Measuring noise from ships underway

Final report of the SHIPNOISE project

Swedish Environmental
Research Institute

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Ship, noise, airborne, underwater

Summary

In the project SHIPNOISE we have developed a measurement station for both airborne and underwater noise from ships underway. The airborne noise levels indicate that there is a risk to exceed recommended indoor low-frequency noise limits for dwellings positioned up to several hundred meters from the passing ships, although the effect on public health is uncertain

The underwater noise recorded at the SHIPNOISE measurement locations is strong enough to have an environmental impact on harbour porpoises, fish and also to some extent on invertebrates. During ship passages, thresholds for several different effects are exceeded. Harbour porpoises, herring and salmon are likely to avoid or escape the area when a loud ship passes. These effects are far more common at Böttö than at Lurö. Cod reproduction is also likely to be affected, again more at Böttö than at Lurö. The noisiest ships may even cause temporary hearing damage to porpoises at Böttö.

Innehåll

1 Introduction

Noise from car traffic, train traffic and air traffic is a major, and increasing, environmental and health problem. The WHO has recently published stricter guidelines for traffic-related noise to avoid negative health effects (WHO, 2018). In Sweden, it is estimated that approximately twice as many people die prematurely due to noise than are killed in traffic every year. It is known that low-frequency noise from e.g. air traffic has negative effects on health and well-being (Araujo-Alves et. al.). The Swedish Transport Administration is currently investigating the effects that a future establishment of high-speed trains will entail and has established that measures to reduce low-frequency noise from high-speed trains might become very extensive, much depending on the fact that low-frequency noise in particular is very difficult to suppress effectively since the attenuation by a normal house facade is small. It is also known that noise from large ports disturb nearby residents. For example, an Irish study from 2013 shows that noise levels in the vicinity of the Port of Cork, Ireland, exceed WHO guidelines which have since also been significantly sharpened. The study found high levels of low-frequency noise that was thought to be likely coming from the ships' auxiliary or propulsion machinery. Another example is the airborne low-frequency noise generated by cruise ships in Värtahamnen in Stockholm, where a major effort was put into dealing with the problems caused by the noise in connection with new housing development (Ramboll, 2017). It has been shown that even the best windows on the market, in terms of soundproofing properties, do not satisfactorily dampen low frequencies, and this has presented major challenges when building homes near harbors where low frequency noise is prevalent. Over all, studies of airborne noise from ships mainly concern moored ships as one of many sources of noise in ports, and several research and mitigation efforts to handle noise from ports are of have been performed in many different countries see (Shi and Xu, 2019) for an overview, and an example from the Port of Gothenburg which acted as a part in the international research project Noise Exploration Program to Understand Noise Emitted by Seagoing Ships (NEPTUNES) where a protocol for measuring noise from moored ships in ports has recently been developed. The protocol suggests positioning of measurement microphones based on the size of the ship in question which allows handling measuring noise emissions from ships of varying tonnage.

As one of few examples considering noise from ships underway, the Swedish consultancy company WSP carried out some measurements of individual ship passages at Södertälje Canal in 2007 and found that the low-frequency noise that was measured risked exceeding the National Board of Public Health guidelines for low-frequency indoor noise (WSP, 2007). Basis for calculating facade attenuation is, however, lacking for frequencies lower than 50Hz, even though the guideline values include lower frequencies, and the ships radiate high levels at lower frequencies. One problem is that there has been a lack of sufficiently good methods to measure facade attenuation and sound levels indoors for really low frequencies. This is something that has received international attention, and there is ongoing work to develop methods for standardized measurements in these frequency ranges.

Overall, limited attention has so far been paid globally to airborne noise from ships under way, and whether airborne noise from shipping has negative consequences for the health of residents adjacent to waterways is unknown.

Underwater noise (UV noise) is an environmental problem that increases with increased shipping. Underwater noise disturbs marine life and can affect fish stocks and entire ecosystems. The area is receiving more and more attention, but limited knowledge prevents effective measures and policy instruments. Relatively much is known today about noise levels out in the oceans from shipping and natural sources, but significantly less about levels within the ocean and effects on marine life, especially over the long term. Shipping is in many places the dominant source of underwater noise, and the EU Marine Directive requires the measurement and regulation of underwater noise levels at 63 and 125 Hz, where shipping noise predominates. In contrast to air noise, there are still no limit values for underwater noise, partly due to too few measurement data being available. Many studies have shown a clear environmental impact of underwater noise. For example, Dyndo et al 2015 observed that porpoises avoid ships at distances over 1 km even though most of the ship noise is not at frequencies that porpoises can hear. Stanley et al 2017 showed that when a ship passes, the opportunities for cod and other fish to communicate, which is important for reproduction, shrinks. Underwater noise can thus affect reproduction and, by extension, population levels of important food fish. Other authors have shown avoidance responses, reduced foraging and increased stress in both fish, marine mammals and invertebrates exposed to underwater noise of the same characteristics and level as measured ship noise near a ship track.

Measurement of traffic noise is usually carried out in accordance with ISO standards that prescribe the placement of the measuring microphone close to the road or track to obtain good quality of the signal. At the same time, the vehicle type and speed of the vehicle are noted as these characteristics are decisive for radiated noise. For the measurement of ships under way, it is complicated to place measuring equipment on a vessel, and manually controlling measurements is impractical if aiming for collecting levels from many different ships. An unattended measuring station would neatly fulfill the requirements of the situation.

2 Method

2.1 AIS data

In order to correlate any measurement results from the unattended measurement station developed within the SHIPNOISE project, information about ship movements is needed. All merchant ships that adhere to the International Convention for the Safety of Life at Sea (SOLAS) are equipped with an Automatic Identification System (AIS) transponder that broadcasts information about the ship's Maritime Mobile Service Identity (MMSI), position, heading, speed and size among other information, time stamped with highest possible accuracy. For the first of the two measurement sites AIS data was supplied by the Baltic Marine Environment Protection Commission, better known as the Helsinki Commission (HELCOM). The data was provided in files covering most of the Swedish waterways during one month and was thus filtered to cover the area immediately surrounding the site during the time interval when the measurement station was in operation. AIS transponders broadcast packages of data at a rate, depending on the speed of the vessel, between every 2 to every 10 seconds. The data obtained from HELCOM did not provide full resolution of AIS data making the closest point of approach between each individual ship and the measurement station difficult to determine exactly. For the second measurement site we therefore added a Wegmatt dAISy AIS receiver to log AIS broadcasts in real-time, providing better resolution at the cost of slightly increased power consumption.

2.2 Measurement sites

Two measurement sites were used for data recording. Böttö on the Swedish west coast and Lurö in the largest lake in Sweden, Vänern.

Figure 1. Positions för the two measurement sites used in the SHIPNOISE project marked with red stars. Böttö is situated west of Brännö in the southern Gothenburg archipelago. Lurö is situated in the middle of Sweden's largest lake Vänern.

Both sites are located within a few hundred meters from major shipping lanes in the respective area.

2.2.1 Böttö

Figure 2. The islet Böttö with its old and new lighthouse.

Böttö is an islet in the inlet to the port of Gothenburg on the Swedish west coast. The manned lighthouse was in use until 1964 and is now privately owned. Through fortunate contact with the current owners the opportunity was given to place the SHIPNOISE measurement station at Böttö.

Figure 3. The wide-band microphone (top left) and the low frequency sensor (middle left) at Böttö with bitumen tanker Bitland passing on it's way toward Port of Gothenburg.

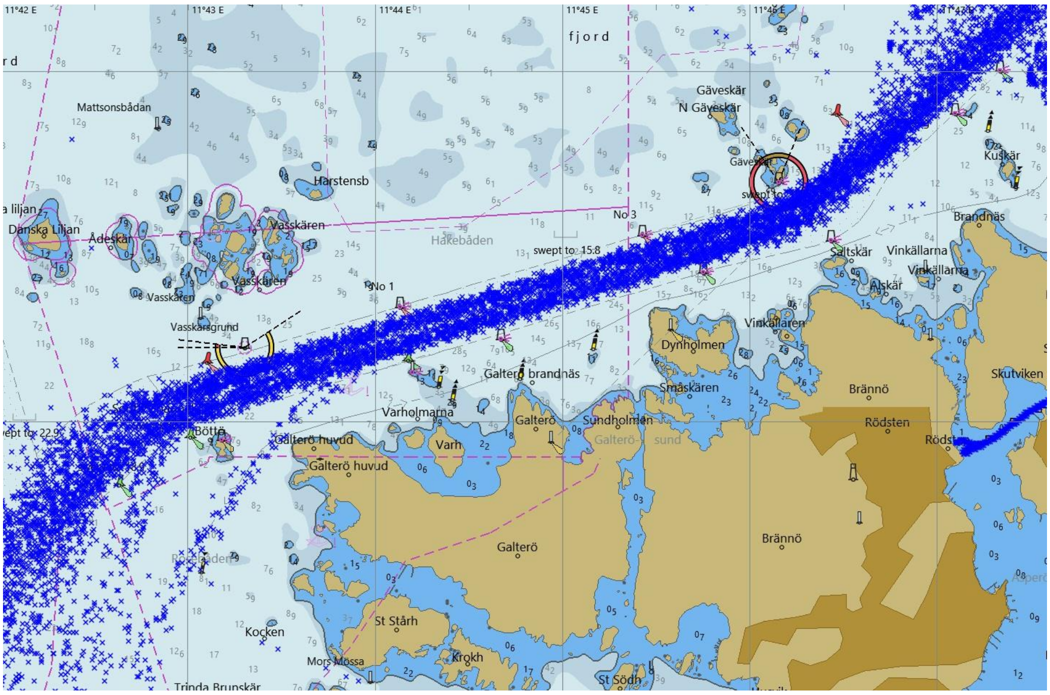


Figure 4. AIS ship positions near Böttö in the HELCOM dataset for the measurement period.

There are two main fairways leading in to the port of Gothenburg. The North Channel guarantees a minimum depth of about 22m, whereas the South Channel guarantees a minimum depth of 18m. The South Channel is also called the "Böttö fairway" and passes directly adjacent to the Böttö islet. When investigating ship movements in the Böttö fairway it is clear the traffic separation between inbound and outbound vessels is strongly adhered to, creating two distinct lanes in the AIS data (Figure 4). As the AIS data used for passage identification was of limited resolution so that each passing ship movement was only described by 10 to 20 data points sometimes several minutes apart, the exact position and closest proximity to the position of the measurement station at Böttö was not possible to determine. Therefore the AIS data for all ships passing during the period of interest were used to define one average inbound lane and one average outbound lane, and each ship was then assumed to be following the average lane when passing Böttö, giving all ships the same closest proximity distance for inbound or outbound passes respectively (Figure 4). Depending on to what extent outlier AIS positions were removed the closes proximity between ships and measurement station was found to be about 200m for inbound traffic and about 300m for outbound traffic.

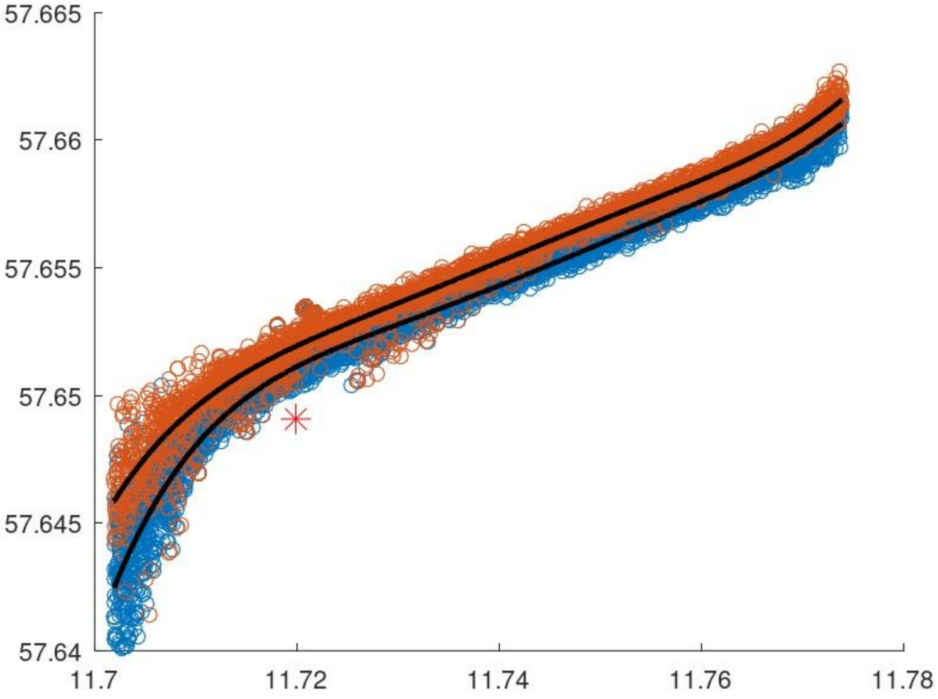


Figure 5. Longitude (x-axis) and latitude (y-axis) AIS data for inbound (blue circles) and outbound (orange circles) vessels passing Böttö (red asterisk) during the period of interest. The average tracks are marked as black lines.

2.2.1.1 Ship traffic

From the available HELCOM AIS data, relevant information was extracted by discarding data outside of the measurement period, as well as discarding ships' positions outside the Böttö fairway. The resulting data set comprised 188 unique vessels passing Böttö a total of 986 times during the period of interest. The frequently passing Stena Line passenger ferries on route to Fredrikhavn in Denmark och Kiel in Germany, together with maritime pilot boats and tug boats make up for many of the repeated passes of the same unique vessels. Figure 6 shows the distribution of speeds in the AIS data points of interest and it can be noted that there is a relatively large range of speeds that is covered in the data.

