REAL-TIME SIMULATION OF SENSOR REVERBERATION TIME-SERIES FROM A MOVING SONAR ARRAY

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Abstract: *Fast simulation of time-series output from the individual hydrophones of a moving sonar array is of high interest when developing and implementing new sonar algorithms, embedded applications or in training contexts. In the special case of ASW low frequency active sonar, dominating interferences are reverberation and clutter arising from the underwater environment. Modelling realistically this key effect is a challenging task in term of computational complexity and time, especially when considering modern Doppler sensitive waveforms. This paper illustrates a new method for generating efficiently reverberation time-series on hydrophones, based on a sparse representation of the impulse response between sonar and reverberating seabed or surface facets. The technique is designed to handle diverse Doppler sensitive waveforms, array geometry, self-induced Doppler and sonar motion. Underwater propagation is modelled with a Thales proprietary ray module: RAMSES, which inputs various environmental parameters, such as sound speed profile, maps of seabed depth and sediment nature, etc... We assess the benefit of the method by simulating a reverberation-limited dataset from the open literature. Comparison versus real data indicates a reasonable level of similarity with the energy distribution of the simulated signals. Moreover, the statistical validation of the matched-filter reverberation envelope ensure to control false alarm rates realistically.*

Keywords: *Sonar Modelling, Reverberation, Active Sonar, Synthesis of time-series, Doppler.*

1. INTRODUCTION

Fast and realistic simulation of raw hydrophone time series of a sonar array, prior to signal processing is of high interest and can serve several purposes, e.g. in the development, evaluation and implementation of new sonar algorithms, or in real time simulations for training. In the specific case of low-frequency active sonar for anti-submarine warfare (ASW), the dominant interferences are reverberation and clutter from the underwater environment [1-5]. Capturing these environmental effects in the simulation is essential, especially in littoral waters, as they can greatly affect system performance by masking potential threats and significantly increasing the probability of false alarms [3, 4].

Realistic modelling of the backscattered signals, especially when considering modern Doppler sensitive waveforms, is a challenging task in terms of computational complexity and time due to the complex physics of underwater propagation and the number of dimensions to explore.

The objective of this paper is to illustrate a method developed at Thales DMS for efficiently generating reverberation time series on hydrophones, based on a sparse representation of the impulse response between the reverberating seafloor or surface facets and a moving triplet array sonar. We demonstrate the utility of the method by simulating a reverberation-limited dataset from the open literature. Comparison with real data indicates a reasonable degree of similarity with the energy distribution of the simulated signals. Furthermore, statistical validation of the matched-filter reverberation envelope ensures that false alarm rates are realistically controlled.

2. SIMULATION METHOD

A general overview of the simulation procedure is given by the flowchart in Figure 1. A first part consists of a modelling of the incoherent envelope of the reverberated impulse response from the sea surface and the sea bed, which requires a fast propagation modelling algorithm. Inputs are environmental data (sea state, seafloor bathymetric and acoustic models, sound velocity profile) and sonar configuration parameters (frequency, array geometry, speed, transmitted pulse). After ray propagation with a Thales proprietary module (RAMSES), we build statistics on the distributions of eigenrays received in different directions and times. The method is based on the concept of the sparse (or "concise") impulse response introduced by Cristol & Gawel [6], where it was shown that the impulse response of surface and seafloor reverberation can be reconstructed with minimum effort from a small number of statistical moments.

In a second part, we generate time series on the array consistent with the incoherent envelop previously tabulated. The three-dimensional acoustic wavefield received at the phase centre of the array is computed by fast convolutions between the transmitted dopplerized waveforms and Monte-Carlo realizations drawn from the impulse response envelop combined with statistical assumptions (normality, K-law, etc.). Finally, hydrophone time series are synthesised after applying appropriate phase shifts to individual elements. All operations are performed on baseband signals, making the overall computation process very efficient.

