Nano-Resolution Sensors For Disaster Warning Systems

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***Abstract*—New high-resolution sensing technology has been developed for oceanic, seismic, and atmospheric measurements. Depth sensors, accelerometers, and barometers employing force-sensitive resonant quartz crystals have demonstrated their effectiveness in measuring tsunamis, earthquakes, and infrasound signals with a sensitivity of parts-per-billion. The nano-resolution depth sensors offer an improved ability to separate earthquake vibrations and other oceanic noise from tsunami waveforms. Seismic signals can be measured with new strong motion sensors to a few nano-g's. Atmospheric infrasound signals can be measured to a small fraction of a milli-Pascal. Geophysical measurements can now be made with unprecedented clarity from beneath the seafloor, to the ocean bottom, through the water column, and through the atmosphere in a single coherent array. Nano-resolution sensors will improve the identification and prediction of the magnitude, location and path of natural disasters such as earthquakes, tsunamis and severe weather with increased warning times. Examples are given of Sea-Air-Land Tomography and seismic, oceanic, and infrasound measurements of the March 11, 2011 earthquake and tsunami disaster.**

Keywords- nano-resolution; tsunami, infrasound, seismic

I. Sensor Technology

Quartz crystal resonators convert analog force inputs to digital outputs with a sensitivity of parts-per-billion (Nano-Resolution)[1]. The changes in resonant frequency of vibrating quartz crystals are functions of applied input forces as shown in Fig. 1. The period (inverse of the frequency) changes ± 10% with full-scale tension and compression. The technology is described at: http://paroscientific.com/pdf/dqadvantage.pdf. Advanced electronics and frequency counting algorithms enable these inherently-digital sensors to make measurements at -180dB relative to full scale range. This Nano-Resolution Technology has been applied to quartz resonator depth sensors, barometers, and seismic instruments. See: http://www.paroscientific.com/Nano-Resolution.pdf.

Fig. 2 shows the experimental power spectral density of an isolated quartz resonator. IIR (Infinite Impulse Response) counting was employed with sampling at 40 Hz. The IIR filter band was set from 0 to 5.5 Hz. The 5-stage low-pass (anti-aliasing) filter attenuates all values above the cutoff at -100 dB/decade above the selected corner frequency.

