A TARGET ECHO STRENGTH REDUCTION TECHNIQUE

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Abstract: *During the last decades, considerable effort was made to successfully minimize the radiated acoustic noise of submarines – especially of the diesel-electric types. Such ultra-quiet submarines are difficult to detect by passive sonars; therefore, new active sonar techniques were developed which dramatically increased the acoustic detection ranges of the nowadays submarines. This technological development motivates the reduction of the target echo strength (TES) of a new concept study.*

A basic analysis of sound propagation at several oceanographic locations was used to determine the azimuthal threat sector. The stealth technique known from previous efforts in radar cross-section reduction was adopted for underwater sound impinging onto a submarine hull. The exposed hull areas ware shaped accordingly to refract the impinging sound out of the vertical threat sector. The shaping concept requires that the outer hull form be sufficiently opaque, so as not to allow the objects behind it (with potentially high TES levels) to determine the total TES. Therefore, a transmission-loss coating is applied over the outer hull casing of the submarine. The required transmission-loss properties of the acoustic coating were attained through sound reflection; hence the coating is also sometimes referred to as a reflective coating.

The stealth-shape reflects the incoming sound in a sharp beam away from the azimuthal threat sector. To ensure that the shape is properly formed, a concept of acoustic eigenray interaction was derived to verify that sound propagating along one acoustic path is not reflected onto another acoustic path.

After deriving the azimuthal threat sector from sound propagation-analysis and presenting the ray interaction concept, the results of a stealth-optimized shaped submarine will be compared to a classical shaped submarine with and without an acoustic coating. This will be demonstrated on the model submarine denoted as "BeTTSi".

Keywords: *Target Echo Strength, Sonar, Sound Propagation*

1. INTRODUCTION

One of the main advantages of a submarine for military application is to enable its user to operate undercover. In the early days of submarine development, the driving factor was the enormous reduction of the visible (optical) signature. However, soon other signatures were found pertinent to submarine detection. Due to the efficient sound transmission in water, sound is predetermined for detection of submarines during nominal diving condition. During the last decades, passive sonars were the preferred detection method. They identified and pinpointed the radiated acoustic noise source(s) of a submarine. Consequently, considerable effort was made to successfully minimize the radiated acoustic noise of the submarines. Such modern submarines are difficult to detect by passive sonars, forcing many navies to resort to active detection sonars. In the active sonar detection field, minimizing the submarine's propensity to reflect the incoming acoustic energy (the TES) is of the utmost importance.

Not only were submarine techniques improved in a continuous process, sonar techniques were also improved in turn. Sonar technology benefitted especially from the growing computational calculation power, allowing for geometrically sharper beams and more sophisticated signal processing techniques. One very promising signal processing technique benefits from the data-synthesis of a bi- or multistatic network. Successful demonstrations of this technique suggest that detection ranges of a nowadays-submarine will dramatically increase in the future. TES reduction methods will be needed to allow the submarines to operate with the present-day tactical advantage also in the future.

At distances as commonly found in submarine sonar applications, sound propagation in the water is characterized by refraction through the varying sound speed with depth (due to temperature, density and salinity variation) and reflection at the water boundaries. Therefore the sound impinging onto a submarine may have an elevation angle different from the horizontal plane. In order to reduce the TES of a submarine, it may not be sufficient to reduce the TES for the horizontal plane only, but for a range in elevation angle. This angular range, called the threat sector, is derived for sound propagation studies of several world ocean locations. Subsequently a submarine with a TES optimized shape is derived and compared to a classical submarine shape.

2. VERTICAL TES THREAT SECTOR

Sound propagation studies of several world ocean locations have been conducted to determine the threat sector. The first region of study was the Ionian Sea (part of the Mediterranean Sea). During the summer, a relatively shallow but very distinct sonar channel is formed, with its axes at about 150 m depth. Very long detection ranges can be achieved with this kind of sound speed profile. The sound generated by an acoustic source can travel only at distinct paths to the target. If the ray-tracing method is used to simulate the sound propagation, these paths are named eigenrays. The eigenrays between the sound source (sonar) and the target (submarine) - both at 150 m depth - have been computed over the horizontal distance of up to 120 km (e.g. Fig. 1 shows the eigenrays for a horizontal distance of 20 km). The distribution of vertical incident angles of all eigenrays (including surface-reflected but excluding bottom-reflected), was generated to highlight the threat sector. For this sound speed profile (as for many others), the eigenrays impinge onto the submarine within a vertical angle of ±20°. Most of them impinge even within ±10° (Fig. 2) and also within ±5° for the waters in the north-eastern Atlantic. The distributions of the vertical incident angles - for the winter sound speed profiles - of the Ionian Sea, Labrador Sea, Norwegian Sea and the Barents Sea are shown in Fig. 3. From this sound propagation study, a vertical threat sector of ±20° with an increased focus on ±10° is deduced (Fig. 3).

Different sea waters have different vertical threat sectors. To encompass the most of existing ocean areas, thyssenkrupp Marine System assumes a threat sector of ±20°. For shallow waters and for waters without any distinct sound channel, the vertical threat sector is usually narrower than ±10°.

