Development of a linear towed system for underwater acoustic measurements in shallow waters

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Abstract

The Underwater Acoustics Research Group of the Federal University of Santa Catarina develops studies on acoustic propagation in the water column, interaction of the sound field with the ocean bottom and underwater acoustics signal processing. Aiming to develop knowledge on the underwater acoustics experimental field, and concomitantly, obtain data to validate the studies of the group, an underwater acquisition system adapted for shallow waters has been developed. This paper describes the design and assembly steps of the acquisition system, as well as the data acquisition software. The designed system can be used, among others, to validate deconvolution and matched filter techniques, surface and subsurface imaging using image source and shallow water seismic techniques and in the estimation of the type of sediment that composes the seabed. The system may also supply a set of real data useful for future studies.

Introduction

The growing of civil and military activities in coastal region leads to a constant need of development and improvement of tools to study shallow waters environments. Considering this, the Underwater Acoustics Research Group of the Federal University of Santa Catarina (UFSC) has been developing research in underwater acoustics, mainly in the topics of acoustic propagation in underwater environment, acoustic interaction with the seafloor, sonar algorithms, arrays and seismic signal processing. In addition to theoretical research, the group seeks to develop the knowledge in the experimental field in order to validate theoretical models implemented in previous studies. For this, an underwater experimental system has been designed and manufactured. This work aims to describe the system designing process as well as details in its assembly and use. Also, the signals used to ensonify the environment and the software developed to manage the measurements are presented, together with preliminary data obtained with the system.

Method

The system design was done considering three main experiments: detection of buried objects using the image source method (PINSON et al., 2014), obtainment of reflection coefficient of the seafloor for different incident angles (BOUSFIELD, 2014) and validation of acoustic propagation models in underwater environment (CARVALHO; CORDIOLI, 2014). Each test has specific requirements and the system was designed to meet in the best way the largest number of them. Also, the manufacturing of a flexible system that can be modified for different survey configurations was pursued. Next paragraphs describe the system requirements and the specifications that were raised based in these requirements.

Regarding the experiments requirements, an individual analysis of each study to be validated can be done. Considering the detection of buried objects using the image source method, a linear horizontal array of sensors towed behind a sound source is required. The method uses sound pressure data measured by an array to perform the Kirchhoff migration and consequently image the substrate layers, as described by Pinson et al. (2014). Considerations regarding the array's dimensions and number of sensors can be found in Azevedo et al. (2015). A common number of sensors found in this kind of array range between 12 and 40 hydrophones.

To obtain the curves of the variation of the seafloor reflection coefficient usually a vertical array of sensors is used, in order to obtain wavefronts coming from different angles (ISAKSON et al., 2005). Nonetheless, it was decided to use an horizontal array for the purpose of reuse the system employed for the image source method. In this case, the array needs to have larger dimensions, in order to be able to capture incident waves with low grazing angles. A typical requirement for this kind of experiment would involve an array covering grazing angles from 20° to 80°, with minimum spacing of 10°. In the case of a horizontal array, hydrophones position must be calculated based in a specific depth, that should be chosen considering the size of the array and the environment reverberation for this depth.

Regarding validation of the acoustic propagation models in marine environment there is no specific requirements. Studies will aim on the attempt to reproduce the direct wave signals captured by a set of hydrophones, focusing on the travel time, phase and amplitude of the signal. In this case, the requirements are just a sound source and hydrophones positioned in different distances from this source.

Limitations of the project are summarized by the equipment available for the construction of the system and by the budget. Regarding the sensor array, only 20 hydrophones were available. The budget for the acoustic source allowed purchase only one unit and the budget for assembly materials and catamaran manufacturing had to be kept to a minimum. Equipment for analog signal acquisition and generation were also limited to those already available in the laboratory.

To meet the established limitations and requirements, the system was designed to have four main components: a support boat, responsible for towing the whole system and to house electronic equipments and operators; a catamaran supporting an acoustic source that is connected to the hydrophone array; the array itself, compound by 20 sensors arranged in line; and a carrier system, responsible for keep the array in the desired depth. The concept of the system is illustrated in Figure 1.

