

## Real-time Framework for SONAR Ocean Simulation

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### Introduction

Underwater acoustic simulations are important for a SONAR system design and evaluation, marine research, and defense applications, because field experiments remain costly and environmentally constrained. Therefore, the digital ocean framework can serve as an artificial environment to synthesize signals in the real-time framework of a SONAR system. The digital simulation of the underwater scenarios allows for the lower cost of the experiments and speeds up the testing of hypotheses under field conditions. One simulation example is the acoustic signature of a ship, consisting of localized sound sources (e.g., propellers, engines, hull vibration) that are operating simultaneously. In the current simulator, transmitted signals can interact with underwater digital objects such as a ship, sea surface, or seafloor. However, the signal emitted from the local sound source has a limited functionality up to now, as only a single sound source can be attached to the target object. Thus, the extension of the digital ocean with a multi-compound target structure has become the main focus of this paper. The proposed improvement can enhance the simulation precision of the acoustic signature of the ship and the performance of the signal processing of objects in the real-time framework.

### SONAR Ocean Simulator

Modelling of the dynamic environment with underwater objects is a part of the simulation software Kiel Real-time Application Toolkit (KiRAT) [1]. This versatile software consists of the following structures: *algcore*, *algstruct*, and *exo*.

- **Algcore:** the core component responsible for signal processing algorithms, implemented in ANSI-C to ensure compatibility and seamless portability across different platforms;
- **Algstruct:** an overarching algorithmic structure that integrates a graphical user interface (GUI) with an algorithmic core and provides an intuitive environment for users to interact with KiRAT and visualize its outputs;
- **Exo:** “extra window” for the real-time control panel of KiRAT, specialized on the needs of users and independent of the common KiRAT style in the rest of the GUI;

The module “System simulation” consists of the SONAR simulation [2], which is presented in Figure 1 with the connection diagram of this system in Figure 2. This module is responsible for the signal processing of the digital

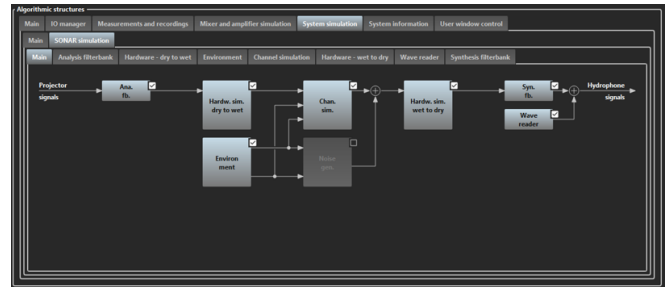


Figure 1: A SONAR simulation in the digital ocean in the “System simulation” module.

ocean environment. The input is the projector signals, which are supplied to the “Analysis filterbank”. There is the transformation of the signal from time to the short-term frequency domain. The chain proceeds next to the “Hardware dry-to-wet” component. The equipment sensitivity signals are applied to the signal processing of the underwater environment. Next, “Channel simulation” provides the convolution of the transmitted signal with the object in the digital environment. Further, the sensitivity of the hydrophone is applied to the processed signal in the “Hardware wet-to-dry”. In the “Synthesis filterbank” the signal is transformed from the frequency to the time domain with an inverse FFT, and signal frames are saved in the buffer to apply the overlap-add approach. The output is saved in the hydrophone signals.

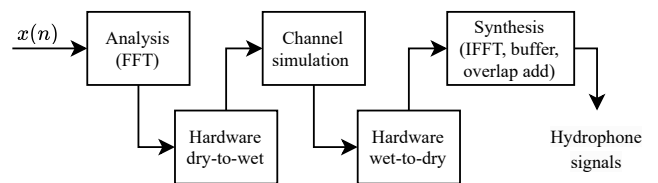
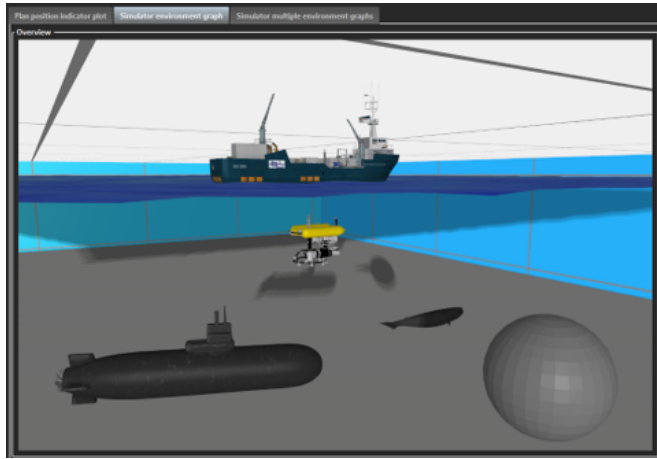


Figure 2: The graph of the SONAR structure in the system simulation.

