IDENTIFICATION OF A RESONANT TARGET IN THE FREE FIELD AND BURIED IN A SEDIMENT USING ITERATIVE, SINGLE-CHANNEL TIME REVERSAL

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Abstract: *Numerical studies demonstrate enhanced signal-to-noise ratio and convergence to a narrowband signal using iterative time reversal of the monostatic scattered return from a resonating target [Pierson, David M., "Buried Object Detection Using Time-Reversed Acoustics," PhD Dissertation, North Carolina State University, 2003]. The center frequency of the converged-upon signal is a resonance frequency of the target whose value can be used for classification and identification purposes. This technique could offer a straightforward means for enhancing target return levels in a noisy or cluttered environment using existing sonar systems. We report results from scaled experiments performed in a water tank using broad band (Q~2) piston transducers operating in the 500 kHz – 2 MHz frequency range. The target is a 6.35-mm diameter hollow steel sphere suspended in the free field and buried at different depths in a medium-grain sand layer. The procedure consists of exciting the target with a broadband pulse, digitizing the echo return, reversing the data stream in time, and using this signal as the source waveform for the next interrogation pulse. Free field results indicate that the spectrum of the echo rapidly converges to a frequency corresponding to a resonant mode of the target. The signal to noise ratios of targets buried in sand are enhanced as the iterations converge to the strongest available target resonance.*

Keywords: *Time Reversal, Buried Objects, Matched Filter*

1. INTRODUCTION

The identification of targets resting on, and buried beneath, the seafloor is an important and challenging problem. Strong echo returns from the water-sediment interface, attenuation of sonar signals in the sediment, and the presence of coherent returns from clutter in the ocean bottom hinder the detection of buried targets. This paper investigates the application of single channel iterative time reversal to help mitigate the difficulties in buried object detection by exploiting target resonances in order to enhance the signal to noise ratio of backscattered echo returns.

The advent of time reversal in underwater acoustics took place in the mid 1960's with the development of the matched signal (MESS) processing technique, credited to Antares Parvulescu [1]. It was not, however, until the last two decades that the application of time reversal in acoustics began to proliferate [2 3]. Recent experiments have utilized time reversal to obtain the spatial focusing of acoustic energy in the oceanic waveguide over large distances [4 5]. The detection of submerged targets using time reversal has been examined in work by Gaumond *et al*. who were able to focus on and estimate the location of an echo-repeater suspended in shallow water during the TREX-04 experiments [6]. Schemes for the detection of targets resting on or buried beneath a sediment layer were investigated by Sabra *et al*. who used time reversal to enhance the level of the strongest scatterers in reflectivity maps of the ocean bottom [7]. These methods rely on the spatial focusing of acoustic energy through the use of an array of transducers, also known as a time reversal mirror.

Previous numerical results developed by Pierson [8] indicate that a form of iterative time reversal using a single-element transducer can increase the signal-noise ratio of a backscattered echo while simultaneously converging to a narrowband signal characteristic of the scattering target's dominant spectral response frequency. The technique, which is described below, automatically generates a matched filter for the spectral response of a target and does not rely on spatial focusing to generate an enhancement in return levels. This paper presents results from laboratory experiments in which Pierson's single channel iterative time reversal technique was applied to enhance the level of backscattered returns from targets in both the free field and buried beneath a layer of sediment.

2. MATERIALS AND METHODS

The iterative time reversal technique consists of exciting a target with a broadband pulse, digitizing the windowed echo return, reversing the data stream in time, and using this signal as the source waveform for the next interrogation pulse. If this process is performed iteratively, the level of a target's signature can potentially be enhanced while at the same time decreasing the level of coherent returns from clutter often present in the shallow water environment. The procedure is as follows:

1.) Interrogate the target with a broadband pulse.
2.) Sample, using a time-domain window, a portion of the return signal.
3.) Filter the return signal to account for the frequency response of the system, which is determined separately via a calibration procedure (see below).
4.) Reverse the temporal order of the windowed and filtered signal
5.) Transmit the new, time reversed, signal, where the transmit signal amplitude is normalized to a predefined maximum value.
6.) Repeat steps 1-5 iteratively.

Time reversal experiments were conducted in a water-filled test tank using a target (described below) suspended in the free field and buried beneath a layer of medium grained sand. The tank is made of aluminium and has internal dimensions 0.75 m wide x 2.40 m long x 0.57 m deep, appropriate for pulse-echo experiments in the frequency range of interest (0.5 – 2 MHz). The water was filtered and degassed nightly.

