SONAR DATA SIMULATION WITH APPLICATION TO MULTI-BEAM ECHO SOUNDERS

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Abstract:

The capability to simulate sonar data is a major asset when investigating new sonar designs. It is advantageous to perform simulations of the sonar setup due to the high cost in development, prototyping and testing new sonar design and concepts.
In this work, we present a sonar data simulator built on Field II, a robust and flexible modelling environment, highly recognized and widespread in the ultrasound community. Field II models the wave-field emitted by all kind of element design with arbitrary pulse shape. Then it computes the signal recorded by the transducer from the backscattered field using the concept of spatial impulse response. We model the seafloor topography with a distribution of point scatterers associated to reflectivity values. The user can define a navigation map to position in space and time the acquisition platform relative to the bathymetric model. The output of the simulator are unprocessed channel data.
We use UltraSound ToolBox, an open access package for the processing. The workflow is fully modular and flexible. It includes pulse compression, beamforming, all processing steps are configurable. Eventually it leads to bottom detection then to a bathymetric map and the estimation of its quality.
We simulate a realistic multi-beam echo sounder setup, corresponding to a shallow-water mapping scenario. We produce synthetic data at different processing stages, from raw data to depth soundings. We illustrate the simulator's capabilities by showing the impact of the pulse form on hydrographic performance.

Keywords: *Simulation, Sonar, UltraSound, Multi-beam echo sounder.*

1. INTRODUCTION

A powerful and efficient sonar simulator is a useful asset when developing a new sonar system. Feasibility studies provide the possibility to compare setup performance in order to select the best design. It can help to isolate and understand single phenomena. Ultimately, it allows to minimize the cost of the on sea testing stages and to reduce development time.

Modelling is a major field in the underwater acoustics community, [1], [2] and [3], where the main emphasis is on acoustic propagation in the underwater environment. In this study, we intend to model a high frequency sonar system including element angular response, propagation and signal processing. We present a simulator that can generate raw sonar data from various sensor geometries and pulse forms, allowing flexibility in signal processing approaches.

The solution proposed here builds on Field II, [4] and [5]. This modelling environment has been widely used in the ultrasound community [6] and it is considered powerful and reliable. We simulate a multi-beam echo sounder (MBES), a sonar used for seafloor mapping. We generate data with Field II, process them with the open access "UltraSound Toolbox" (USTB) [7], then we evaluate and quantify mapping performance for two different pulse shapes.

2. SIMULATOR

The simulation key steps are presented in Fig. 1. Inputs to the Field II simulation engine are the number of transducers, their dimensions and positions in space, allowing advanced array design possibilities. Any type of pulse shape can be generated and associated with individual transducers. The seafloor consists of a collection of points scatterers with the possibility to define their respective backscatter level. Points can be distributed to model realistic seafloors. Finally, it is possible to customize the survey geometry by defining the array position for each pings, relative to the bathymetric model. The signal processing part is performed thanks to USTB, this package can process either real or synthetic data with a broad choice of tested beamforming algorithms.

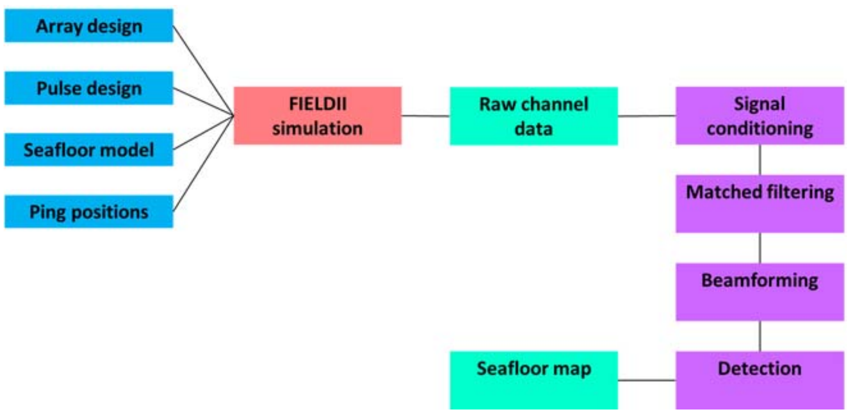

Fig. 1: Main steps of the simulation and signal processing.

