A High-Frequency Active Underwater Acoustic Barrier Experiment Using a Time Reversal Mirror; Model-Data Comparison

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Abstract. An underwater acoustic barrier based upon forward scattering in a Time-Reversal Mirror (TRM) was experimentally demonstrated for the first time in 2000 by Song *et al.* [1]. The barrier consisted of a TRM, a vertical receive array (VRA) and a co-located probe source working at 3,500 Hz in an ocean waveguide near the western coast of Italy. In April 2003 further barrier tests were performed by applying for the first time at sea a new method [2] that provided the capability to focus at different depths by using only the TRM transducers without the complication of additional probe sources. An echo repeater towed by R/V *Alliance* crossed the barrier, emulating the field forward scattered by a possible intruder insonified by the TRM. The presence of a target between the time reversal mirror and the focus can be detected if it significantly disturbs the quiescent region. A normal mode code is used to model the sound propagation in a waveguide. This is applied to predict the unperturbed and perturbed focused acoustic field measurements conducted at sea. Model-data comparison suggests that target detection performance is reasonably predictable using a numerical propagation model.

INTRODUCTION

The hypothesis under test in this study was whether mathematical modeling of an underwater acoustic barrier based on forward scattering in a time reversal mirror could accurately account for observations from a controlled at-sea experiment. The reason that a time reversal implementation is of interest is that a traditional forward-scatter acoustic barrier must detect forward scattered energy from a target arriving at a receiver together with the incident field, the so-called "looking into the sunlight" problem [3]. However, by focusing the transmitted blast in space and time on the downstream receive array, the signal of interest then becomes any temporal or spatial aberration on the receive array caused by the introduction of a scatterer into the propagation medium. As such, the implementation may lend itself to applications in an autonomous tripwire mode of operation.

Based upon earlier work by Song *et al.* [1], an underwater acoustic barrier experiment was conducted using a time reversal mirror in April 2003. In order to verify earlier work and plan future tests for a family of barrier systems under consideration, a data-model comparison was then conducted. The experiment was conducted using an omnidirec-

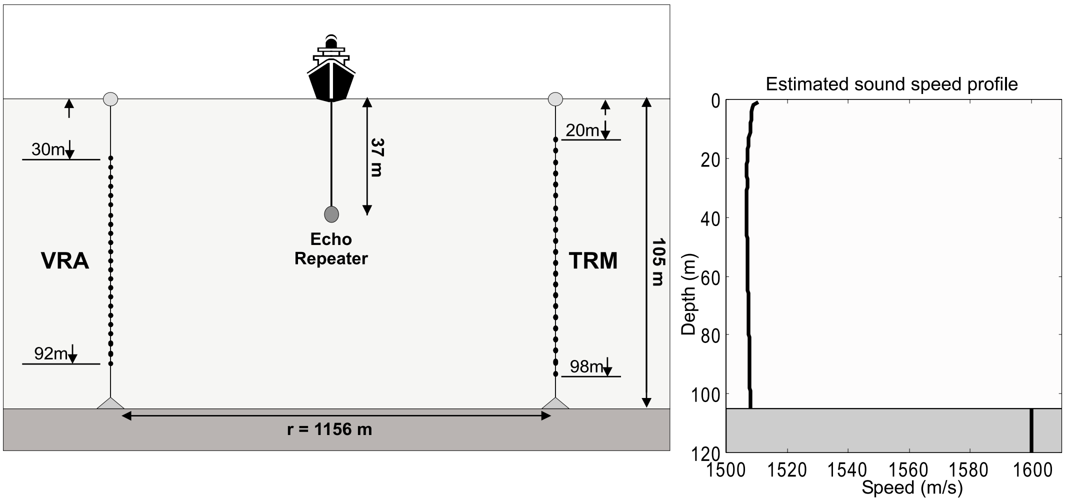

FIGURE 1. The experiment configuration, not drawn to scale. The SRA's 29 tx/rx transducers spanned 78 m of the water column. The VRA's 32 hydrophones covered 62 m of the water column. One VRA hydrophone did not function. The two arrays were linked to a common data acquisition point aboard the ship via RF telemetry.

tional echo-repeater as a target. We chose, for practical reasons, to study a simple case first. Also, a new method of focusing was implemented, the round-robin method described by Roux *et al.* [2].

