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An underwater vehicle shape with reduced acoustic backscatter

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ABSTRACT

In some underwater applications, acoustic backscatter might have undesired consequences, such as interferences in underwater communications or echoes in the sonar image. Acoustic backscatter of an underwater object is classically reduced by applying appropriate absorbing materials on the surface. Absorbing materials convert the acoustic energy into heat and their thickness is usually on the order of a quarter wavelength. In some cases, the application of absorbing materials might have unacceptable drawbacks on other design criteria. For long-distance acoustic propagation (by way of the acoustic channel propagation,) it can be shown that undisturbed sound travels nearly horizontally within a limited vertical angle of no more than ± 20° from the horizontal plane. Hence, for long-distance applications, the acoustic backscatter can be reduced by proper shaping of the vehicle's lateral outer hull. In case the outer hull is not opaque enough to shield the vehicle's inner structures (with potentially high backscatter risk), reflective material can be applied. The working mechanism of reflecting materials is the impedance mismatch and hence, reflecting materials can be much thinner than absorbing materials. This conference contribution will address the worldwide sound spreading in the ocean and show the guidelines for a geometric outer hull shaping.

Keywords: underwater sound propagation, target strength, scattering

1. INTRODUCTION

During the last decades, considerable effort has been made to reduce the radiated acoustic noise of submarines – especially of the diesel-electric types. Such ultra-quiet submarines are difficult to detect by passive sonars alone; therefore, new multi-static 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) for newly built submarines. A technique to reduce the backscattering towards the sonar system is based on specular reflection. The idea for this technique is known now for nearly 100 years (3). Later on, the technique was adopted to reduce the radar cross-section and is often called the stealth technique.

Although this technique is successfully used for radar cross-section (RCS) reduction, it was never used consequently on an underwater vehicle to reduce its target echo strength (sonar cross-section).

The question arises: why this technique is used for RCS reduction but not for TES reduction. Is this technique possibly inappropriate for TES reduction?

This TES reduction technique involves three interacting domains, which need to be considered in an overall concept. These are: the sonar system, the sound propagation and the reflectivity of the submarine. The sonar signal is transmitted by a sonar system – most often directed into a certain spatial direction or domain. The sound propagation through the sea determines the signal paths and the potentially disturbing reflections from the sea surface and the sea floor. The submarine itself will reflect and/or scatter the sonar signal, which has to travel again through the sea to arrive at a sonar system where it could be detected.

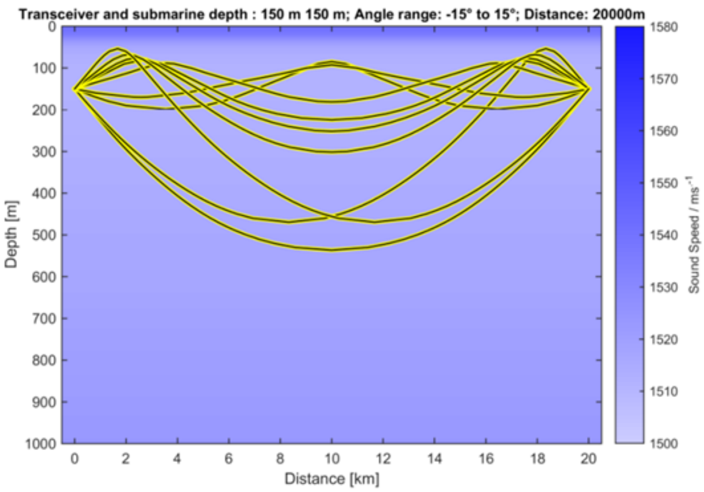
The first part of the paper is a general analysis of worldwide sound propagation in the sea and determines the long distance angular propagation sector of the sonar signal. The second part calculates the reflection of different geometrical shapes for the previously derived long distance angular propagation sector. Hence, appropriate design criteria can be derived for a TES reducing shape. Finally, the TES of a classical shaped submarine (with and without anechoic material) is compared to a stealth shaped submarine.