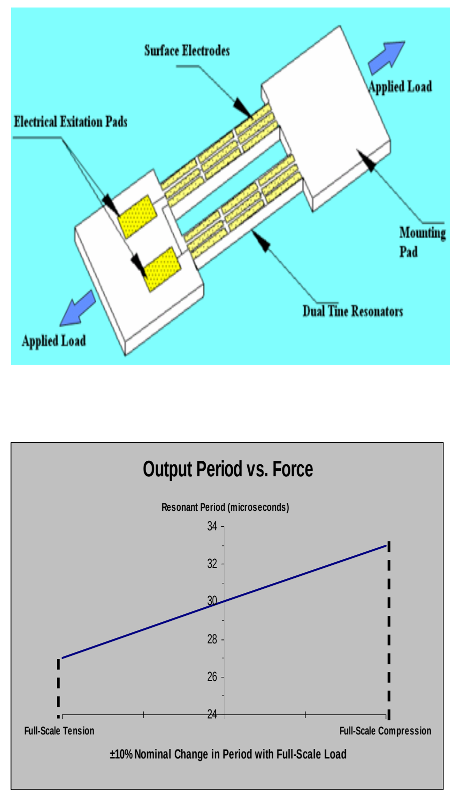

Fig. 1

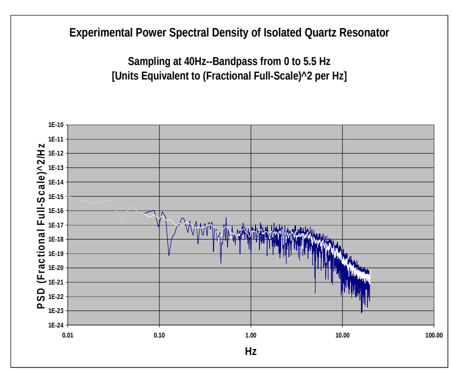

Fig. 2

II. Sea-Air-Land Tomography (SALT)

SALT involves the installation of arrays of sensors on land and under the sea to provide improved detection and warning times associated with disasters. These sensor networks determine the magnitude and direction of disasters with unprecedented resolution to allow additional time for evacuation thereby saving lives and reducing property damage. For example, nano-resolution accelerometers and nano-resolution depth sensors can continually monitor plate movements of the sea floor. Very small uplift, subsidence and tilt can be detected. The undersea sensors measure the seismic and oceanic signals associated with earthquakes and tsunamis. On land, a seismo-acoustic system comprises a nano-resolution accelerometer to identify the magnitude and location of a seismic event and a nano-resolution barometer that detects the infrasound signals produced by forcing of the atmosphere by the tsunami waves. The infrasound signal makes landfall quicker than the tsunami wave allowing improved warning times.(2)

Highly stable nano-resolution depth sensors not only measure the vertical deformation of the sea-floor during disasters, but the data collected can be used to more clearly understand the source and magnitude of the tsunami. Y. Ito(3) et al reported on the uplift of the seafloor preceding the 2011 Tohoku Earthquake using OBPS (Ocean Bottom Pressure Recorders). The vertical uplift of 5 m was preceded by a smaller one on March 9 with slippage of 15 mm per day leading to the major disaster. Such information could be important as an early warning sign. H. Tsushima(4) et al studied the recordings from various offshore tsunami stations 5-10 minutes before the tsunami made landfall. They concluded that the pressure measurements could contribute to reliable near-field tsunami warnings. The reliability and long-term stability of Digiquartz® depth sensors were extensively studied at the Center for Prediction of Earthquakes at Tohoku University.(5)

The following sections present examples of nano-resolution sensors used for geophysical measurements and disaster warning systems.

III. Oceanic Applications

This breakthrough technology shows promise for improved local tsunami warning systems.(6) Through a partnership between Paroscientific, Inc., NOAA, and the University of Washington, a nano-resolution depth sensor was tested for 17 months at the Monterey Accelerated Research System (MARS) cabled observatory located in Monterey Bay, CA. http://paroscientific.com/UW_nanopress_flyer_sm1.pdf. The nano-resolution depth sensor was installed on a NOAA Bottom Pressure Recorder (BPR) equipped with a standard Paroscientific, Inc. pressure sensor for comparison. Resolution is several orders of magnitude improved over the standard pressure sensor. The nano-resolution depth sensor shown in Fig. 3 measures pressure from an incoming tide, microseismic seafloor motion equivalent to 1 mm pressure variations, and longer-period infragravity waves with a resolution of microns.

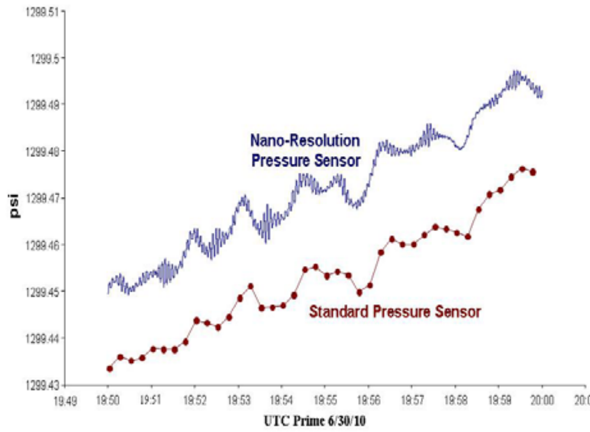

Fig. 3

During the first few weeks of testing, the Nano-Resolution Depth Sensor measured ocean signals with unprecedented clarity including the detection of 4 earthquakes. The M5.4 EQ near Palm Springs on 7/7/2010 at 23:53:33 UTC was measured and analyzed. The arrival of the p-waves from this earthquake was compared to seismic data from the nearest land-based station at San Juan Grade (see Fig. 4). The improved resolution helps to separate the oceanic from the seismic signals.

