ANGLE-OF-ARRIVAL ESTIMATION IN SHALLOW WATERS USING A LINEAR ARRAY

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Abstract: *Shallow water acoustic communication systems are key to efficient monitoring of territorial waters, with both civilian and military purposes. Being able to reach a vessel, or a station, located miles off the coast with minimum disturbance to marine life is a clear advantage and must be a designer's target. Beamforming is a valuable asset for improving untethered communication efficiency and range, and angle-of-arrival (AoA) estimation is an important part of beamforming design. In this paper, we show the first results of AoA estimation tests conducted at Enseada dos Anjos, located in the northeast coast of the State of Rio de Janeiro, Brazil. We used a receiver specially designed and constructed for the experiment, consisting of a linear array of eight uniformly spaced underwater acoustic sensors. We provide a detailed description of the array, including how the acceptance and calibration tests were carried out, as well as measured and theoretical directional responses of the array for a set of frequencies ranging from 6.46kHz to 8.46kHz. The main goal of the experiment in the ocean was to analyze and compare vertical AoA patterns of the signal received at the array calculated with the MUSIC algorithm using spatial smoothing, with those predicted from simulations with the BELLHOP finite element beam code. In our simulations, bathymetric data was obtained from a nautical chart, and the sound speed profile was calculated with the aid of a CTD (Conductivity, Temperature, Depth) sensor. For the experiment, the receiver apparatus was installed in a vessel positioned within the line-of-sight of an omnidirectional transmitter installed in an anchored ferry. The results obtained at four different distances, ranging from 150 meters up to 1684 meters, showed excellent agreement with the model, which indicates its suitability for shallow water AoA estimation.*

Keywords: *Angle-of-arrival, shallow water, underwater acoustic communication*

1. INTRODUCTION

Monitoring the underwater environment has strategical importance to all modern nations with both military and civilian applications. Being able to communicate with underwater stations improves safety in operations in the oil and gas industry, with faster response to disasters and even the ability to anticipate faults with increased situational awareness. Moving data to and from remotely located sensors is as important as collecting them. Submarines need to remain unnoticed while patrolling near the coast, but need to be reached during routine or tactical military operations without surfacing.

Communication efficiency is improved in receivers when the directions of the beams match the directions of arrival of desired signals. In transmitters, efficiency is improved when beams point in the directions that will more easily reach the target. In any case, if beamforming is to be used, transceiver front-end design benefits greatly if knowledge of these directions is either available, or can be estimated. Beamforming is one of many signal processing techniques capable to enhance communication range when severe energy constraints are enforced [1]. With an appropriate linear combination of the signals captured by an array of sensors, considered isotropic, reception beams are formed towards desired directions. Similar reasoning applies to transmission beamformers.

With a coastline of more than 7000 km, Brazil is well aware of the importance of underwater communication to maintain sovereignty in its territorial waters. Several funding initiatives have spawned multidisciplinary research and development teams with interests in marine life surveillance, oil and gas industry, and military communications. In this context, IEAPM (Institute of Sea Studies Admiral Paulo Moreira) is a key national player, due to its localization in the northeast coast of the Rio de Janeiro State, relatively close to marine life sanctuaries, touristic hotspots and undersea oil fields.

In this paper, we report the results of a series of experiments carried out by UFRJ in cooperation with IEAPM to estimate the vertical angle of arrival of signals impinging a receiver in shallow water. Simulation results using ray tracing were compared to the measurements. In the next sections, we describe the uniform linear array (ULA) used in the experiments, the experiment setup, the results obtained, and some conclusions.

2. THE UNIFORM LINEAR ARRAY

Arrays may have sensors placed according to different geometries; they can be linear, planar, or spatial, with different capacities in terms of resolving azimuth and elevation angles. In our experiments, we used a uniform linear array with eight sensors, which means that there were eight underwater acoustic transducers equally spaced along a line. Figure 1 illustrates a typical ULA with N sensors.