2. Vertical propagation sector

The sound speed in the ocean is not homogeneous. Compared to the vertical variations, the horizontal variations are usually small. The vertical sound speed variations have a strong impact on the long distance sound propagation. Increasing hydrostatic pressure with depth yields an increasing sound speed with depth and warm water masses near the sea surface increases the sound speed near the sea surface. Hence, a sound speed minimum is found at a certain depth, which is, for tropical and subtropical climate zones, usually at about 1000 m. In temperate climate zones, this minimum is at a lower depth (50 m – 200 m). For polar and subpolar zones, it is usually at the sea surface, due to the lack of warm water masses at the surface on account of the frigid conditions.

The acoustic waves are refracted towards waters with lower sound speed, i.e. towards the depth of the minimum sound speed. They overshoot this depth and subsequently, they are again refracted towards the minimum. The sound is trapped within the sound channel axis and it can travel over very long distances without coming in contact by the sea surface or the sea floor. This is important, because every contact with the sea surface or sea floor will reduce the acoustic signal into the propagation direction. Consequently, the undisturbed sound propagates within a certain vertical angular range, depending on the sound speed profile.

A basic worldwide sound propagation study has been conducted to determine the range in elevation angle of long distance sound propagation. The example of the sound propagation in the Ionian Sea (a part of the Mediterranean Sea) is used to explain the procedure. During the summer, a relatively shallow but very distinct sonar channel is formed, with its axes at about 150 m depth. Due to the refraction of the sound by the inhomogeneous sound speed profile, sound generated by an acoustic source can travel at multiple but 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. Figure 1 shows the eigenrays for a horizontal distance of 20 km together with the corresponding elevation angles at the sound source and the submarine). In the left panel of the Figure 2, these elevation angles at the submarine are plotted as dots with respect to the horizontal distance (up to 120 km). The arrival angles of the undisturbed rays are marked with red dots, the rays with surface reflections are marked with cyan dots and the rays, which also experience bottom reflections, are marked with blue dots. With every bottom or surface reflection, the blue color is faded out a bit, to emphasis that with every reflection the sound signal weakens in intensity. The distribution of vertical incident angles of all eigenrays (including surface-reflected but excluding bottom-reflected), was generated to highlight the propagation sector. For this sound speed profile, the eigenrays impinge onto the submarine within a vertical angle of about ±17°. It is this maximal vertical angle, which defines the *vertical propagation sector* for this particular region. Including the surface-reflected but excluding the bottom-reflected rays highlights the fact that the surface reflected rays often could be used for sonar detection, however the bottom reflected usually not.



Ray ID	Elevation Angle at Source	Elevation Angle at Target
-1	-4.53°	4.53°
-2	-4.13°	-4.13°
-3	-1.47°	1.47°
-3	-0.76°	0.76°
+3	1.09°	-1.09°
+3	1.80°	-1.80°
+3	2.13°	-2.13°
+3	2.77°	-2.77°
+2	4.13°	4.13°

Figure 1 – Left: Eigenrays for the Ionian Sea summer profile. Sound source and submarine are both at 150 m depth and with a horizontal distance of 20 km. Right: Table with the corresponding elevation angles at the sound source and the target (submarine).

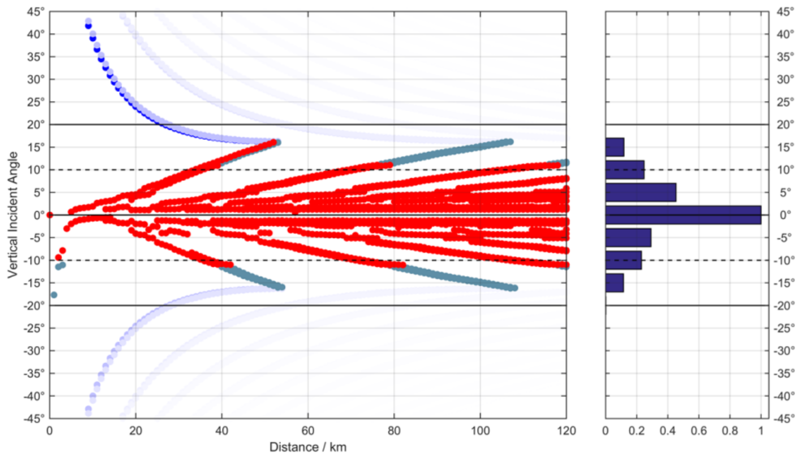


Figure 2 – Vertical incident angle of eigenrays vs. distance (left) and the corresponding distribution of all rays without any bottom reflections (right). The eigenrays are color coded as red: undisturbed, cyan: surface reflected, blue: bottom/bottom-surface reflected.

