The underwater soundscape in the port of Gothenburg and estimations of the underwater radiated noise from ships

EMILIA LALANDER, MIKAEL SVEDENDAHL,
ROBIN NORDSTRÖM-LARSSON, TORBJÖRN JOHANSSON*,
MATHIAS H. ANDERSSON

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Emilia Lalander, Mikael Svedendahl, Robin Nordström-Larsson, Torbjörn Johansson*, Mathias H. Andersson

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*Torbjörn Johanssons affiliation is IVL Swedish Environmental Research Institute.

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Summary

The past decade underwater noise has gained increased attention due to its potential negative impact on the marine environment. In Swedish waters there have only been a few studies of the underwater soundscape in harbour environments. This study aims to increase the knowledge in this field, first by investigating the soundscape in a specific area, and second by developing a framework for automatic acquisition of underwater radiated noise (URN) from ships from opportunistic measurement data.

For the first step, three positions with different acoustic environments, in and around the port of Gothenburg were chosen. The port includes an important habitat for many fish species, as one of the largest rivers of Sweden has its outflow in the area. The area is also exposed to intense ship traffic and other port activities.

Influencing factors on the measured sound pressure level (SPL) were the number of ship passages and their distance from each position. Natural sound events and other identified anthropogenic noise sources had minor impact on the SPL. The acoustic environmental parameters, such as bottom type and topography, as well as the sound speed profiles are well-known to effect the measured SPL, however, these were outside the scope of this study.

For the second step, a method using data on ship movements from AIS and measured SPL data was developed. The results showed that the method works well to estimate the URN from ship for certain frequencies. More validation is needed to verify the method for the full bandwidth of typical ship URN.

Keywords: underwater noise, soundscape in ports, URN, AIS.

Sammanfattning

Undervattensbuller har under det senaste decenniet fått ökad uppmärksamhet p.g.a. dess möjliga påverkan på den marina miljön. I svenska vatten finns endast ett fåtal studier av undervattensljud i hamnmiljö och denna studie syftar till att öka kunskapen inom detta område, först genom att studera undervattensljud i ett specifikt område, och sedan genom att utveckla ett ramverk för automatiskt identifiering av fartygs utstrålade buller under vattnet (URN) från opportunistiska mätningar.

I det första steget valdes tre positioner ut med olika typer av ljudmiljöer, belägna i och omkring Göteborgs hamn. En av de största älvarna i Sverige har sitt utflöde i hamnen, som också är ett viktigt område för många fiskarter. Samtidigt är det ett område med intensiv fartygstrafik och andra hamnaktiviteter.

Resultaten visade att den uppmätta ljudnivån (SPL) beror främst på antalet fartygspassager samt avståndet till dem. Naturliga och andra identifierade antropogena ljudkällor bidrog till mindre del. Miljöparametrar, som bottentyp och topografi, och ljudhastighetsprofil påverkar SPL, men detta studerades inte då det föll utanför denna studies mål.

Metoden som utvecklades under det andra steget använder data på fartygsrörelser och uppmätt ljudnivå från autonoma hydrofonsystem. Resultaten visade att metoden fungerar väl för att beräkna fartygens URN inom vissa frekvensband. Metoden behöver utvärderas ytterligare för att säkerställa dess funktion över den fulla bandbredden för typiska fartygs URN.

Nyckelord: undervattensbuller, ljudmiljö i hamnar, URN, AIS.

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1 Background

The ambient noise in the ocean consists of anthropogenic sounds as well as natural sound from wind and biological life. In a coastal environment and in ports, the most common anthropogenic sound sources are commercial ships, workboats, tugs, and recreational vessels, but also sounds from land activities that propagate into the water (Johansson *et al.*, 2020). Ambient noise has gained increased attention in recent years (Duarte *et al.*, 2021), and to assess the potential environmental problem connected with noise pollution, knowledge of the sound sources present in the ocean and their related noise level is needed. There are only a few publications regarding long term noise measurements in Sweden, e.g. noise monitored within the national monitoring programme in Sweden (Lalander and Andersson, 2017), and a study regarding sound levels in a Swedish port (Petrović *et al.*, 2008).

The oceanographic environment is of great importance when measuring sound levels in the ocean, and the stratification in the water affects how the sound is propagating (Urick, 1983; Andersson *et al.*, 2017). The position of the hydrophone in the water column will also affect the measured sound. Distance to the noise sources, either stationary or moving, natural or athropogenic, and their underwater radiated noise (URN) will contribute to the measured sound. Therefore the sound pressure level (SPL) will vary with time and might differ significantly at different locations within the same area.

To get a good estimation of the various sound sources, their source characteristics needs to be described. Commercial ships are a common, and often dominating, source in ambient noise measurements, and there are international standards and class notations that describe how to measure their acoustic URN (ANSI, 2009; ISO, 2012; Bureau Veritas, 2014). The method used to calculate the URN differs and the accuracy varies between the standards, due to their different requirements on e.g. the estimation of the sound propagation loss, also called transmission loss. The transmission loss is related to environmental parameters such as bottom type, topography and sound speed profile. In a near future, international regulations might require knowledge of the URN from commercial ships (IMO, 2014) and both the shipping industry and authorities see a need for a simple and cost-effective estimation of the radiated noise from commercial ships. However, it should be noted that a simplified method to estimate the URN with opportunistic sound recordings together with a simple model for the sound propagation will include uncertainties. Depending on the purpose of the URN estimations, such methods could still be adequate.

Source level models for different ship categories can be used to make soundscape maps (Macgillivray and de Jong, 2021). These maps are important tools for regulators to establish the environmental impact of noise. To improve these source models, a large number of ships URN need to be measured. To date, however, very few such attempts have been made (e.g. Wladichuk *et al.*, 2019).

In light of this, the current project has two aims:

1. Present a study of the background noise in Gothenburg's harbour inlet (figure 1). This is done by recording the ambient noise at three different locations, and making a statistical description of the SPL. Furthermore, the ship movements in the area and their impact on the measured SPL are analysed. Finally, other existing sound sources are identified.
2. Develop a simplified method for estimating the URN from commercial ships by using already recorded acoustic data. This method should use a modified version of the Bureau Veritas (Bureau Veritas, 2014) measurement and analysis recommendations when possible, and also use data on ship movements. Furthermore, the process should be automated so that a larger number of estimations of ships URN can be calculated and stored in a database.

These aims are described in separate chapters, each with a concluding section at the end.

This project was funded by the Swedish Transport Agency, which in turn was supported from the Swedish Agency for Marine and Water Management grant 11.1.

2 Soundscape in the entrance to the port of Gothenburg

In this section the performed sound measurements are described and analysed, together with analysis of the AIS traffic and weather data for the measurement period.

2.1 The port of Gothenburg

Gothenburg is Sweden’s largest port and is located near the entrance to Göta älv, one of the major fresh water rivers in the south of Sweden. More than 6000 commercial ships pass through the port area each year. The port of Gothenburg, shown in figure 1, has container, ro-ro, car, passenger and oil and energy terminals. There is a main entrance to the port in the southwest, but ships can also access the harbour from the west and south (figure 2). During this project, dredging was occurring close to one of our measurement stations, which is a common activity in order to maintain the depth in the port (figure 1).

Figure 1. One of the measurements stations in the port of Gothenburg with a dredger (yellow ship) in action. Photo © FOI.

2.2 Methods

2.2.1 Measurement location

Measurements of the soundscape at and near the port of Gothenburg were performed at three positions during 2020-09-17 to 2020-12-09. The positions were chosen to be located very close to the port (A1, Älvsborg fortress), close to a shipping lane with low numbers of passing ships (B1, Danska liljan) and close to the southern shipping lane with a high number of passing ships (C1, Böttö), see table 1. The number of ships is quantified as ship density in hours per square kilometre and month. In figure 2, a map of the measurement area is shown together with ship density based on automatic identification system (AIS) data, giving information on the major shipping routes around the port of Gothenburg. There are large differences between the three positions regarding depth, bottom topography and distance to the passing ships, which will influence the SPL.

