Performance of Self-Adaptive Techniques for Multi-Static, Concurrent Detection, Classification and Localization of Targets in Shallow Water Using Distributed Autonomous Sensor Networks.

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LONG TERM GOALS

To develop coherent space-time-frequency processing algorithms to enhance the multi-static concurrent detection, classification and localization of proud and buried targets in shallow ocean waveguides using distributed autonomous sensor networks.

BACKGROUND

In the context of low-frequency active SONAR, a key interest for MCM applications is the ability to identify acoustic echoes from man-made targets (eg. elastic shell) from ocean reverberation (e.g. due to bottom or volume scattering) and ambient noise, especially in the presence of multipath8. In particular, time-frequency analysis has been shown to be a relevant tool for the acoustic detection and classification of elastic shells. Furthermore, the development by the Navy of MCM sonar systems, using a network of autonomous systems in unmanned vehicles, provides a practical means for bistatic measurements (i.e. when the source and receiver are widely separated) allowing for multiple viewpoints of the target of interest. Such systems can potentially yield bistatic enhancement for detection and classification capabilities when compared to traditional monostatic systems (i.e. where the source and receivers are co-located or closely spaced). Consequently, in order to design optimum receiver and signal-processing algorithms for such bistatic SONAR systems, it is then fruitful to further understand the spatial and temporal variations of the bistatic acoustic scattering responses of elastic shells.

The physics of acoustic scattering from elastic shells with simple shapes, such as spheres or infinite cylinders, has been extensively studied both theoretically and experimentally. In particular, a fluid loaded and thin spherical shell produces a specular or direct reflection (similar to any acoustically reflective object of comparable shape) as well as guided waves (or Lamb waves) circumnavigating the shell. Consequently, for traditional monostatic systems, a key energetic feature of spherical shell is the mid-frequency enhancement echo (MFE)-also called the coincidence pattern- that is created by the coherent addition of the first antisymmetric Lamb waves (A0 mode) propagating clockwise and counterclockwise around the shell (see Fig. 1). This MFE yields energetic acoustic echoes radiating in the surrounding fluid and thus provides a unique acoustic signature of the fluid loaded and thin shells, as previously demonstrated theoretically and experimentally. Most time-frequency analysis of the MFE have focused on source-receiver configuration closed to monostatic (i.e. when source and receiver are close in azimuth with respect to the shell's centroid) where the MFE is most energetic. But the MFE persists for bistatic configurations and thus still carries information about the physical features of the elastic shell (see Fig. 2). However, a practical challenge is that the amplitude of the bistatic MFE is significantly reduced when compared to monostatic measurements, which render its detection more difficult in the presence of high clutter or ambient noise levels. Consequently, bistatic detection of the MFE would need be enhanced for instance by combining the signals measured on an array of receivers using array beamforming techniques. But, the design of an optimal beamformer for MCM applications should then be determined by the speci_c time-frequency coherence of the bistatic MFE echoes in order to allow for a fully coherent addition of these echoes across a bistatic aperture.

