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Exploitation of frequency information in Continuous Active Sonar

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Abstract

In pulsed active sonar, short duration coded waveforms insonify the area of interest. The low duty cycle limits detection opportunities and decreases average energy. A recent concept is continuous active sonar (CAS), which has continuous source transmission over a broad frequency band. The low duty cycle limits detection opportunities and decreases average energy. A recent concept is continuous active sonar (CAS), which has continuous source transmission over a broad frequency band. Previous work by the authors has investigated the utility of extracting the propagation-induced frequency structure in pulsed sonar. The broadband, continuous CAS waveforms particularly lend themselves to this approach. The presence of active striations in CAS data has been recently identified in the shallow water Target and Reverberation Experiment (TREX13). In this paper we provide additional examples of frequency structure in both the TREX13 and simulated data, and discuss methods for exploiting the striations to improve tracking performance.

Keywords: Active sonar, array beamforming

1 Introduction

A recent topic in the underwater acoustics processing community has been the exploitation of propagation structure to enhance detection, localization, and tracking. Data recorded from an underwater source propagating in a shallow water channel can show intensity structure related to the acoustic frequency structure relative to source range. A particularly useful formulation is the waveguide invariance equation which – as the name implies – is roughly invariant for a broad range of propagation environments. Use of the invariance relation has typically been developed quite extensively for application to passive acoustic data, but it is only recently that the concept has been demonstrated to apply to active data []. Algorithms have been developed to exploit the structure for improved tracking [] and striation beamforming. More recent work has begun to explore the use of limited horizontal aperture (i.e., a physical array) to capture striation patterns, and some understanding of the system constraints have been presented [].

In this work, active invariant structure is examined for the new Continuous Active Sonar (CAS) waveforms. These waveforms have an advantage of constantly illuminating a target with a continuous frequency sweep []. The time-dependent frequency structure of the waveform increases the complexity of the processing, since the target returns cannot be easily isolated with a time-delay or frequency band processing approach [].

This paper presents simulation results for the Target and Reverberation Experiment (TREX13). Data results for TREX13 were previously published [], [] with the observation that not all of the CAS data showed an easily recognizable striation structure and that – unlike other active data sets – the structure did not appear sloped in the frequency/range target spectrograms. To understand the physical mechanisms influencing the striation patterns, subsequent work employed propagation models to reproduce the effects observed in the data. Results of those simulations are provided here.

2 Active Striations

As stated in the introduction, the concept of a waveguide invariant has received considerable attention in recent years, first as a method to improve passive processing and – more recently – suggested for use in active systems to improve clutter discrimination and track filtering. An important difference in the application of the active invariant (relative to passive sonar) is that relatively few samples are acquired over time because Pulse Repetition Intervals (PRIs) are typically on the order of minutes. This has a notable impact, because the invariant structure is typically exploited by processing time-frequency data (for example, to confirm a hypothesis of a target range profile and this can be difficult with data that has poor resolution in the time domain. One solution to address this challenge is to directly observe the change in the intensity structure across an array aperture. The appearance of this structure will depend critically on the aperture attributes, which is quantified in the following section.

2.1 Array length and striations

A given array length can be expressed in wavelengths as,

$$L_\lambda = N d_\lambda \cos\theta_t \tag{1}$$

Where N is the number of hydrophones, $d\lambda$ is the phone spacing in wavelengths, and is the target bearing, θ_t.

For active sonar, the striation slope in the phone-frequency spectrogram of an array can be expressed, in Hz/wavelength, as

$$\frac{\Delta_f}{L_\lambda} = \gamma\left(\frac{c}{2R_t}\right) \tag{2}$$

Where Δ_f is the change in frequency along the array and $L\lambda$ is calculated from the array length and target bearing. In (2), g is the waveguide invariant, R_t is the target range and c is the sound speed. In shallow water the waveguide invariant is approximately 1, but the absolute value of the waveguide invariant can be much larger in the deep ocean. Therefore, (2) indicates that, all other factors being equal, the change in frequency, Δf, along the length of the array will be smaller in shallow water environments. It will also be reduced when L_λ is small, which is true if there are relatively few phones and/or the target bearing is far away from endfire. The striation slope will be larger at shorter ranges and smaller at more distant ranges. The region in which target echoes can be extracted from active sonar data is bounded by reverberation from the direct arrival and the signal-to-noise ratio of the echo signal at distant ranges.

