Comparative Beamforming and Acoustic Inversion Studies Employing Acoustic Vector Data in Shallow Water

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Award Number: N0001407WR20143

LONG-TERM GOALS

The goals of this research included comparisons of standard and novel, non-standard processing techniques on linear arrays of vector sensors, and development of new inversion methods based on information contained in the acoustic vector field. A result of this study is then to show how the additional information contained in the acoustic vector field (pressure and particle velocity) may be used to improve the results of inversion schemes and provide more robust estimates of source direction from array beamforming.

OBJECTIVES

The specific objectives of this work included the calculations and detailed comparisons of direction of arrival (DoA) from a towed array of vector sensors to a noisy target for a variety of processing schemes and in the presence of multiple targets. The processing schemes included standard, linear (Bartlett) beamforming techniques, standard, non-linear adaptive (MVDR) techniques, and novel, non-linear techniques based on multiplicative processing. Specific features of the results, such as DoA resolution, left/right ambiguity rejection, and peak-to-sidelobe levels, were examined.
In addition, features of the acoustic vector field that may be exploitable on a vertical array of sensors were examined. Specifically, the impact of signal attenuation on the components of the complex acoustic intensity were considered in hopes of developing an algorithm for extracting estimates of attenuation parameters from measurements of the field.

APPROACH

For this work, a previously developed technique for computing acoustic particle velocities from a PE model,[1,2,4] was employed to produce synthetic acoustic vector field data (pressure and particle velocity) in shallow water environment for a range of source parameters. The data modeled corresponded to signals received on a linear, towed array[5] for six different sources at various ranges and source/array bearings. This data was then used to test processing routines for plane-wave beamforming using a variety of algorihtms.[5,6,7,8,9]

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Comparative Beamforming And Acoustic Inversion Studies Employing Acoustic Vector Data In Shallow Water**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Code PH/Sk, Department of Physics,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

code 1 only

14. ABSTRACT

The goals of this research included comparisons of standard and novel, non-standard processing techniques on linear arrays of vector sensors, and development of new inversion methods based on information contained in the acoustic vector field. A result of this study is then to show how the additional information contained in the acoustic vector field (pressure and particle velocity) may be used to improve the results of inversion schemes and provide more robust estimates of source direction from array beamforming.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

For the inversion studies, the focus was on geoacoustic properties, specifically bottom attenuation. In this case, no model results were employed but rather a formal, theoretical treatment of the influence of attenuation on the complex acoustic intensity field was examined. Techniques for extracting the attenuation parameter were then considered.[10]

WORK COMPLETED

In order to verify the accuracy of the propagation model used to compute the acoustic vector field, a second, independent model was adapted for comparison. The Couple normal mode model[3] was adapted to compute the components of particle velocity in the plane of propagation. The results from this model were compared to the results from the PE model and shown to provide good agreement. The remaining numerical simulations were then carried out using the PE model.

Various plane-wave beamforming algorithms were developed an tested both on synthetic, plane-wave data and on more sophisticated, shallow water propagation model results. These algorithms included linear (Bartlett) processors employing both standard cardioid steering and dynamic null steering (to enhance left/right discrimination), non-linear but non-adaptive processors that combine different forms of linear processors, and adaptive, non-linear (MVDR) processors designed to maximize the resolution of the DoA estimate. Strengths and weaknesses of each algorithm have been compared and contrasted.[5,7,8,9]

A theoretical algorithm for extracting bottom attenuation parameters was also developed based on ratios of components of the complex acoustic intensity field. This technique requires an array of vector sensors capable of extracting unique modal information, and remains highly sensitive as the attenuation values are low and primarily affect only the highest, trapped modes. An examination of the asymptotic nature of this algorithm has been performed.[10]

RESULTS

The confirmation of the algorithms for computing the particle velocity field was performed at 200 Hz in the standard ASA benchmark wedge. Figure 1 shows the comparisons between the PE and normal mode models for the pressure transmission loss curves, and corresponding horizontal and vertical velocity components. The agreement was found to be quite good, confirming the implementation and general accuracy of the particle velocity calculations.

