Calculation of ship source level in shallow water by propagation modelling

Lian WANG1; Stephen ROBINSON2; Pete THEOBALD3
National Physical Laboratory, Teddington, UK

ABSTRACT
The impact of the man-made noise on marine life is a very active area of research. Shipping noise is potentially a major contributor to ocean environmental noise due to ever increasing commercial ship traffic. For assessment of environmental impact, it is necessary to have a measure of the acoustic output of commercial ships, both to understand the noise radiated by individual ships, and as an input to the creation of a noise map of the sound field generated by ship traffic in the vicinity of a region of interest. It is important that accurate ship source levels should be determined for an accurate noise mapping to be undertaken. The most direct way to determine the source level of a ship is to measure it under specified conditions, and work is underway in ISO TC43 SC3 to prescribe the appropriate methodology. In order to determine the source level from shallow water measurements, propagation models must be used to convert the pressure levels measured by hydrophones to the monopole source level. In this paper, a comparison of propagation modelling results for a measurement setup in shallow water is described, and some sources of uncertainty are identified.

Keywords: Source, Propagation models

1. INTRODUCTION
Anthropogenic noise in the oceans has increased in the last decades due to the exploitation of oceans, for example, for transportation, development of offshore energy, and extraction of natural resources such as oil and gas. Shipping noise has become a main contributor among all the man made noise sources due to the rapid increase of shipping traffic, and observations indicate that the rate may have reached about 3 dB per decade in some part of the oceans (1). The increasing noise level is potentially detrimental to marine life and the impact of the noise on marine life is a very active research area.

To assess the impact of a specific noise source, a noise map can be generated over the area of interest for a given source, or source distribution, by modelling. In creating a noise map, it is important that accurate source level (SL) data is used to achieve a good prediction of the noise level with the modelling. This is very demanding particularly for modelling ship noise since there are huge number of ships in the oceans but very few with known source levels.

The radiated noise level (RNL) of a ship can be determined according to two standards, including ANSI S12.64 (2009) and the recently published ISO 17208-1 (2, 3). Here, measurements are made in deep water, and a simple range correction of spherical spreading is applied to a measured received signal level to derive the radiated noise level for a ship under test. Work is currently underway in ISO TC43 SC3 to prepare a part 2 for ISO 7208 where the RNL measured according to part 1 may be converted into source level with a simple equation. In addition, work is underway to prepare a standard for measurement in shallow water where propagation losses from the ship to the locations of the measurement hydrophones have to be taken into account for the source level calculation. A recent European project, AQUO has developed a new European underwater noise measurement standard (4).

Sound propagation in shallow water is subject to many variations due to sound wave interaction with both sea surface and bottom, and sound speed profile in the water column. These variations

1 lian.wang@npl.co.uk
2 stephen.robinson@npl.co.uk
3 pete.theobald@npl.co.uk
introduce uncertainty in the measured source level. It is important to assess the effects of sound propagation in shallow water channels on the measured noise level. In this paper, simulations are carried out to estimate the effects of randomly varied conditions in an underwater channel on the source level in terms of its mean level and standard deviation using a scenario that conforms to the configurations currently under discussion for inclusion in the part 2 ISO 17208 standard for shallow water measurement.

2. SHIP SOURCE LEVEL MEASUREMENT

There may be a number of different configurations (4, 5) to measure ship noise in shallow water. The simplest is a single vertical array consisted of three hydrophones at different depths deployed at a distance away from the closest point approach (CPA) of the ship course line (4). The other one is to deploy a number of vertical arrays with multiple hydrophones (≥3) at different distances in a line normal to the ship course line (5) as shown in Figure 1. The vessel under test will transit along a straight line course in opposite directions under a nominally constant operational conditions during the measurement process.

Each configuration has certain advantages and disadvantages. The first one is easiest to deploy. However, the test ship has to pass the CPA 4 times, two for port side and two for starboard side for a complete measurement. One of many considerations in choosing a specific configuration is the time needed to take the required number of measurements. It has been shown (5) that a number of measurements can be carried out simultaneously at different distances with a number of hydrophone arrays in order to complete the measurements quickly. Only two passes are necessary to measure the port and the starboard of a ship in this case.

A ship is a very complex noise source that may have multitude of radiation centers with different directivities (6). Such a source is beyond the scope of this work. It is assumed that the ship noise is from a point source located at a specified depth below the surface. The radiated sound from a ship is recorded by the hydrophones for a number of ship passes. In order to determine the averaged sound pressure level, the one third octave (OTO) band signal spectrum level of the received signal corresponding to a time window of the ship passing over a track length of ±30° with respect to the
CPA as shown in Figure 2 from the nearest measurement hydrophone, is calculated firstly for all the hydrophones. The received signal level is then adjusted for background noise, if necessary, before the sensitivity of the hydrophone and the gain of the data acquisition system are applied to obtain the received sound pressure level (RL).

The individual source level from the ship to one hydrophone is obtained by adding the propagation loss (PL) between the source and the hydrophone to the RL of the hydrophone for all the hydrophones. Finally, the ship source level is obtained by a power average of the individual source levels from all hydrophones from one run and then by a geometry average of the source levels from all the runs.