We hoped to answer the question of whether one can mathematically model the observations provided from a simple barrier experiment conducted under highly controlled conditions. If one cannot model reality in a simple case, *e.g.*, with an echo repeater as a target, then proceeding down this path in the future for real targets with their own radiation patterns is probably fruitless. However, if one can model reality for a simple case, then perhaps this line of research deserves further investigation. It may eventually lead to a predictive tool when designing forward-scatter barrier experiments using focused acoustic fields.

EXPERIMENT CONDUCT

The at-sea experiment was conducted off the western coast of Italy in a region described by Akal *et al.* [4]. Transmit (SRA) and receive (VRA) arrays spanning most of the water column were deployed 1,156 m apart, determined from acoustic travel time. Element spacing within the arrays was roughly six acoustic wavelengths. Any tilt in these arrays was diregarded. A ship, R/V *Alliance*, towed an echo-repeater while slowly drifting between the arrays. The hardware suite is described by Hodgkiss *et al* [5]. The experiment configuration is shown in Fig. 1. Note that the term SRA (Source Receive Array) is often used interchangeably with the term TRM (Time Reversal Mirror) in common parlance. Both terms refer to an array of transducers that are used both as receivers and transmitters.

The barrier experiment was performed at 3,500 Hz by applying for the first time at sea a new implementation of time reversal acoustics [2]. This new technique, sometimes called the "round-robin" technique, provided the capability to focus time reversed signals at any desired hydrophone on the VRA without the hardware complication of additional probe sources. However, it did require telemetry between the two arrays. An additional requirement of this method is that the propagation medium must remain adequately stationary during the procedure of forming a focus.

Briefly summarized, the procedure consisted of the following steps. A pulse was sent out separately from each transducer of the TRM and received at each hydrophone on the VRA at the other end of the barrier. We call this first step the forward propagation phase of focusing. The signals received by one VRA element at a selected depth are then transferred to the TRM, synchronized (or time-aligned), time reversed and sent out simultaneously, each signal from the respective transducer. We call this second step the back propagation phase of focusing.

Having established a focus at one hydrophone of the receive array, a target consisting of a towed Echo Repeater (ER) was introduced into the propagation medium. The signal of interest in this type of experiment is any temporal or spatial aberration observed on the receive array once a target is introduced.

We conducted the data-model comparison in two steps: (1) propagation from TRM to ER and (2) propagation from ER to VRA. The signal observed from TRM to VRA was then compared to the sum of steps (1) and (2). This was possible because the transmitted signal was captured at the ER in this controlled experiment, which would not normally be the case in an operational implementation of the technique. The echo-repeated signal was delayed in time due to the mechanics of the experimental set-up, so it could be separately added in post-processing. The data analyzed correspond to a nominal ship position at 568 m from the TRM and 645 m from the VRA (the sum is not exactly the straight-line distance between the two arrays, 1,156 m, because this was not the ship crossing point).

MATHEMATICAL MODELING

A numerical normal mode code (KRAKEN) was used to model the sound propagation in a waveguide. The KRAKEN normal mode program is a wave-theory model based on the expansion of the wave-equation solution into normal modes. KRAKEN only includes real-axis eigenvalues, and attenuation in the media is described by a perturbation theory. The continuous spectrum and attenuation in elastic media is not included. KRAKEN only includes the discrete set of normal modes, hence steep propagation angles at short ranges are not covered [6]. Approximate isospeed conditions were measured in the water column at 1,507 m/s. The average density of the sediment was estimated at 1.75 g/cm^3. The sediment propagation loss was estimated around 0.13 dB/λ, and the average sound speed of 1,610 m/s was determined by a tuning process.

