BETSSI IIB : SUBMARINE TARGET STRENGTH MODELING WORKSHOP

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Abstract: *In September 2016, the BeTSSi IIb (Benchmarking of Target Strength Simulations) workshop was held in The Hague, The Netherlands. Participants were offered the chance to benchmark their numerical simulation tools using a number of predefined structures that are relevant for understanding the target strength of submarines. In addition to a generic submarine model (with internal parts) and a number of simple structures (with and without internal components), which were simulated during the first and second workshop (2002 and 2014), the test cases were expanded to investigate the contribution of an isolated corner reflector and torpedo tubes. An overview of the workshop is given and a selection of the results is presented.*

Keywords: *Target Strength, Numerical Modelling, Benchmarking*

1. INTRODUCTION

The BeTSSi workshop for Target Strength (TS) calculations has an almost 15-year history. The first workshop was initiated by FWG in mid-2001 as a Benchmark Target Strength Simulation workshop. FWG defined and delivered a generic submarine model [1] which was nicknamed BeTSSi and made a worldwide announcement seeking participation. The objective was to calculate a number of TS test cases and to meet at a workshop to compare results and evaluate the performance of each participant's software. The workshop was held at FWG in Kiel in November 2002 with participation from six teams from Germany, Sweden, Canada, Australia and the Netherlands. The results were published in several scientific papers including the International Conference on Sound and Vibration (ICSV) which took place in Stockholm in 2003 [2]. The calculations provided interesting and valuable results. However it was obvious that there were many problems for realistic TS calculations that could not be solved with the algorithms and computational power available at the time.

More than ten years later WTD71/FWG, TNO and DRDC believed that the scientific and computational advances warranted another look at the topic of TS calculation and the BeTSSi workshop. They organized a new workshop, called BeTSSi II, which took place in Kiel in 2014 and was considered a huge success with teams from ten countries taking part and contributing results. The workshop test cases comprised several simple structures that included parts/features of submarine designs and that are very well suited to test the performance of numerical methods when applied to problems such as double hulls and corner reflectors. Additionally, the original BeTSSi submarine model was repeated, with hard-walled and more realistic boundary conditions, as a test case and was calculated for monostatic and bistatic cases. The workshop results were published in several scientific papers (for a selection of results see for instance [3,4,5,6,7]).

At the end of that workshop, it was agreed that a second BeTSSi II workshop (called BeTSSi IIb) should be organized in 2016 to give the participants time to further develop their codes with the information learned at the 2014 workshop and again compare the results with those of other participants. As before, several geometrically simple objects (some similar to previous BeTSSi II test cases) and the BeTSSi submarine have been set up as test cases for participants.

A document meticulously describing the different benchmark cases was distributed prior to the BeTSSi IIb workshop. The document described the calculation frequencies, the material parameters and the geometry of the problem and the test objects together with technical drawings and mathematical descriptions of the objects. CAD models of the objects in IGES and 3dm format were also made available to all participants as well as meshes of the objects with a standard discretization with triangle elements. In this paper, an overview of the benchmark cases for the BeTSSi IIb workshop is given and a selection of the results is presented.

2. CONSIDERED GEOMETRIES

The simple geometries representing the submarine features of interest that are considered in the BeTSSi IIb workshop are shown in Fig 1. The BeTSSi submarine is shown in Fig 2 with several of its individual components highlighted.