3. PROPAGATION MODELS AND ENVIRONMENTAL PARAMETERS

3.1 Underwater channel

It is assumed that the measurements are carried out in a shallow underwater channel with a water depth less than 150 m and a flat bottom with a sediment of a few hundred meters deep as shown in Figure 1. It should be reasonably easy to find such a channel in practice. There are many variables in an underwater channel that affect the sound propagation from a source to a receiver, such as the roughness of sea surface, sound speed profile, seabed properties, water depth. In order to estimate the spread of predicted source levels caused by environmental variations, Monte Carlo simulations were carried out in propagation loss calculations.

The environmental parameters used here for the simulations are listed in Table 1. The sediment is modelled as a fluid with a mean and standard deviation for the sound speed and the density derived from all 9 types of sediments described by Hamilton (7). This approach may introduce a larger spread of predicted source level due to the largest possible spread of the properties of the sediment.

3.2 Positioning of ship and hydrophones

The locations of the ship and hydrophones are subject to uncertainty due to errors in positioning system and ocean conditions, for example, GPS position, ocean current. There is also uncertainty at the depth of the source. These uncertainties were included with random variations of source depth, hydrophone range and depth, range of CPA in the Monte Carlo simulations.

3.3 Propagation models

Many computer models using different methods to calculate propagation loss are freely available (8). A number of these propagation models were compared in the shallow water channel with the mean parameters in Table 1 to verify the suitability of the models for the prediction of propagation loss at some of one third octave centre frequencies between 10 Hz up to 50 kHz listed in Table 2 for a maximum range up to 300 m.

The results of the comparison are shown in Figure 2. PLs for a source at a depth of 3 m and a hydrophone at a depth of 53.8 m, and at 12 one third octave centre frequencies as listed in Table 2, 10 Hz, 25 Hz, 63 Hz, 100 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 5 kHz, 10 kHz, 20 kHz and 50 kHz were calculated with Bellhop model (ray tracing method) (9) and OASES (wave number integration) (10) in blue and red lines in the figure. Bellhop is only applicable at high frequency. OASES is considered as a de facto standard for propagation loss modelling, therefore used here to compare the other models. The low frequency results from 10 Hz to 125 Hz by KrakenC (normal mode) (11) and RAMGeo (parabolic equation) (12) are plotted in cyan and green lines in the figure. It is noticed that there are large discrepancies between the other models and OASES at frequencies below 63 Hz. The cutoff frequency (13) in this channel is 10.9 Hz. It is not unexpected that the results at 10 Hz with the Bellhop,
KrakenC and RAMGeo differ significantly from that of OASES. It seems that there are a number of contributing modes in the channel within the range of interest as it is shown by the interference pattern from OASES at 10 Hz. The monotonically increasing PL predicted by KrakenC indicates that it found just one dominant mode in the channel at this frequency. The starting field of the RAMGeo is derived from normal mode solution (14), consequently, it affects the result of RAMGeo especially at close range at such a low frequency. The differences are smaller between OASES and RAMGeo in comparison with Bellhop and KrakenC at 25 Hz. This frequency is well above the cut off frequency in the channel.

All models produce comparable results with the same trend and interference patterns at frequencies from 63 Hz and above. It is expected they all can be used to predict propagation loss at all the frequencies tested here except the lowest two in the channel. However, Bellhop was used for the PL calculation in the Monte Carlo simulation due to its ability to model seabed with elasticity and rough surface.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sediment density</th>
<th>Sound speed</th>
<th>Attenuation in sediment</th>
<th>Source depth</th>
<th>Hydrophone range</th>
<th>Hydrophone depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>g/cm³</td>
<td>dB/O</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>mean</td>
<td>1.70</td>
<td>1.065</td>
<td>0.25</td>
<td>3, 5</td>
<td>100, 200, 300</td>
<td>D/N</td>
</tr>
<tr>
<td>STD</td>
<td>0.18</td>
<td>0.051</td>
<td>0.05</td>
<td>0.6, 1</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2 – Frequencies used in PL calculations

<table>
<thead>
<tr>
<th>F (Hz)</th>
<th>10</th>
<th>25</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
<th>10000</th>
<th>20000</th>
<th>50000</th>
</tr>
</thead>
</table>

Figure 2 Propagation loss as a function of range predicted by a number of models at a selection of frequencies in table 2: source depth 3 m, the other parameters are in table 1.
4. ESTIMATED SOURCE LEVELS

4.1 Propagation loss simulation

In order to estimate source level, a point source of unity source level at 0 dB re 1 μPa2m2 was used in the channel in Figure 1 at two different source depth, 3 m and 5 m at the OTO frequencies listed in Table 2. The water depth, D=100 m. The sound speed profile in the water column is assumed to be constant with a sound speed at 1490 m/s. The maximum number of hydrophones in a vertical line array is N=9 with an equal spacing. Three vertical line arrays were used at 100 m, 200 m and 300 m respectively as shown in Figure 2. Propagation losses at 10 frequencies with an equal increment within each of OTO frequency were calculated in order to produce a simulated response from an OTO band pass filter with a frequency average within the band. It has been observed that the number of the frequencies per OTO band is adequate at low OTO frequencies, but not at higher OTO frequencies. This may introduce additional uncertainty in the estimated source level.