The resulting beamforming is called narrowband, given that it cannot discriminate different frequencies [1]. For a particular choice of the coefficients that weight the signals captured by the sensors, we can steer the lobes of the array's spatial response, called beampattern, towards a desired direction, as illustrated in Figure 2

We built our 8-sensor ULA based on piezoelectric ceramics spaced 10.5cm apart, and held under pressure in a four-rod metallic cage by rubber rings, as illustrated in Figure 3. The metallic cage was encapsulated in a rubber tube and filled with a fluid which approximates the water acoustic impedance. At the top of the array, a sealed box was custom-made in nylon to hold the electronics, which consists of eight identical preamplifiers designed as balanced common-mode rejection amplifiers with 50dB gain at 7240Hz. Each pre-amplifier was fed by signals coming from two second-order highpass filters with cutoff frequency set at 4093Hz, one for each terminal of the piezoelectric ceramic. Figures 4 and 5 show the highpass filter and pre-amplifier circuitry. After amplification, the output of the each pre-amplifier was fed to a balanced-unbalanced (BALUN) amplifier for mitigating noise at the differential input of the data acquisition equipment. The circuits were individually tuned for identical performance. Figures 6 and 7 show the BALUN circuit and a picture of the final circuitry placed inside the sealed box.

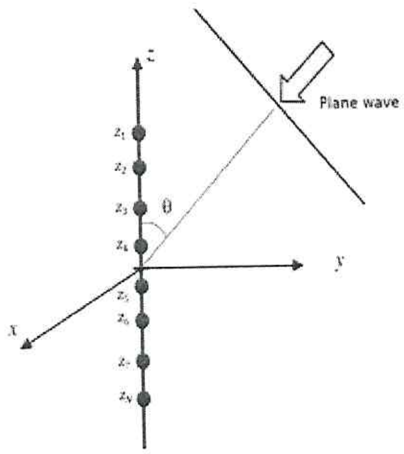

Fig. 1: Uniform Linear Array.

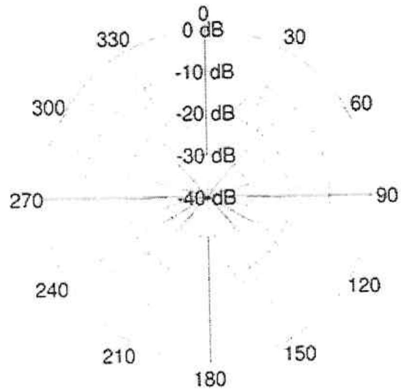

Fig. 2: Beampattern of an ULA steered to 60°.

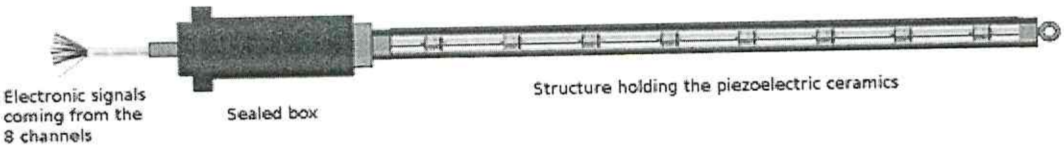

Fig. 3: Illustration of the 8 sensor ULA.

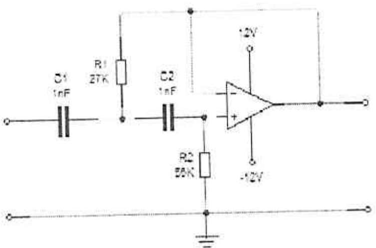

Fig. 4: Second-order highpass filter.

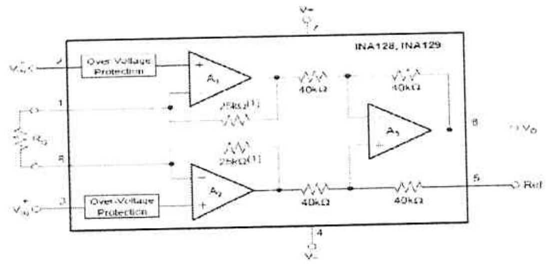

Fig. 5: 50dB-gain pre-amplifier.

The directional response of the array was obtained in a tank with the array placed in the horizontal position. Measurements were taken at intervals of 0.5°. The distance between the projector and the array was greater than L^2/λ, where L is the maximum separation between sensors and λ was the wavelength [2]. We discarded from the received signals the reflections of the tank walls and added the signals from the eight sensors for each angle. Figure 8 shows the measured beampattern compared to the theoretical beampattern of a uniformly weighted linear array with similar construction parameters. Although the absolute zeros have been lost, there is remarkable agreement as far as gain, sidelobe rejection, and directivity are concerned

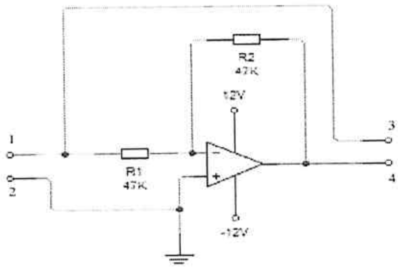

Fig. 6: BALUN amplifier.