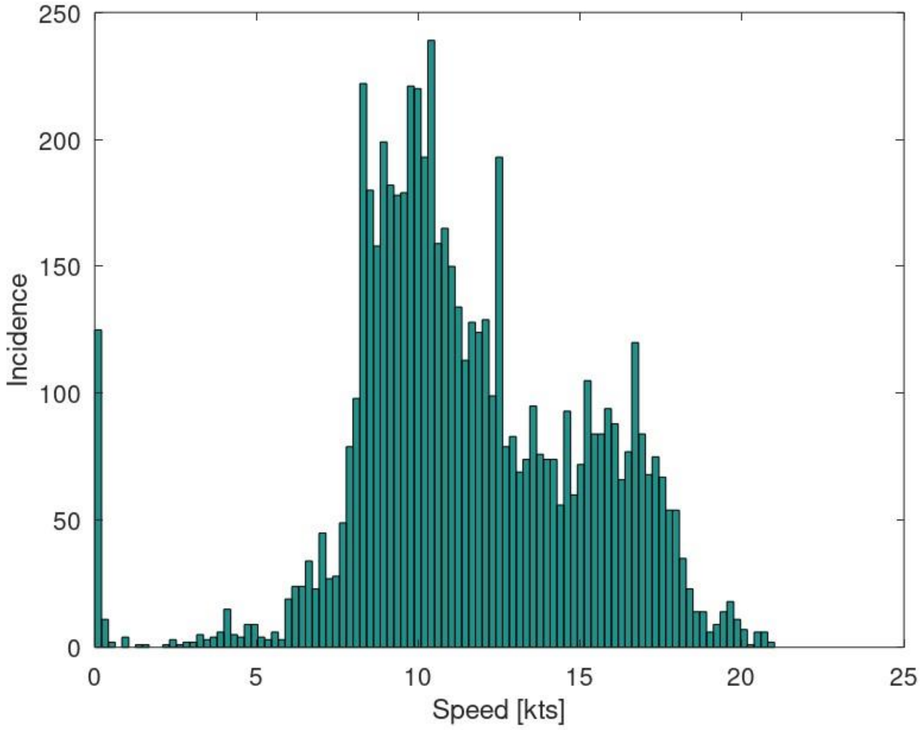


Figure 6. Histogram of the extracted AIS vessel Speed Over Ground (SOG) data points for the Böttö fairway during the measurement period.

Figure 7 shows the distribution of overall ship lengths present in the relevant AIS data points. Several types of ships are regularly operating in the area and the relatively wide distribution of ships' sizes is covered by shorter vessels like tugboats, maritime pilot boats and coastguard boats up to longer vessels like the Stena Line passenger ships and large container ships.

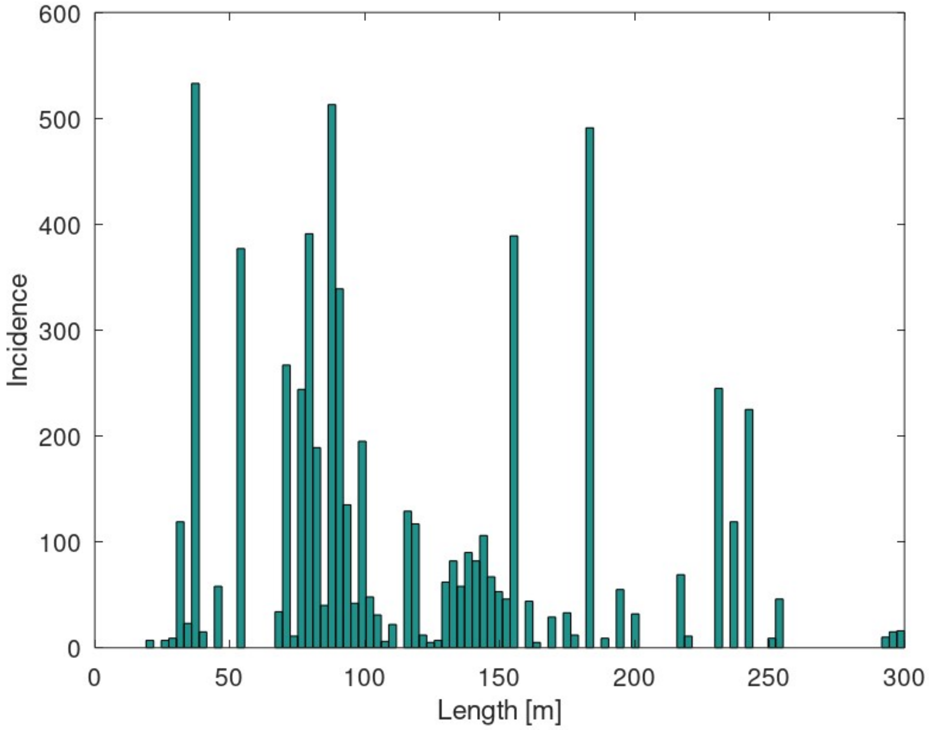


Figure 7. Histogram of ships' lengths as calculated from the AIS data fields "Dimension to bow" plus "Dimension to stern" in the AIS data points of interest.

2.2.1.2 Weather

As weather may severely affect measured noise levels, wind and precipitation data was collected for the period of interest at the measurement sites. For Böttö, it can be seen that several occasions during the measurement period experience wind speeds well above 10 m/s, but that there are calmer periods in between (Figure 8).

As for precipitation, there seem to have been just one short period with rain during the measurement period, occurring around the 12th of September (Figure 9).

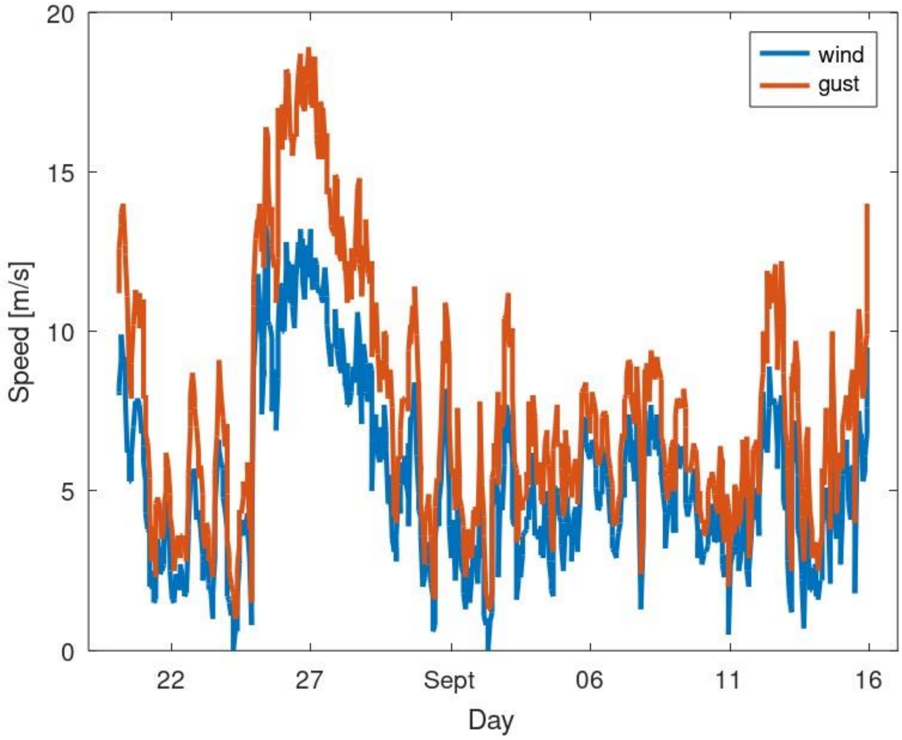


Figure 8. Hourly wind and gust speeds at the meteorological station at Vinga just west of Böttö for the measurement period.

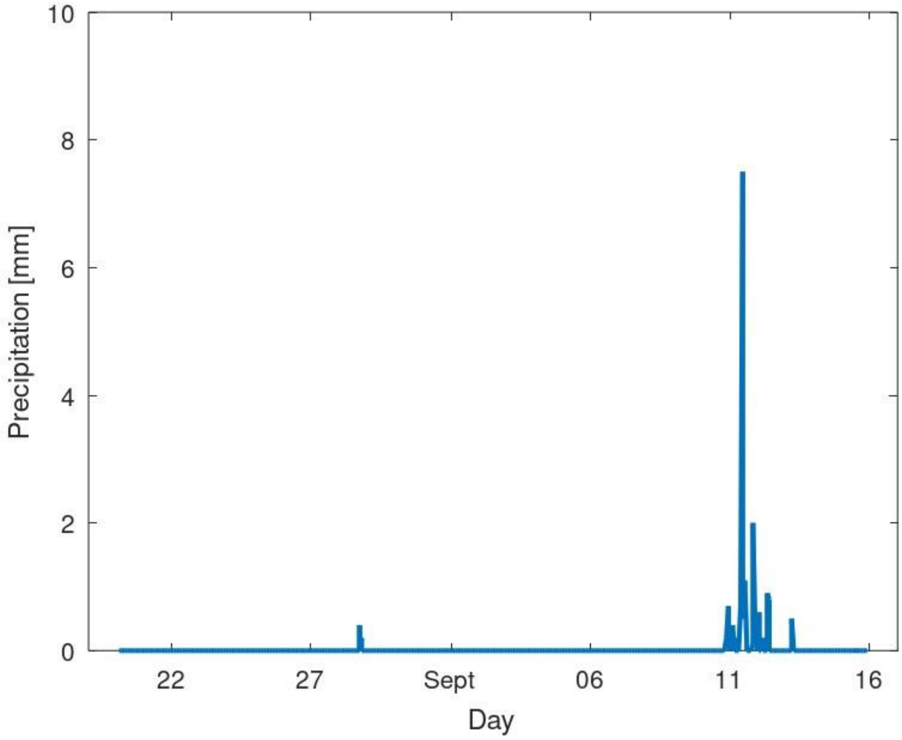


Figure 9. Precipitation data for the meteorological station at Vinga just west of Böttö for the measurement period.

2.2.2 Lurö

Figure 10. Stångudden lighthouse on Lurö in lake Vänern in Sweden. The red lateral fairway mark in line with the Stångudden point marks the northwest edge of the fairway.

Stångudden (Figure 10) is the southeast point of the island Lurö in Sweden's largest lake Vänern. Just below the lighthouse the rock drops down to the main shipping lane between the southwest and northeast part of the lake passes a narrow channel. The opposite side of the fairway is marked by the Lurö Röskär lighthouse (depicted in Figure 13). Most ship traffic passing Stångudden travel between ports in the northeastern part of Vänern, such as the port of Katrineholm, and the Trollhätte Canal leading to Gothenburg and on out to Kattegat and eventually the North Sea. When vessels approach the Lurö archipelago from southwest they round the cassion lighthouse Pålgrunden which can be seen depicted in (Figure 12).

Due to the physical limit of the locks that make up part of the Trollhätte Canal, the maximum length for ships passing the Lurö measurement site is 88m, and corresponding limits for beam is 13.2m and for draft 5.4m. As maximising the cargo for each trip is the most economically sound solution, most ships used for the route are specifically designed to use the full available space in the locks and thus most traffic passing the Lurö measurement site (Figure 11) is of almost identical size.

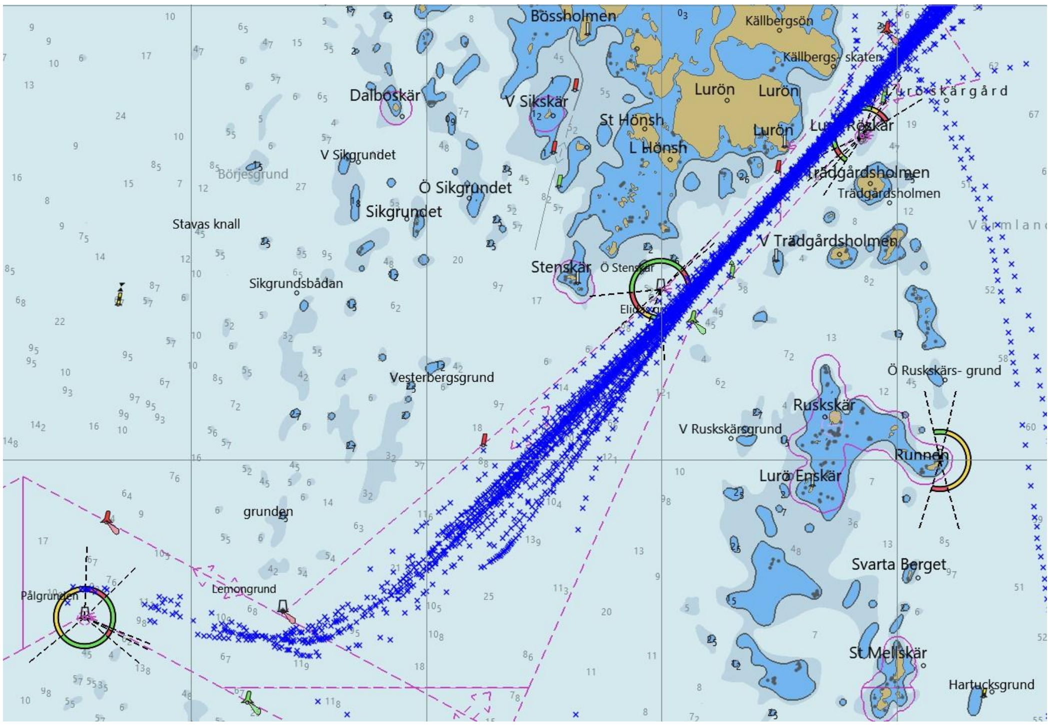


Figure 11. Received AIS ships positions around Lurö during the measurement period. The cassion lighthouse Pålgrunden (Figure 12) can be seen bottom left. The red lateral fairway marking and the Stångudden lighthouse seen in Figure 10 as well as the lighthouse Lurö Röskär (seen in Figure 13) is found top right.