Table 1. Measurement positions and water depth.

Station number	Station name	Position (lat, long)	Depth (m)	Hydrophone depth (m)
A1	Älvsborg fortress	N57°41.05; E 11°50.13	11.5	8.5
B1	Danska Liljan	N57°40.10; E 11°41.98	18.5	15.5
C1	Böttö	N57°38.28; E 11°42.66	20.5	17.5

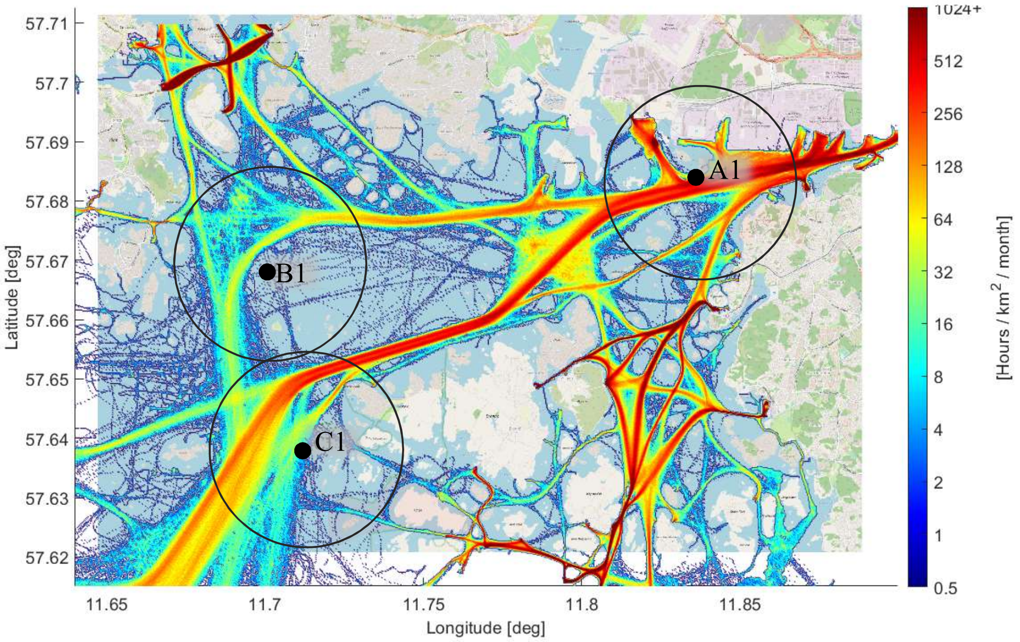


Figure 2. Overview of the entrance to the port of Gothenburg with measurements positions marked A1, B1 and C1. AIS traffic for 2020-09-17 to 2020-12-09 is shown where colours indicate ship density in hours per square kilometer and month, and shows the major shipping lanes. The black circles indicate the area in which AIS statistics were calculated.

2.2.2 Ship movement data

The ship movement analysis is based on AIS data recorded from the AIS live stream service of the Swedish Maritime Administration, which provides good coverage for the port of Gothenburg. The Swedish Defence Research Agency (FOI) has a subscription of the live stream which is continuously being stored locally at FOI and has for this report been decoded for the relevant area and the time period from 2020-09-17 to 2020-12-09. In addition to enabling illustrative overview images of the vessel intensity, the ship movement data was used to calculate statistics for the distances between ships and hydrophone systems, as well as for ship speed. The statistics on ship movement were calculated for ships within 1.5 km from each station (marked out with circles in figure 2). This distance was chosen to only include the ships from the nearest shipping lanes. Statistics of AIS information is important when analysing differences in measured sound levels between the three stations.

2.2.3 Measurement instrumentation

Measurements were performed with three Soundtrap 300 STD from Ocean Instruments that recorded data in between 2020-09-17 to 2020-12-09. The instruments were set to collect data in 30 min intervals each hour. The system has a sampling rate of 48 kHz and a 16 bit analog to digital converter. The hydrophones sensitivity was 175 dB re 1 µPa/V with a gain of 0 dB. The system has a high pass filter at 20 Hz, which reduces the sensitivity up to 50 Hz.

The hydrophone systems were each positioned in an underwater rig mounted on the bottom, with the hydrophone located at three-four meter height above the bottom and a floatation buoy at 2 m above the hydrophone (figure 3). The rig had an acoustic releaser which, upon recovery, disconnected from the ballast weight (a gravel bag) and surfaced with the hydrophone.

Figure 3. Photo and rig design of the hydrophone rig with a gravel bag as ballast weight, an acoustic releaser (light grey), a Soundtrap hydrophone system (black) with external battery pack and floatation buoys.

2.2.4 Acoustic signal processing

Raw data processing of the recorded data was done using the signal processing standards developed in the EU project JOMOPANS (Wang, Ward and Robinson, 2019). Data was transformed to the frequency domain over 1 s periods and the SPL was calculated over 1/3-octave frequency bands, in this case from 10 Hz to 20 kHz. Due to the 20 Hz high pass filter in the system, data are only presented from 50 Hz to 20 kHz. All presented frequencies are 1/3 octave centre frequencies (f_c).

2.2.5 Environmental data

Wind data was collected from the weather station on Vinga island through the website of Swedish Meteorological and Hydrological Institute (SMHI).

2.3 Results and discussion

2.3.1 Ship movements and distribution

Based on analysed AIS data for the measurement period, there were in total 8908, 922 and 4736 ship passages for positions A1, B1 and C1 respectively. The majority of the traffic at A1 was within 500 m from the hydrophone, heading east or west with a speed below 10 kn (figure 4). Far less traffic came close to B1 and the passing traffic was more spread out in both distance, heading and speed. For position C1 most traffic was passing approximately 1 km away, heading either southwest or northeast with speeds between 8 to 25 kn.

Over the measurement period, the traffic intensity was nearly constant with small variations over time (figure 5). The amount of traffic passing B1 shows higher variations, which is a consequence of the much lower number of ship passages. Notably, there was a peak in traffic on Thursdays, which originated from more passing fishing vessels. Approximately half of the traffic passing A1 is also passing by C1. A1 and C1 follow the same trends for weekdays and hour of the day trends, with slightly more traffic during the middle of the week and most traffic during early mornings and afternoons.

Distribution of ship types passing A1 and C1 was similar with the exception of the ship types Tug and Other types, which both were much more frequent at A1 (figure 6). A small part of the traffic passing

A1 and C1 was also passing B1 with the exception of fishing vessels, for which an equally large part of the traffic was passing all three measurement positions.

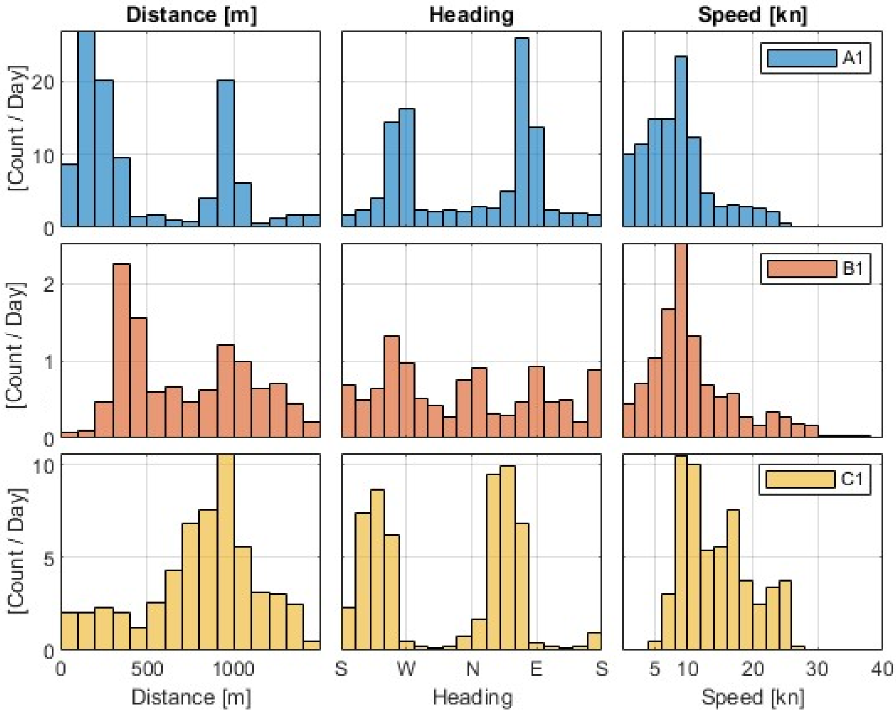


Figure 4. Distribution of closest point of approach (CPA) distance, heading and speed of traffic crossing within 1.5 km of each measurement position.

