Nano-resolution technology demonstrates promise for improved local tsunami warnings on the MARS project

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Abstract— **Recent advances in deep-ocean tsunami measurement technology coupled with tsunami forecast models have reliably demonstrated that tsunami impact can be predicted before the tsunami reaches the affected coastlines. These forecast models are based on observations that are typically 1000 km or more from the earthquake epicenter. The major challenge today is to forecast tsunamis in the near field where the tsunami wave is often overwhelmed by the seismic event. Nano-resolution pressure sensors have the necessary resolution to distinguish between tsunami and seismic signals and ocean noise in the near field. This study describes the results of a 17 month experiment that was initiated on June 30, 2010, at the Monterey Accelerated Research System (MARS) cabled observatory in Monterey Bay, California. The experiment compared a conventional pressure sensor and a nano-resolution pressure sensor at a depth of approximately 900 m. The results presented include examples of near- and far-field earthquakes and micro-tsunamis that were detected by the nano-resolution pressure sensor. Through wavelet analysis several micro-tsunamis were identified. The paper also describes additional testing planned by NOAA on the nano-resolution pressure sensors for potential application to the NOAA DART System.**

Keywords-Tsunami, warnings, DART, BPR, pressure, measurement, nano-resolution, cable, observatory, MARS

I. INTRODUCTION

This paper updates and expands upon an experiment performed at the Monterey Accelerated Research System (MARS) cabled observatory in Monterey, California [1].

Deep water (up to 6000 m) distant tsunami detection capability has been demonstrated by the NOAA (National Oceanic and Atmospheric Administration)-led U.S. National Tsunami Hazard Mitigation Program [2]-[6]. One of the remaining challenges is to forecast tsunamis in the near field where the tsunami signal may be obscured by earthquake vibrations and other ocean "noise" not commonly found at deep water installations.

New high-resolution pressure sensors have been developed that can distinguish between earthquake, ocean "noise" and tsunami frequencies without losing precision. Improved counting techniques can measure the frequency outputs of quartz resonator sensors to parts-per-billion precision (nano-resolution). See: http://paroscientific.com/Nano-Resolution.pdf. All nano-resolution measurements taken in this paper use nano-resolution counting with multi-stage digital IIR low pass filters [7].

A nano-resolution pressure sensor was incorporated into a geophysical instrument package that was already funded by the National Science Foundation (NSF) and under development by Oregon State University (OSU) and NOAA/Pacific Marine Environmental Laboratory (PMEL). The original OSU/PMEL instrument was designed for submarine volcano monitoring and included high- and low-resolution tilt sensors and a standard bottom pressure recorder (BPR) for detecting vertical displacements of the seafloor due to volcanic inflation/deflation [8]. Part of this project was to test the instrument for one year on the MARS cabled observatory, located in Monterey Bay, California, and operated by the Monterey Bay Aquarium Research Institute (MBARI). MARS is a test bed for instrumentation that could be used by NSF's Ocean Observatories Initiative (OOI) (http://www.mbari.org/mars/general/about_mars.html). Fig. 1 illustrates the location of the MARS test bed. The OSU/PMEL instrument was designed to be eventually deployed at Axial Seamount, an active submarine volcano that will be a node on the cabled observatory component of the OOI in the NE Pacific (http://www.interactiveoceans.washington.edu/).