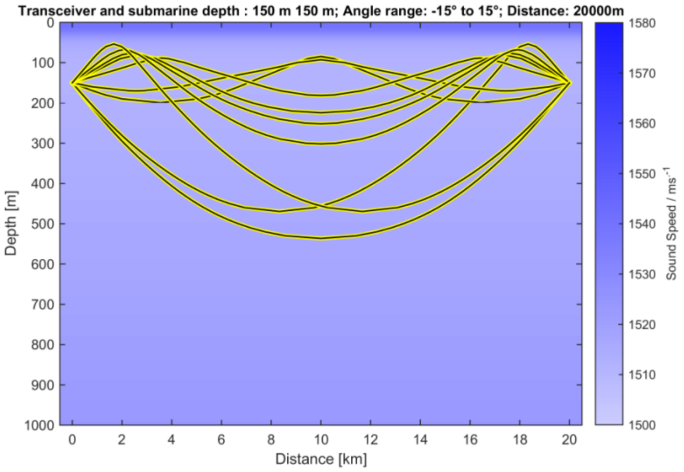


Fig. 1: Eigenrays for the Ionian Sea summer profile. Sound source and submarine are both at 150 m depth and with a distance of 20 km.

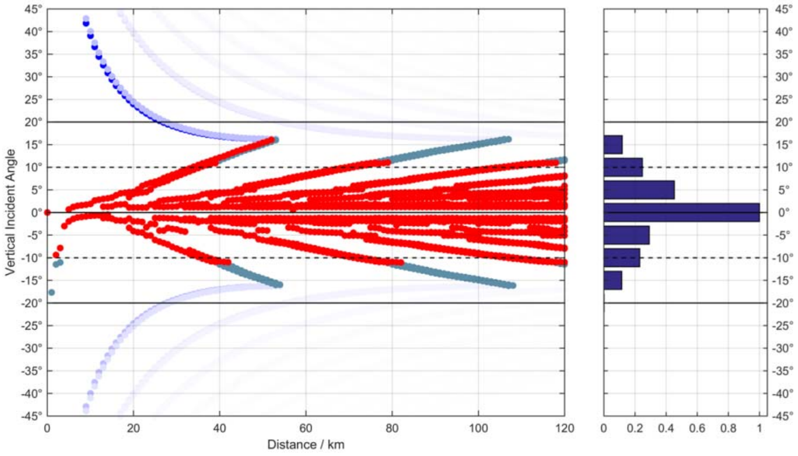


Fig. 2: Vertical incident angle of eigenrays vs. distance (left) and the corresponding distribution of all rays without any bottom reflections (right). The eigenrays are color coded as red: undisturbed, cyan: surface reflected, blue: bottom/bottom-surface reflected.

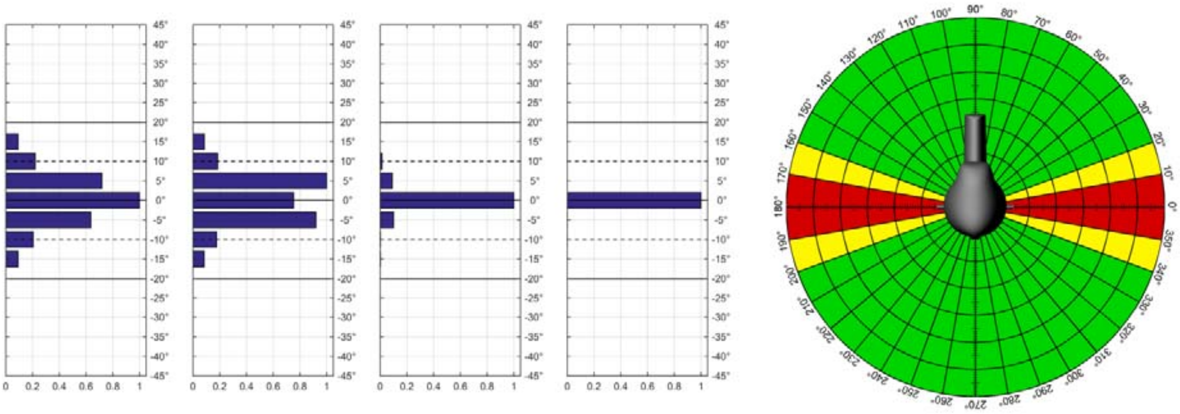
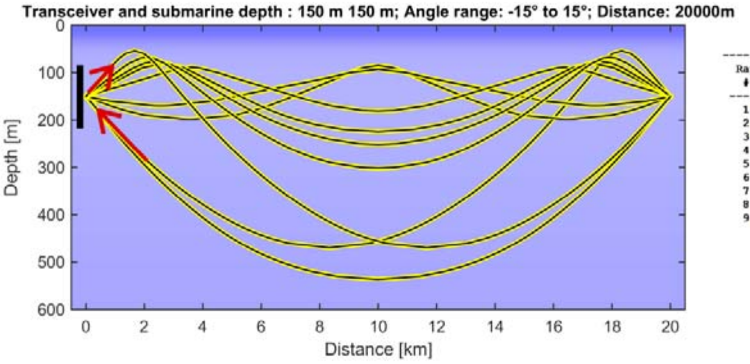


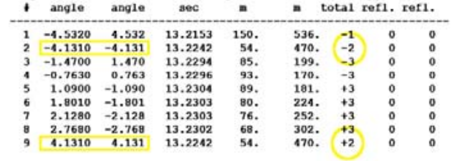
Fig. 3: Vertical incident angle distributions for the Ionian Sea, Labrador Sea, Norwegian Sea and the Barents Sea (from left to right) for their winter profiles respectively and the visual representation of the vertical threat sector.

