Broadband Vibrating Quartz Pressure Sensors for Tsunameter and Other Oceanographic Applications

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Abstract - *Broadband quartz pressure sensors have been used for a variety of oceanographic applications such as tsunami detection, wave and tide gauging, volcano monitoring, ROV/AUVs, offshore platform leveling, pipeline laying, climate studies, drifting buoys, ocean drilling, seafloor wellhead monitoring, depth and profiling instruments, and towed arrays. Of these many applications, perhaps the most prominent one relating to public safety is NOAA's tsunami detection network.*

NOAA's Pacific Marine Environmental Laboratory ("PMEL") has developed and installed seven portable tsunameters for near real-time detection of tsunamis in the deep ocean environment. Measurement of tsunamis in the deep ocean provides data free from coastal effects that is essential for accurate forecasting of tsunami impacts. The most critical element of the system is the broadband vibrating quartz pressure sensor that makes tsunami detection possible with sufficient time to evacuate coastal residential areas. Expansion of the deep ocean tsunameter network will provide appropriate data to protect life and property during damaging tsunamis and avoid costly false alarms of non-damaging tsunamis.

This paper describes the Paroscientific broadband vibrating quartz pressure sensor technology and the NOAA tsunami detection and reporting system. For further information, please visit http://www.pmel.noaa.gov/tsunami/ and http://www.paroscientific.com

I. Background and Introduction

The tsunameter is an instrument that measures the amplitude over time of tsunamis in the deep ocean (greater than 1000 m depth). Just as seismometers have been essential to progress in the field of earthquake research, a tsunameter is critical to the further advancement of tsunami research and hazard mitigation. The U.S. National Tsunami Hazard Mitigation Program (NTHMP), led by the National Oceanic and Atmospheric Administration (NOAA), has developed and field-tested the first generation of reliable tsunameters (Figure 1) and successfully established a Pacific network (Milburn et al., 1996; Meinig et al., 2001; Bernard et al., 2001). The operational network, though currently small, is a powerful catalyst for the revolutionary paradigm shift now underway in tsunami research and forecasting—away from indirect observations and toward direct, high-quality measurements and analyses of the tsunami itself.

Until now tsunami research and operational decisions of NOAA's Pacific Tsunami Warning Center (PTWC) and West Coast and Alaska Warning Center (WCATWC) have depended primarily on analyses of seismic information and coastal tide gage measurements. Though valuable, these data are essentially indirect and their interpretation is difficult. Seismic data interpretation involves poorly understood seismic/hydrodynamic coupling. Similarly, the interpretation of tide gage data is difficult because of the complex tsunami transformations induced by interaction with continental shelf, coastline, and harbor features. Furthermore, a tide gage may not survive the impact of the tsunami itself and, if it does survive, the data are not reported until after the tsunami strikes a coastal community. Finally, though coastal tide gages are very useful to warning operations (and extremely

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valuable in post-event scientific case studies) they cannot provide data that are especially important to operational hazard assessment—direct, deep ocean measurements of tsunamis as they propagate from the source to coastal communities.

Engineering advances at NOAA's Pacific Marine Environmental Laboratory (PMEL) have led to a highly reliable system that acquires and delivers direct tsunami measurements at deep ocean locations between the source and distant communities, and transmits these data in real time to tsunami warning centers and the Internet.

II. The Engineering Challenge

Development of an operational tsunameter was an extraordinary engineering accomplishment. The task was to design, develop, test, and deploy real-time reporting, deep-ocean instrumentation capable of surviving a hostile ocean environment while performing with the quality and reliability demanded of an operational tsunami warning system on which so many lives depend. The PMEL Tsunameter Project was initiated to meet this challenge, with the primary requirements listed in Table 1 as goals that would guide tsunameter design. No such system had ever been developed until the successful effort of the NOAA/PMEL Engineering Development Division.

Table 1.
Tsunameter Design Goals

Reliability and data return:	> 80%
Maximum deployment depth:	6000 m
Minimum deployment duration:	> 1 year
Survivability:	Survive N. Pacific winters
Maintenance interval	> 1 year
Sampling interval, internal record:	≤ 15 sec
Sampling interval, event reports:	≤ 60 sec
Sampling interval, tidal reports:	≤ 15 min
Measurement sensitivity:	≤ 1 mm in 5000 m (~ 2×10^{-7})
Tsunami data report trigger	a. Automatically by tsunami detection algorithm b. On-demand, by warning center request
Reporting delay:	< 2 min
Maximum status report interval:	< 6 hours
Cost:	< $250,000 US

The Strategy

As with most effective research and development strategies, "reinventing the wheel" was avoided by an effort to build upon the experience and success of PMEL and others. A number of approaches were explored, but the final basic design consisted of four components: (1) a bottom pressure recorder (BPR) and (2) an acoustic link to (3) a surface buoy equipped with (4) a satellite telecommunications capability (Figure 1).