During the development of the OSU/PMEL instrument, a nano-resolution pressure sensor was added, through a collaboration of NOAA-PMEL, University of Washington, and Paroscientific, Inc., in a joint effort to demonstrate the capability of forecasting tsunamis in the near field using this new technology. The OSU/PMEL instrument package was deployed on the MARS cable on June 30, 2010, at a depth of approximately 900 m. The experiment and analysis compared a standard NOAA BPR (http://nctr.pmel.noaa.gov/Dart/Pdf/DART_II_Description_6_4_05.pdf) to the nano-resolution pressure sensor. Both sensors are installed on the same tripod platform as shown in Fig. 2.
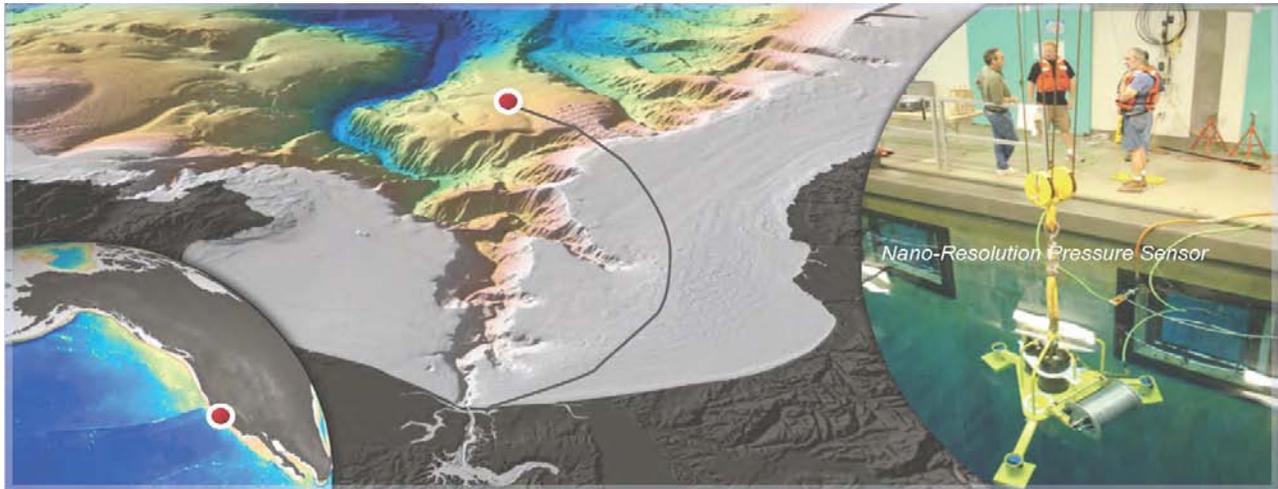
Figure 1. The Monterey Accelerated Research System (MARS) cabled observatory is located in Monterey Bay, California. Please see http://www.youtube.com/noaapmel#p/u/0/ig9IxOPBOcc for a short video on the experiment.

II. DATA FROM THE MONTEREY ACCELERATED RESEARCH SYSTEM (MARS) EXPERIMENT

The new nano-resolution pressure sensor, manufactured by Paroscientific, Inc., has several orders of magnitude higher resolution than a traditional sensor installed in a NOAA BPR. While power requirements of the nano-resolution sensor are higher, it is also capable of recording data at much higher sampling rates. This unprecedented resolution allows scientists to better distinguish between oceanographic signals/noise and seismic events for improved tsunami detection and modeling. The Nano-resolution pressure sensors are able to measure ocean signals with fine scale clarity, including the detection of microseisms, infra-gravity waves and earthquakes. The plot in Fig. 3 compares the standard NOAA BPR to a nano-resolution pressure sensor. The nano-resolution pressure sensor is able to distinguish pressure changes equivalent to a fraction of a millimeter that are the result of microseisms and longer-period infra-gravity waves.

Figure 2. OSU/PMEL BPR/Tilt instrument showing relative placement of nano-resolution and standard BPR sensors.

The nano-resolution pressure sensor can be configured through software commands to change the measurement parameters, and it was co-located with a standard resolution NOAA BPR to enable comparative measurements between the two. This experiment has shown that seafloor measurements of absolute water levels, tides, infra-gravity waves, microseisms, and signals from distant and nearby earthquakes can be made with greater accuracy than with previous instrumentation.

Earthquakes can produce dynamic pressure variations, which are infrasonic acoustic waves. These waves, produced by local earthquakes with magnitudes as low as 3.0, have been detected by the nano-resolution pressure sensor at MARS. At longer periods, the entire water column above the sensor moves up and down in response to the passing tsunami wave train with an amplitude that can be computed from the seafloor pressure fluctuations with the scaling $P = \rho\, g\, h$ (water density, gravity, and height). Accurate time series of a tsunami signal, for comparison with pre-computed model scenarios, are the basis of the forecast system [3]. The high-frequency earthquake signal is noise for the tsunami detection process. With standard sensors, this noise overwhelms the tsunami signal, making tsunami detection difficult. The improved temporal sampling and vertical accuracy provided by nano-resolution pressure sensors shows promise for tracking the earthquake vibrations while recording the tsunami signal, opening the possibility of earlier near-field tsunami detection.

III. EARTHQUAKE DETECTION

Data from the M5.4 earthquake near Palm Springs on July 7, 2010, at 23:53:33 was analyzed. The arrival of the p-waves from this earthquake coincided with seismic data from the nearest land-based station at San Juan Grade (see Fig. 4). The largest amplitudes were equivalent to +/- 8 mm water height (however, it would have been larger with a higher low-pass filter cutoff in the counting algorithm).