3. EIGENRAY INTERACTION

The sound propagation in the ocean is in general a multipath propagation. Sound transmitted from an acoustic source can reach the submarine via multiple paths. The submarine does not reflect the impinging sound in one direction only, but scatters the sound effectively into all directions. The scattering is not uniform over the directions; however, a significant TES contribution may occur from sound coming from path A and being scattered into path B.

As an example, we could look more closely at the two eigenrays with two turning points in Fig. 1/Fig. 4. The first is impinging onto the target at a vertical aspect angle of -4.1°, the second at an angle of +4.1°. Because of the reciprocity of the eigenrays (Fermat's principle), the eigenrays for the sound traveling from the sonar to the target are the same as for the sound travelling back from the target to the sonar. A large vertical plate as a target would have a small TES for the two aspect angles ±4.1°; however the specular reflection would bounce the energy from the -4.1°-ray into the +4.1°-ray and vice versa. Subsequently the plate would have an even higher TES as would be the case for (single ray) normal incidence. This phenomenon can be named as eigenray interaction.





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------------------------------------------------------------------------
 Ray Source  Receiver   Time   Upturn Lowturn Turns Upper Lower
  #   angle    angle     sec      m       m   total refl. refl.
 -----------------------------------------------------------------------
  1  -4.5320   4.532   13.2153   150.     536.   -1     0     0
  2  -4.1310  -4.131   13.2242    54.     470.   -2     0     0
  3  -1.4700   1.470   13.2294    85.     199.   -3     0     0
  4  -0.7630   0.763   13.2296    93.     170.   -3     0     0
  5   1.0900  -1.090   13.2304    89.     181.   +3     0     0
  6   1.8010  -1.801   13.2303    80.     224.   +3     0     0
  7   2.1280  -2.128   13.2303    76.     252.   +3     0     0
  8   2.7680  -2.768   13.2302    68.     302.   +3     0     0
  9   4.1310   4.131   13.2242    54.     470.   +2     0     0
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Fig. 4: Same as Fig. 1 but with highlighted ray interaction and added ray table.

To describe the eigenray interaction mathematically, we start at the sonar equation for the receiving level in dB:

$$RL = SL + TL + TES + TL \tag{1}$$

The received acoustic pressure (in Pascals) for the acoustic ray i (ray path reciprocity) is:

$$p_i^{Rx} = p^{Tx} \cdot tl_i \cdot tes_{ii} \cdot tl_i \tag{2}$$

And the received acoustic pressure for the incident acoustic ray path i and the reflected acoustic ray path j is:

$$p_{ij}^{Rx} = p^{Tx} \cdot tl_i \cdot tes_{ij} \cdot tl_j \tag{3}$$

The received acoustic pressure for all combinations of acoustic rays i and j can be written using vectors and matrices:

$$tl = [tl_1 \; tl_2 \; tl_3 \cdots tl_N] \tag{4}$$

$$p^{Rx} = p^{Tx} \cdot tl \cdot \begin{bmatrix} tes_{11} & \cdots & tes_{1N} \\ \vdots & \ddots & \vdots \\ tes_{N1} & \cdots & tes_{NN} \end{bmatrix} \cdot tl^T \tag{5}$$

The tl_i and tes_{ij} values must be complex valued to account for travel time variations (between the different ray paths) and the correct phase of reflections (e.g. water-surface reflections reflect the phase of the signal).

To deduce the levels within the ray interaction matrices tes_{ij}, all multistatic TES combinations were calculated for the vertical incident and reflected angles ranging from -20° to +20°. Results for four different geometrical shapes with identical cross section of 30m×6m (cylinder, flat plate, corner backside and foreside) are shown in Fig. 5. The dots in the center of each panel mark the positions where to pick-up the tes_{ij} levels of the ray interaction matrix which correspond to the eigenrays shown in Fig. 4. The energetic (incoherent) mean of the tes_{ij} levels is indicated by a line in the color bars. The cylinder has a remarkably uniform scattering of the acoustic intensity over the whole vertical angular sector (uniform color over the whole panel). Besides the normal incidence case (0°, 0°), the flat plate shows high bi-static TES levels at the specular reflection axis (from the lower right corner to the upper left) whereas the foreside of the corner reflector show very high monostatic TES levels (from the lower left to the upper right corner). The backside of the corner reflector (roof shape) has comparably low TES levels over the whole angular range considered.

The concept of eigenray interaction is used to ensure that the TES reduction efforts on a submarine are not limited to the horizontal plane only. It enables to combine the sound propagation effects with the scattering characteristic of the submarine (or more generally of an arbitrary acoustic target). This is especially important in oceanographic regions where sound propagation is characterized by a wide angular (vertical) spread.

