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Acoustic Blind Deconvolution and Unconventional Nonlinear Beamforming in Shallow Ocean Environments

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LONG-TERM GOALS

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain, partially known, or unknown ocean environments. During the last year, this project has focused on further determining the utility of a fully passive propagation-physics-based technique for blind deconvolution of array-recorded sounds from a remote source with emphasis on determining how sparse-array measurements might be used for this task, and how source-to-array range information can be robustly extracted from the deconvolution process.

The long term goals of this project are: *i*) to determine the effectiveness of synthetic time reversal (STR) for the purposes of blind deconvolution in noisy unknown ocean sound channels, *ii*) to effectively apply STR to marine mammal sounds recorded in the ocean with vertical and/or horizontal arrays, and *iii*) to utilize the STR-estimated signals and ocean-sound-channel impulse responses to classify, localize, and/or track individual marine mammals (or other sound sources) of interest. Progress this year has primarily been made toward goals *ii*) and *iii*).

OBJECTIVES

Since early 2009 this project has focused on developing an acoustic-ray-based version of synthetic time reversal (STR), a fully-passive technique for recovering the original signal and the source-to-array-element impulse responses for a remote unknown sound source in an unknown underwater waveguide [1,2,5,6]. The current specific objectives are to: a) simulate the performance of STR and frequency difference beamforming for different signal-to-noise ratios, array sizes, array element numbers, environmental conditions and signal frequencies and bandwidths, *b*) obtain and process relevant underwater array recordings of remote-but-cooperative sound sources, and *c*) obtain and process marine mammal vocalizations for the purposes of marine mammal localization, tracking, and identification. This research effort extends the prior mode-based version of STR [1] to higher frequencies, smaller receiving arrays, sparse receiving arrays, and sound channels with modal dispersion.

APPROACH

Over the last year, this project has focused on understanding and processing acoustic array measurements from two different sets of underwater sound measurements to determine the capabilities and limitations of STR and two unconventional nonlinear beamforming techniques. The bulk of this research is contained in the Ph.D. thesis of Dr. Shima Abadi, which she successfully defended during the summer of 2013. Two new graduate students, Ms. Jane Kim and Mr. Brian Worthmann (both US citizens), have been attracted to this research project.

The first data set, the primary focus of this year's work, contains natural bowhead whale calls recorded with a 12-element vertical array in the Arctic Ocean off the north coast of Alaska. This data set was collected and shared with this research project by Dr. Aaron Thode of Scripps Institution of Oceanography. The whale call frequencies range from 50 to 500 Hz, and the water depth at the experimental site was approximately 55 meters. The approximate sound channel characteristics are shown in Fig. 1. Modal propagation under these circumstances is dispersive. The purpose for examining this data set was to determine if STR might beneficial for efforts to monitor marine mammals. To fully understand and utilize this data set, Dr. Abadi spent May through August of 2012 at SIO as a visiting graduate student working directly with Dr. Thode. Since then, she and Dr. Thode have continued to collaboratively investigate the performance of STR and conventional mode filtering for ranging the recorded whale calls.

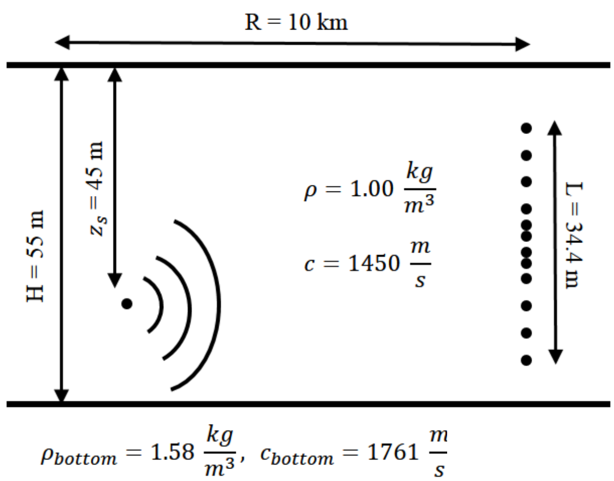

Figure 1. Arctic ocean sound channel used for simulations of the whale call recordings. The signal frequency range (50 Hz to 500 Hz), channel depth (~55 m), and the bottom properties lead to dispersive modal propagation in this ocean environment. Here the source depth, source range, and source signal are all unknown. However, whale-call-to-array ranges can be estimated from a simple model of the sound channel and the vertical array recordings corrected for modal dispersion.