### Target Object

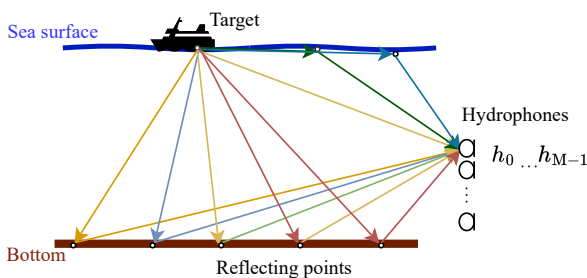
The target is an object of the digital ocean simulation, defined with coordinates to place it in the environment. It also can be moved dynamically in the digital ocean with a waypoint structure that includes specific coordinates via which the target can interpolate the path and change its position during run-time. Also, different types can be chosen for the target simulation, such as a ship, whale, AUV, submarine, or sphere (Figure 3). The target strength can be assigned to each target type, otherwise, the default value will be a non-attenuated reflection of

the transmitted signal.



**Figure 3:** A digital underwater environment with different target types: a ship, whale, submarine, sphere, AUV.

Figure 4 depicts the direct sound propagation of the active local sound signal  $l(n)$  from the target, the reflection from environment objects (e.g., the sea surface and sea floor), that are recorded with a set of receivers (e.g., a hydrophone). The signal reflection from the bottom and the sea surface can be set as time-dependent. The impulse response of the channel simulation includes the time delay and distance attenuation and is applied in the signal processing of underwater objects.



**Figure 4:** A direct local sound signal from the target source and the reflected sound signal propagation from sea surface and bottom.

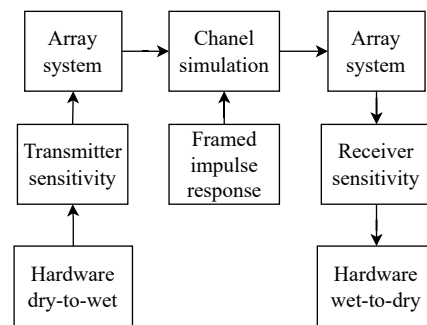
### Target Group Object

The extension of the target structure consists of adding a set of subtargets that belong to the single object of the target group. The implementation is based on the target structure, it includes a waypoint simulation, a wavereader, and an analysis filter-bank. Each target group has parameters that contain the object type, actual coordinates, initial direction, and transmission signals. The existing point cloud structure in KiRAT is used as a base for multiple subtargets that are located relatively to the center position of the target group. They are rotating and moving with each change of movement and direction of the target group during the run-time simulation. In the channel response simulation, the following signal processing functions are added for the target group: the convolution of the transmitted signal with the target group, the interaction of the emitted signal of the local sound

source with the receiver, and a reflection from digital objects in the environment. Additionally, the local sound source can be enabled for each element in the configuration file.

### Framed Impulse Response

KiRAT software is used to process the impulse response of the target of the size less than a frameshift. This approach was used to minimize the complexity of the software by handling the target signal (e.g., ship) within a single frame. As a result, it worked with limited scenarios for local sound emission, and a longer impulse response would be partially processed and cut to the necessary size for the signal processing.



**Figure 5:** The changed modules connection of the framework to handle the framed extended impulse response.

Therefore, the implementation of a longer impulse response was added in the convolution of the target and target group signals. It required replacing a multiplication of a magnitude of the frequency response by a dirac-delta signal, which is responsible for delay management. The vector value of the impulse response was used instead of the scalar value. In the analysis filterbank, the impulse response is split into impulse frames in the frequency domain, and an additional loop over frames is introduced. Next, the convolution of the framed impulse response is processed in the channel simulation module, as shown in Figure 5. The transmitted signal from the array system is processed with the target group signal over all impulse frames. The extension with the longer impulse response has influenced the implementation of the dry-to-wet and wet-to-dry hardware simulation. These modules provide the built-in delay for sensitivities of the transmitting and receiving hardware to enhance the precision of the real-time simulation.

