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Marine seismic surveys with vector acoustic sensors

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Summary

Vector acoustic data will allow accurate 3-D imaging of a complex environment while corresponding pressure hydrophone data will fail. Newly developed sensors make vector acoustic based surveys practical. This concept is demonstrated with data from an acoustic water tank. Using a simple but novel imaging algorithm, all of the main structures in the water tank were correctly located. This imaging algorithm uses none of the existing imaging or inversion methods common in exploration seismology.

Introduction

Vector acoustic sensors, or acoustic intensity sensors, are compact devices that measure the direction of motion of an acoustic wave (Berliner and Lindberg, 1996; Fahy, 1977; Fahy, 1989). They generally measure either the particle motion or the pressure gradient caused by the passing waves. Data from vector acoustic sensors used in geo-acoustic surveys of the seafloor provide additional information not present in traditional pressure data from hydrophones (Lindwall, 2006). A combined vector sensor and controlled source gives both range and bearing for the sound source as well as scattering and reflection points. In principle, a single sound pulse recorded at a single vector acoustic sensor can provide a three-dimensional acoustic picture of the local environment. In practice, there are numerous ambiguities caused by overlapping signals from two or more reflections or scattering targets. These ambiguities can be resolved with a single line of source or sensor locations in most cases. Hydrophone data can, at best, give only a two-dimensional image of the environment from the same survey configuration. Three-dimensional structures in the environment that can be correctly imaged with vector sensor data will be incorrectly located in a hydrophone-based 2-D image.

Seismic and acoustic surveys of marine environments use towed arrays of hydrophones that acquire scalar pressure data. The arrays need to be about 20 wavelengths long in order to give a directional resolution orthogonal to the direction of the array of one or two degrees. Unambiguous determination of direction requires three orthogonal arrays of scalar sensor arrays. This cumbersome arrangement can be avoided by using vector acoustic sensors. This paper presents how a vector acoustic sensor may be used for marine geo-acoustic 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.

The experiment

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 Hz 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 grams. This sensor is neutrally buoyant in water so as to have the best motion coupling with the water.

We suspended the sensor near the center of a pool of water with five, thin, elastic strands (Figure 1). The sound source was a single transducer driven with a single cycle of a sine wave of 8 kHz. The vector sensor remained stationary and the source hydrophone 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 in the water as highly reflective targets. All of the data presented in this paper have the medium target floats in the same horizontal plane as the source and receiver. This is to present the concepts of vector acoustic data in the simplest form.

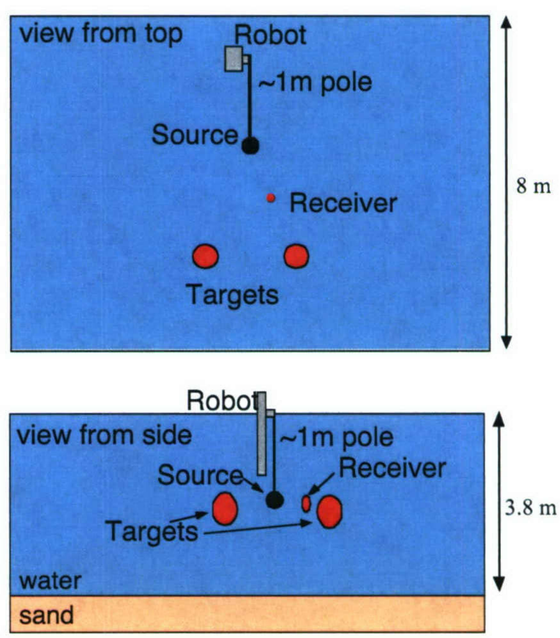

Figure 1: The experimental set up in a water tank.

A common receiver-point gather of the x-axis accelerometer data (Figure 2) shows the hyperbolic direct arrival from the source as the most prominent signal with the sensor node at the hyperbola's apex. 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 ms.

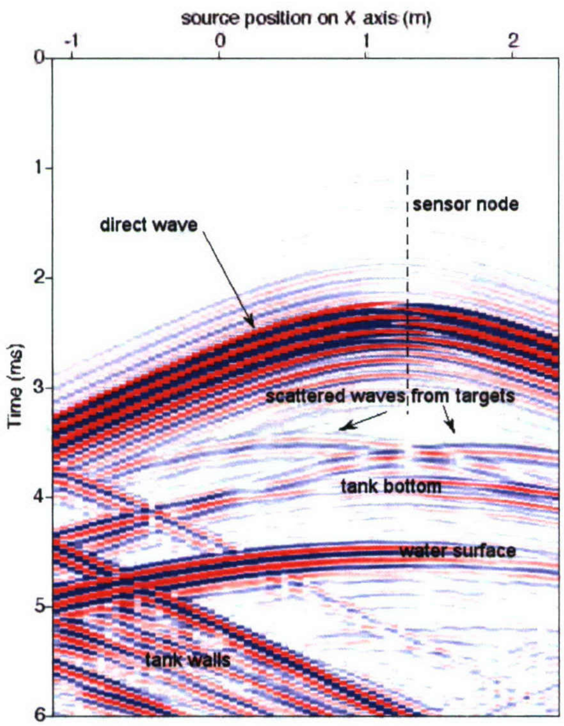

Figure 2: Common-receiver data from the x-axis accelerometer. The main pulse of the signal has a delay of 15 ms from the time break.