The setup of electronic instrumentation is depicted in Figure 1. Monostatic pulse-echo experiments were conducted, in which the same transducer was used to send and receive. Matlab was used to generate all outgoing waveforms and was interfaced with a GAGE D/A board, whose output was amplified, routed through a Ritec RDX-6 diplexer (also known as a transmit-receive switch), and sent to a 12.7-mm diameter Panametrics V-303 unfocussed broadband (Q ~ 2) piston transducer nominally centered at 1 MHz. The diplexer consists of a diode clamp, which prevents high amplitude signals from saturating the pre-amplifier in transmit mode, and a diode expander, which limits interference from broad band electrical noise generated by the power amplifier in receive mode. Received signals were low pass filtered below 2 MHz using an active filter/preamplifier. Waveforms were monitored in real time using an analog oscilloscope and a GAGE A/D board was used to digitize and store signals at a sampling rate of 25 MHz. A function generator clocked both the D/A and the A/D boards.

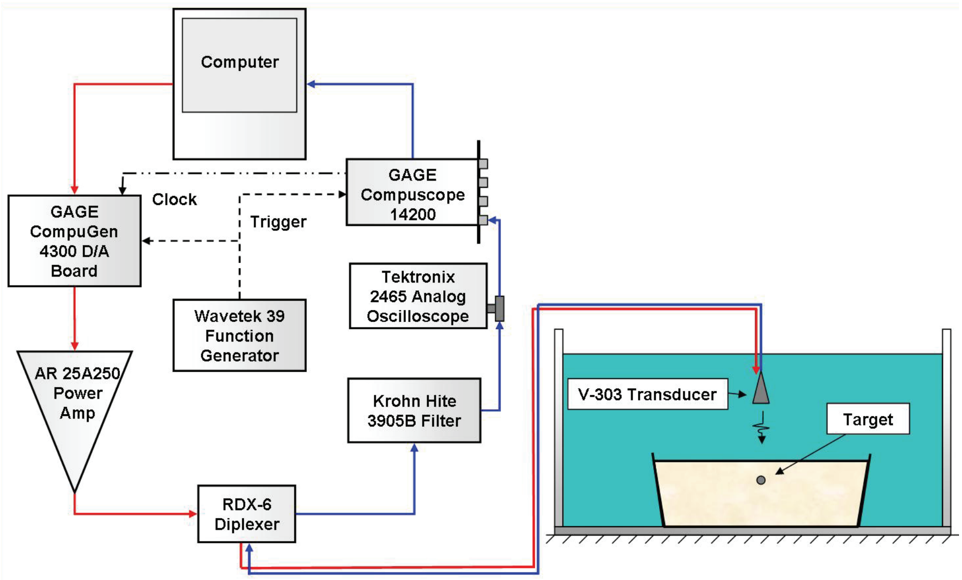

Fig.1: Diagram of experimental instrumentation. Experiments were performed both with the target suspended in the free field beneath a layer of transparent tape and buried in a tub of medium grained sand. This illustration depicts the configuration used for buried target experiments.

The target used in all experiments was a 6.35 mm outer-diameter hollow spherical shell made of aluminium 3003. The wall thickness was measured to be 0.28 mm, yielding a ratio of inner radius to outer radius of 0.91. This target was chosen based upon its strong resonances in the 0.5 – 1.5 MHz frequency range as predicted theoretically by a model developed by Hickling [9]. The target was positively buoyant and, for the free field experiments, was suspended beneath a horizontal strip of ~50 um thick Scotch 3170 polypropylene packing tape, which spanned the width of the tank. The tape was clamped between two acrylic holders on either side of the tank, and was determined to be acoustically transparent through pulse-echo measurements. The target was positioned at a distance of 10 cm from the transducer's face, which is beyond the Rayleigh distance (8.5 cm) for this transducer when driven at 1 MHz.

For experiments with a buried target, the sphere was wrapped in a thin layer of nylon and secured to the bottom of a plastic tub using a piece of monofilament line. The tub was then filled with a layer of medium grained sand, burying the target at a depth of 2.5 cm, corresponding to about 15λ at 1 MHz, based on a sediment sound speed of 1700 m/s.