The second data set received less attention than the first. It comes from a laboratory cylindrical-water-tank experiment (1.07 m diameter and depth) supported by NAVSEA through the Naval Engineering Education Center (NEEC) and involves three-dimensional multipath propagation (reverberation), signals in the 30 kHz to 120 kHz bandwidth, and recordings from a 16-element receiving array (sampled at 1 MHz per channel). The technical goal with this data set is to determine the performance of STR and the nonlinear beamforming techniques with a near-field source, variable array geometry, and fully three-dimensional reverberation.

WORK COMPLETED

The status of the investigations with the two data sets is as follows.

The research work with the marine mammal data set for robust remote whale-call ranging with a partial-water-column-spanning vertical array is nearly complete. This effort includes side-by-side quantitative comparisons between ranging techniques based on: (*i*) conventional mode filtering of vertical array measurements, (*ii*) STR applied to vertical array measurements, and (*iii*) azimuthal direction finding from directional autonomous seafloor acoustic recorders (DASARs). At the present time a total of 20 naturally-occuring whale calls have been considered, and these cover call-to-array ranges of 7 to 35 km. Both vertical array ranging techniques involve fitting and estimation steps that compensate for dispersion in the modal propagation in the ocean environment. This effort also involves companion simulations that have been used to better understand the ranging-accuracy limitations found from the measured whale-call data. A full-length journal manuscript covering these results should be submitted to *J. Acoust. Soc. Am*. during the fall of 2013.

The initial research work with the laboratory tank data was undertaken to determine the performance of spherical-wave frequency-sum beamforming, an unconventional technique that can improve the spatial resolution of conventional beamforming under ideal circumstances [3]. When combined with simulation work involving multipath propagation, a final understanding of frequency-sum beamforming's utility has been determined. A letter-to-the-Editor length manuscript covering these results is now in the final proof reading stage before submission to *J. Acoust. Soc. Am*. – *Express Letters*.

RESULTS

To date, this investigation has determined the following about remote whale call ranging using a partial-water-column-spanning vertical array in a dispersive sound channel.

First, an approximate dispersion correction can be determined based on the array-recorded signals alone, and this correction allows the whale-call-to-array range, R, to be estimated. The process involves several steps. To begin, the original whale call waveform is reconstructed from conventional mode filtering or from STR using two different modes, typically modes 1 and 2. Then, these two estimated waveforms are repeatedly cross correlated with a varying correction phase, $2\pi\Delta_{12}/\omega$, that is inversely proportional to frequency. Grachev [4] found that the difference between horizontal wavenumbers, k_2 and k_1 for example, in a dispersive waveguide is proportional to $\omega^{-1/\beta}$, where β (the *waveguide invariant*) is close to unity for waveguides defined by reflecting boundaries (i.e. most shallow water waveguides). The correction phase that yields the maximum cross correlation between reconstructed signals must be proportional to the source-array range: $(k_2 - k_1)R \approx 2\pi\Delta_{12}/\omega$. Thus, an estimate of the source-array range is obtained by minimizing the means square error (MSE) between the two sides of this approximate equality over the bandwidth of the whale call when where k_1 and k_2 are determined from a simple range-independent acoustic model of the environment. Plotted simulation results for these two data reductions steps for conventional mode filtering and STR are shown in Figure 2 for the 1-2 mode pair and the 2-3 mode pair for a synthetic 60 Hz to 300 Hz whale call from a depth of 45 m and a range of 10 km.