2.2 TREX13 experiment

The 2013 TREX experiment [] was conducted approximately 3 km from the coast of Florida near Panama City, as shown in Figure 1. A monostatic sonar system was mounted to the sea floor in shallow water approximately 20 meters deep and powered by the research vessel (R/V) Sharp moored nearby. The sound source transmitted a number of PAS and CAS chirp waveforms, while the R/V CFAV Quest towed an echo repeater (E/R) along two different tracks. The Five-Octave Research Array (FORA) near the source was used to record the echo returns.

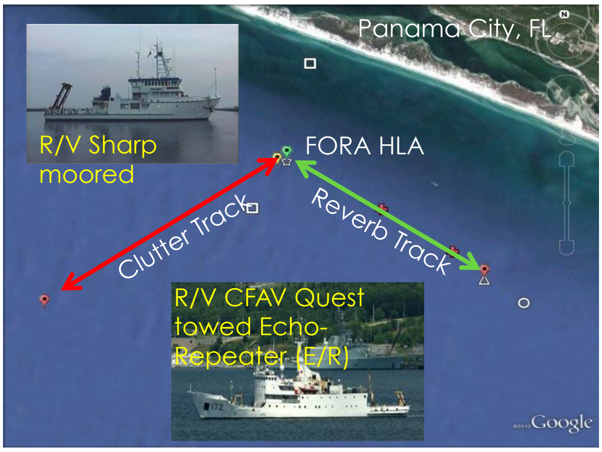

Figure 1: Map showing placement of the Five-Octave Research Array (FORA) horizontal line array (HLA) during the 2013 TREX data collection. The R/V Sharp collected monostatic sonar data from the HLA while R/V CFAV Quest towed an echo repeater (E/R) along the clutter and reverb tracks.

Figure 2 shows the target and array configuration during the 2013 TREX data collection. The FORA array was mounted 2 meters above the sea floor and oriented with endfire at approximately 353 degrees, while the E/R was towed along a reverb track at 130 approximately degrees and a clutter track at approximately 240 degrees.

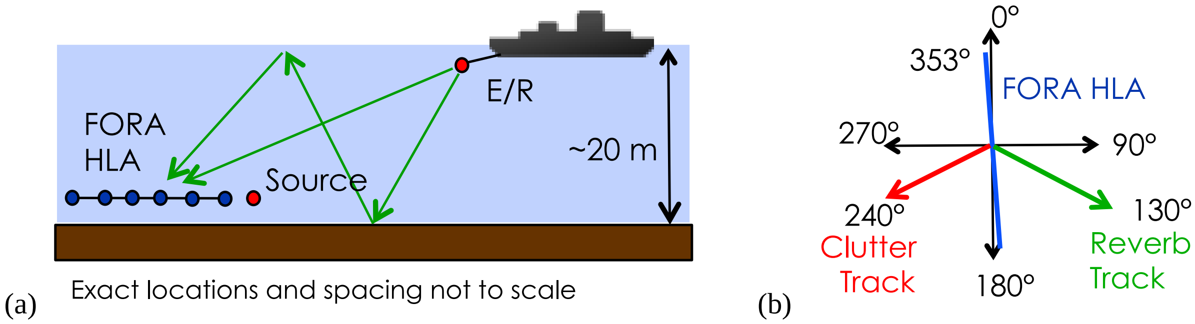

Figure 2: Diagrams showing configuration of the HLA during the 2013 TREX data collection.

The pulse repetition interval (PRI) was 20 seconds and the E/R was set to operate in “ping pong” mode, returning an echo ping in every other PRI. Two linear frequency modulated (LFM) up-chirps from 1800 – 2700 Hz were used for the analysis presented in this section, with the amplitude of the chirps set to provide equal energy in both pulses. The chirp duration and ship track were altered in a series of runs as shown in Table 1. The target strength of the E/R was reduced during runs 80 and 82 of the experiment. Results from runs 63, 65 and 67 are discussed in this section. The cardioid section of the FORA array consists of 78 triplets spaced 0.2 meters apart for a total length of 15.6 meters. However, only 48 of the triplets were operational during the experiment, reducing the effective length of the array to 9.6 meters. One of the three phones in each triplet was used for the processing presented in this section. Thus, the array length, L_λ, in (1) is maximum at endfire and approaches zero at broadside. For the TREX experiment, the length of the array when looking in the direction of the target was approximately 10.5 wavelengths during the reverb runs and 5.6 wavelengths during the clutter runs.

2.3 Simulations

As shown in [], plots of the intensity across the frequency band of the CAS waveform showed evidence of striation patterns. However, the structure did not appear as marked as previously observed in conventional pulsed active sonar data, and thus the need arose to investigate the propagation physics in the underwater channel.