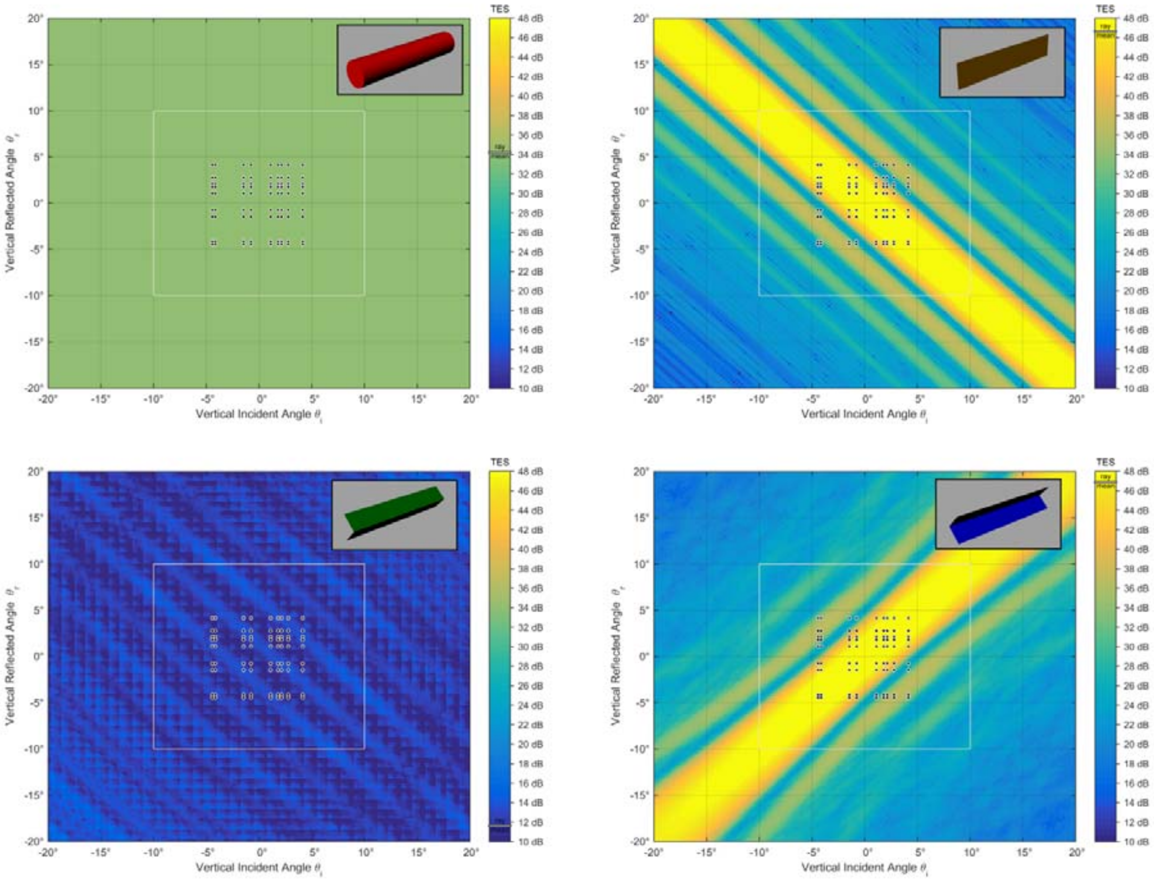

Fig. 5: Multistatic TES combinations for vertical incidence angles and vertical reflected angles ranging from -20° to +20° respectively. Results for four different geometrical shapes with identical cross sections of 30m×6m are shown (cylinder, flat plate, corner backside and foreside). The dots mark the positions where to pick-up the tes_{ii} *levels of the ray interaction matrix for the eigenrays shown in Fig. 4. The energetic (incoherent) mean of the* tes_{ii} *levels is indicated by a line in the color bars. Sonar signal: a sweep in frequency from 2.7 kHz to 3.3 kHz.*

4. MATERIALS FOR TES REDUCTION

Hydro-acoustic materials can be used as coating materials to reduce the TES of a submarine. Most self-evident is to cover the outer hull with an echo reduction material. However echo reduction materials for low sonar frequencies are thick, bulky and often heavy. TES reduction can also be obtained with transmission loss (TL) materials. In case there is an object with high TES behind a semi-transparent surface with low TES, then coating the semi-transparent surface with a TL material lead to shadow/shield the object with the high TES [2].

The TL material is extremely thin and at the same time suitable for very low sonar frequencies. It achieves 10 dB transmission loss up to 150 m diving depth, while the thickness is less than 15 mm. The nearly neutral buoyancy for seawater may allow an implementation on existing submarines.

The echo reduction (ER) material can be used on large surfaces with high reflectivity. This is in general at the pressure hull, which is not semi-transparent but fully reflecting and also at the sail (if its sides have nearly vertical orientation).

The already reached laboratory performance of an ER material is 10 dB reflection-loss while working at pressures equivalent from 150 m to 500 m diving depth. This ER material also has nearly neutral buoyancy for seawater but has a thickness of 200 mm.