3. MBES SIMULATION

In this example, we want to show the simulator's capabilities for multi-beam echo sounder synthetic data generation with two different pulse shapes: a linear frequency modulated pulse (LFM) and a gated continuous wave pulse (CW). The choice of the simulation setup parameters has been made to fit this purpose.

We simulated 50 pings along a line with 0.5 m spacing. The scene geometry consists of a flat seafloor located at a depth of 40 m with three artificial targets separated from each other in the along-track direction. The scene 3D model is given in Fig. 2a). The first target is located broadside and consists in a staircase composed of squared blocks (2x2 m), with three different heights: 10, 20 and 60 cm above the seafloor. The second target is a single point located at 10 m off broadside and 1 m above the seafloor. The last target is composed of four square boxes (1x1x1 m) arranged at the edges of a 3x3 m square, on the seafloor and located at 8 m off the along-track axis.

The seafloor and the target are discretized in a dense set of points scatterers, randomly distributed among the across-track and along-track dimensions and normally distributed in depth around 40 m with a standard deviation of $\lambda/2$ (2.5 mm). This ensure a proper statistics of the seabed and a good evaluation of the backscatter level. The water column is homogeneous with a sound speed of 1500 m/s and an attenuation of 60 dB/km.
The sonar array consists in two identical linear array orthogonally oriented according to the Mill's Cross geometry [8] commonly used for MBES. Transmitter and receiver arrays are composed of 128 elements equally spaced, leading to an aperture length of 32 cm and a width of 12.5 mm.
We simulated two datasets, differing only by the choice of the pulse used. Both signals have the same length of 0.5ms and center frequency of 300 kHz. One is a CW pulse, the other is a LFM pulse with a 10 kHz bandwidth. We applied to each pulses a tapered cosine window (Tukey: r=0.5) leading to a theoretical range resolution of 40 cm for the CW and 14 cm for the LFM. Field II computes the echo response of the emitted wave-field, reflected back from each points scatterers in the scene, into each receiver.

We processed the two datasets with the same procedure; we conditioned raw channel data by adding white Gaussian noise, to achieve a SNR of -20 dB before processing. Then we applied matched filtering and delay and sum beamforming to the simulated data using USTB. Bottom detection has been performed from maximal amplitude, with the center of gravity method presented by Lurton [9] and [10].

4. RESULTS

The bathymetry 3D map for the LFM case is given in Fig. 2b). We observe that the computed bathymetry provides a reasonable estimation of the real seafloor topography. We can clearly distinguish the three targets (staircase, four boxes and single point) and identify their respective characteristics. We deliberately omit to show the CW case, since differences are hardly noticeable on a large-scale map.
A representation for one ping of the simulated backscattered signal after beamforming and pulse compression is shown in Fig. 3. The ping is located at a position of 10.5 m along track and corresponds to the LFM case. We observe two events corresponding to the top of the target at 39.4 m and the flat seafloor at 40 m.

Since we expect to see a difference in mapping performance between CW and LFM, we can compare the vertical traces on the along track profile.

The received vertical beams on the along track profile are given in Fig. 4 a). First, we notice a superior range resolution with the LFM pulse, thanks to its larger bandwidth. This consequent impact performance when trying to map a more complex seafloor like the staircase situated between 5 m and 12.5 m along track. We observe interferences in the signal response induced by closely spaced reflectors.