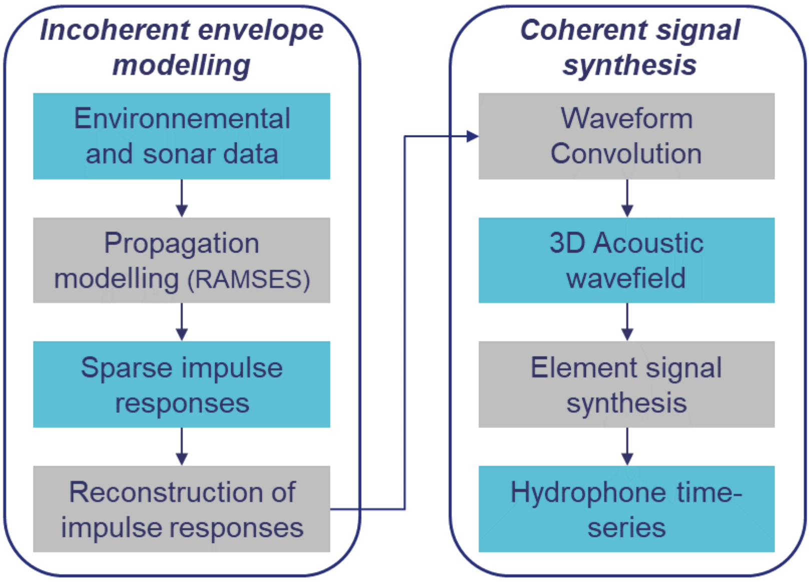

Figure 1: General procedure for hydrophone time-series generation. (In blue: data, in grey: processing)

3. SIMULATED SCENARIO

Following an approach similar to that used in [7], we compare the simulation results with previously published measured data [8] obtained in the north of La Coruña, Spain, in a highly anisotropic environment.

The ship speed (5 knots) and the array describing parameters used as simulation inputs correspond to the information published in [8], while the environmental parameters described in Figure 2 follow [7]: the sound velocity profile is constructed from a one-month average extracted from the world ocean atlas database [9], we used the GEBCO data [10] for the bathymetric model. The sediment porosity is roughly derived from classes extracted from the SHOM database [11]. We simulate three different sonar locations, indicated by a color code in Figure 2.

The transmitted pulses consist of two different waveforms: A 500 Hz, 4 s long hyperbolic frequency modulated (HFM) pulse centered at 1900 Hz and two 4 s cosine tapered CW pulses centered at 1100 Hz and 1900 Hz, in addition, the system sampling frequency is 10 kHz. For simplicity, we simulate the array as a 32λ uniform linear with 64 omnidirectional elements and generate port and starboard data independently. In all scenarios, the array is oriented in the same direction (end-fire in E-W). On each half-space, we compute eigenrays in 64 equally spaced 2D profiles, resulting in a cumulative number of approximately 10000 rays.

