Improving Sonar Simulation with a Bistatic Active Target Model

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Abstract: *At the 2017 UACE conference we gave examples on how active sonar performance predictions could be improved by simulating the sonar response with a time domain ray trace model coupled to a target echo model (TEA, Target Echo Analyzer). Using the sonar equation with wave propagation calculations in the frequency domain for a broad band active sonar generally predicts detection distances much longer than those actually experienced in the field by sonar operators. Our solution to this problem was to simulate the sonar detection problem with a ray trace model working in the time domain, coupled to the target echo model. We then observed a loss in detection performance in accordance with field trial results. We attribute this loss to time spread due to multipath transmission. A limitation was that TEA could only handle monostatic reflections. Thus, for rays where the reflected angle was different from the incoming angle (i.e., the bistatic case) we had to replace the two angles with the bisectrix between them.*

The new target echo model, GRATIS (Graphics Accelerated Target-strength Integration Scheme), demonstrates a method to calculate the target strength for any acoustically hard body. By using standard libraries from computer graphics, most of the geometric and acoustic processing is performed by the GPU, thus giving fast execution times. Bistatic acoustics is supported, but, since the Kirchhoff approximation is used, good results are only expected within limited bistatic angles. Here we propose a method to calculate the impulse response for the body in a similar fashion to make the target model useful with a time-domain propagation software.

Examples are given to demonstrate how sonar signal simulations can improve sonar performance predictions.

Keywords: *Active sonar, sonar performance prediction, sonar simulation, active target model.*

1. INTRODUCTION

At the 2017 UACE conference [1,2] we demonstrated how active sonar performance predictions could be improved by simulating the sonar response with a time domain ray trace model (REV3D, [3]) coupled to a target echo model (TEA, Target Echo Analyzer). We could give an explanation why wave propagation calculations in the frequency domain and sonar equation computations usually give too long detection distances.

The TEA model [4] is very fast and can model corner reflectors, coating and inner/outer shell structures, but is limited to the monostatic case which is a drawback for modelling the echo in a multipath propagation environment. The generated impulse response is quite rough-cut but fits well together with the way multipath echoes are modelled in REV3D.

This time we use a physical optics target model, GRATIS [5], which is inherently multistatic, but currently limited to acoustically hard objects. The simplistic impulse response from TEA is substituted with a Fourier transform method. With a proper impulse response from the target, the echo from any pulse shape can be generated by convolution.

In section 2 we discuss the differences between time and frequency domain calculations. Some examples of performance degradation are discussed in section 3. Section 4 sketches out how the impulse response is derived. Conclusions are given in section 5.

2. SCIENTIFIC OBJECTIVES

Our main objectives for this work are to extend the model to full multistatic calculations and to improve processing speed by using a graphics card.

As the REV3D ray trace model is fully three-dimensional [6], and can simulate the performance of a multistatic sonar, it is desirable that the target echo model can support this. However, in the implementation we describe in this work we only support bistatic echo calculations for a monostatic sonar.

In Fig. 1 we compare simulations of how time series of matched filtered signals varies with the aspect angle of the target. Using the monostatic TEA model gives fewer more distinct echoes (Fig. 1, left) compared to the bistatic GRATIS model (Fig.1, right).

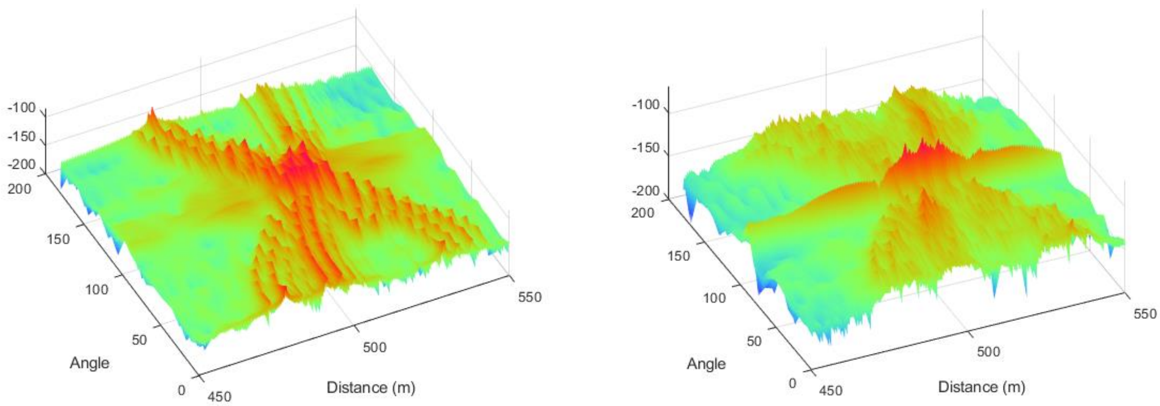

Fig. 1: "Butterfly" plots of echo levels as a function of aspect angle from a generic submarine in an environment with horizontal bottoms and a constant sound speed profile. Time is converted to distance in the plots. Left: Calculations with the monostatic TEA model. Right: Calculations with the bistatic GRATIS model.