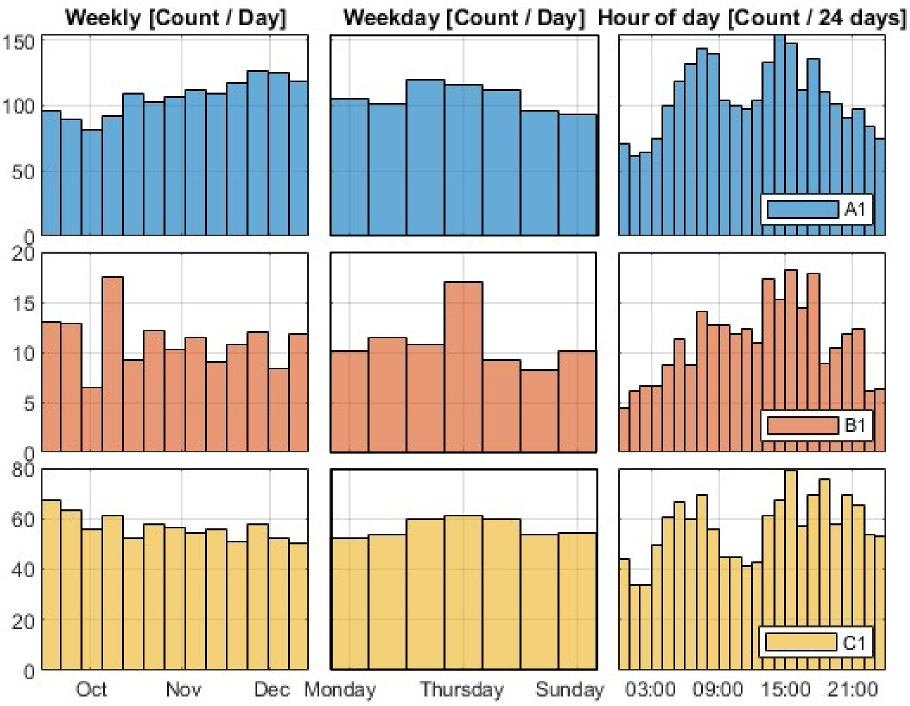


Figure 5. Temporal distribution of number of ships passing within 1.5 km of each measurement position.

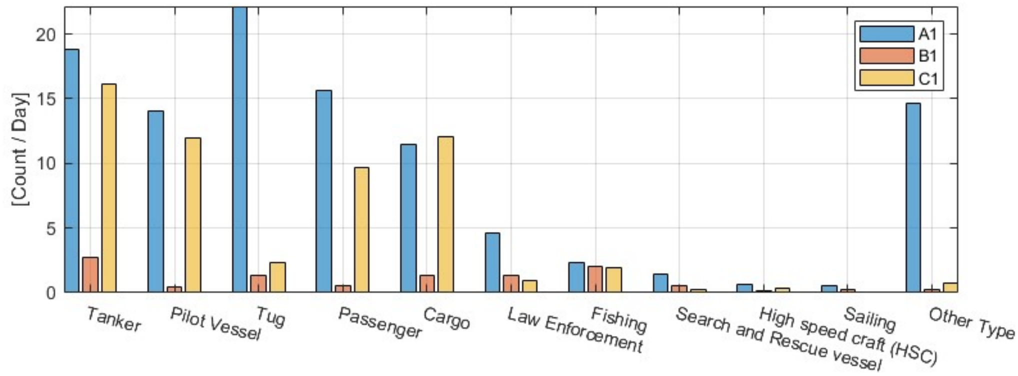


Figure 6. Distribution of the 10 most common ship types within 1.5 km of each measurement position based on AIS message information.

2.3.2 Soundscape in the port

2.3.2.1 Sound pressure level over time

The broadband (50 Hz - 10 kHz) SPL is shown in figure 7 for the three positions A1, B1 and C1, together with daily distribution (median, 5% and 95% percentile). The 95%-percentile shows the level that occurs 95% of the time; only the loudest noise recordings will surpass this level. By comparing the peaks in figure 7 with ship position it was concluded that the peaks coincide with ship passages and since the 95%-percentile levels roughly follows the variation in SPL peak levels, it is considered a good indication of the ship traffic intensity. The 5% percentile is an attestation of the lowest noise level; most of the time the SPL will be above this level. This is an indication of the background noise that changes with events occuring over longer time periods. A period of strong winds occurring over several days will raise the 5% percentile level. Another parameter that has an importance for the measured SPL is the sound speed profile, which is dependant on the salinity and the temperature in the water. When the temperature is higher in the surface, such as during summer, the sound waves are refracted downwards. In areas where the sound sources are far from the hydrophone, the measured SPL can be affected. This effect has however not been studied in this report. There were large variations between the hydrophone stations considering bottom topography, depth and mean distance to passing ships, all of which affects the measured SPL.

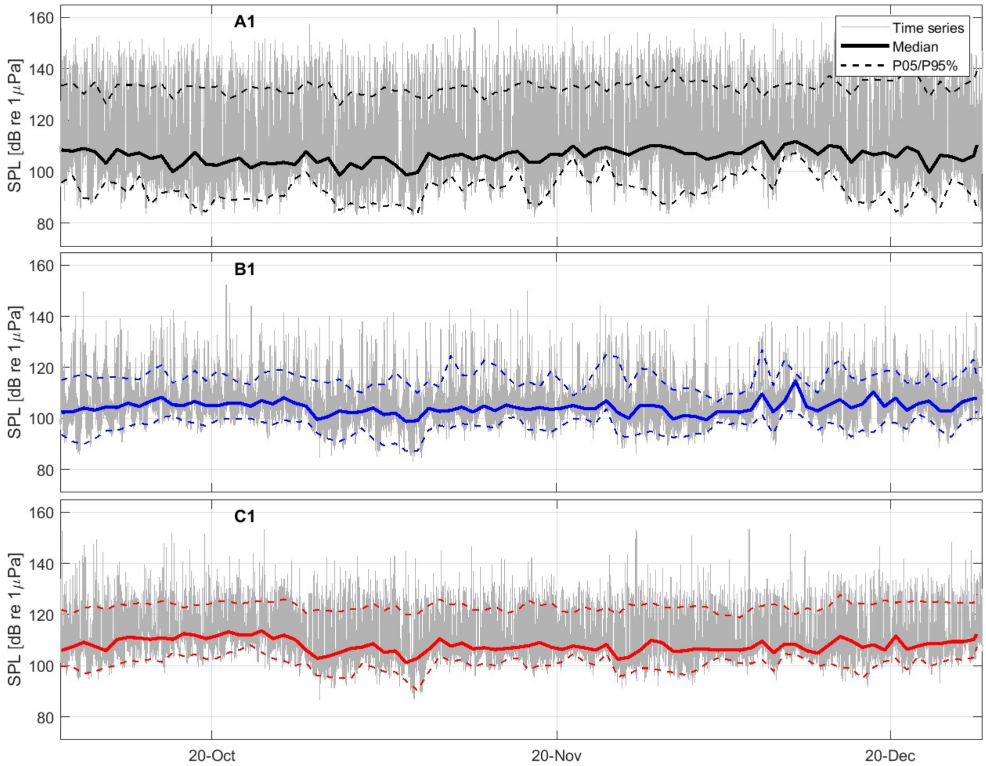


Figure 7. Time series for the broadband (50 Hz to 10 kHz) SPL at A1, B1 and C1 for the measurement period 2020-09-17 to 2020-12-09. Dashed lines show the SPL 5% and 95% of the time calculated over 24 h while solid lines shows the median.

