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Measurements of Harbor Features and Acoustic Properties

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***Abstract*— A series of data collections have been undertaken in Weymouth Fore River, Massachusetts, to characterize acoustic propagation in one enclosed basin. The goal of the work was to obtain data to describe the sound propagation in the basin, and to calibrate modeling systems for sound within ports and harbors. An ability to accurately model sound in these environments would inform future acoustic system design and deployment. Both monostatic and bistatic acoustic systems were used in the field work. The main data are from a (monostatic) bathymetric sonar, and a bistatic system composed of moored stationary receivers and mobile sound sources. The site, the systems used, data, and research findings are described here.**

Keywords—three-dimensional underwater sound propagation, bathymetric survey, bistatic scattering

I. Introduction

As part of a project to improve three-dimensional underwater sound propagation modeling in confined harbor areas, acoustic and environmental data were collected in four one-day periods at a small formerly highly industrial basin adjacent to Boston Harbor, Massachusetts. The site was the Quincy Fore River Shipyard area of Weymouth Fore River. The river is a tidal estuary here, with deep dredged areas, retired drydock spaces, shoal areas, and other features such as mooring dolphins and derelict concrete and rock wharfs. The intention of the work was to collect data describing the interaction of sound with all of the various features, for the purpose of developing methods to effectively measure the acoustic properties of the features, then incorporate the properties into sound models. The three-dimensional (3D) modeling of underwater sound in such places is similar in some ways to modeling of indoor sound by architects or acoustical consultants [1,2], who must also incorporate measured or inferred boundary interaction characteristics into acoustic models. For example, sound waves encountering a wall can reflect specularly, emerge from the wall more diffusely as from a slightly rough surface and fill a small range of angles, or emerge from a diffusive wall over a broad range of angles [2]. Indoor acoustic simulations are often done prior to construction to optimize (or at least improve) indoor acoustic conditions for specific activities or purposes. Similar 3D modeling of harbor sound propagation, including not only the traditional underwater sound/seabed interaction and perhaps a rough surface, but also rough or fully diffusive man-made boundary elements of any shape, can be used to understand limitations in the use of sound for security purposes or other purposes. Setting up such a model requires measurements of the boundary geometry, which we have done with a traditional monostatic sonar, and with measurements of sound reflection or scattering from boundary features, which we have done in a bistatic configuration. The methods used in this work and the results that were obtained are reported here.

II. Data Collection Methods

A. Vessels and Platforms

An unmanned surface vehicle and a manned vessel were used in our work. The hybrid autonomous/remote control WHOI bathymetric Jetyak [3,4] carried a (monostatic) Ping DSP Inc. swath bathymetric sidescan sonar mounted approximately 0.6 m below the waterline at the base of a centerline keel. The sonar, model 3DS-DX-450 operates at 450 kHz. The bistatic work involved moored acoustic receivers and two mobile sources. The Jetyak carried one sound source. A second source was towed behind the 9.5-m length motor vessel *Dawn Treader.*

B. Bistatic Acoustic Equipment

The receivers were of two types: SoundTrap 300 single hydrophone recorders from Ocean Instruments NZ, and a four-channel SonoVault II-4 system (Compact Version) from