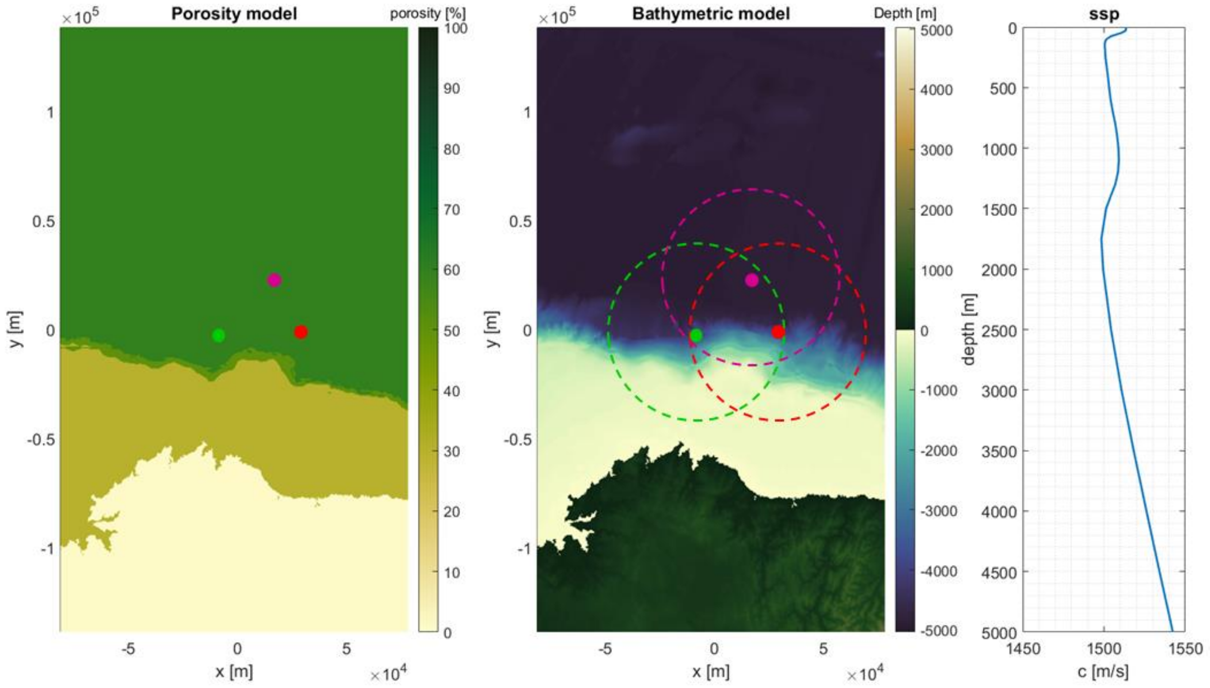

Figure 2: Environmental data used in the simulation. Left: seabed porosity model, Middle: bathymetric model, the sonar locations are indicated by coloured dots. Circles illustrates the maximum range used for modelling propagation. Right: sound speed profile.

Finally, after the procedure described in Figure 1 – the produced raw hydrophone time series are processed with a typical active sonar chain. This consists of Fourier domain beamforming followed by matched filtering in the HFM case and FFT analysis in the CW case.

4. RESULTS

Figure 3 shows the reverberation time series envelopes after beamforming and matched filtering in the HFM case, for different sonar locations indicated in Figure 1. At first order, we can see that the distribution of signal energy in pseudo time is well captured by the simulation. As in the real data (see Figure 4), we observe a significant increase in acoustic levels after a propagation time equivalent to 2.5 nautical miles. We attribute this effect to the shortest direct arrivals and therefore do not expect significant variations in travel time with sonar location and orientation. In addition, for ranges less than 5 nautical miles, the pseudo bearings are stretched towards the broadside, as most of the energy comes from beams with significant elevation angles.

The comparison between different sonar locations shows an important anisotropy towards the continental margin, where the submarine continental slope and regional reliefs contribute to spatially extended energy patches. Although differences with the real data are noticeable, we explain them by uncertainties on the real sonar location, by the simplified low resolution seafloor model (topography and sediment properties) and finally by the absence of ambient noise and volume reverberation.

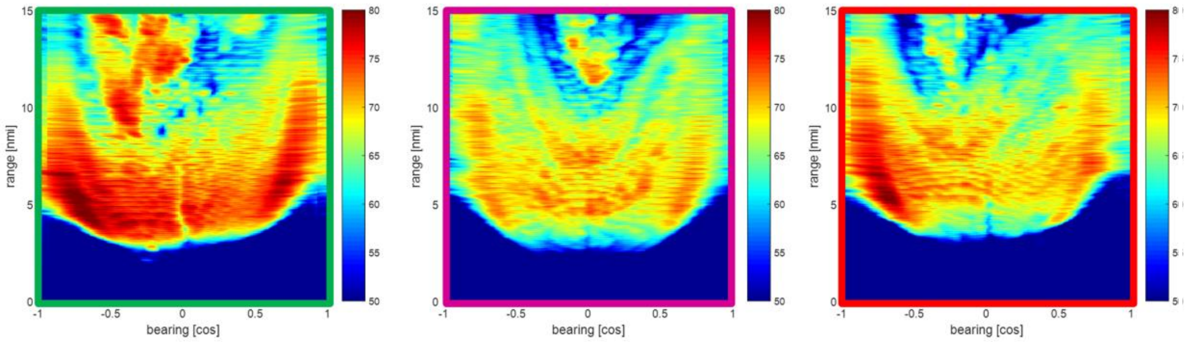

Figure 3: Simulated data after beamforming and matched-filtering (HFM case). The colour frames correspond to the three sites locations indicated in Fig.2.

