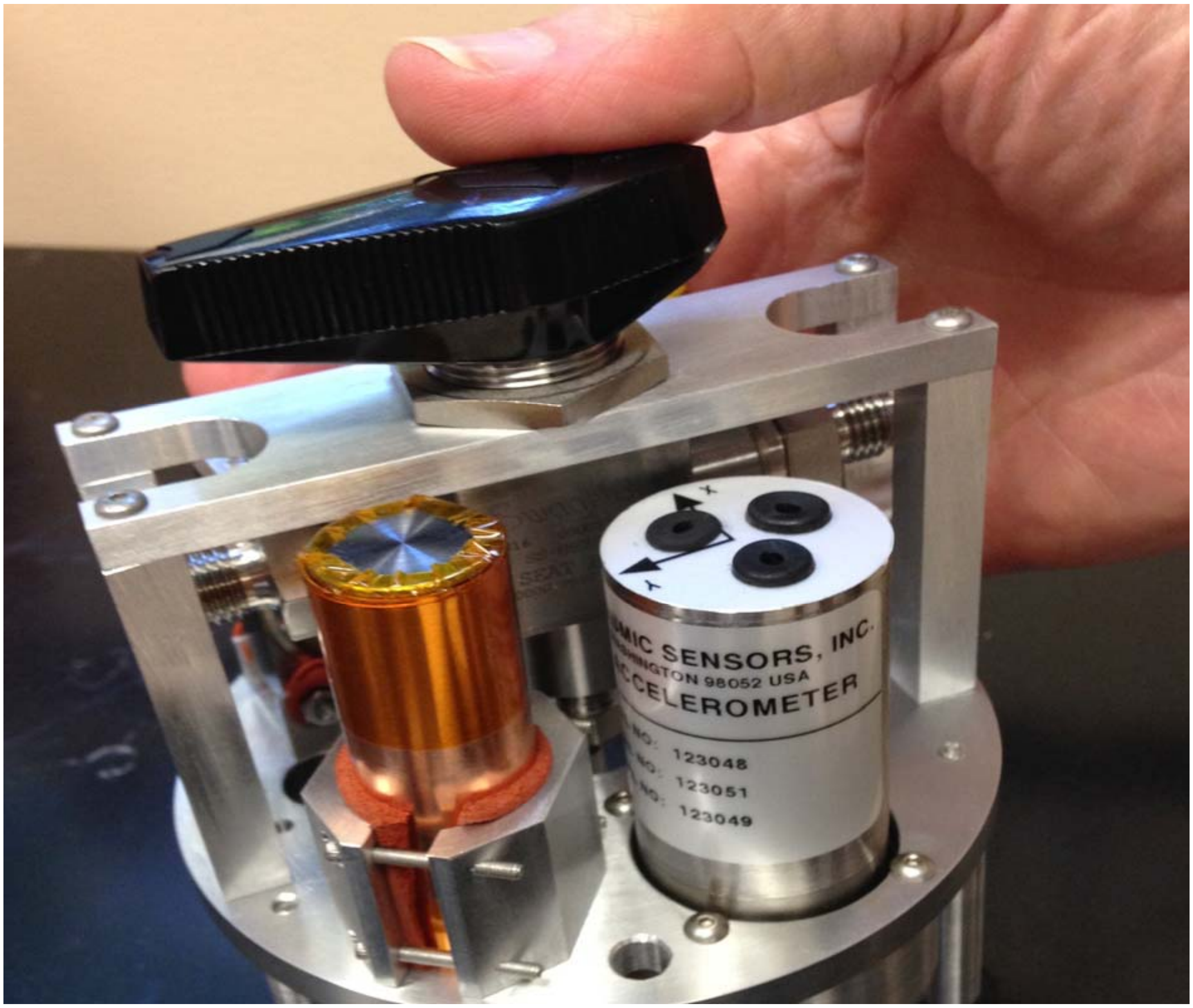
GODS CONSTRUCTION



The GODS module contains (2) absolute pressure gauges with available ranges of 1400, 2000, 3000, 4000, and 7000 meters plus (1) Triaxial Accelerometer with an internal alignment matrix, plus (1) Digiquartz® Barometer, plus (3) Nano-resolution processing electronics. The pressure connection lines are vacuum oil-filled to (1) Swagelok 3-way ball valve that switches between seawater pressures, (A), and an interior oil reservoir, (0).