Detection and location

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

$$\overline{S} = \overline{G} + \hat{d} \cdot t \cdot v \tag{1}$$

where $\overline{G}$ is the receiver position. The direction vector $\hat{d}$ is the unit vector aligned with the particle motion, t is the travel time and v is the sound speed. Locating a single scattering target with a single vector sensor is also simple with knowledge of the source location and start time (Figure 3). Even if the source time is 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 $\overline{T}$ is calculated:

$$\overline{T} = \overline{G} + \hat{d} \cdot r \tag{2}$$

$$r = \frac{s(s - t \cdot v)}{b \cdot \cos^2(\theta/2) - s} \tag{3}$$

$$s = \frac{t \cdot v + b}{2} \tag{4}$$

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

r is the range to the target, b is the source to receiver range, $\overline{d}$ is the target vector and $\hat{d}$ is the target vector of unit length, θ 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 and small dots are multiplication.

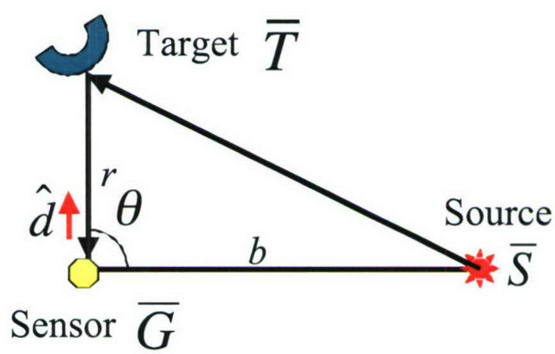

Figure 3: Geometry of target location.

A hodogram of the motions in the x-y plane of the scattered signals from the target floats graphically illustrates that acoustic scatterers and not just the sources can be directly sensed with vector acoustic data (Figure 4). The signals were time windowed and from a source location that gave the best separation from other signals. The motion has not been corrected for the different sensitivity of the x and y axis accelerometers.

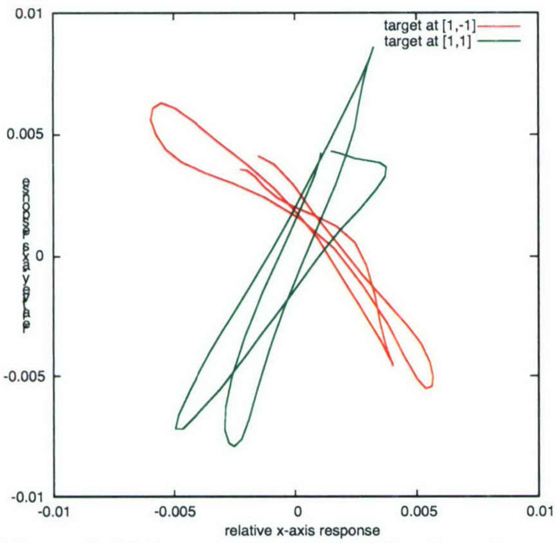

Figure 4: Hodogram of sensor accelerations due to scattered waves from the two target floats.

If scattered signals from several targets or surfaces overlap, such as in the data in Figure 2, then the targets cannot 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. A single sensor or receiver will not be able to correctly locate two scattering targets that are positioned symmetrically with respect to the axis of the line. This two-target ambiguity can be resolved in several ways. If either the source or the vector-sensor is held fixed while the other is moved along a line, the fixed device can be place off-axis of the line. This reduces the location ambiguity to objects at symmetric positions on a single plane.

Rectifying the signal

The oscillating nature of the source signal produces sensor responses in the positive and negative direction of the wave direction. The sensor response must be rectified so as to calculate an unambiguous wave direction. The sensor we used has an integral hydrophone, but its response has a different phase and different frequency than the accelerometers (Figure 6). The hydrophone signal must first be filtered before it can be used to rectify the accelerometer signals.