5. TES CALCULATION

In general, the TES depends on the acoustic frequency, the aspect angle and the shape of the reflecting object [1]. Often, the TES calculations assume fully reflecting objects, i.e. reflection coefficients of unity. However, a submarine's outer hull is not completely reflecting and therefore a submarine consists of numerous scattering objects of different sizes and shapes - which can all be found beneath the hydrodynamic casing. In particular, it is not adequate to consider solely the outer hull for the TES calculation.

TES reduction concepts imply the application of hydro-acoustic materials over the submarine's various surfaces. Therefore the TES calculating program needs to be able to work not only with semi-transparent surfaces, but also with absorbing surfaces.

Various TES calculations and their differences are emphasized on a model submarine named BeTSSi [3] (Fig. 6). BeTSSi has features of a modern submarine without sharing specific similarities with a particular submarine class. That makes it an ideal neutral candidate to study TES behaviour and reduction. BeTSSi's overall length is 62 meters and the diameter of the pressure hull is 7 meters. The casings of the bow, upper deck, sail and stern are constructed from 10 mm steel. These areas are flooded with sea-water. That means that the medium in front and behind the steel casing is seawater. In such conditions, a 10mm steel plate is nearly transparent for low sonar frequencies [4]. Obviously the objects lying within the flooded areas, such as bulkheads, torpedo tubes, masts and tanks, become important for the TES calculation. The arrangement of the bulkheads forms several corner reflectors, which in turn increase the TES over a wide angular range.

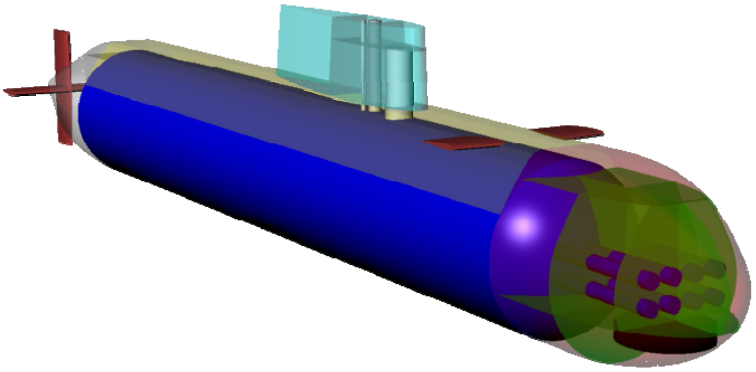

Fig. 6: The fictive submarine "BeTSSi" used for exemplary TES calculations.

Fig. 7 shows a contour plot of BeTSSi's mono-static TES with respect to frequency and aspect angle. Several sharp peaks of high TES are present over the whole frequency range: the bow peak (at 0° aspect angle) and the beam peaks (at 90° and 270° aspect angle). Above 5 kHz, there arises another peak at ~100° and ~260° aspect angle. The 180° peak is due to the bulkheads in the sail and the vertical end of the casing. Due to the vertical sail casing, peaks at 100° and 260° aspect angle arise. Besides these distinct peaks, an area of intermediate levels can be found between ±135° aspect angles. Here, multiple reflections between the along ships’ and athwart ships’ bulkheads are responsible for the relatively high TES levels found within this range.