2.3.2.2 Sound pressure level over frequency

The SPL varies over frequency due to parameters such as the bottom sediment, the sound speed profile and ship traffic intensity, but the variation can also be an effect of how the measurements were made such as the depth of the hydrophone and the high-pass filter in the measurement system. To study how the SPL distribution varies with frequency, spectral probability densities were calculated for the entire measurement period, as seen in figure 8. The figure shows the change of SPL with frequency, and the colour shows the mode of the data in each frequency bin. For reference the median as well as the 5% and 95% percentile levels for the entire measurement period are also shown.The sound environment of B1 and C1 is comparable when looking at the SPL variation with frequency in figure 8. Both positions are situated in the outer archipelago at similar depth, but significantly more ships pass by C1 which could explain the approximately 6 dB higher SPL in the frequency band 200 Hz – 1 kHz at C1. Below 200 Hz the sound waves are likely suppressed (Morén *et al.*, 2019), and there are limitations on the capability of the measurement system to sample low frequency sounds. Highest SPL occurs around 500 Hz for both stations.

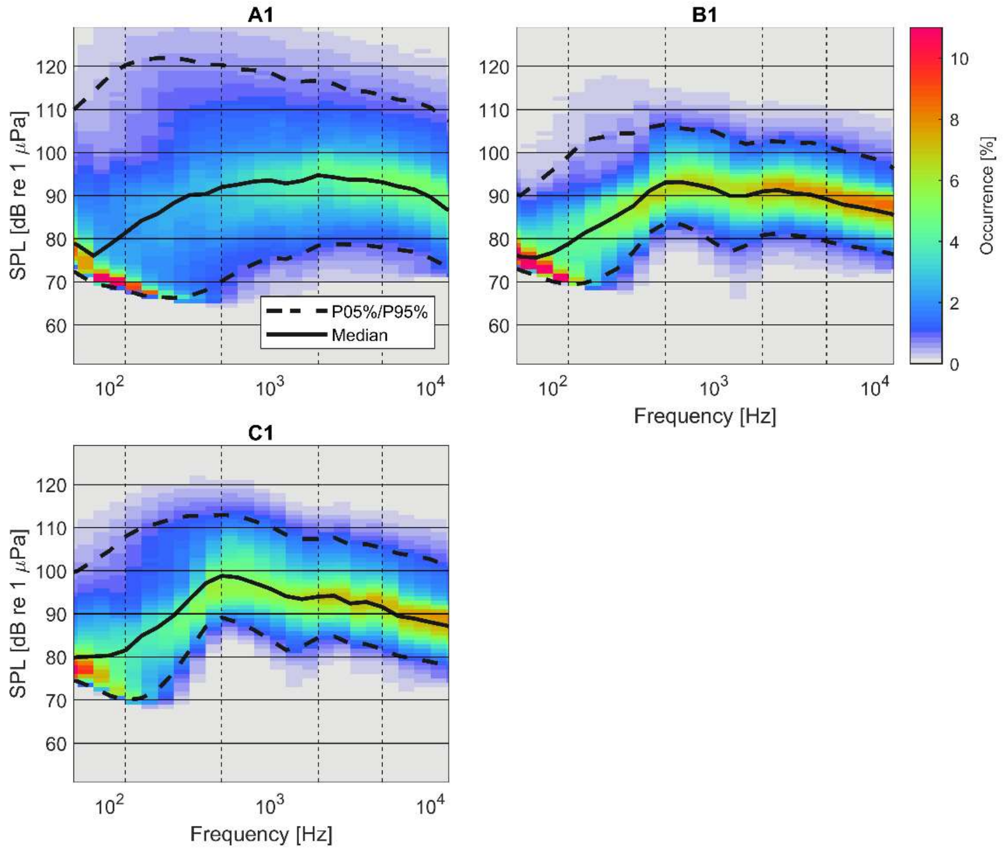


Figure 8. Spectral density histogram showing the SPL as a function of frequency for the three measurement positions during the entire measurement period. The colour shows the distribution of the data in each frequency bin. The dotted vertical black lines shows the frequencies 125 Hz, 500 Hz, 2 kHz and 5 kHz.

A comparison was made for the SPL at f_c 500 Hz including passing ship data (table 2). This is a frequency where the risk of dampening, due to the bottom sediment, is smaller, compared to lower frequencies (Andersson *et al.*, 2017) and the cut-off frequency due to the shallow water depth (Urick, 1983). At higher frequencies than 500 Hz, the noise contribution from ships starts to decline. The highest peaks in SPL were noticed at A1, where the distance to the ships often is less than 300 m. The median level, on the other hand, is similar between A1 and B1 in this frequency band, while the median level of C1 is greatest. Although there are twice as many ships passing by A1, the median SPL is lower. A possible explanation is that there are fewer ships passing at high speed, but this has not been studied in depth.

Table 2. Mean distance from the hydrophone to the ships, mean and std of ship speed, number of ships per hour and SPL for the median and the 95% percentile level at 1/3 octave band with center frequency (f_c) 500 Hz at the three positions.

Position	**Water depth (m)**	**Distance to ships (m)**		**Ship speed (kn)**		**Number of ships per hour**	**SPL for $f_c = 500$ Hz (dB re 1 μPa)**	
		Median	*5%-percentile*	*Mean*	*STD*		*Median*	*95%-percentile*
A1	11	287	84	8.6	5.5	5	92	120
B1	18	660	290	11	6.9	0.6	93	108
C1	20	863	139	14	5.4	2.5	99	114

2.3.3 Sound pressure level variation with weather

The influence of wind speed on the measured SPL at f_c 5 kHz for the position B1 is shown in figure 9. The lowest levels of the SPL is seen to follow the wind variation. However, only at the rare occasions, when there were strong winds, the median levels were raised due to winds (see for instance end of November in figure 9). In conclusion, the maximum SPL was mainly due to ship noise at this location. Other changes in the SPL time variation can be due to the sound speed profile which varies with both water temperature and salinity. Due to lack of data this effect has not been studied.

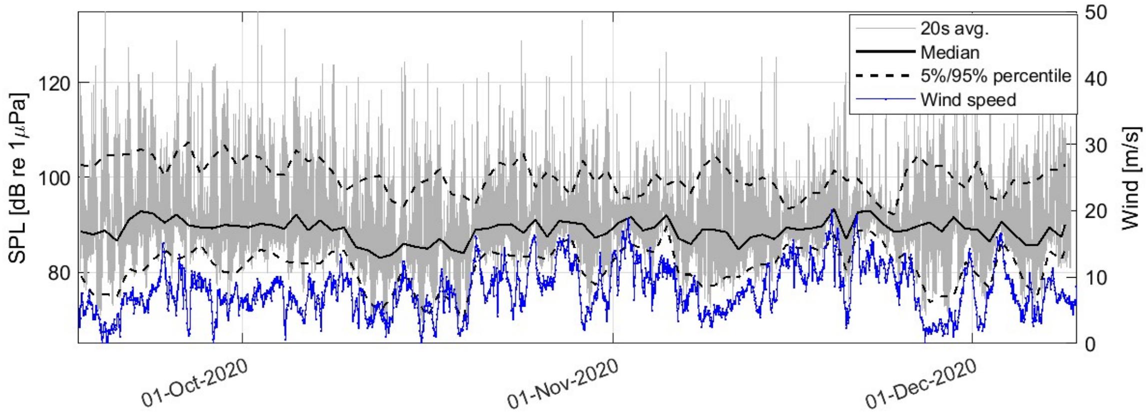


Figure 9. Time series (20 second averages) of SPL at B1 and weekly median as well as 5% and 95% percentile levels for the 1/3 octave band with center frequency 5 kHz superimposed with wind speed (blue line) from the SMHI weather station on Vinga island.