3. TRANSDUCER CALIBRATION

In order for time reversal to converge to the dominant resonance of a target, the transducer used will ideally have a flat response in both send and receive so that its own resonant characteristics do not interfere with the time reversal operator's convergence. Most real transducers do not satisfy this requirement, therefore a transducer normalization method similar to the one employed by Feuillade *et al.* [10] was used to account for the combined send-receive response of the transducer. If we assume that scattering experiments can be described in terms of a linear time invariant system, the measured return from a scattering target in the frequency domain would be of the form

$$R_1 = T_S T_R S_T V \ , \tag{1}$$

where T_S [Pascal/volt] and T_R [volt/Pascal] are the frequency responses of the transducer upon acoustic transmission and reception, respectively, S_T is the non-dimensional backscatter response of the target, and V [volts] is the driving signal sent to the transducer. To determine the combined send-receive response, $T_S T_R$, the transducer is pointed vertically up at the free-water surface, a pulse V_0 is transmitted and a pulse R_0 reflected from the surface of the tank is received. An inverse filter, H, can then be generated from the transducer's response such that

$$H = \frac{1}{T_S T_R} = -\frac{V_0}{R_0}, \tag{2}$$

where the negative sign accounts for the 180° phase shift at the pressure release surface.

In order to avoid singularities due to small values of R_0 at certain frequencies, a Weiner filter [11] was applied such that

$$H = -\frac{V_0 R_0^*}{| R_0^2 | + \varepsilon}, \tag{3}$$

where ε is a small correction term. The inverse response was then exponentially extrapolated outside of the frequency range of interest, and a Yule Walker recursive digital filter design function in MATLAB was used to generate the coefficients of an infinite impulse response filter. The transducer response was then removed from measured echoes by application of the inverse filter. This allows the technique to be free to converge to the dominant backscatter mode(s) of the target.

The inverse filter was tested by pointing the transducer at the pressure release surface and transmitting a linear frequency chirp spanning 0.5 - 2 MHz, as seen in Figure 2a in the time domain and Figure 2b in the frequency domain. The backscattered return from the water surface is depicted in Figures 2c and 2d, along with the magnitude response of the inverse filter, which is the dashed line in Figure 2d. When applied to the backscattered waveform, the inverse filter normalizes the transducer's response, resulting in the waveform shown in Figures 2e and 2f, a return that one would expect to measure using a transducer with a flat frequency response.

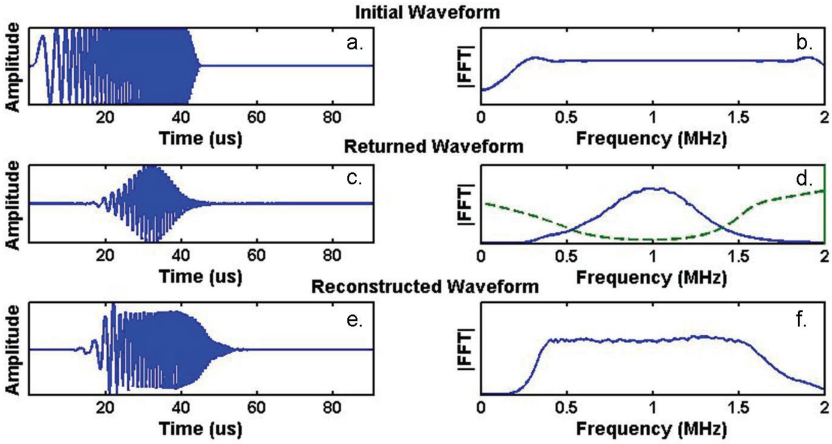

Fig.2: Waveforms and associated spectra from tests of the normalization procedure for the Panametrics V-303 unfocussed broadband (Q ~ 2) piston transducer nominally centered at 1 MHz. (a.) Linear chirp driving voltage sent to the transducer in which the transmitted pulse was directed normally at the pressure release water surface. (b.) Magnitude spectrum of (a). (c.) Transducer voltage for the first reflection from the pressure release tank surface. (d.) Solid line is the magnitude spectrum of (c) and the dashed line is the magnitude response of the inverse filter used in the transducer normalization procedure. (e.) Waveform (c) after application of the inverse filter. (f.) Magnitude spectrum of (e). The amplitudes for all plots are in arbitrary units.

4. FREE FIELD EXPERIMENTS

A linear frequency chirp spanning 0.5 – 2 MHz, depicted in Figures 3a and 3b, was used to interrogate the spherical shell target. The backscattered echo from the target is shown in Figures 3c and 3d. The return, after application of the transducer calibration, is depicted in Figures 3e and 3f, along with the inverse filter's magnitude response shown as a dashed line. The target's measured response possesses a number of strong resonances, which show qualitative agreement with an analytical prediction of the target's backscattered far-field acoustic form function (not shown).