Temperature compensated and linearized RS-232 outputs are provided from all sensors and include:

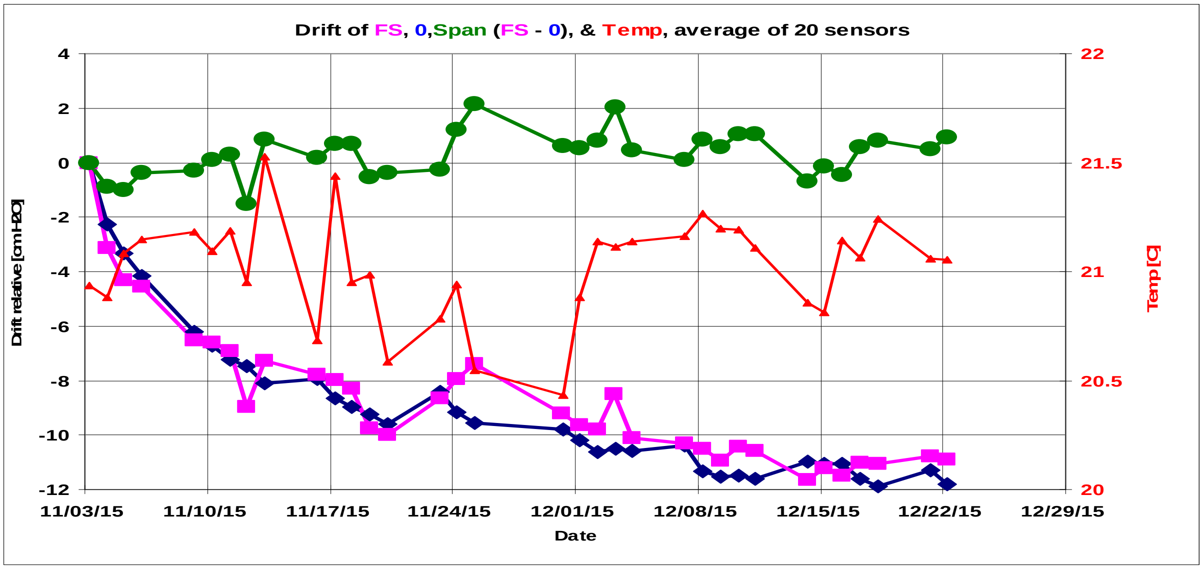
- Seawater pressures (A) and temperature readings from each pressure gauge (1 port).
- X-Y-Z plus total Vector accelerations and accelerometer temperature readings (1 port).
- Interior housing barometric pressures (0) and barometer temperature readings (1 port).
- All sensors can be synchronized and time-stamped using PPS inputs.