### Local Sound Source

While simulating the acoustic signature of the ship, it usually has several sound sources. Among them are a propulsion diesel engine, an diesel generator to provide the energy for the processes on the ship, cavitating propellers with a number of blades, and most of these elements are working simultaneously on the ship. Correspondingly, the processing of the local sound signal of the object with multiple sub-sources increases the complexity of the signal processing structure. Thus, the signal processing of the local sound signals of the target group and reflected signal was updated. The following equation 1 is adjusted for the passive acoustics simulation, without

the transmitted signal from the SONAR.

$$\begin{aligned}
 Y_m(e^{i\Omega_\mu}, k, t_{ch}) &= H_{hydr,m}(e^{i\Omega_\mu}, t_{ch}) \cdot \\
 &\left( \sum_{s=0}^{N_{sources}-1} \left( \sum_{j=0}^{N_{shift}-1} L_s(e^{i\Omega_\mu}, k - j - d(t_{ch,s})) \cdot \right. \right. \\
 &\quad \cdot H_{s,j}(e^{i\Omega_\mu}, k - d(t_{ch,s})) + \\
 &+ \sum_{r=0}^{N_{refl}-1} \sum_{j=0}^{N_{shift}-1} L_s(e^{i\Omega_\mu}, k - j - d(t_{ch,s,r})) \cdot \\
 &\quad \left. \left. \cdot H_{s,r,j}(e^{i\Omega_\mu}, k - d(t_{ch,s,r})) \right) \right) \quad (1)
 \end{aligned}$$

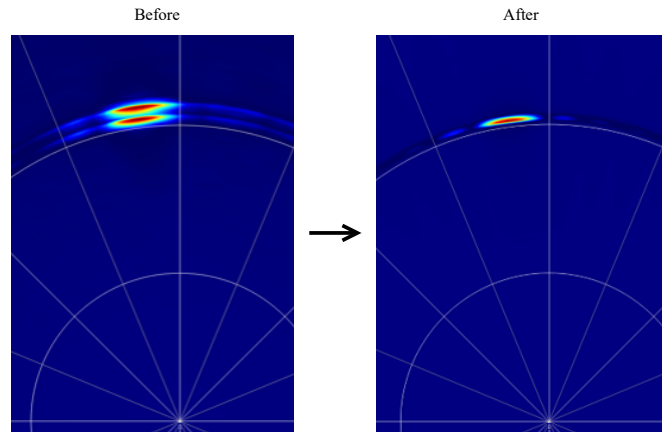
Equation 1 describes the signal processing of the active local signals of the target  $l(n)$  and its reflected signals from other objects. An analysis part provides the FFT into the frequency domain  $L_s(e^{i\Omega_\mu}, k)$ , where the current  $k$ -frame is processed in the equation. Initially, for the direct propagation, the local sound source signal is summed over the number of sound sources at the target group  $N_{sources}$  and the number of frameshifts in the frame  $N_{shift}$ . Then, it is multiplied by the impulse response of the channel simulation  $H_{s,j}(e^{i\Omega_\mu}, k - d(t_{ch,s}))$ , which includes the attenuation due to the traveled distance and the environment properties. The corresponding delay of the channel simulation  $d(t_{ch,s})$  is applied to  $L_s(e^{i\Omega_\mu}, k)$  and  $H_{s,j}(e^{i\Omega_\mu}, k)$ , and the delay in frameshifts is applied to  $L_s(e^{i\Omega_\mu}, k)$ .

Further, reflected signals of the local sound source from digital objects are added. In this instance, it is summed over  $N_{sources}$ ,  $N_{shift}$ , and the number of reflection points in the environment  $N_{refl}$ . The corresponding delay of the channel simulation for the reflected signal  $d(t_{ch,s,r})$  and the delay in frameshifts are applied to the  $L_s(e^{i\Omega_\mu}, k)$ . Next, it is multiplied by the impulse response of the interacting object  $H_{s,j}(e^{i\Omega_\mu}, k - d(t_{ch,s,r}))$ . It includes the attenuation of the propagation path from the local source to the reflection point of the object, and to the hydrophone. The summed total local sound source signal processing is multiplied with the impulse response of the hydrophone  $H_{hydr,m}(e^{i\Omega_\mu}, t_{ch})$ , including its sensitivity. The result is saved in the hydrophone output  $Y_m(e^{i\Omega_\mu}, k, t_{ch})$ .