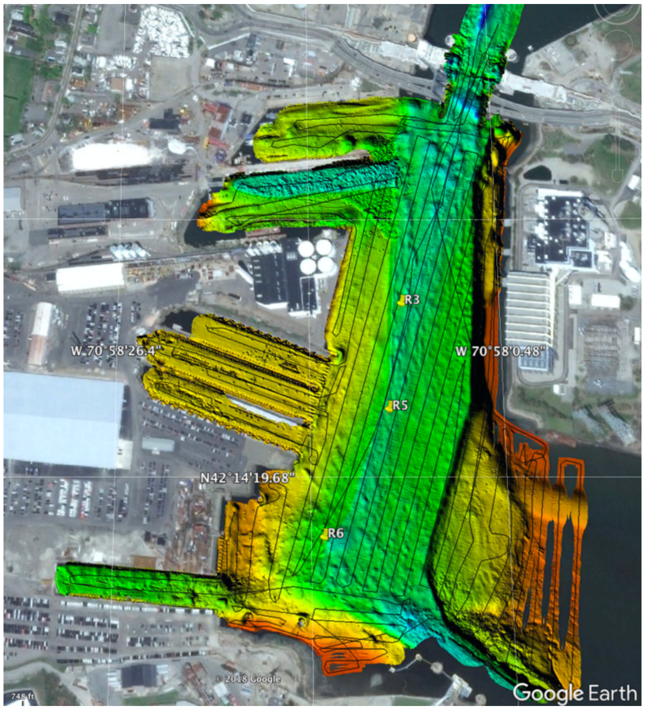

Fig. 1. The bathymetry measured with the Jetyak is plotted in color, with shadows for emphasis. Red is a few meters deep, yellows are 5 to 8 m deep, moving to blue at about 15 m deep. The survey track is shown in black. The pins show the receivers moorings for Mission 3 (of four) of the June 2019 experiment. The surveyed area is 280 m wide at the latitude of receiver R3.

Develogic. The Jetyak source, transmitting linear frequency modulation (LFM) chirp signals of 21 to 34 kHz, was an M18-C-2.5 transducer from Geospectrum Technologies, Inc., mounted 2 m below the waterline on a swinging ballasted stainless steel rod. The other source was an ITC-1007, made by International Transducer Corp., transmitting LFM chirps from 8 to 16 kHz. Amplifiers for each source took signals from notebook computers using Cambridge Audio USB-port D/A converters operating at 96 kHz input sample rate.

III. Field Work Summary

Data were collected during four work days. A bathymetric survey was performed on 20 Nov. 2017. An acoustic propagation study with the bistatic equipment was performed on 24 May 2018. A second bathymetric survey was done on 4 June 2019, measuring specific boundary features in greater detail. A second propagation study took place on 12 June 2019, emphasizing sound reflection and scattering from specific boundary features.

A. *Initial Bathymetric Survey*

The Jetyak survey was undertaken to measure the bathymetry to great accuracy, including objects with scales of meters or less. The sea state was relatively flat in the protected area despite strong winds, and the tide was changing over a 3-m range or greater during the survey. To achieve the needed accuracy, the Jetyak carried a Novatel precision navigation system, which includes a real time kinetic GPS unit (RTK GPS) and an inertial measurement unit (IMU). The system is securely mounted to the sonar keel and the dimensions and alignment are designed to be secure and reproducible. With precise and accurate attitude and location information, the scatterer-detecting sonar system could localize reflections, from object or seabed, to precision of 10 cm or better. Fig. 1 shows survey tracklines and the bathymetry product. At the center left are three inundated disused drydocks, and at the lower left is a single drydock. Comparisons of co-located seabed profiles made from different passes were found to agree to 10 cm after processing. An estimate of the accuracy of a gridded product is thus taken to be of order 10 cm. Moored vessels obscured some areas.

B. *First Bistatic Acoustics Study*

This study consisted of three experiments, each having three moored receivers. During each experiment, both mobile sources operated in an objective manner with respect to the investigation of sound radiating from specific boundaries. The first experiment had three receivers (center, north and south in the basin) and moved both sources over all accessible waters of the space. Fig. 2 shows the energy from the Jetyak source received at the south instrument, moored 5 m above the seabed, plotted as a function of source location. The signals were matched-filter processed (normalized to have unity gain, so that the filtering preserves signal level and reduces noise). The maximum for each one-second period is used in the plot, the LFM pulse rate, with open gray circles showing samples with insufficient peak height with respect to noise to confirm detection, mostly occurring when the source was in the drydocks. The mean source level was 180 dB for the LFM signals, so the figure shows transmission loss levels of about 16 dB to 70 dB. Fig. 2 shows that the Jetyak source provided good coverage during this first experiment.

The second experiment had three receivers at the south end and also involved both mobile sources (Fig. 3). The third experiment at the north end was similar in scope.

