

Autonomous Hydrophones at NOAA/OSU and a New Seafloor Sentry System for Real-time Detection of Acoustic Events

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Abstract- Development is under way of a new intelligent autonomous hydrophone system, the Quasi-Eulerian hydrophone, or *QUEphone*. A tether-free portable hydrophone float with built-in data processor, it is capable of repeated vertical ascents and descents from seabed to surface using an internal buoyancy controller. While on the seafloor, it runs an acoustic event detection algorithm continuously; upon detection of a significant acoustic event, or at regular intervals, it surfaces to transmit its position at the surface and a small data file to shore via satellite. Issues of detecting acoustic events at low false alarm rate and applications of this new technology to monitoring other geochemical, biological, and oceanographic properties associated with the world's ecosystem are discussed. Float payload, depth limitation, and vertical travel speed are also discussed.

I. INTRODUCTION

Since 1996, the National Oceanic Atmospheric Administration (NOAA) and Oregon State University (OSU) have successfully operated and maintained arrays of autonomous hydrophones (AUHs). Using these arrays, 2.7 terabytes of low-frequency digital acoustic data have been collected from remote areas where no previous long-term historical record existed. Analysis of the AUH acoustic data has led to numerous discoveries, including magmatic activity at the Lucky Strike segment of the Mid-Atlantic Ridge in 2001 [1] and the discovery of endangered right whales on the Scotian Shelf at unexpected times of year in 2005 [2].

The AUH is portable and battery-powered, making deployment simple, and is built so that the instrument can be moored at the depth of the SOFAR channel to take advantage of low acoustic propagation loss over long distances. The AUH's timing accuracy is better than 1 sec/year, allowing accurate localization of acoustic events such as T-waves (tertiary waves) and whale calls. An array of AUHs, typically consisting of 4 to 6 units, allows monitoring of an area as large as 2 million km². As of fall 2006, NOAA/OSU's AUH monitoring network covers parts of four oceans, including the Atlantic, Pacific, Indian and Southern Oceans.

While the moored autonomous hydrophone is robust and is well-suited for long-term hydroacoustic monitoring at relatively low cost, it is not real-time and requires routine cruises for servicing. As a result, opportunities are missed for observing seafloor eruptions or whale migration as they occur.

Anticipation has been increasing for the proposed real-time cabled ocean-bottom observatory, but its cost is still high and schedule of cable deployment remains uncertain [3]. For transmission of low-bandwidth data, such as ocean salinity and temperature data, the existing IRIDIUM satellite communication service appears to be sufficient to monitor the ocean in near-real time. For example, as of July 2006, approximately 2500 Argo profiling floats are continuously monitoring the temperature and salinity of the upper ocean in near-real time [4, 5]. These Lagrangian floats are battery-operated, low-cost, and disposable, and have been proven to be useful in understanding the role of the ocean in a global climate system. In 2004, Simons et al. [6] successfully recorded the T-wave signal generated by a magnitude 6 earthquake originating in Colombia using a MARMAID float equipped with a hydrophone offshore of California. It demonstrated the feasibility of a tether-free float as a low-cost alternative monitoring system for seismic activities, and showed that wavelet analysis appears to be promising as a means to detect T-waves and discriminate them from airguns.

At NOAA/OSU, similar development is under way of a new autonomous hydrophone system, called the Quasi-Eulerian hydrophone, or *QUEphone*. Taking advantage of the existing Argo float technology, a tether-free portable hydrophone float with a built-in data processor is capable of monitoring acoustic events in near-real time. In contrast to the free drifting Lagrangian float, the *QUEphone* monitors ambient sound in a small area by staying on the seabed while maintaining negative buoyancy over most of its lifespan. Our goal is to design a low-cost, disposable system which ascends/descends between the sea surface and the seafloor. While on the seafloor, the system continuously monitors acoustic events, and upon detection of a

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significant number of events, or at regular intervals when no events occur, it will surface to transmit its position and a small data file to shore via satellite.

A series of tests were conducted in a freshwater lake, followed by sea water tests in the shallow coastal water off Oregon. Issues of detecting acoustic events at low false alarm rates and applications of this new technology to monitoring other geochemical, and oceanographic properties associated with the world's ecosystem are discussed.