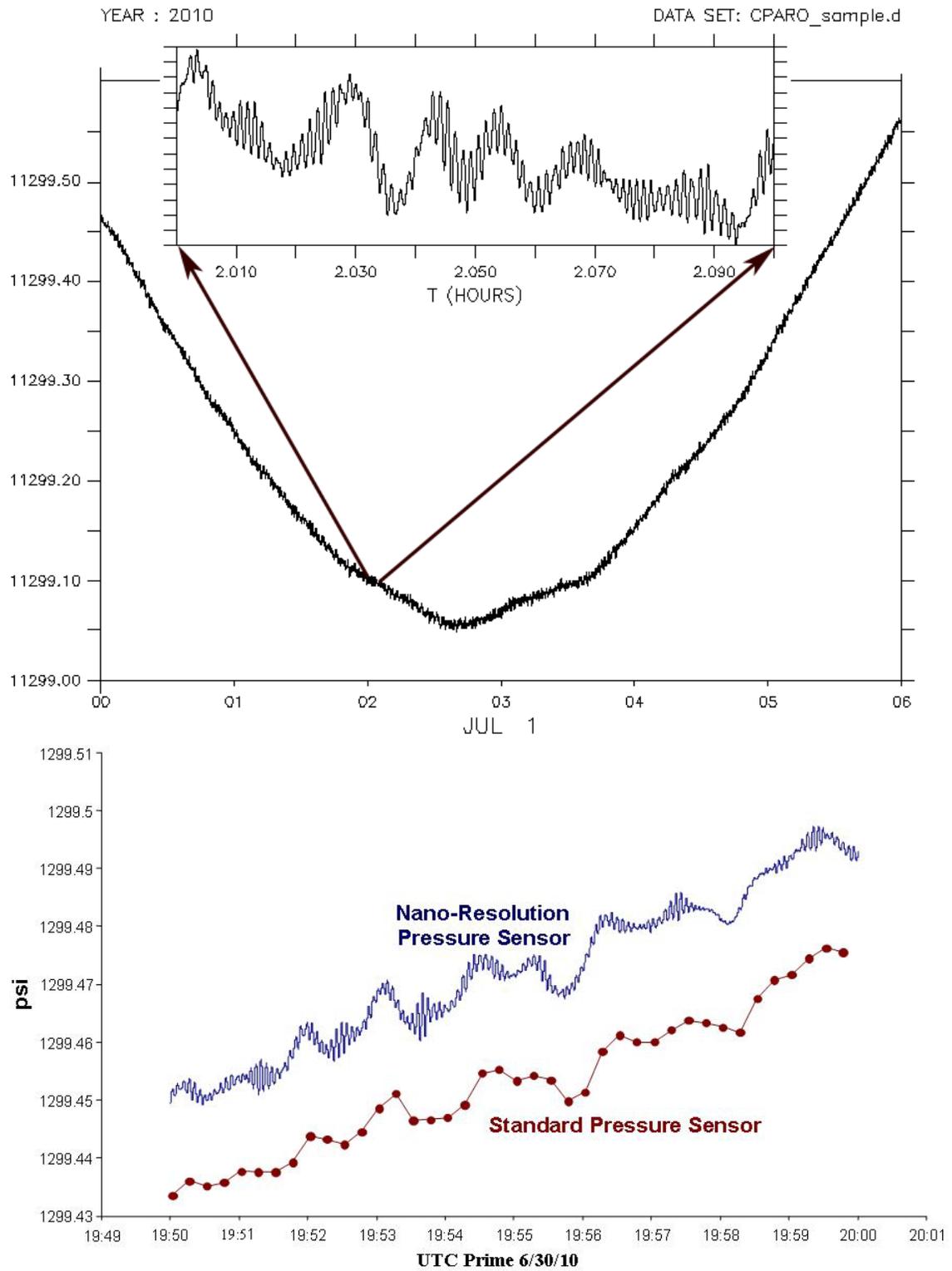YEAR : 2010   DATA SET: CPARO_sample.d

Figure 3.   Nano-resolution pressure sensor data are shown (in blue on lower plot) hours after initial deployment. The overall pressure is rising from an incoming tide. Near 0.2 Hz, the data is dominated by microseismic acceleration of the seafloor (equivalent to 1 mm pressure variations). At longer periods, near 1 minute, pressure variations of a few millimeters water heights are from surface waves that are detected at the deployed depth of 900 m. The red data are from the co-located standard tsunami sensor at much lower sampling rate (15 seconds) and resolution (but still capable of resolving typical 1 mm waves at long periods). Note: the plots are arbitrarily offset to allow the reader to see differences in plotted data.
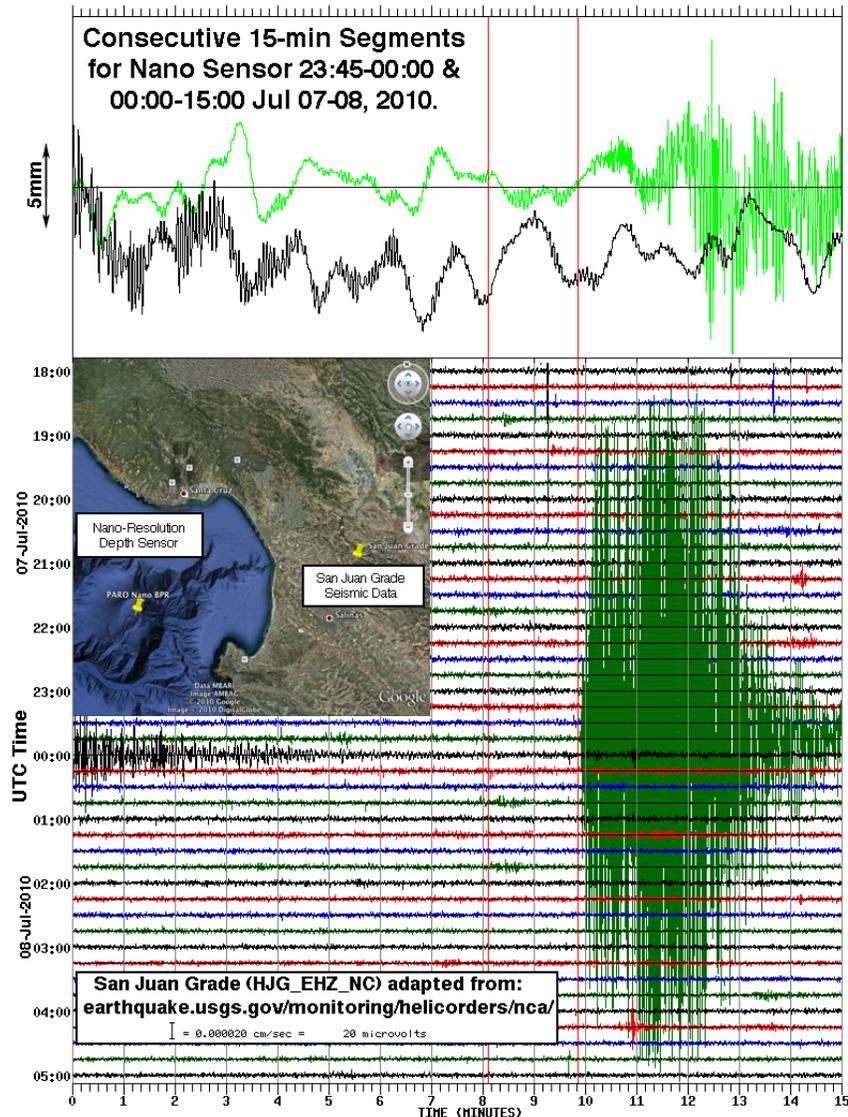
Figure 4. The upper panel shows consecutive 15-minute segments of the nano data (detrended) that correspond to the similarly colored traces in the USGS record from San Juan Grade in the lower panel. Inset is a locater map for the two locations which are separated by about 56 km. Vertical lines in red show the earthquake time and the arrival at the seismometer. The nano-resolution pressure sensor begins to respond a couple of minutes later and its earthquake signal has a similar duration to the land-based instrument.

IV. DISTANT MICRO-TSUNAMI DETECTION

A micro-tsunami was recorded by the nano-resolution pressure sensor on December 21, 2010 (M7.4 Bonin Island earthquake). Using wavelet analysis, spectrograms were computed (see plot in Fig. 5 below). The cutoff period for tide removal is 1 hour, using Butterworth filters. Note the color scale in the plot was set to emphasize the tsunami, so the high-frequency components are muted. The red line is the modeled tsunami amplitude time series. In Fig. 5, the tsunami appears from 645 to 745 minutes (indicated by white dashed line) with a period of about 14 minutes and a maximum tsunami amplitude of about 0.2 cm.