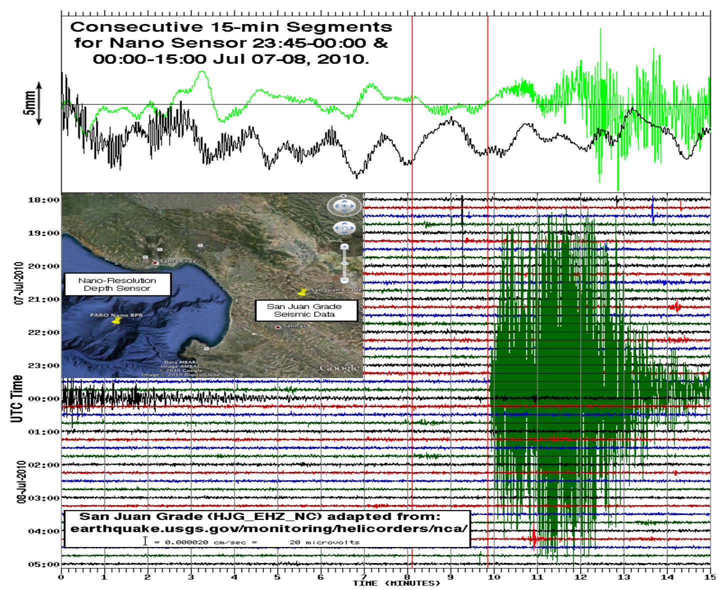

Fig. 4

A micro-tsunami was recorded by the nano-resolution pressure sensor on December 21, 2010 (M7.4 Bonin Island earthquake). Using wavelet analysis, a spectrogram was computed for the tsunami (see Fig. 5). 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 in the upper panel is the modeled tsunami amplitude time series. The tsunami appears from 645-745 minutes (indicated by white dashed line) with a period of about 14 minutes. The maximum tsunami amplitude is about 0.2 cm.

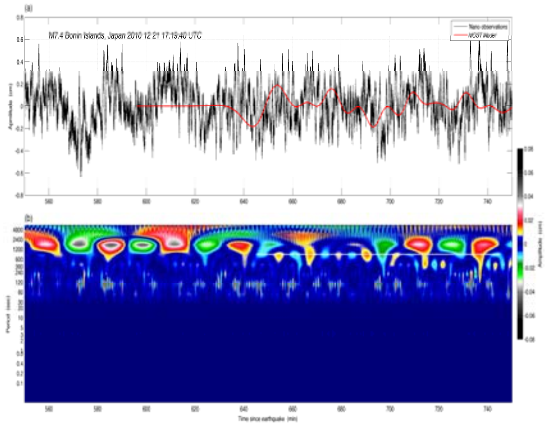

Fig. 5

On March 11, 2011 the Honshu Earthquake and subsequent devastating tsunami struck the northeast coast of Japan. The Nano-Resolution depth sensor installed in Monterey Bay, California measured the tsunami that propagated across the Pacific Ocean. Fig. 6 is a plot of absolute water depth for 7 hours on March 11, 2011. Prior to the tsunami, the sensor was able to resolve the background microseismic and infragravity wave signals to a fraction of a millimeter. The main tsunami in Monterey Bay after 15:30 UTC measured about 25 cm (at the offshore location of the sensor), followed by hours of wave disturbances with characteristic harmonic components on top of the tidal signal.

