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# Imaging marine geophysical environments with vector acoustics

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**Abstract:** Using vector acoustic sensors for marine geoacoustic surveys instead of the usual scalar hydrophones enables one to acquire three-dimensional (3D) survey data with instrumentation and logistics similar to current 2D surveys. Vector acoustic sensors measure the sound wave direction directly without the cumbersome arrays that hydrophones require. This concept was tested by a scaled experiment in an acoustic water tank that had a well-controlled environment with a few targets. Using vector acoustic data from a single line of sources, the three-dimensional tank environment was imaged by directly locating the source and all reflectors.

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Vector acoustic sensors, sometimes called acoustic intensity sensors, are compact devices that measure the direction of motion of an acoustic wave.[1–3] They generally measure either the particle motion or the pressure gradient caused by the passing waves and produce data as a three-component vector. Three-dimensional vector acoustic data does not have the axisymmetric directional ambiguity of hydrophone array data. Vector sensors have been used to study the directional nature of noise in the ocean as well as to track whales.[4,5] Using a vector sensor with a controlled pulse source, one can determine both range and bearing for the sound source as well as scattering and reflection points. In the case of nonoverlapping reflections, the vector time series from a single source pulse recorded at a single position can provide a three-dimensional acoustic picture of the local environment. In practice, much of the data has overlapping signals from two or more reflections or scattering targets. Identification of reflecting surfaces requires multiple source or receiver positions. If multiple reflections are strong enough, they will appear as ghosts behind the real reflectors.

Data from linear hydrophone arrays used for geoacoustic surveys or seismic profiling are mapped onto half planes that are either the (usually flat) seafloor on one side of the ship track or vertically below the ship track. Three-dimensional (3D) structures in the environment that can be correctly imaged with vector sensor data will be incorrectly located in a hydrophone-based 2D image. This paper presents how a vector acoustic sensor may be used for marine geoacoustic applications and shows that vector acoustic data can be acquired with existing sensors. This is verified by an experiment using an accelerometer-based vector acoustic sensor in a water tank with a short-pulse source and passive scattering targets.

Vector sensing seismometers have been used to measure local particle motion in the solid earth since the start of observational seismology. These seismometers usually measure displacement or acceleration and with three sensors arranged orthogonally, produced a vector description of the local motion. One significant practical difficulty with seismometers is the coupling between the solid earth and the sensors as well as the device resonance.[5] Using seismometers in water posses even more difficult coupling problems but new developments in miniature accelerometers have solved the largest part of this problem by designing a small, rigid, neutrally buoyant sensor. Moving an accelerometer-based sensor through the water would require a more practical suspension solution while minimizing the flow noise.

Pressure gradient sensors have been around for many years, particularly in air acoustics[1] but there have been few demonstrations in water acoustics and they have never been used for geoacoustic survey applications. A typical pressure gradient sensor consists of six hydrophones

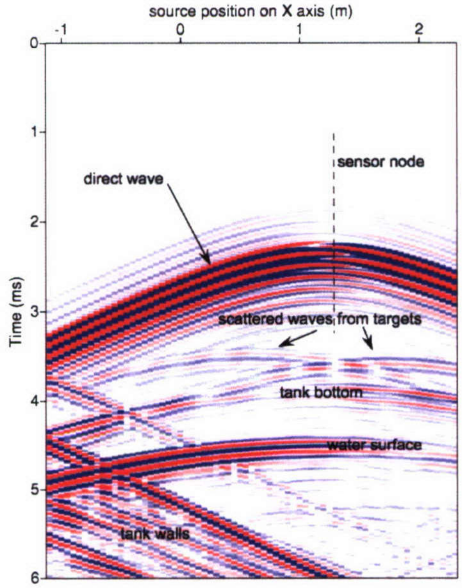

Fig. 1. (Color online) Time-series offset plot of the *x*-axis accelerometer. This display is in the seismic sense with time increasing downward and red and blue colors denoting positive and negative amplitudes. The direct arrival from the source is the most prominent signal and is hyperbolic with the *x*-axis node and its phase shift at the hyperbola's apex. The main pulse of the signal has a delay of 15 ms from the time break. The sandy bottom of the tank and the water surface reflections are visible as hyperbolic reflections with their apexes at the same offset as the direct arrival and times of 3.9 and 4.5 ms. The scattered waves from target floats in the tank show up as similar hyperbolic reflections with apexes that are offset to the sides and beginning times of about 3.5 s and having about 0.01 the amplitude of the direct wave.

arranged in three orthogonal pairs or four hydrophones on the vertices of a tetrahedron. The hydrophones must be exactly matched in phase but may result in a more robust package than a three-axis accelerometer.