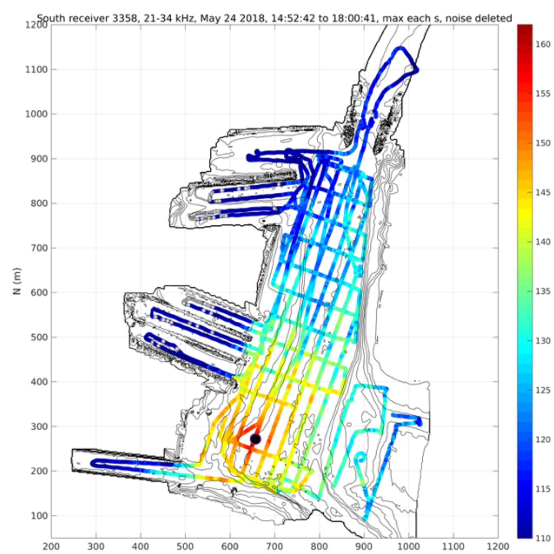

Fig. 2. The colored dots show sound pressure level estimates at the receiver (black dot) made from matched filtered receptions of the Jetyak LFM signals emitted from the dot positions. No detectable arrival is indicated with an open gray circle, mainly in the shadowed areas on the west side with no direct path.

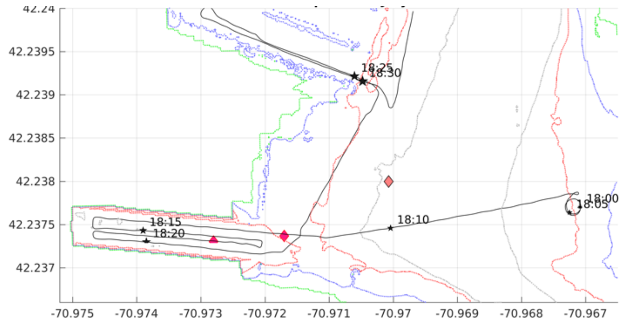

Fig. 3. The three receivers for the south experiment of the first bistatic field day are plotted as shapes, shown with the Jetyak source track. Times are indicted (UTC time). The eastern receiver position is the same one used in the immediately prior basin study (Fig. 2). Depth contours at 1, 5, 9 and 13 m are shown.

Receptions of sound from one boundary structure are shown in Fig. 4. The data shown are for the Jetyak source approaching the structure. One delayed multipath arrival that is echoing off a structure between drydocks is analyzed in this figure. The bistatic delay time shrinks from 47 to 16 ms. The ellipses of constant bistatic delay for the tracked continuous reflection intersect at, and identify, a boundary reflector (~645 m, 435 m).

C. *Second Bathymetric Survey*

After identification of targets through bistatic delay analysis, a detailed survey of the about a dozen features was made. This was done with repeated close passes of each target with the bathymetric sonar-equipped Jetyak. The data revealed some highly reflective and non-reflective surface sections in close proximity to each other, and large variations in back-scattering strength. Fig. 5 shows the survey trackline around nine target structures in one corner of the basin. These structures were all found to reflect sound in the 2018 bistatic acoustics study (See Fig. 3). Fig. 6 shows the variable echo returns from Target 5 along with a photo of the target, a round mooring cell.