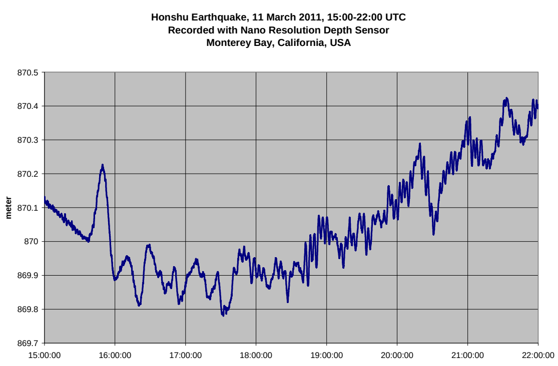

Fig. 6

IV. Atmospheric Applications

An array of absolute-pressure Digiquartz® Nano-Resolution Barometers (Model 6000-16B) were co-located at the international infrasound monitoring station IS30 in Isumi, Chiba prefecture, near Tokyo(7). The sensor noise floor spectrum was approximately 10^{-7} Pa^2/Hz over the infrasound range.

On 3 October 2009, an eruption of Sakurajima Volcano generated infrasound signals measured 987 km away. http://paroscientific.com/EM/G8221NC.pdf . Fig. 7 shows the signature of the infrasound signal measured at IS130. Note that ocean-generated microbarom signals with amplitudes of 0.1 Pa were measured with a sensitivity of 0.0003 Pa before and after the eruption.

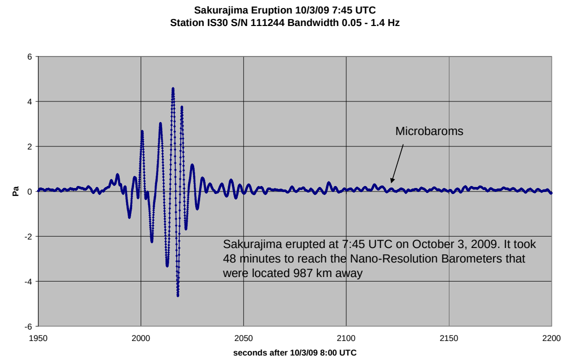

Fig. 7

The main shock wave reached the station at 8:33 UTS (48 minutes after the explosion). The wave was dispersed over almost a minute because of different frequency-dependant propagation velocities in the atmosphere followed by 15 minutes of smaller infrasonic signals. The spacing of the data-points (dots) is 50 ms.

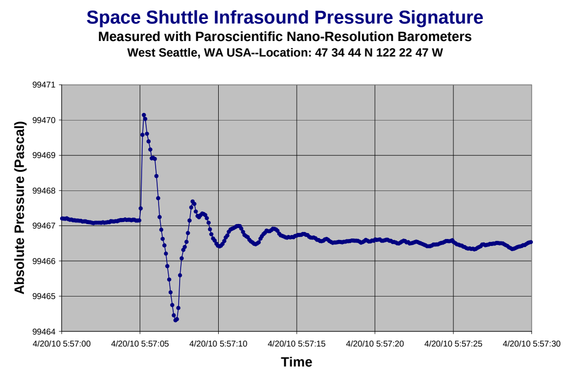

Fig. 8

On April 20, 2010 the Space Shuttle re-entered the atmosphere over Vancouver Island in British Colombia, Canada. Fig. 8 above shows the pressure signal measured from a location in West Seattle, approximately 150 miles away. The pressure change shown is the typical N-Wave that is generated from supersonic flight.

Atmospheric pressure changes caused by the 2011 earthquake off Tohoku, Japan (Mw=9.0) were reported by Arai(2). Sensitive barometers recorded atmospheric pressure changes that were identified as atmospheric boundary waves generated by the uplift and subsidence of the ocean surface caused by the seismic event as shown in Fig. 9. Fig. 10 shows the short period pressure changes at the Mizusawa VLBI Observatory from approximately 05:46 to 05:52 which were induced by the passing of large amplitude seismic waves. Following these, a long period atmospheric wave is visible followed by a sharp decline after the wave passes. The onset time and peak-peak amplitude of the wave train are estimated to be 05:52 and 64 Pa. An important point is that infrasound arrives faster than the ocean tsunami wave and this detection technique can save precious time by implementing tsunami warning systems on land.