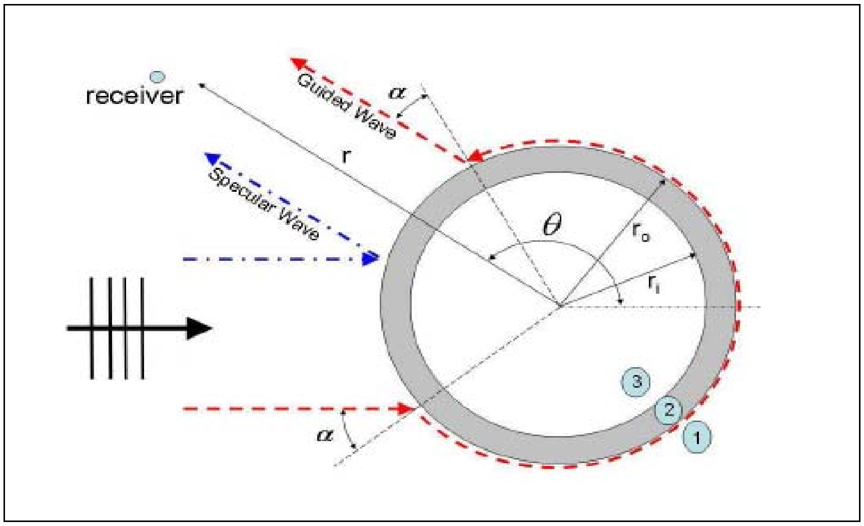


Fig. 1 *Schematic and ray diagram for the acoustic scattering problem under consideration. A plane-wave broadband pulse is incident from the left on a thin empty spherical shell in water (modeled as a three layers problem). The ray diagram is also displayed for the specular reflection (dash dot line), and surface guided waves (dashed line) circumnavigating the shell and giving rise to the mid-frequency enhancement echo. The surface guided wave couples into the shell's wall at angle* α *measured from the normal direction to the shell's wall - and radiates out towards a bistatic receiver (located at a distance r and azimuthal angle* θ *) at the same angle* α*.*

APPROACH

This research work has investigated theoretically and numerically the bistatic variations of the MFE for a fluid loaded and thin spherical shell. This canonical target shape was selected as its acoustic scattered field and echo generation mechanism is well understood. The acoustic scattered _eld is computed here from a modal expansion whose coefficients are determined by the shell's physical properties and appropriate boundary conditions at the fluid interface using the classical formulation of Goodman and Stern (JASA, 1969). The time-frequency analysis of the most energetic bistatic echoes, associated with the circum--navigating anti-symmetric Lamb waves, is performed using the Wigner-Ville transform. The main contribution of this work is to quantify the dependence of the time-frequency shifts of the MFE on the bistatic receiver angles and explain the observed time-frequency shifts using a previously derived quantitative ray theory for spherical shell's scattering by Zhang and Marston (JASA 1993). Additionally, the advantage of an optimal array beamformer based on joint time delays and frequency shifts of the bistatic MFE arrival (over a conventional time-delay beamformer) is illustrated for enhancing the bistatic detection of the MFE for spherical shells.

