A FAST TARGET STRENGTH MODEL AND ITS APPLICATION WITH A MULTIPATH PROPAGATION MODEL

Lennart Bossér, Jörgen Pihl

FOI, Swedish Defence Research Agency, SE-164 90 Stockholm, Sweden

Lennart Bossér, Division of Defence & Security Systems and Technology, FOI,
SE-164 90 Stockholm, Sweden. Fax: +46 8 555 034 94, Email: lennart.bosser@foi.se

Abstract: *Full-scale target strength measurements of submarines indicate that major contributions arise from parts between the pressure hull and the casing. Even tanks inside the pressure hull itself can give large contributions to the target strength under some circumstances. The design of the submarine generally incorporates structures of plates in the form of straight angle corners or cat´s-eye shapes which are excellent acoustic reflectors. Prudent application of transmission-loss and/or reflection-loss coatings to parts of the submarine can yield significant reduction of the target strength. Essential requirements on any target strength modelling method are therefore the abilities to model sound transmission through outer structures, double- and triple-bounce sound reflection, and the effect of coating materials in conjunction with a backing steel plate. The monostatic target strength model SubSig-TS was presented at UACE 2015. Two significant features of the model are: a) It is very fast and thus suitable for real-time or near real-time applications, b) It can be used as a target model in simulations, e.g. in conjunction with wave propagation models, due to its stream IO-interface. ROSES (Robust Operational Submarine Echo Simulator) is an application where SubSig-TS is combined with the REV3D ray trace model to predict the echo from a submarine including environmental effects such as multipath propagation and reverberation. ROSES is fully integrated in COMBIS (Combined Maritime Background Information System) which provides a uniform and comprehensive interface to a wide range of prediction models using existing hydrographical and meteorological data. This paper will present a brief overview of the SubSig-TS model and the ROSES application.*

Keywords: *Submarine design, Target strength, Underwater acoustic modelling, Multipath propagation, Reverberation*

1. INTRODUCTION

FOI has a long tradition of research in hydroacoustics applied to the shallow waters and varying bottom conditions in the Baltic Sea. The ROSES application presented in this paper is the result of the successful integration of models from several different research projects at FOI.

REV3D [1] is a ray-tracing hydroacoustic propagation model based on the stochastic ray model MOCASSIN [2]. It is enhanced with 3-dimensional propagation and coherent ray summation and considers both surface and bottom reverberation as well as Doppler effects. One motif for developing REV3D was to produce sound fields for evaluation of active sonar signal processing algorithms and underwater communication performance. The ability in REV3D to model the time-domain effects of multipath propagation in a reverberation environment suggested the use together with the SubSig-TS to model the echo of a submarine in a realistic environment.

The monostatic target strength estimation model SubSig-TS [3, 4] was developed as part of the project SubAn (Submarine Analysis) [5], dedicated to analysis and conceptual design of submarines. (SubSig also contains other models for estimation of radiated noise, induced magnetic field and UEP/ELFE signatures.) Initially SubSig-TS only returned the integrated target strength but, after a suggestion from Jörgen Pihl, the model was further developed to deliver a time-resolved response. A stream I/O interface was also added, for integration with ROSES or other applications. The client program supplies pulse center frequency, range and aspect and elevation angles and receives a response that can be convolved with the actual pulse shape to create the time series of the echo.

COMBIS (COmbined Maritime Background Information System) [6] is a tactical decision aid user environment which integrates several hydroacoustic and electromagnetic wave propagation models with an environmental database. This database contains bathymetric and hydrographic data, climatology forecasts and bottom sediment information. The sensor support function in COMBIS handles information on platform signatures and sensor performance and enables investigation of detection probability for user-defined tactical scenarios.

ROSES combines the REV3D propagation model with the SubSig-TS target strength model for use in the context of the COMBIS tactical support environment. In this manner it is possible to simulate the echo from any submarine, in any environment, and with any active sonar. The returned echo is similar to what could be expected in a real world case and gives a realistic basis for the classification problem. To this end it is a powerful tool for ASW research, training and operations.

A general problem, common to all target strength modelling methods, is the fact that it is impossible to include all features of a real, complex, target in a computational model. The cost for data preparation and the computational effort limit the level of detail that can be handled in practice. So which physical phenomena are essential in any such model? Which structural features are significant and should thus be included? What detail can be left out as less important? These questions should be asked in the context of the complicated hydroacoustic environment encountered in real-life situations. The ROSES integration of environmental modeling with target strength modeling gives a path to advance the understanding of this subject.