The PE model was then employed to generate predictions of broadband arrival structure on a towed array of vector sensors in a shallow water environment. A simple, Pekeris waveguide was defined, and uncorrelated source signals transmitting continuously over the band 1250-1750 Hz were assumed. Various combinations of source depths and ranges relative to the towed array were modeled. In Fig. 2, an example of a comparison between plane-wave beamforming employing pressure-only signals and the full acoustic vector signal is provided for three, independent sources. The upper panel displays the results as a time-evolving beamformer output, while the lower panel shows the power average over the time window. Table 1 provides the output levels in the true (“look”) and ambiguous (left/right) directions. Note for this calculation, only standard, linear processing with cardioids was employed.

Figure 3 shows the theoretical plane wave responses of a number of different types of processing algorithms for vector sensor line arrays. The polar plots represent 50 dB of processor output normalized to a peak of 0 dB. The upper left panel presents a comparison of the responses of linear (cardioid) processing and non-linear, non-adaptive (hippioid, cardynull) processing for a single arrival at 30 deg off broadside. The upper right panel presents a similar comparison between the non-linear, non-adaptive processors and a non-linear, adaptive (MVDR) processor. Finally, the lower panel compares each of these processor responses to multiple arrivals (3 different directions with relative amplitudes 1:1:0.5).

Of these results, the fully adaptive processor achieves the best results in terms of DoA resolution, peak-to-sidelobe level, and left/right ambiguity discrimination. However, the data used to make this determination were highly idealized. The other non-linear but non-adaptive processing techniques also showed improvements over the linear, cardioid processing both in terms of peak-to-sidelobe level and left/right ambiguity discrimination.