Three of these four technologies were already in use at PMEL, but had to be modified and integrated into an operational tsunameter. BPR systems with an excellent track record of meeting the tsunameter requirements of

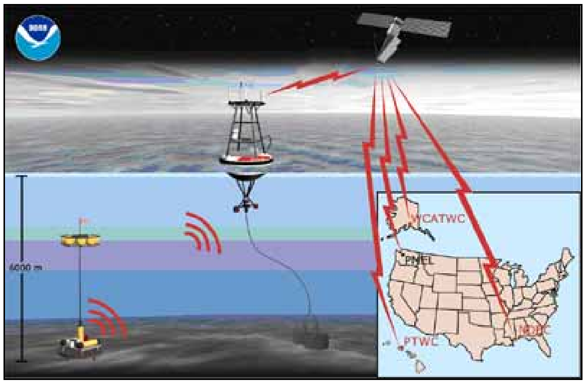

Figure 1. The NOAA tsunameter, illustrating the four major components that had to be integrated into a single system (see text): BPR, acoustic link, surface buoy, and satellite telecommunications.

reliability, sensitivity, sampling, deployment depth, and deployment duration had been developed earlier by PMEL (Eble and González, 1991; González et al., 1991) using the Digiquartz® Broadband Pressure Sensing Technology (see section 3). Deep-ocean surface buoy technology at PMEL was also well developed, as witness the success of the Tropical Atmosphere and Ocean (TAO) array, the largest deep-ocean array in existence (Hayes et al., 1991; McPhaden, 1993; McPhaden, 1995; McPhaden et al., 1998); a significant challenge had to be overcome in adapting this technology to the needs of a tsunameter network—i.e., development of a buoy and mooring system that would survive the hostile environment of high latitude conditions. Satellite telecommunications had for years been routinely used by PMEL for near real-time data delivery to ground stations from the TAO array, and this technology was also used successfully to deliver real-time seismic data as part of a prototype local tsunami warning system that is still operational in Valparaiso, Chile (Bernard et al., 1988; Bernard et al., 1991). The remaining component—an acoustic link to provide robust, reliable transmission of BPR data from the seafloor to the surface—represented new, ground-breaking technology, on which much of the development effort focused.

The development, modification and integration of all four components into a unified tsunameter system, though ultimately successful, proved to be a major engineering challenge. As might be expected, early efforts had to deal with and systematically eliminate a variety of potential problems leading to data dropouts (González et al., 1998). The overall effort, which began in 1996 (Milburn et al., 1996), was remarkable in scope. In time, the enterprise utilized eight different ships for 18 different cruises totaling about 90 days at sea, and the number of participants grew to include more than 25 PMEL engineers, technicians and scientists, and individuals from more than 85 partner firms and suppliers (Bernard et al., 2001). In September 1997, the first successful deployment of an integrated tsunameter system provided a 3-month record off the Oregon coast, and by 1999 a three-station array was transmitting data from seafloor to desktop with a return rate of 97%, significantly higher than the original goal of 80% presented in Table 1 (Meinig et al., 2001).

III. Digiquartz® Broadband Pressure Sensing Technology

The bottom pressure recorder (BPR), as shown in Figure 2, is a critical component of the tsunameter system and includes a Digiquartz® Broadband Depth Sensor, a computer, data logger and an acoustic transducer to communicate with the surface buoy.