2. SUBSIG-TS

2.1. General Principles

The SubSig-TS model is based on the assumption that, from any given direction and frequency, the major contributions to the target strength emanates from a few dominating features *e.g.,* for broadside aspect the pressure hull dominates over all other parts of the submarine. Experience so far gives support for this assumption.

There exist well known analytical solutions for the backscattering cross-section of rigid objects of simple shape, *e.g.,* spheres, ellipsoids, cones, and circular or rectangular plates under certain conditions of distance and wavelength compared to object size, see *e.g.,* [7]. Most of the major features of a submarine can be approximated with such simple shapes, hereafter called reflectors, at typical detection distances and sonar frequencies.

One important aspect is that for any given direction of the incoming sound only some parts of the submarine are insonified. This is modelled with the help of an aperture function associated to each reflector which describes the directions where it is active, i.e. can be insonified and also back scatter sound. This aperture is set considering all the other parts of the submarine which might be hiding this reflector.

In some circumstances, *e.g.*, for the air-backed parts of the pressure hull at medium to high frequencies, the rigid-body assumption is a good approximation. For most of the other parts of the submarine the transmission of sound through the structure has to be considered. In some situations, especially when using anechoic coatings, the energy loss in the material is also an important factor. These cases are handled by adjusting the rigid body solution with local transmission and reflection coefficients calculated with regard to the frequency, angle of incidence, material properties and shell thickness of the object.

Currently 14 different reflector types are treated in the model. There are basic shapes such as sphere, cylinder, cone, rectangular plate and circular disc, and also composite objects such as corner reflectors, cat's-eye reflectors, fins and propellers. Some special objects such as an air-bubble cloud and a wing tank are also handled. Some of the reflectors are illustrated in Fig. 1.

A reflector can be hidden behind another reflector. In such a case the transmission loss of the outer reflector is applied to the incoming sound as well as the reflected sound, see Fig. 2.

The target strength of the complete submarine is obtained by summing the backscattering cross-sections of all insonified reflectors [8, 9], compensated for reflection coefficient and transmission losses as outlined above. There are options for how to perform this summation, where the basic mode is the incoherent summation

$$TS = 10\log_{10}\sum_{i}\left(\frac{\sigma_i}{r_{\mathrm{ref}}^2}\right), \qquad (1)$$

where σ_i is the effective backscattering cross-section of reflector i and r_{ref} = 1m is a reference distance.

Since the position of each reflector's acoustic centre, the position of the sonar and the speed of sound are known, it is also possible to generate an approximate time-domain response composed from the target strength of individual reflectors and the corresponding arrival times of the echoes. This mode is used when generating a response to the ROSES application. The response consists of a series of time-stamped reflector target strength values sorted by arrival times.

SubSig-TS models are automatically generated from submarine concepts, designed with the SubAn design tool, at the click of a button.

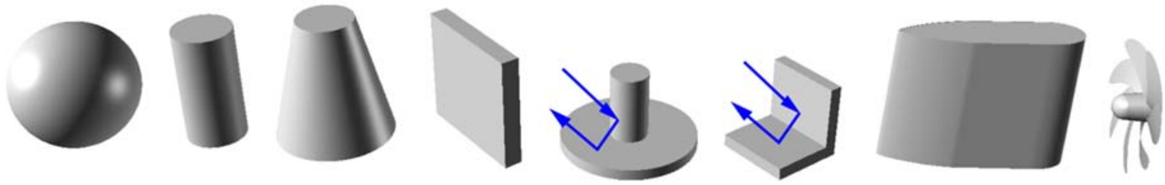

Fig. 1: Some simple and composite reflector objects. From left to right: sphere, cylinder, truncated cone, rectangular plate, cylinder on plane, corner reflector, fin, and propulsor.

