Passenger ship source level determination in shallow water environment

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To study sound radiation from an individual ship, it is required to analyze its spectral and spatial distribution. For an analysis in deep water, standard measurement procedures can be used. Such approach may not be valid in shallow water conditions, where the loss must be determined by sound propagation modelling. In the ambient noise measurements in the Baltic Sea, the shipping noise sources were identified by temporal tracking of their distances from the measuring hydrophone using the Automatic Identification System (AIS). The large dataset obtained from the recorded, identified and tracked ship noise events enabled us to assess transmission loss between the measurement point and each tracked ship location. Accurate modelling needs a sound speed profile in the water column, which can be found by measurements. For calculations at the sea bottom, some typical data sets can be used that fit best the attenuation rate of the measured ship noise data. Once the dependence of the loss upon azimuth and the range is estimated, it can be used for the back-calculation of the source level (SL), allowing us to find the radiated underwater noise directivity patterns of the ship in shallow water conditions.
1. INTRODUCTION

The Marine Strategy Framework Directive (MSFD) requires that European Member States develop strategies for achieving or maintaining Good Environmental Status (GES) in the European seas. For the indicator concerning the ambient underwater noise, a combined use of measurements and modelling is considered a very effective way to ascertain the levels and trends of underwater noise in the relevant frequency bands for larger sea areas. Close studies of the spatial distribution of sound radiation from individual ships would further improve the modelling in the combined method.

Controlled measurements of commercial ship source level and its directionality have been performed in previous investigations (Arveson and Vendittis, 2000). An effort has been made to obtain uniform distribution of measurements at all angles on a hemisphere centred at the ship propeller. For lower frequencies (up to 24 Hz), nearly circular directivity pattern in azimuthal direction was found. For higher frequencies (340-350 Hz) that are dominated by propeller cavitation, the directivity was slightly decreased in the front and rear directions as the bow aspect radiation is partially blocked by the hull, and the stern aspect radiation is partially absorbed in the bubble wake of the ship. A difficulty of shipping noise prediction by modelling due to discrepancies in the environmental and ship data was reported by Heitmeyer et al., (2003). Extensive research on the spectral characteristics of commercial ships has been described by McKenna et al., (2012). These studies address underwater measurements in deep water conditions. However, the procedures there may be inapplicable in the shallow water conditions of the Baltic Sea. Focus in the present study was on underwater recordings made in shallow water conditions. The aim was to assess the directivity patterns of commercial ships.

![Passenger ship in the Gulf of Finland.](image)
2. UNDERWATER NOISE MONITORING

In the frames of BIAS Life+ project (Sigray et al., 2016), the ambient noise was measured in four different positions in the Estonian EEZ during the year 2014. The monitoring equipment and procedures are described in the BIAS standards for noise measurements (Verfuß et al., 2015). Fig. 2a presents the BIAS rig design used for the measurements in Estonia.

Ship traffic is quite intense across the Baltic Sea as well as in the Estonian EEZ. Density of ships per square kilometre during January 2014 and the location of Estonian measurement positions are shown in Fig. 2b. The highest density of passenger ships in the Baltic Sea is between Tallinn and Helsinki where the BIAS20 recording station is located. At this position, it was possible to record individual noise signatures from several regularly operated passenger ships.

Table 1 presents the geographical coordinates of the deployment positions, water depths, position types and recording times in days. According to the recommendations made by Dekeling et al., (2014), category A stations were located further from the shipping lanes. The aim of these stations was to record ambient noise from distant shipping. Category B stations were located close to the shipping lanes. Their aim was to record the noise generated by individual ships. As seen from Table 1, type B station BIAS20 recorded almost continuously during the year 2014.