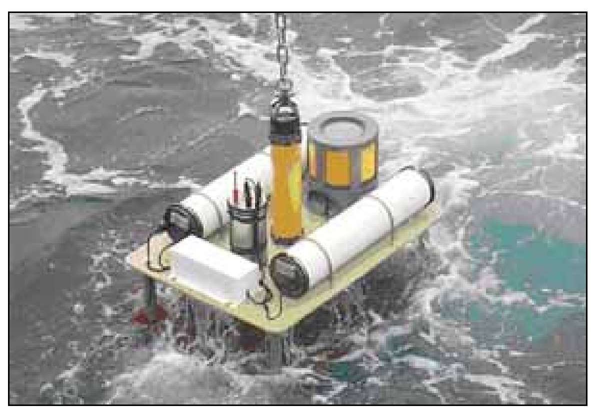

Figure 2. Tsunameter BPR

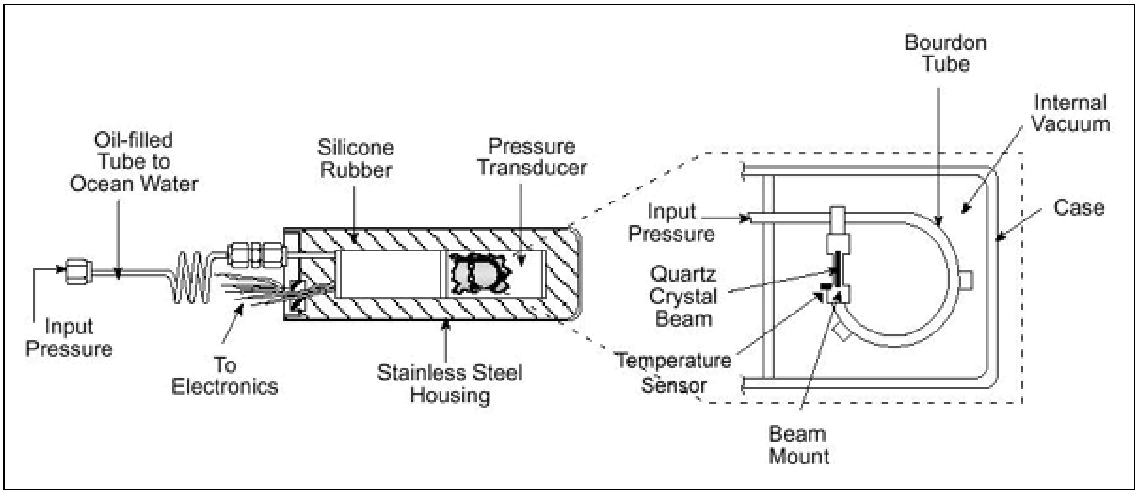

Figure 3. Digiquartz® Bourdon Tube Broadband Depth Sensor

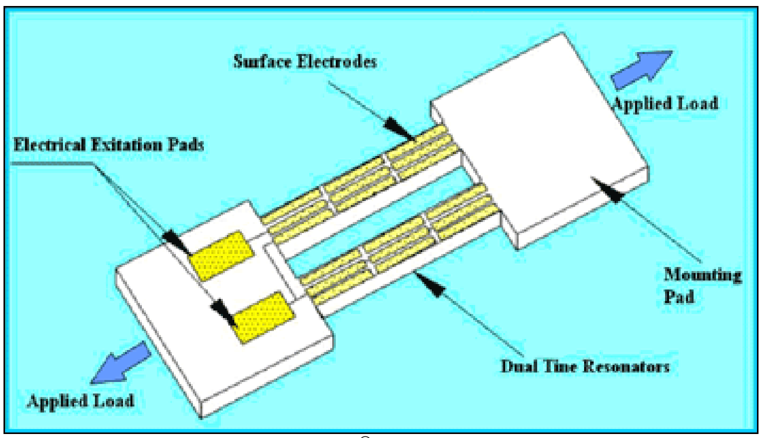

Figure 4. Digiquartz® Vibrating Quartz Crystal

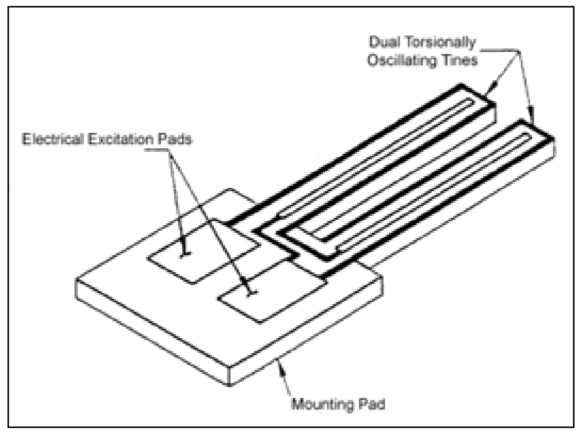

Figure 5. Temperature Crystal

The Digiquartz® Broadband Depth Sensor is the main sensing element in the bottom pressure recorder. This sensor monitors pressure continuously and if the pressure reading changes above a set threshold, then the tsunameter automatically transmits data to a surface buoy. The surface buoy makes a satellite connection to Tsunami warning centers that evaluate the threat and issue a tsunami warning.

The most important sensing requirement is the detection of very small pressure changes at water depths up to 6000 meters. The change in water depth due to a tsunami in the open ocean is generally less than one centimeter. The resolution capability of Digiquartz® Broadband Depth Sensors makes it possible for tsunameters to detect water level changes of less than one millimeter at the deployed depth of 6,000 meters (one part in six million).