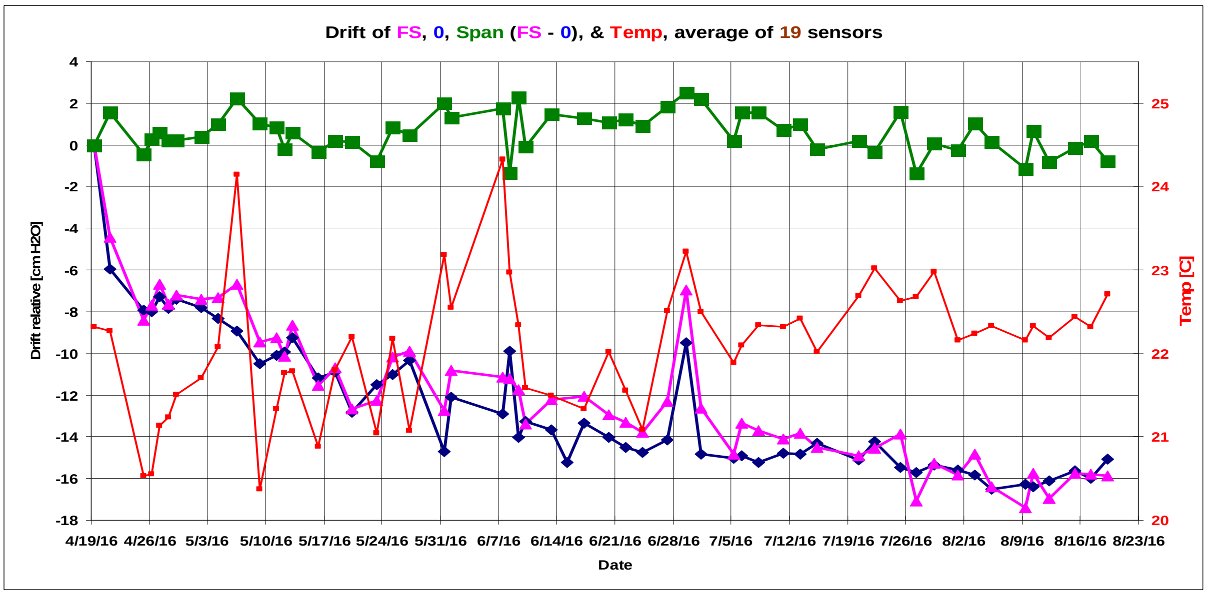


TEST RESULTS OF A-0-A CALIBRATION METHOD

Testing of the A-0-A calibration method (http://www.paroscientific.com/pdf/g8097.pdf) began at Paroscientific in September 2014 and included 80 sensors of 3,000 meters range over the next 2 years. Additional tests were run on 6 sensors of 10,000 meters range at the National Metrology Laboratory of Japan (AIST). Mathematical models of quartz sensor stability were developed (See: http://www.paroscientific.com/pdf/g8095.pdf). The root causes of quartz sensor drift were determined (See: http://www.paroscientific.com/pdf/g8101.pdf).

The A-0-A calibration method was applied to 20 sensors of 3000 meters range from Nov. 3, 2015 to Dec. 29, 2015. At the end of the test, 19 sensors were released to atmospheric pressure for several months until another simulated full-scale deployment from April 19, 2016 to August 19, 2016. The results of these two tests are shown below. For the two simulated deployments, the average drifts of span were within ± 1.4 cm (equal to ± 5ppm of the full scale accuracy band of the DWT standard). The third plot shows that the residuals of the tests on the 10,000 meters sensors were less than 1 part-per-million of full-scale.


Drift of FS, 0,Span (FS - 0), & Temp, average of 20 sensors
Drift relative [cmH2O]
Temp [C]
Date
11/03/15
11/10/15
11/17/15
11/24/15
12/01/15
12/08/15
12/15/15
12/22/15
12/29/15


Drift of FS, 0, Span (FS - 0), & Temp, average of 19 sensors
Drift relative [cmH2O]
Temp [C]
Date
4/19/16
4/26/16
5/3/16
5/10/16
5/17/16
5/24/16
5/31/16
6/7/16
6/14/16
6/21/16
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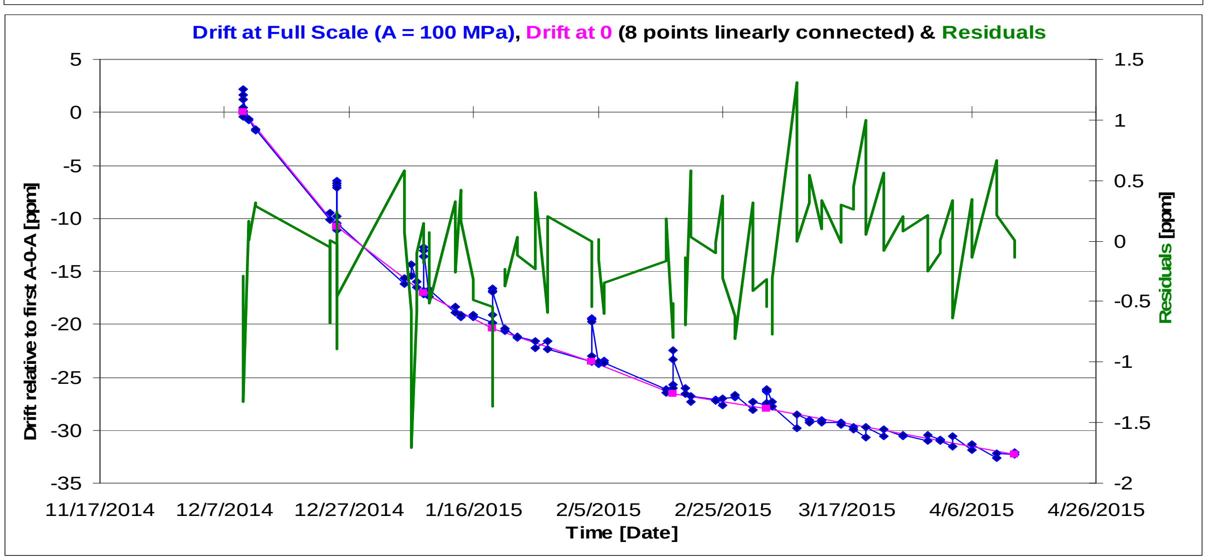
8/23/16