2.3.4 Dredging at A1

During the measurement period, dredging activities occurred within 1 km from station A1 from 2020-10-12 to 2020-11-10. Data during this time period were extracted and compared with the data from the time period when dredging did not occur. The results showed that there were only small differences between SPLs with or without dredging (figure 10). The variation in sound could also be a result of other noise generating sources than dredging. However, this does not imply that dredging does not impact the SPL. During the time period for dredging, actual dredging was only taking place on a few occasions each day, but due to lack of information these time periods could not be extracted. During shorter time periods, dredging was clearly audible, but not very loud compared with the passing ships.

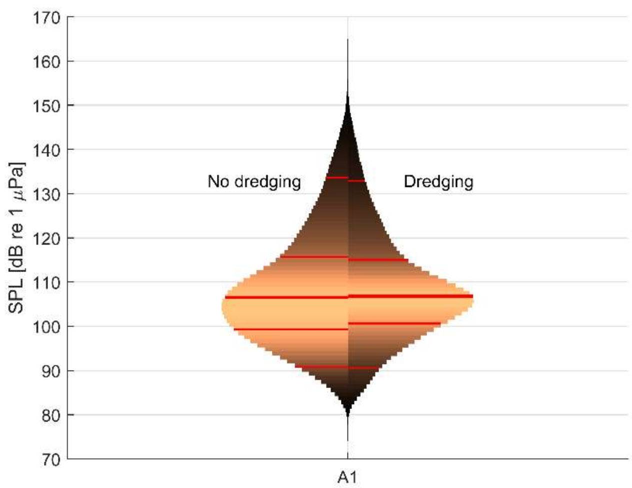


Figure 10. Violinplot of the statistical distribution of broadband SPL data at A1 with (38 days) and without (43 days) dredging activities with red lines indicating 5, 25, 50, 75 and 95%-percentile levels seen from bottom to top.

2.3.5 Noise from port operations

Loading and unloading, docking and other port operations generate noise, which can propagate through the ground and solid structures, including ships into the water. These events could possibly generate broadband, short transients of underwater noise. Looking for signs of such events, we searched through the data from A1 for short transients of sound that could not be explained by passing ships. The data was first processed into 1 and 20 second windows, and then analysed in the 125, 500, 2000 and 5000 Hz 1/3 octave bands as well as the broadband (total) level. The 20 strongest transients at each temporal resolution and each frequency band were extracted and played back through loudspeakers. It was found that every transient was caused by a passing ship; there were no port operation generated sounds among these transients. This does not mean that port operations do not generate strong sounds on land that propagates into the water, but sounds generated by ships moving in the port were stronger at this location.

2.3.6 Implications for marine life

The highly variable soundscape at the three positions can be a challenging environment to live in for many animals. If the noise is not linked to any negative effect, the animals might be used to it and not react in any negative way. However, the opposite might be true as well. A soundscape with occasional loud noise such as passing ships at close distances, can impact the marine life negatively (Popper and Hastings, 2009). Fish can show avoidance behaviour (De Robertis and Handegard, 2013), masking and disruption of communication (Stanley, Van Parijs and Hatch, 2017) and stress (Sierra-Flores *et al.*, 2015). All these effects have been demonstrated for several fish species, but the link of this impact to a negative effect on a population level is not yet established.

To get a better understanding of the environmental effects of the anthropogenic noise in the port of Gothenburg, a more detailed analysis needs to be performed, taking into account the present marine species and the knowledge on how these respond to noise and resulting potential negative impact. One possibility could be to study migrating fish, such as eel and salmon, as they pass through the port. Underwater noise is not the only environmental pressure the animals are subjected to and most likely not the most harmful, compared to e.g. eutrophication, but at the same time the one we know the least about.

2.4 Conclusions and further work

The study regarding the soundscape in the port of Gothenburg concludes that many factors contribute to the measured SPLs presented here: the proximity of the hydrophone to the shipping lane and/or port, the average ship speed, the amount of ships, the geographical position of the hydrophone, water depth, bottom topography and type, natural sound sources such as wind, and also the water sound speed profile. At all positions, the largest contribution to the total noise level was ship traffic; this had also been observed in Petrović et al. (2008). The highest peak SPL observed occurred at A1, i.e. the position closest to the shipping lane with a much higher traffic density than at the other locations. However, the lowest SPL was also observed at A1, due to its position in a shallow channel sheltered from distant noise sources. This shielding effect of islands could be further studied with acoustic modelling.

Other analysed sound sources included dredging, port operations and weather induced noise, but none of these affected the SPL to a greater extent during this measurement period.

A more detailed analysis of the sound levels observed in the port of Gothenburg needs to be done to assess whether the anthropogenic noise has a negative impact on the marine life. It would also be highly valuable to study other locations within the harbour to determine any effect from on-land activities contribution to the underwater soundscape (Marley *et al.*, 2017). Only one position was located close to the harbour area and it is not unlikely that many sources of on-land acitivites were not captured in this study.

3 Framework for an automatic estimation of ships URN

The level of noise a commercial ship is allowed to emitt into the marine environment, could be subjected to legislation in the future if policy makers sees the need to reduce the underwater noise in the marine environment (IMO, 2014). There are several standards and notations describing how to calculate the URN of commercial ships described in section 1. The standards all have different accuracies, mainly depending on the accuracy of the chosen sound propagation model including input parameter errors and the number of ship passages required. The hydroacoustic environment, which affects the sound propagation, has a great impact on the accuracy and uncertainty of the URN calculation (Andersson *et al.*, 2017).

In the future, dedicated URN measurements of a commercial ship might be done as part of a regulatory framework after the construction of the ship. However, follow-up measurements of the URN of the ship might be challenging due to both practical and economical reasons. Standards and class notation require repeated passages close to a hydrophone system during one day. This is expensive since a ship is not operational during this time.

To overcome this, a simplified method to estimate the URN of ships automatically, based on hydrophone recordings close to a shipping lane and on AIS was designed, and is presented in this chapter. The method is also evaluated by comparing the URN from one reference ship using this method with the results of a measurement that followed the Bureau Veritas class notion methodology (Bureau Veritas, 2014). The challenge of this simplified method is the lack of several environmental and ship parameters, such as the present sound speed profile, the current load of the ship and the technical information of the performance of the ship, which could lead to deviating results.

3.1 Data

To develop and demonstrate the process, two sets of data were used. The first data set consisted of hydrophone recordings made in between July and October 2020 in southern Kattegat at coordinates N56°19.374, E12°22.146, using a similar system as the one described in section 2.2.3, a ST500 from Ocean Instruments. The instrument was deployed at a depth of approximately 30 m. This data was used to calculate a large number of URN levels of passing ships.

The second data set came from the measurement in the port of Gothenburg (section 2.2.1) and was used to validate the method by comparing the results with a URN measurement of the reference ship made in 2014.The ship movement data was based on AIS data achieved as described in section 2.2.2.

3.2 Method of analysis

Opportunistic URN measurements of commercial ships were based on detecting individual ship passages at each hydrophone position. Ship passages were detected using AIS data and suitable time periods were selected based on the closest approach distance as well as the distance to other ships.

3.2.1 AIS-based detection of single ship passages at a hydrophone station

The following steps were followed to extract time periods suitable for opportunistic URN measurements:

1. Decode AIS data within a suitable area and time period.
2. For each ship with a unique identification number (MMSI) within the area, detect time periods, where the distance from the ship to the hydrophone station is below *D1* m and ship speed is larger than *V1* m/s.
3. Keep only passages with time periods longer than *T1* s.
4. Keep only time periods where all other moving ships (ship speed > *V2* m/s) are at least *D2* m away from the hydrophone station.
5. Keep only time periods where the closest point of approach (CPA) is below *D3* m.

6. Keep only time periods where the longest duration between AIS messages is less than *T2* s.

Parameter values (thresholds) to detect ship passages that was used were location dependent and summarised in table 3. Here, V is the minimum ship speed, D the maximum allowed distance to the hydrophone and T the minimum time in seconds that the ship should be detected in order to be included in the analysis.