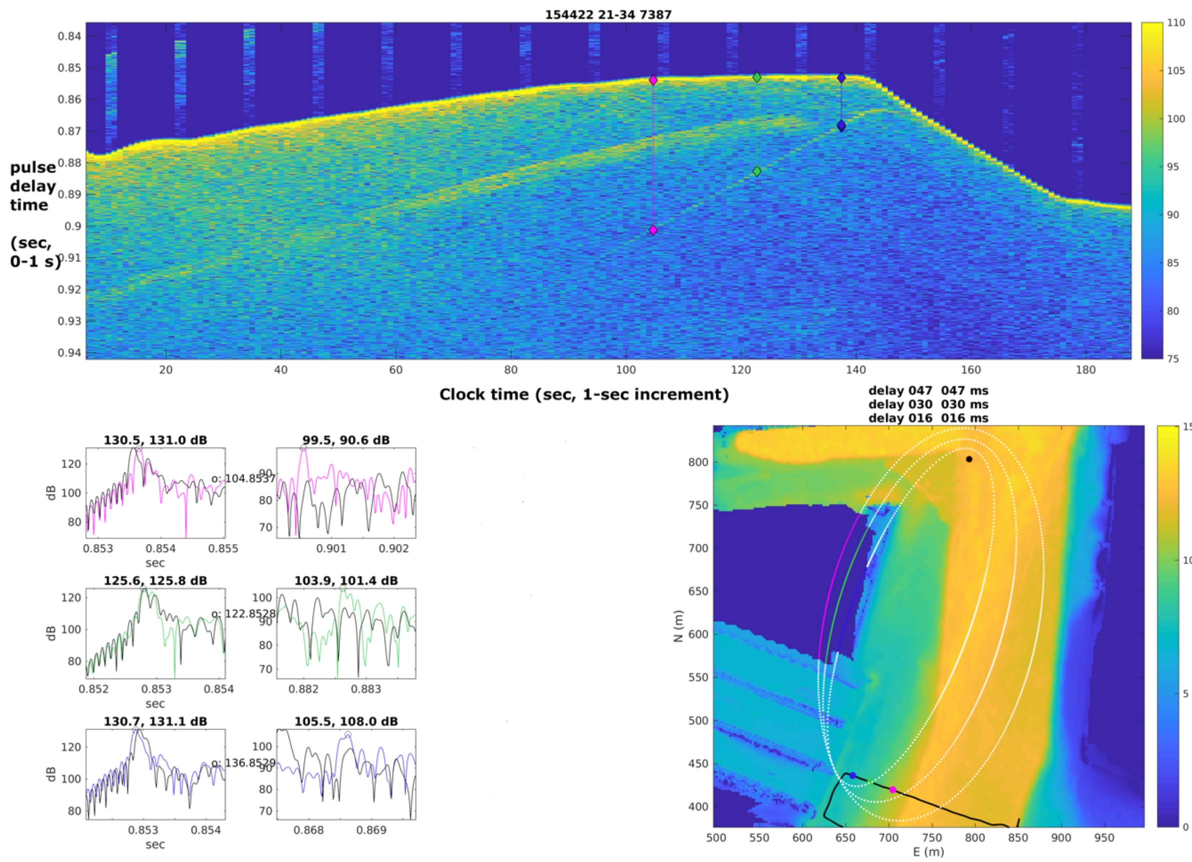

Fig. 4. Bistatic acoustic data GUI summary plot for recorder file 15:44:22 (time) 21-34 kHz analysis (top) Sound pressure level (dB) of roughly 180 s of matched-filter data are shown, with a vertical scan of one second of data shown each second (Time starts at upper left, runs down 1 s, to the right, down 1 s, repeating.) The top and bottom of the one-s scan period are cropped away. The direct arrival (top-most high-energy peak) and one delayed arrival are selected at three times. The first selected peaks are shown in the upper panel in color magenta, the second in green, the third in blue. Time series of sound level near the selected peaks are shown in the lower left panels. These have the following levels: First time direct arrival 130.5 dB; Second time direct arrival 125.6 dB, Third direct 130.7 dB; First time multipath 99.5 dB at delay 47 ms; Second time multipath 103.9 dB, delay 30 ms; Third time multipath 105.5dB, delay 16 ms. The plots also show time series and list peak level for the pulse one second after the selected pulses, for comparison. The lower right panel shows depth in color, the source track, the selected source positions, the receiver position, and the ellipses of possible reflector positions drawn using the bistatic time and location parameters. The tracked multipath yields ellipses that cross at a structure that we call Target 3, between drydocks. The broad echo from 20 to 130 s clock time, 0.92 to 0.88 s delay time is from a wharf with pilings that is west of the direct paths from the source locations to the receiver located at the north.

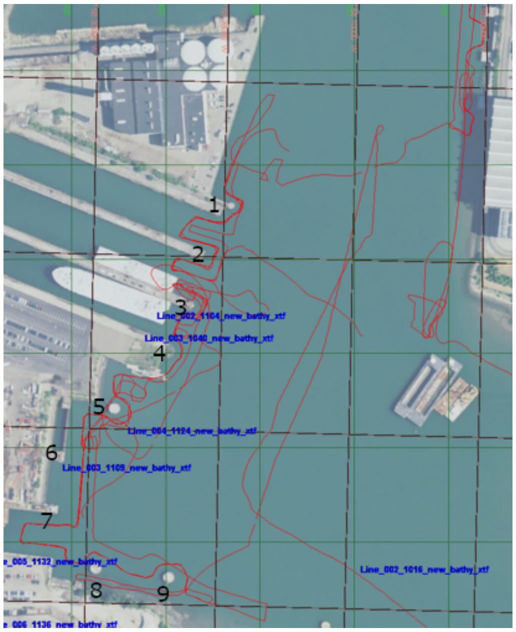

Fig. 5. The Jetyak path for the 2nd survey is shown in red. Nine target structures in the southwest portion of the basin are indicated with numerals 1 to 9.