Drift at Full Scale (A = 100 MPa), Drift at 0 (8 points linearly connected) & Residuals
Drift relative to first A-0-A [ppm]
Residuals [ppm]
Time [Date]
11/17/2014
12/7/2014
12/27/2014
1/16/2015
2/5/2015
2/25/2015
3/17/2015
4/6/2015
4/26/2015

Appendix - Excerpts from Papers on Disaster Warning Systems & Geodesy

Papers published in 2016 describe seafloor instrumentation used for short-term disaster warning systems as well as long-term geodetic measurements. The excerpts below show examples of absolute pressure gauges used for tsunami warning systems and slow slip measurements as well as triaxial accelerometers used for both seismic measurements and tilt.

A complete sensing system has been developed that includes absolute pressure sensors, triaxial accelerometers and X-Y tiltmeters together with an in-situ calibration method to eliminate sensor drift. See: "Quartz Sensors Solutions" (http://www.paroscientific.com/pdf/Quartz_Sensors_Solutions.pdf). There are 3 different sensors to independently measure dynamic seismic and pressure events such as earthquakes and tsunamis. There are 2 independent methods to measure earth movements – depth changes and tilt. The in-situ A-0-A calibration method provides measurements to eliminate long-term sensor drift (http://www.paroscientific.com/pdf/g8097.pdf).

Excerpts from Papers:

Measuring slow slip offshore

Anne M. Tréhu *Science* 06 May 2016: http://science.sciencemag.org/content/352/6286/654

This has led to development of alternative techniques for obtaining seafloor geodetic data such as differencing of swath bathymetric data, seafloor and borehole strain meters, and arrays of absolute pressure gauges (APGs), which measure changes in the mass of overlying ocean, from which seafloor uplift or subsidence can be determined. Because of their relatively low unit cost, APGs can achieve the spatial coverage needed to understand complex environments, although there are a number of challenges to be overcome, including long-term sensor drift and separation of tectonic signals from oceanographic effects.

Slow slip near the trench at the Hikurangi subduction zone, New Zealand

Laura M. Wallace, Spahr C. Webb, Yoshihiro Ito, Kimihiro Mochizuki, Ryota Hino, Stuart Henrys, Susan Y. Schwartz, Anne F. Sheehan Science 06 May 2016:
http://science.sciencemag.org/content/352/6286/701

The range of fault slip behaviors near the trench at subduction plate boundaries is critical to know, as this is where the world's largest, most damaging tsunamis are generated. Our knowledge of these behaviors has remained largely incomplete, partially due to the challenging nature of crustal deformation measurements at offshore plate boundaries. Here we present detailed seafloor deformation observations made during an offshore slow-slip event (SSE) in September and October 2014, using a network of absolute pressure gauges deployed at the Hikurangi subduction margin offshore New Zealand. These data show the distribution of vertical seafloor deformation during the SSE and reveal direct evidence for SSEs occurring close to the trench (within 2 kilometers of the seafloor), where very low temperatures and pressures exist.

