Acoustic Propagation Studies For Sperm Whale Phonation Analysis During LADC Experiments

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Abstract. The Littoral Acoustic Demonstration Center (LADC) conducted a series of passive acoustic experiments in the Northern Gulf of Mexico and the Ligurian Sea in 2001 and 2002. Environmental and acoustic moorings were deployed in areas of large concentrations of marine mammals (mainly, sperm whales). Recordings and analysis of whale phonations are among the objectives of the project. Each mooring had a single autonomously recording hydrophone (Environmental Acoustic Recording System (EARS)) obtained from the U.S. Naval Oceanographic Office after modification to record signals up to 5,859 Hz in the Gulf of Mexico and up to 12,500 Hz in the Ligurian Sea. Self-recording environmental sensors, attached to the moorings, and concurrent environmental ship surveys provided the environmental data for the experiments. The results of acoustic simulations of long-range propagation of the broad-band (500-6,000 Hz) phonation pulses from a hypothetical whale location to the recording hydrophone in the experimental environments are presented. The utilization of the simulation results for an interpretation of the spectral features observed in whale clicks and for the development of tracking algorithms from single hydrophone recordings based on the identification of direct and surface and bottom reflected arrivals are discussed. [Research supported by ONR.]

INTRODUCTION

Studies of the acoustic vocalizations and phonations of marine mammals have become one of the hot topics of underwater acoustic research in the last few years. There has been increasing anthropogenic noise in the ocean and an overlap between the spectral content of naval sea operations and the vocalizing and phonating frequencies of deep-diving marine mammals. There is concern that this is a potentially disturbing factor in the mammals' habitat. Unlike visual surveys, biological sampling, and radio-tagging, passive acoustic recordings offer a variety of advantages for the investigation of free moving large marine animals (such as different types of whales): they are unobtrusive and do not change the social behavioral pattern of an animal, they can contain simultaneous information about many individuals at different distances from a receiving system, and they can provide the continuous monitoring of species spending most the their time under water. When using passive acoustics, studying the vocalization/phonation patterns of different animals and species and trying to discern acoustic sound of a specific individual is the way to gain the knowledge (which does not exist at present time) about social acoustic communication of large marine mammals. A considerable amount of the mammals' broadband acoustic data has been collected by the Littoral Acoustic Demonstration Center (LADC).

The Littoral Acoustic Demonstration Center (LADC) is a consortium of the University of New Orleans (UNO), the University of Southern Mississippi (USM), the University of Louisiana at Lafayette, and the Naval Research Laboratory at Stennis Space Center (NRL-SSC), with guidance and support from the Naval Oceanographic Office (NAVOCEANO). It was formed to perform and analyze underwater acoustic measurements of ambient noise and marine mammal phonations, namely endangered sperm whales. The first experiment was conducted in the Gulf of Mexico (GoM) in the summer of 2001 from 17 July to 21 August. Figure 1 shows the LADC study area, which is the same area used in summer 2002. The black dots indicate oil platforms and the whale symbols indicate sperm whale sightings. The second set of measurements was made in conjunction with the Saclant Centre (SACLANTCEN) exercise Sirena02 in the Ligurian Sea from 01 July to 23 July in the summer of 2002. The third set of measurements was made during the late summer and early fall of 2002 in GoM. All the acoustic measurements were accomplished with vertically moored Environmental Acoustic Recording System (EARS) buoys from NAVOCEANO. Each of the EARS buoys had a single omni-directional hydrophone and an instrument package which autonomously recorded the acoustic signals up to 5,859 Hz in the GoM and up to 12,500 Hz in Europe. The hydrophones for these buoys were suspended 50 m from the bottom. The remainder of the mooring, spanning almost all the rest of the water column, was instrumented with self-recording environmental oceanographic sensors which provided time series data of temperature, conductivity, and pressure. In both the summers of 2001 and 2002, the moorings were deployed along an approximately straight line at the 600, 800, and 1,000 m contours, 5.3 km (between 600 m and 800 m moorings) and 13 km (between 800 and 1,000 m moorings) apart [1]. Additional oceanographic data were gathered on various cruise legs to augment the mooring measurements and give a more complete description along the study tracks. In the summer of 2001, a chirp sonar survey along the study tracks was also performed. The data have been inverted to give sound speeds and densities in the bottom [2].