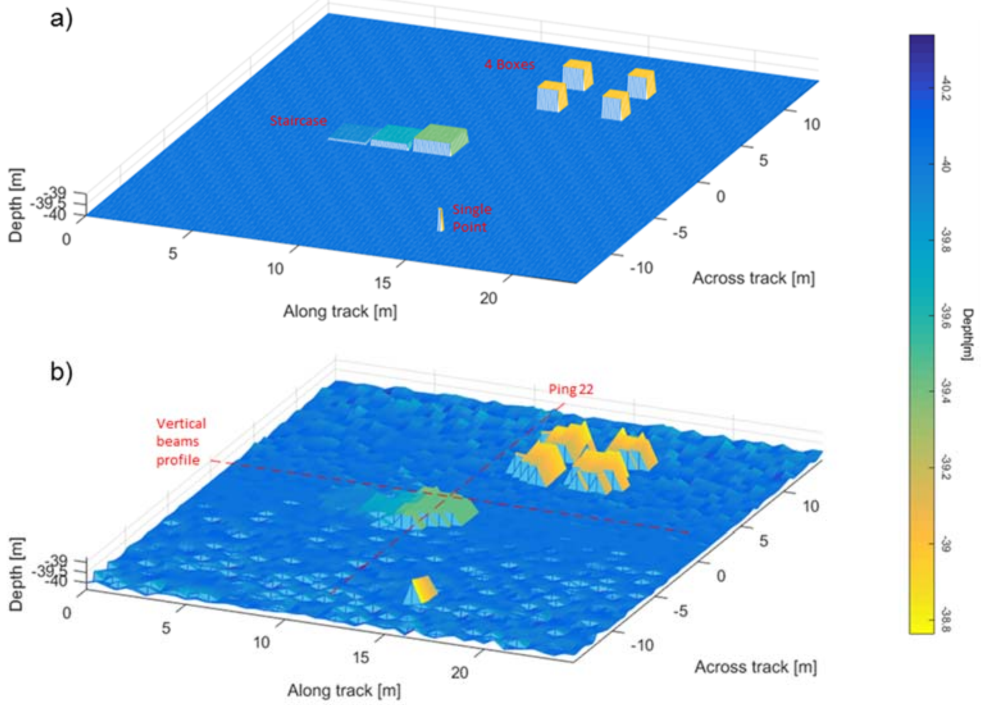

Fig. 2: a) 3D depth model. b) Bathymetry 3D map after bottom detection, LFM case. Dashed lines indicate the location of profiles presented in Fig. 3 and Fig. 4.

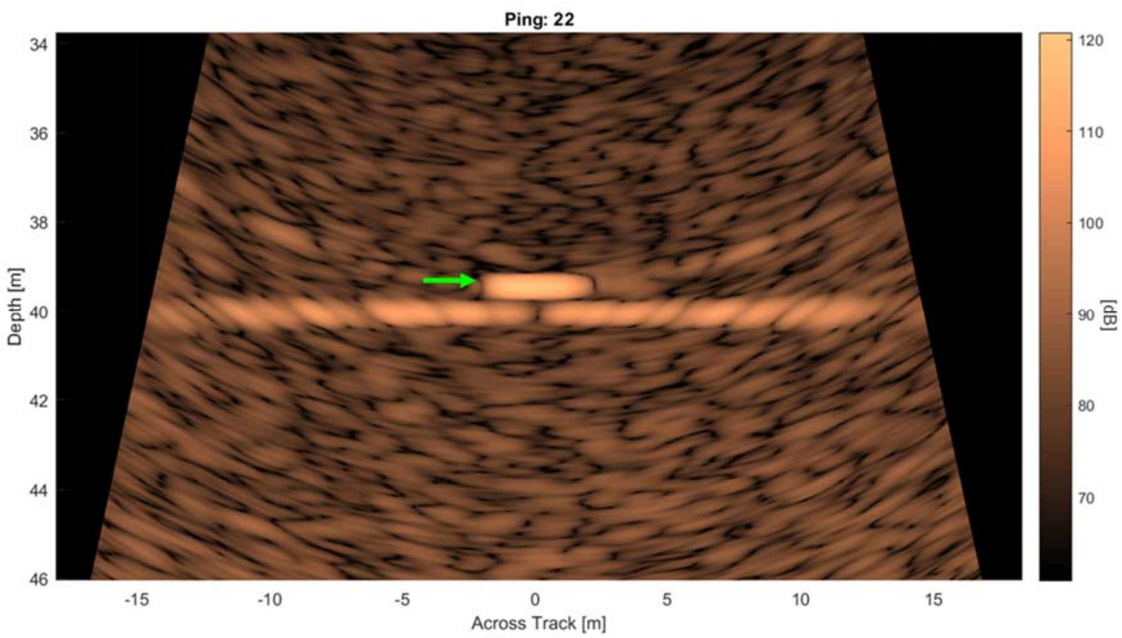

Fig. 3: Sector-scan image, for ping 22, LFM simulation. The green arrow points the highest step of the staircase (39.4 m). The event located below corresponds to the seabed (40 m).