Rough sea surface was generated using a Pierson and Moskowitz spectrum (15) with two sea states, 0 and 3 in the simulation. The propagation losses obtained with fixed parameters at their mean values were used as references for comparison. Monte Carlo simulation was applied to the propagation loss runs where the parameters in Table 1 varied randomly within the range of [-STD STD] with a uniform distribution around the mean value. In order to achieve good statistical estimates with a manageable time scale, the total number of Monte Carlo simulation was 100.

4.2 Mean and standard deviation of source level

We consider only a point source here to examine the effects of the propagation in a shallow water channel on the source level. The noise source level of a ship is determined by the received signal level plus the propagation loss. The RL is effectively the inverse of the propagation loss for a unity point source.

The PL from one hydrophone was calculated with a frequency average over the ten frequencies with a given OTO band first and then averaged over a range sector of data window length. The data window length is defined as the distance of the ship travels between ±30° with respect to the CPA at 100 m as shown in Figure 3.

The simulation allows a number of comparisons with difference configurations in terms of the numbers of hydrophones used in each array and source-receiver distances. This will help to select the optimum configurations that are cost effective.

It is very informative to examine the uncertainty introduced by variations in the predictions of the PLs. To make comparisons, reference PLs were generated with fixed parameters which are the mean value of the data from Table 1 at all 12 OTO frequencies in Table 2. Monte Carlo simulation was then applied with random parameters with the mean and STD in Table 1 to obtain PLs. The differences between the reference data and the run data indicate the bias in the estimated source level, and the standard deviation of the differences demonstrate the spread of the estimated source level caused by the parameter variations in the simulation.

The differences in SLs between the mean of the Monte Carlo runs and the reference under various conditions and configurations for two source depths at 3 m and 4 m are plotted in Figure 4 and 5 respectively. The standard deviations of the runs are also plotted in the same figures. The frequency range is from 63 Hz to 50 kHz since the PLs calculated by Bellhop at lower frequencies differ more than 10 dB at some ranges from OASES.

The top plots in the two figures show the differences in SLs for hydrophone arrays at three ranges, 100 m, 200 m and 300 m respectively. The bottom plots are the corresponding STDs of the runs. The solid lines are for the 3 hydrophone average under two different sea states, while the dotted lines for the 9 hydrophone average.

It is noticed that the maximum STD is about 2 dB at the most distant array with a source depth of 3 m. STDs are higher under sea state 3, than that at sea state 0 with a maximum close to 1 dB. It is noticed that the mean SL is higher at the low frequencies at sea state 3 in this simulation. One explanation is that the rough surface introduced relative depth change of the source, resulting in large change at low frequencies.

There is also a peak in the STDs from 250 Hz to 1 kHz. This is because the interference pattern of the acoustic field in range and depth varies with frequency. The frequency average and range average used here in calculating the PLs are the most effective at high frequencies to smooth out the rapid amplitude fluctuations, but have little impact at lowest frequencies. The PLs are most sensitive at the
middle frequencies where the variation of the interference pattern of the acoustic field is in the same order of the size for range average.

Figure 3 Differences and STDs of SLs for a source at 3 m with 3 hydrophone average (solid lines) and 9 hydrophone average (dotted lines) at 2 sea states.

Figure 4 Differences and STDs of SLs for a source at 5 m with 3 hydrophone average (solid lines) and 9 hydrophone average (dotted lines) at 2 sea states.

It is to be expected that there is a smaller STD with 9 hydrophone average compared with that by 3 hydrophone average as demonstrated by the results in these two figures. However, one has to evaluate
the performance gain against the cost. The STD increases with range since the size of the range average sectors become smaller at longer ranges, therefore, an increase of variation. In addition that the signal to noise ratio may be much lower at longer distance, this means that the multiple array approach may have a larger uncertainty in its measurements.

5. CONCLUSIONS

Monte Carlo simulations were carried out to examine the effects of variable environmental conditions on measure source level of a ship in a shallow water channel with measurement configuration following the procedure under consideration for ISO/CD 17208 2.2. The results of the simulations were compared with reference results with fixed environmental parameters. It is seen that the variations caused bias and spread in SL with a maximum STD less than 2 dB at 10 OTO frequencies between 63 Hz to 50 kHz in this case. The Monte Carlo simulation is very useful to generate the required mean value of the source level and potential uncertainty. It is however not able to identify the contributions of the individual parameters.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the National Measurement and Regulation Office of the UK Department of Business Innovation and Skills. This work was undertaken as part of the Acoustics and Ionising Radiation metrology programme. © Crown copyright 2016.

REFERENCES

11. Porter, M. B., 2001, The KRAKEN normal mode program, SACLANT Undersea Research Centre