Seafloor geodetic constraints on interplate coupling of the Nankai Trough megathrust zone

Yusuke Yokota, Tadashi Ishikawa, Shun-ichi Watanabe, Toshiharu Tashiro & Akira Asada Nature (2016) doi:10.1038/nature17632:
http://www.nature.com/nature/journal/vaop/ncurrent/full/nature17632.html

Interplate megathrust earthquakes have inflicted catastrophic damage on human society. Such an earthquake is predicted to occur in the near future along the Nankai Trough off southwestern Japan—an economically active and densely populated area in which megathrust earthquakes have already occurred.

Megathrust earthquakes are the result of a plate-subduction mechanism and occur at slip-deficit regions (also known as 'coupling' regions where friction prevents plates from slipping against each other and the accumulated energy is eventually released forcefully. Many studies have attempted to capture distributions of slip-deficit rates (SDRs) in order to predict earthquakes. However, these studies could not obtain a complete view of the earthquake source region, because they had no seafloor geodetic data. The Hydrographic and Oceanographic Department of the Japan Coast Guard (JHOD) has been developing a precise and sustainable seafloor geodetic observation network in this subduction zone to obtain information related to offshore SDRs. Here, we present seafloor geodetic observation data and an offshore interplate SDR-distribution model. Our data suggest that most offshore regions in this subduction zone have positive SDRs. Specifically, our observations indicate previously unknown regions of high SDR that will be important for tsunami disaster mitigation, and regions of low SDR that are consistent with distributions of shallow slow earthquakes and subducting seamounts. This is the first direct evidence that coupling conditions might be related to these seismological and geological phenomena. Our findings provide information for inferring megathrust earthquake scenarios and interpreting research on the Nankai Trough subduction zone.

Tsunami data assimilation of Cascadia seafloor pressure gauge records from the 2012 Haida Gwaii earthquake

Gusman, A. R., A. F. Sheehan, K. Satake, M. Heidarzadeh, I. E. Mulia, *and* T. Maeda (2016), Geophys. Res. Lett., 43, *doi:* 10.1002/2016GL068368.

Recent addition of pressure gauges to ocean bottom seismometers (OBSs) provides alternative data for tsunami forecast simulation. Because OBSs are usually deployed in a dense array, they provide high-density tsunami observations as well.

Here we use the tsunami waveforms recorded on the Cascadia OBS array to demonstrate two different approaches for tsunami forecast: (1) estimation of the fault slip distribution of the 2012 Haida Gwaii earthquake by tsunami waveform inversion and then forecasting the coastal tsunami heights by numerical forward modeling and (2) progressive assimilation of the tsunami waveforms recorded in the array, reproduction of wavefields in the vicinity of the array, and then forecasting of wavefields by numerical modeling.

The tsunami amplitudes recorded by the DPGs are less reliable than those recorded by the DARTs and APGs. Therefore, only 27 tsunami waveforms at DART and APG stations are used for waveform inversion.

The accuracy of the tsunami forecast strongly depends on the spatial distribution of the stations. A denser array would predict the wavefield between the stations both accurately and quickly, which in turn widens the lead time of an accurate forecast. Although the APG and DPG data during the 2012 Haida Gwaii tsunami were not transmitted in real time, our retrospective data assimilation demonstrates the capability of such a dense tsunami array to forecast an incoming tsunami. Real-time tsunami observation technologies, such as the cabled offshore dense tsunami array of S-net (about 150 stations spaced at 30–50 km intervals) that is being deployed in the Japan subduction zone, would provide data required for real-time tsunami forecasts using the methods presented in this paper.

The tsunami forecast from the tsunami data assimilation method produces similar results as those from the traditional tsunami-forecasting method which starts from a fault model. The tsunami data assimilation method that we present can be run continuously in real time and does not require a tsunami source model. The method can be tested further for various configurations of tsunami source and coast to be implemented for future tsunami warning systems.

Connecting slow earthquakes to huge earthquakes

Kazushige Obara* and Aitaro Kato, *Science* 15 Jul 2016: Vol. 353, Issue 6296, pp. 253-257 DOI: 10.1126/science.aaf1512, http://science.sciencemag.org/content/353/6296/253 .