We used an accelerometer-based vector sensor designed specifically for use in water by Roger Richards and others of the NAVSEA division of the Naval Underwater Warfare Center in conjunction with Wilcoxon Research Inc. This sensor is called the TV-001 Miniature Vector Sensor, has a sensitivity of 1.0 V/g and a frequency response of about 3 to 9 kHz, has the shape of a cylinder with two hemispherical end caps, and is 71 mm long and 41 mm in diameter with a mass of 54 g. This sensor is neutrally buoyant in water to produce the best motion coupling with the acoustic waves in the water. The sensor was suspended near the center of a pool of water with five, thin, elastic strands. This allowed the sensor to move freely in all directions and had a resonant frequency of approximately one hertz. The electrical cables were left slack so as to minimize their motion influence on the sensor. The sound source was a single transducer using a single cycle sine wave at 8 kHz. The vector sensor remained stationary and the source transducer was moved along several lines so as to cover multiple directions and distances from the sensor and targets. After shooting several reference lines, we placed two medium-sized floats and two small floats in the water as highly reflective targets.

Figure 1 is a time-series offset plot of the *x*-axis accelerometer. The reflections from objects that are broadside to the source line appear as hyperbolas and the reflections from objects beyond the ends of the source line appear as straight lines. The gain on this display is very high, clipping the direct wave, so that the much weaker reflections are visible. The weak precursor to the main signal pulse, which is one of the noise sources, is also visible. The coherency of the main pulse as well as the precursor across all source positions is some indication of the consistent receiver response over a wide range of angles.

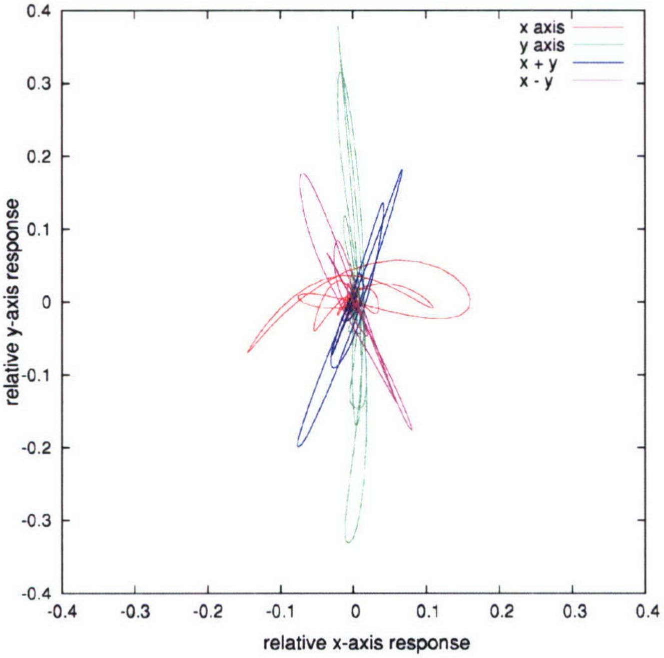

Fig. 2. (Color online) Hodogram of the $x$ and $y$ components of the accelerations from direct waves from the source. Two of the signals are aligned with the $x$ and $y$ axes and two are at 45-deg angles from the axies. The $y$-axis accelerometer of this sensor is about twice as sensitive as the $x$-axis accelerometer. The 45-deg off-axis signals appear to be about 30 deg from the $y$ axis because there have been no amplitude corrections applied to these data.

Figure 2 illustrates the directional sensitivity of our accelerometer-based vector sensor and also shows some of the inaccuracies of the sensor and of the experimental setup. This is a hodogram of the raw data from the $x$ and $y$ components of the accelerations from direct source signals at four different locations. Two of the signals are aligned with the $x$ and $y$ axes and two are at 45-deg angles from the axes. The $y$-axis accelerometer of this sensor is about twice as sensitive as the $x$-axis accelerometer. The sensor motion from the source in the $y$-axis direction was aligned well with the $y$ axis but the sensor motion from the source in the $x$ direction deviated substantially from the axis. We speculate that the $x$-component deviations were caused either by an internal defect in the sensor or by motion restrictions from the electrical cables. The 45-deg off-axis signals however do not show such interference and indicate a direction of about 30 deg from the $y$ axis because they have not been corrected for the lower sensitivity of the $x$-axis accelerometer. The principle of vector acoustic surveys can still be demonstrated with these data in spite of the different sensitivities and the nonlinear $x$-direction response.

