Journal of Communication and Computer 10 (2013) 72-81

A novel Matlab-based underwater acoustic channel simulator

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Received: May 2, 2012 / Accepted: June 2, 2012 / Published: January 31, 2013.

Abstract: An accurate modeling of the underwater acoustic channel (UAC) can facilitate the development of an efficient architecture for an underwater acoustic modem (UAM). The performance comparison of different architectures can be performed rapidly and at a low cost in a simulation environment, compared to testing the modems in sea water. This article presents the development and utilization of an underwater acoustic channel simulator. The simulator can be used by a communications engineer in characterizing the time variability of the physical channel's parameters or by a hardware engineer in designing an underwater acoustic modem. This tool is programmed in Matlab and is based on the algorithms Bounce and Bellhop. The input parameters of these algorithms must be saved in text files after a specific template and are cumbersome to process manually. To streamline the modeling of an UAC and the simulation of various communication algorithms the simulator automatically creates the input files based on key parameters entered by the user, hiding the algorithmic dependent ones and allows a quick visualization of the simulation results with a few routines specially created. The use of this simulator is emphasized with results obtained from the design of a low-power UAM for long-term monitoring activities.

Key words: Underwater acoustic channel simulator, underwater acoustic channel, underwater acoustic modem.

1. Introduction

When a hardware engineer wants to design a new architecture for an underwater communications system he must take into account the variability of the UAC in the location where the modem is intended to be placed. Testing the new system in a real environment is performed at a high cost because a lot of sophisticated equipment is needed. On the other hand the observation period is usually quite short while the parameters of the underwater acoustic environment might be constant. Thus the behavior of the new system must be observed when different parameters of the environment are changing. In conclusion the testing must be done in different periods of the year and this will raise the total cost of the designing process.

To overcome these shortcomings an UAS must be used to design and test the new architecture. An accurate modeling of the variation of the parameters of the underwater acoustic communication channel can facilitate the development of efficient system architecture. In Ref. [1] and Ref. [2] it was shown that the simulated impulse responses obtained after modeling the parameters of the underwater environment with real measurements were very close to those obtained from the ocean or seawater. The simulated results were obtained with the algorithms Bounce and Bellhop [3], [4]. It must be emphasized that these routines represent the core of the simulation tool described in this article. The input parameters of the algorithms must be saved in text files after a specific template and are cumbersome to process manually. To streamline the modeling of the UAC and

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the simulation of various communication algorithms the simulator, which is programmed in Matlab, automatically creates the simulation files based on key parameters entered by the user and hide the algorithmic dependent ones. The values of the dependent features were chosen so that high quality simulation results can be obtained. The key input parameters like the acoustical and geophysical parameters, the location of the emitter and receiver or the transmission frequency can be easily introduced in an xlsx file by the user. Afterwards the simulator processes this file, runs the algorithms and allows the visualization of the results.

This tool came from the need to simulate the operation of an underwater communications system at the physical level in a synthetic environment that can imitate the real one. The simulator was designed to enable the rapid configuration of the underwater environment and the modem's parameters and this was possible using Excel and Matlab.

In Ref. [1] the authors propose a simple underwater acoustic channel simulator which can predict the quality of a transmission for future field trials. The channel estimates are obtained in AcTUP (Acoustic Toolbox User interface and Post processor) [2], [3], which is a guide user interface written by Amos Maggi and Alec Duncan and can facilitates the application of different acoustic propagation codes. The signal processing scheme attempts to characterize the operation of an existing commercial modem and is presented as a block diagram. The authors emphasize the processing results and provide a brief description about the simulator's modules. There are several other free underwater simulators with which the operation of a system at the networking layer can be characterized [4]-[6].

The article is organized in the following manner. Section II presents the organization of the simulator emphasizing how the input data are introduced and how they are processed. Section III highlights the results obtained from the design of a low-power UAM for long-term monitoring activities. Section IV presents the conclusions of this article and how the simulator can be improved.