Second, the ranging techniques based on conventional mode filtering (CMF) and STR have been found to be reasonably robust and accurate when compared to established techniques based on triangulation from multiple bottom-mounted sensors (DASARs) that individually determine the azimuthal direction of the whale call. A selection of results from the whale call recordings is provided in Table 1. Here the DASAR-based technique is considered to be the most reliable, and the other two techniques provide results that are generally within ±10% of the DASAR-determined ranges. However, throughout this investigation, STR provided slightly superior performance in terms peak cross correlation coefficient (CCC), robustness, and accuracy when compared to CMF.

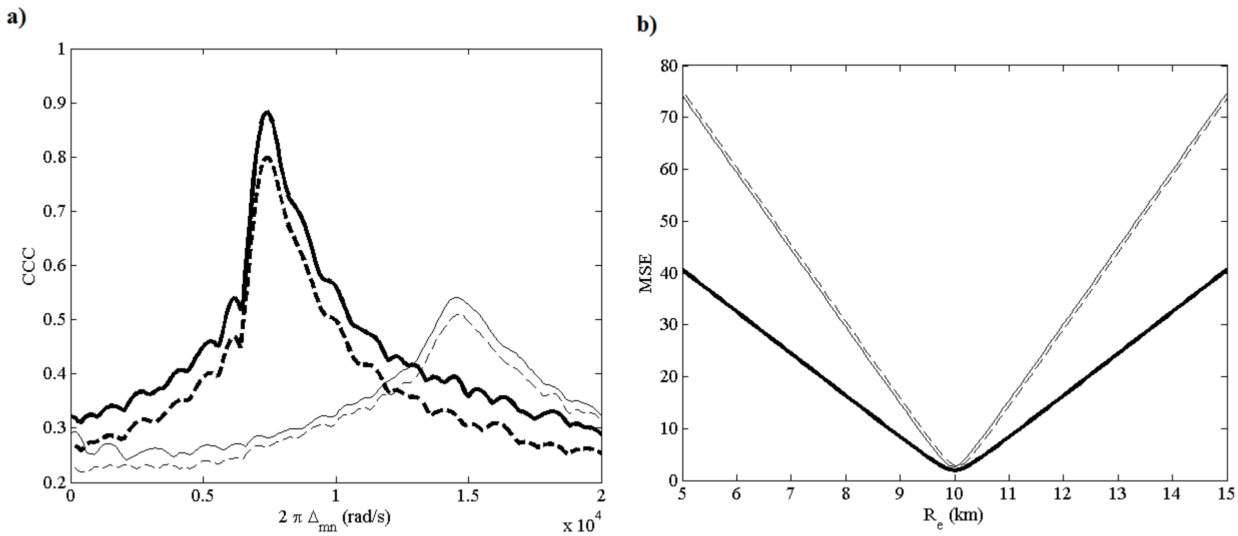

Figure 2. Conventional mode-filtering (dashed lines) and synthetic time reversal (solid lines) for simulations using the sound channel of Fig. 1 for a 60 Hz to 300 Hz synthetic whale call at 45 m depth and 10 km range. (a) Cross-correlation coefficient between mode-1 and mode-2 estimates of the whale call waveform vs. the fitting constant Δ_{12} (thick lines) and between mode-2 and mode-3 estimates of the whale call waveform vs. the fitting constant Δ_{23} (thin lines). Clear maxima occur in both sets of curves and both sets correctly indicate the range via their minimum mean-square error (MSE). STR produces a slightly higher cross-correlation coefficient than conventional mode filtering.

Table 1. Selected whale call ranging results from conventional mode filtering (CMF), synthetic time reversal (STR), and multiple directional sensors (DASAR). Overall the three techniques generally agree within their associated uncertanties, even when the peak cross correlation coefficient (CCC) values are near, or even below, 50%.

call #	Recorded time at the vertical array on 31-Aug-2010	Bandwidth (Hz)	SNR (dB)	CMF (km)	STR (km)	DASAR (km)	Peak CCC CMF (%)	Peak CCC STR (%)	Modes
13	01:00:56 a.m.	80-420	8.0	7.9±0.7	5.9±1.3	7.1±1.0	37.7	44.1	2&3
14	01:01:12 a.m.	140-240	12.4	7.7±1.3	10.6±1.2	10.2±3.2	54.2	55.3	2&3
15	01:24:19 a.m.	180-400	16.1	17.4±1.3	16.8±0.4	16.0±2.8	58.9	61.2	1&2