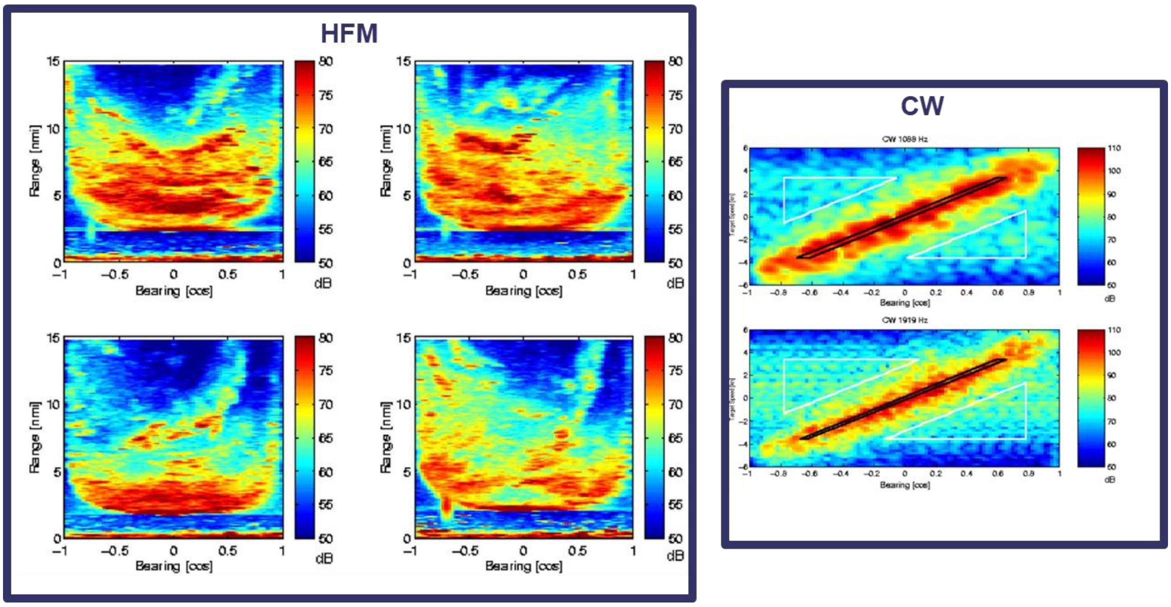

Figure 4: Experimental data originally published in [8]. Left HFM data for several locations. Right CW data for different central frequencies (1088 Hz and 1919 Hz)

A fundamental property of reverberation data is the statistical distribution of the signal envelope after beamforming and matched filtering. Controlling this property in the simulation is needed as it directly affects the probability of false alarms [3]. In the case of a homogeneous seafloor consisting of randomly distributed scatterers with Gaussian amplitude, the probability density function of the envelope will tend towards the Rayleigh distribution according to the central limit theorem if the number of scatterers per resolution is large enough. Conversely, if the number of scatterers per resolution is too small, the envelope will tend to a heavy-tailed distribution [3].

Statistical analysis of the signal envelope is performed on the HFM data set after beamforming and matched filtering, 18 seconds after transmission, in a 1-s time window and within a beam close to the broadside in the direction of the abyssal plain. Our choice of parameters is similar to the approach taken by [4] on real data and with a comparable system. The histogram computed from the distribution of the signal samples is shown in Figure 5, we observe a good fit with the Rayleigh pdf. This result is consistent with the nature of the simulated abyssal plain, which is characterised by a relatively homogeneous environment with no dominant scatterers [3,4].

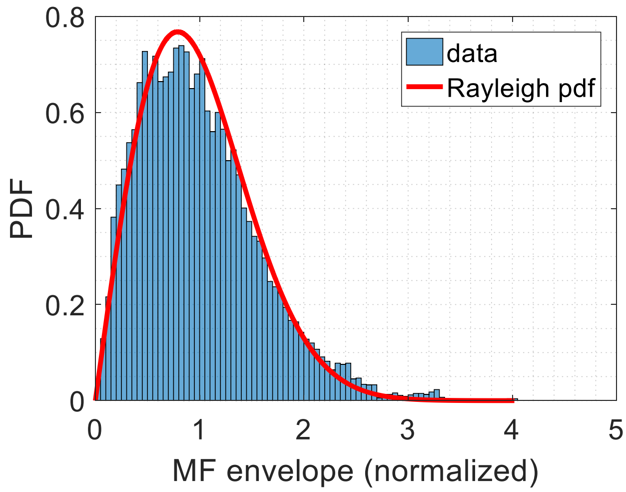

Figure 5: Normalized matched filter envelope data for a beam pointed toward the abyssal plain. The fitted Rayleigh pdf is plotted in red.