The differences between Fig.1 left and right are expected due to the differences in the target models. TEA uses a combination of distinct individual features whose contributions are added incoherently to the time-line, whereas GRATIS models a stiff outer hull where the impulse response is calculated by inverse Fourier transform of the frequency response. TEA also models inner structures and corner reflectors, which can give major contributions to the echo. This is currently is not possible in GRATIS.

3. COMPARISON WITH CONVENTIONAL CALCULATIONS

As the problem with performance degradation in active sonar is discussed in detail in [1] we only give a summary here. We found that there were two causes to degradation:

- Environmental effects
- Target effects

3.1. Environmental Effects

The environmental effects are especially significant in very shallow waters such as the Baltic where the sound speed profile can have large variations even at short distances [6]. The result is that the sonar pulse is split into several rays, with different travel times. When the rays then are coherently summed in the receiver, there will be a loss in the signal gain compared to what is predicted by the reverberation limited active sonar equation:

$$SE_R = SL - 2TL + TS - RL - DT_R\,. \tag{1}$$

Where DT_R is defined as:

$$DT_R = 5\log d - 10\log(\tau\, w). \tag{2}$$

SE_R is the signal excess and respectively, SL the source level, TL the transmission loss, TS the target strength, RL the reverberation noise level, DT_R the detection threshold, d the detection index, τ the pulse length and w the pulse bandwidth.

The signal gain in (2) due to pulse compression from replica correlation assumes that the transmitted and reflected pulses are coherent over the full pulse length and bandwidth, which is not the case if many rays with different travel times are added together.

In a frequency domain model these losses cannot be calculated, but a time domain ray trace model makes it possible to calculate the intensities and travel times in a correct way. As can be seen in Fig. 2 (left), the difference is 10 dB or more between the two calculations. The calculations were made for a 15 kHz sonar, using a 3 kHz FM-pulse. The environment was a horizontal bottom and a sound speed profile with a waveguide, typical for the Baltic in the summer.

Fig. 2 (right), depicts the time series for echoes at different target distances, after matched filtering. The aspect angle of the submarine was 50 degrees.

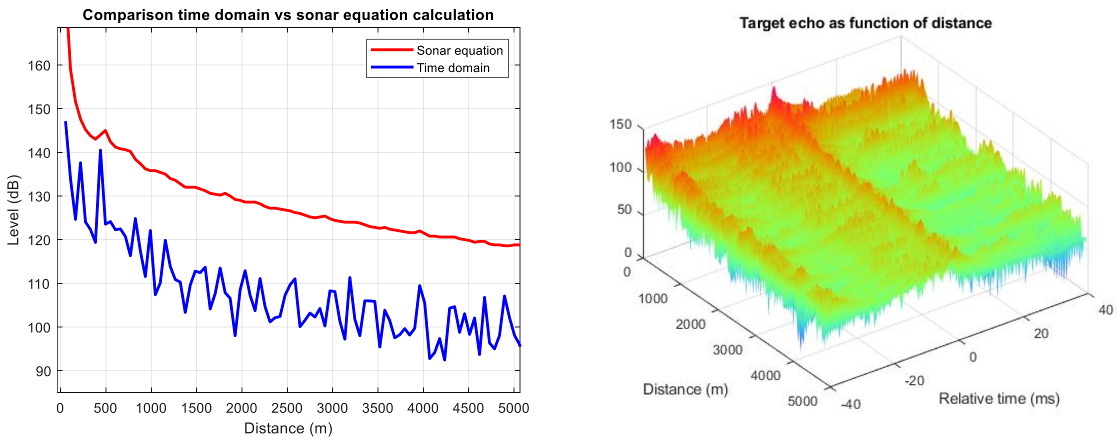

Fig. 2: Left: Target echo levels as a function of distance for conventional sonar equations calculations compared to sonar simulations in the time domain. Right: Simulated time series of echoes as a function of target distance.

3.2. Target Effects

Time spread due to the target is similar to spread from environmental effects. In Fig. 3, left, sonar equation calculations are compared to sonar simulations. And again, there is a difference of 7-10 dB, except for the broad-side echo, which has little time spread.

Fig. 3, right, shows the time series (with time converted to distance) of the target echo as a function of aspect angle.