Applying the model to this environment, Fig. 2 gives an indication of the expected fidelity of the data-model comparison. This figure shows a superposition of all the individual arrivals on the VRA, providing a depiction of the impulse response of the waveguide at the TRM if a point source were located at the VRA at depth 86 m. The

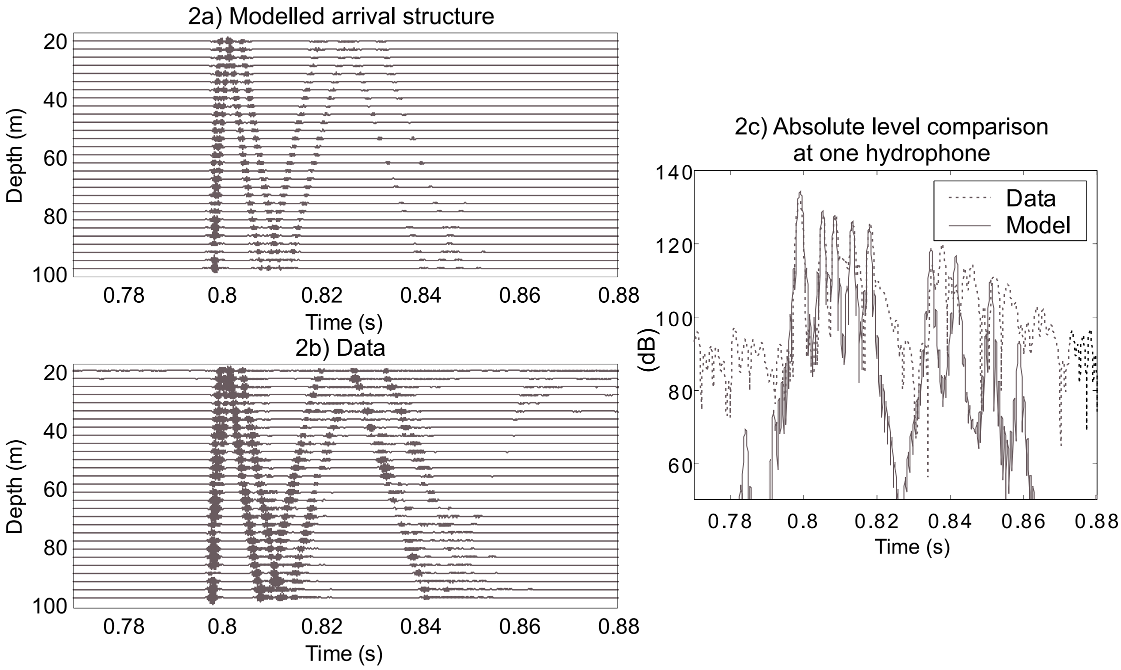

FIGURE 2. Modeled and measured impulse response of the waveguide given a point source at a depth of 86 m. The figure on the right shows the amplitude, in absolute level, of a representative arrival time series at one hydrophone (depth 67 m) on the VRA. The time envelope of pressure is shown. There is extremely good model-data fit for the first arrival and following four multipath echoes.

envelope of the raw pressure time series is presented. This figure also shows, in absolute decibel levels, that the model accurately accounts for the first arrival and following four multipath echoes, implying that knowledge of the channel impulse response is generally good. This is the required starting point for any data-model comparison. Discrepancy in the later arrivals when the number of multipaths (particularly of sea-surface bounces) becomes relatively high.

RESULTS

Modeling the Focus Unperturbed by a Target

Having achieved some confidence that the model could account adequately for the observed channel impulse response, we apply the model to the scenario wherein a focus is established but no target is present, i.e., the unpurturbed scenario. We ask the following questions: (1) How well does the model predict the observed received signal on a hydrophone at the focus? and (2) How well does the model account for the observed signal on a hydrophone in the quiescent region? Figure 3 shows the answers in absolute levels. Agreement is satisfactory. Note that the model is, of course, noise-free. However, the at-sea apparatus measured the actual noise floor present. Figure 4 shows the comparison at the focus in greater detail.