Table 1. Underwater noise recording positions in Estonian waters

<table>
<thead>
<tr>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth, m</th>
<th>Category</th>
<th>Rec. time, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIAS20, Tallinn</td>
<td>59°46.5’N</td>
<td>24°50.5’E</td>
<td>73</td>
<td>B</td>
<td>324.5</td>
</tr>
<tr>
<td>BIAS21, Paldiski</td>
<td>59°27.2’N</td>
<td>23°43.4’E</td>
<td>81</td>
<td>A</td>
<td>201.5</td>
</tr>
<tr>
<td>BIAS22, Hiiumaa</td>
<td>59°09.0’N</td>
<td>21°59.4’E</td>
<td>80</td>
<td>B-A</td>
<td>203.5</td>
</tr>
<tr>
<td>BIAS23, Saaremaa</td>
<td>57°58.3’N</td>
<td>21°00.0’E</td>
<td>82</td>
<td>A</td>
<td>179.5</td>
</tr>
</tbody>
</table>
3. SHIP POSITIONING WITH AIS

Automatic Identification System (AIS) is intended to enhance safety of life at sea, the safety and efficiency of navigation and protection of the marine environment (Revised Guidelines, 2016). AIS equipment aboard vessels transmits continuously and autonomously information about the vessel including its identity, position, course and speed (Tetreault, 2005). These data were used to position the ships relative to recording positions. Due to irregular sampling, interpolation was used. Speed over ground (SOG) and course over ground (COG) were interpolated uniformly between the AIS data points. The directivity angle $\gamma$ can be approximated from the COG and the cartographical azimuth between the recording station and the ship (Fig. 3). On a normal pass of the ship from the recording station, the azimuthal directivity angle $\gamma$ changes between 0-180° or 180-360° depending on the ship's and the recording station’s relative positions.

![Figure 3. Ship and recorder position geometry. The azimuthal angle $\gamma$ is measured between the ship’s COG and the location of the hydrophone.](image)

4. TRANSMISSION LOSS MODELLING

Received level (RL) indicates the sound pressure level received by the measurement station. To calculate the RL 1/3 octave band values from the measured data, the data were processed according to the BIAS Standards for Signal Processing (Betke et al., 2015). The RL is related to the source level (SL) by the equation

$$RL = SL - TL,$$

where TL denotes transmission loss. SL is defined as the sound pressure level at 1 meter of the source in the direction of reception. All terms of the equation are expressed in decibels relative to 1 $\mu$Pa. To be able to assess SL, the TL must be known. In deep water conditions, spherical spread of acoustic waves can be considered for the back-calculation and TL can be expressed as

$$TL = 20 \log \left( \frac{r}{r=1m} \right)$$

In shallow water conditions, the influence of the sea bottom cannot be neglected. In this case, sound propagation modelling must be used to take into account the influence of bathymetry, acoustical properties of the sea bottom (sediments) and the sound speed profile. Considering the
needed relatively low frequency ranges, inhomogeneous medium and preferred one-way propagation direction from the ship to the hydrophone, the parabolic equation (PE) method can be used. In particular, the PE method implementation RAM, i.e. the range-dependent acoustic model (Collins, 1993, 1995), was used to solve the problem. The inputs of the RAM include bathymetry, sound speed profiles and acoustical properties of the waveguide, as well as the position of the source and the receiver. The output of the code is the TL in the plane of the source and the receiver.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure4.jpg}
\caption{Red line - data measured from a container ship (L=152m), limiting dotted lines - RL for 20log(r) and 15log(r) spreading, black line - modelling with the bottom type sandy mud. a – 63 Hz 1/3 octave band and b – 125 Hz 1/3 octave band results.}
\end{figure}
To validate the method, position BIAS23 near the Island of Saaremaa was chosen because of its rather flat bathymetry and less intensive ship traffic, resulting in less interference from distant shipping. It must be pointed out that in January the sound speed profile is quite constant with the water depth in this region, which will also simplify validation. The ship positions can be found using the AIS data. For the ships passing close to the hydrophone position, the 2D sound propagation can be derived by the hydrophone location and the estimates of the ship position. Although the sediment probes were locally taken during deployments, uncertainty about the sediment type remains. However, the attenuation rate of measured data helps to determine a suitable sediment type for the model. It can be seen that sandy mud bottom gives quite realistic results to the distances up to 6 kilometres [Fig. 4]. Finally, the SL must be fitted to the modelling and measured data. For example, in Fig. 4a and b, the measured data from a cargo ship 1 were best fitted in the case of sandy mud bottom and SL=176 dB re 1 μPa for 63 Hz and SL=168 dB re 1 μPa for 125 Hz ⅓ octave bands. The measured data (RL) were averaged for every second. The proximity of other ships was systematically checked to minimize distant shipping noise interference.