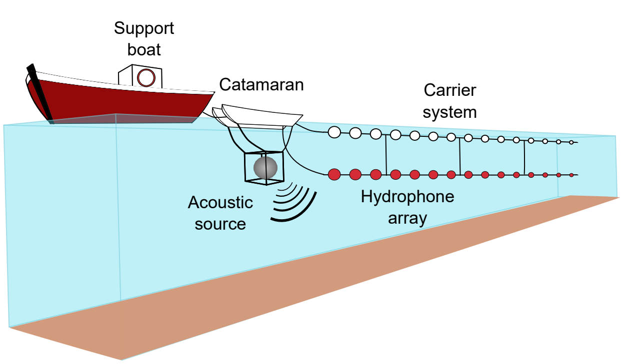


Figure 1: Conceptual illustration of the linear two dimensional acquisition system.

The hydrophone array was designed to meet the requirements of the image source method and of the seafloor reflection coefficient research. In this way, 16 hydrophones were selected to create an array for image source processing and four hydrophones summed with those to get information of the variation of reflection pattern with the grazing angles. The hydrophones were respectively called seismic hydrophones and angle hydrophones.

It was decided to operate the sensor array in a depth of 2 m to avoid sea ripple effects and surface reflection events. A submerged array ensures stable navigation and prevent that the hydrophones eventually leave the water and stop receiving acoustic signals. To ensure the desired depth for all the array a carrier system was designed. The carrier system uses buoys to stay at the surface and have cables that are connected to the array.

Angle hydrophones were placed in order to obtain specific grazing angles for a depth of 9 m (this depth was select in view of possible testing sites). In general, deeper regions provide more robust data due the reduced reverberation and the longest time for wave propagation before the reflection. Nonetheless, as the depth increases there is a need to increase the required array length to measure incoming waves from low grazing angles. The 9 m depth value was chosen to keep the array with restricted dimensions, facilitating its manufacturing and reducing the cost with materials. Table 1 shows the distances of each hydrophone in relation to the source centre to recover data from grazing angles of 20°, 30°, 40° and 80°, considering a 9 m depth water column. Angles between 40° and 80° are covered by the seismic hydrophones (Table 2) and do not need to be covered by angle hydrophones. Figure 2 shows the system configuration layout, in which the green circles represent the angle hydrophones and the purple represent the seismic hydrophones. Is important to notice that the system can be normally used in other depths, wherein the grazing angles measured by each hydrophone will only not match the ones given by Tables 1 and 2.

Table 1: Position of angle hydrophones in relation to the source centre and the related grazing angles.

Position [m]	2.47	16.08	24.24	38.46
Grazing angle	80°	40°	30°	20°

Seismic hydrophones were placed 0.35 m apart, totalizing a 5.60 m aperture, with the center of the aperture localized at 7 m from the acoustic source. The separation between hydrophones was chosen aiming to maximize the array's response for 2 kHz, considering half wavelength of the desired frequency. Frequency of 2 kHz was chosen considering acoustic wave penetration in the seafloor, array dimension and frequency peak of the acoustic source.

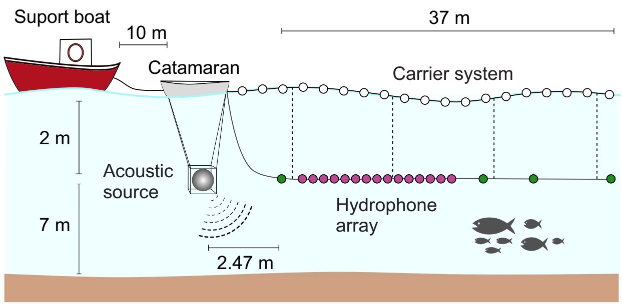


Figure 2: System layout.

Table 2 shows the positions of each seismic hydrophone in relation to acoustic source centre and the respective grazing angles related to those distances, considering a 9 m depth water column.

Table 2: Position of seismic hydrophones in relation to the source centre and the related grazing angles.