The measurement site was positioned just below the Stångudden lighthouse. Estimated height above the lake surface was 5m for the tripod supporting the wide-band microphone and the dynamic low-frequency sensor (Figure 12).

Figure 12. The wide-band microphone and the low-frequency sensor mounted on a tripod at Stångudden on Lurö. The cassion lighthouse Pålgrunden can be seen on the horizon above the tripod.

Figure 13. Establishing the hydrophone outside Stångudden on Lurö. The lighthouse Lurö Röskär can be seen across the fairway top left in the photo.

2.2.2.1 Ship traffic

A total of 39 passing ships were registered in the AIS receiver during the measurement period. When analysing the distribution of speeds and sized of the passing ships at Lurö in a similar manner to what was done for Böttö, the size limitation of the Trollhätte Canal again becomes obvious (Figure 14) as all vessels are of the same length of about 88m to fit in the locks, and it would also seem the average speed for these ships are very similar as well, ending up at around 11 knots (Figure 15).

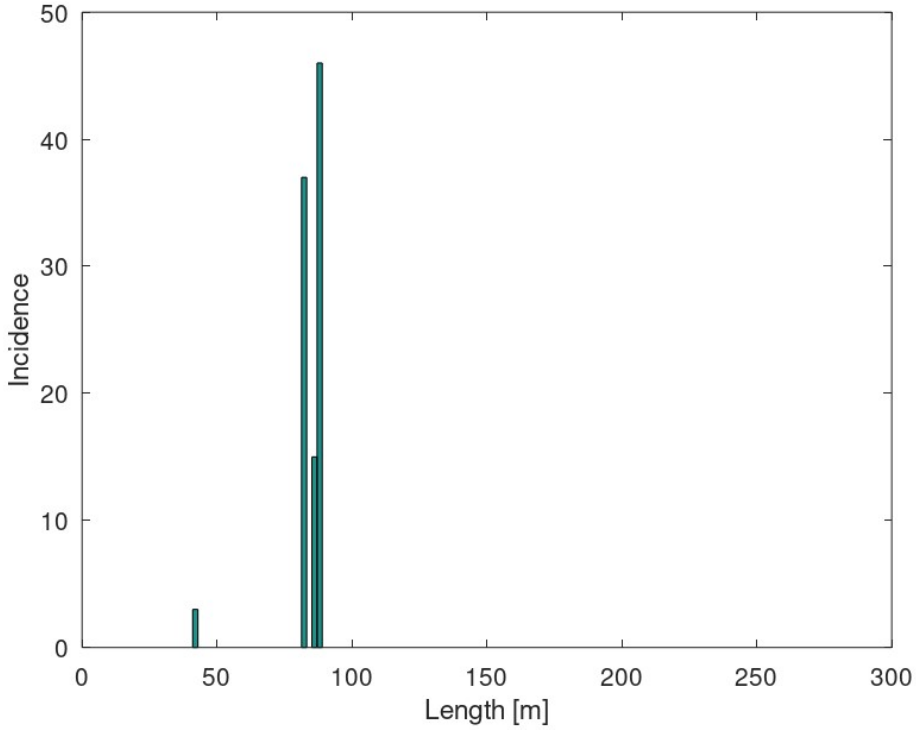


Figure 14. Histogram of ships' lengths as calculated from the AIS data fields "Dimension to bow" plus "Dimension to stern" in the AIS data points received at Lurö.

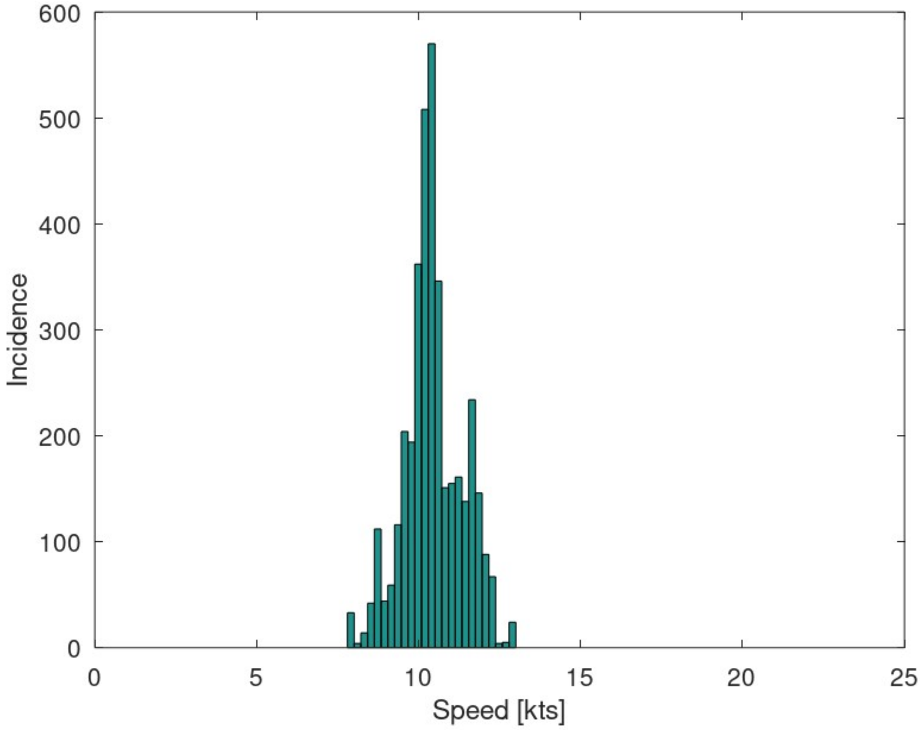


Figure 15. Histogram of the received AIS vessel Speed Over Ground (SOG) data points for the Lurö fairway during the measurement period.

2.2.2.2 Weather

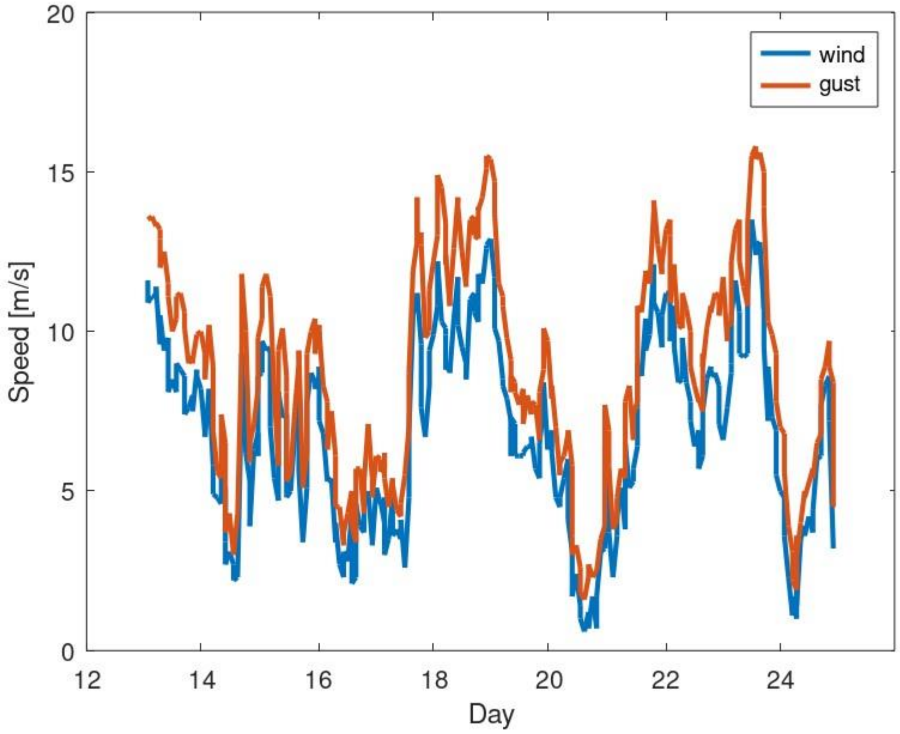


Figure 16. Hourly wind and gust speeds at the meteorological station at Pålgrunden southwest of Lurö for the measurement period.

As for Böttö there are occasions with high wind speeds at Lurö as well, seemingly resulting in almost half the measurement period experiencing wind speeds above 10 m/s, still leaving several calmer periods in between (Figure 16). On the other hand, there was very little precipitation in the period with only one occasion with very light rain (Figure 17).

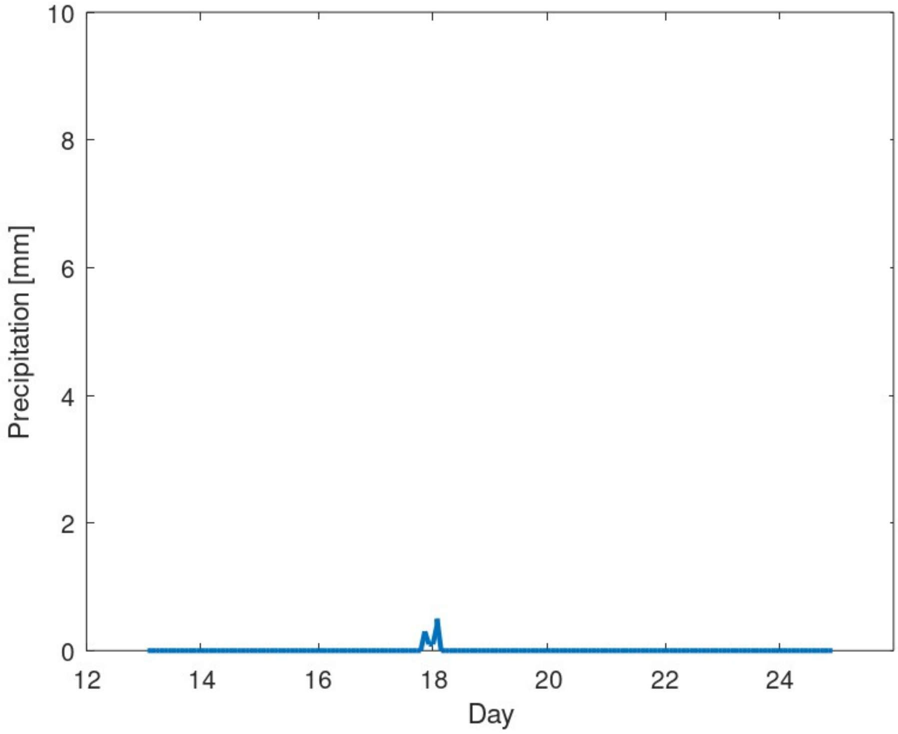


Figure 17. Precipitation data from the meteorological station at Naven south of Lurö.

2.3 Measurement station

A major part of the SHIPNOISE project concerned developing an unattended measurement station for airborne and underwater noise. Our main requirements on the measurement station were:

- Battery operation for several weeks
- User friendly interface
- High quality audio sampling for both microphones and hydrophones
- At least four channels of simultaneous data collection
- Selectable sampling frequency up to at least 48 kHz
- At least 16-bit ADC resolution
- Interfaces to weather station and AIS receiver
- Possible to implement remote connection and control
- Continuous sampling and data storage for several weeks
- Realtime processing and display of audio data levels and/or spectra

- Temperature tolerance at least 0 to 40 degrees
- Possible to develop and debug software using low cost IDE
- Ready-made libraries for common peripherals, such as serial communications, display and touchscreen interface, in order to speed up the development

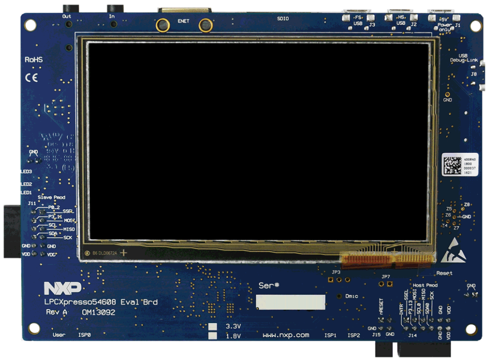
These requirements were set to allow us to meet the project goals within the project budget.

Selection of electronics platform considered Raspberry Pi, which promises rapid development. However, two major hurdles were identified. The first is power consumption, which is not a focus of the Pi; indeed, the Pi is a miniature computer and can do a lot more than our measurement station needs, which comes at the cost of a higher power consumption. Figures found online indicated a consumption of the Raspberry Pi 3 och 700 mA to 1 A. 12 V batteries that are (barely) portable come in up to 100 Ah. With a 1 A consumption, we would get 4-6 days of continuous operation. That did not mee our criteria. Further, the Raspberry Pi does not have a four-channel high quality audio interface expansion board. Another board, not from the Pi universe, may be used, but then the value and ease of use of the Pi system is lower.

Another consideration was Arduino and its relatives. It is less capable than the Pi and may fit our requirements better. However, the power consumption is still high and there is no suitable audio expansion board. It is also rather difficult to exercise precise control over what an Arduino does (indeed the same applies to the Pi) as there are many background processes running to handle functionality that might not be necessary for our current needs.