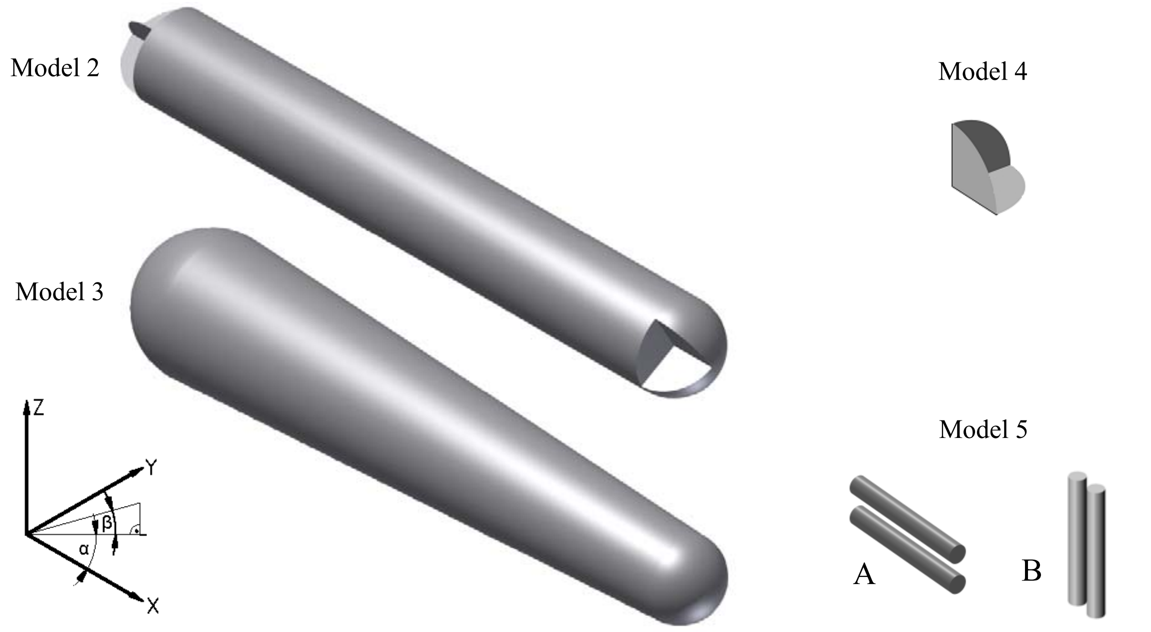

Fig.1: BeTSSi IIb geometries. Model 2 and 3 are identical to Model 2 and 3 as defined for the previous BeTSSi II workshop and have a length of 46 m and 49 m respectively. The quarter circle plates of Model 4 have a radius of 3 m, while the length of the tubes of Model 5 is 4.8 m.