Position [m]	9.45	9.10	8.75	8.40
Grazing angle	56.0°	57.0°	58.0°	59.0°
Position [m]	8.05	7.70	7.35	7.00
Grazing angle	60.1°	61.2°	62.3°	63.4°
Position [m]	6.65	6.30	5.95	5.60
Grazing angle	64.6°	65.7°	67.0°	68.2°
Position [m]	5.25	4.90	4.55	4.20
Grazing angle	69.4°	70.7°	72.0°	73.3°

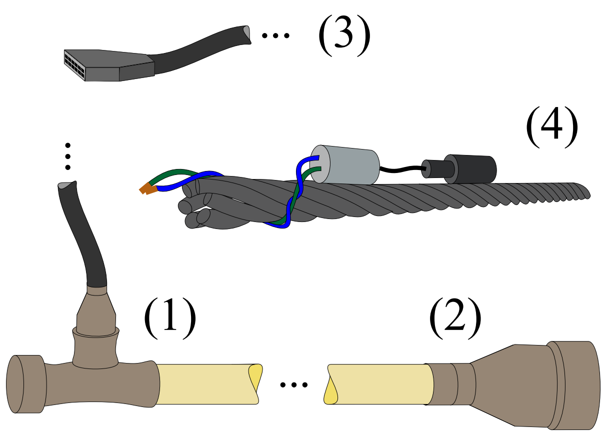
Instrumentation selection was done by robustness criteria. In this sense, most of the selected electronic equipments are commercial and just the manufacturing and assembling of the system was done internally to the laboratory. For the sensor array, 20 piezoelectric hydrophones from Benthowave, type BIII-7140, were used, which can operate in the frequency range of 0.1 Hz to 160 kHz. Simple preamplifiers for these hydrophones were designed using IEPE (Integrated Electronic Piezoelectric) paradigm, requiring a polarization current which is provided by the acquisition board. The preamplifiers were made in the laboratory, enclosed in a plastic cylinder which was filled with silicone. A reference hydrophone from Brüel & Kjær, Type 8104, was used to gauge the hydrophone array. Its frequency operation range from 0.1 Hz to 120 kHz and its sensitivity is calibrated before every measurement using the calibrator B&K Type 4229. Pre-amplification of the reference hydrophone was done using B&K Type 2626 amplifier.

Regarding sound generation, a Lubell LL-1424HP piezoelectric transducer was used, with operation frequency ranging from 200 Hz to 9 kHz and capable of generating signals up to 197 dB in a frequency of 600 Hz (ref 1 µPa @ 1 m). Signals sent to the transducer are amplified by a Crown CDi 2000 power amplifier, with 1600 W of power in bridge mode (used by the source) and plane frequency response between 20 Hz and 20 kHz. A bridging box, model AC1424HP, was used to do the impedance matching between the acoustic source and the power amplifier.

For signal generation and data acquisition, two systems from National Instruments were used. Signal generation was done using a NI USB-4431 board, with $\pm$3.5 V output, sampling rate of 102.4 kHz and 24 bits resolution. The acquisition was done through five NI-9233 modules connected in a NI cDAQ-9172 chassis, which allow a 50 kHz sampling rate with resolution of 24 bits. The interface with A/D and D/A boards was done using a laptop. With all instruments grouped together, the maximum analysis frequency of the acquisition system (acquisition board and hydrophones) was limited to 25 kHz while the generation system operates up to 8 kHz. The extended range for acquisition was chosen to allow a more detailed analysis of the environmental noise.

The hydrophone array manufacturing was based on a guide to constructing hydrophone arrays from NOAA (National Oceanic & Atmospheric Administration) developed by Rankin et al. (2013). The core of its construction was a 1/8 inch steel cable, which provides resistance to navigation stress. The hydrophones were placed along the steel cable according to its positions and its data cables were rolled up in it. To finalize, the array was enclosed in a flexible 1" PVC hose and filled with soybean oil. Hose and oil provide protection for the hydrophones and improve the impedance matching between sensors and water column. Usually castor oil is used for this purposes, however soybean oil was opted for its ease of access and because can exert the same function. The extremities of the array were built with rigid PVC, as well as the coupling between the hydrophone array and the data cable.