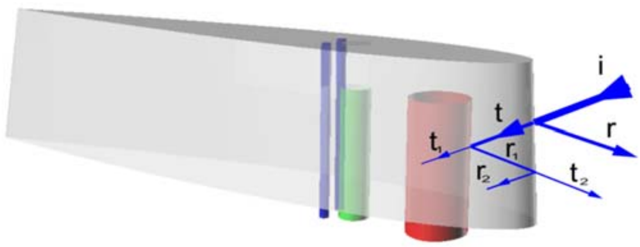

Fig. 2: Reflection by objects hidden behind a shell. Of the incoming intensity (i), a part (r) is reflected by the shell and a part (t) is transmitted. When the transmitted sound hits an interior object surface, a part (r_1) is reflected and a part (t_1) is transmitted through the surface. For the outgoing intensity (r_1), a part (r_2) is reflected by the outer shell and a part (t_2) is transmitted through the shell. The effect of multiple reflections between shell and inner objects are neglected, and t_2 is identified as the contribution from the hidden part.

2.2. Comparison with other results

The BeTTSi II Workshop[10] gave an opportunity to compare the results from SubSig-TS with the results from several other codes using Kirchhoff, BIE, FEM, and ray tracing methods. An example is shown in Figs. 3 and 4. Full details of the models, the methods used, and the results can be found in the BeTTSi II proceedings. Good agreement with other codes was found for several target models, among them the one illustrated in Figs 3 and 4.

Fig. 3: The BeTTSi model 32, with length 49m, outer shell of 8mm thick steel, small radius 3m, and big radius 5m. The inner body is 46m long with all radii 3m and made of 20mm thick steel. The inner body is air-filled and the volume between the bodies is water-filled.

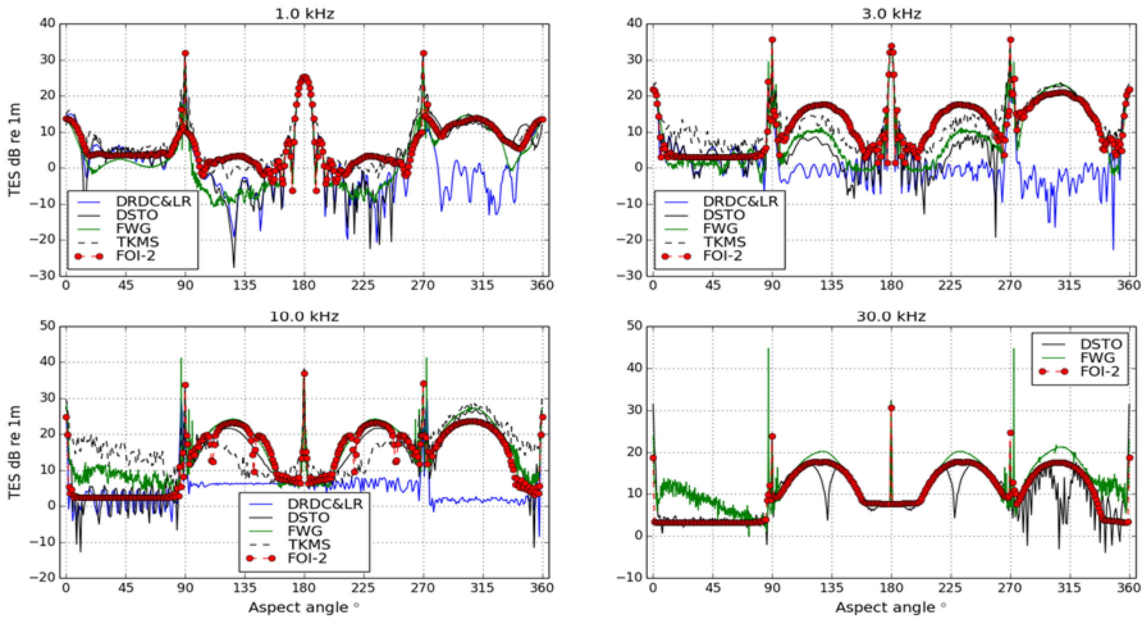

Fig. 4: Far field target echo strength for the BeTTSi model 32 in horizontal elevation for 4 different frequencies as calculated by 5 different models. The results from SubSig-TS are presented with red dots (legend FOI-2). The too high SubSig-TS predictions at 1 kHz and 3 kHz at 135° and 225° aspect are probably due to different transmission properties for the cat's-eye reflectors. It can be noted that the green curve is plotted with 0.1° resolution (whereas the other curves uses 1° resolution) and thus catches the top of sharp peaks near 87.5° and 272.5° degrees.