Therefore, we searched for demonstration boards fitted with the peripherals we needed and a capable but not too power-hungry microprocessor at the centre. Several such boards were found, and the choice fell to the NXP LPCXpresso 54628 evaluation board (below, left). It is a development board design to facilitate evaluation of the LPCXpresso family of microprocessors.

A separate ADC board (below, right) designed to demonstrate the capabilities of the Texas Instruments, Inc, TLV320ADCx140 family of analog-to-digital conversion devices is used to capture data. An electronic interface was designed in this project and used to control the ADC from the LPC board as well as to receive audio data at the LPC.



The LPC54628 microprocessor on the LPCXpresso board controls the measurement station. User interface is via the touchscreen TFT display that is mounted on top of the board. The ADC module is configured and controlled through an I2C serial communication interface. Sampled data is transferred using the I2S protocol, which allows multiple stereo channel configurations and supports sample rates above 200kHz. The ADC6140 device on the ADC module supports sampling at up to 768kHz.

The boards are powered by 5VDC generated by a switching DC/DC converter from a 12 V battery source. The converter likely generates noise at the switching frequency of 140 kHz, but since this is far above our sampling frequencies it will not cause any problems in this project.

Phantom power (48V) to the wideband microphone and the hydrophone is provided by an ART II Phantom power generator, which is powered directly from the 12 V battery.

The software for the measurement station was developed in the free NXP IDE MCUXpresso. The associated software development kit (SDK) comes with the libraries required for development of the measurement station.

The I2S library included in the MCUXpresso SDK only supported two channels at the time of development. A workaround was implemented by interpreting 4 channels of 16-bit data as 2 channels at 32 bits and then translating back to 4 channels. The TDM protocol, which allows multi-channel transfer at very high rates, is used.

The software is written in C and consists of a large number of modules, each handling a specific function. It can collect four channels of ADC data simultaneously at 16 bits resolution and at sampling rates up to 48 kHz.

The data is stored in WAVE format files on an SD card. Cards of size up to 256 GB are supported by the software. At a sampling rate of 32 kHz, 4 channels of data at 16 bits consumes 922 MB per hour. A 256 GB card is then expected to last around 1,5 weeks.

When the display is on, the measurement station consumes approximately 410 mA. Without display this drops to approximately 280 mA. The station is programmed to turn off the display after 1 minute of inactivity. The ADC board and its interface board consumes approximately 160-170 mA. The ADC itself is very low power; the consumption is rated at 12-20 mA. It should be possible to operate the ADC without its motherboard, probably reducing the power consumption by at least 100 mA, but this has not been attempted. The processor board further has several peripherals and connections that are not used here; disabling those would save further power.

Recordings are restarted if the data collection has frozen, which can occur if there is a problem in the communication with the external ADC. A new file is started when the current file has reached a user configurable size, currently selected as 1 GB.

The measurement station has a built-in real-time clock (RTC). After power up, the user sets the time and date. Files are named according to the date and time that they were created.


SHIPNOISE mätstation

2020 Jun 15 12 00

Spela in med 16 bitar i 48 kHz

☐ Line in

	Kanal 1	Kanal 2	Kanal 3	Kanal 4
	☑ På	☑ På	☑ På	☑ På
Analog gain	24	24	24	24
Digital gain	0	0	0	0
Mikrofon	☑	☑	☑	☑
dBre1uPa/V	100.0	100.0	100.0	100.0

Line out: Kanal 1

Volym: 100

The ADC permits detailed configuration of gain and recording options. Analog and digital gain can be configured directly for each channel in the user interface of the measurement station (see above). It is also possible to set the sensitivity of the sensor. This information is written into the header of the WAVE files. For this to work, the header has been extended and custom readers implemented in Matlab. The files can still be opened with any WAVE file reader, but the first few samples should be ignored as they are part of the extended header. The extended header is 1680 samples long. Only a few of these samples are filled with header data; the rest are there to secure correct channel alignment. (1680 is dividable by 1,2,3,4,5,6,7 and 8, which is indeed the maximum number of channels supported by the SHIPNOISE WAVE format.)

When recording, the display indicates current peak levels in each channel. This permits verification of the function of the data collection as well as verifying that the selected gain settings are appropriate.

The below table describes the settings used during the data collections.

Data	**Channel**	**Analog Gain**	**Digital Gain**
Wideband microphone	1	6	0
Hydrophone	2	12	0
Low frequency microphone, front	3	24	0
Low frequency microphone, rear	4	24	0

2.3.1 Noise issues

The SHIPNOISE measurement station reliably collected data during the measurement campaigns. No self-noise could be detected in the recordings. However the ART II phantom power interface turned out to be sensitive to external disturbances. The station was deployed close to power cables and electrical infrastructure. Low-frequency disturbances were found in the wideband microphone and hydrophone channels. Such disturbances were not detected during desktop tests and also not during trial recordings during the first day of deployment atBöttö. It is possible that the ART II was damaged by conditions of the outdoor environment that it was not designed for, e.g. high temperature or moisture.

When ships are present, levels are high enough that the power generator noise is drowned in ship noise. But the noise generated by the ART II power generator unfortunately precludes analysis of background noise levels, i.e. noise levels when ships are not present.

2.3.2 Airborne noise sensors

Two types of sensors were used for recording airborne noise from the passing ships.

2.3.2.1 Mems

One channel of the measurement station was dedicated to a Micro Electro-Mechanical System (MEMS) microphone. MEMS is a technique incorporating moving parts into semiconductor component designs. The resulting sensor is very robust compared to conventional (pre polarized) condenser microphone types traditionally used for measurement purposes. The membrane in a conventional condenser measurement microphone is extremely light in order to achieve high sensitivity. If any amount of moisture is deposited on the membrane the moving mass in the microphone mass-spring system will increase significantly, increasing the corresponding mechanical impedance. The MEMS microphone has a very high corresponding mechanical impedance to begin with meaning that the same small amount of moisture that would reduce the sensitivity of a conventional measurement microphone with several dB will not affect the microphone sensitivity as severely. The properties of the MEMS microphone used in SHIPNOISE is listed in Table 1.

Table 1. Properties of the IK Multimedia MEMS microphone used as wide-band sound sensor in SHIPNOISE. The microphone is originally intended for the IK Multimedia ARC 3 studio monitor room correction system (https://www.ikmultimedia.com/products/arc3).

	Type:	High performance MEMS element

	Polar pattern:	omnidirectional, free field.
	Capsule frequency response:	20-20,000 Hz.
	Sensitivity:	-38 dBv/Pa (1kHz, 94dB SPL)
	Signal to Noise Ratio:	65 dB
	Max SPL:	124 dB SPL (10% THD)

2.3.2.2 Baz

Two channels of the measurement station were dedicated to a bespoke dynamic low frequency sensor. Since each of the two sensors were fastened to either end of a 4-inch plastic pipe and then covered with wind shields, the visual impression immediately evoked the nickname Bazooka for the contraption and is consistently referred to as “Baz” in all graphs from the analysis.

Since SHIPNOISE focus on the low frequency airborne noise from ships that is radiated mainly from the main engine exhaust there be needed a sensor specifically useful at lower frequencies. In the SHIPNOISE project we decided to test a bespoke sensor that would be robust enough to handle rough weather and sensitive enough to yield good signal levels without active electronics. An ordinary loudspeaker as a dynamic microphone has been successfully applied as a low frequency sensor in other areas of interest such a low frequency sound from earthquakes. A loudspeaker driver can be regarded as a simple mass-spring-damper system, where the mechanical impedance is described by the mass and the spring stiffness of the system. For low frequencies the dominating property is the stiffness and as long as keeping to the stiffness-controlled frequency range, the response of the low frequency sensor will be essentially linear. Also, the mass of the membrane is significantly higher than a few small droplet that may condense onto the membrane and will thus not affect the sensitivity severely.

The sensors comprised two ordinary 3.5-inch dynamic loudspeaker elements, Visaton SL87 XA (Figure 18). The driver is membrane is made of a plastic material that is waterproof as well as UV-resistant. It has a free air resonance frequency of

550Hz, making the stiffness-controlled region of the mechanical mass-spring system impedance useful up to at least 275Hz.

Figure 18. The Visaton SL87 XA 3.5-inch speaker driver used as low-frequency sensor.

The 3.5-inch drivers were mounted at each and of a 4-inch diameter by 1m length PVC pipe used to avoid acoustic feedback around the driver membrane edges, and to have the two drivers situated at a well-defined distance. Compensating for the time/phase shift of the 1m distance, the signals from the two drivers were averaged, increasing the signal-to-noise ratio. As the drivers were mounted in opposite directions, one of the signals were also phase shifted 180 degrees before summation. Around each end of the pipe was then mounted a wind shield comprising a metal wire frame (Figure 19) covered with a waterproof, but acoustically transparent, fabric. The completed “Bazooka” can be seen mounted on a fixed support at measurement site on Böttö in Figure 20.

Figure 19. Wind shield frame for the low-frequency sensor. The frame was suspended with elastic bands to avoid structure borne sound.

Figure 20. The low-frequency sensor mounted at the Böttö mesasurement site.

2.3.2.3 Calibration

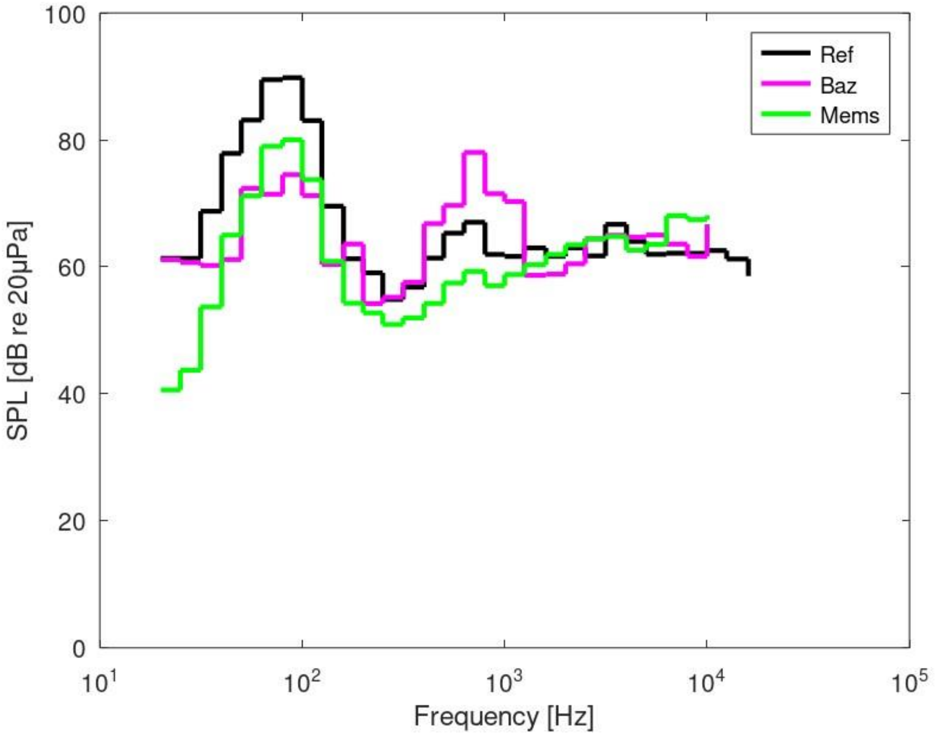


Figure 21. Frequency response for a reference measurement microphone (Brüel&Kjaer 4189) from a bespoke low frequency noise source (black) compared to the corresponding response from the 'Bazooka' low frequency sensor and from the 'MEMS' wide band microphone.

Neither the wide band MEMS micrpophone nor the bespoke dynamic low frequency sensor could be expected to have similar properties to an IEC 61672 Class 1 sound level meter. In order to calibrate the frequency response and overall level a low frequency source was used to measure the frequency response of a reference measurement microphone, a Brüel&Kjear 4189, the MEMS microphone and the "Bazooka" simultaneously at as close to the same position as possible. The calibration was performed outdoors to avoid room modes that could affect the results. The respective frequency responses can be seen in Figure 21, and the deviation from the reference microphone response curve was adjusted for the MEMS microphone and the "Bazooka" for all measurements.

2.3.3 Underwater noise sensor

An Aquarian Scientific AS-1 hydrophone connected to a 26 dB preamplifier was used to collect underwater noise data. This hydrophone has a flat frequency response from 5 Hz to 20 kHz. The preamplifier was placed in watertight mold near the hydrophone and connected to a 100 m reinforced underwater cable, which rested on the seabed when deployed. The hydrophone was placed on a vertical line between a 5 kg bottom weight and a small float (Figure 22). The hydrophone sat approximately 1 m above the seabed and the float 3 m above the seabed. A rope was attached to the underwater cable and used to deploy and retrieve the payload.

Figure 22. Float and weight used to position the hydrophone vertically above the sea floor.

At landfall, the cable was protected from wear due to rubbing against rocks and gravel by placing it inside a plastic tube (Figure 23).