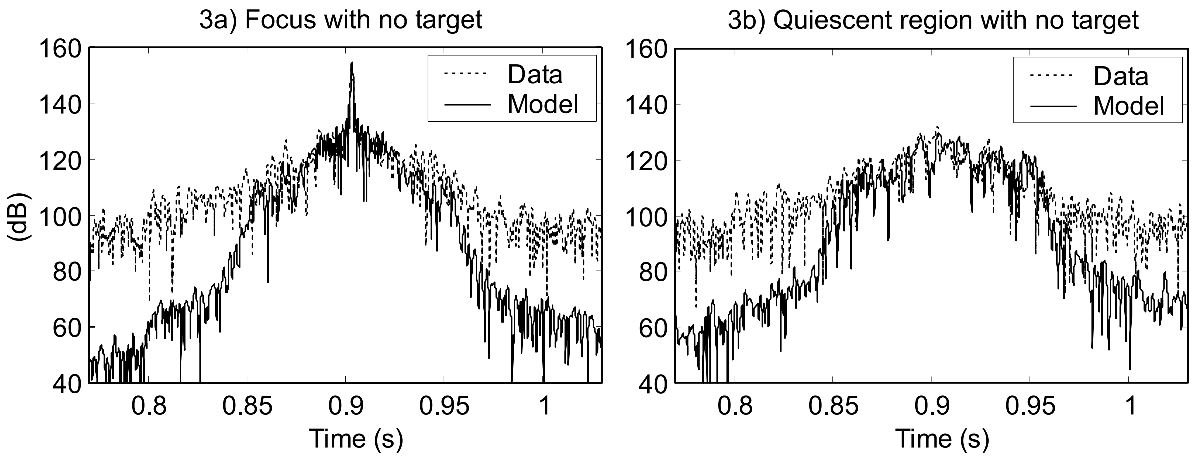

FIGURE 3. Comparison between data and model predictions for an unperturbed (no target present) focused field at two hydrophones on the VRA, one at the focal point at depth 86 m and the other in the quiescent region at depth 64 m.

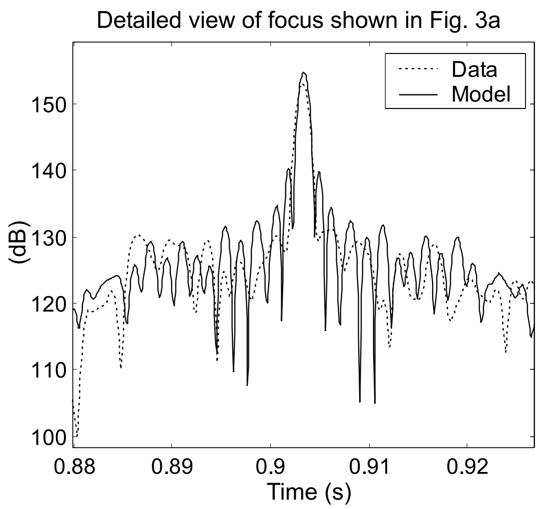

FIGURE 4. A more detailed view of Fig. 3a during a 50 ms time period spanning the focus. Model-data agreement is good to within a few dB at the focus.

Modeling the Received Field after Introducing a Target

The procedure described above was next repeated after introduction of a target into the field. The target was simulated, at sea, by an omnidirectional Echo Repeater (ER) with gain set at 60 dB. Here the data-model comparison process is conducted in two steps: propagation from SRA to ER, then from ER to VRA. One can initiate the SRA transmission with either the true signals, as derived from Fig. 2b or a model prediction (Fig. 2a). Likewise, the next link in the chain can be formed with either a modeled ER reception or the received signal. The significant difference is how noise is introduced and repropagated at each step. Figures 5 and 6 show how data and model compare. Of