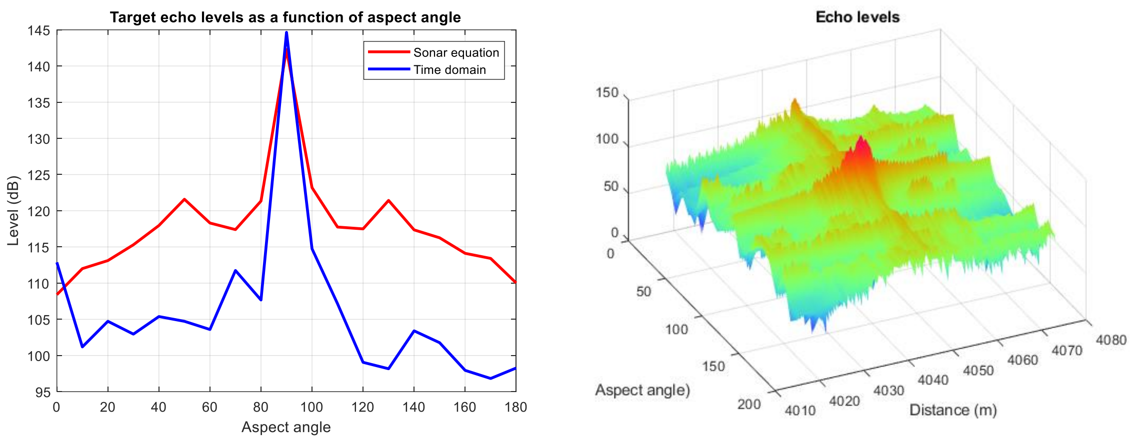

Fig. 3: Left: Target echo levels as a function of aspect angle from a submarine using time domain (blue) and frequency domain (red) calculations. Right: Calculated matched filtered echo signal as a function of aspect angle.

4. GENERATING THE IMPULSE RESPONSE OF THE TARGET

The complex frequency response for a continuous wave signal is calculated in GRATIS with a method inspired by the radar cross-section code GRECO [7]. The OpenGL graphics pipeline is used for calculating the complex integrand on every pixel in a viewport from the listening sonar direction. All pixel contributions are summed to yield a complex value of the target strength. This method is discussed in more detail, together with investigation of validity and accuracy limits in [5].

The impulse response is now produced by calculating the complex response for a number of frequencies and then performing the inverse Fourier transform. Since we are dealing with band-limited pulses, only frequencies inside the sonar bandwidth are considered.

The bandwidth needed follows from the required distance resolution. Here we have set this value to 0.25 meters, which is achieved with a bandwidth of 3 kHz. The number of frequencies to sample within this bandwidth is determined from the target extension. After inverse Fourier transform the time signal of the impulse response must cover the full extension of the target. So, the number of frequencies needed is trivially found from target extension divided by the distance resolution.

4.1. Interference effects

You are probably familiar with the blowfish-like shape of target strength, or radar cross-section, presented in a polar plot, see Fig. 4 (left).

The impulse responses generated by this approach shows a similar jagged appearance. Small adjustments of the projector and receiver positions will affect the details of the impulse response significantly. Experience from the field tells us that several pings must be integrated to get a good measure of the nature of the target echo, in part due to the movements of sonar and target in a medium with varying speed of sound. If we try to simulate this effect here, by introducing small variations of the hydrophone positions, we can observe the individual impulse responses will vary a lot, but the maximum values for all angles will in fact trace the shape of the target well, see Fig. 4 (right).