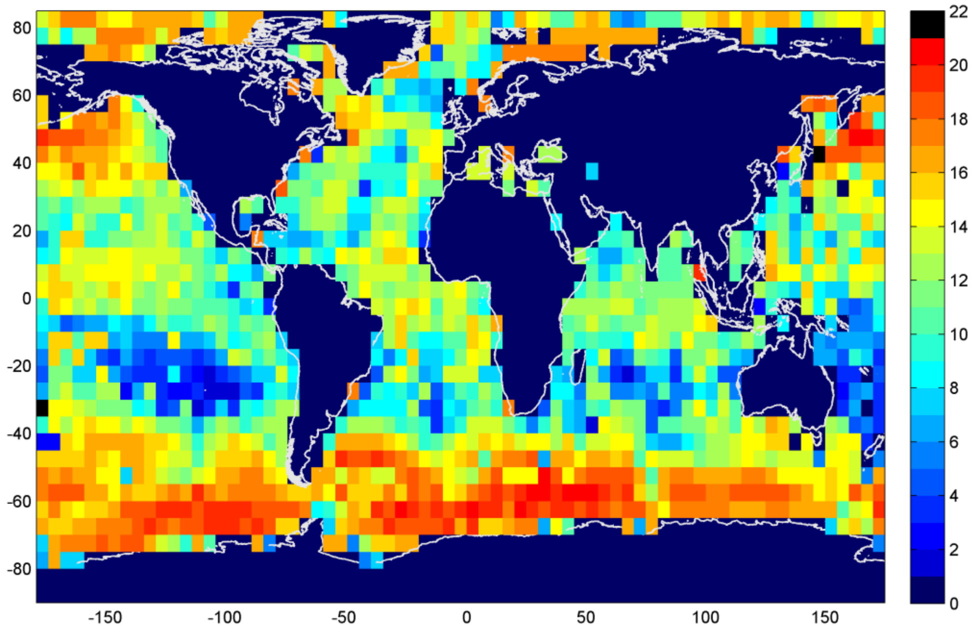


Figure 3 – Worldwide vertical propagation sector

The maximal vertical propagation angle is calculated worldwide on a 5° x 5° latitude-longitude-grid and displayed in Figure 3. From this figure it can be deduced, that the vertical propagation sector is not more than ±20°, no matter where in the World Ocean the submarine is operating. The reverse conclusion is that if the sonar signal is reflected away from the vertical propagation sector, the scattered signal will not arrive at the sonar system and hence the submarine will most likely not be detected. If a stealth shape is used to reduce the TES of an underwater vehicle, the shape then has to ensure, that the sonar signal is reflected in a vertical direction either above +20° or below -20°.

2.1 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 possible 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 Figure 1 (Ray ID -2 and +2). The first impinges 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, 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 a single ray having normal incidence. This phenomenon can be denoted as eigenray interaction.

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

$$\mathrm{RL} = \mathrm{SL} + \mathrm{TL} + \mathrm{TES} + \mathrm{TL}$$

where SL is source level and TL the transmission loss (propagation loss). The received acoustic pressure (in linear scale) for the acoustic ray i (ray path reciprocity) is:

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

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

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

The received acoustic pressure for all combinations of acoustic rays i and j can be written using vector and matrix formalism:

$$tl = [tl_1 \; tl_2 \;\; tl_3 \cdots \; tl_N \;]$$

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

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 changes of reflections (e.g. the water-surface reflections reflect the phase of the signal).

To deduce the reflectivity levels within the ray interaction matrices (tes_{ii}), multipath 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 area of 30m×6m (namely the cylinder, flat plate, corner backside and foreside) are shown in Figure 4. The dots in the center of each panel mark the positions where to pick-up the tes_{ii} levels of the ray interaction matrix which correspond to the eigenrays shown in Figure 1. The energetic (incoherent) mean of the tes_{ii} levels is indicated by a line in the color bars. The cylinder has a remarkably uniform scattering of the acoustic intensity over the entire vertical angular sector (note the uniform color over the entire panel in the Figure). 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 entire angular range considered.