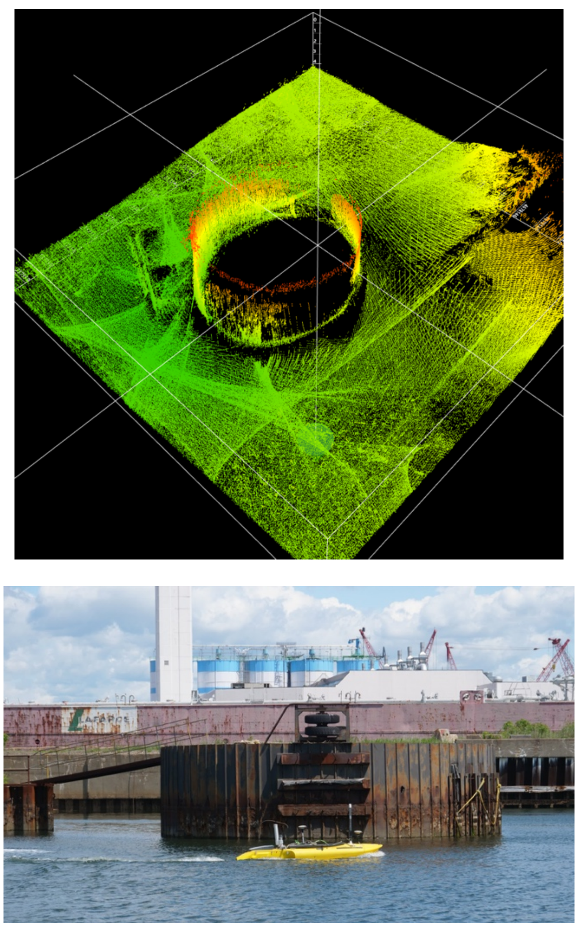

Fig. 6. A point cloud image of identified echo energy from Target 5 is shown at the top. Below is a photograph of Target 5 looking north with the Jetyak passing in the foreground.