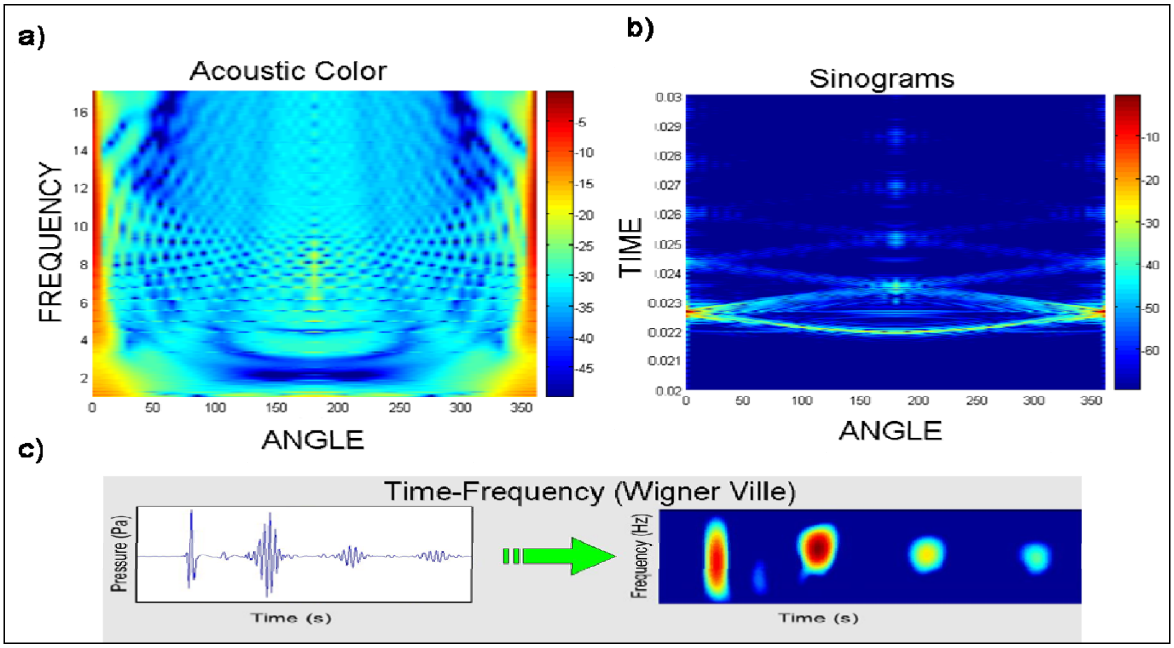


Figure 2: *a) Bistatic response of an elastic shell (shell is 1m diameter, 1.5 cm thick steel) in the frequency-angle domain ("Acoustic color"). The angular variable measures the angular spacing between the source and receiver location. Note the stong coincidence pattern at $\Theta=180^{o}$ (monostatic direction). b) Time-angle representation of the same bistatic response ("Sinogram"). The first wavefront correspond to the specular echoe and is followed by successive wavefronts corresponding the shell elastic resonances (S0,A0) circling around the shell. c) Time-frequency analysis of the backscatter response of an elastic stell (monostatic response, i.e. $\Theta=180^{o}$). Note the various strong resonances (narrowband) appearing beyond the firstg broadband specular echo. The locations of these resonances vary in the time-frequency plan*

WORK COMPLETED

A space-time-frequency analysis allows understanding the echo formation mechanisms and their bistatic evolution, as illustrated for instance in Fig .2-4. Most importantly the energetic coincidence pattern (resulting from the interactions of A0+ and A0- waves) appears to vary in the time-frequency plan when bi-static receiver angles changes. This occur since the A0+ and A0- waves shift and separate as path lengths to the receiver vary for bi-static receiver angles (see Fig.1- 2). A simple quantitative ray theory (developed by Zhang and Marston-JASA 1993) can be used to predict these observed time-frequency shifts of the MFE arrival, which primarily results from the combined effect of 1) the bistatic variations of the path length around the spherical shell of the clockwise or counter-clockwise circumnavigating A0 waves, and 2) the frequency dependence of the radiation damping parameter for the A0 wave (see Fig. 4).

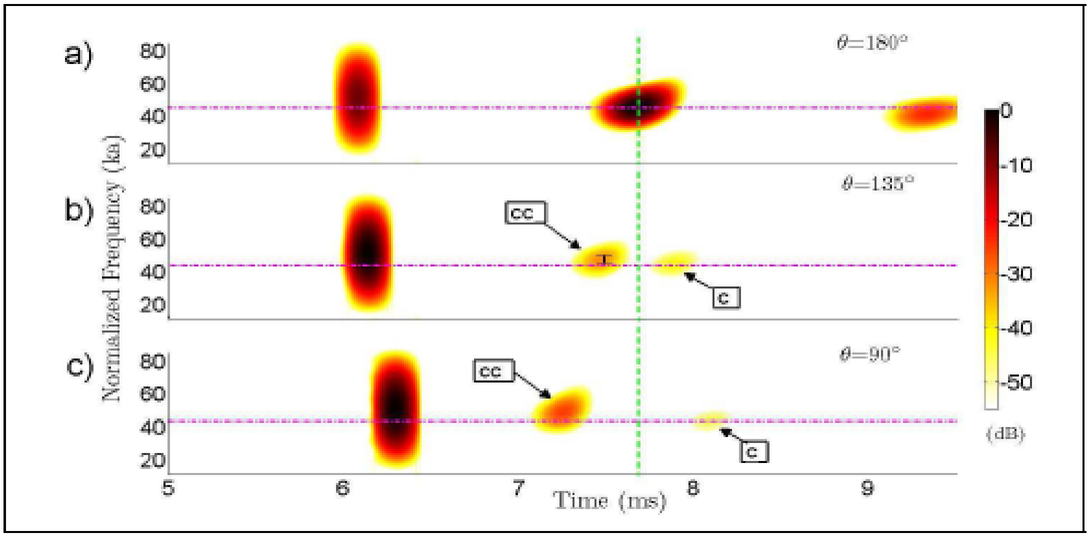


Figure 3: *Splitting of the bistatic time-frequency signature of the elastic shell in two patterns (#1 and #2) corresponding to the two coherent interference of A0+ and A0- waves when their path lengths around the sphere vary (bistatic configuration). Measurements of time-delay and frequency shift of the coincidence pattern vs. bistatic angle.*