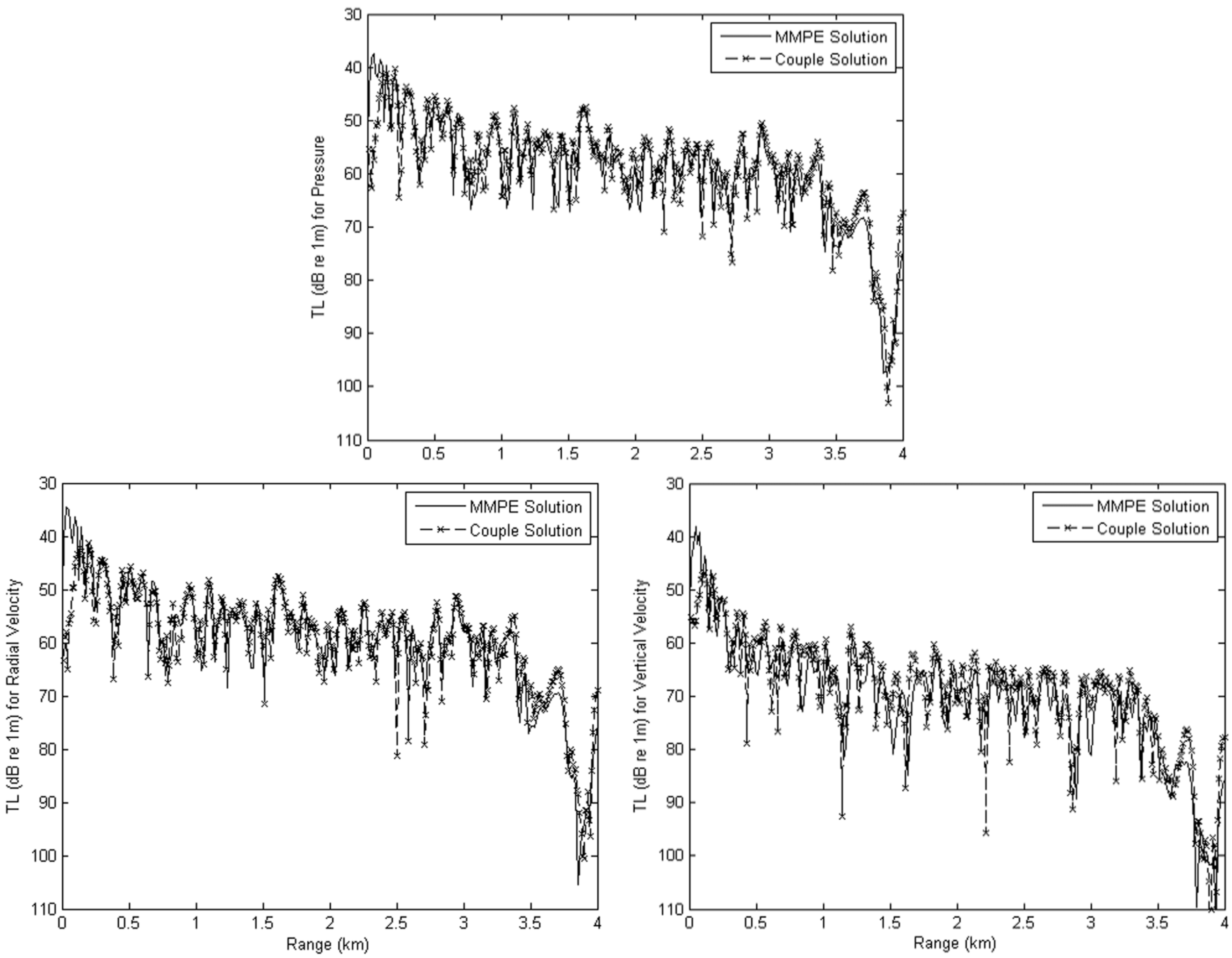

Figure 1: Comparison of transmission loss traces at a depth of 30 m between MMPE solution (solid) and Couple solution (dash) for ASA benchmark wedge calculation at 200 Hz: (a) pressure; (b) radial component of particle velocity; (c) vertical component of particle velocity.

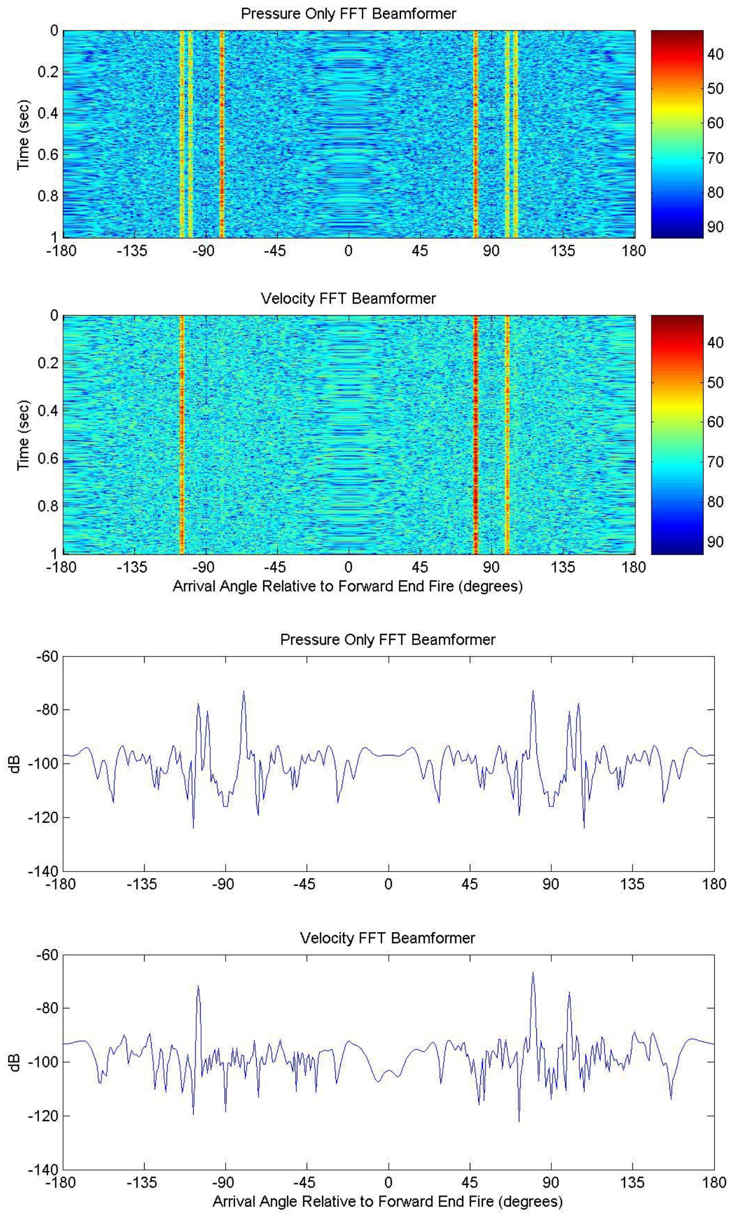

Figure 2: Plots of time-evolving (upper panels) and power-averaged (lower panels) linear, plane-wave beamformer responses for array of pressure-only sensors versus vector sensors given 3 uncorrelated sources in noise (SNR 30 dB).