Table 3. Location dependent parameters used to extract time periods suitable for opportunistic URN measurements in this study.

Station	**D1 (self) [m]**	**D2 (other) [m]**	**D3 (CPA) [m]**	**V1 (self) [m/s]**	**V2 (other) [m/s]**	**T1 [s]**	**T2 [s]**
Kattegat	800	1000	500	1	0.2	30	30
A1	400	500	300	1	0.2	30	30
B1	700	750	600	1	0.2	30	30
C1	1500	1600	1300	1	0.2	30	30

3.2.2 URN calculation based on AIS data

Data from the hydrophones were processed in several sequential steps to calculate the URN of the ships, based on the guidelines from Bureau Veritas (Bureau Veritas, 2014). The guideline treats the ships as omnidirectional sources, i.e. the SPLs measured in different directions from a ship are treated equally and averaged to form the final URN from the ship. The signal processing steps can be summarized as follows (Bureau Veritas, 2014; Svedendahl *et al.*, 2021):

1. Combine position and hydrophone data.
2. Divide each run into 19 time segments.
3. Calculate power spectral density (PSD) from each of the 19 time segments.
4. Convert to 1/3 octave bands (optional).
5. Correct for background in each window.
6. Correct for transmission loss (TL) in each window.
7. Combine the windows into one PSD for the entire run.
8. Combine multiple hydrophone channels (if applicable).
9. Combine multiple runs (if applicable).

Below follows a more detailed description of steps 1-9:

1. The GPS position of the ship(s) were extracted from the AIS data and combined with the acoustic data from the hydrophone(s) to synchronize acoustic data and ship position. Importantly, both the distance and angle between the hydrophones and the ship were retrieved, as well as the ship heading from AIS data.

2. Each run was divided into 19 time segments, centred around a given set of angles between the ship and the hydrophone system. The set of angles was given in steps of 5°, depending on angle of the ship facing the hydrophone, from 45° to 135° or from −45° to −135°, as exemplified in figure 11. In order for the time segments to contain a certain amount of data, the time segments correspond to 100 m long distances or the ship length, whichever is greater.

3. Subsequently, for each segment, the PSD was calculated using Welch method (1 s segments with 50 % overlap and a Hanning window function).

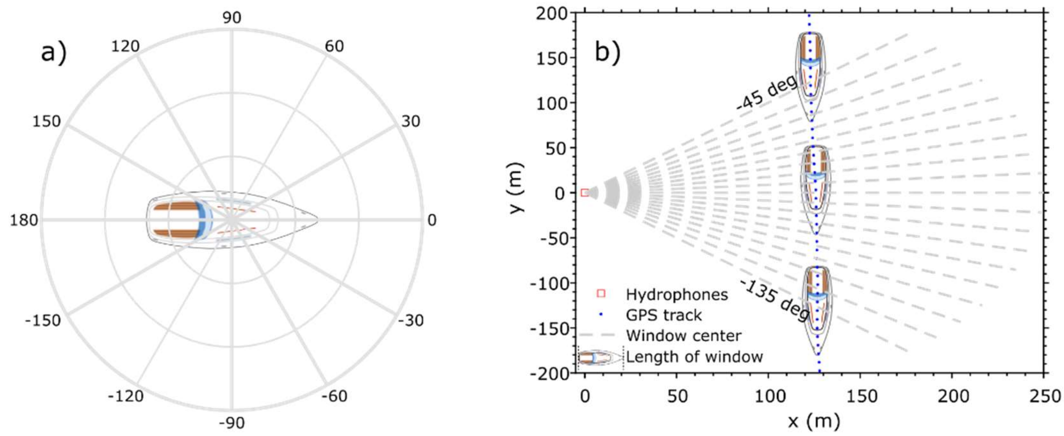


Figure 11. The ship angle and data window definitions. a) The ship angle is defined from the source centre to the hydrophone(s) and, therefore, b) varies as the ship passes through the measurement area. In this case, a southbound route yields negative angles, while a northbound route results in positive angles. The centre of each data window is given by the angles ±45° to ±135° in 5° steps and the width is 100 m, as indicated by the ship illustration length.

4. For 1/3 octave band analysis, the narrow band spectrum was converted into 1/3 octave bands by taking the total narrow band energy in the respective 1/3 octave band and normalising with the 1/3 octave bandwidth. Thus, the bands do not correspond to the traditional 1/3 octave band metric, instead they correspond to the frequency averaged spectral density level in each band.

5. At this step, the calculated spectrum was compared to the background spectrum. If the signal-to-background was larger than 10 dB, the spectrum was used directly without any modifications. For a signal-to-background ratio of 3-10 dB, the background was subtracted from the signal spectrum. Lastly, if the signal-to-background was less than 3 dB, this data was removed from further analysis.

6. The transmission loss was corrected for in each time segment, by taking into account the distance from the hydrophones to the centre of each time segment. A simple formula was used in this case: TL = 17log(R), a formula that often yields relatively good agreement with measurements in the study area, based on previous FOI experiences (Bergström *et al.*, 2013; Andersson *et al.*, 2015). Nevertheless, this estimation is the source of the largest uncertainty; the environmental parameters are known to effect the estimation of a ships URN and are not included in this model. However, measurements or more refined modelling of the TL was not feasible in this study.

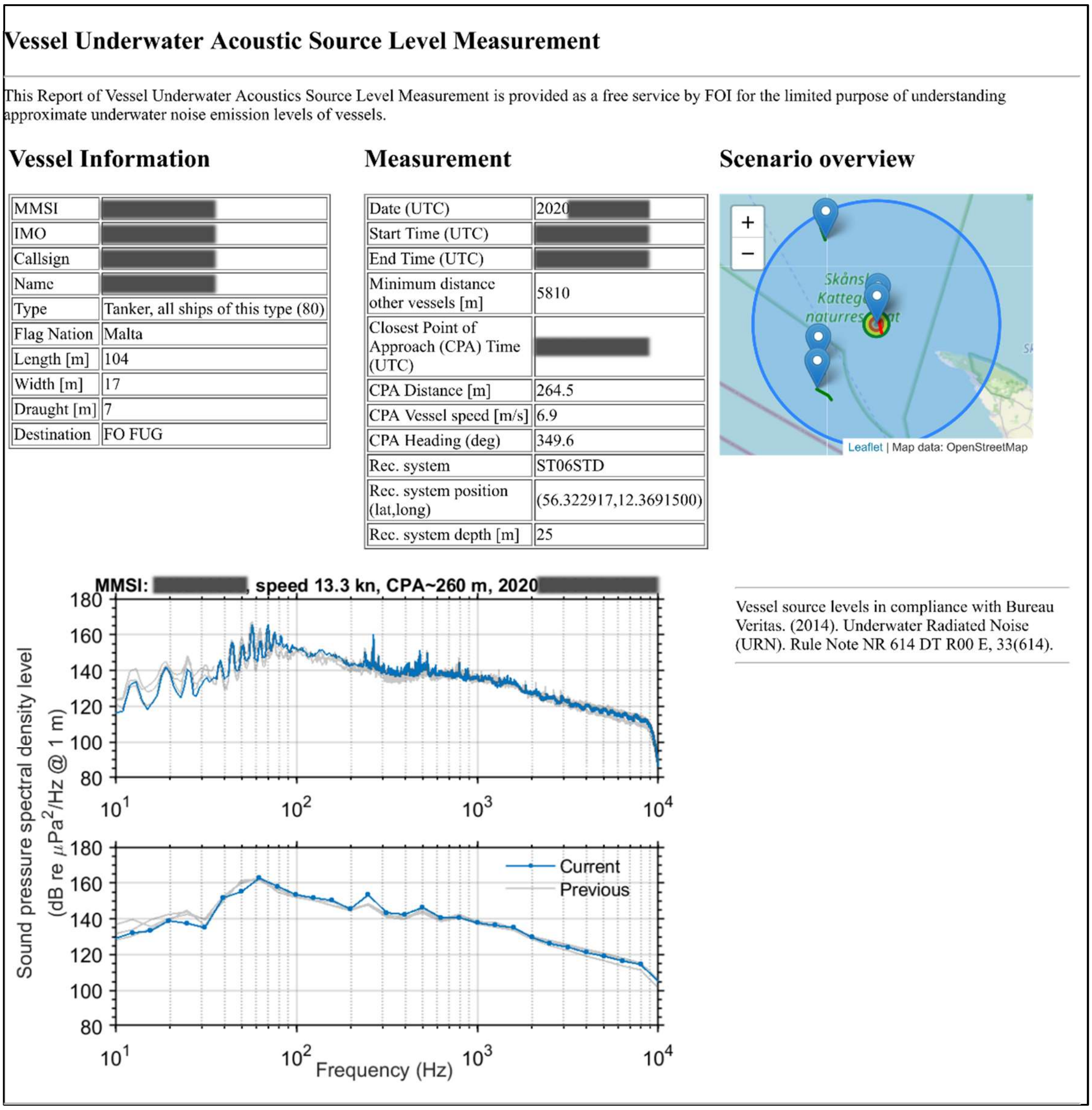
7. If several hydrophone channels were used, the power spectrum densities of all time segments were averaged over.