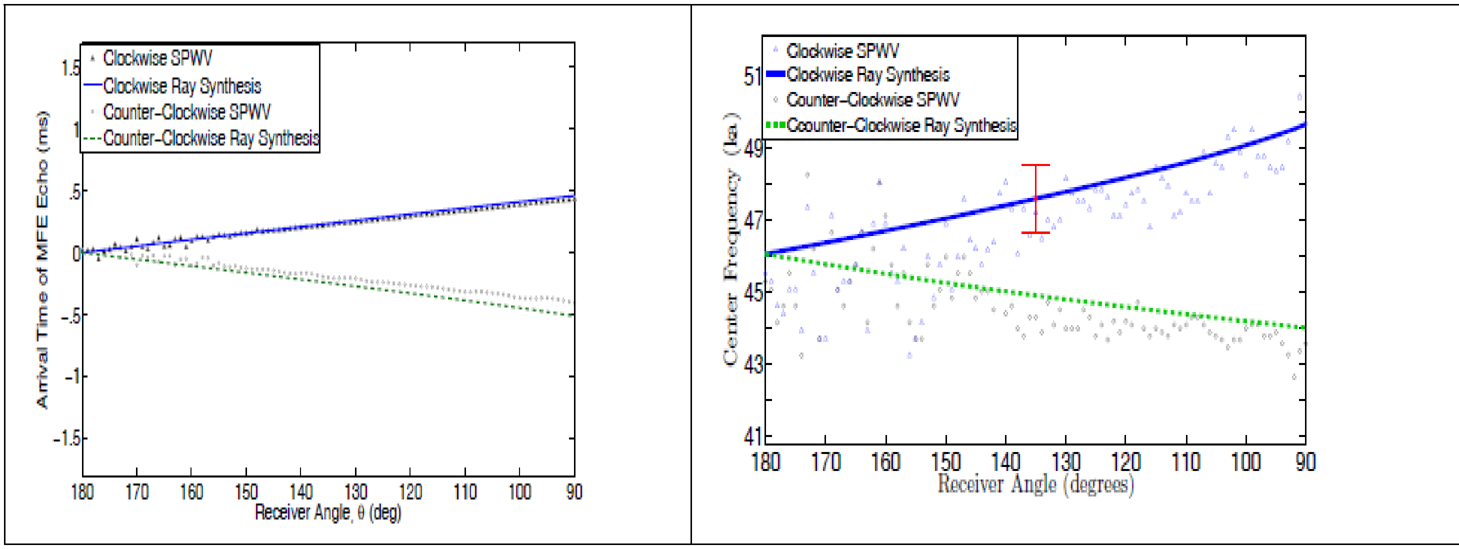
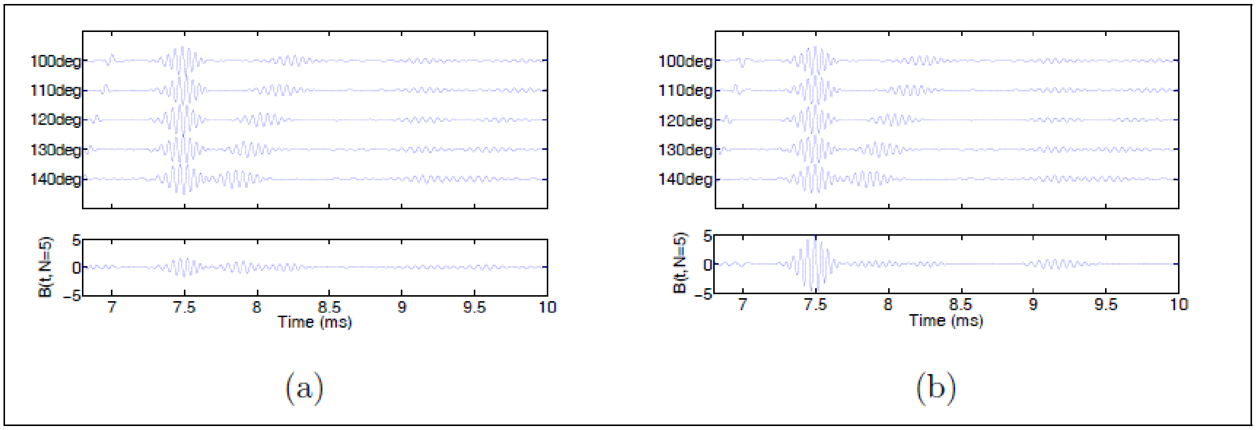