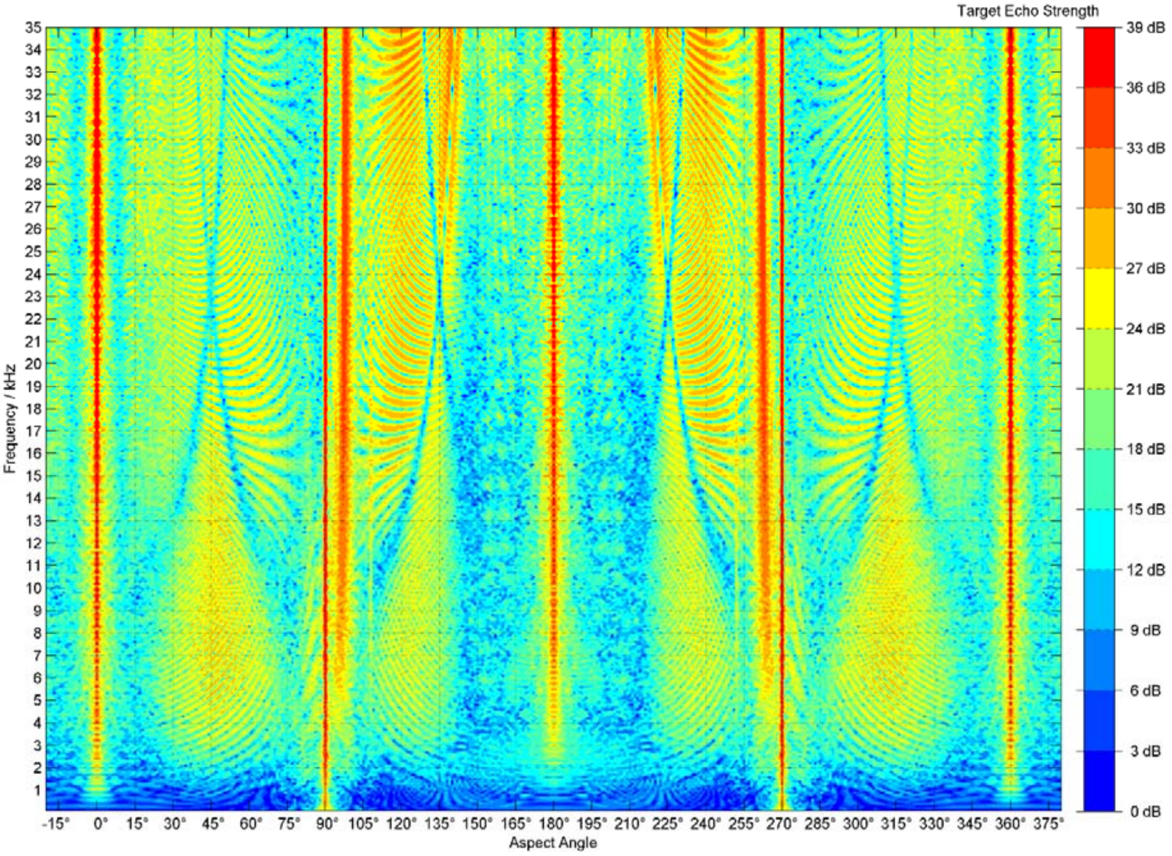

Fig. 7: Target echo strength of the fictive submarine model BeTSSi.

These high TES levels develop only if the correct treatment of corner reflectors is implemented within the calculation method, whereas traditionally the TES is calculated assuming a fully reflecting outer submarine hull (rigid hull).

Fig. 8 emphasizes the large difference between these calculations. In addition, a calculation without correct corner reflections is included for comparison. All three calculations can reproduce the beam aspect peak at 90° and the increased TES values between roughly 80° and 110°. The calculation without the correct corner reflections also is capable to reproduce the bow and stern peaks at 0° and 180°, however it underestimates the TES at the intermediate aspect angles (20° – 60° and 110° – 150°) by up to 15 dB. The rigid hull calculation underestimates the bow and stern peaks by 50 dB and 27 dB respectively and in addition the intermediate aspect angles by 20 dB to 30 dB.

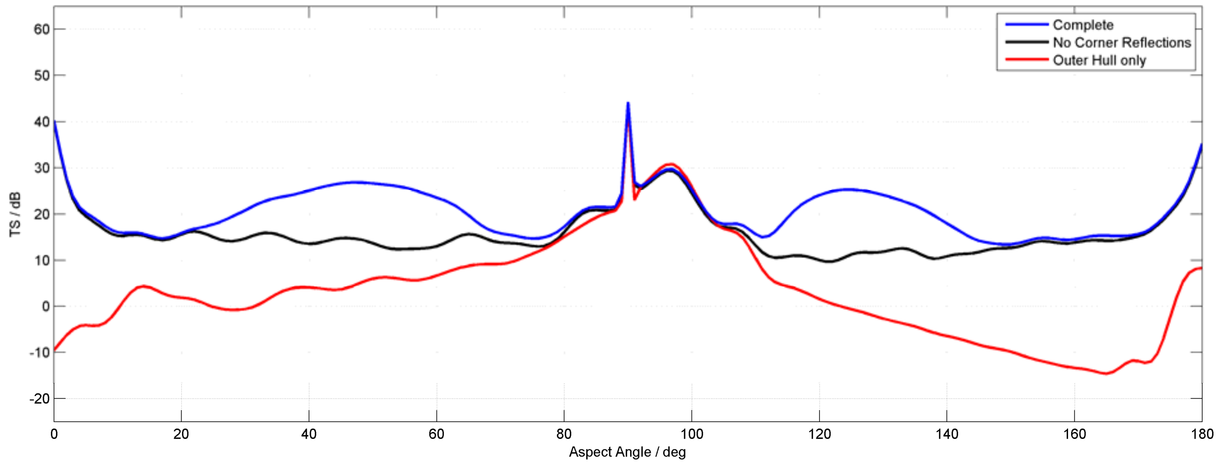

Fig. 8: Different TES calculations for a 10 kHz sonar frequency.

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7. COATING CONCEPT FOR TES REDUCTION

The main influence on the TES spatial distribution is from the shape of the reflecting object. A flat plate, if large compared to the acoustic wavelength, will reflect the sound in a narrow beam whereas a sphere will distribute the reflected sound over a wider angular range [1]. This matter of fact can be used, together with the hydro-acoustic materials, to develop a coating concept for TES reduction for the model submarine BeTSSi.

As a starting point for the TES reduction, we assume an active sonar source with a transmitting frequency of 1 kHz and 3 kHz. The TES of the uncoated submarine is shown again, but now only for 1 kHz and 3 kHz, as the blue curve in Fig. 9. The overall TES value is somewhere between 10 dB and 25 dB with the already mentioned peaks. The bow casing is curved and has, compared to the bulkheads, a smaller TES level. Therefore the first coating step is to apply the TL material onto the bow casing. The TES-calculation predicts a reduction of the bow peak of more than 10 dB, as shown in Fig. 9 (red curve). The beam aspect peak may be reduced by applying the ER material (with an assumed reflection loss of 10 dB) to the pressure hull and the sail. In the case of the BeTSSi model, the 90°/270° peaks could be reduced by 8 dB. In addition, the submarine stern was also coated with the TL material which reduced the peak at 180° by more than 15 dB. The overall TES value could also be reduced slightly at 1 kHz and significantly at 3 kHz.