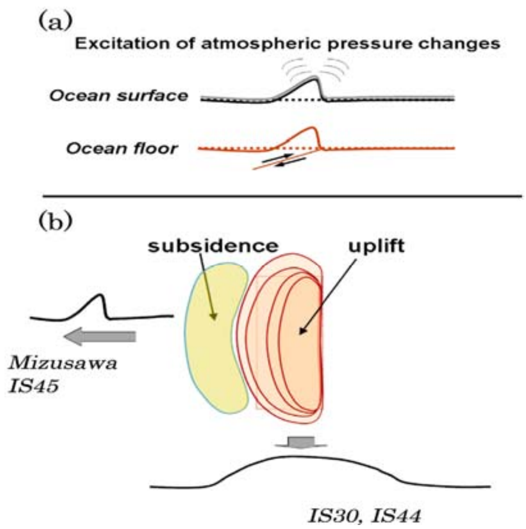

Fig. 9

Fig. 9 courtesy of Dr. Nobuo Arai of the Japan Weather Association

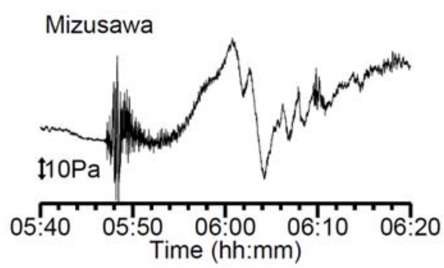

Fig. 10

Fig. 10 courtesy of Dr. Nobuo Arai of the Japan Weather Association

V. SEISMIC APPLICATIONS

Seismic sensors with a full scale range of several g's have been developed with resolution of a few nano-gs (microGal). These strong-motion sensors have a much higher dynamic range (-180 dB at 1 Hz) than traditional earthquake sensors. The Nano-Resolution Accelerometers have a high sensitivity over a broad spectrum from a fraction of a second to very long periods. Examples include measurements of P and S waves from local and distant earthquakes, measurements of the microseismic peak, and Lunar-Solar Gravitational Tides. Fig. 11 is a week-long comparison plot of Nano-Resolution Accelerometer measurements in Seattle versus corresponding Earth tides in the Indian Ocean halfway across the world.

Fig. 12 is a plot of the March 11, 2011 earthquake recorded in Seattle, Washington with a Nano-Resolution Accelerometer. Prior to the arrival of the P-wave and S-wave signals, the typical microseismic background was being recorded.

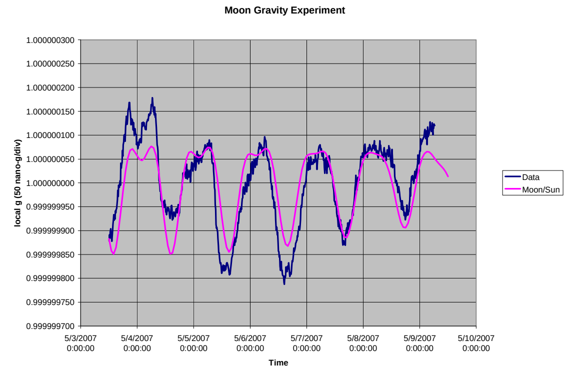

Fig. 11

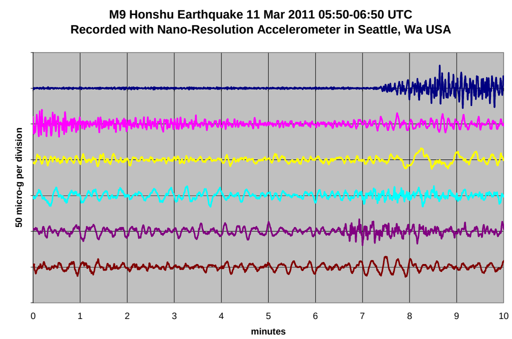

Fig. 12

CONCLUSIONS

Nano-resolution sensors have demonstrated improved capability of identifying and predicting the severity, location and path of natural disasters such as earthquakes, tsunamis and severe weather. Implementation of Sea-Air-Land networks of nano-resolution sensors will increase disaster warning times and thereby save lives and reduce property damage.

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