2. The Organization of the Underwater Acoustic Channel Simulator

Fig. 1 highlights the modular organization of the underwater acoustic channel simulator. The simulator is based on two routines, written in Fortran by Michael Porter, called Bounce and Bellhop [7] and are often used to simulation the propagation of high-frequency sound underwater because they produce very accurate results [8]-[10]. These routines accept text files with the input data.

A text input file, when is created, requires detailed knowledge of its structure and each parameter. An input file must be created for each particular scenario and for each transmission frequency making the file management process to become cumbersome. These inconveniences were eliminated by automating the process of creating the input files. Therefore the important input data are entered into an xlsx file and the specific parameters of the algorithms were hidden from the user, but carefully chosen in order to obtain simulation results at a good resolution without hinder the running time of the algorithms. Two routines have been developed to characterize the bathymetric profile and the organization of the sedimentary layer and also for the sea surface there are two routines to characterize the surface profile and the reflection loss at the surface.

Bounce and Bellhop algorithms will process the input files and will create amplitude-delay profiles that can be post processed with the communications module or can be plotted using the plotting module. Next the detailed structure and functionality of each module from Fig. 1 is presented.

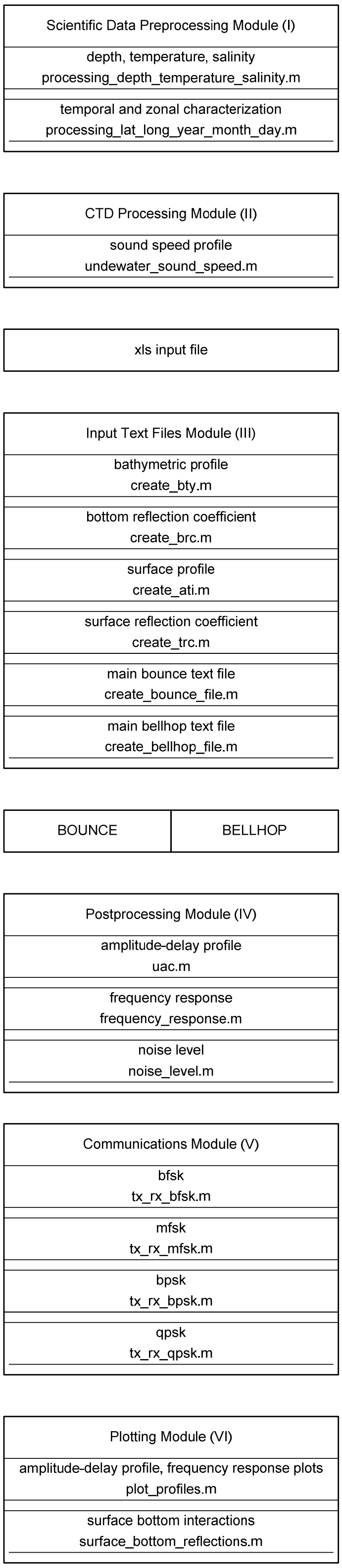

Fig. 1 The organization of the underwater acoustic channel simulator.

2.1 The Scientific Databases

The characterization of a certain area in terms of the propagation of sound underwater requires the knowledge of the acoustical and geophysical parameters. They can be found in the databases GEBCO [11], NGDC [12] and NOAA [13]. If the data are complete and have the necessary resolution, automating the process of obtaining them is natural [14]

The data on the databases highlighted above were recorded during scientific expeditions and were useful in various research projects. Depending on the purpose of the project there have been recorded only certain parameters. In some cases the recorded data are incomplete or do not have the resolution to characterize in detail the transmission of sound underwater. In other cases the data are nonexistent. In conclusion automating the process of obtaining the scientific data from the above databases is very difficult to perform and is therefore better that the data is processed by the user with a few routines.