II. SYSTEM DESCRIPTION

A. Float

The *PROVOR*® from Metocean, Canada, was selected as a float platform because of its relatively large payload capacity. The CTD sensor was removed from the top shroud of the end cap to make room for the hydrophone and other components critical to the operation of *QUEphone*. In addition to the *PROVOR*'s onboard buoyancy engine, battery and oil bladders, we have packaged and interfaced additional components, including an *IRIDIUM*/GPS communication unit, dual purpose deep water antenna, RF switch, low noise amplifier (LNA), pressure sensor, a single-element hydrophone, pre-amplifier, and CF2 based data logger/processor (Fig. 1). In all, these components add 1.5 kg of weight to the payload. In sea water, however, we found that it still has 1.0 kg of positive buoyancy to spare. This 1 kg of extra payload may be useful when we modify the float in the future for a chemical sensor for CO₂ or methane. For now, 1.0 kg of ballast weight was added to make the float slightly buoyant at the sea water surface. In total, it allows carrying 2.5 kg of payload capacity.

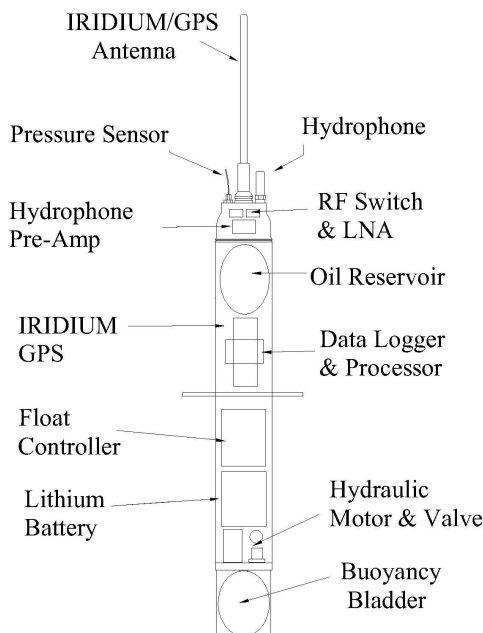


Fig. 1 Internal diagram of the *QUEphone*.

The onboard data logger/processor communicates with the *PROVOR*'s buoyancy controller and *IRIDIUM*/GPS unit through two serial ports. It also oversees the entire descent and ascent process, and monitors the depth, pump and valve actions. Once it reaches the bottom or parking depth (chosen to minimize the effect of drift), it starts digitizing the acoustic signal from the hydrophone at a sampling rate of 100 Hz (with 44 Hz cutoff frequency) and stores the acoustic data. While recording the sound, it also runs an interrupt-driven detection routine so that when an acoustic event meets certain criteria, it records the time and the event's signal to a "detection file" in flash memory. It then ascends to the surface by changing the buoyancy of the *PROVOR* float. The vertical descent/ascent speed is 2.5-5 cm/sec.

While at the surface after each dive, *QUEphone* locates its position by GPS, synchronizes its internal clock to the GPS, and transmits its position and the detection file to shore. It also accepts a simple command from the shore at the end of the satellite connection, then commences another dive. Upon reaching the bottom, it maintains negative buoyancy to keep itself on the bottom. It then monitors until either another event occurs, its internal data buffer gets full, or a pre-scheduled ascent time is reached. The position on the seafloor where the *QUEphone* stayed is estimated from the GPS positions before and after each dive.

The onboard processor also stores local bathymetry, which allows estimation of the next bottom depth based on the current position and average current speed from the past drift. The float is rated for a maximum of 2000 m. Therefore, knowing the next target bottom depth is critical to deciding whether it is safe to dive all the way to the bottom. If the next bottom depth is deeper than 2000 m or unknown, the *QUEphone* is programmed to adjust the target depth shallower than 2000 m. With the current battery capacity (100 Ahr), we estimate that the *QUEphone* can monitor up to a year with up to 12 dives, allowing updates once a month. Currently a prototype is undergoing trials. It is our plan to acquire multiple *QUEphones* to deploy in an area of interest, allowing estimation of sound source locations in near-real time.

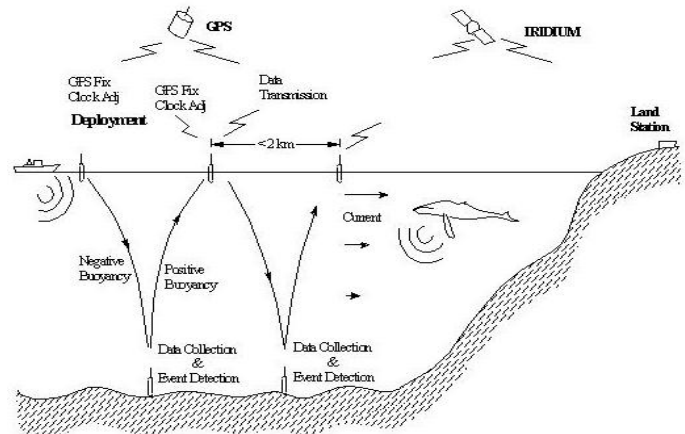


Fig. 2. Concept of a seafloor *QUEphone* monitoring operation.