Fig. 4 *Variations of the arrival time of MFE echo vs. bistatic receiver angle with respect to the monostatic arrival time of the MFE (i.e. θ = 180deg). The triangle and circle symbols indicate the measured arrival time for respectively the clockwise and counter-clockwise A0 wave using the local maxima in the time-frequency plane of the smoothed pseudo-Wigner-Ville representation of the bistatic scattered field (see Fig. 3). For comparison, the solid and dashed lines correspond to the arrival-times predicted from the ray synthesis for the same clockwise and counter-clockwise A0 waves. (b) Same as, but showing instead the variations of the normalized center frequency of MFE echo (i.e. coincidence frequency) vs. bistatic receiver angle θ (see geometry in Fig. 1) with respect to the monostatic center frequency of the MFE (i.e. θ = 180deg. The error bar depicts the measurement resolution along the frequency axis on the SPWV representation, which accounts for most of the spread in the measured values.*

The sinogram displayed in Fig. 2 shows that the MFE persists for bistatic source- receiver configurations, and thus still carries information about the physical features of the elastic shell. However, the bistatic amplitude of the A0 wave arrival is significantly reduced compared to the monostatic configuration. Consequently, bistatic detection of this thin spherical shell could potentially be challenging in the presence of high clutter or high ambient noise levels. Therefore, bistatic detection of the MFE would need to be enhanced for practical implementations. To do so, it is necessary to use a generalized time-frequency beamformer to account for the time-frequency shifts occurring between the various bistatic A0 wave echoes recorded on array of sensors surrounding the spherical shell (see Fig. 5). This generalized time-frequency beamformer can be implemented using a similar formalism developed for compensating wideband Doppler effects when tracking a fast moving acoustic source based on companded (or time-scaled) replica of the Doppler-free source signal. The term “companded" is a portmanteau of compressed and expanded.



(a)

(b)

FIG. 5. (a) *Upper Panel: Stacked representation of the time-aligned arrivals of counter-clockwise propagating A0 waves recorded at five different bistatic angles. The relative bistatic time-shifts, with respect to first bistatic angle θ= 100deg were obtained from the SPWV analysis (see Fig. 4). Lower Panel: Coherent addition of the five time-shifted waveforms using a conventional time-delay beamformer (i.e. when setting the companding parameter as j = 1- see Eq. 8). (b) Upper Panel: same as (a), but each waveform was also companded to account for the apparent frequency shift of the bistatic counter-clockwise propagating A0□arrival-with respect to the first bistatic angle θ= 100deg -based on the measured frequency-shifts values from the SPWV analysis (see Fig. 4). Lower Panel: Coherent addition of the five time-frequency shifted waveforms using a generalized time-frequency beamformer. Note that each bistatic waveform, in both upper panels, was normalized to its maximum, such that one would expect a maximum beamformer output of 5 when an optimal coherent addition of these waveforms is achieved.*

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IMPACT

This work is focused on developing potential MCM procedures to improve multi-bistatic concurrent Detection, Classification and Localization of elastic target by investigating the full space-time-frequency coherence of their echoes. This study should provide valuable insights to guide the design of optimal receiver architecture for low-frequency bistatic SONAR systems (e.g. using distributed sensor networks) and SAS imaging algorithms.

PUBLICATIONS

S. Anderson, K.G. Sabra, M. Zakharia “Time-frequency analysis of the bistatic acoustic scattering of spherical elastic shells” Submitted to JASA, October 2010.