A data cable was designed to carry the voltage signals from the hydrophone array to the acquisition board. It was manufactured with 20 ground/phase pairs of 0.5 mm thick copper wires that wrap around a steel cable to ensure stress resistance. The connection of the data cable with the acquisition board was done with a mechanical fuse, that automatically disconnects in case of excess of stress, safeguarding the electronic system. The cables are enveloped by a plastic shield and a metallic shield to prevent electromagnetic noise contamination. Finally, a flexible hose was used to enclose the data cable, to ensure robustness and sealing. Figure 3(a) depicts the array components, including the frontal extremity with the coupling between the hydrophone array and the data cable (1), the tail (2), the mechanical fuse of the data cable (3) and position of a hydrophone in the core steel cable (4). The real assembly of a hydrophone can be seen in Figure 3(b).



(a) Array components.

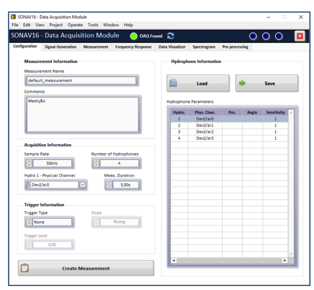
(b) Hydrofone in the array.

Figure 3: Hydrophone array.

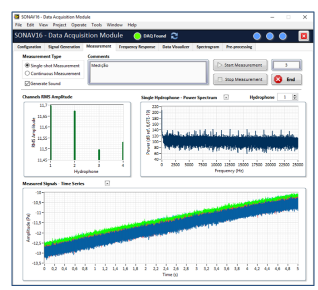
The catamaran was built with marine plywood and sealed with waterproofing ink. The system that lift the acoustic source and the carrier system were made using 12 mm braid polyester rope. The buoyancy of the carrier system was guaranteed through 50 fishing net floats of 10 cm. A float with keels made of PVC was placed at the tail of the carrier system in order to create a drag pattern and keep the system aligned during navigation. All connections between systems were made using snap hooks to ensure their fast assembly. The finished catamaran with the acoustic source positioned and fixed with the lifting rope, the hydrophone array, the data cable and the connection of the carrier system can be seen in Figure 4.

Figure 4: Built catamaran.

A software was created to manage the whole chain of experiments using the developed system. The software was coded in LabView in view of its good interface with the used data acquisition system and allows the configuration of the measurement (including acquisition channel selection, sampling rate and acquisition duration), signal generation for the sound source, real-time visualization of the measured data and data analysis (including frequency response function, spectrogram, matched filter, among others). Figure 5 shows some screens of the developed software.



(a) Channel selection.



(b) Time and frequency data visualization.

Figure 5: Interface of the developed software.

Results

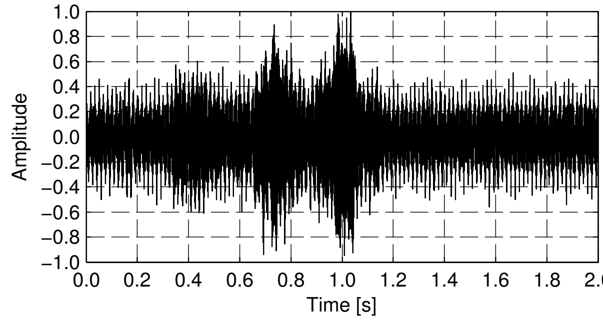
Preliminary tests were done at the Coastal Oceanography Laboratory (LOC) in Florianópolis, on a 4 m depth lake lane (Figure 6). The objective was to evaluate the stability and robustness of the system, to assert it use in a marine environment. In these tests the support boat was not used and conventional electrical network was used to power the instrumentation. However, for real surveys a power generator must be used and the effects of its electrical noise must be taken into account, as well as the noise of the support boat.

Figure 6: Preliminary test in the Coastal Oceanography Laboratory.