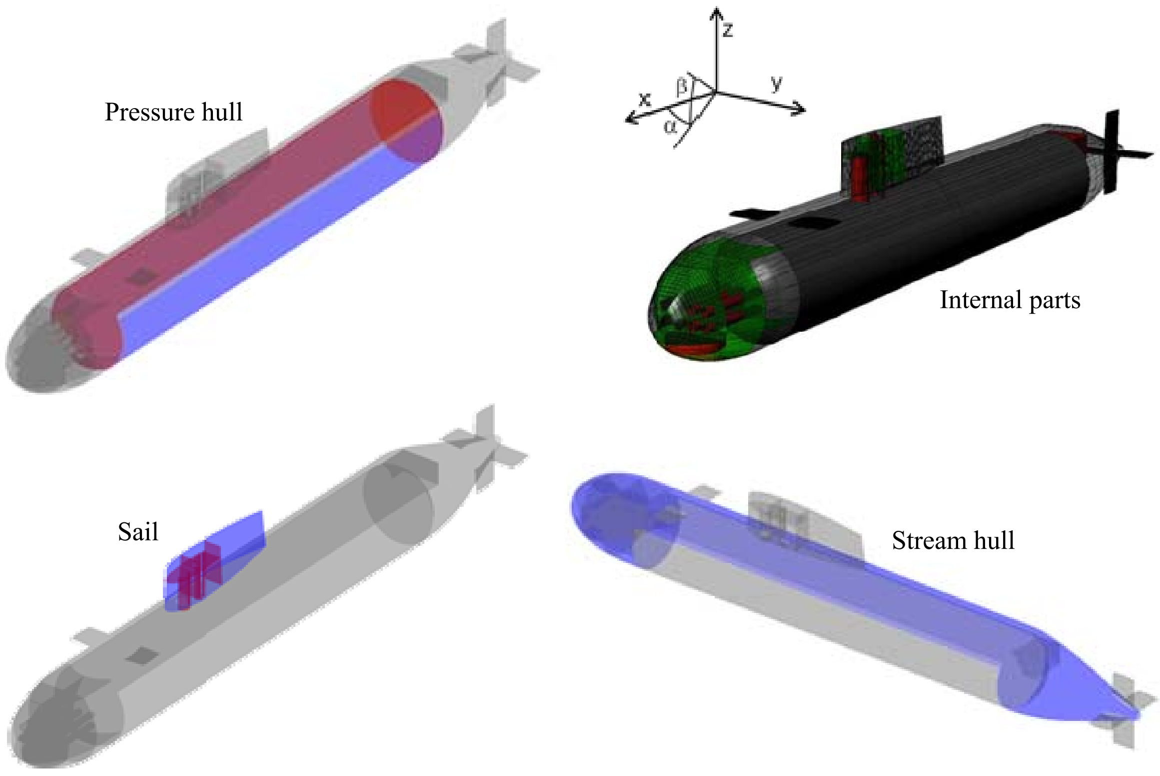

Fig.2: BeTSSi geometry. In the images on the left, the pressure hull and sail consisting of both internal parts (red) and an external part (blue) are highlighted. In the top right image, in addition to the internal parts of the sail, torpedo tubes (red), the bow sonar (red) and the supporting plates in bow and stern (green) that can be seen between the pressure hull and stream hull are highlighted.

3. NUMERICAL METHODS

Participants to the workshop were free to choose a numerical method for calculating the TS. Several participants used different numerical models depending on frequency and the benchmark case. Participants supplied results for all considered benchmark cases for which they have a suitable code available. Table 1 lists the numerical methods used by each participant that supplied results for the monostatic TS of the BeTSSi sub for a 360 degrees sweep over aspect angle at 10 kHz (for which results are shown in section 4). Four groups of models are identified which are color coded. The colors and labels defined by the 'Label/(plot color)' column in Table 1 match with the colors and labels of the curves plotted in Figure 3.

Institute	Label (plot color)	**Description** Occlusion handling
Institute 1	Single 1	**Kirchhoff (single bounce)** Illumination/receiver occlusion methods unknown
Institute 2	Single 2	**Kirchhoff (single bounce)** Illumination/receiver occlusion methods unknown
Institute 2	Ray 2	**Ray tracing** (TS based on ray density at receiver) Illumination/receiver occlusion using ray tracer
Institute 3	Iterative 3	**Iterative Kirchhoff, 3 bounces (nested integral)** Illumination/receiver occlusion determined by "Hidden-Surface Algorithm"
Institute 4	Single 4	**Kirchhoff (single bounce)** Illumination based on normal Receiver occlusion method unknown
Institute 5	Single 5	**Kirchhoff (single bounce)** Illumination occlusion based on normal Receiver occlusion methods unknown
Institute 5	Multiple 5	**Kirchhoff, multiple bounces (method unknown)** Illumination/Receiver occlusion methods unknown
Institute 6	Iterative 6	**Iterative Kirchhoff, multiple bounces (recursive)** Illumination/receiver occlusion determined by "Hidden-Surface Algorithm"
Institute 7	Single 7	**Kirchhoff (single bounce)** Illumination occlusion based on normal Receiver occlusion method unknown
Institute 8	Multiple 8	**Kirchhoff, multiple bounces (Beam tracer)** Illumination/receiver occlusion using beam tracer
Institute 9	Single 9	**Kirchhoff (single bounce)** Illumination/receiver occlusion based on normal
Institute 9	Multiple 9	**Kirchhoff, multiple bounces (Beam tracer)** Illumination/receiver occlusion using beam tracer
Institute 10	Multiple 10	**Kirchhoff, multiple bounces (Beam tracer)** Illumination/receiver occlusion using beam tracer

Table 1: Numerical methods used by each participant for the benchmark case involving a sweep over the azimuth angle