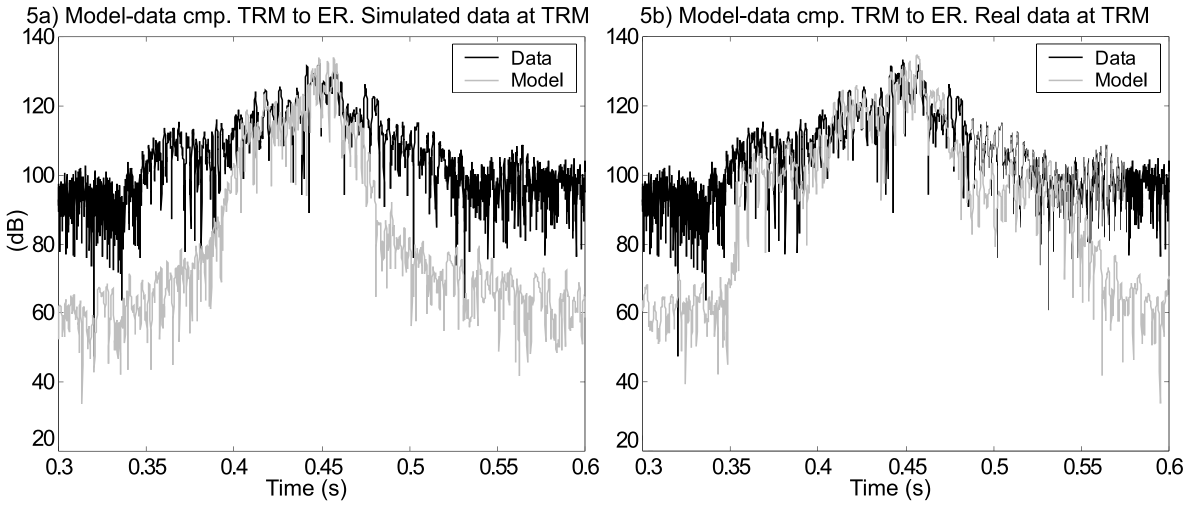

FIGURE 5. Model-data comparison of the field transmitted from the TRM and received by the echo repeater (ER). In the modeling result (Fig. 5a) the field transmitted is either simulated (Fig. 2a) or measured (Fig. 2b). The result using the measured signal includes noise recorded during the forward propagation phase, then time-reversed and retransmitted from the TRM. This noise contribution is not modeled.

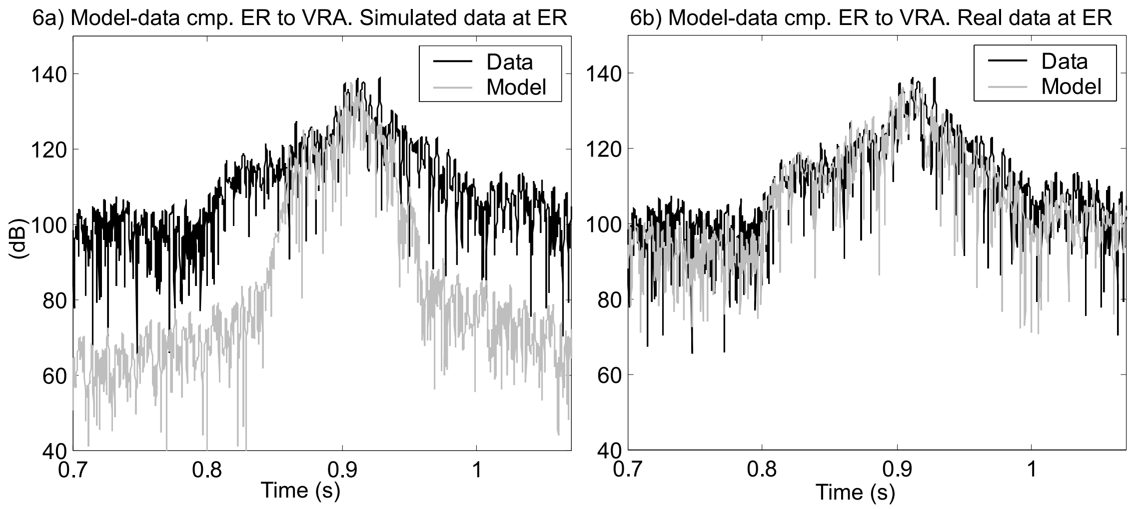

FIGURE 6. Model-data comparison of the field transmitted from ER to VRA, showing the received field that includes scattering from an insonified target. The ER gain simulated a target with an approximate TS of 60 dB. As in Fig.5, there is a noise contribution present when the measured signal is used that is not accounted for in the purely modeled prediction. However, in the 100 ms period spanning the focus, agreement is within a few dB. The data are from a VRA hydrophone at depth 64 m.

note is that the signal duration looks different because the result using a measured signal includes some noise recorded during the forward propagation phase, then time-reversed and transmitted back from the TRM. Noise is also amplified by the echo repeater when the actual received signal is used. This noise contribution is not modeled.