Digiquartz® Broadband Depth Sensors are based on the inherently digital, highly stable, vibrating quartz crystal technology developed by Paroscientific over the last three decades. Paroscientific pressure transducer mechanisms, oscillator circuits, and digital interfaces are carefully designed for high resolution.

As illustrated in Figure 3, Digiquartz® Broadband Depth Sensors employ a Bourdon tube as the pressure-to-load generator. Pressure applied to the Bourdon tube generates an uncoiling force which applies tension to the quartz crystal shown in Figure 4. The change in frequency of the quartz crystal oscillator is a measure of the applied pressure. Temperature

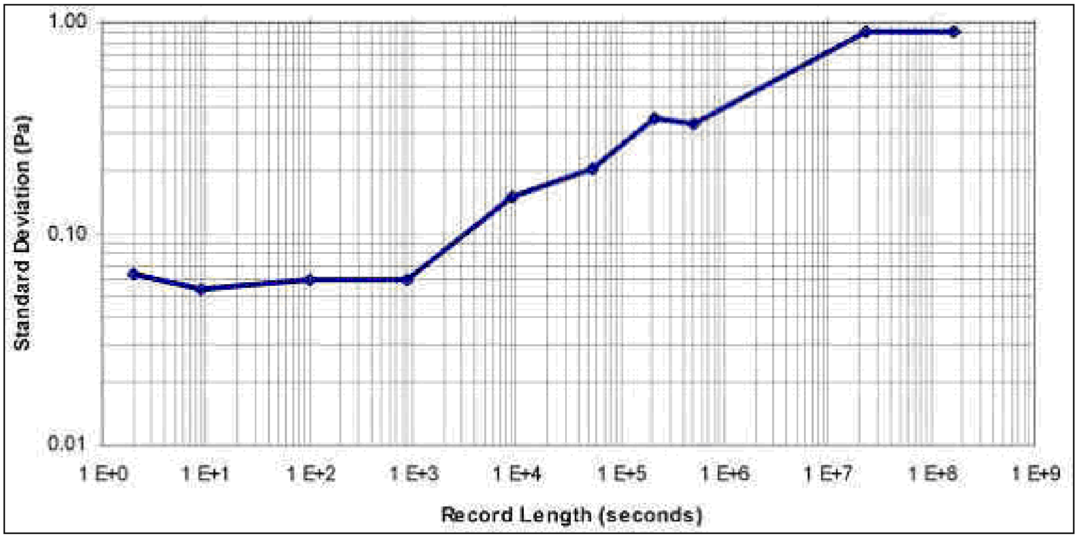

Figure 6. Noise vs. Record Length

sensitive crystals, as in Figure 5, are used for thermal compensation. The mechanisms are acceleration compensated with balance weights to reduce the effects of shock and vibration. The transducers are hermetically sealed and evacuated to eliminate air damping and maximize the Q of the resonators. The internal vacuum also serves as an excellent absolute pressure reference.

The high performance of the Digiquartz® Instruments is achieved through the use of a precision quartz crystal resonator whose frequency of oscillation varies with pressure induced stress. Quartz crystals were chosen for the sensing elements because of their remarkable repeatability, low hysteresis, and excellent stability. The resonant frequency outputs are maintained and detected with oscillator electronics similar to those used in precision clocks and counters.

The quartz crystal consists of two identical beams driven piezoelectrically in 180° phase opposition such that very little energy is transmitted to the mounting pads. The high Q resonant frequency, like that of a violin string, is a function of the applied load; increasing with tension and decreasing with compressive forces. The digital temperature sensor consists of piezoelectrically-driven, torsionally oscillating tines whose resonant frequency is a function of temperature. Its output is used to thermally compensate the calculated pressure and achieve high accuracy over a wide range of temperatures.

The ultimate resolution achievable with a transducer is limited by its noise level. The goal is to have the sensor noise levels much smaller than the expected real signals at all frequencies of interest.

Typical rms noise levels for Digiquartz® Pressure Transducers are shown in Figure 6. For records shorter than about 1 hour, the rms noise level is less than 1 part per million. The rms noise increases for longer data records because of sensor drift and because temperature and other environmental contributors to noise tend to vary more over a longer period of time. The rms noise rises slowly with record length, reaching approximately 10 ppm for records several years long.