V. MARCH 11, 2011 HONSHU EARTHQUAKE AND SUBSEQUENT TSUNAMI

On March 11, 2011, a huge M9.0 earthquake occurred off of the northeast coast of Japan. The earthquake was centered off the Pacific coast of Tōhoku and is known as the 2011 Tohoku earthquake. The megathrust event occurred at 14:46 JST (05:46 UTC). The epicenter was approximately 70 km (43 mi) east of the Oshika Peninsula of Tohoku. The earthquake triggered powerful tsunami waves that reached heights of up to 40.5 m (133 ft) in Miyako, in Tōhoku's Iwate Prefecture, and which, in the Sendai area, travelled up to 10 km (6 mi) inland. The earthquake moved Honshu 2.4 m (8 ft) east and shifted the
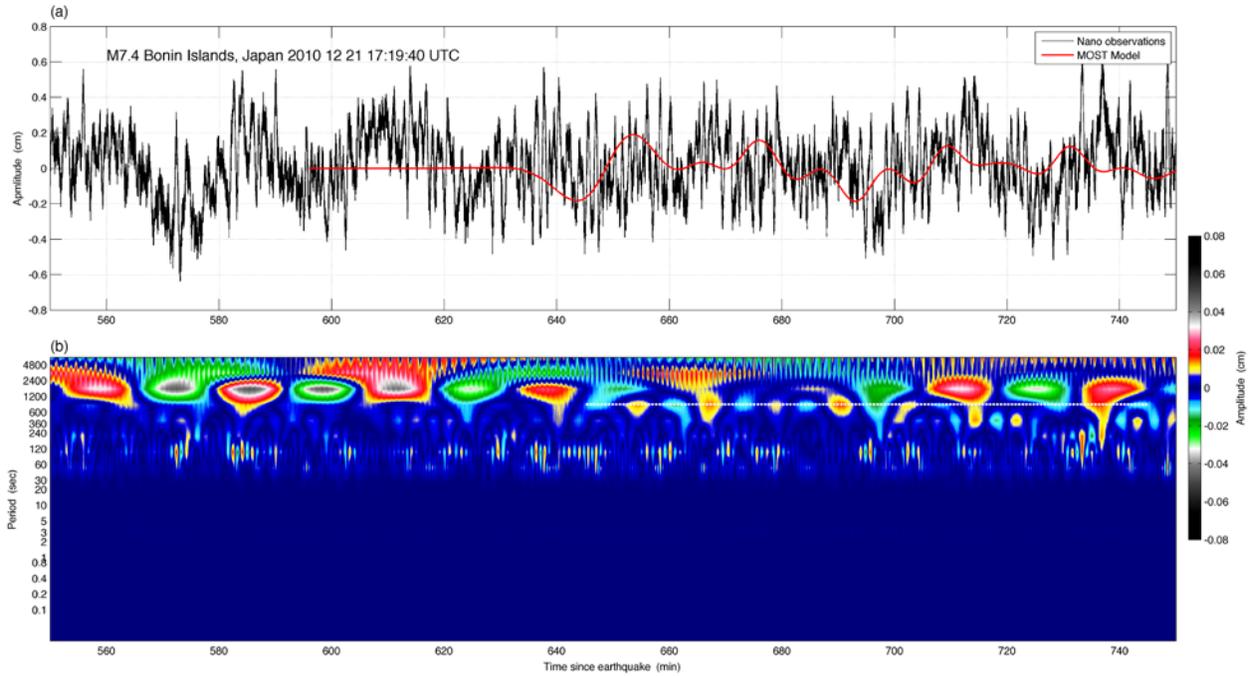
Figure 5. A micro tsunami generated by the M7.4 Bonin Island Earthquake on December 21, 2010 was recorded by the nano-resolution pressure sensor. (a) The black line is the nano-resolution observations with tides removed by a Butterworth filter with a cutoff period of 1 hour. The red line is the modeled tsunami amplitude time series. (b) Wavelet-derived amplitude spectrogram of the observations. The white dashed line indicates the existence of the tsunami signals.

Earth on its axis by estimates of between 10 cm (4 in) and 25 cm (10 in).