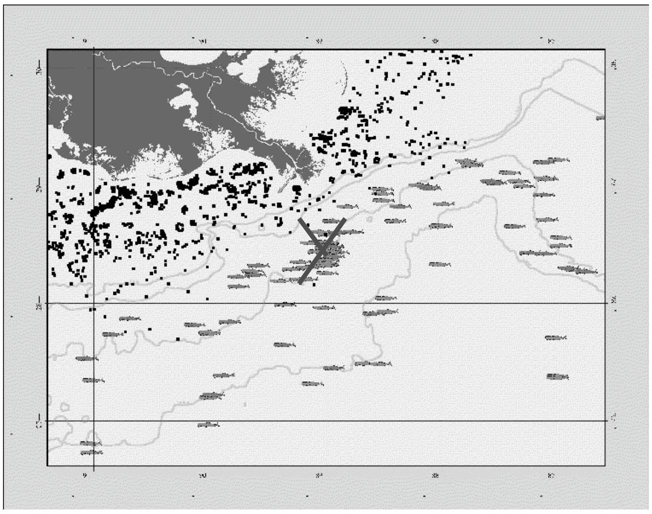

FIGURE 1. Ship track locations for oceanographic sensing. Oil platforms are black dots and whale sightings are whale symbols. Louisiana coast is at upper left. (Reproduced from [1])

SPECTOGRAMS OF THE LADC DATA

The analysis of the LADC recordings reveals a considerable amount of anthropogenic noise, as well as well-identifiable (by aural analysis) phonations of marine mammals (predominantly sperm whales), in approximately 600 Gbytes of recorded data. Distant shipping noise is generally dominant in a frequency range from 10 Hz to 300 Hz with a peak in the spectrum near 50 Hz. More local shipping effects often include many tonal lines superimposed upon the distant shipping spectra [3]. Seismic exploration sources are widely present under 300 Hz in addition to the ship noise. Figure 2 shows a representative four-second fragment of a 60 sec segment of LADC data from the 800 m buoy. It contains very clear recordings of sperm whales. The recording begins on Julian Day 213, Zulu 0 hr, 9 min, 37 sec. In this figure, the top graph shows the structure of the time signal, originally recorded by the mooring. The bottom two graphs in the figure are spectrograms. The first one shows all frequencies up to 5,859Hz while the bottom spectrogram contains only frequencies to 1,000 Hz. Broadband transform lines in the middle figure are sperm whale clicks and closely spaced clicks sound like creaks, although they are distinct from the spectrogram patterns which correspond to what are generally known as creaks in the literature [4-7]. The seismic exploration source (107 km away) is clearly visible as the red peak in the bottom spectrogram of Fig. 2. The low frequency noise without the seismic source present, which still dominates the spectrum, is visible before the seismic pulse arises.

Figure 2 and extensive spectrogram analysis reveals well-defined null patterns in the phonation spectrograms, as, for example, the sequence of clicks at the 49-second mark. More detailed information can be gathered by overplotting the magnitude of the spectra in a single group of clicks. Fifteen distinct groups were identified in the previously mentioned 60-second segment based on the temporal grouping of the clicks. The results of the comparison for five groups are presented on Fig. 3. Some groups show the unique and stable null patterns despite the considerable variations in amplitude in-between. A legitimate question to ask is if the interference pattern in the mammal's spectrograms is caused by propagation effects, or if it can be associated with an individual animal. The second part of this paper presents the results of modeling the propagation effects of the LADC experiment.