The concept of eigenray interaction is used to ensure that the TES reduction efforts on a submarine covers the entire vertical propagation angle. It enables one to combine the sound propagation effects with the scattering characteristic of the submarine (or more generally that of an arbitrary acoustic target). This is especially important in oceanographic regions where the sound propagation is characterized by a wide angular (vertical) spread.

An inclined flat surface is able to reflect the sonar signal away from the vertical propagation sector, if its inclination from the vertical is sufficiently high (more than ~30°). In addition, its dimensions have to act as a reflector and not as an acoustic scatterer.

2.2 Hydroacoustic materials for TES reduction

Hydro-acoustic materials can be used as coating materials to reduce the TES of a submarine. Most self-evident is simply to cover the outer hull with an echo reduction material. However, echo reduction materials for low sonar frequencies are very 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 leads to shadow/shield the object with the high TES (1).

The TL material is relatively thin and at the same time suitable also for very low sonar frequencies. It achieves 10 dB transmission loss up to 150 m diving depth, while the thickness is less than 20 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). However, for low frequencies the required material thickness is unfortunately high. A thickness comparable to a quarter of (the sonar signal) wavelength is usually used for absorbing materials. For 1 kHz, this results in an absorber thickness of 375 mm.

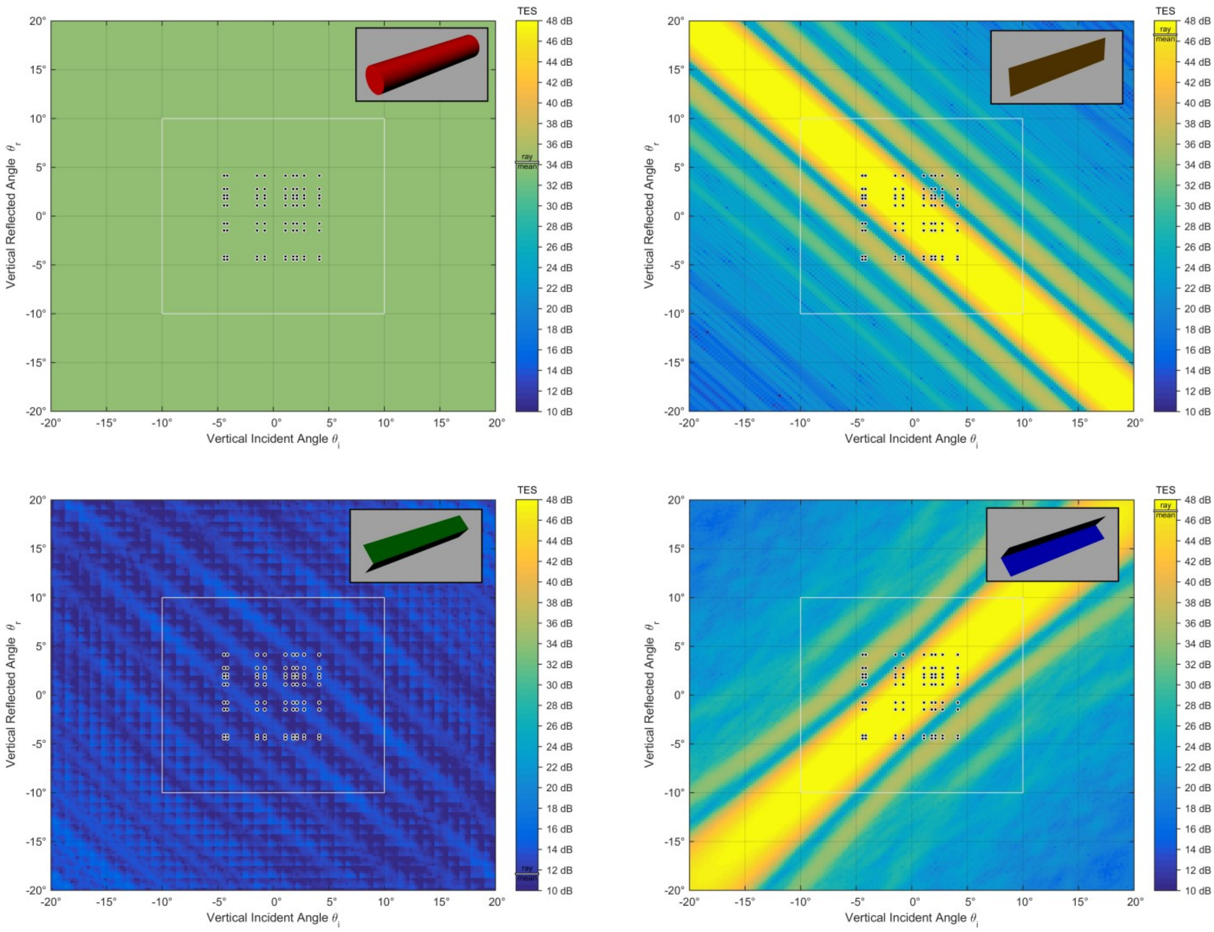


Figure 4: Multi-static TES combinations for vertical incidence angles and vertical reflected angles ranging from -20° to +20° respectively. Results for four different geometrical shapes with identical cross section area of 30m×6m are shown (namely the cylinder, flat plate, corner backside and foreside). The dots mark the positions where to pick-up the $\boldsymbol{tes_{ii}}$ levels of the ray interaction matrix for the eigenrays shown in Figure 1. The energetic (incoherent) mean of the $\boldsymbol{tes_{ii}}$ levels is indicated by a line in the color bars. Sonar signal: a sweep in frequency from 2.7 kHz to 3.3 kHz