8. STEALTH-SHAPE CONCEPT FOR TES REDUCTION

As already proposed in 1978 [5], the TES can be reduced even further, if the outer shape is modified according to the rules known from the radar cross section reductions [6]. Such a shape needs an opaque surface to work as intended. Therefore, a TL material would need to be applied nearly over the entire outer hull. The TES calculations with these types of shapes show very promising results. One such result is shown in Fig. 9 in comparison to the uncoated and coated BeTSSi model results. The beam aspect peak could be reduced by 12 dB to 25 dB at 1 kHz and 3 kHz; the bow and stern peaks could be reduced by 15 dB and 25 dB respectively. Notable, beside the few sharp TES peaks, the stealth-shape concept is able to reduce the TES over the whole horizontal plane. This property is not observed with this intensity for the coating concept and will be even more impressive for the muti-static scenario.

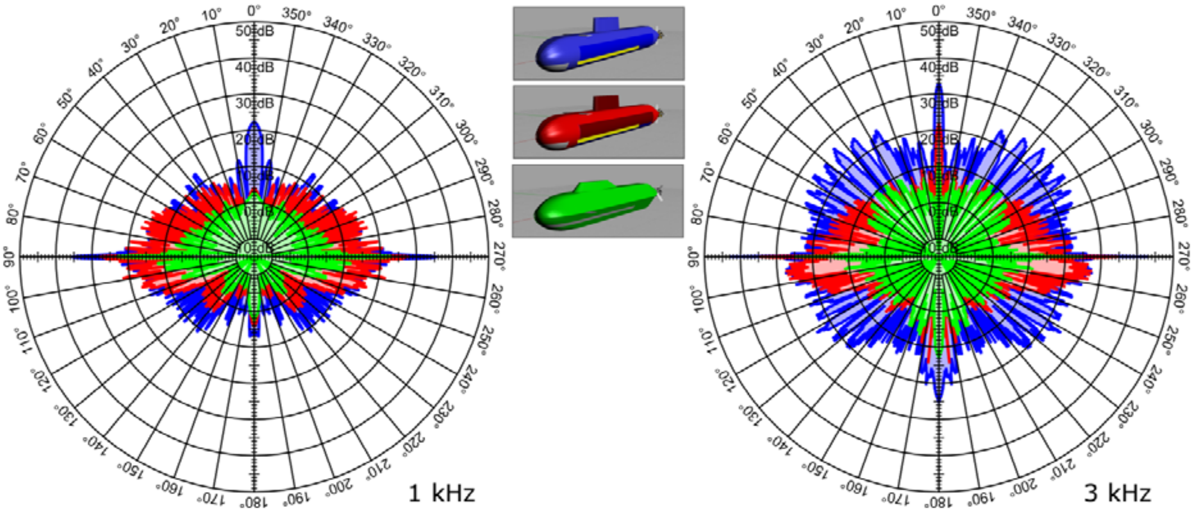

Fig. 9: Monostatic TES of a stealth-shape submarine (green) compared to the coated (red) and uncoated (blue) model BeTSSi. Left: 1 kHz, right: 3 kHz.

9. COMPARISON OF THE MULTISTATIC TES

New multistatic active sonar techniques were developed which dramatically increased the acoustic detection ranges of the nowadays submarines. Due to the reflecting nature of the stealth-shape concept, it is often believed that this concept would not perform in a multistatic sonar scenario, as has been sometimes observed with stealth-shaped airplanes. However, the stealth-shape concept proposed by thyssenkrupp Marine Systems reflects the acoustic energy into the vertical sector such that sound propagation over long horizontal distances is no longer possible.

Fig. 10 compares the multistatic target echo strength for the three submarines: the stealth-shaped submarine and the coated and uncoated BeTSSi submarine. The azimuthal receiver aspect angle relative to the submarine is plotted on the x-axis and the transmitter aspect angle on the y-axis. The TES levels for all receiver/transmitter aspect angle combinations are color-coded. The upper panel shows the TES levels for a sonar frequency of 1 kHz and the lower panel for 3 kHz. On the left side, the TES levels of the original BeTTSi submarine and on the right side the TES levels of the stealth-shaped submarine are displayed. In the center the TES levels of the coated BeTSSi submarine are shown.