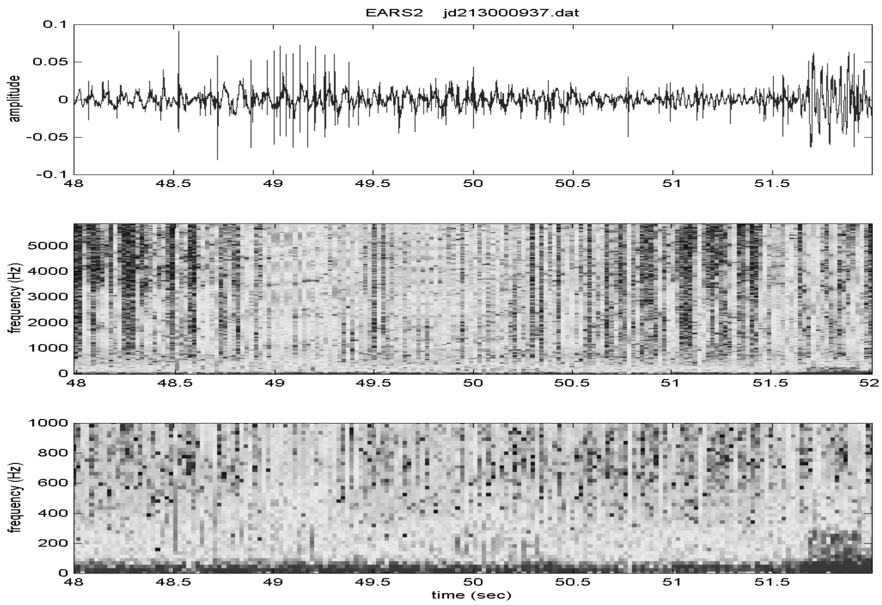

FIGURE 2. 800 m mooring LADC time data extracted from a 60 sec segment beginning at Julian Day 213, Zulu 0 hr, 9 min, 37 sec., and their spectrograms.

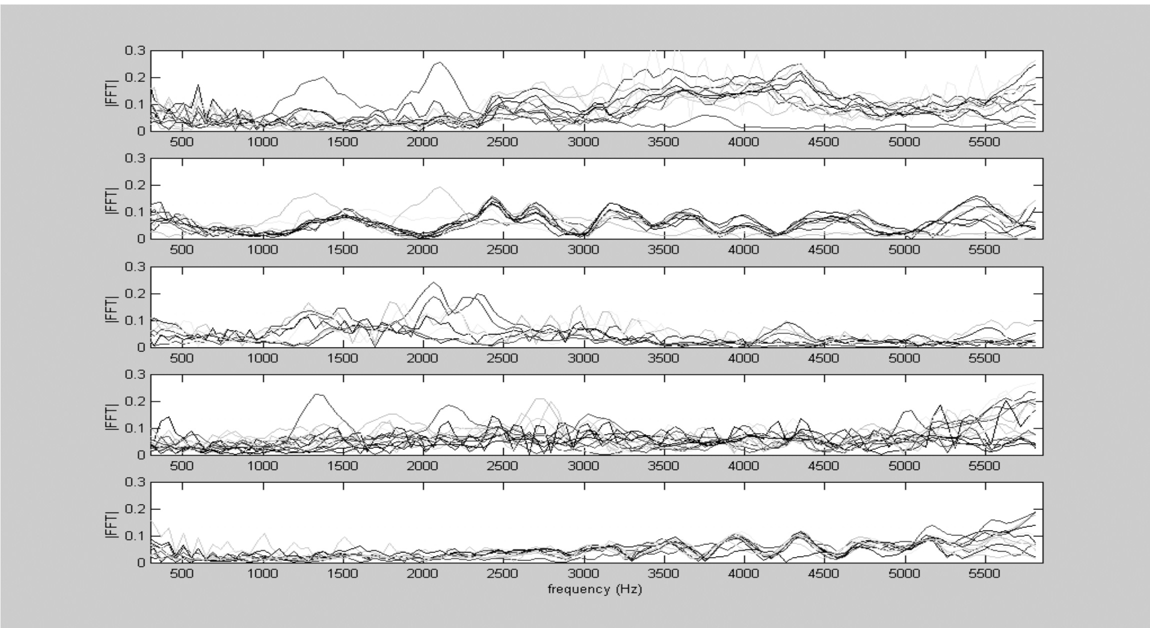

FIGURE 3. Spectrograms for 5 different groups of clicks.