Figure 7 shows the filtered output of a 6000 meter depth sensor used to detect earthquake-generated tsunamis. The real signals are resolved to 1 mm of water (1 part in 6 million) and clearly show the signature of the tsunami which is only several centimeters magnitude at the deployed depth of thousands of meters. (Gonzales et al., 1988)

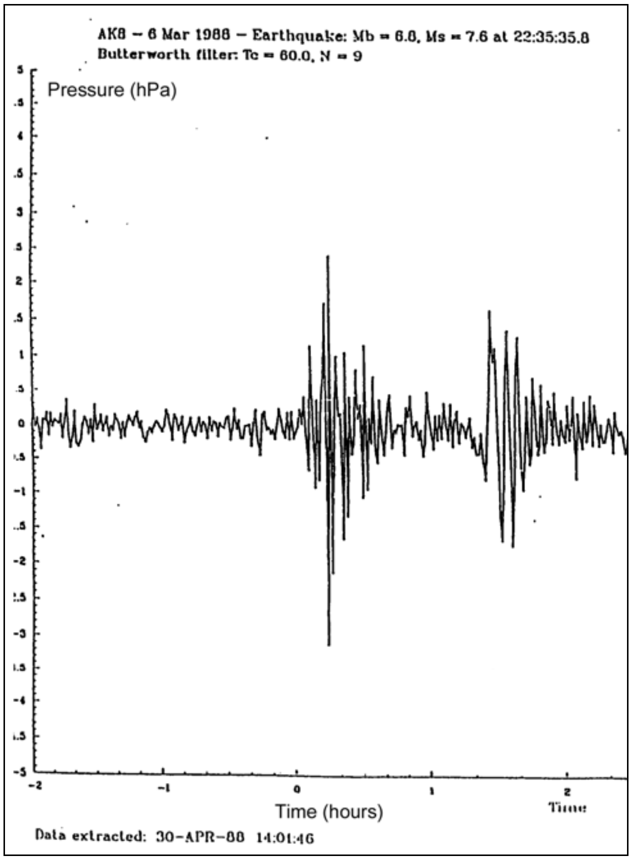

Figure 7. Earthquake-Generated Tsunami

IV. Performance

The NOAA tsunameter was developed in response to the high priority assigned by the Pacific States to "… quickly confirm potentially destructive tsunamis and reduce false alarms" (Tsunami Hazard Mitigation Federal/State Working Group, 1996). To this end, even without sophisticated forecasting tools, the immediate value of the network is clear—tsunameter records, especially those acquired directly seaward of the source, can help verify the existence or absence of destructive tsunami energy propagating toward heavily populated communities. Since the network was established, its value has been demonstrated by a number of earthquake events with tsunamigenic potential.

The most recent event occurred on 17 November 2003 at 06:43 UTC when a warning was issued for Alaska at 07:07, then cancelled at 08:12, shortly after a tsunameter registered a maximum deep-ocean tsunami amplitude of 2 cm (Figure 8) (Titov et al., 2004). This timely cancellation of the warning avoided an evacuation of Hawaii coastlines. Using the 1986 "false alarm" as a cost basis, the early cancellation in 2003 saved Hawaii $68M in lost productivity (Hawaii Economic Analysis, 1996).

V. Summary and Conclusions

The NOAA-led U.S. National Tsunami Hazard Mitigation Program has established an operational tsunameter network in the Pacific, consisting of six deep-ocean stations located seaward of known tsunamigenic zones presently operated by the National Data Buoy Center. This major engineering accomplishment responds to a State-driven priority for the Warning Guidance component of the NTHMP—i.e., increase the accuracy and reliability of tsunami warnings, to "… quickly confirm potentially destructive tsunamis and reduce false alarms." The network is reliable and the real-time data stream has proven its value to warning center decision-makers during a number of potentially tsunamigenic events. The performance and quality of Digiquartz® Broadband Depth Sensors is vital for the continuing success of the tsunameter network. Network improvements are underway—network stations will be increased from the current six to ten by 2008, implementation of real-time tsunami forecasting tools is proceeding, and a next-generation tsunameter is under development that features on-demand data delivery and increased deployment duration and maintenance cycles.

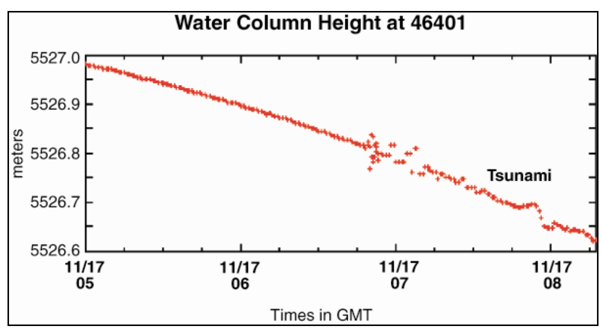

Figure 8. Tsunami of November 17, 2003 as measured at the tsunameter located at 50°N 171°W in 4700 m water depth.

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