The investigation of frequency-sum beamforming, an unconventional high-resolution array-signal processing technique, initially provided positive results in a simulated single-path environment and when using direct-path laboratory-water-tank acoustic measurements. However, the next research step involved simulations of multipath environments and these clearly indicated that frequency-sum beamforming is flawed. Sample results that compare conventional plane-wave beamforming and frequency-sum beamforming are shown in Fig. 3 for a simple scenario when a 600 to 900 Hz chirp signal arrives at a linear vertical array with 16-elements from two nearby angles: θ = 0.0° and 3.1°. Here, conventional plane-wave beamforming, Fig. 3a) and the dashed curve in Fig. 3c), produces correct and useful results. Peaks in the beamformed output indicate the angles of the two arrival paths. For exactly the same scenario, frequency-sum beamforming, Fig. 3b) and the solid curve in Fig. 3c), does produce two narrower peaks at the correct arrival angles (0.0°, 3.1°), but it also produces a strong fictitious peak at 1.5°.

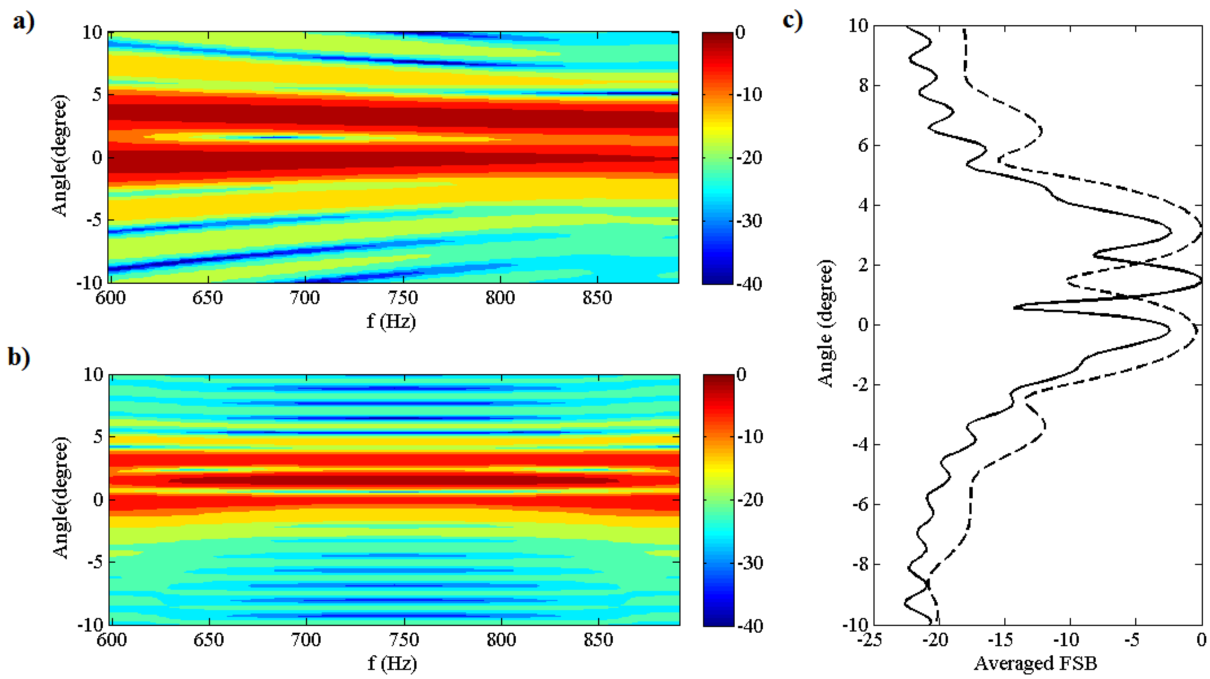

Figure 3. (a) Conventional plane-wave beamforming of the simulated chirp signal as a function of beam steering angle θ and frequency in the signal bandwidth (600-900 Hz) in dB scale. (b) Same as (a) except this is for frequency-sum beamforming for a sum frequency of 1.5 kHz. (c) Conventional plane-wave beamforming (dashed line) and frequency-sum beamforming (solid line) results from the simulated signals integrated over the signal bandwidth, 600 Hz ≤ f ≤ 900 Hz, vs. beam steering angle θ. The angular range of all panels is ±10° to highlight beamforming results near θ = 0° and θ = 3.1°. Here, frequency-sum beamforming produces an artificial peak between the two actual arrival angles.

Additional multipath simulations (not shown here) indicate that the fictitious peak problem shown in Fig. 3c) gets worse with an increasing number of propagation paths. Thus, frequency-sum beamforming need not be further pursued or developed for underwater sound applications. However, its counter part, frequency difference beamforming [6], which was the focus of this project in FY12, remains of interest.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when environmental information is absent, incomplete, or uncertain. The capabilities of future Naval sonar systems will be enhanced when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research effort into the effectiveness and utility of STR and unconventional beamforming schemes may eventually impact how transducer (array) measurements are processed for detection, classification, localization, tracking, and identification of remote unknown sound sources. In particular, the novel marine mammal ranging techniques described here may aid in the continuing efforts to monitor marine mammals and thereby streamline the permitting process for active underwater acoustic experiments and other tests.