### Extension of the Convolution Engine

The SONAR Ocean simulator operates frame-based, where the sequence is divided into segments (blocks) and processed piecewise. The circular convolution engine was used to speed up the simulation time of the system without storing the channel simulation result in a single vector. As can be seen in Figure 6, this structure has eventually resulted in a doubling of the target appearing on the SONAR PPI-plot ("ghost" targets). When the shifted signal exceeds the frame and continues from the start of the frame, the "ghost" targets emerge. One of the ways to solve the problem was to change the circular convolution into the linear one by adding a zero padding in the analysis and synthesis filterbank of the frameshift and FFT size. After that, the overlap-add approach would

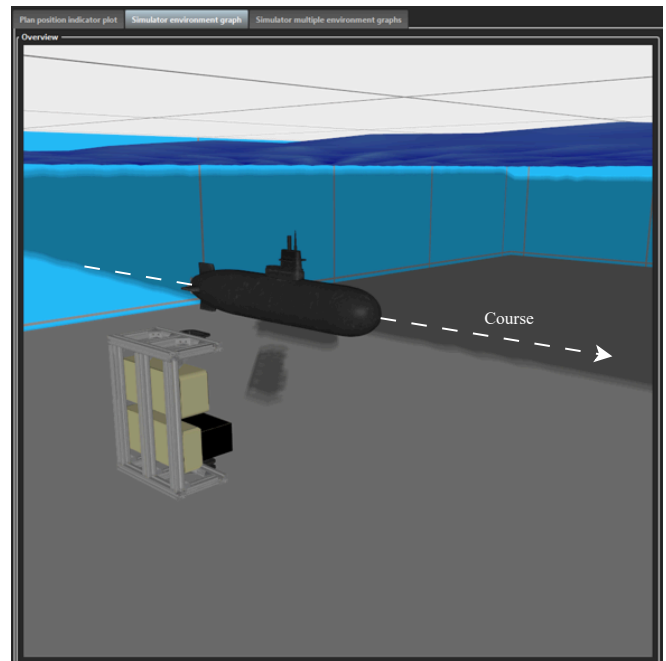
be applied between frames.



**Figure 6:** The image of the SONAR PPI-plot with a "ghost"-target before and after the extension.

### Discussion

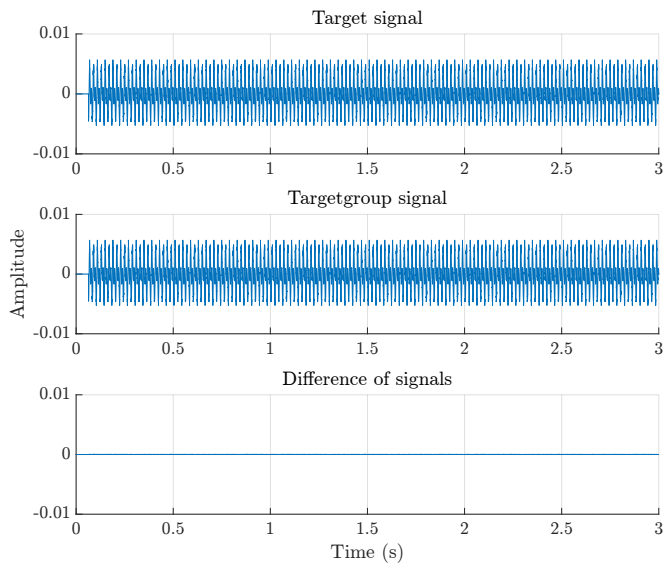
In order to evaluate the performance of the extension, the comparison between recorded target and target group signals was proposed. It allows to verify, if the expected signal of the target group with subtargets is the same as the precombined signal of the target. These results will help to identify, if the system processes the convolution of distributed signals from a target group correctly.



**Figure 7:** The view of the target/target group (submarine) scenario of moving along the defined course in the digital ocean environment.