The steps that define the data collection process are as follows. The first step is to obtain, for a certain area, the csv files in which the user can find information about the parameters. The second step is to import and process the csv files in Matlab using the routines from the Scientific Data Preprocessing Module.

Following the above steps the user obtains the location on the globe, the year, the month, the day and the time of the day the data were recorded and information about temperature, salinity and depth. In case the information about the wind speed and sedimentary composition do not exist, the user can choose general values or a thorough documentation in the scientific literature is required.

2.2 The CTD Processing Routine

The salinity, temperature and depth data, also called CTD data, are processed with the program named underwater_sound_speed.m. This routine provides the sound velocity profile and is based on the underwater sound speed equation, [15], which is highlighted in relation 1

$$c = 1449.2 + 4.6T - 5.5 \cdot 10^{-2} T^2 + 2.9 \cdot 10^{-4} T^3 + + (1.34 - 10^{-2} T)(S - 35) + 1.6 \cdot 10^{-2} z \quad (1)$$

Relation 1 is an empirical equation that is valid for $0^\circ \leq T \leq 35^\circ C$, $0 \leq S \leq 45 ‰$ and $0 \leq z \leq 1000$ m.

The sound velocity profile can be further processed to obtain velocity averages depending on the season, the mouth or the day. Afterwards the underwater sound speed and the data about the wind speed and the composition of the sedimentary layer can be introduced by the user in an xlsx file. This file will be used to automatically create the input text files for the Bounce-Bellhop algorithms.

2.3 The xlsx Input File

To allow the user a quick and easy configuration and modification of the acoustical and geophysical parameters, these input data will be entered in an xlsx file. The structure of this file is shown in Fig. 2. The user can enter in the first sheet a sound profile or a collection of sound profiles. In the second sheet the user can introduce the geophysical properties of each sedimentary layer. It must be emphasized that the organization of the first two sheets is approximately identical to the structure of the main input text files for the Bounce and Bellhop algorithms. Therefore the user will enter in the xlsx file only the important parameters. The algorithm specific parameters were masked from the user. It must be pointed out that in case there were entered several sound speed profiles, they will be processed individually and not as a 2D surface, where consecutive profiles are considered for particular locations on the transmission distance between the transmitter and receiver.

In the third sheet the user can configure the way the transmission frequencies will be interpreted. If the user wants to simulate the transmission of the underwater sound at a single frequency or for a range of frequencies, defined as $f_{\min} : \Delta f : f_{\max}$, can enter the value 1.

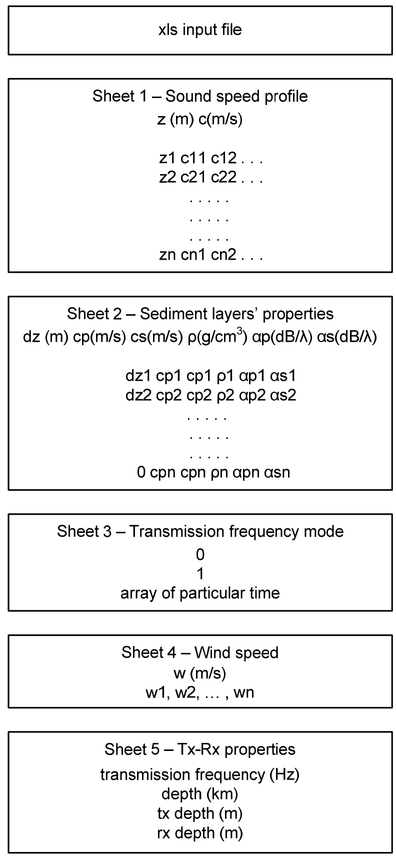

Fig. 2 The organization of the xlsx input file.