Once the sea bottom parameters are chosen, it is possible to determine the TL around the hydrophone position as a function of range $r$ and azimuthal angle $\gamma$ to be used further for back-calculation of the SL of the ships with arbitrary trajectories inside the 7-km ring centred around the hydrophone. An example of the TL at the position BIAS20 in January 2014 is shown in Fig.5.

![Transmission Loss, dB re 1μPa, 1/3 oct. 63Hz, B20](image)

**Fig.5.** TL centred at the position BIAS20 (depth 70m) in January 2014 as a function of range and azimuth of the source. Reception at the depth of 73 m, depth of the source at 3 m. Bottom sediment - coarse silt.

5. **DIRECTIVITY PATTERN CALCULATION**

For different azimuthal angles $\gamma$, the SL was back-calculated from the known positions of the ship. Due to low water depth and considerably great distances between the ships and hydrophone, all directivity diagrams neglect the depression angle under the ship. The following
Directivity diagrams present the SL for the 63 Hz and 125 Hz 1/3 octave bands. All measured data used in Figs. 6-7 correspond to the period of January 2014. At the angular diagrams, data points were averaged for the time intervals of 10 seconds. Each curve of the plot corresponds to a different recording of the same ship. In the legend, SOG is speed over ground in knots, CPA - the closest point of approach in km and Ws - wind speed in knots. The latter reveals the sea state during the recording.

Directivity diagrams in Figs. 6-7 are quite symmetrical with respect to the ship axis, in particular at similar ship speeds and distances. Fig. 6 shows side lobes in the directivity diagrams at 45° and 135°. For the angles close to bow and stern directions, the results of the directivity diagram are not reliable enough, as the distance used for back-calculation grows considerably and ambient noise starts to interfere with distant recordings. The directivity is slightly decreased in the front and rear directions where the propeller radiation is masked by the hull or partially absorbed in the bubble wake of the ship, as reported by Arveson and Vendittis (2000). In Fig. 7, the directivity diagram is quite omnidirectional for the 1/3 octave band centred around 125 Hz. The differences in the angular diagrams of the same ship can be explained by inaccurate modelling resulting from averaging of sediment and water column properties in the region of interest. Also, time drift of the logger, if not properly considered, can mislead in terms of timing of the acoustical event and its real distance from the logger. Thus, time drift will produce an angular shift of lobes in the directivity diagram. The results obtained show spread exceeding the requirements in deep water (ISO/PAS 17208-1:2012), but they can be considered as a cost-effective alternative for the assessment of ship source level and directivity in shallow water.

![Figure 6. Passenger ship (Length = 185 m) BIAS20 directivity diagrams.](image)
6. CONCLUSION

Our analysis shows that it is possible to calculate the source level based on ship noise recordings in shallow water, if modelling is accurate and AIS data are available and a transmission loss map for the region around the recording station can be composed. In this case, the ship SL can be back-calculated. Further refinement of the model will improve the results and reduce their variation. Our approach has its natural limits for directivity angles approaching 0° and 180° where the reduction of the signal to the ambient noise ratio lowers the reliability of the results. Particular care should be taken for accurate synchronization of the AIS data with the acoustical recordings, as time drift of the datalogger clock can give inaccurate estimates of the ship’s range and angle. There is significant angular variability of the SL in the frequency band ⅓ octave centred around 63 Hz, showing that in several cases, the omnidirectional ship source model broadly implemented can be disputed. Typically, the maxima of the diagrams are in the ship beam aspect (90° and 270°) but quite high side lobes in the angular diagrams can occur, as shown for a passenger ship (Fig. 6). To provide more information about the directivity of a ship’s acoustical radiation, other frequency bands should be further investigated.

ACKNOWLEDGMENTS

BIAS project team and ETF Grant IUT1917 are gratefully acknowledged. This work was funded by the European LIFE+ Program. We also want to acknowledge external co-financers, the Estonian Ministry of Defence and the Environmental Investments Centre (KIK).

REFERENCES