At approximately 15:40 UTC, the wave arrived in Monterey Bay, California, at the MARS cabled observatory. The nano-resolution pressure sensor recorded a wave height of approximately 25 cm as shown in Fig. 6. Prior to the arrival of the wave the pressure sensor was detecting small microseisms at the typical background level.
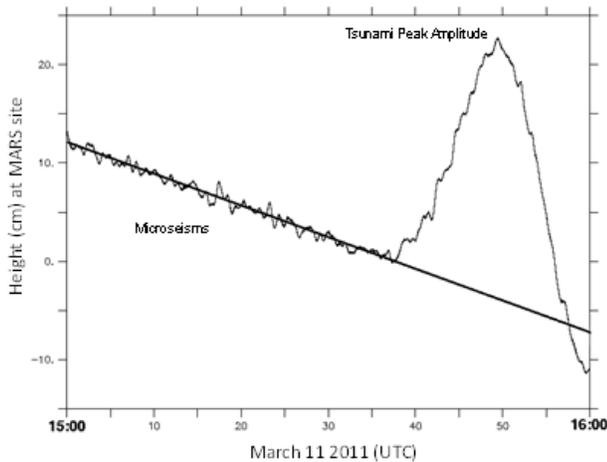

Figure 6. Nano-resolution pressure sensor at 40 Hz measures a 25 cm tsunami wave in Monterey Bay, California, which was a result of the Honshu, Japan earthquake on March 11, 2011.

VI. LONG-TERM MEASUREMENTS

Both the standard bottom pressure transducer and the nano-resolution pressure sensor contain internal digital temperature sensors for thermal compensation. The pressure sensors are calibrated over a broad range of temperatures, and the outputs of the quartz pressure-sensing crystal and quartz temperature-sensing crystal are measured. Coefficients are calculated for insertion into an algorithm to generate fully temperature-compensated and linear pressure outputs. Fig. 7 plots pressure and temperature for about one month of data for both the standard BPR and the nano-resolution pressure sensors. As shown in Fig. 2, the nano-resolution pressure sensor is exposed directly to the seawater, whereas the standard pressure transducer is contained within the BPR housing with additional electronic equipment. As a result, the temperature within the BPR housing is higher by about 3.5°C. The packaging also affects dynamic temperature behavior whereby thermal gradients can cause pressure errors. The transient "spikes" shown in red in Fig. 8 for the standard BPR were caused by loss of power and subsequent warm-up effects. The nano-resolution pressure sensors showed little effect due to the reduced thermal effects from the power conditioning electronics.

Fig. 8 shows the de-tided pressure records (converted to depth) for the nano-resolution pressure sensor and standard BPR for the entire 17 month deployment. Not only was the nano-resolution pressure sensor insensitive to the dynamic thermal effects of warm-up after power outages, but it showed no discernable drift. The standard BPR had a drift rate of 21 cm per year equivalent to 30 parts-per-million of full-scale range
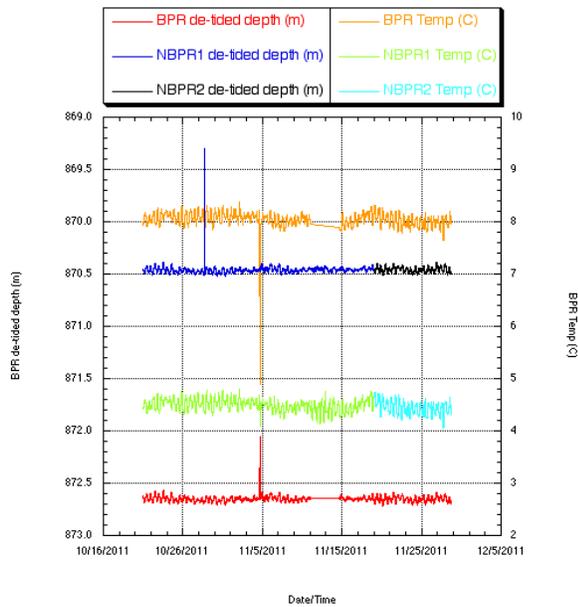
Figure 7. Pressure and temperature measurements of nano-resolution pressure sensor and standard BPR. The spike in the BPR de-tided depth time series (red) is due to transient temperature effects (orange) after a power cycle. In contrast, the spike in the nano-BPR de-tided depth time series (dark blue) is due to a known timing error and mismatch with a tide prediction model
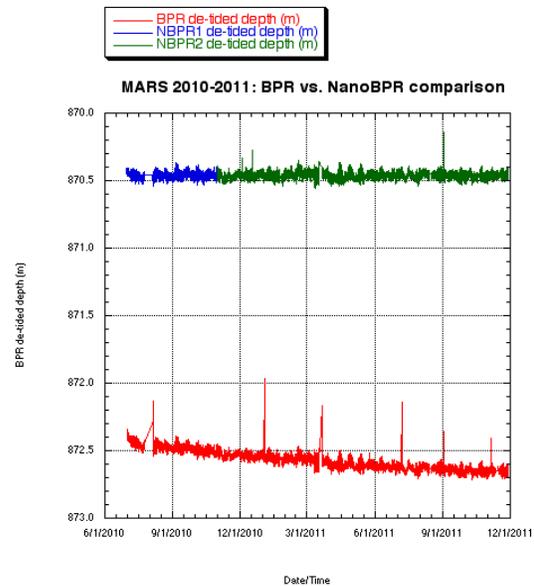