The model type 'Kirchhoff' implies the use of Kirchhoff diffraction theory (for a good introduction for the case of optic diffraction see [8]). In these models, all surfaces of the target are discretized into flat facets. The contribution of each facet is calculated using an approximate form of Kirchhoff diffraction theory and the total response is calculated by summing the contribution of all facets. Depending on the assumptions made for the boundary conditions on the virtual plane extending from the facet, the approximate Kirchhoff solution is called a Fresnel-Kirchhoff approximation (assuming zero velocity and pressure on the virtual plane extending from the facet) or a Rayleigh-Sommerfeld approximation (assuming either zero pressure or zero velocity on the virtual plane extending from the facet). The approximations are related since the Fresnel-Kirchhoff approximation is the average of the two Rayleigh-Sommerfeld approximations. For the special case of a monostatic setup (source and receiver are collocated), it can be shown that all approximations are identical. It is still under debate which approximation is more accurate for bi-static cases (especially in the near field [8]), however. Throughout this paper, all approximate versions of Kirchhoff diffraction theory are simply referred to as Kirchhoff approximations.

Note that a distinction is made between ray tracer and beam tracer models. For the beam tracer models, the contribution of each sound ray/beam to the total TS is determined by using a Kirchhoff approximation to calculate the sound radiated by each facet of the mesh that is illuminated by the beam (and is visible from the receiver position). For the ray tracer model the TS is determined by the density of reflected rays intersecting a control surface at the receiver. Iterative Kirchhoff models use a Kirchhoff approximation multiple times, each time calculating how the object illuminates itself based on the pressure distribution on the surface calculated in the previous step (in the first iteration, the pressure distribution is given by the incident field). Finally, a Kirchhoff approximation is used to calculate the pressure at the receiver based on the total pressure distribution on the targets surface (i.e., an accumulation of the pressure distribution calculated in each iteration).

4. RESULTS

The calculated monostatic TS for the BeTSSi submarine at 10 kHz are shown in Fig 3 for a sweep over the aspect angle at zero degrees elevation. The trends of all models agree fairly well for the hard walled case with the exception for one of the models based on beam tracing which produces wildly different results for aspect angles between 110 and 170 degrees (note that these results were produced using a code not previously tested at these frequencies) and the TNO models above 170 degrees aspect angle (the TNO mesh was missing the flat circular plate closing the tail cone in the BeTSSi models).

For the case with realistic boundary conditions, different trends can be observed for the different color coded groups associated with different types of models. The different model types which yielded similar results for the hard walled case yield different results for realistic boundary conditions since they are not equally equipped to calculate the effects of transmission, occlusion, multiple reflection and acoustic properties of steel layers of different thickness correctly. The difference between the models that are capable (blue, orange and purple) and are unable (red) of taking multiple reflections into account is most striking and are mostly related to corner reflectors formed by flat internal plates.