A controlled source can be located with a single vector sensor measuring the bearing and the delay time. The source position vector $\boldsymbol{S}$ is

$$\boldsymbol{S} = \boldsymbol{G} + \hat{\boldsymbol{d}}tc, \tag{1}$$

where $\boldsymbol{G}$ is the receiver position vector. The direction vector $\hat{\boldsymbol{d}}$ is the unit vector in the direction of the accelerometer response, $t$ is the travel time, and $c$ is the sound speed. Locating a single scattering target with a single vector sensor can be done if the source location and pulse timings are known. Even if the source timings are unknown, the target bearings are known and there is a linear relation for the source and target ranges. Multiple scattering targets can be located with a single vector sensor provided that the individual scattered pulses are separated in time at the sensor. The target position vector $\boldsymbol{T}$ is calculated by

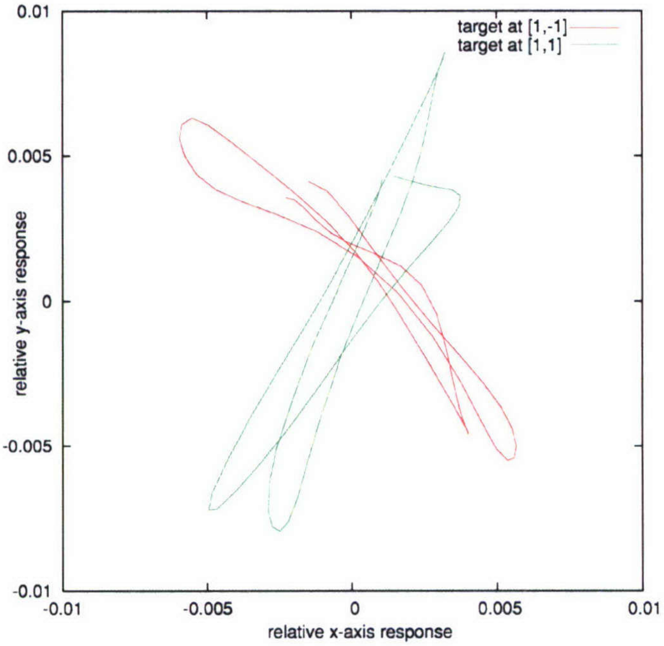

Fig. 3. (Color online) Hodogram of the $x$ and $y$ components of the accelerations due to waves scattered from the target floats. The signals were time windowed and selected from a position that had the best separation from other signals.

$$\boldsymbol{T} = \boldsymbol{G} + \hat{\boldsymbol{d}} r, \tag{2}$$

$$r = \frac{s(s - tc)}{b \cos^2(\theta/2) - s}, \tag{3}$$

$$s = \frac{tc + b}{2}, \tag{4}$$

$$\theta = \cos^{-1}\left(\frac{\boldsymbol{d} \bullet \boldsymbol{S}}{b|\boldsymbol{d}|}\right). \tag{5}$$

$r$ is the range to the target, $b$ is the source to receiver range, $\boldsymbol{d}$ is the target vector, $\theta$ is the angle between the receiver-source and the receiver-target vectors, and $||$ denotes the norm, or length, of the vector. The large dot denotes the vector dot product.

A hodogram of the motions in the $x$-$y$ plane of the scattered signals from two target floats graphically illustrates that an acoustic environment and not just the sources can be directly sensed with vector acoustic data (Fig. 3). The signals were time windowed and from a source location that gave the best separation from other signals. These data have not been corrected for the different sensitivity of the $x$ and $y$ axes accelerometers.

If scattered signals from several targets or surfaces overlap, such as in our data, then they cannot always be located with a single source and receiver location. Locating each target within a field of scattering targets depends on target spacing relative to the signal wavelength. For most cases, a single line of either source or vector receiver locations is sufficient.

The data from our acoustic tank experiment were mapped into a volume image by binning the target vectors and summing the signal amplitudes in each bin. Figure 4 shows three slices through the $z$ axis of the volume map showing the two float targets as well as more distant walls.