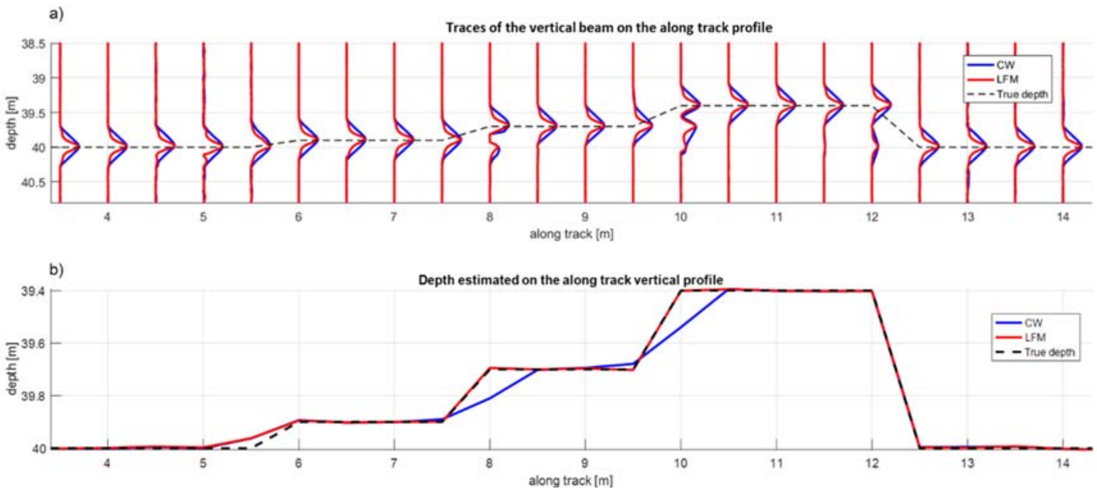

Fig. 4: a) Normalized traces of the vertical beam on the along track profile. b): Along-track depth profile after bottom detection. It illustrates the performance of larger bandwidth. The depth at the edges of the staircase is not perfectly estimated when the depth difference is smaller than the range resolution. (The RMSD values are 0.51 mm for the CW case and 0.39 mm for the LFM).

A layover effect appears since the size of the beam footprint is not negligible compared to the target dimension. A beam illuminating the edge of the staircase will stack traces reflected back from both depths. When the separation between two events is shorter than the vertical resolution, it will be difficult to detect accurately the true bottom depth. This is particularly visible for two traces situated at 8 m and 10 m along track.

In the CW case, the signals shape are deteriorated by interferences from the sea bottom reflection. Fig. 4 b) shows the depth estimated on the along track profile broadside, using center of gravity detection. We observe that the LFM pulse is able to estimate accurately the depth profile, except the first transition located at 5.5 m along track where de depth difference is 10 cm. The CW pulse produce only a correct estimation at the ultimate edge, located around 12 m along track, when the depth difference is larger than its vertical resolution. We computed the Root Mean Square Error (RMSE) of the estimated depth. We find 0.51 mm for the CW case and 0.39 mm for the LFM. Thanks to this simple example, we can evaluate the ability of our modelling environment to simulate properly various pulse shape in an MBES scenario. We used in this example an elementary seafloor model in order to test mapping performance in a simple case. The results being satisfactory the next step will be to generate data from more complex and realistic seabed models.

5. DISCUSSION

We believe that Field II and USTB can be useful tools for exploring with sonar design and pulse shapes. However, to benefit from its full potential, additional physical effects will be necessary. One relevant factor to simulate is the motion of the ship. Displacements between receiving and transmitting locations can introduce Doppler shift. This can potentially affect performance, depending on the pulse shape and sensor geometry. Furthermore, in the current state it is not possible to model multi-path reflection. This last point is probably the hardest limit imposed by a point scatterers simulator, and prevent modelling the full waveform response of a complex seafloor.

6. CONCLUSION

We showed that the joint contribution of open access packages can be used to generate sonar synthetic data satisfactorily. The solution that we propose here has the advantage of being modular simple and reliable. It offers the possibility to simulate raw sonar data from diverse choices of sensor geometry and pulse shape. This will allow testing various sonar systems setup and comparing their performance. The next step will be to implement additional physical effects such as Doppler.

7. ACKNOWLEDGEMENTS

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