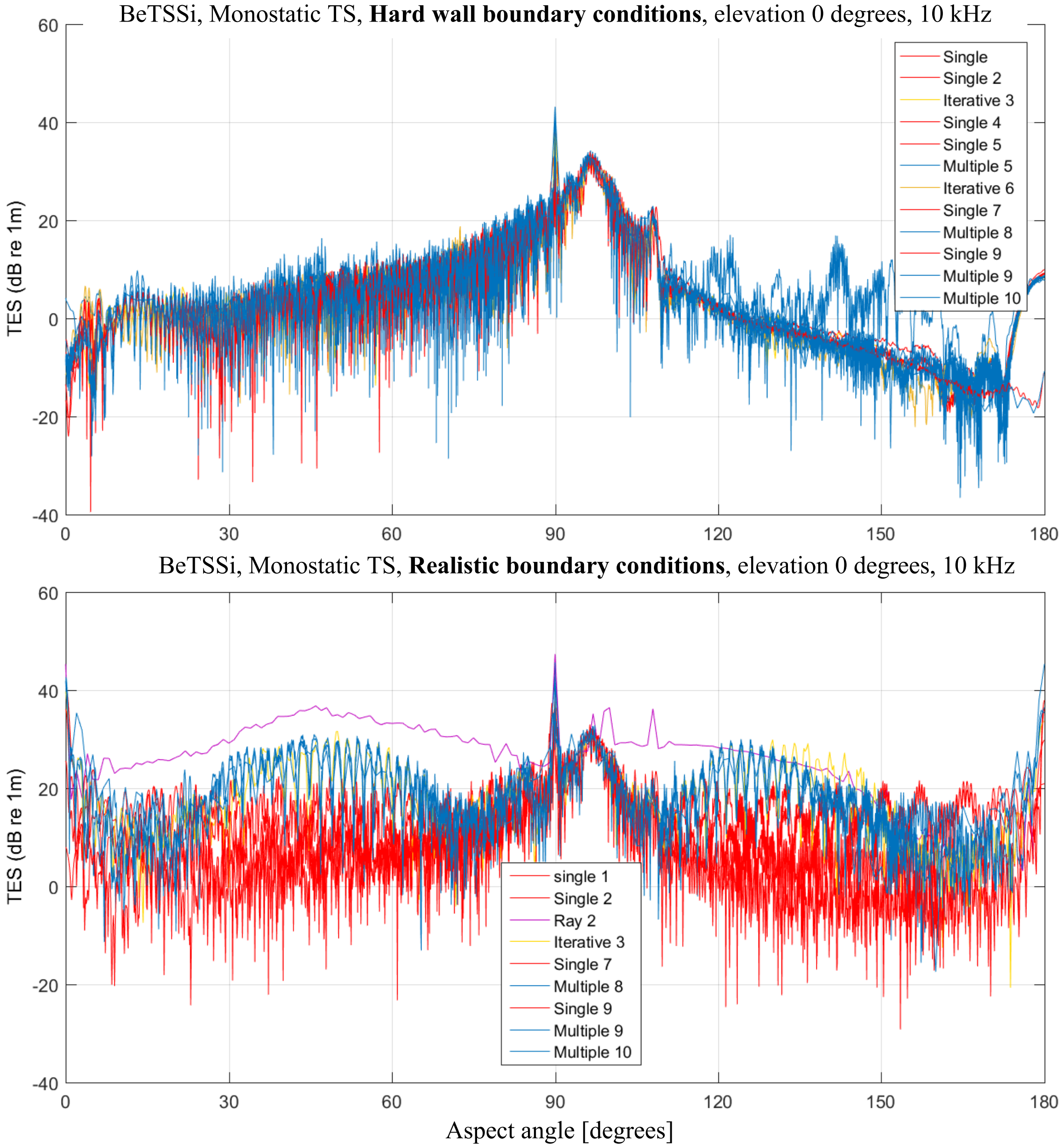

Fig.3: Monostatic TS for the BeTSSi case at 10 kHz for hard walled boundary conditions on all outer surfaces (top panel) and realistic boundary conditions (bottom panel)

While the reason for the consistent over-prediction of the TS by the ray tracer model was not discussed, an informed guess can be made about the difference observed within each color-coded group. The difference observed between results for the group of models using a Kirchhoff approximation with a single bounce can likely be attributed mostly to the fact that the approach to determining which facets are illuminated by the source, and which facets are occluded by others as seen from the receiver differs for almost each model. For the beam tracer models including multiple bounces, the number of included bounces varies and the details of branching a beam when interacting with a facet varies, which is likely the main cause of the difference observed for the results in this group.

All models that are capable of calculating the case with realistic boundary conditions use an approximation of the reflection and transmission coefficient (that represent the acoustic properties of the submarine surfaces) which is based on the assumption of a plane wave incident on an infinite flat plate. However, in the implementation of these acoustic plate models, there are different approaches used to calculate the reflection and transmission coefficients. For instance, for some of the models the coefficients are dependent on the angle of incidence, but not for all models. This contributes further to the difference observed in model results.

Despite all the differences between the models, some features (such as broad side glint) are predicted correctly by all models (even for the case with realistic boundary conditions), while other features lead to wildly different predictions. The features that need to be modelled correctly dictates which model types are suitable.

Another striking feature of all presented curves (except the curve labelled 'Ray 2') is the highly oscillatory behavior of the TS as a function of aspect angle. The oscillations are interference patterns caused by the phase differences in the scattered sound from different parts of the target. The model corresponding to the curve labelled 'Ray 2' does not exhibit such oscillations, since it is based on ray density at the receiver which represents the energy in all reflected rays instead of a coherent sum of contributions from different part of the target.