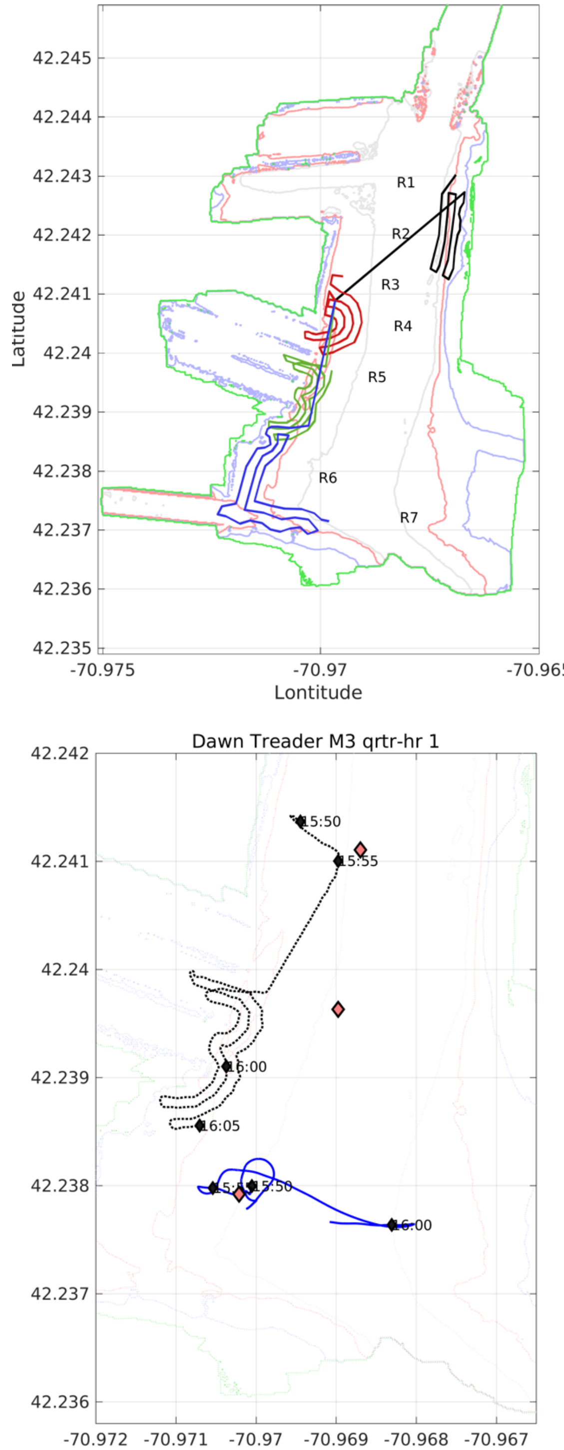

Fig. 7. (top) Jetyak 21-34 kHz source track plans for the 2nd bistatic acoustics study are shown along with seven moored receiver positions. Passes by a group of concrete structures were planned (upper right) at a few distances. This is Mission 1. Arc passes (Mission 2 in red and Mission 3 in green) and line passes (Mission 4, blue at lower left) were planned for targets 1 to 9 (see Fig. 5). Mission 1 used R1, R2 and R3. Mission 2 used R3, R4 and R5. Mission 3 used R3, R5 and R6. Mission 4 used R5, R6 and R7.(bottom) The actual mooring positions and 15 minutes of Jetyak and vessel tracklines are shown for Mission 3.

D. Second Bistatic Acoustics Study

This study featured bistatic echo studies with the sources passing close to selected targets. Receivers were moored as in the first study. With the Jetyak equipped with the controllable source, straight line passes past target features were made, as well as semi-circle passes at constant radius from the target features, repeated at multiple radii. The small semi-circle passes quickly yielded data for sound reflected from the targets to moored receivers over many bistatic angles. One reason for having the source close to the scattering target is that the conditions were downward refracting in this estuary, with warm fresher water at the surface above the salty and cooler bay water below. In this case the source-receiver direct path had the same number of bottom bounces as the path of sound scattered from the target (zero). This allows the analysis described in the next section.

Fig. 7 shows in the top panel the tracks that were planned for the Jetyak source, and seven planned receiver stations for the three moored receiver packages. Four mission tracklines are shown in the figure. Some of the Mission 1 Jetyak tracks (northeast corner) were not as straight as in this plan because of a brief equipment failure. Fortunately, the section of logged Mission 3 jetyak track that is drawn in the lower panel of the figure shows that the source position control was usually very good.

IV. Results

Joint analysis of direct-path pulse signals and pulse signals scattered from a target allows us to estimate the reflection coefficient of the target for specific path geometry at that moment of the analysis. The source, receiver and target positions provide reasonably good estimates of the bistatic scattering angle θ and the three relevant sound path distances (source to receiver, source to target, target to receiver). However, they do not determine the exact location on the target where the scattered energy is coming from, and therefore do not completely determine the incident and outgoing angles of the sound at the target. The reflection factor R at the scatterer is found from the decibel relations

$$I_{SR} = I_S - L\,\log_{10}(D_1) - B \qquad (1)$$

$$I_{STR} = I_S - L\,\log_{10}(FD_1) - B - R \qquad (2)$$

where I_{SR} is the direct-path (source to receiver) sound pressure level in dB, I_{STR} is the scattered path (source to target to receiver) sound pressure level in dB, L is the spreading loss rule for the environment, which we set to $L = 18$ for the downward refracting conditions (20 would represent spherical spreading), B is loss from bottom reflection (which we prefer to be zero dB, no seabed reflection) and $F = D_2/D_1$ is the ratio of scattered path to direct path distance. Subtracting (2) from (1) gives

$$\Delta I = I_{SR} - I_{STR} = R + L\,\log_{10} F \qquad (3)$$

which provides an estimate of R for each pulse that has a scattered arrival. Fig. 8 shows $R(\theta)$ results for one target pass, with data points provided once per second for almost 50 s.