3. TES of a classical submarine

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 numerous scattering objects of different sizes and shapes can be found beneath the hydrodynamic casing. Hence, it is not adequate to consider solely the outer hull for the entire TES calculation.

The TES calculation and TES reduction techniques are emphasized on a geometrical model submarine named BeTSSi (2) (Figure 5). BeTSSi has features of a modern submarine without sharing specific similarities with any particular submarine class. That makes it an ideal neutral candidate to study TES behaviour and reduction. BeTSSi's overall model-length is 62 meters and the model-diameter of the pressure hull is 7 meters. The casings of the bow, upper deck, sail and stern are modelled as 10 mm steel. These areas are modeled with flooded 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. Obviously the objects lying within the flooded areas, such as the bulkheads, torpedo tubes, masts and tanks, become important for any accurate TES calculation. The arrangement of the bulkheads forms several significant corner reflectors, which in turn increases the resulting TES over a wide angular range.

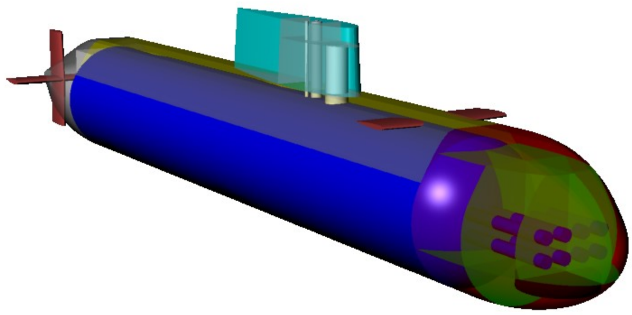


Figure 5: The fictive geometrical submarine "BeTSSi" used for exemplary TES calculations.

We assume an active sonar source with a transmitting frequency of 1 kHz and 3 kHz. The TES of the uncoated submarine is shown as the blue curves in Figure 6. The overall TES value is somewhere between 10 dB and 25 dB. Several sharp peaks/highlights of high TES are present:

- The bow peak (at 0° aspect angle) arises from the bulkheads of the ballast tanks in the bow
- The beam peaks (at 90° and 270° aspect angle) are due to the large cylindrical pressure hull.
- The 180° peak is due to the bulkheads in the sail and the submarine's stern.

Besides these distinct peaks, an area of intermediate levels can be found. Here, multiple reflections between the along ships' and athwart ships' bulkheads are responsible for the relatively high TES levels - especially at 3 kHz.