In Figure 4 are shown the results of an experiment where 50 iterations of the time reversal procedure, outlined in Section 2, were performed with the time reversal window centered on echo returns from the target. Time domain signals for iteration 0 (the first backscattered echo return), iteration 2, and iteration 10 are shown in Figures 4a, 4b, and 4c, respectively, and their frequency domain counterparts are presented in Figure 4d along with the inverse filter's magnitude response. The two solid vertical lines in each time trace specify the position of a cosine squared time reversal window with an envelope covering 10% of the total length of the window. Ten iterations of the time reversal procedure resulted in a convergence of the echo returns to a narrowband signal centered at the dominant frequency of the target's backscattered response, located near 800 kHz.

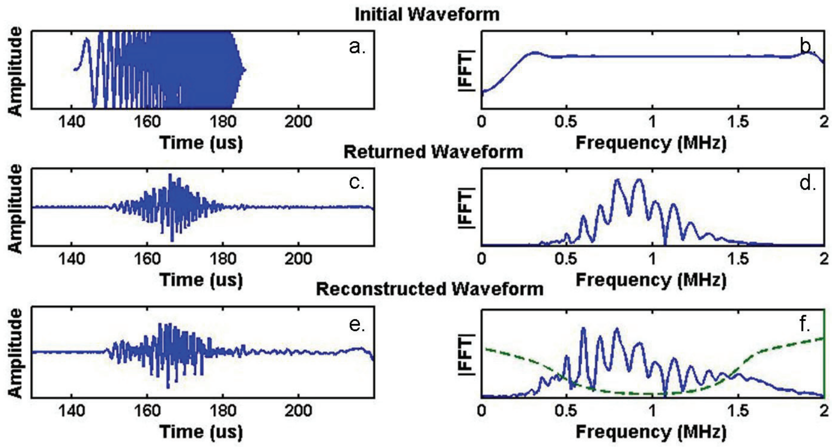

Fig.3: Waveforms and associated spectra from the target characterization experiment. (a.) Linear chirp driving voltage sent to the transducer in which the transmitted pulse was directed at the spherical shell target. (b.) Magnitude spectrum of (a). (c.) Transducer voltage for the first reflection from the spherical shell target. (d.) Magnitude spectrum of (c). (e.) Transducer voltage from (c) after application of the inverse filter. (f) Solid line is the magnitude spectrum of (e) and the dashed line is the magnitude response of the inverse filter used in the transducer normalization procedure. The amplitude for all plots is in arbitrary units.

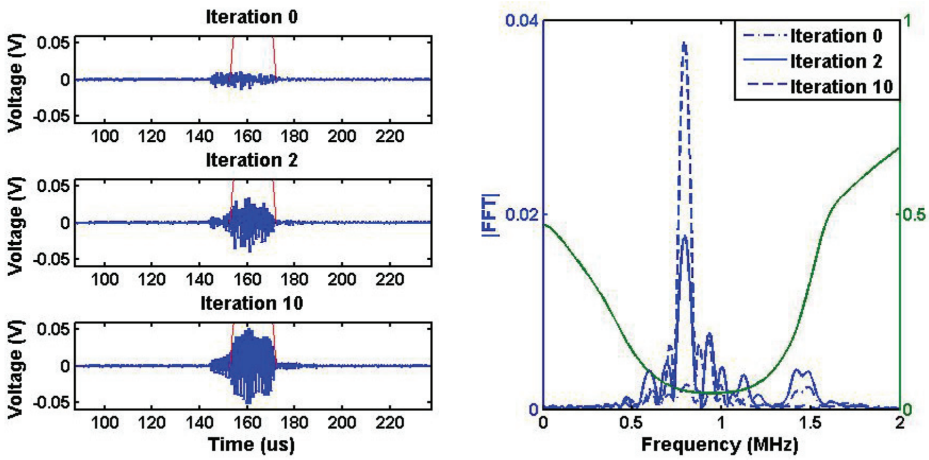

Fig.4: Backscattered echo returns from the spherical shell target suspended in the free field. Vertical lines in (a)-(c) depict the position of the time reversal window. (a.) First backscattered echo return. (b.) Iteration 2 of the time reversal procedure. (c.) Iteration 10 of the time reversal procedure. (d.) Magnitude spectrum of (a) through (c) shown with the magnitude response of the inverse filter used in the transducer normalization procedure.