PROPAGATION MODELING FOR LADC DATA

The environmental data collected as a part of the LADC experiment in Summer 2001 (Fig. 4) were input into the Range-dependent Acoustic Model (RAM) by Michael Collins to simulate the broad-band acoustic response on a receiving hydrophone. The hypothetical animal depth is 700 m which corresponds to common foraging depths of sperm whales. The receiver position is 740 m. The source spectral function is assumed to be flat over the frequency range between 500 and 5,859 Hz to study only the effects of the waveguide propagation.

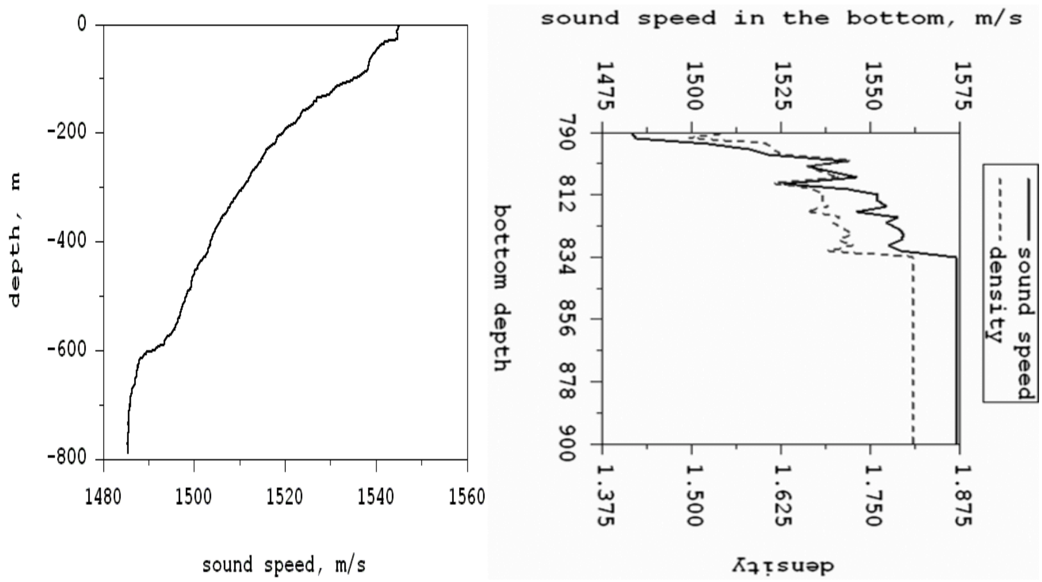

FIGURE 4. Environmental input into the RAM model: sound speed profile in the water column and bottom sound speed and density functions.

Figure 5a represents the frequency dependence of the amplitude of the modeled waveguide transfer functions. The color coding indicates the different horizontal distances between the hypothetical source location and a receiver. We can see the "sine-like" behavior of the transfer function that indicates only direct and bottom reflected pulses are responsible for the most energy transfer between the source and receiver. The 10 Hz frequency step size in the simulations does not account for the fine-scale structure due to surface and multiply reflected arrivals. The frequency of oscillations is decreasing as a hypothetical animal swims away from the buoy. At the horizontal separation of 3 km, the structure of the transfer function becomes more irregular indicating the partial time overlapping between direct and bottom reflected arrivals and the contribution of the surface reflected one. Using the Fourier synthesis procedure, the time domain response can be obtained. The time-domain structure of the transfer function, which is color-coded in accordance with the horizontal separation between a source and receiver, is shown on Figure 5b.