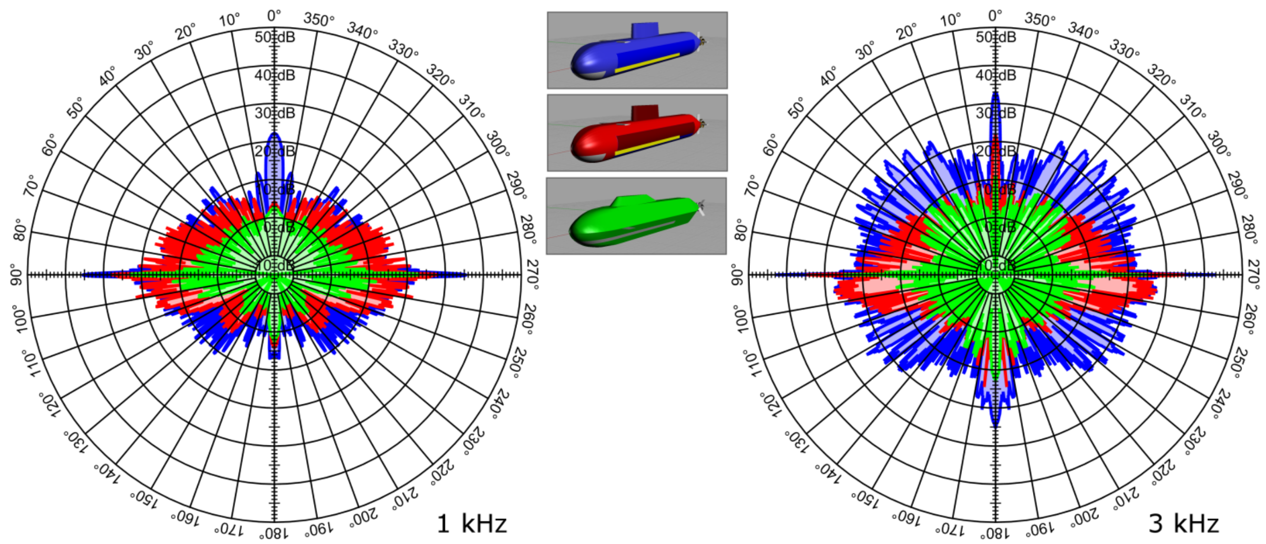


Figure 6: Monostatic TES of a stealth-shape submarine (green) compared to the coated (red) and uncoated (blue) submarine model BeTSSi. Left: 1 kHz, right: 3 kHz.

4. Coating concept for TES reduction

For a reflecting object, the main effect on the spatial TES characteristics comes from its geometric shape. 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. This matter of fact can be used, together with hydro-acoustic materials, to develop a coating concept for TES reduction for the model submarine geometry BeTSSi.

The first coating step is to apply the TL material onto the bow casing. This will decrease the transparency of the bow and hence the TES contribution of the large flat bulkheads behind the casing is reduced. Even if the reflectivity of the bow's outer shell is increased, the TES of the bow peak will be reduced. The TES-calculation predicts a reduction of the bow peak of more than 10 dB, as shown in Figure 6 (red curves). The pressure hull is already fully reflecting, therefore applying TL material on its surface will not reduce the beam aspect peak. The beam 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 monostatic TES value could also be reduced slightly at 1 kHz and significantly at 3 kHz.

5. Stealth-shape concept for TES reduction

As already proposed in 1922 (3), the TES can be reduced if the outer shape is modified according to the rules known today from the radar cross section reductions. 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 Figure 6 (green curves) 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. Note that, beside the few sharp TES peaks, the stealth-shape concept is able to reduce the TES over the wider angular range. This property is not observed with this intensity for the coating concept and it will be even more pronounced for the muti-static scenario.

6. Comparison of the multi-static TES

New multi-static 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 multi-static 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 further sound propagation over long horizontal distances is no longer possible (without high attenuation).

Figure 7 compares the multi-static target echo strength for the three mentioned submarines: the stealth-shaped submarine and the coated and uncoated BeTSSi model 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 model 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 model submarine are shown. At the diagonal from the upper left corner to the lower right corner, the monostatic TES levels are depicted again. The high TES levels from the lower left corner to the upper right corner represent the specular reflection of the broad side of the submarine. It can be seen that with the coating concept, the monostatic TES levels could be reduced - however the overall multi-static levels of the coated BeTSSi model differ not greatly from the uncoated BeTSSi model. Here clearly the advantages of the stealth-shape concept are highlighted. The stealth-shape concept achieves a significant reduction of the TES levels for virtually all multi-static transmitter/receiver aspect angle combinations.