Slow earthquakes are characterized by a wide spectrum of fault slip behaviors and seismic radiation patterns that differ from those of traditional earthquakes. However, slow earthquakes and huge megathrust earthquakes can have common slip mechanisms and are located in neighboring regions of the seismogenic zone. The frequent occurrence of slow earthquakes may help to reveal the physics underlying megathrust events as useful analogs. Slow earthquakes may function as stress meters because of their high sensitivity to stress changes in the seismogenic zone. Episodic stress transfer to megathrust source faults leads to an increased probability of triggering huge earthquakes if the adjacent locked region is critically loaded. Careful and precise monitoring of slow earthquakes may provide new information on the likelihood of impending huge earthquakes.

If we can retrieve a precursory signal prior to a megathrust earthquake, it would be useful for disaster mitigation.

Slow earthquakes provide phenomenological evidence for the existence of a transition zone between locked and creeping zones proposed by thermal modeling studies and the partial release of slip deficit. In the past two decades, slow earthquakes have been detected in many subduction zones along the Pacific Rim. Among the various slow earthquake types observed along the Pacific Rim, ETS behavior in Cascadia is similar to that seen in Nankai; however, the scale of activity is much larger in Cascadia, where the ETS zone extends for 1200 km along the strike of the subducting plate and is divided into several segments.

Recently, seafloor pressure gauge observations revealed that the slip area of the SSE extends close to the (Hikurangi) trench.

Slow earthquakes with various time scales in and around the rupture area of the Tohoku earthquake had loaded the mainshock fault. A decade-long SSE took place in the deepest part of the Tohoku mainshock rupture area and accelerated over time. Near the mainshock rupture initiation point, SSEs were detected geodetically by seafloor pressure gauges in 2008 and 2011 in the vicinity of the high-slip area of the mainshock rupture zone.

Long-term monitoring of slow earthquakes is required so that a reliable picture of these phenomena can be built over all time scales, and so that physics-based numerical simulations that reproduce the observed plate boundary faulting behavior can be developed.

Sensing of upslope passages of frontal bores across the trench slope break of the Japan Trench

Fukao, Y., H. Sugioka, A. Ito, H. Shiobara, J. M. Paros, and R. Furue (2016), J. Geophys. Res. Oceans, 121, doi:10.1002/2015JC011432.

The original purpose of our observations is to detect postseismic seafloor disturbances, including submarine landslides, in the epicentral region of the 2011 Tohoku-Oki. The observations are made with a free-fall/pop-up ocean bottom accelerometer (AOBS) and a free-fall/pop-up broadband ocean bottom seismometer (BBOBS). The AOBS contains a triaxial accelerometer developed by Quartz Seismic Sensors, Inc., which uses quartz crystal resonators to convert the analog force inputs to digital outputs. The accelerometers have ranges of 20 m/s^2, sensitivity in ppb, and a good long-term stability. They can measure strong earthquakes without clipping and can use the invariance of the Earth's 1 g gravity vector as a reference. The triaxial accelerometer senses both the acceleration change due to ground displacement and the component change of the 1 g gravity vector due to ground tilt. The former is dominant in the frequency range related to strong seismic waves, and the latter is dominant well below that range. The latter is the frequency range of our interest, where the root-mean-square (RMS) noise floor is below 10^{-8} g. The three axes of the accelerometer are designed to be mutually orthogonal, and any small internal mechanical misalignments are corrected in the retrieved data using the alignment matrix table prepared by the factory. Using the alignment matrix allows accurate measurements of seismic signals and tilts on the decoupled orthogonal axes. The sampling rate is set at 1 Hz. In practice, the measured total acceleration value is not time invariant but decreases quasi exponentially through the observational period of 10 months. This decrease is due to the long-term drifts of the component sensors, but it is slow enough to ignore for the analysis of the transient events of our interest. The accelerometer contains an internal quartz crystal temperature sensor to compensate for thermal effects on acceleration. Even though there is a thermal time lag, the internal temperature is a good measure of external temperature changes.