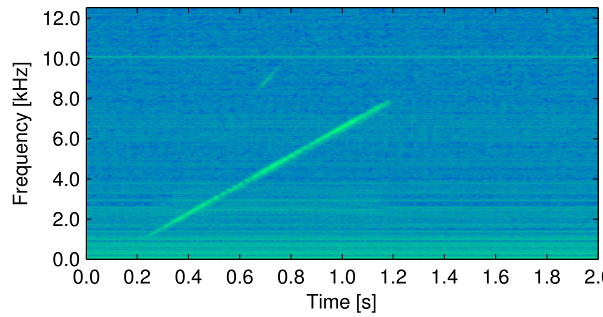
A CHIRP signal was used to ensonify the environment in order to ensure range resolution (in the direction of wave propagation) and signal to noise ratio. With this type of signal the range resolution required for shallow waters can be achieved using matched filter techniques (RISTOW, 2015) while a long duration signal (and consequently high energy) is used. Low frequency signals were prioritized due the need of acoustic penetration in the substrate and the frequency range used was from 800 Hz to 8 kHz, which ensures a theoretical range resolution of 0.1 m after the matched filter. The duration of the emitted signal was 1 s to ensure an appropriate signal to noise ratio. To protect the sound source and avoid signal distortions a Gaussian window was applied to the first and last 10% of the signal.

Figure 7(a) shows a time domain signal acquired from a hydrophone of the array. Figure 7(b) shows its respective spectrogram, where is possible to see that the entire frequency range of the CHIRP signal is is generated and recorded.

The effect of the matched filter applied in all channels can be seen in Figure 8. The gain in range resolution is evident compared to Figure 7(a). The first peak in each signal is related to electronic noise associated to the shot of the acoustic source. This peak allows the calculation of the travel time, since the signal acquisition and generation are not synchronized. Subsequent peaks corresponds to the direct path of the acoustic signal and the reflections in the seafloor and the surface. The difference in travel time of each channel caused by different positions of the hydrophones can also be seen in Figure 8.



(a) Time series.



(b) Spectrogram.

Figure 7: Raw data recorded by one hydrophone of the array.

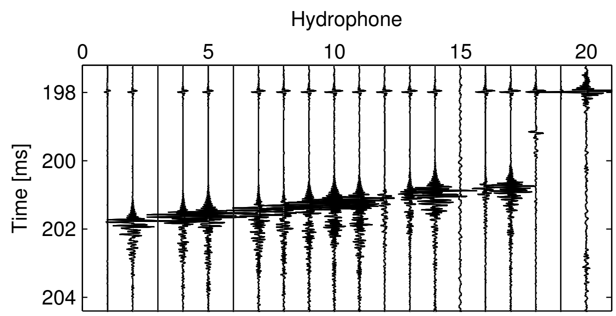


Figure 8: Processed data from all hydrophones for a single shot.

The tests shown that the system have adequate buoyancy, stability and navigation for sea trials. The carrier system and the couplings showed up secure and capable of keeping the array at the desired depth during navigation. The software was able to meet the trial demands and correctly control all the instrumentation. The sound pressure data measured by the array are coherent with the signal generated by the acoustic source and the reflections can be distinguished amid the noise using the matched filter. The measured travel times for each hydrophone are proportional to its respective position, showing the effectiveness of the matched filter processing the data. Lastly, some channels have shown problems in signal reception, that can be related to broken wires or hydrophone malfunction. These channels will be verified to correct the problems and ensure full coverage for angles from 20° to 80°.

Conclusions

This paper described the specification design and manufacturing of a linear tow system for shallow waters acoustics measurements. The equipment was developed to perform the imaging of subsurface layers and to recover reflection coefficient curves for different substrates. The system try-out was done in a calm lake, but the buoyancy and navigation tests have shown that the system is suitable for sea use. Initial measurements have shown that the instrumentation is performing as expected. In this way, the system is ready for real measurements. The confection of the system provided to the group an increase in the knowledge in underwater equipment design and the possibility of realize experimental surveys in open field.

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