A ray tracing model, Bellhop, was used to simulate Transmission Loss (TL) in the TREX environment. The known (approximate) echo-repeater depth of 5 meters and a receiver depth of 18 meters was used in the simulation. The channel was assumed iso-speed with a sound speed of 1500 m/s. The ray simulation was calculated for a single frequency, and then repeated for each frequency in the CAS transmission band. Although frequency content varies as a function of transmit time for the CAS waveform, the relative motion of source/receiver was negligible and was not part of the propagation simulation.

Results of the simulation are shown in Figure 3. The left-hand plot shows the predicted intensity structure as a function of source/target range over a 4 km extent. This range extent could either represent a source moving in time (with the range changing as function of the motion) or it could represent energy received by a long, array with horizontal extent. The plot clearly shows the frequency and range dependent structure introduced by the multipath propagation. Estimation of the invariance slope (β in the literature) gives a value of 1.2, which is quite close to the expected value of unity for shallow water channels.

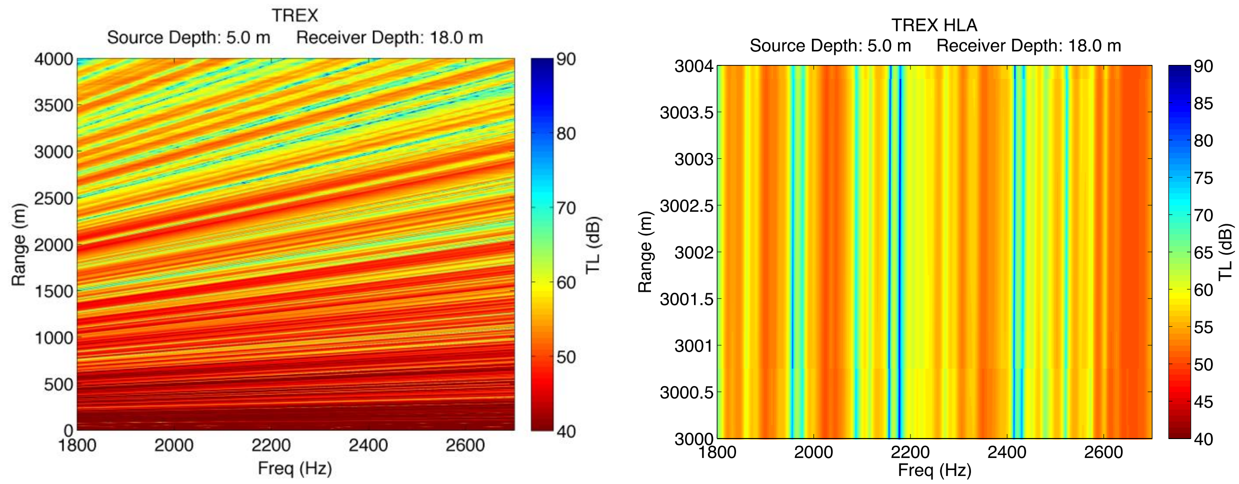

Figure 3: Ray propagation simulation for HLA with spacing equivalent to the TREX array. Left-hand side : range-frequency striations for 4000 meter separation. Right-hand side: Range extent of actual array (~ 4 meters) in which striations appear vertical.

The right-hand plot is an enlargement (zoom) in the region of 3 km, which corresponds to the actual source/receiver separation in the TREX data []. Not the range extent is much more limited (~4 m), and corresponds to the aperture length of the TREX data using (1). The striations in this limited range extent appear much more vertical. As discussed in [], the smaller aperture extent implies that conventional beamforming (as opposed to striation beamforming []) can used without “smearing” the striation patterns – reducing the complexity of the CAS processing chain considerably. The simulation results confirm the structure observed in the TREX data and provide further physical insight.

3 Conclusions

The acoustics signature observed in underwater environments is complicated by multipath propagation. Typically, the exact nature of this structure is difficult to predict, unless extensive knowledge of the underwater environment is known (sound speed profile, bottom type, etc.). The waveguide invariance provides a robust method of understanding the frequency-range variation of the acoustic intensity, and has recently been utilized in active sonar for enhanced tracking and localization.

The CAS waveforms are ideal for continuous broadband illumination appropriate for striation processing. A recent shallow water experiment, TREX, produced results showing striation structure which did not show the characteristic slope observed in previous data []. This paper presents simulations using a propagation model (Bellhop) to explain the striation structure, and provide quantitative measures for the array aperture and its correspondence to the structure.

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