Fig. 7: Array electronics for the eight ceramics.

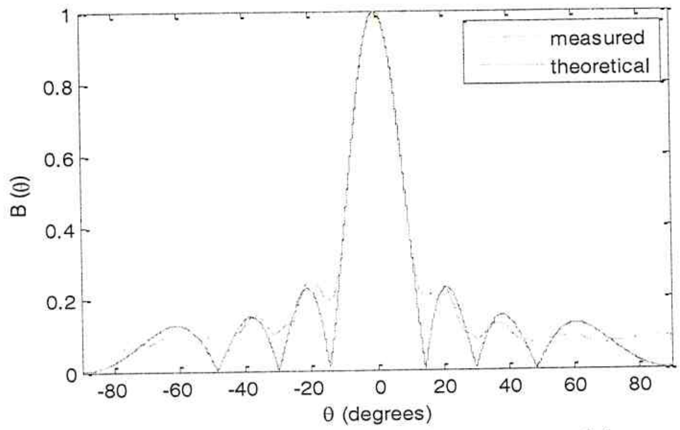

Fig. 8: Measured and theoretical responses of the array.

3. EXPERIMENT SETUP AND RESULTS

The goal of our experiments was to estimate the angular spread of signals transmitted using an omnidirectional source in shallow water. The signals were captured by the sensors in the array, recorded, processed, and the obtained magnitude response as a function of the angle of arrival was compared with simulation results.

The reception setup consisted of a portable data recorder Dash 8HF-HS connected to a 1kW voltage inverter Hartronic E-1k0-1211 with power supplied by a 60Ah automotive battery. Power for the array circuitry was supplied by two 12VDC/5Ah batteries. Common "ground" was done by a steel plate thrown in the water.

The transmission setup consisted of a diesel generator supplying power to a laptop computer feeding a 10V analog output module from National Instruments (NI9269), a Crown CDI6000 power amplifier, a transformer to raise voltage and match impedance, and a spherical transducer ITC-1001. Common "ground" was also done by a steel plate thrown in the water. The transmitted signals were continually monitored using a Tektronix TDS2004B oscilloscope. The transducer was previously calibrated within the frequency range of interest.

The experiments were carried out in Arraial do Cabo, with the transmitting gear placed on-board an anchored ferry, in a configuration similar to that illustrated in Figure 9. The receiver was placed in four different positions, with distances ranging from 150 meters up to 1684 meters from the transmitter, in a configuration similar to that illustrated in Figure 10 for the first three experiments. In the fourth experiment, the array was not fixed to the bottom of the ocean. In the figure, the device marked with number 3 is a mini Valeport CTD sensor, the devices marked with numbers 6 and 8 are pressure sensors, and number 12 indicates a GPS.

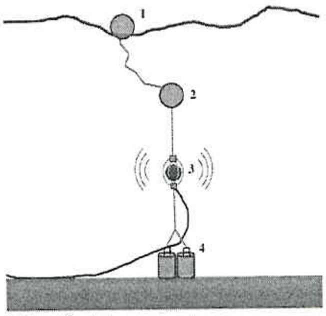

Fig. 9: Transmission gear.

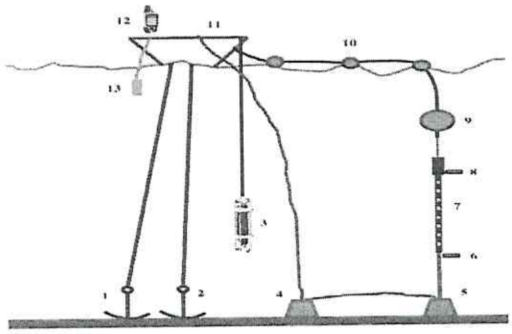

Fig. 10: Reception gear.