Table 1. Comparison of power-averaged beamformer peak responses for 3 uncorrelated sources in noise (SNR 30 dB).

	Look			Ambiguous		
Angle (degrees)	80	100	-105	-80	-100	105
Pressure (dB)	-72.80	-80.48	-77.55	-72.80	-80.48	-77.55
Velocity (dB)	-66.70	-73.92	-71.53	-97.76	-104.17	-93.30

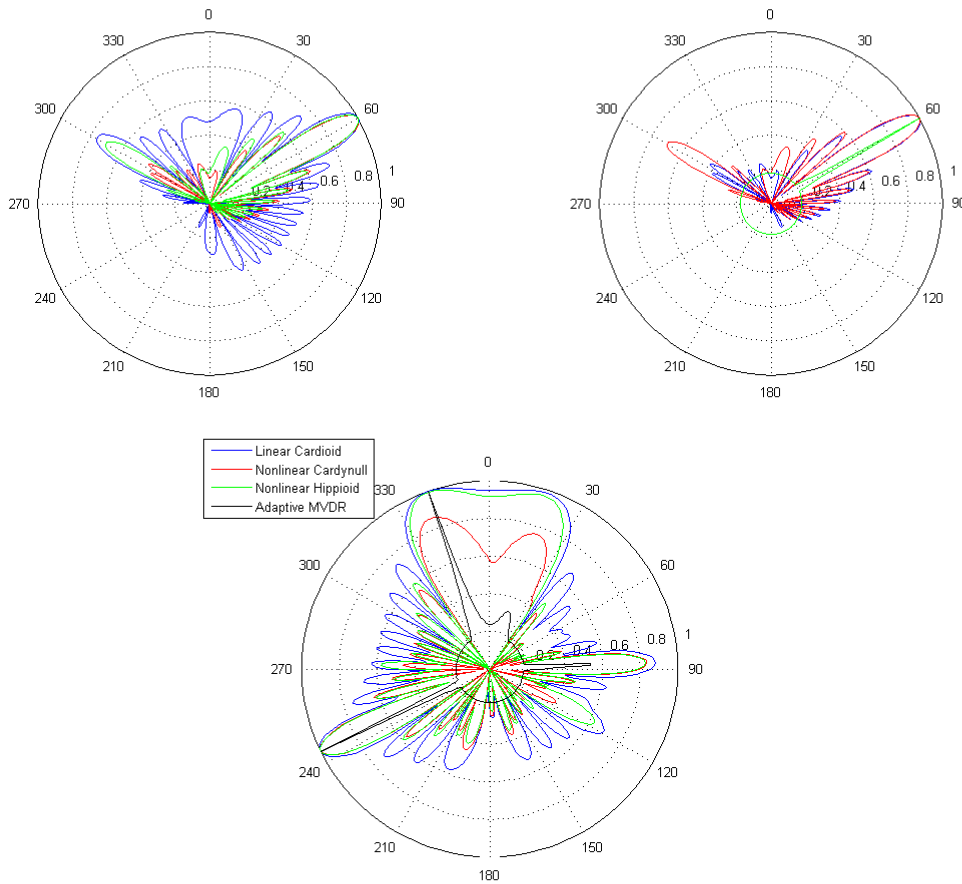

Figure 3: Plots of theoretical plane-wave responses of various linear and non-linear processors for an array of vector sensors: (upper left) responses of cardioid (blue), cardynull (red), and hippioid (green) for plane wave incident at 60 deg from end-fire; (upper right) responses of cardynull (blue), hippioid (red), and MVDR (green) for plane wave incident at 60 deg from end-fire; (lower plot) responses of cardioid (blue), cardynull (red), hippioid (green), and MVDR (black) for 3, uncorrelated plane waves incident at 244 deg, 341 deg, and 87.5 deg with relative weighting 1:1:0.5, respectively.