Fig. 3. The QUEphone during a sea trial.

Fig. 3 shows a *QUEphone* resting on the surface while undergoing a sea trial. The dual-purpose antenna, hydrophone, and pressure sensor are visible above the water line. As of July 2006, *QUEphone* has been tested in water shallower than 100 meters but not undergone the full deep-water test to run the detection routines for T-waves. The deep water test is scheduled at Axial Volcano (1500 m) in late August of 2006 in the area of the Juan de Fuca Ridge.

B. Shore System and Data Transmission

NOAA's Pacific Marine Environmental Lab (PMEL) at NOAA has successfully implemented a web-based data downloading and uploading system which allows users to connect through the IRIDIUM gateway server [7] to many NOAA surface buoys, including Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoys. When the data are delivered to a host server onshore, the user receives an e-mail message with notification of the arrival of data from the buoy, and the data file is immediately posted on a web directory for download by the user.

We took advantage of this proven data communication framework and protocols to develop computer software that sends and receives data from *QUEphone*. Although the data speed is only 2400 bps, compared to a conventional direct modem-to-modem dial-up at sea, data transmission here is faster and has fewer errors. A typical 8 kilobyte detection file is large enough to hold time and magnitude information for approximately 1000 events: 4-byte time in seconds, 1-byte duration in ten-millisecond increments, 2-byte event magnitude, and 1-byte space. This would take less than 1 minute to transmit once the connection to the host gateway is established.

III. DETECTION ROUTINES

We have developed a simple and robust algorithm (Fig. 4) to detect T-waves which can be implemented on low-power battery-operated instruments, including the *QUEphone*. The algorithm uses two 2-pole bandpass filters with two different sets of cutoff frequencies: $s_1(t)$ with a passband of 3-10 Hz, and $s_2(t)$ with a passband of 5-12 Hz. The absolute value of the difference of the two signals, $|s_1(t)-s_2(t)|$, is compared to a moving threshold value $\zeta(t)$, and when it exceeds the threshold, the algorithm generates an interrupt pulse to a data processor. The threshold $\zeta(t)$ is calculated as a sum of the past 10-minute signal average and a standard deviation,

$$\zeta(t) = n \sqrt{\frac{1}{T} \int_{t-T}^t (s_1(t) - s_2(t))^2 dt} + \frac{1}{T} \int_{t-T}^t |s_1(t) - s_2(t)| dt \quad (1)$$

where T is the time length of used for averaging (10 min) and n is a factor to control the sensitivity of the threshold; currently $n=8$. The ambient noise level changes depending on the weather condition and ship noise, so using a time-variant threshold with a long time constant appeared to be effective. These bandpass filters are simple enough to implement with analog circuits with a very low power budget. All the functionality of event detection is realizable by either analog or a digital signal processor (DSP). The interrupt pulse from this circuit is sent to a data logging/control computer to record the time of detection and the signal magnitude. Because of its simple time-domain approach, this algorithm can be easily implemented with low power consumption using analog circuits.

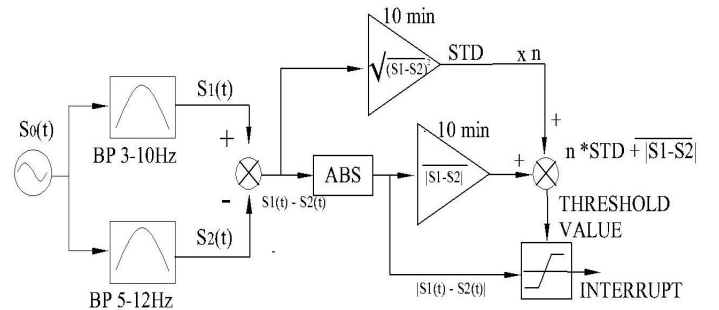


Fig. 4. Signal flow diagram of event detection

As of this writing (July 2006), the *QUEphone* is scheduled for an open-ocean trial in late August 2006. We therefore demonstrate the detection algorithm using data collected in 2001 by an AUH near the Mid-Atlantic Ridge (MAR).