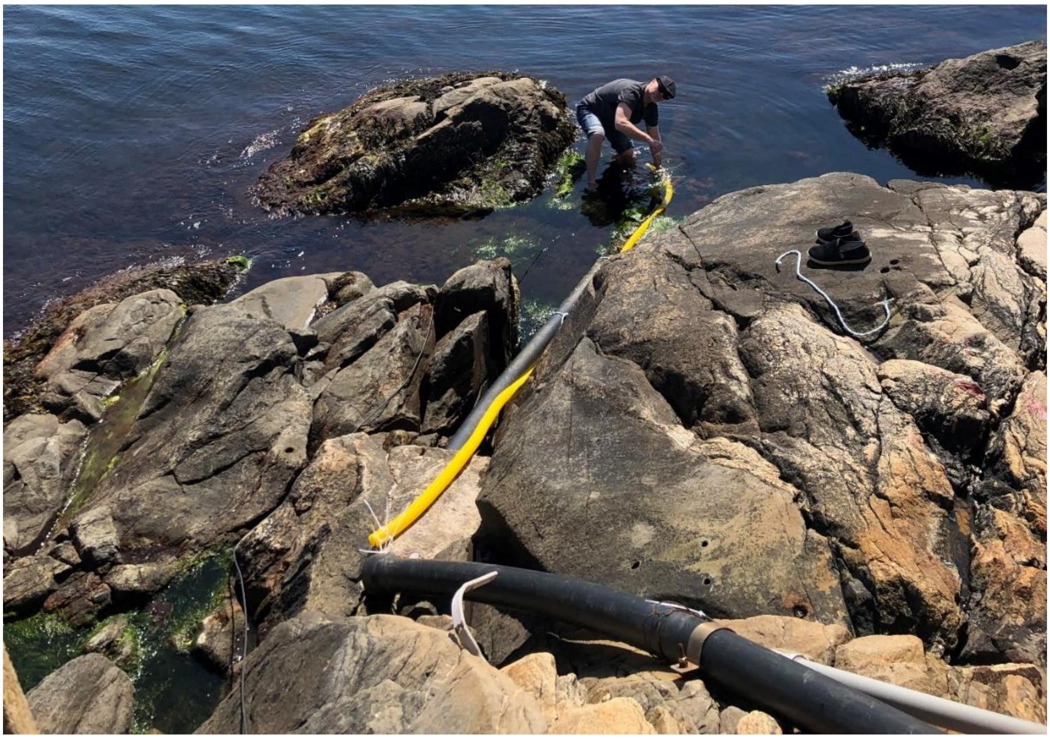


Figure 23. Establishing the hydrophone cable wear protection at the waters edge.

The hydrophone has a sensitivity of -209 dB re 1 V/μPa. The preamplifier gives 26 dB amplification, resulting in a sensitivity of -183 dB re 1 V/μPa before ADC. The ADC adds 12 dB analog gain for a system sensitivity of -171 dB re 1 V/μPa. The range of the ADC is -2.82 to 2.82 Volts. This range is mapped to the WAVE file range of values which is -1 to 1. Interpreting the data units in the WAVE file as Volts, we add $20\log_{10}(2.82)$ to compensate, resulting in a system sensitivity from sound pressure in the water to WAVE file Volts of -180 dB re 1 V/μPa.

The maximum RMS sound pressure that can be represented can be estimated as 180 – 3 dB = 177 dB re 1 μPa. Ship source levels have been reported in the range of 170 to 210 dB re 1 μPa @ 1m. We expect ranges of at least 100 m, which should correspond to transmission losses of 35-40 dB.

The peak level in the Böttö data is 0.25 WAVE file Volts. This corresponds to 165.0 dB re 1 μPa; 12 dB below the maximum that can be captured without clipping.

3 Measurement results

Two field recording campaigns were undertaken. The measurement station was deployed on Böttö in the inlet to Gothenburg harbour from Aug 20 until Sept 15, 2021. It was then deployed on Lurö in Lake Vänern from June 13 to June 24, 2022. It was programmed to record continuously on both occasions. The four channels were sampled simultaneously at 32 kHz, 16 bits.

3.1 Böttö data

In total 380 hours of audio data was recorded at Böttö and stored in 326 GB of WAVE format files. Due to insufficient battery capacity, there are gaps in the recorded data from Böttö. Figure 24 shows the data availability.

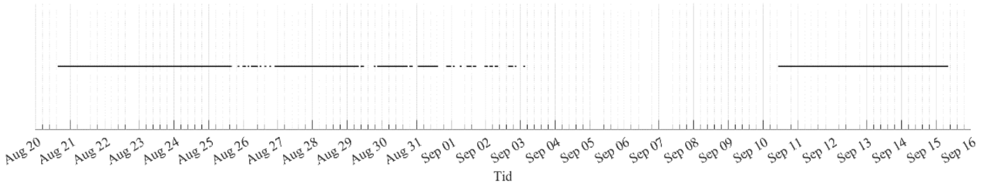


Figure 24. Graphical representation of data availability from Böttö during the measurement period.

The measurement station was placed at coordinates WGS84 57° 38.958' N 11° 43.186' E (SWEREF 99 TM N 6394402, E 304262). The hydrophone was placed at 13 m depth at coordinates WGS84 57° 38.9798′ N, 11° 43.1853′ E (SWEREF 99 TM N 6394443, E 0304263).

3.2 Lurö data

In total 288 hours of audio data was recorded at Böttö and stored in 247 GB of WAVE format files. The data was recorded continuously until the memory card in the measurement station was full.

The measurement station was placed at coordinates WGS84 58° 47.365' N 13° 15.043' E (SWEREF 99 TM N 6517924, E 398894). The hydrophone was placed at 10 m depth at coordinates WGS84 58° 47.334' N, 13° 15.120' E (SWEREF 99 TM N 6517865, E 398967).

3.3 Airborne noise

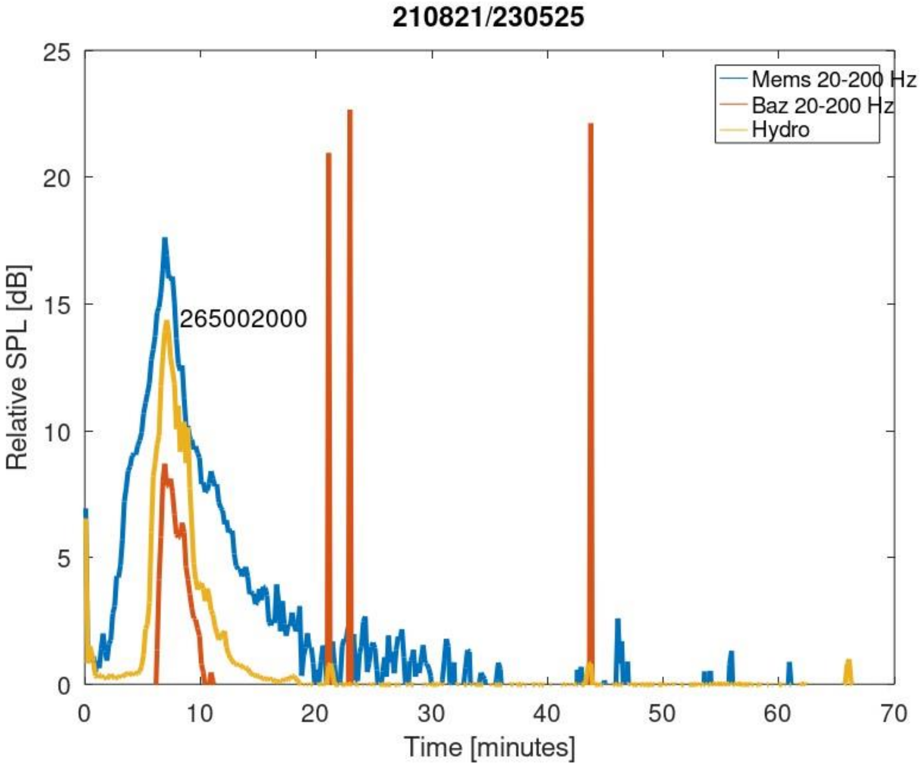


Figure 25. Raw signal from the three sensors for one of the WAV-files extracted from the measurement station when placed at Böttö. The airborne noise signals have been band pass filtered to obtain just the frequency band 20 – 200 Hz. The vertical lines just after 20 minutes and after 40 minutes are likely some sort of mechanical noise in the sensor construction.

When evaluating the signals obtained by the measurement station it was quickly obvious that some signal processing would be needed to get reliable results. As the low frequency range is what is of interest, the first step was to band pass filter the recorded sound to discard all frequencies outside the range of interest. A second order Butterworth bandpass filter with cutoff points at 20Hz and 200Hz was applied to all airborne noise signals. Figure 25 shows Root Means Square (RMS) values over time for the band passed airborne noise signals together with the unfiltered hydrophone signal. The peak for each signal in the left hand of the graph corresponds to a passing ship, and the MMSI number for the ship extracted from the obtained AIS data can be seen next to the peaks. In this case the MMSI number belongs to the oil tanker Tresfjord. The levels presented are not calibrated and are just presented relative to a generic background level constructed from some periods of time with no passing ships and little wind. As can be seen in Figure 25 some mechanical disturbance was recorded by the “Bazooka” resulting in short clicks or snaps that were not present in the "MEMS" signal. These were removed by detecting transient events in the time signal and averaging these out. The same kind of graph was produced for all recordings in order to visually investigate the quality of the signal. Form some of the recordings the effect of high winds was clearly visible.

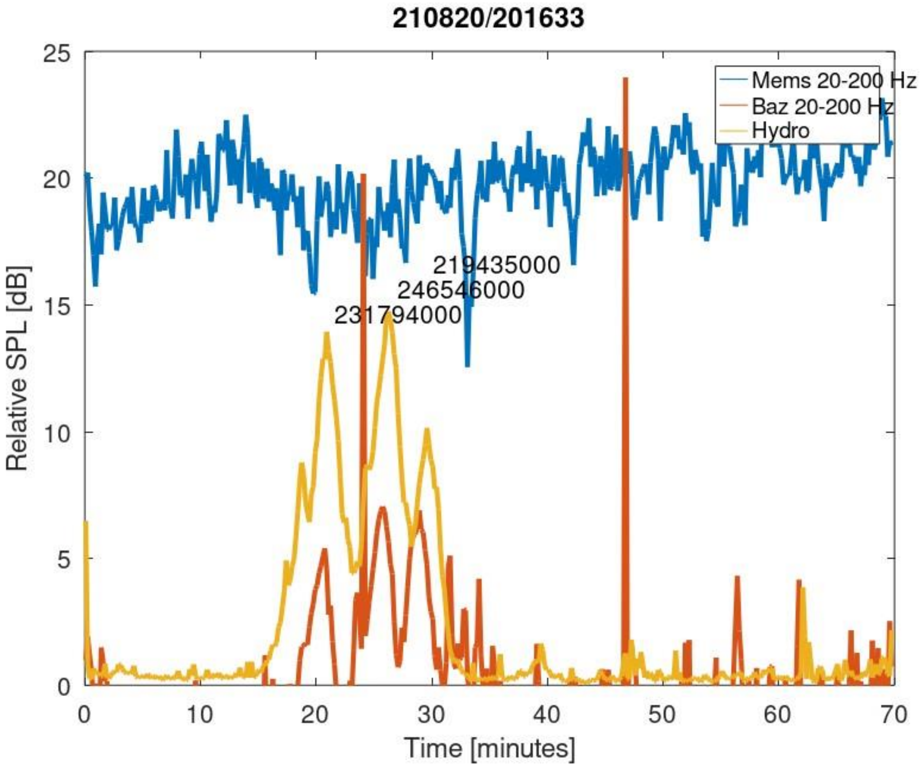


Figure 26. Example of three consecutive ship passes being recorded by the hydrophone (yellow) and the low frequency sensor (orange) while the wide band microphone signal (blue) is dominated by wind noise.

As can be seen in Figure 26, the MEMS microphone was sometimes dominated by wind noise, the main reason being that the open cell foam wind shield did not suffice in the current wind. On such occasions the noise from the passing ships was not registered at all in the wide band microphone but was still registered by the low frequency sensor as well as in the hydrophone. The hydrophone was for natural reasons the least wind sensitive sensor and could thus be used to identify ship passes in the data. However, in some cases the underwater noise level for a passing vessel could be high without noticing any low frequency airborne noise. This was likely due to some passing vessels being smaller, such as maritime pilot boats, with a higher engine rpm and smaller engine size and thus not radiating much low-frequency noise.

By partly automatically discarding ships passes occurring at average hourly wind speeds above 10 m/s and partly performing visual inspections of the raw sensor RMS signals some 280 ship passes at Böttö were extracted that were judged to be of sufficiently high signal-to-noise ratio for analysis.

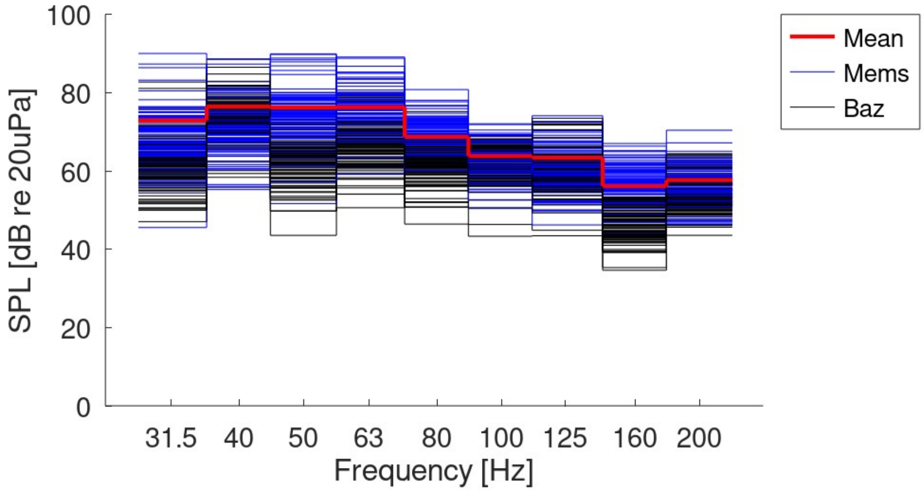


Figure 27. One-third octave band levels for each of the extracted 288 ships passes for the two different sensors, compensated for difference in distance between outbound and inbound traffic.