This mode is used when there is a need to know the optimal transmission frequency. If the user wants to simulate the transmission for a few random frequencies can enter the value 0. This mode is used when there is the need to characterize the transmission for each season or month of the year. For this mode the number of frequencies must be equal to the number of sound speed profiles. If the underwater sound speed is measured at intervals of a few minutes or hours during several days, the user can enter an array with the exact moments when the data were recorded. This mode is used when there is a need to characterize the transmission during the day and night.

Therefore the must define two transmission frequencies. It is known that the mean sound speed profile is different for the two periods of the day which means that there will be two optimal transmission frequencies.

In the fourth sheet the wind speed can be introduced as an average value or as an array of values for certain moments of time. In the fifth sheet the user can configured the transmission distance, the depth of the transmitter and receiver and the values of the transmission frequencies according to the parameter set in third sheet.

2.4 The Input Text Files

At this moment the program run_bellhop.m is run in Matlab, having as input parameter the xlsx file. This routine imports and processes the data from the xlsx file and calls the routines that are intended to create the input text files for the Bounce and Bellhop algorithms. The routine create_bellhop_file.m constructs the main input text file for the Bellhop algorithm.

The program create_ati.m produces a file in which the surface profile is defined as a sinusoid. The routine has two input parameters, the wind speed and the maximum depth, and computes the root mean square height and the wavelength of the sea surface with the following relations

$$h_{rms} = \frac{0.14784 v^2}{g} \quad (2)$$

$$\lambda_v = \frac{2\pi\sqrt{gd}\,v}{0.877g} \quad (3)$$

In the above relations v is the wind speed in m/s measured at an altitude of 19.5 m, g is the gravitational acceleration in m/s^2, d is the maximum depth of the water column in m, h_{rms} is the root mean square height and λ_v is the wavelength of the sea waves both in m. The above equations are based on the Pierson and Moskowitz spectrum [16].

The program create_trc.m creates a text file in which the reflection coefficient at the surface is defined. This routine has three input parameters: the transmission frequency, f, measured in Hz, the wind speed, v, in m/s and the grazing angle, θ, measured in degrees and is based on the relation 4, which is describe in detail in Ref. [17]

$$RL \approx 8.6 \cdot 10^{-2} f^2 v^4 \theta^2 \quad (4)$$

The routine create_brc.m and the Bounce algorithm create a text file in which the reflection coefficient for the sedimentary layer is defined. The routine create_bty.m creates a text file with a flat bathymetric profile.

At this moment the main text file and the auxiliary files described above are processed by Bellhop which will generate output files with the amplitude-delay profiles for each transmission frequency and for each sound profile, for the defined transmission distance and transmission-receiver depth.

2.5 The Post Processing Module

The user can use the routines of this module to process the amplitude-delay profiles and to obtain detailed information about the optimal transmission frequency, the attenuation in the underwater communication channel and the noise level.

2.6 The Plotting Module

The routines of this module can be used to plot the amplitude-delay profiles, the frequency response or the interactions of the sound waves with the sea surface and the seafloor.

2.7 The Communications Module

With the use of the routines of this module the user can simulate the transmission of digital signals in the underwater acoustic communication channel. The amplitude of the transmitted signals is computed using a specific amplification value and the transmitting voltage response of a particular transducer. Then these signals are BFSK, MFSK, BPSK, QPSK modulated and are convolved with the amplitude-delay profiles. Afterwards over the convolved signals is added white Gaussian noise with a standard deviation that depends on the wind speed. The resulted signals are passband processed and the signal-to-noise ratio is computed.

3. The simulation results

This section presents the way in which the underwater acoustic channel simulator was used in designing a low-power underwater acoustic modem for long-term monitoring activities in the north-western part of the Black Sea.