8. After the transmission loss correction, all power spectrum densities were averaged to create a single spectrum for the run. This averaging method is recommended by Bureau Veritas and treats the ships as omnidirectional sources instead of focusing on the maximum levels radiated in a specific angle.

9. If several runs were made with equivalent running conditions (route, speed etc.), power spectrum densities of the runs were averaged over to create a single spectrum for the ship.

3.3 Results

About 300 ship URN levels were calculated using the steps defined in section 3.2. The output from each calculation was saved in an Extensible Markup Language (XML) file, containing information of the ship, the passage near the hydrophone, a scenario overview (a map indicating the hydrophone position, the route of the ship, and other nearby ships, if any), and URN level plots with both 1 Hz and 1/3 octave band resolution. Previously generated URN level, if available, were also added in the background of the URN plots for comparison. The XML-format was chosen as it can be used as an input to an automatic report-generator script, once the layout of such a report has been defined. An example of how such a report could look like is shown in figure 12.



Vessel Underwater Acoustic Source Level Measurement

This Report of Vessel Underwater Acoustics Source Level Measurement is provided as a free service by FOI for the limited purpose of understanding approximate underwater noise emission levels of vessels.

Vessel Information

MMSI	[redacted]
IMO	[redacted]
Callsign	[redacted]
Name	[redacted]
Type	Tanker, all ships of this type (80)
Flag Nation	Malta
Length [m]	104
Width [m]	17
Draught [m]	7
Destination	FO FUG

Measurement

Date (UTC)	2020[redacted]
Start Time (UTC)	[redacted]
End Time (UTC)	[redacted]
Minimum distance other vessels [m]	5810
Closest Point of Approach (CPA) Time (UTC)	[redacted]
CPA Distance [m]	264.5
CPA Vessel speed [m/s]	6.9
CPA Heading (deg)	349.6
Rec. system	ST06STD
Rec. system position (lat,long)	(56.322917,12.3691500)
Rec. system depth [m]	25

Scenario overview

Vessel source levels in compliance with Bureau Veritas. (2014). Underwater Radiated Noise (URN). Rule Note NR 614 DT R00 E, 33(614).

Figure 12. An example of how a report from a ships URN estimation could look like. The ship's details have been removed in order not to reveal its identity.

3.4 Evaluation of the accuracy of the automatic URN estimation

This section evaluates the method for automatic determination of the URN of a ship by comparing the output with previously measured URN levels. Here, a ship that was measured in a dedicated trial in 2014 according to the Bureau Veritas methodology is used (Bureau Veritas, 2014). These URN levels, calculated from runs at a speed of 8 and 11 kn, are used as reference values, to which the automatically determined URN are compared. The ship is a work vessel of approximately 80 m length and will be called the "reference ship" in what follows.

URN recorded during nine passages of the reference ship was extracted from the data recorded in the port of Gothenburg (table 4). The ship passed the three positions over 100 times, but all passages when other ships were nearby, passages at long range, when the speed or heading were not constant or outside the intervall 5 to 14 kn were excluded.

Table 4. Passages by the reference ship that were analysed for URN estimations.Speed and position data is taken from the AIS live stream.

Passage nr	Position	Date (2020)	Speed (kn)	Direction	Range (m)
1	A1	7 Oct	9.7-11.2	W	84
2	B1	10 Nov	10.2-11.3	S-SW	411
3	B1	18 Nov	10.7-11.8	S-SW	444
4	C1	23 Oct	13.0-13.2	S	1365
5	C1	28 Oct	11.3-11.7	S	1306
6	C1	3 Nov	9.3-10.1	N	847
7	C1	16 Nov	12.8-13.2	N	1155
8	C1	20 Nov	13.2-13.4	SW	1327
9	C1	30 Nov	12.4-13	SW	1060

An example of AIS and noise data from a passage of the reference ship at C1 is shown in figure 13. The plots show various aspects of the ship's passages, such as distance to next closest ship, which in this case was over 3 km (figure 13c). The reference ship had a steady speed of about 13 kn (figure 13b) and during this passage, it had a straight course (figure 13a). The lighter colours in figure 13d shows the noise from the reference ship and there are no other sound sources in the data that could affect the URN estimation.

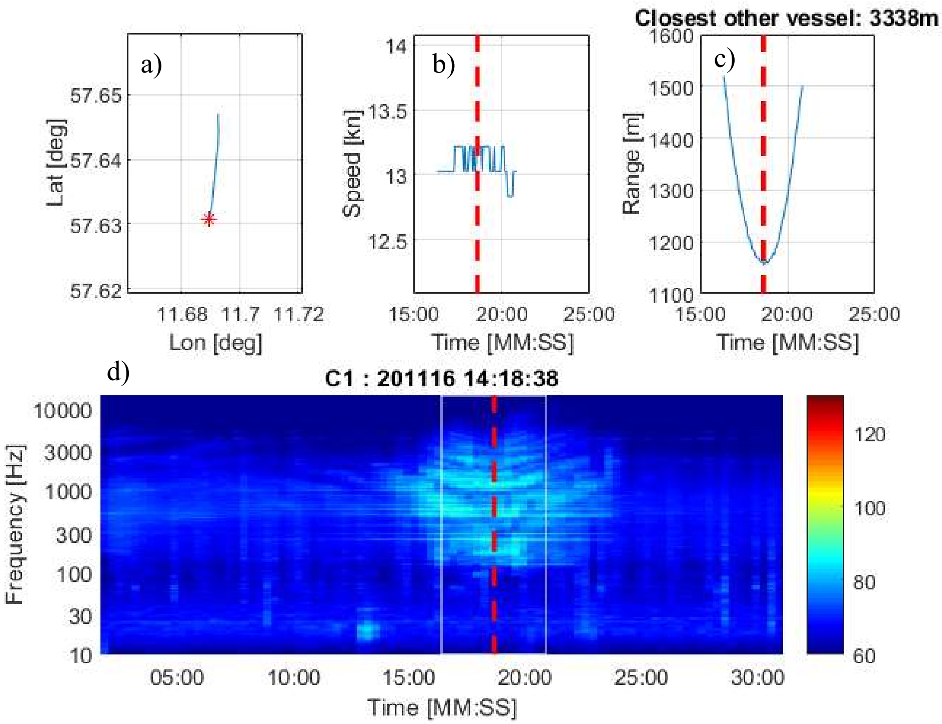


Figure 13. Position (top left), speed (top middle) and range to the nearest hydrophone position (top right) extracted from AIS data. The lower plot shows a spectrogram of noise near the passage. The red dotted line indicates the closest point of approach (CPA), and the white lines indicate the start and end of the data in the AIS plots. Colour indicates sound pressure spectral density level in dB re 1μPa^2/Hz.

The URN levels were estimated in the same manner as described in section 3.2. The results were compared to the URN level at a speed of 11 kn that was previously calculated for the reference ship (figure 14). In addition, environmental parameters which affects the sound propagation, and thus the comparison, are not included in the analysis, such as bottom sediment and sound speed profile.