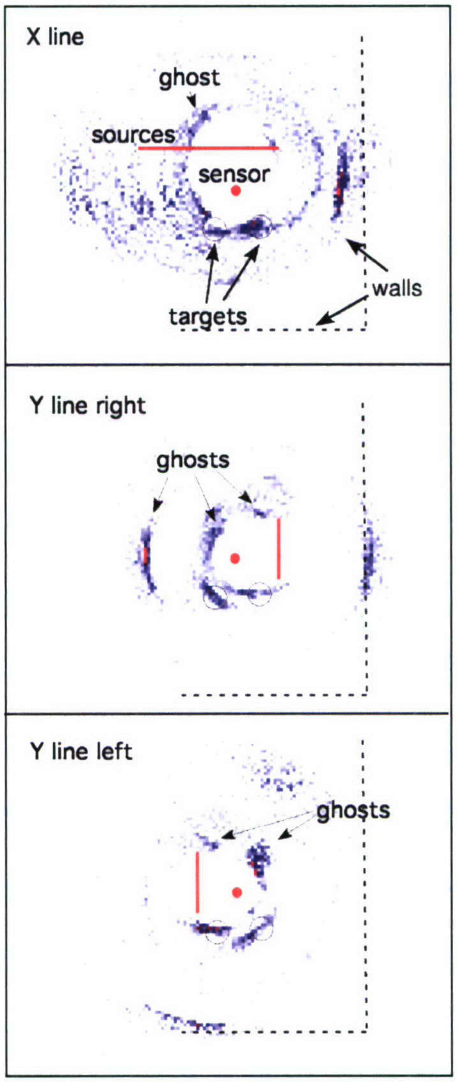

Fig. 4. (Color online) Horizontal slices of the volume image of the tank environment from three different source lines. The sensor is at the red dot in the center, the sources are every 5 cm along the red line, and the targets are located at the centers of the black circles. The source lines have a minimum distance of one meter from the source. These images ware made by calculating the range and bearing for each time sample using Eq. (2) and adding the magnitude of the signal to the corresponding grid point. The ghosts are due to the unrectified signals.

Since the scattered target position vector is calculated with a different equation than the source position vector, a time window was applied that eliminated most of the direct wave. The targets and walls are well positioned except for the wall in the top figure. Most of the targets and walls have ghosts caused by the unrectified negative parts of the signals. The noise causes uncertainty in the direction to the targets but not for most of the ranges. The data were corrected for different sensitivities of the axies before imaging.

The imaging of these vector sensor data can probably be improved substantially by incorporating existing techniques such as migration and phase coherence. These existing processing techniques can reduce the noise and may be able to separate overlapping arrivals from different targets such as seen in Fig. 1.

In conclusion, this work demonstrates the application of a vector acoustic sensor to marine geoacoustic surveys. The accelerometer data show the direct source wave as well as the target scattered waves and reflections from the nearby water surface, tank bottom, and sides. Vector data from single shots show that the wave motion direction can be readily determined for both direct waves and scattered waves. Without resorting to the usual methods of imaging used in seismic exploration, which in this case would have only been two dimensional and relied entirely on the use of a synthetic source aperture, the three-dimensional volume of the tank environment was imaged. Vector acoustics in marine environments may be applicable to a wide range of problems ranging from long-range ocean acoustics to subseafloor seismic exploration surveys.

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## References and links

[1] M. J. Berliner and J. F. Lindberg, *Acoustic particle velocity sensors: Design, performance, and applications* (AIP Conf. Proc. **368**, 1996).

[2] F. J. Fahy, "Measurement of acoustic intensity using the cross-spectral density of two microphone signals," J. Acoust. Soc. Am. **62**, 1057–1059 (1977).

[3] F. J. Fahy, *Sound Intensity* (Elsevier Science, New York, 1989).

[4] G. L. D'Spain, W. S. Hodgkiss, and G. L. Edmonds, "Energetics of the deep ocean's infrasonic sound field," J. Acoust. Soc. Am. **89**, 1134–1158 (1991).

[5] G. L. D'Spain, W. S. Hodgkiss, and G. L. Edmonds, "The simultaneous measurement of infrasonic acoustic particle velocity and acoustic pressure in the ocean by freely drifting swallow floats," IEEE J. Ocean. Eng. **16**, 195–207 (1991).