Figure 27 shows one-third octave band spectra in the frequency range of interest for the extracted 280 ships passes. The spectra include a simple propagation correction for the difference in distance between outbound and inbound traffic. Still there is a large spread of levels within each one-third octave band of about +- 20dB or even more. There are several reasons for this wide spread of noise levels. Firstly, it is not unlikely that the passing ships really exhibit very different noise emissions. This was also found in the underwater noise analysis (see 3.4.2) although the spread wat not as wide as for the airborne noise. Secondly, the height of the source and the height of the receiver determines how direct sound and indirect sound reflected in the water surface interact at the receiver. As there is no easily available information about height of the exhaust funnel, compensating for the source height is not possible. Also, the exact distance between source and receiver is affected by the source height and thus there is some uncertainty there as well. However, if using a mean low-frequency one-third octave band spectrum to represent an "average ship" the risk of overestimating the effects is reduced.

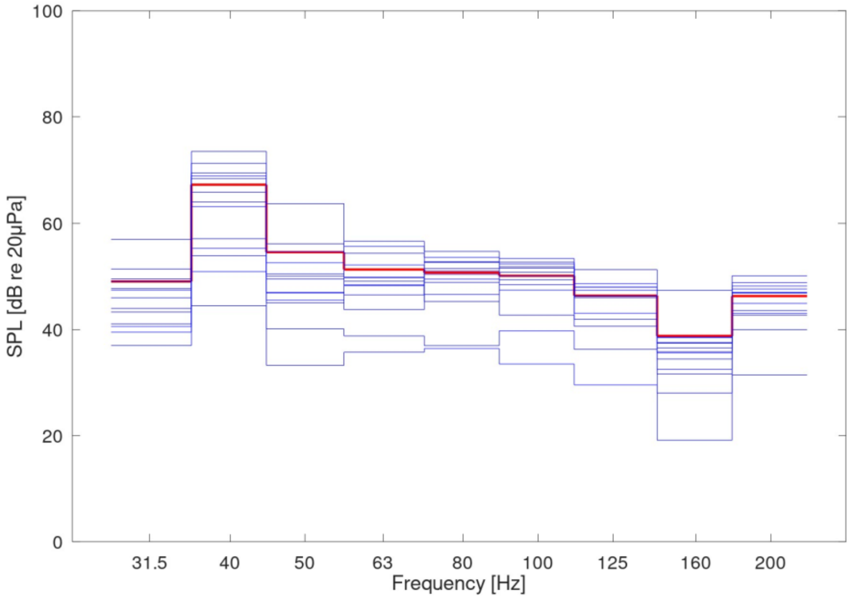


Figure 28. One-third octave band levels for each of the extracted 13 ships passes at Lurö for the two different sensors, compensated for difference in distance between each individual pass.

Figure 28 show the corresponding low-frequency one-third octave band levels for the Lurö measurement site. Only 13 passes out of 39 were unaffected by weather. The average spectrum, marked with a red curve in the figure, is found to be significantly lover than that for Böttö indicating that many of the ships passing Böttö are noisier than the ships passing through the Trollhätte Canal.

3.4 Underwater noise

3.4.1 Filtering of recordings from Lurö

The underwater noise data from Lurö was heavily polluted by an external disturbance, influencing the hydrophone recording and the wide band air-borne noise recording. Looking at the received signal level over time in the underwater signal (Figure 29) it is apparent that there is an unnatural change in the background noise level measured between the ships passing by. This is seen since the background noise decreases sharply each morning, sometime between 8:00 and 10:00, and rises again at nightfall between 19:00 and 22:00. Since the levels of the background noise is very stable between the "day-periods" and the "night-periods", this is likely not caused by any acoustical effect nor any weather-related effect. One likely source of the disturbance is power lines to the nearby lighthouse.

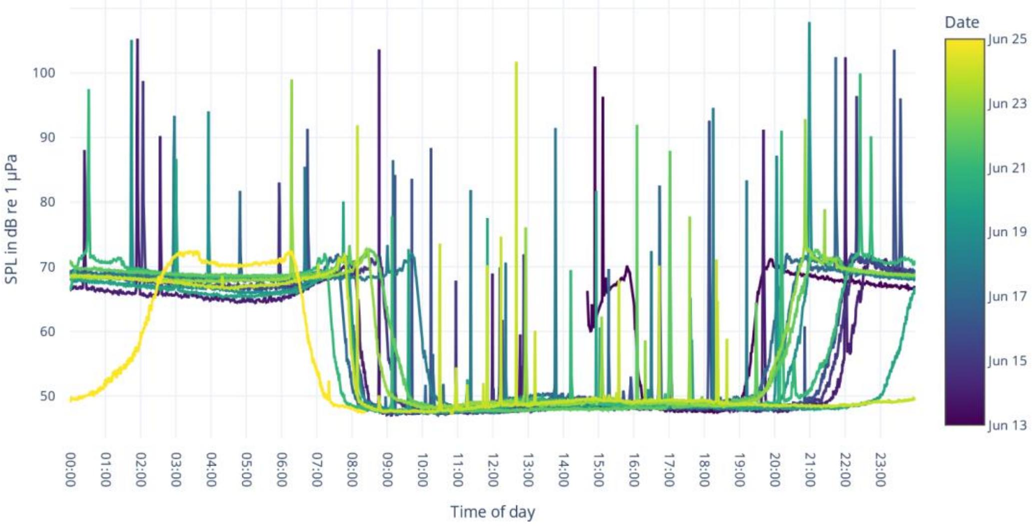


Figure 29. Hydrophone signal level as a function of time of day for the measurement period.

While the levels in the hydrophone recordings were still notably above this disturbance, the wide band air-borne recordings contained mostly this disturbance. Since the disturbance impacted the two channels with almost the same time signal, the air-borne signal could be used to clean up the hydrophone signal. This was done using a "Least-Mean-Squared" filter, which is an adaptive filtering method designed to estimate the correlated parts in one signal based on a reference signal. This was leveraged here to estimate the disturbance in the hydrophone signal using the wide band air-borne signal as the reference. This was in many cases able to remove the disturbance to the point where it no longer is apparent over the passby. An example spectrogram of the passby at 2022-06-14 02:34:34 is shown in Figure 30.

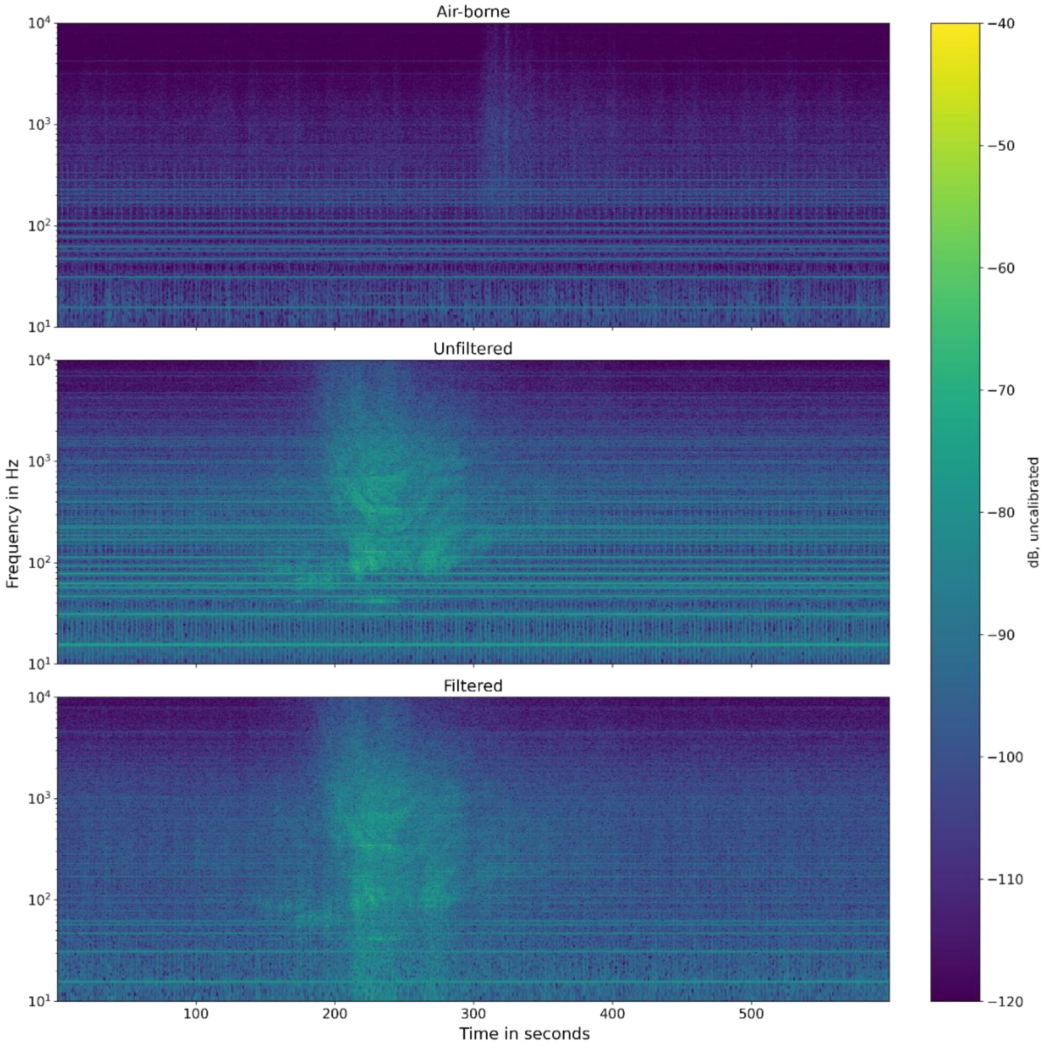


Figure 30. Spectrogram of hydrophone signal and wide band airborne noise signal as well as of hydrophone signal with external disturbance removed using a "Leas-Mean-Squared" filter.

3.4.2 Noise levels

A ten-minute analysis window was centered at the passby time approximated form the AIS data. The acoustic signal power was calculated in each analysis window using a standard exponential averaging filter with an averaging time of 1 s. These broadband signal envelopes were inspected manually to filter out passbys with more than one event in the selected time window. Such multiple events can occur if there is a second ship nearby the target ship. If the second ship does not have an AIS transponder it would not appear in the list of passbys extracted from the AIS data, meaning that this multiple event detection cannot be done automatically. Of the 595 recorded passbys, 481 were judged as successfully recorded single events. For each recorded event, the power envelope was used to determine the onset time and the duration of the passby. This was selected as the range where the power envelope was above the lower quartile of the power in the total analysis window. Since the duration of the analysis window is much longer than the typical passby, this selection is relatively robust against changing the percentile threshold.

To quantify the strength of each passby, the sound exposure level was determined in the third-octave bands with center frequencies between 10 Hz and 10 kHz. This was done by first calculating the time-varying power spectral density using Welch's method, with each block consisting of 1 s worth of signal, using a Hanning window and overlapping each block by 50%. A set of 8th order Butterworth bandpass filters were applied to the time-varying power spectral density, yielding the power envelope within each third-octave band. These power envelopes were finally integrated over time and converted to decibels to obtain the sound exposure levels.

The distribution of the sound exposure levels among the passbys at Böttö are shown in Figure 31 and at Lurö in Figure 32, with each third-octave band represented by a filled shape. This shape shows histograms of the calculated levels on the left side, with a 1 dB width for the bins. On the right side, kernel density estimates of the same data is shown. This is calculated using Silverman's rule of thumb for the bandwidth in the estimation. Both these representations are normalized to their highest values for each third-octave band individually, for visual clarity.

The distributions from Böttö are quite smooth, due to the high number of passages. The highest levels are recorded in the bands from 63 Hz up to a few hundred hertz. The levels are decreasing slightly above 1 kHz, and decreasing substantially below 40 Hz. The spread within each third-octave band is roughly 20 dB to 30 dB. There are relatively few studies that measure the SEL from individual ship passbys in the literature. Merchant et al. (2012) measured the SEL in 24 hour periods outside Falmouth Bay in the UK and separated this in estimated contributions from ships and from natural background sources. Their results show a comparable spread in the distributions within each third-octave band, and the same general trend that the levels decrease slightly at high frequencies and substantially at low frequencies. They also conclude that the total SEL from both ships and natural sources is largely dominated by the contributions from ships.

Comparing the SEL from Lurö with the SEL from Böttö, the levels at Böttö are overall 5 dB to 10 dB higher, except for the low frequencies. However, due to the low number of passages at Lurö, the variability in the data is much higher.