The formulas (1) to (3) hold when B is the same for each path, i.e. the number of bottom bounces is the same for the two paths, and thus far we have applied them to cases where we believe that neither path exhibits a bottom reflection. With the source close to the receiver, as in the case of the four missions of our second acoustic study, all that is needed is to be sure that the receiver is not too far away. The area within the domain where sound from a target can reach a receiver without bottom interaction can be found using ray tracing and the sound speed profiles obtained from CTD casts.

The data presented in Fig. 8 show that the detailed survey information is important for identifying the source locations of the scattered sound. Fig 9 shows $R(\theta)$ for a briefly illuminated scatterer near the scatterer of Fig. 8.

Acknowledgment

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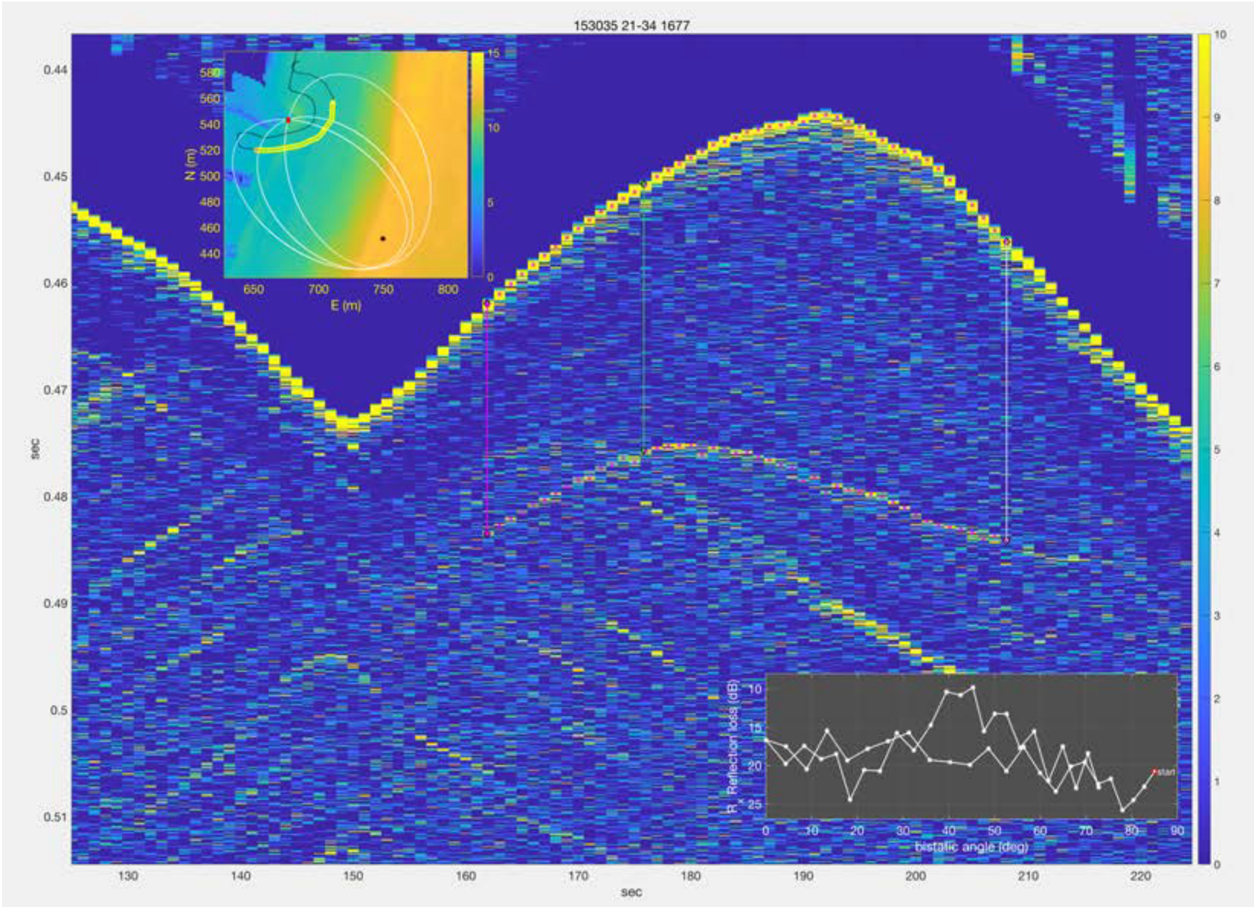