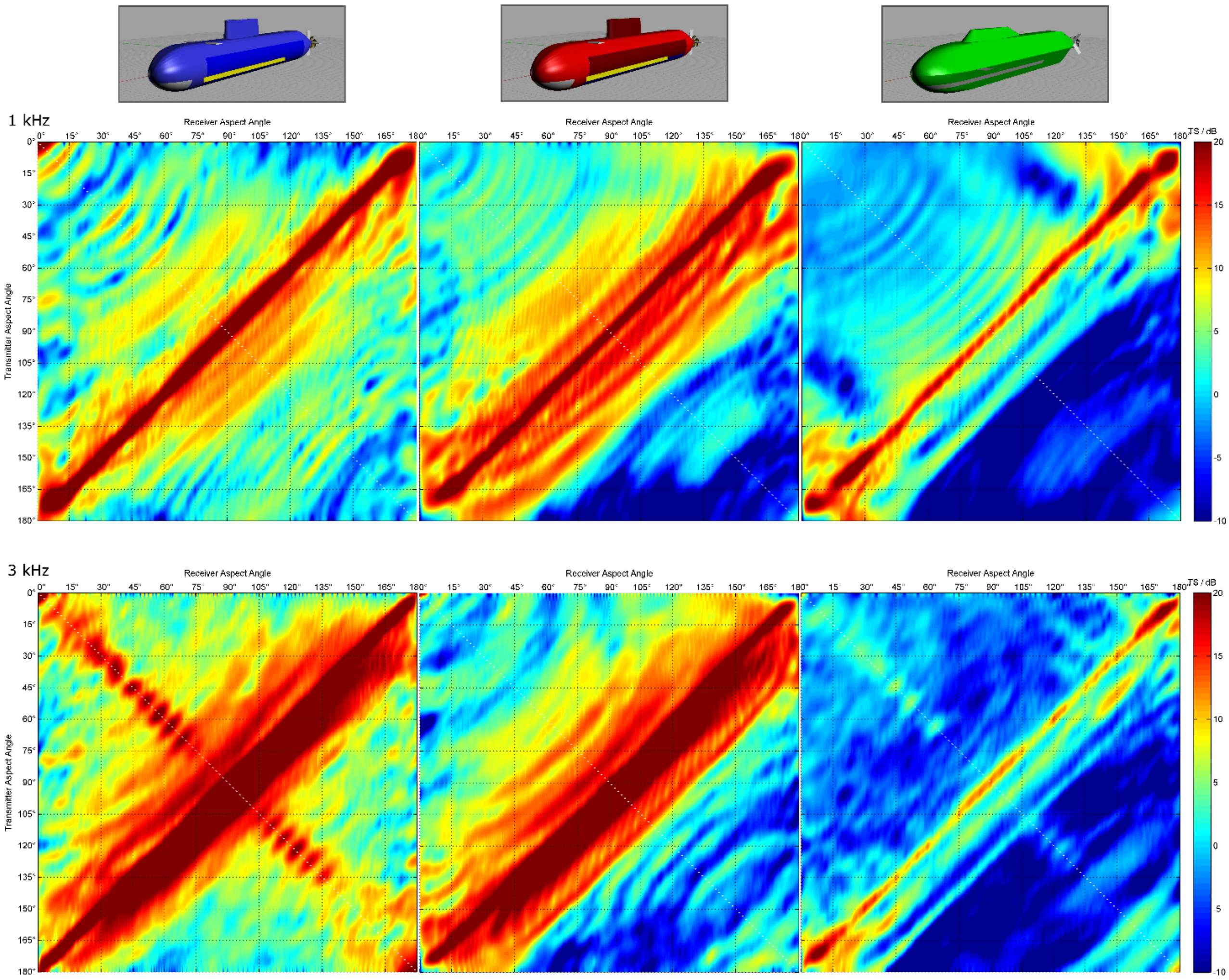


Figure 7: The multi-static target echo strength with respect to the transmitter and receiver aspect angle for the three submarines: uncoated BeTSSi model, coated BeTTSi model and the stealth-shaped submarine.

7. 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 the use of 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, however 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 multi-static case scenario, the ability to reduce the overall TES levels - for any combination of transmitter/receiver positions - is only observed from the standpoint of the submarine form-shaping concept.

REFERENCES

1. Avsic, T. Taking the next step in stealth submarine development, Proceedings of the 22th International Congress on Sound and Vibration, Florence, Italia, 12–16 July, (2015).
2. 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/
3. Knox Samuel Lippincott Griswold, Submarine construction, Patent US1500997A (1924)