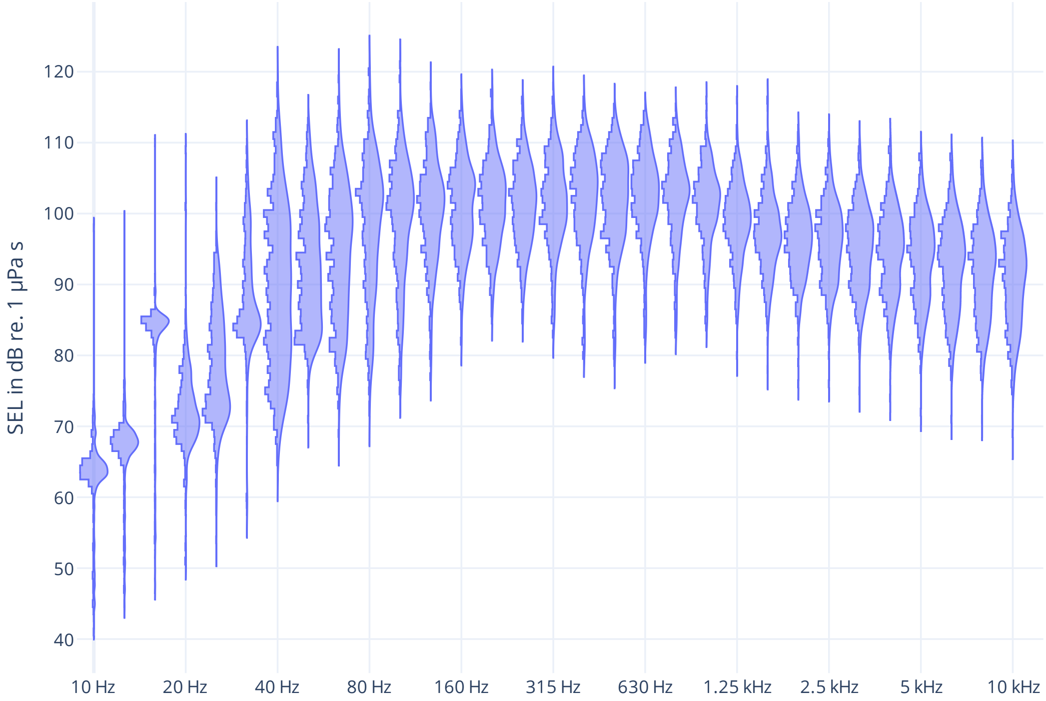


Figure 31. Sound exposure at Böttö

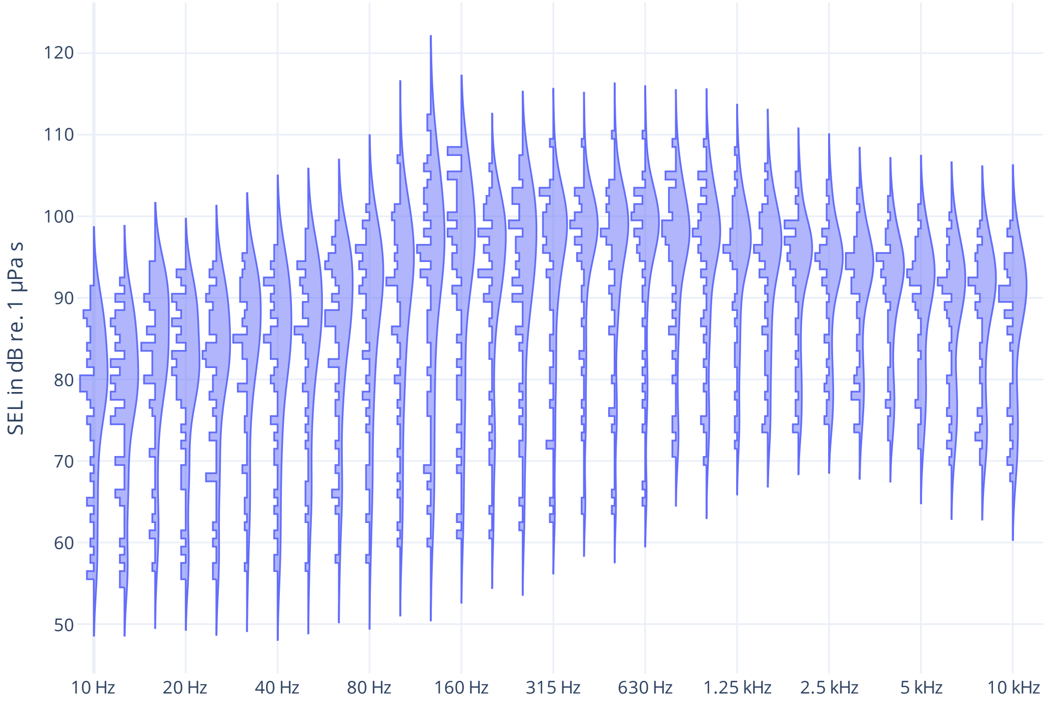


Figure 32. Sound exposure at Lurö

The total sound energy during a passby is a relevant measure of the noise emitted into the ocean. The duration of the event and its temporal energy distribution likely also affect how the noise event impacts the marine environment. Below we describe the state of the art of the environmental impact of underwater noise, with a focus on species occurring in Swedish waters. Previous scientific studies have mainly reported sound pressure levels, including durations, averages and peak values. To facilitate discussion of the environmental impact of the noise recorded at our two recording locations, we report sound pressure levels in addition to noise energies.

The below figures show statistics of the sound pressure levels encountered during a time window of 10 minutes centered at each pass-by. The sound pressure level is recorded from 20 Hz to 16 kHz. It is calculated at the averaging time of 20 s which was recommended by Tougaard et al, 2015.

Figure 33 and Figure 35 show statistics of the 20 s mean SPLs encountered during passbys at Böttö and Lurö, respectively. A longer time window at each passby would result in different results here; the purpose of these figures is to compare the sites. It is clear that noise levels during passbys at Böttö are higher than at Lurö. This may be caused by different ranges to the sources, noisier ships at Böttö than at Lurö or lower ship speeds at Lurö than at Böttö. The AIS data indicates that ranges are similar, but speeds are lower at Lurö. The ships passing Lurö are also smaller than the ones passing Böttö (see 2.2.1 and 2.2.2).

Figure 34 and Figure 36 show statistics of the maximum underwater noise sound pressure levels during passbys at Böttö and Lurö, respectively. These values are the maxima of the 20 s mean values during each passage. It is clear that both low and high percentiles of the maximum value distributions are higher at Böttö.

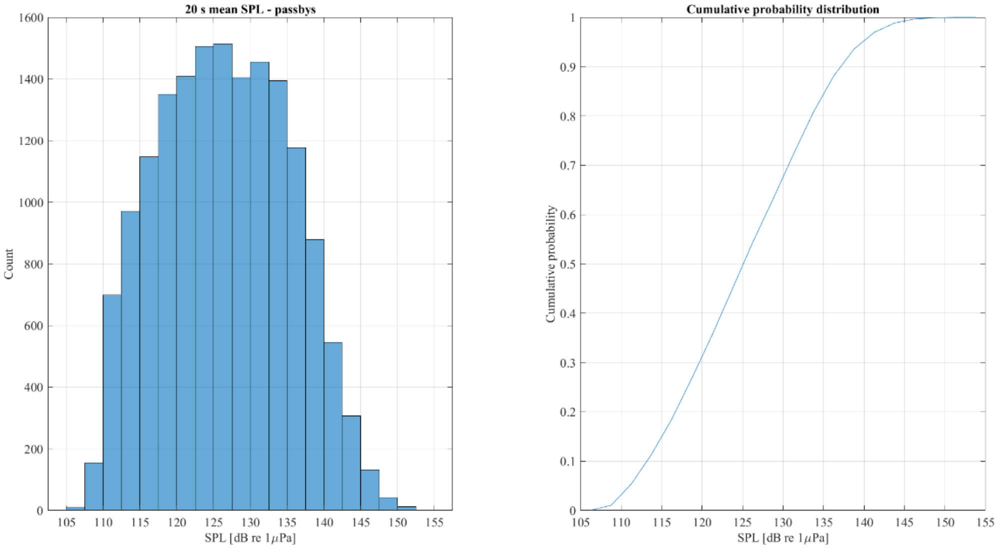


*Figure 33. Statistics of **20 s mean** underwater noise sound pressure levels (SPL) recorded during passbys at **Böttö**. Left: Histogram. Right: Cumulative probability distribution.*

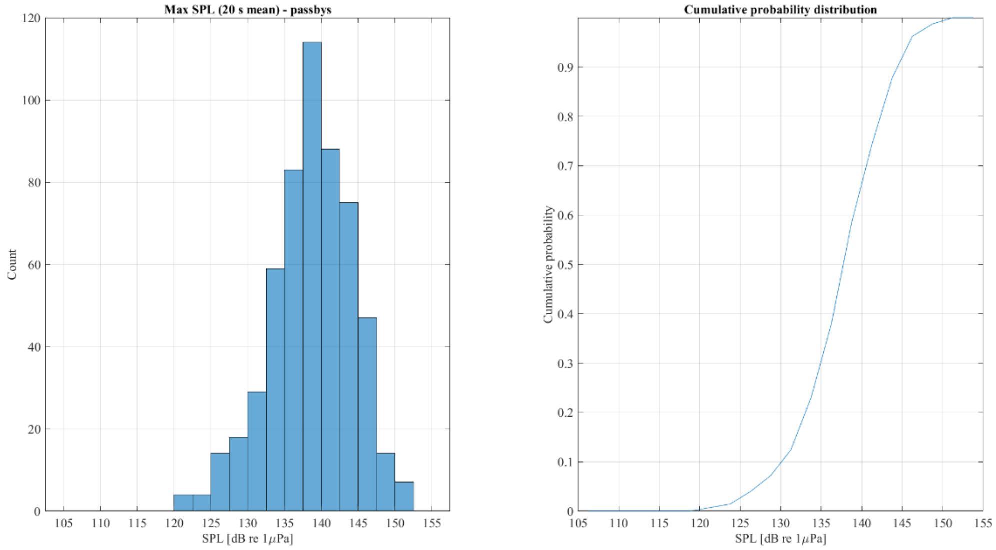


*Figure 34. Statistics of the **maximum** underwater noise sound pressure levels (SPL) recorded during passbys at **Böttö**. Left: Histogram. Right: Cumulative probability distribution.*

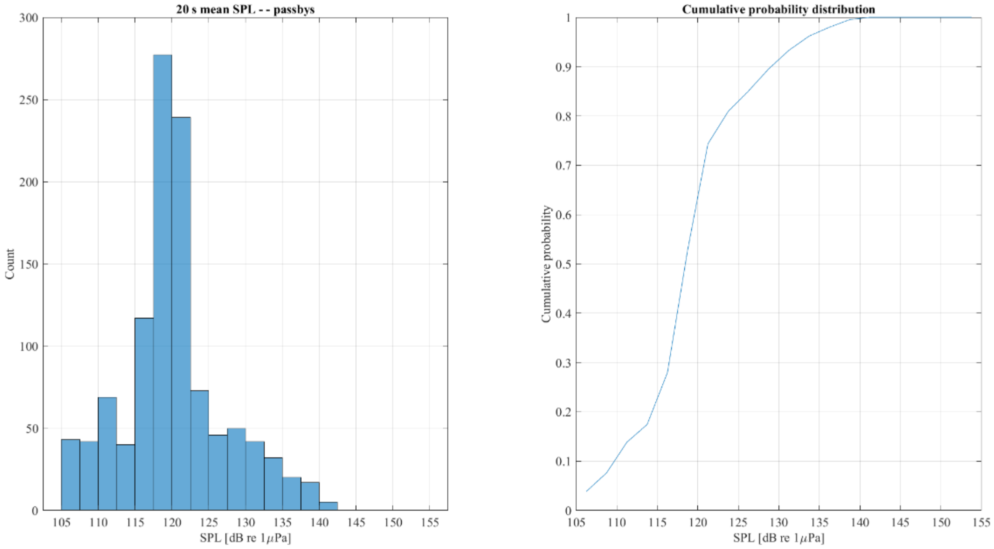


*Figure 35. Statistics of **20 s mean** underwater noise sound pressure levels (SPL) recorded during passbys at **Lurö**. Left: Histogram. Right: Cumulative probability distribution.*

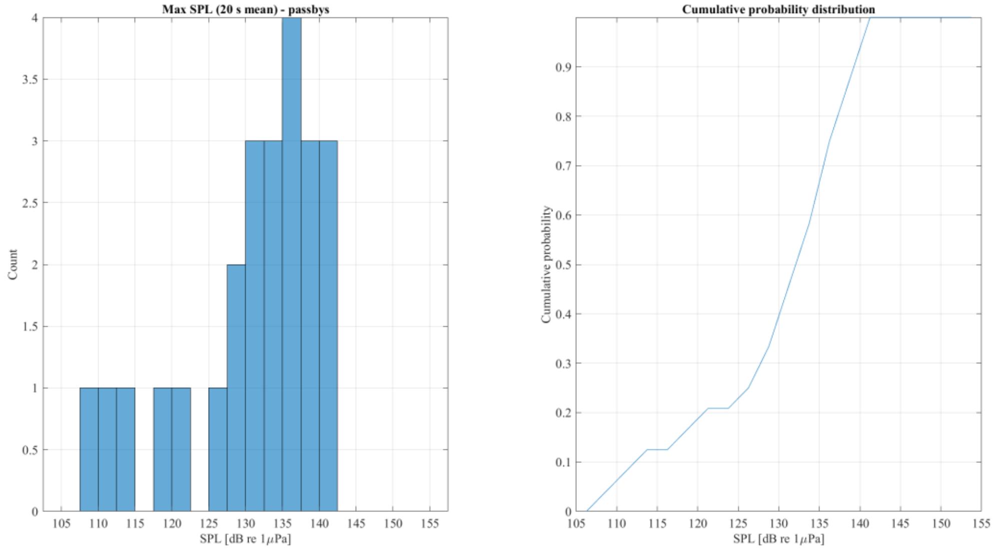


*Figure 36. Statistics of the **maximum** underwater noise sound pressure levels (SPL) recorded during passbys at **Lurö**. Left: Histogram. Right: Cumulative probability distribution.*

4 Effects of airborne noise

In order to briefly investigate the risk for noise exposure from ships under way on the community we make a few assumptions and limitations. The most important limitation is that we only consider indoor noise levels. There are two reasons for this. The first is that low frequency noise is difficult to block so any source of high levels of low-frequency noise will likely contribute to high levels indoors as well. The second is that there are no guidelines or noise limits specifically for low frequency noise at a building façade. The guidelines that do exist concern a-weighted noise levels, and the a-weighting severely underestimates low-frequency dominated noise. In Sweden there are guidelines for indoor low-frequency noise (FoHM) specifying one-third octave band levels for frequencies between 31.5Hz and 200Hz. Estimating indoor levels is very complex as the shape and size of each room will affect the occurrence of e.g. room modes (standing waves between the walls, floor and ceiling) making levels vary largely between different positions inside one room. In this case we just estimate what levels reach through the façade and thus discard the effects of the room size. A research project investigating effects of noise from wind turbines in Denmark measured the difference in one-third octave bands between indoor and outdoor noise levels for a large number of dwellings and established an average reduction spectrum (Delta/Force - EFP-06).