In Figure 7, the simulator environment graph provides a 3D visualization of the digital ocean environment with the submarine scenario in front of the SONAR system. The image presents a target/target group positioned within the simulated underwater scene with two local sound sources (engine and propeller). The SONAR system, mounted on a structured frame, is placed 25 m be-

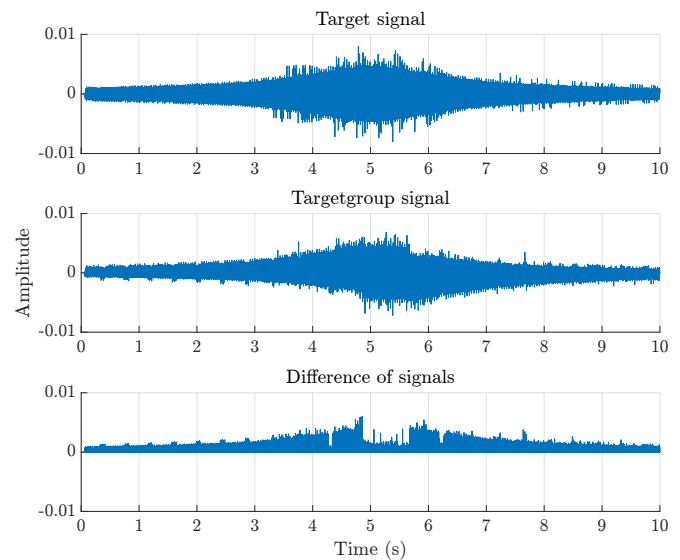
low the sea surface at the start of the environment border, allowing for controlled signal transmission and reception. For this purpose, artificial signals of the engine and propeller were created in the shape of a sinusoidal waveform. The engine noise consisted of a low frequency tone of 50 Hz, and the propeller noise had a frequency of 100 Hz with a sampling rate  $F_s = 192$  kHz, the signal length was 1 s. The amplitude of the resulting combined signal was in the range  $[-1, 1]$ . The local sound source output of the target would be the combined signal of the artificial engine and propeller. For the target group, the noises of the engine and propeller would be placed at the specified relative position from the center.



**Figure 8:** The view of the recorded stationary combined submarine signals in the form of target and target group object in the SONAR ocean simulation, and the difference of both signals.

The tested scenario included stationary and moving submarines as targets or target groups in the digital ocean. For the first case, the simulation setting was a submarine placed 10 m away in front of the SONAR system. A target group output signal contained both signals at the same relative position (0,0,0) m. It would allow us to verify if the simplest scenario with the target group result corresponds to the outcome of the target. The signal results of the stationary submarine with artificial input signals for the propeller and engine are presented in Figure 8. It can be seen that the simulation system produces a similar response, and the difference between the signals is around 0. Thus, the target group response was implemented correctly.

For the second scenario, the submarine would move dynamically for 100 m with a speed of 10 m/s, 10 m away and parallel in front of the array of receivers. A target group output signal contained both signals at the different relative positions (0,0,0) m and (5,0,0) m. This scenario was chosen to show the geometrical spreading effect in the simulation of both objects during their movements and verify if subtargets move within the same path as a central point of the target group. The signal results of the ship movement with artificial input signals for the



**Figure 9:** The view of the recorded moving separated submarine signals in the form of target and target group object in the SONAR ocean simulation, and the difference of both signals.

propeller and engine are presented in Figure 9. It can be seen that the simulation system produces a plot of the approaching and leaving vessel with a gradually rising and descending amplitude. The difference between signals is varying due to signals being emitted not from the same location but 5 m spaced. Thus, the target group response shows the simulation of the moving object with spaced sound sources on it.

## Conclusion and Outlook

This paper introduces advancements aimed at enhancing the realism and versatility of digital ship simulations. The extended target version allows the setup of objects with multiple sound sources and follow along the same path in the simulation. By extending the target group capabilities, the system now accommodates complex acoustic signatures, offering a more accurate representation of the behavior of the ship. Additionally, the convolution engine's improvement, particularly in adjusting the circular to linear convolution with the help of zero padding and overlap-add approach, further enhances the fidelity of the model. In the future, efforts will concentrate on improving the reflection dynamics of moving target groups and the simulation of the Lloyd's mirror effect. These advancements promise to enhance the accuracy of digital simulations, broadening their use in naval engineering and acoustic modelling.

## References

- [1] KiRAT - Kiel Real-time Application Toolkit, 2025. <https://kirat.de/>. Online, last access: 25.03.2025.
- [2] Hodges, R. P., 2011. Underwater acoustics: Analysis, design and performance of sonar. John Wiley & Sons.