In a cooperative work involving Netherlands, Canada and Sweden, during spring 2017, there was an opportunity to compare the SubSig-TS predictions to measurements of integrated target strength on a Zwaardvis class submarine. There was good agreement with measurements for frequencies up to 5 kHz in near horizontal elevation and for all aspect angles measured in 2 degrees spacing. Unfortunately, the details from this comparison cannot be published.

The results from SubSig-TS was also, in 2016, compared to time-domain data from measurements on a Swedish submarine. The model shows ability to predict the major aspects of the time-domain echo structure with good agreement in magnitudes and arrival times. Further analysis is in progress to quantify the prediction accuracy.

3. ROSES

The input to ROSES is a COMBIS scenario file, containing all relevant parameters for the bathymetric and hydrographic environment, the sonar position and pulse type and the target position, orientation and its active signature, in this case the name of a SubSig-TS reflector file.

SubSig-TS is invoked to predict the monostatic impulse response using the pulse center frequency, the current aspect angle of the target and a selected elevation angle. Each response is consolidated by power summation for time slots and stored in a table. This is repeated for all elevation angles with one degree resolution. REV3D now calculates the intensities, elevation angles and arrival times for all rays reaching the target. The above table and the bistatic theorem[11] are used to calculate the intensity and time delay for a large number of reflected rays. These are back propagated by REV3D to the sonar position. Convolving with the emitted sonar signal produces the time-domain echo for all returned rays which can be processed by REV3D to generate lobe, stave or element signals[12].

The default output from ROSES is two sound files in .wav format. One file for the target echo and one for the environmental reverberation. Both files represent the signals received in the sonar lobe aimed at the target. The lobe signal as function of time (or distance) can be plotted, see Fig. 5. It is also possible to compare the target echo to the reverberation in the lobe, see Fig. 6.

Due to the integration in the COMBIS user interface it is possible to interactively explore the impact of different hydroacoustic environments and the consequences of changing sonar parameters and target position/orientation.

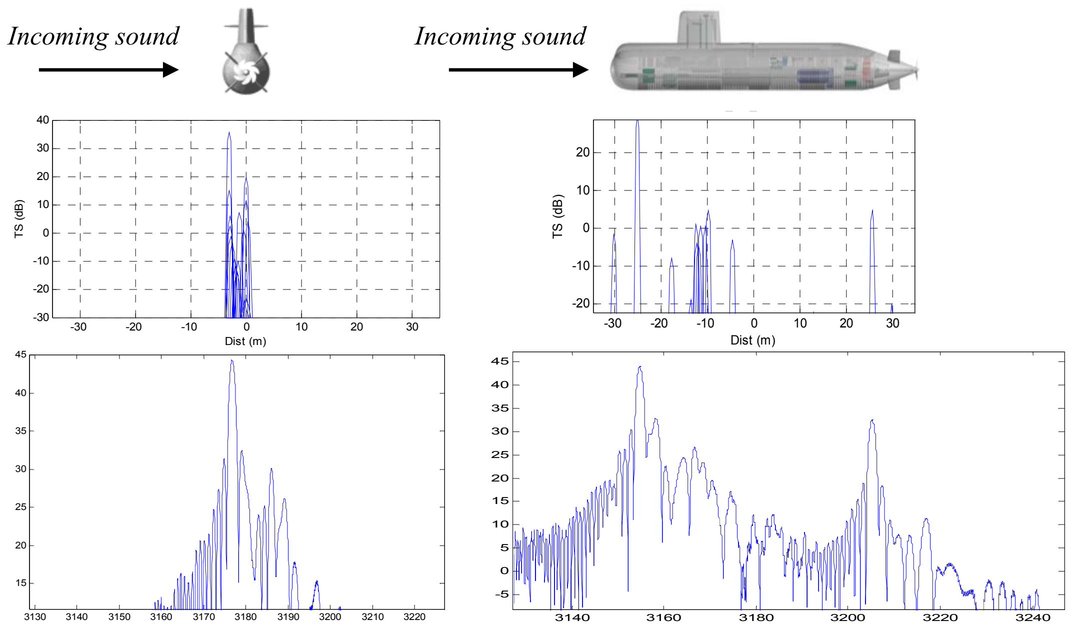

Fig. 5: The impact of the environment on the received echo. The left column shows the situation for a near-broadside aspect and the right column shows the echo at near-ahead aspect. The upper pair of graphs illustrates the echo in an isotropic environment. Vertical axis is peak target strength and horizontal axis is distance relative the centre of the target. The lower pair of graphs depicts the results in a multipath propagation environment, where different travel times will stretch and distort the echo. Vertical axis here is the replica correlated signal strength in dB and the horizontal axis is distance from the sonar.