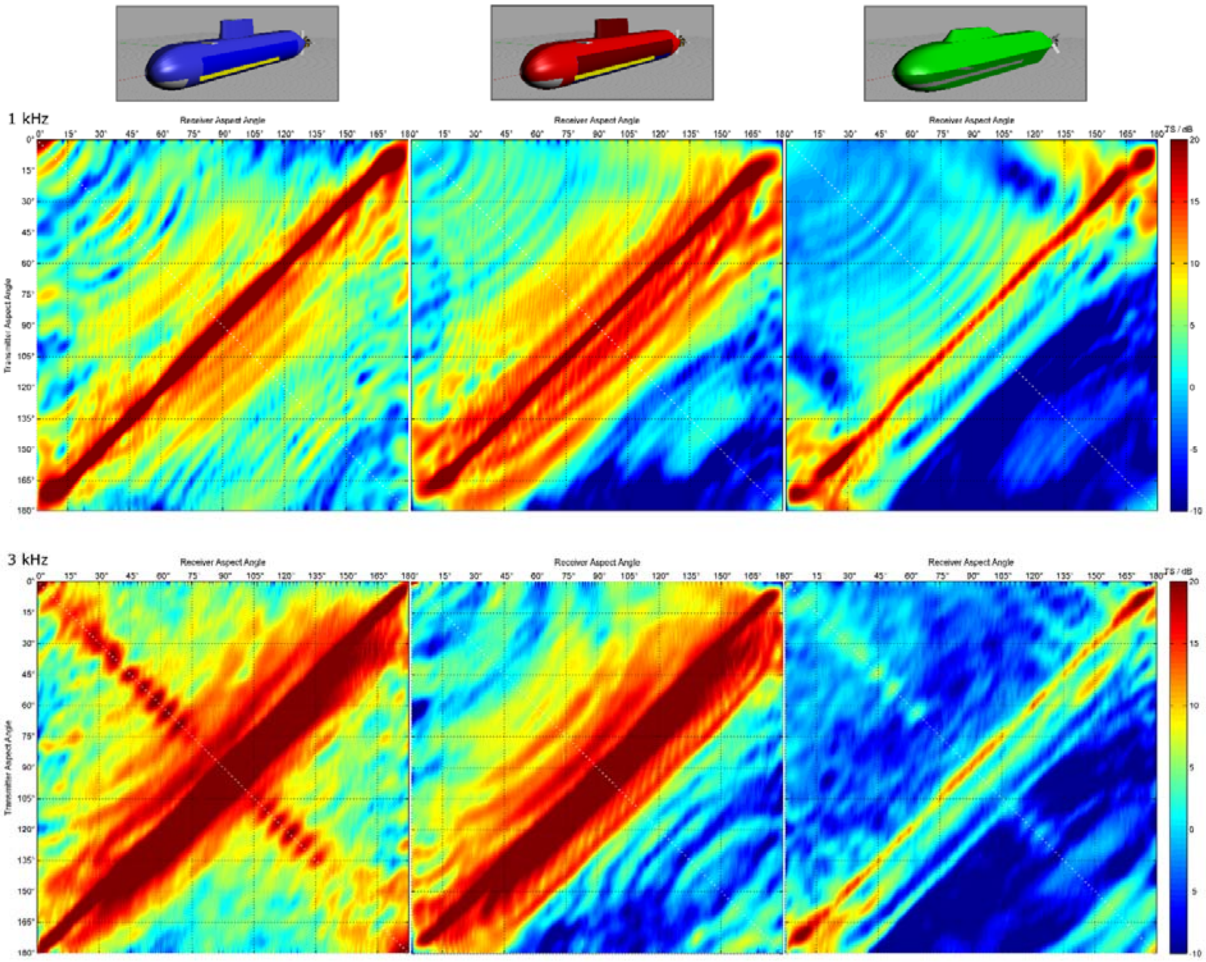

Fig. 10: The multistatic target echo strength with respect to the transmitter and receiver aspect angle for the three submarines: uncoated BeTSSi, coated BeTTSi and the stealth-shaped submarine.

10. SUMMARY

The degree of reflection of acoustic signals is denoted as the “target echo strength” (TES). Concerning the “visibility” of submarines, this backscatter phenomenon is of the utmost importance. A correct prediction of the TES is fundamental for an efficient TES reduction concept. With hydro-acoustic materials, which are applied as a cover over the outer hull of the submarine, two TES reduction concepts were presented. The first concept is a classical coating concept, where different surfaces are covered with absorptive and reflective material without changing the outer shape of the submarine. The second concept uses only a thin reflective material, but strongly changes the outer shape in accordance with the known stealth technique for reducing the radar cross section.

Both concepts - the coating and the shaping concept - reduce significantly some very distinct monostatic TES peaks. However switching from the monostatic to the multistatic case, the ability to reduce the overall TES levels, for any combination of transmitter/receiver positions, is only observed from the submarine form-shaping concept.

11. REFERENCES

1 Hodges, R. P. Underwater Acoustics: Analysis, Design and Performance of Sonar, John Wiley & Sons, 167–173, (2010).

2 Avsic, T. Taking the next step in stealth submarine development, *Proceedings of the 22nd International Congress on Sound and Vibration*, Florence, Italia, 12–16 July, (2015).

3 Gilroy, L., De Jong, C., Nolte, B. and Schäfer, I., *BeTSSi II Benchmark Target Strength Simulation*, available: http://www.dwt-sgw.de/wt-aks/arbeitskreis-akustik/veranstaltungen-2014/

4 Folds, D. L., and Loggins, C. D. Transmission and reflection of ultrasonic waves in layered media, *The Journal of the Acoustical Society of America*, **62** (5), 1102–1109, (1977).

5 Rich, B. R. and Janos, L. *Skunk Works: A Personal Memoir of My Years of Lockheed,* Little, Brown and Company, 271-273, (1994)

6 Knott, E. F., Shaeffer, J. and Tuley, M. *Radar Cross Section,* Second Edition. SciTech Publishing, 279-294, (2004)