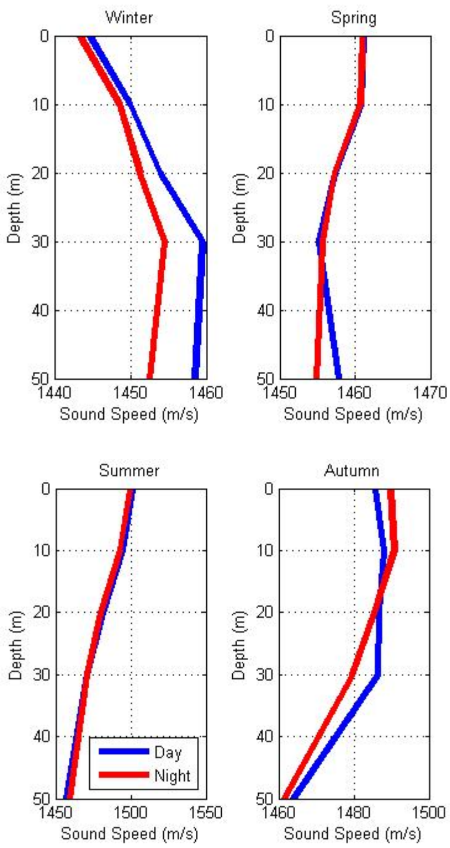

Fig. 3 Sound speed profiles organized by season and time of day.

The acoustical data were imported from NOAA database for the region of interest and were processed using the routines from the first module from Fig. 1. The CTD data were processed using the routines from the second module and the sound speed profiles were obtained. Afterwards the profiles were averaged depending on the season and the time of day and are shown in Fig. 3.

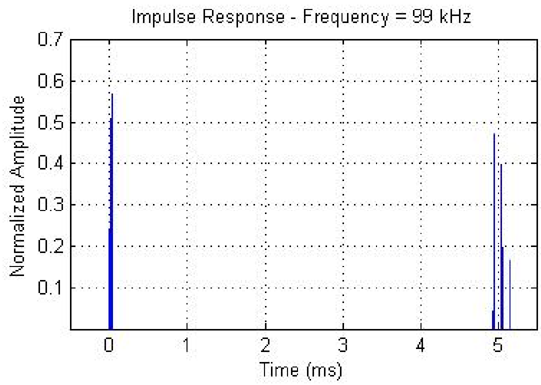

Fig. 4 A sample amplitude-delay profile.

The diurnal sound speed profiles are represented with blue and the nocturnal sound speed profiles are shown in red. The geophysical data were characterized using the information from [18]. The wind speed was chosen 10 m/s, the transmission distance was chosen 500 m, the transmitter and receiver were placed at 0.5 m above the sea floor and the simulations were done in the range 1 kHz – 99.9 kHz.

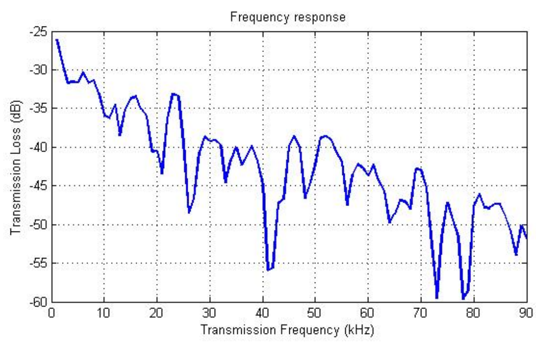

Fig. 5 A sample transmission loss profile.

An xlsx file was created using the above data then the routine run_bellhop.m was run in Matlab to obtain the simulation results. The routines from the fourth module were used to process the simulation results. The programs from the sixth module can be used to plot the results of the simulations. Thus Fig. 4 shows a sample impulse response and in Fig. 5 a sample transmission loss profile (frequency response) could be seen. Posts processing the simulation results the optimal transmission frequencies were obtained and are shown in Fig. 6.