Figure 8. Pressure data (converted to depth) from nano-resolution presure sensor and standard BPR over the entire 17 month deployment at MARS. The spikes in the BPR time series (red) are due to transient temperature effects after a power cycle. In contrast, the spikes in the nano-BPR time series are due to a known timing errors and mismatches with a tide prediction model

(7000 m). The nano-resolution pressure sensor in the MARS tests has a full-scale range of 1400 m. The absolute drift rate (cm per year) is a strong function of full-scale range. Therefore, the highest resolution and best stability is achieved when the pressure transducer range matches the deployment depth.

VII. Potential Application to NOAA DART System

Research and development is continuing on special versions of the nano-resolution technology [7] that are being considered for incorporation into future near-field NOAA DART systems, The near-field system will build on proven DART performance and will be enhanced to provide high-resolution, user-configurable, multi-mode, low-power, and extended-life tsunami warning systems.

VIII. Conclusions

Nano-resolution pressure sensors have been developed with the capability to measure pressure changes with unprecedented precision over an extended frequency spectrum. Tests at the MARS cabled observatory have demonstrated the ability to make high-resolution pressure measurements of micro-tsunamis, earthquakes, microseisms, and infra-gravity waves. These developments hold promise for improving forecasts for tsunamis in the near field.

References

[1] J. Paros, E. Bernard, J. Delaney, C. Meinig, M. Spillane, P. Migliacio, L. Tang, W. Chadwick, T. Schaad, and S. Stalin, "Breakthrough underwater technology holds promise for improved local tsunami warnings," IEEE Conference Publishing, UT11+SSC11, Tokyo, Japan, March 2011.

[2] E. N. Bernard: The U.S. National Tsunami Hazard Mitigation Program: A successful state–federal partnership. Nat. Hazards, vol. 35(1), Special Issue, U.S. National Tsunami Hazard Mitigation Program, 2005, pp. 5–24.

[3] V. V. Titov, F. I. González, E. N. Bernard, M. C. Eble, H. O. Mofjeld, J. C. Newman, and A. J. Venturato, "Real-time tsunami forecasting: Challenges and solutions," Nat. Hazards, vol. 35(1), Special Issue, U.S. National Tsunami Hazard Mitigation Program, 2005, pp. 41–58..

[4] E. N. Bernard, F. I. Gonzalez, and C. Meinig, "Early detection and real-time reporting of deep-ocean tsunamis," International Tsunami Symposium 2001, 7–10 August 2001, Seattle, WA.

[5] C. Meinig, M. Eble, and S. Stalin, "System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997–2001." ITS 2001 Proceedings NHTMP Review Sessions, Paper R-24.

[6] M. Yilmaz, P. Migliacio, and E. N. Bernard, "Broadband vibrating quartz pressure sensors for tsunameter and other oceanographic applications," Oceans 2004, Kobe, Japan, http://paroscientific.com/pdf/realtimetsunami.pdf.

[7] T. Schaad, "Nano-Resolution. Oceanic, Atmospheric and Seismic Sensors with Parts-Per-Billion Resolution," G8218 Rev. E., 10 March 2009. http://paroscientific.com/Nano-Resolution.pdf.

[8] S. L. Nooner, and W. W. Chadwick, Jr., "Volcanic inflation measured in the caldera of Axial Seamount: Implications for magma supply and future eruptions," Geochem. Geophys. Geosyst., vol. 10, Q02002, 2009, doi:10.1029/2008GC002315.