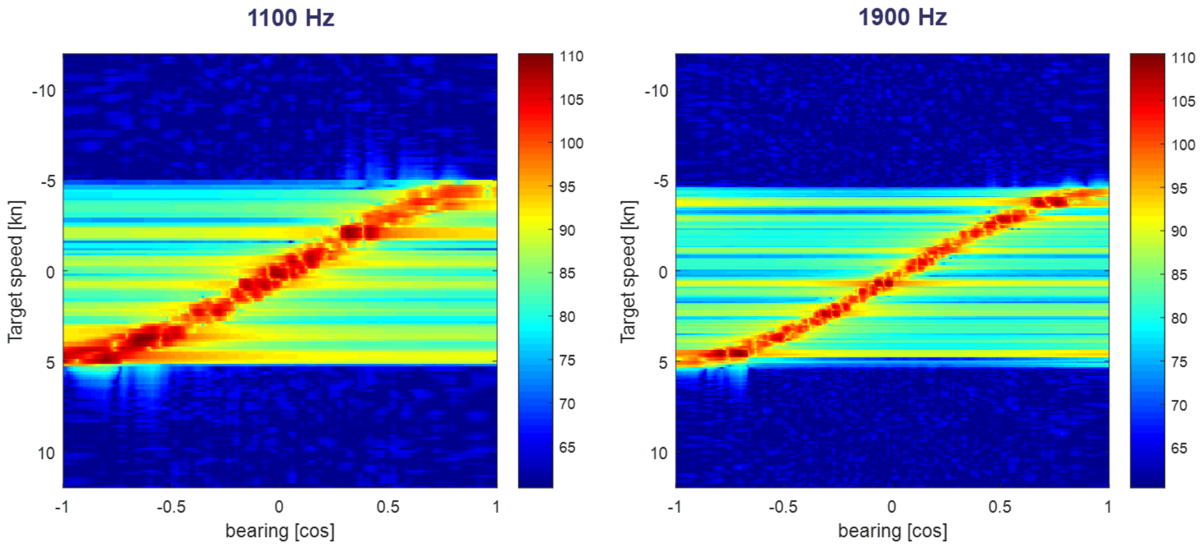

Figure 6: Doppler-bearing reverberation spectra for two CW pulses. (time slice 16-20s)

Figure 6 shows the simulated reverberation spectra of the two CW pulses (purple case) after beamforming and Doppler processing. The analysis is performed on a 4s window starting at 16s. We can see the presence of the three reverberation zones described in [8, Fig. 5]. Comparing this result with [8] (see Figure 4), we can see that the energy distribution in bearing and Doppler dimensions matches well the experimental data.

5. COMPUTATION PERFORMANCE

Processing step	***Computing time***
Propagation modelling	2s in total (37ms/sec of signal)
Convolution	5 ms /sec of signal
Hydrophone signal synthesis	30 ms /sec of signal
Inverse Fourier transform and modulation	15 ms/sec of signal
Total time	87 ms /sec of signal

Table 1: Computation time associated to the different simulation steps.

We present the measured computation time for the HFM case, estimated on a relatively modest processing unit: an Intel(R) Core(R) i5-6300 CPU @ 2.40GHz with two cores. The values associated with the different operations are given in Table 1, where times have been normalized to the length of the simulated signal. The total time required to synthesize one second of signal on a 64-element array is 87 ms which is compatible with real-time applications. These results appear to be comparable with the range of values communicated in other publications [5] (although this example differs in terms of sonar characteristics and propagation modelling approach).

6. CONCLUSION

A method for simulating active sonar reverberation time series is presented. Its performance is illustrated by comparing the simulation output with previously measured data from the open literature. The results show good agreement with real data in terms of energy distribution in the range, bearing and Doppler dimensions. Furthermore, we demonstrate the ability to reproduce seafloor topographic effects on sonar data at the scale of the continental margin, such as continental slope, seamounts and abyssal plain, or other geomorphological landscapes.

The technique presented is based on computationally efficient modelling concepts and signal processing implementations that allow individual time series of a 64-element array to be synthesised in real time.

Future development will address multi-static impulse response modelling, more complex array geometries and signal synthesis with non-Rayleigh probability density functions.

7. ACKNOWLEDGEMENTS

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