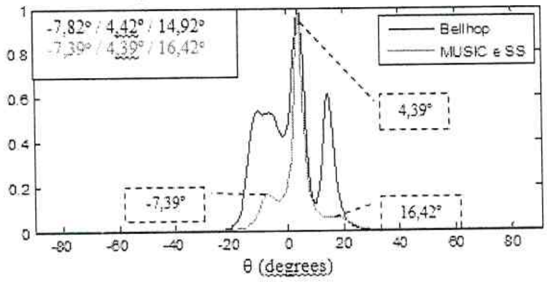

Fig. 11: Target at 152m distance, transmitter at 5m depth, receiver at 7.6m depth.

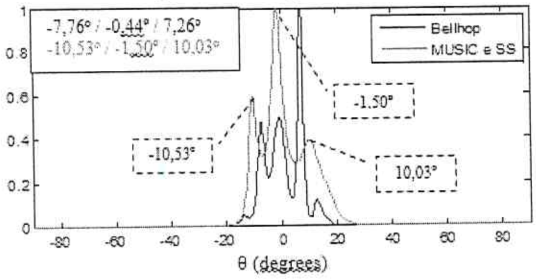

Fig. 12: Target at 343m, transmitter at 5.9m depth and receiver at 10.3m depth.

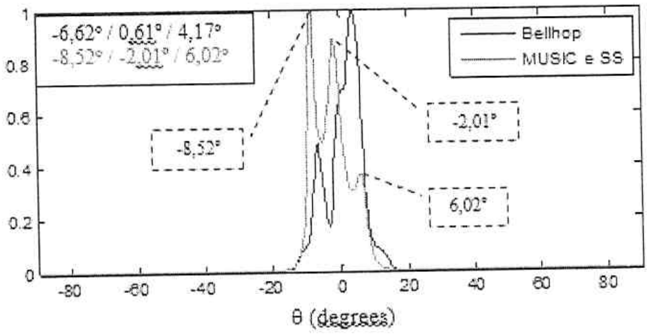

Fig. 13: Target at 556m distance, transmitter at 5.9m depth and receiver at 12.8m depth.

We transmitted streams of 1000 or 10000 randomly generated bits at a rate of 128bps using 2-FSK modulation with Hann pulse formatting for a bandwidth of approximately 362Hz, centered at 7240Hz. The beginning of the streams was marked by a 100ms chirp followed by 400ms of guard period.

We calculated the beampattern using the signals captured by the array and using the spatial smoothing (SS) MUSIC algorithm [3][4]. These measured beampatterns were compared with those obtained using the BELLHOP model from the Acoustics Toolbox [5] with MATLAB. BELLHOP uses ray tracing for estimating several useful quantities in underwater acoustics, such as those related to multipath with individual calculations for path loss, direction of arrival, propagating time, and phase distortion. As input information, the software uses a comprehensive set of data from the environment, such as bathymetric data, link length, sound speed, depth of transmitter and receiver, ocean surface and bottom characteristics, etc. We collected this information from the CTD and pressure sensors, and from a nautical chart.

Figures 11 to 13 show the results of three experiments, where the target was located at 152m, 343m, and 556m from the receiver, respectively. Although the gains at angles which correspond to measured peaks did not match perfectly those obtained from simulations, the observed angles for the main lobe and for the sidelobes did agree well with simulations. Furthermore, the angular spread of the measured magnitude response matched closely the results from the simulations. For the fourth experiment, the array was not at a fixed depth. The distance between receiver and transmitter was equal to 1684m, and the array was placed at 10 different depths, from 3.3m to 12.5m with the transmitter at 8.8m. Table 1 shows average measured angular ranges.

Depth	3.3m	4.2m	5.2m	6.3m	7.3m	8.3m	9.3m	10.3m	11.3m	12.5m
$\Delta\theta$	24.4°	27.1°	22.6°	13.0°	33.3°	26.2°	25.4°	26.6°	19.3°	16.2°

Table 1: Measured angular ranges at different depths.

4. CONCLUSIONS

We performed several measurements using an ULA for estimating the angle of arrival of signals transmitted using an omnidirectional source in shallow water. In our experiments, we were able to verify that the channel magnitude response as a function of angle of arrival is time varying and does not match perfectly the simulations, even if very accurate ray-tracing models are used together with actual data from the evironment, such as sound-speed profile, CTD information, and bathymetric data from nautical charts. However, if one is interested in the breadth of angular spread, simulations can be a valuable asset for receiver design. Furthermore, in our experiments, this angular spread was relatively narrow, which justifies the use of a receiving array in underwater communication modems.

5. ACKNOWLEDGEMENTS

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