TRANSITIONS

The results of this research effort should aid in the design of sonar signal processing tools for tactical decision aids. However, at this time no direct transition links have been established with more applied research or development programs. Past Navy contacts for blind deconvolution with Dr. George B. Smith (NRL-SSC, retired) and Dr. Steve Finette (NRL-DC) are no longer active in this research area. The search for a transition path through NRL or one of the Navy's Warfare Centers continues.

RELATED PROJECTS

This project currently uses acoustic array recordings of sounds that propagated through the ocean. In FY13, Dr. Aaron Thode of SIO shared acoustic array data collected in the Arctic Ocean that includes man-made and marine mammal sounds. The use of blind deconvolution and noise-reduction techniques for the recovery of free-field sound source signatures, sound levels, and transfer functions from measurements made in reverberant laboratory test facilities is also of interest for hydro-acoustic testing at the Naval Surface Warfare Center - Carderock Division which is supporting the UM NEEC acoustics student team and the laboratory water-tank experiments mentioned above.

REFERENCES

[1] Sabra, K.G., and Dowling, D.R. 2004, “Blind deconvolution in ocean waveguides using artificial time reversal,” *Journal of the Acoustical Society of America*, Vol. 116, 262-271.

[2] Sabra, K.G., Song, H.-C., and Dowling, D.R. 2010 “Ray-based blind deconvolution in ocean sound channels,” *Journal of the Acoustical Society of America – Express Letters*, Vol. 127, EL42-EL47.

[3] Abadi, S.H., Van Overloop, M.J., and Dowling, D.R. 2013 “Frequency-Sum Beamforming in an Inhomogeneous Environment,” presented at the 165th Meeting of the Acoust. Soc. Am., Montreal, Canada.

[4] Grachev, G. A. 1993 "Theory of acoustic field invariants in layered waveguides," *Acoust. Phys.,* Vol. 39, 67-71.

PUBLICATIONS

[5] Abadi, S.H., Rouseff, D., and Dowling D.R. 2012 "Blind deconvolution for robust signal estimation and approximate source localization," *Journal of the Acoustical Society of America* Vol. 131, 2599-1610.

[6] Abadi, S.H., Song, H.-C., and Dowling D.R. "Broadband sparse-array blind deconvolution using frequency-difference beamforming," *Journal of the Acoustical Society of America* Vol. 132, 3018-3029.

HONORS AND AWARDS

Prof. Dowling was elected Fellow of the American Physical Society in November 2012.