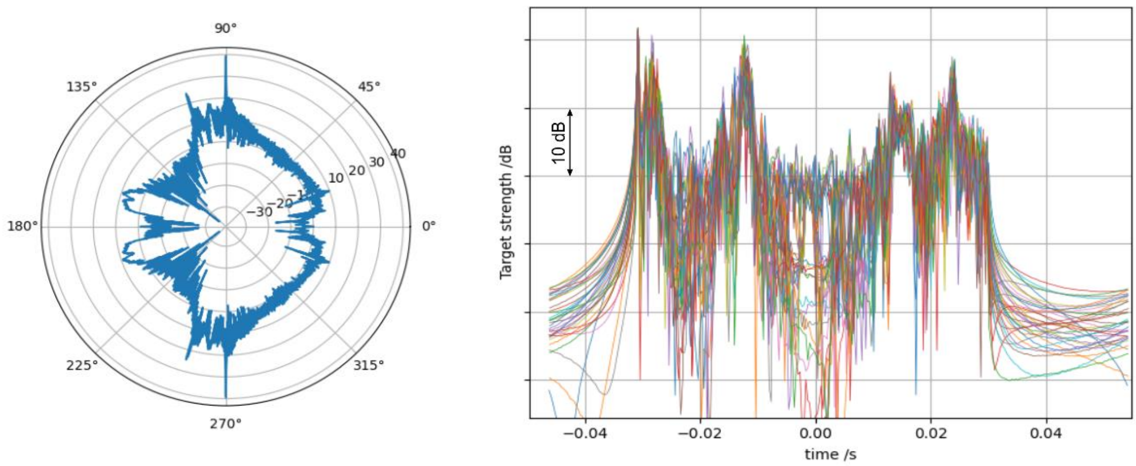

Fig. 4: Left: Typical polar plot of the monostatic target strength at 15 kHz of a submarine in the horizontal plane. Right: Impulse responses from a submarine at 45° aspect and 36 bistatic combinations of elevations 89°-91° in 0.4° steps (right). Centre frequency 15 kHz and bandwidth 3 kHz.

4.2. Performance

The GRATIS software in its current state, written in GLSL and Python, with summation in NumPy, can generate the complex target strength in about 10 ms and an impulse response for a submarine sized target in 1-3 seconds on an ordinary laptop computer when a 1-megapixel resolution is used. This is clearly not fast enough for real-time use. We want to evaluate at least ten of the most significant propagation paths, which thus will take 10-30 seconds to evaluate for one ping with this setup. At least a 10-fold speed improvement is needed to run this in real time.

The pixel summation stage takes most of the processing time. There exist well-known efficient summation algorithms for the graphics card, but these are not yet implemented here. Reducing the number of pixels will also speed up the calculations, in linear proportion, with some loss of accuracy. In this work we have not studied a reasonable low limit for the resolution.

For smaller bandwidths we will have shorter processing times. So, all this considered, we do not rule out the possibility of a future implementation with real-time performance.

5. CONCLUSIONS AND FURTHER WORK

As in our earlier study [1] we find a difference between conventional sonar equation calculations in the frequency domain and high-fidelity simulations of the sonar signal in the time domain. The extension to bistatic modelling has been made by the integration of a bistatic target model with a time domain propagation code including target echo and reverberation. Compared to the earlier study we observe a similar loss in target echo levels, which we attribute to time spreading. This is in accordance with our experience from field trials in the Baltic [8].

For acoustically hard bodies we have a smooth workflow from a CAD model to target model and propagation calculations. But many interesting sonar targets are multi-layered structures with acoustically semi-transparent parts. Such targets can currently not be modelled in GRATIS which limits its usefulness, especially at lower frequencies. The raytracing propagation code REV3D is also best suited for high frequency sonars, as those commonly used in the Baltic.

The long-time goal of this work is to develop a model fast enough for interactive training of sonar operators and tactical officers. A requirement here is to generate the target echo and reverberation faster than the travel time for sound from projector via target to receiver.

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] **J. Pihl and L. Bossér**, Improved active sonar performance prediction, In *Proc.4th Underwater Acoustics Conference and Exhibition*, Skiathos, Greece, pp. 253-258, 2017
[2] **L. Bossér and J. Pihl**, A fast target strength model and its application with a multipath propagation model, In *Proc.4th Underwater Acoustics Conference and Exhibition*, Skiathos, Greece, pp. 405-412, 2017
[3] **S. Ivansson,** Stochastic ray-trace computations of transmission loss and reverberation in 3-D range-dependent environments. In *Proc. 8th European Conference on Underwater Acoustics*, Faro, Portugal, pp. 131-136, 2006.
[4] **L. Bossér**, A fast target strength model, In *Proc 3rd Underwater Acoustics Conference and Exhibition*, Crete, Greece, pp. 787-792, 2015
[5] **L. Bossér and J.D. Bossér,** Target echo calculations using the OpenGL graphics pipeline, *Applied Acoustics,* vol 181, id 108133, 2021
[6] **S. Ivansson, J. Pihl and J. Schön,** 2-D and 3-D ray modelling of TL and RL measurements in the Baltic. In *Proc.2nd Underwater Acoustics Measurement: Technologies and Results,* Crete, Greece, pp. 633-640, 2007
[7] **J. Rius, M. Ferrando, and L. Jofre**, Greco: Graphical electromagnetic computing for RCS prediction in real time, *IEEE Antennas and Propagation Magazine*, vol. 35, no. 2, pp. 7–17, 1993
[8] **J. Pihl, I. Karasalo, P. Morén and E. Parastates,** Target strength measurements in shallow water. In *Proc*. 4th *Underwater Acoustics Measurement: Technologies and Results,* Kos, Greece, pp. 1211-1216, 2011