The oscillations observed for all other models makes comparison of TS curves difficult. During the workshop the question was raised to what extend the precise nature of the curves is most relevant, or if there is an 'averaged quantity' that is more informative for practical usage (e.g., comparing model/measurement data, setting requirements).

Two logical ways to average TS results that are calculated as a function of angle and frequency is an averaging over either angle or frequency. The downside of averaging over angle, is that it will not only smooth out deep ridges and throughs due to interferences at a given frequency, but also any feature that exhibits large changes in the gradient of the TS (such as the broad-side glint and the contribution of the sail and tail cone as indicated in Fig. 4 by the white, green and cyan arrows, respectively).

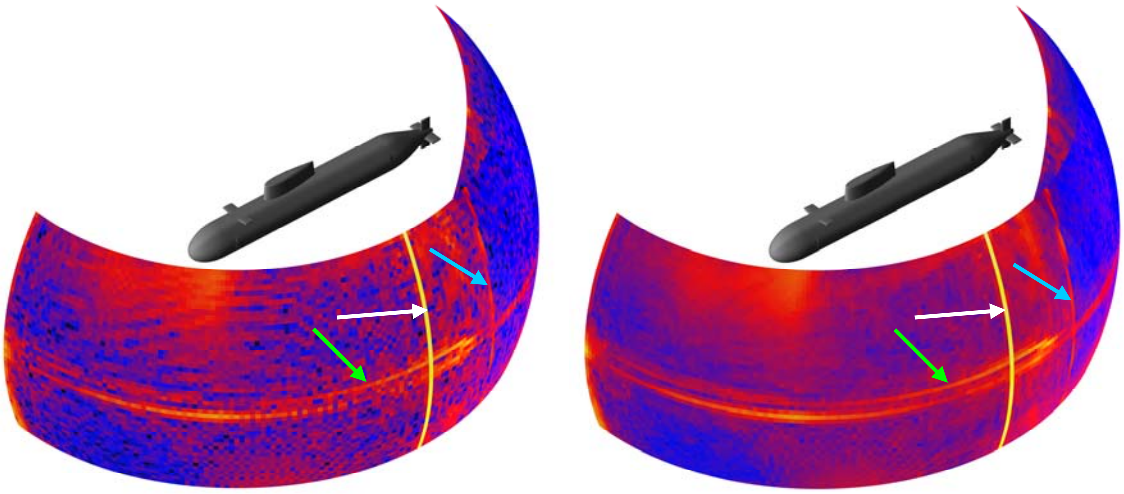

Fig.4: Monostatic TS for the BeTSSi case at 10 kHz for hard walled boundary conditions as a function of aspect and elevation angle. Yellow indicates a high TS, blue indicates a low TS. The white, green and cyan arrows indicate the TS features associated with the broadside glint, sail and tail cone, respectively. The left plot shows result at a single frequency (i.e., 10 kHz), while the right plot shows the TS based on the average of the sound pressure amplitude from 7 frequencies equally distributed over a band of 2 kHz (centered at 10 kHz).

Averaging over frequency on the other hand will smooth out the oscillations due to interference patterns at individual frequencies while preserving features that are consistently observed in the frequency range that is used for averaging. As an example the monostatic TS as a function of aspect and elevation angle for the TNO2 model is plotted for the BeTSSi case at 10 kHz in Fig. 4. The left plot shows result at a single frequency (i.e., 10 kHz), while the right plot shows the TS based on the average of the sound pressure amplitude from 7 frequencies equally distributed over a band of 2 kHz (centered at 10 kHz). Note that in this representation of TS, the frequency smoothing makes it easier to estimate which features will dominate the TS for, for instance, a sonar pulse that has some bandwidth or is subjected to a significant but a priori unknown Doppler shift.

5. ACKNOWLEDGEMENTS

The BeTSSi IIb organizers at TNO, WTD71 and DRDC are thankful to all participants to the BeTSSi IIb workshop: Atlas Elektronik, Atlas Elektronik UK, DST Group, FFI, FOI, Heat Light and Sound Research, Norwegian University of Science and Technology, Novicos, QinetiQ, Rafael Advanced Defense Systems, Tel-Aviv University, Thales UK and ThyssenKrupp Maritime systems.

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