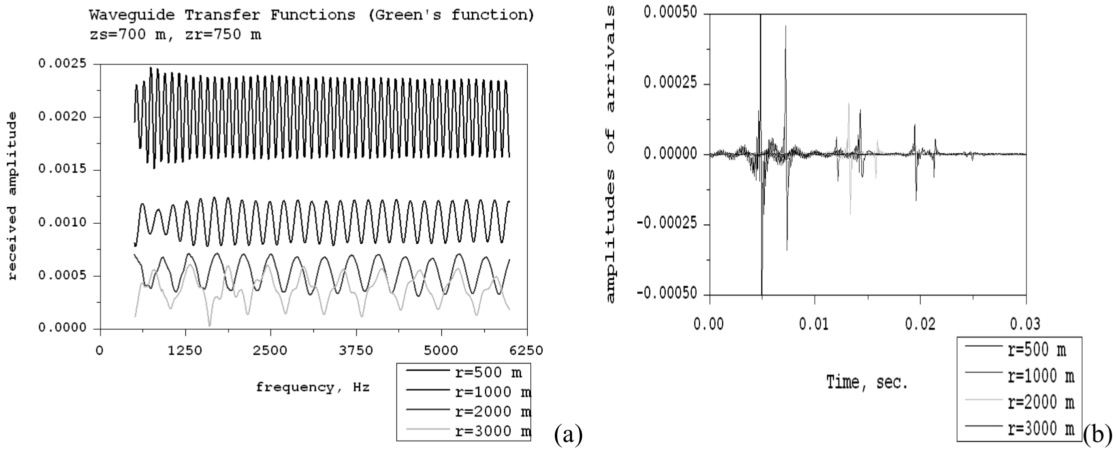

FIGURE 5. (a) - Frequency-domain structures of the waveguide transfer functions for different horizontal distances between the source and receiver for a receiver at a depth of 740 m and a source depth of 700 m; (b) - Temporal structures of the waveguide transfer functions for different horizontal distances between the source and receiver for a receiver at a depth of 740 m and a source depth of 700 m.

From the analysis of time domain response, we can conclude that the temporal delay between the direct and bottom reflected arrival is about 15 msec for a horizontal separation of 500 m and gradually decreases with increasing range. The temporal window for the spectrograms in Figs. 2 and 3 was 4 msec, which corresponds to the average duration of on-axis sperm whale clicks [7]. Applying this windowing function to separate the direct pulse arrival for r=500 m followed by the Fourier transform, we obtain a nearly flat spectrum of the windowed transfer function (Fig. 6). Based on propagation modeling, we can hypothesize that for the short-time spectra and relatively close position of an animal to an EARS buoy the animal phonation apparatus may be responsible for prominent null patterns in the clicks spectrograms presented in Figs. 2 and 3.

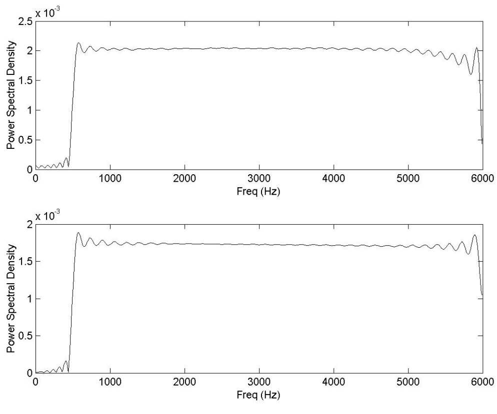

FIGURE 6. Spectrum of the windowed direct and bottom-reflected arrivals.

The series of sound pressure level maps in Fig. 7 show the distribution of acoustic energy with depth and time for the fixed horizontal separation between source and