5. BURIED TARGET DETECTION

To align the transducer for buried target experiments, the target was unburied and the level of backscattered echo returns from the sphere was maximized. The target was then carefully reburied in the same position, and the time reversal procedure described in Section 2 was performed. The location of the time reversal window was shifted from 30 μs preceding to 60 μs following the return from the sand surface in steps of 1 μs. A 50 iteration time-reversal sequence was obtained at each window position, using 3-cycle 1-MHz sine wave interrogation pulses to initiate each time reversal procedure.

The results of this experiment are depicted in Figure 5. Time domain signals for iteration 0 (the first backscattered echo return), iteration 2, and iteration 10 are shown in Figures 5a, 5b, and 5c, respectively, and their frequency domain counterparts are presented in Figure 5d. The two solid vertical lines in each time trace specify the position of the time reversal window. In each time domain waveform, the pulse arriving earliest in time is a strong specular return from the sand's surface which is followed by a lower level echo return from the spherical shell target.

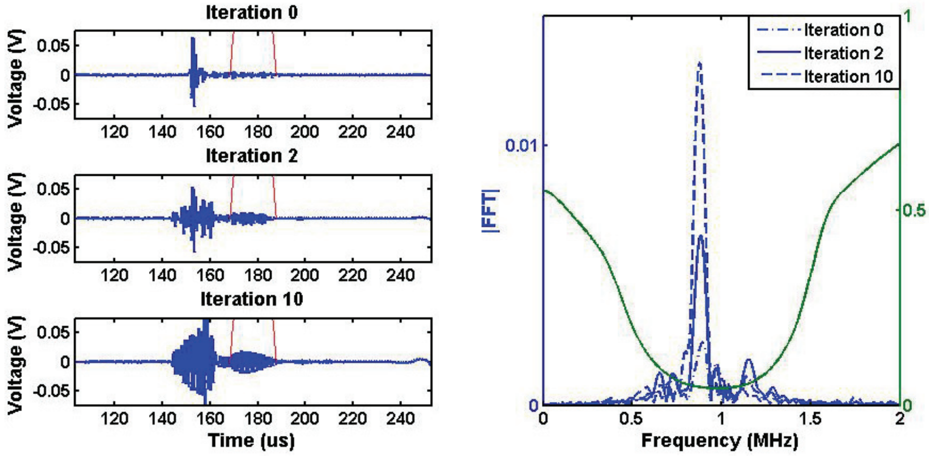

Fig.5: Backscattered echo returns from the spherical shell target buried 2.5 cm beneath a layer of medium grained sand. Vertical lines in (a)-(c) depict the position of the time reversal window. (a.) First backscattered echo return. (b.) Iteration 2 of the time reversal procedure. (c.) Iteration 10 of the time reversal procedure. (d.) Magnitude spectrum of (a) through (c) shown with the magnitude response of the inverse filter used in the transducer normalization procedure.

The first backscattered echo return, iteration 0, is depicted in Figure 5a in the time domain and the Fourier transform of the signal within the time reversal window is shown in Figure 5d. In the time series plot, there is no obvious return from the target visible and in the frequency domain, none of the peaks can be clearly identified as a target resonance. After two iterations of time reversal, the return from the target is enhanced, as evident in Figure 5b, where a pulse following the specular return from the sand surface is clearly visible. The signal within the time reversal window now contains a narrowband resonance that is characteristic of the spherical shell target. By iteration 10, as seen in figure 5c, the location of the target has been identified, and as seen in figure 5d, application of the time reversal procedure has resulted in convergence to a narrowband waveform that is clearly a resonance of the buried target. At iteration 10, a factor of 5 (14 dB) improvement in the amplitude of the target return is observed relative to the first backscattered return.

6. SUMMARY AND CONCLUSIONS

In this paper, a single-channel iterative time reversal technique was presented and shown to enhance the backscattered echo returns from a resonant target suspended in the free field and buried beneath a layer of medium grained sand. Free field results indicate that the spectrum of the echo rapidly converges to a frequency corresponding to a resonant mode of the target, filling the time reversal window. The signal to noise ratio of a target buried beneath a sediment layer is enhanced as the iterations converge to the strongest available target resonance. The center frequency of the converged-upon signal is a resonance frequency of the target whose value can be used for classification and identification purposes. This technique could offer a straightforward means for enhancing target return levels in a noisy or cluttered environment using existing sonar systems.

7. ACKNOWLEDGEMENTS

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