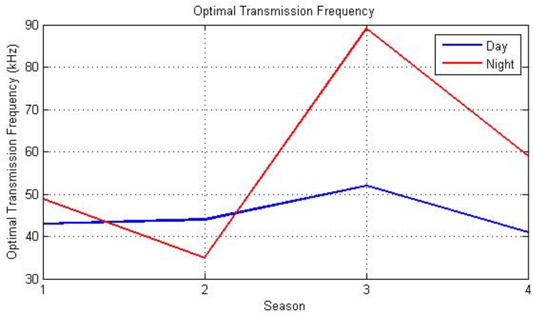

Fig. 6 Optimal transmission frequency organized by season and time of day. Season: Winter (1), Spring (2), Summer (3) and Autumn (4).

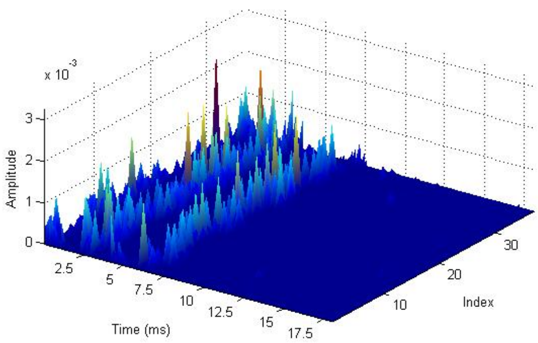

Fig. 7 A series amplitude-delay profile sample.

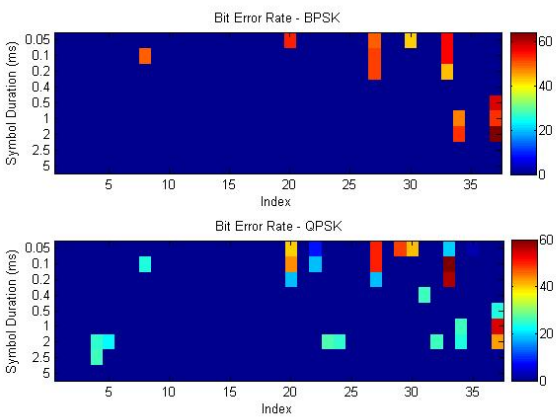

Fig. 8 Bit error rate analysis for the amplitude-delay profiles from figure 7 for BPSK and QPSK modulation schemes.

Afterwards using the optimal transmission frequencies from Fig. 6, a series of data collected in the region of interest at intervals of three hours, during several days, for a few months were processed and a series of amplitude-delay profiles were obtained. A sample of these series of profiles is displayed in Fig. 7 using the routines from the sixth module. These series were post processed with the routines from the fifth move and a sample bit error rate analysis is shown in Fig. 8.

4. Conclusions and future work

This paper presents the organization of a novel Matlab-based underwater acoustic channel simulator and the way it was used in designing a low-power underwater acoustic modem for long-term monitoring activities in the north-western part of the Black Sea. It was attempted, by creating this simulator, to fix the shortcomings of the current simulators and to allow the user a quick and easy configuration and modification of the synthetic underwater environment and the modem's parameters.

The simulator is based on two routines named Bounce and Bellhop. This tool allows the user to introduce only the important parameters and hides those that are algorithmic dependent. Using CTD data from the world's databases, wind speed values and geophysical information the user can thoroughly synthesize an underwater environment similar to the real one. The CTD data are used to characterize the variability of the sound speed profile. The wind speed values are used to create a surface profile and to compute the reflection loss at the surface and the noise level. The geophysical information is used to create a bathymetric profile and to compute the bottom reflection loss.

The user could characterize the underwater acoustic communication channel in terms of the amplitude-delay profile, the frequency response and the optimal transmission frequency. This simulator has a communications module which other simulators don't have, with which the user can compute the bit error rate for BPSK, QPSK, BFSK, MFSK digital modulation techniques. The plotting module allows a rapid visualization of the simulation results.

Currently the simulator implements only a flat seafloor, but in the future the user will be able to select from multiple choices. In addition the user will be able to choose the surface reflection loss scheme and to use the OFDM technique of transmitting digital signals, which will be implemented in the communications module.

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