The full hydrophone time series $P_D(\nu)$ is whitened by dividing it by the direct signal spectrum $P(\nu)$ then multiplied by the accelerometer data spectrum $A_D(\nu)$ to give a filtered hydrophone spectrum $P_A(\nu)$ that can be transformed to the phase-matched pressure time series $p_A(t)$ (Figure 7). The phase-matched pressure time series is used to create the rectifying sign series $sign(p_D(t))$ that can change the accelerometer data $a_D(t)$ into rectified accelerometer data $a_R(t)$:

$$P_W(\nu) = P_D(\nu)/P(\nu) \qquad (6)$$

$$P_A(\nu) = P_W(\nu) \cdot A(\nu) \qquad (7)$$

$$p_A(t) \leftrightarrow P_A(\nu) \qquad (8)$$

$$a_R(t) = sign(p_A(t)) \cdot a_D(t) \qquad (9)$$

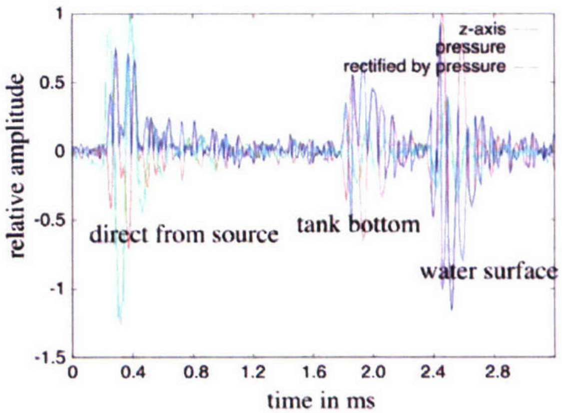

Figure 5: Time series plots of the z-axis accelerometer, the pressure hydrophone and the rectified z-axis signal. The phase-matched hydrophone data is used as the rectifying series. The pressure-rectified data, although not perfectly phase matched, shows most of the tank bottom and water surface reflections coming from opposite directions.

Imaging

The data from the acoustic tank experiment were mapped into a volume image by binning the target vectors and summing the signal amplitudes in each bin. Figure 6 shows a horizontal and two vertical slices through this volume. The horizontal (X-Y) slice is at the same depth as the sensor, sources, and targets and clearly shows the targets as well as the wall near the right end of the source line. The Y-Z vertical slice is through the source line, does not include the sensor or targets, but shows the highly reflective water surface and the less reflective sand bottom as well as the same wall as seen in the horizontal slice. The X-Z vertical slice is orthogonal to the source line and passes through the sensor and between the targets. Since the scattered target position vectors are calculated with a different equation than the source position vector, a time window was applied that eliminated the direct wave so the sources are not imaged here but are drawn in to show their positions. The noise causes uncertainty in the direction to the targets but not to the ranges. The data were corrected for different sensitivities of the axies before imaging. The migrated section of the hydrophone places all of the features in the same half plane.

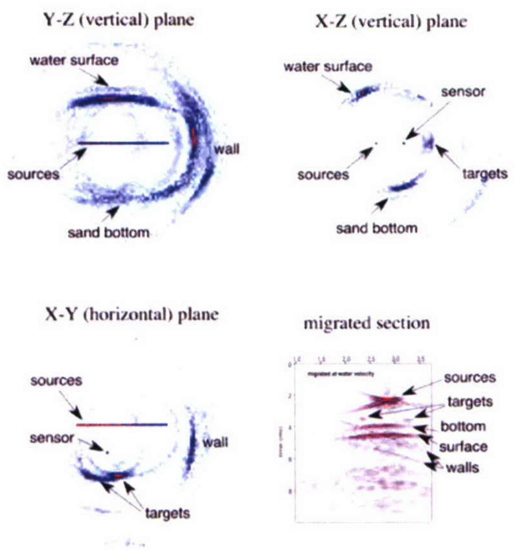

Figure 6: Three orthogonal slices through the vector-derived image volume and a conventionally migrated section of the hydrophone data.

Discussion

This vector imaging approach requires much less computation that methods commonly used for data from pressure arrays. This is not likely to be a factor in choosing vector sensors over pressure sensors since the imaging of vector sensor data can probably be improved substantially by incorporating existing techniques such as migration and phase coherence. These existing processing techniques can effectively separate overlapping arrivals from separate targets such as in Figure 2.

A comparison of the vector-imaged volume with standard seismic imaging (Figure 6) shows the enormous advantage of using vector data over scalar data. All objects and surfaces that are outside of the source-sensor plane are incorrectly imaged in the migrated section. The migration method can not even determine the correct direction for the water surface or the tank floor.

Conclusions

A single line of scalar hydrophone data is unable to correctly image structures in a 3-D volume while vector acoustic data from exactly the same acquisition parameters can accurately image all the major structures within that volume. Existing vector acoustic technology is at the stage to be used for marine surveys and may result in much simplified field efforts for 3-D seismic surveys.

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EDITED REFERENCES

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