As discussed above, work was also completed on the evaluation of the impact of attenuation on the complex acoustic intensity field. Theoretical analyses were performed based on a fairly simple technique of computing the ratio of the radial component of the imaginary part of the intensity (reactive) to the radial component of the real part of the intensity (active) for individual waveguide modes. This should provide information on the attenuation factor for each mode. Specifically, the quantity of interest is defined as

$$\delta_M \approx K_M \frac{\int_0^\infty \left|\frac{Q_r}{I_r}\right| \Psi_M^2(z)\,dz}{\int_0^\infty \Psi_M^2(z)\,dz}, \text{ for } \delta_M \ll \frac{1}{r}.$$

In the expression above, δ_M represents the modal attenuation loss for mode Ψ_M, K_M is the modal wavenumber, and I_r and Q_r are the active and reactive intensities, respectively, of the acoustic field for mode M. In Fig. 4, the asymptotic nature of the ratio is displayed for various modes near cut-off at different frequencies. Although the departure from simple, cylindrical spreading may be observed at relatively short range, it typically takes several kilometers of propagation before the asymptotic limit becomes apparent. This could make real-world observations extremely difficult since this technique requires the extraction of a single mode arrival near cut-off, which is likely prone to significant variability with range.

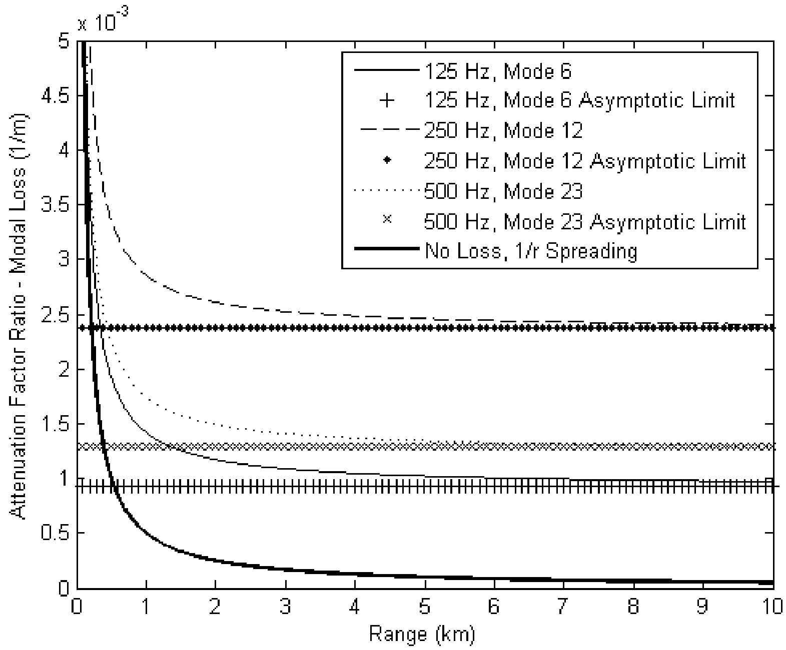

Figure 4: Plots of radial intensity ratio defined above for three modes along with their asymptotic limits. Thick line shows result when no loss is included in the calculation.

IMPACT/APPLICATIONS

In this work, the response characteristics of some new plane-wave beamformers has been examined. The non-linear but non-adaptive processors, referred to as cardynull and hippioid, showed noticeable improvements over standard, linear processing with cardioids. While their performance under idealized conditions was not as good as adaptive methods (e.g., MVDR), their application is data-independent and just as fast as linear processing algorithms. Thus, these new processors may be useful for real-time applications with many sensors or in cases where signal/noise stationarity degrades the performance of adaptive methods.

The theoretical work performed on the modal intensity field suggests promising new ways to exploit the information gained from vector sensors for environmental assessment. Additional work is required, however, to determine the applicability of such methods to real data sets in real environments.

RELATED PROJECTS

Work on the processing of data from arrays of vector sensors is being carried out by various groups under the framework of the ONR-funded PLUSNet program, among others.

New inversion algorithms that incorporate vector field information are also being co-developed with colleagues at the Royal Netherlands Naval College and the Université libre de Bruxelles, supported under an ONR-G NICOP.

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