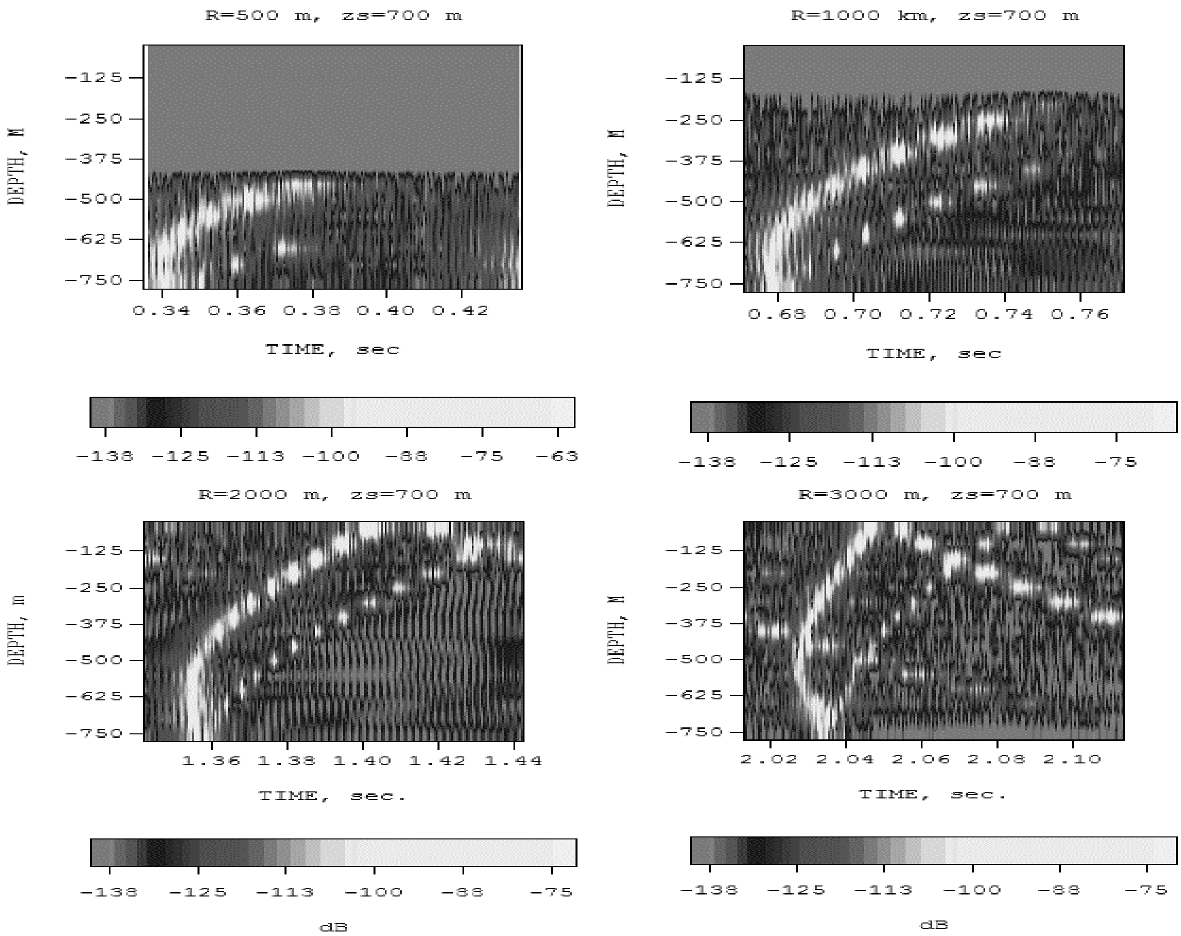

FIGURE 7. Depth-time sound pressure levels for the omnidirectional source for four fixed ranges between the source and the receiver.

receiver. The simulation results clearly indicate that the detectability of the acoustically active foraging animals by a surface array increases with an increase in the horizontal separation. The surface reflected arrivals are delayed by more than 80 msec at bottom hydrophones and should not overlap with direct or bottom-reflected arrivals. The direct and bottom-reflected arrivals can be successfully resolved for narrow directional clicks when an animal is up to 2 km away from the receiver. The temporal delay between these two arrivals can be utilized for developing a tracking algorithm based on single hydrophone recordings [8-10].

CONCLUSIONS

The results of acoustic propagation modeling for the LADC environment suggest the interpretation of null patterns in click spectrograms as being due to distinct features of a mammal phonation apparatus. Many more groups of clicks should be similarly analyzed, and the spectra of individual isolated clicks should be compared before definite conclusions can be drawn. The development of an algorithm, which can provide the identification of individual clicks in continuous recordings, at least with some degree of statistical confidence, should also be addressed in future research.

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