Fig. 5 (a) shows a spectrogram of T-waves recorded by the AUH several hundred kilometers from the epicenter. A signal approximately 5.5 hours long is shown in this figure; 24 T-waves in it were identified by a human operator in the lab as part of a study to locate the epicenters and origin times of MAR earthquakes. T-waves in this figure appear as vertical bright lines between 1 and 40 Hz. Ship noise is visible as

horizontal lines with multiple harmonics. The spectral energy of T-waves is nominally concentrated below 20 Hz.

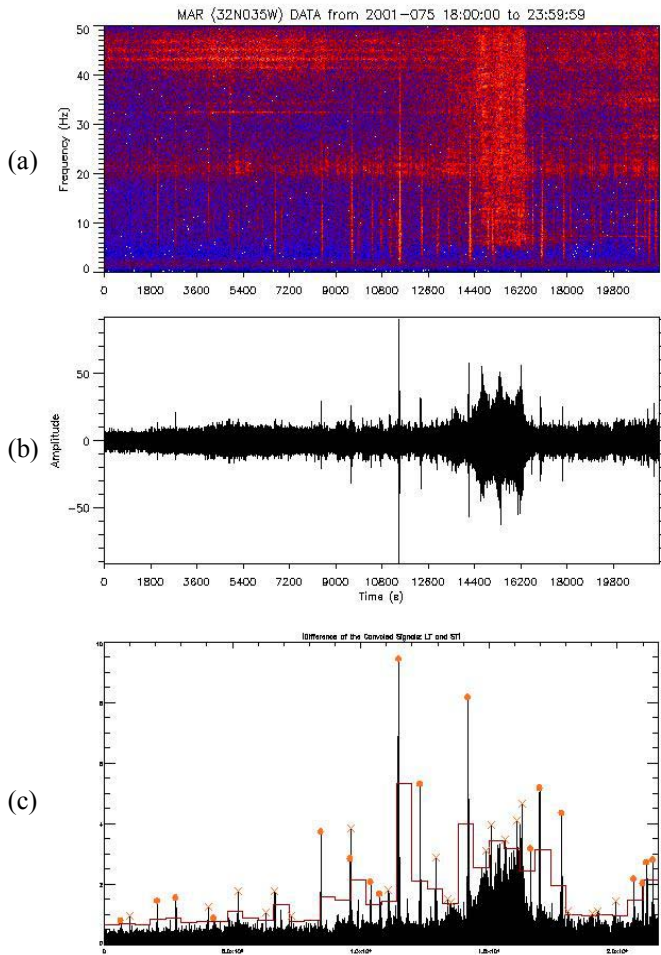


Fig. 5. (a) Spectrogram of acoustic signal received by an AUH at Lucky Strike Seamount, 37° 30' N, 32° 25' W, on March 16-17, 2001. The record contains 24 T-waves identified by a human operator. (b) Amplitude of the same record. (c) Results of the event detection algorithm plotted with the signal magnitude. Round orange marks indicate correct detections of the T-waves, in agreement with the events picked by a human operator. "x" marks are false detections which do not agree with the results by the operator. Some true T-wave events were missed by the detection routine (not shown).

Of the 24 true T-wave events, 18 were correctly detected by the algorithm, for a detection rate of 75%. However, 6 true events were missed. The algorithm detected 38 acoustic events in total, of which 20 were false detections, for a false alarm rate of 52%. The algorithm obviously is not perfect and requires refinement. In particular, a more appropriate time constant value T and multiplication factor n in Eq. (1) would likely improve performance. Here, we have demonstrated only that a simple routine can be effective as a real-time detector.

IV. SUMMARY

A new tether-free hydrophone float, the *QUEphone*, can maintain a nearly-fixed position in the ocean, detect acoustic events in near-real time, and repeatedly travel between the seafloor (to monitor sound) and the sea surface (to transmit data). While on the seafloor, it runs a T-wave detection algorithm; when it surfaces, it reports via satellite the times of detections, signal magnitudes, and position on the sea surface. A time-domain detection algorithm simple enough to implement in low-power analog circuitry was evaluated and appeared to be useful. As of July 2006, the system has undergone shallow-water tests of its dynamics and communication capability, and is scheduled to be tested in deep water in late summer of 2006. The *QUEphone*'s maximum depth is 2000 m, allowing deployment in many areas of interest for monitoring seafloor earthquakes and marine mammal movements. Because it has 1 kg of extra buoyancy, the *QUEphone* will be capable of carrying other light-weight sensors to improve its utility for studying underwater eruptions, marine mammals, and perhaps other areas of study. Sensors for CO₂, methane, and other magmatic volatiles may be good candidates.

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