Fig. 8. The data from which reflection factors *R* from Target 1 are shown in color, with clock time running horizontally in 1-s increments, and pulse time (0-1 s) running vertically. The red dots show a tracked direct arrival with low-pass intensity removed, and below that the tracked arrivals from Target 1. Three bistatic delay ellipses, the receiver position (black dot) and the identified target (red dot) are shown in the inset at upper left. About 45 pulses are analyzed, one pulse per second. The lower inset shows *R* vs bistatic angle, where the bistatic angle starts at 90, falls to zero, then rises again as the Jetyak moves to the northeast.

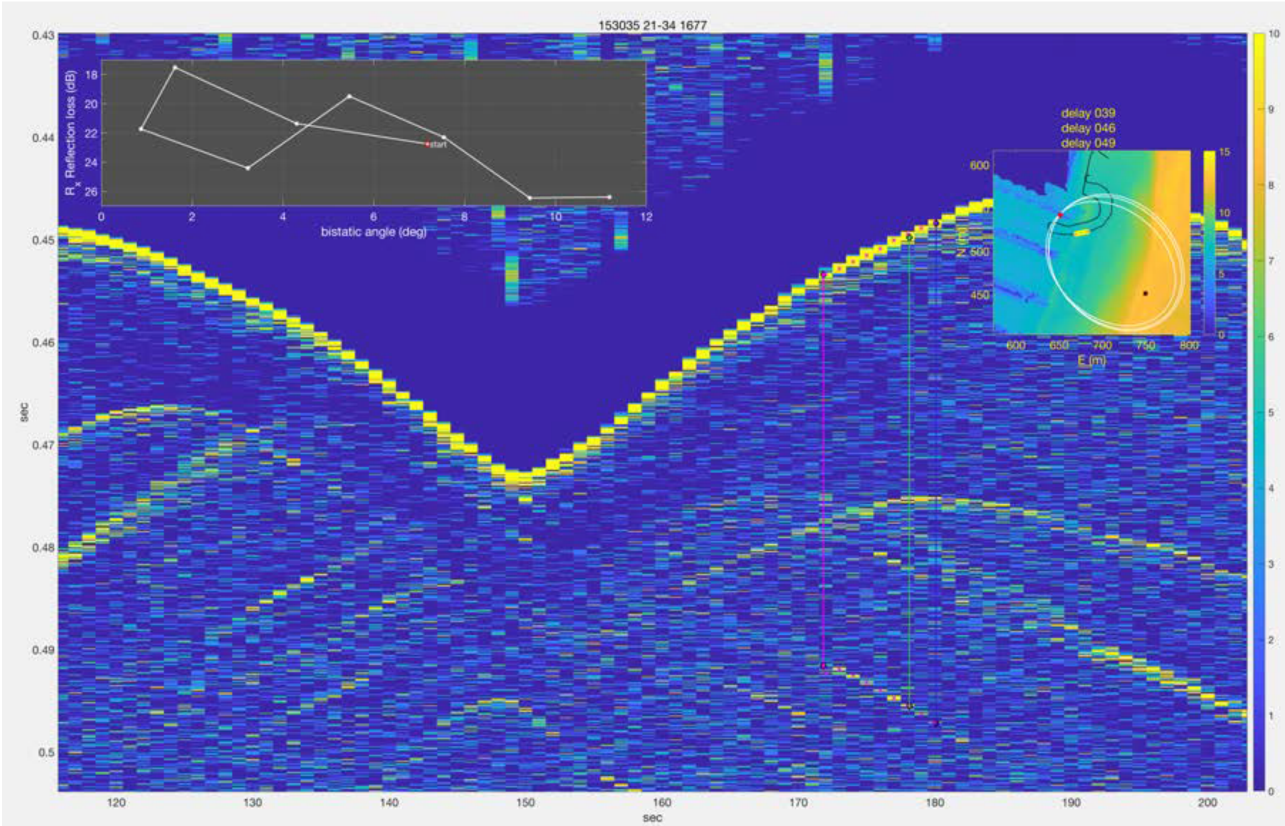

Fig. 9. Similar to Fig. 8. This target scatters sound for less than 10 seconds.