The end result of the experiment is shown in Fig 7. This figure shows a comparison

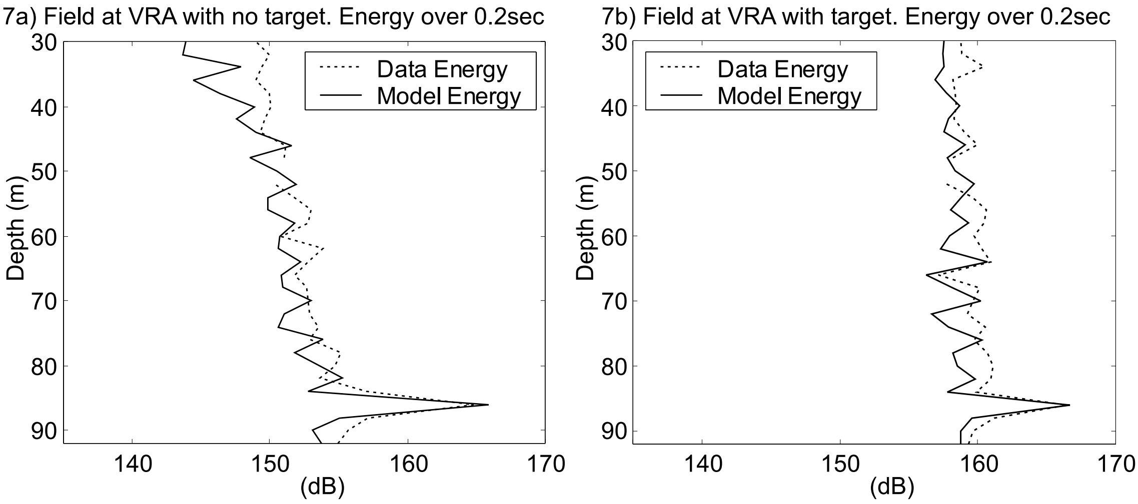

FIGURE 7. Comparison of energy received on the VRA over a 0.2 s time window centered at the signal's maximum peak. Left: model-data comparison with no target present. Right: model-data comparison with the target. Measured data energy is always higher than model prediction due to unmodeled noise, as in Figures 5 and 6.

of received energy at the VRA with and without a target present in the propagation medium. The integration time period is 0.2 s centered at the signal's maximum. Since the energy calculation includes an integration process, the result for data is always higher than model prediction due to noise, as explained above. The result for the case with the target was obtained by adding the unperturbed field to the field radiated by ER, which was possible because these signals were recorded independently. The comparison of the two plots in Fig. 7 suggests that the presence of a intruder with 60 dB of TS provides signal excess at the VRA of about 7-8 dB in the quiescent region. One VRA hydrophone was missing.

Calculated transmission loss (TL) from a rough sonar-equation-based formula [7] predicts TL of around 50 dB at 1,200 m of range. Measurements gave a value of 45 to 55 dB at about 1 km (with a source depth of 60 m). These two values agree reasonably. Calculated absolute received levels are also in general agreement with observation (SL - TL = 180 - 50 = 130 dB, which is roughly the value obtained through our model-data comparison of forward propagation; see Fig. 2c).

DISCUSSION

The echo repeater gain chosen for this study is a reasonably good representation of the foward-scatter TS of an object about the size of a small-medium submarine ensonified by a planewave in the free field (roughly at any incident angle, probably except endfire). Nevertheless, this study was not intended to be a conclusive test for the general performance of the technique in the real world. We chose, for practical reasons, to study a simple, totally repeatable, case first. The fact that we used an omni echo repeater with the gain set at 60 dB was a matter of convenience. The ER is omnidirectional and being the forward field by a target generally much changed by the insonification from many directions, as occurs in a waveguide with respect to a plane wave insonification in the free field. Also, the horizontal radiation pattern is generally smooth enough to work not only at the crossing point but within an azimuthal sector.

CONCLUSIONS

The reason that this study was conducted was to determine if observations made in the sea could be understood using mathematical modelling to provide some future predictive capability for a family of barrier systems. We hoped to answer the question of whether one can mathematically model the observations provided from one simple barrier experiment conducted under highly controlled conditions.

Model-data comparison suggests that target detection performance is reasonably predictable using a simple propagation modeling code and a simple geoacoustic field model of the waveguide. The main message of this study is that an available numerical model is a reasonable tool for prediction and design of experiments.

An echo repeater was used for its simplicity – a good thing in a pilot study like this one. It was not used as a representative surrogate submarine.

It appears that one can model reality for a simple case, so perhaps this line of research deserves further investigation. It may eventually lead to a useful predictive tool when designing forward-scatter barrier experiments using focused acoustic fields. The next step is to apply the method to more complicated targets.

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