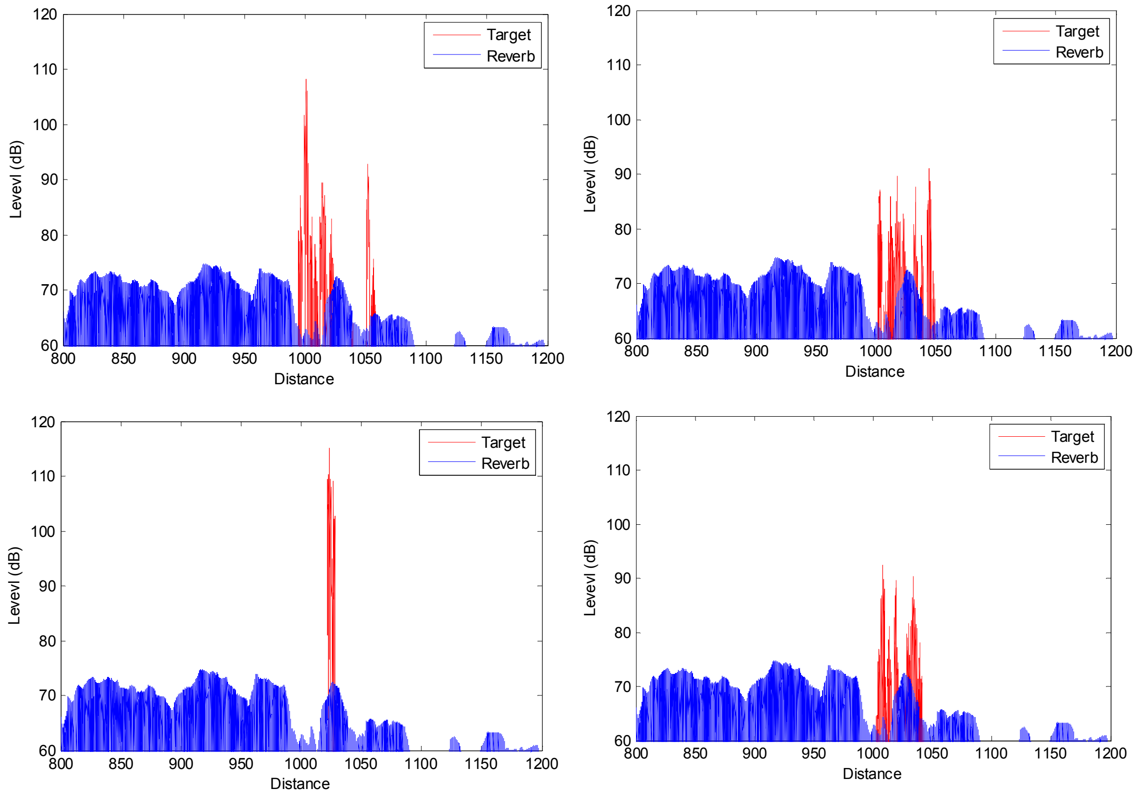

Fig. 6: Target echo (red) and reverberation (blue) time series (after replica correlation) calculated by ROSES for four different target aspect angles. Upper left = 0 degrees, upper right = 45 degrees, lower left = 90 degrees (broadside) and lower right = 135 degrees.

4. CONCLUSIONS

ROSES was developed by merging the competent REV3D propagation model with the target strength prediction model SubSig-TS. This has produced a powerful tool for ASW research, training and operations.

The integration with the COMBIS toolbox yields an environment where target detection can be explored interactively for different environments. Any sonar, target and environment can easily be combined in operative scenarios for near-realtime evaluation. ROSES thus has the potential to be the base for a future computer-aided classification tool (CAC).

SubSig-TS is a small and fast software and it is a quick and easy process to generate target strength analysis models from conceptual submarine design models. These submarine designs can be interactively analysed and compared in SubSig-TS, *e.g.* to evaluate the effect of different hull geometries and anechoic coating strategies. The ability to study such models in a simulated environment, with ROSES, gives a deeper understanding of the implication of different design choices in a realistic ASW situation.

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