The calculated source levels at 11 kn show good agreement (within 5 dB) with the 2014 data at frequencies of 200 Hz and above (figure 14a). Due to the shallow depths at sites A1 and B1, the transmission loss model $TL=17\log_{10}(R)$ is not suitable below 100 Hz, so here the URN estimates are more prone to errors. The 2014 URN level was measured at a depth of 105 m, so this frequency is significantly lowered. In addition, the instruments used in the measurements at Gothenburg are affected by a high-pass filter, so the sensitivity decreases below 50 Hz.

The calculated URN levels show a fairly good agreement at 10 kn, but relatively poor agreement at 11.5 kn (figure 14b). The poor agreement may be caused by larger transmission loss deviations from 17 log10(R) at the time of the 11.5 kn passage.

The four passages at 13 kn shown in figure 14c are not directly comparable to the 11 kn URN level from 2014 due to higher speed, but nevertheless we can make a few observations. There are only small differences between the URN estimated from three of the four passages despite that the first passage was recorded 2020-10-16 and the last 2020-11-30. The fourth passage (CPA 1170 m), is more comparable to the 11 kn passage in the frequency band 100 to 1000 Hz, likely because the ship source characteristics was changed.

The level of URN calculated for passages at 13 kn are higher than those corresponding to 11 kn, which is reasonable since it takes more power to propel the ship at 13 kn than at 11 kn, plausibly translating into more cavitation and more noise in general, although not necessarily at all frequencies. A reduction in radiated noise at lower speed is not always certain and depends on ship design and propeller type (Wales and Heitmeyer, 2002; Kämpeskog and Wenneberg, 2020). However, this particular work vessel is optimised for 8 kn and it has 11 kn cruise speed.

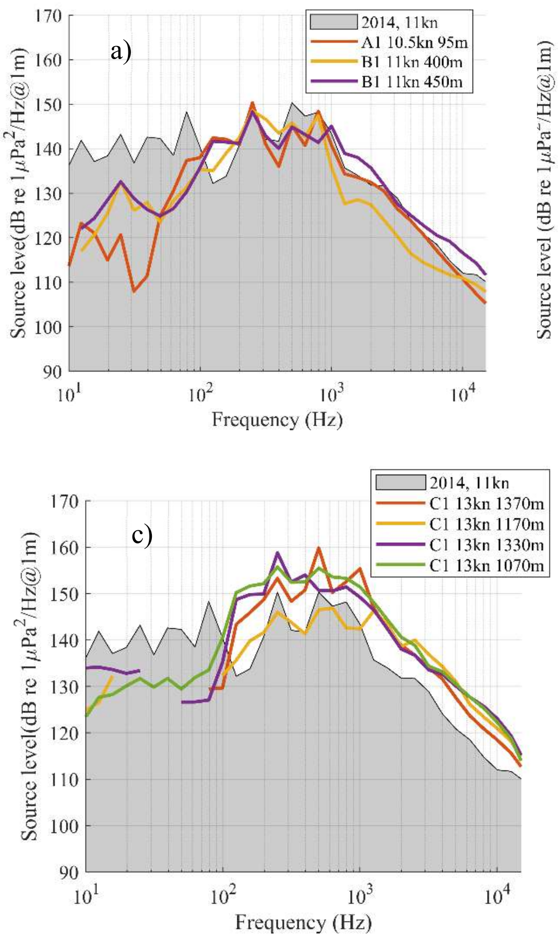


Figure 14. URN level of the reference ship estimated from a) passages 1 to 3, b) passages 5 and 6 and c) passages 4, 7, 8 and 9 (ref.table 4) compared to the 2014 URN level calculated at a speed of 11 kn. Missing data points below 100 Hz is due to low signal to noise ratio.

It is interesting to compare these results with those of a study from the southern Baltic Sea, where passenger / Ro-ro ship URN were measured with a similar hydrophone system. There, the measured URN of a certain ship varied (difference between 99% and 1% percentile) with up to 15 dB over about

20 passages, even though the transmission loss was calculated using sophisticated sound propagation models (Karasalo *et al.*, 2017). The main reasons for the lower accuracy than what is seen in this study are probably that the variation in distance and speed is significantly larger in the study of Karasalo *et al.* (2017), and the distances are also larger, meaning that the uncertainties in transmission loss will be larger. Another factor that may cause the larger variations seen in the Karasalo *et al.* study is that the ship used there is a cargo ship, for which the radiated noise may vary depending on the weight of the cargo at each time, but in this study the reference ship is a work vessel that does not carry cargo and hence can be expected to have a more stable noise radiation.

In conclusion, it appears possible to obtain acceptable accuracy in URN prediction using the AIS-based method described here, but the larger the distance to the ships during measurements, the larger the uncertainties in the estimated URN level can be expected.

3.5 Conclusions and recommendations for future work

The URN of commercial ships acquired using the method developed in this work, can be used to study the emitted noise of different classes of ships from opportunistic measurements. The measured acoustic data, together with AIS-data, is good enough to generate URN estimations for passing commercial ships and, thus, the aim of this part of the study has been fulfilled. Validation against a reference ship shows that the method worked satisfactory for frequencies above approximately 200 Hz, at 11 knots and 20 m water depth. However, environmental parameters such as sound speed profile and bottom condition are not taken into account. The method needs to be further validated against more ships at different locations before it can be considered to function well.

Furthermore, the method can provide information to shipping companies and skippers about the URN of specific ships, which in the future may be of great importance if noise levels for individual vessels are regulated. The accuracy of the calculated source levels can be improved through calculations of transmission loss with input of measured environmental data, which is a recommended in future work.

Future work includes altering the algorithms depicted in section 3.2 to automatically detect passing ships through AIS surveillance, and generate URN reports by using hydrophone data in a real-time measurement station. For instance, the algorithms need to be altered slightly, taking into account real-time AIS-streams as well as hydrophone data acquisition and a searchable database with MMSI, URN estimation and dates need to be assembled. Future work may also include the automatic detection of other ships, such as recreational ships or smaller fishing vessels, without AIS. These may interfere with the URN estimation, but it may also be interesting to study the amount of ships that do not use AIS.

An autonomous system that generates ships URN level reports daily or even more frequently could be very beneficial in several aspects of ship URN estimation. Firstly, as the URN data may be used as inputs to improve ship source level models (Macgillivray and de Jong, 2021). Secondly, the accuracy of the generated URN estimation may also improve with time, as more ship passages could be used to estimate the transmission loss of the nearby environment.

3.5.1 Implication for ship-owners and regulators

The knowledge of the URN level of commercial ships will most likely be very useful in the future if the international authorities move towards any regulation to limit the acoustic footprint of ships. This kind of regulation can only be done at the International Maritime Organization level. Today, a particular monitoring station that has been an inspiration for this work is located outside the Vancouver harbour (Hannay, Li and Mouy, 2016). A ship-owner can get a certificate of their ship's URN if it has passed the monitoring station; the harbour authorities may allow a reduced harbour fee for ships with source levels below a certain threshold. This is a possible future also in Sweden and the EU. Although the economic gains are low for this particular benefit, a silent ship has been proven to increase fuel efficiency due to good maintenance and/or technical solutions (Gassmann *et al.*, 2017), which in turn results in lower running cost.

One or more measurement stations around the Swedish coast, such as those already in place for the national environmental monitoring programme, could function as control stations to verify commercial ship URN to a certain accuracy. In addition, by measuring the URN of ships over time, knowledge can be gained regarding the need for maintenance and service of a ship, since defect propellers and other non-optimal parts and settings can be noticed in an URN report.

Future work can include a study of commercial ships that do not require AIS, such as recreational ships or smaller fishing vessels; automatic detection of other ships and boats, without AIS, can be done by studying peaks in the recorded hydroacoustic data set and compare with AIS data.

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FOI
Defence Research Agency
SE-164 90 Stockholm

Phone: +46 8 555 030 00
Fax: +46 8 555 031 00

www.foi.se