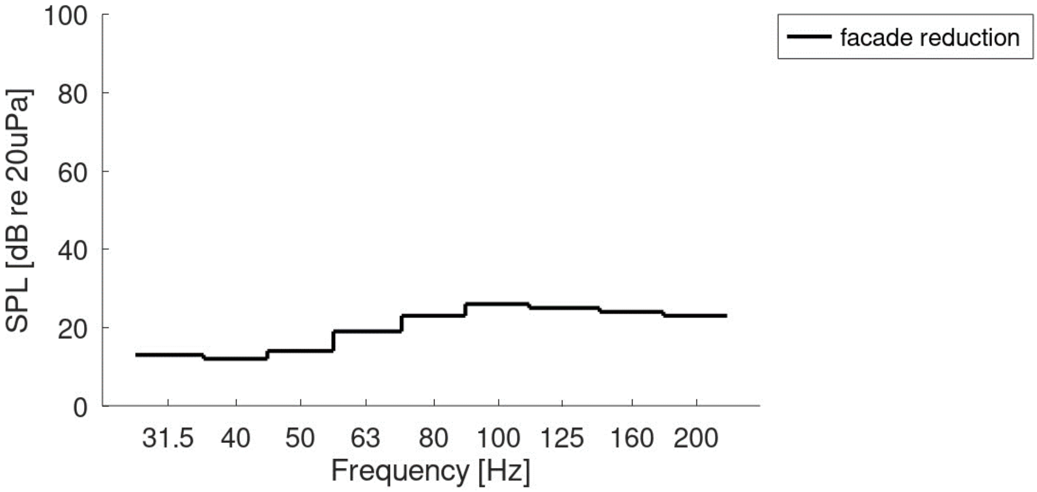


Figure 37. Average low frequency noise reduction for dwelling facades (from EFP-06).

The façade reduction is combined with the reduction due to sound propagation to calculate indoor levels from passing ships at different distances. A simple propagation calculation in steps of 100m shows how the noise levels are affected by propagation ().

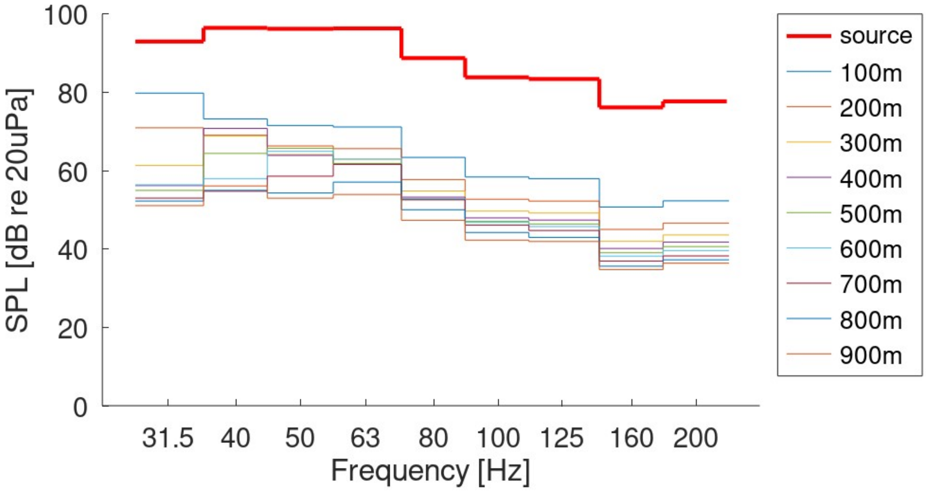


Figure 38. Simple estimation of propagations effects for low frequency noise at different distances.

Taking both the façade reduction and the propagation effects into account the resulting indoor levels can the be compared to the indoor low-frequency noise level guidelines to identify risk for exceeding the guideline levels. As can be seen in Figure 39 the indoor low-frequency noise levels exceed the guideline levels for some of the one-third octave bands. Specifically, for the 50Hz band the guideline level is exceeded for distances up to 800m. Considering the source level is based on the average level for the measurements, it is likely that some individual ships may exceed the guideline levels even more. The guideline does not specify a time period for with the low frequency noise should be evaluated and considering that ship traffic is relatively sparse even in the busy port of Gothenburg area, the equivalent level for a 24h period as used for road or rail traffic noise will be much lower and may not exceed guideline levels at all. Noise annoyance is still likely to occur on a event basis, i.e. for each passing ship, in the same manner as it is for aircraft noise. For aircraft it is often the highest allowed maximum level that is deciding the noise complaints outcome around airports, rather than the equivalent level, and perhaps there is reason to consider maximum indoor low-frequency levels for noise from ships underway.

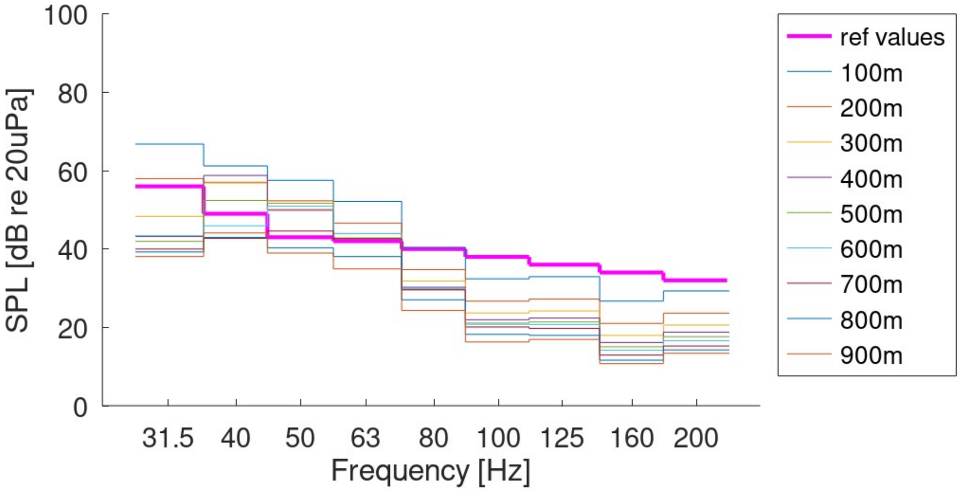


Figure 39. Indoor low-frequency noise levels from ships passing at different distances compared to the indoor low-frequency noise guideline reference levels.

At the much quieter Lurö site, the corresponding risk for exposure is much reduced, indicating that some types of ships may be better suited for traffic in fairways close to dwellings (Figure 40).

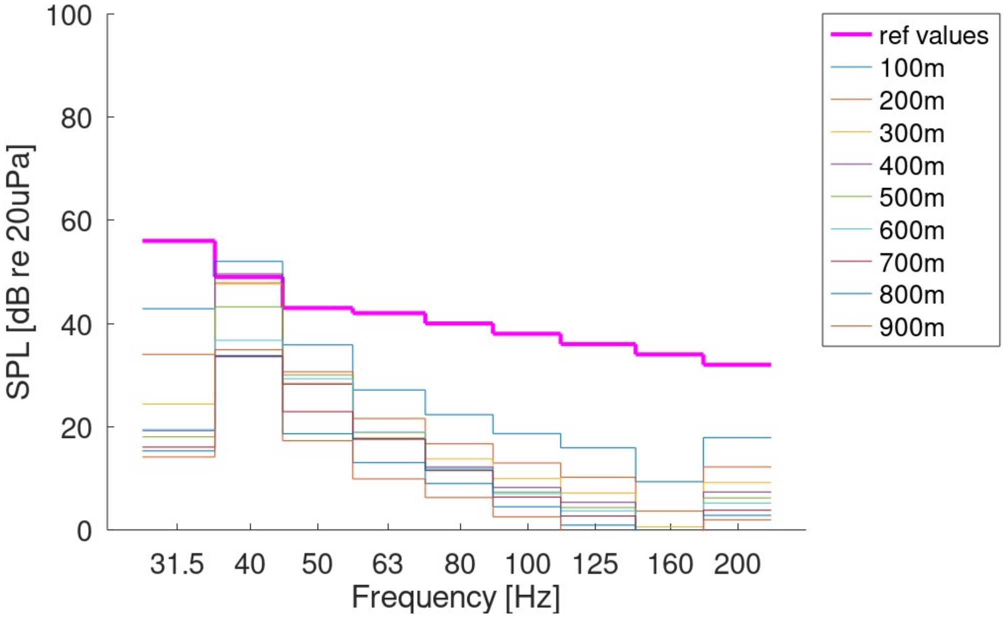


Figure 40. Indoor low-frequency noise levels from ships measured at Lurö passing at different distances compared to the indoor low-frequency noise guideline reference levels.

5 Effects of underwater noise

5.1 Environmental impact of underwater noise at the SHIPNOISE recording sites

Table 2 shows the incidence of maximum values above given thresholds at the SHIPNOISE recording sites.

Table 2. Occurrence of underwater sound pressure levels above relevant thresholds.

	Böttö	Lurö

Threshold (SPL, dB re 1µPa)	Number of passbys above threshold	Incidence, per 24 hours	Number of passbys above threshold	Incidence, per 24 hours
120	556 (100%)	35	20 (51%)	1.7
130	516 (93%)	33	16 (41%)	1.3
140	231 (42%)	15	3 (7.7%)	0.25
150	7 (1.3%)	0.44	0 (0%)	0

The following section describes the current state of knowledge on the environmental impact of underwater noise on species occurring in Swedish waters. With reference to the information presented there, we now discuss the environmental impact of the shipping noise at the SHIPNOISE recording sites.

Harbour porpoise escape reactions due to ship noise have been observed at levels of 110 to 140 dB re 1 µPa. All passbys recorded at Böttö exceed 120 dB re 1 µPa. It is therefore likely that porpoise behaviour is affected at Böttö. There are 35 ship noise events per 24 hours at these noise levels. It is interesting to consider whether this is enough to cause porpoises to avoid this site at all times. However, in order to answer this question, we would have needed to either observe porpoises using a specialized porpoise call logger ("F-POD") or used e-DNA to detect the presence of porpoises. There are no harbour porpoises in Lake Vänern. However, considering Lurö as representative of a low traffic site, let us consider the impact of the noise levels found there. At Lurö, levels are lower than at Böttö, but 110 dB re 1 µPa is exceeded at all but one passbys.

Harbour porpoise temporary hearing threshold shifts (TTS) have been observed at a sound pressure level of 154 dB re 1 µPa using pure tones in the ship noise frequency band. This level is never reached at the SHIPNOISE recording sites. However, the sensitivity to broadband shipping noise may be different due to the different character of tones and broadband noise. At Böttö, levels above 150 dB re 1 µPa do occur, although not very often (on average a little less than once every 2 days during our recordings). This level is only 4 dB below the TTS onset level for pure tones. It is therefore possible that the shipping noise at Böttö may cause TTS, but more experiments will need to be made to establish the TTS onset level for shipping noise. At Lurö, the levels are likely too low to cause harbour porpoise TTS.

<u>Seals</u> are less sensitive to underwater noise that harbour porpoises. It has been reported that ship noise may be audible to seals within a range of 1 km. If a noise disturbance is audible it may make it more difficult for the seals to communicate, but there have been no studies that investigate this. Temporary hearing threshold shifts were found at 171 to 177 dB re 1 µPa in harbour seals exposed to 6.5 kHz tones. While pure tones and ship noise have different character, it appears unlikely that ship noise at levels of up to 152 dB re 1 µPa, which is 19 to 25 dB below the pure tone TTS threshold, would induce TTS in harbour seals.

<u>Fish</u> are likely to be affected by the underwater noise at the SHIPNOISE recording sites.

Herring have been shown to avoid ship noise at levels of 123 dB re 1 µPa. These levels occur during nearly all ship passages at Böttö; with reference to Figure 34, 122.5 dB re 1 µPa is exceeded in all but 4-6 of the recorded passbys. Hence, herring avoidance is likely at least 34 times per day at Böttö. At Lurö, a little less than half the passbys exceed 123 dB re 1 µPa. This level is exceeded 1.3 to 1.7 times per day.

Salmon are less sensitive to noise than herring. Salmon avoidance to ship noise has been observed at a level of 140 dB re 1 µPa. This level occurs 15 times per day at Böttö and 0.25 times per day at Lurö.

Cod reproduction has been shown to be affected at noise levels of 132 dB re 1 µPa. Levels of 130 dB re 1 µPa occur 33 times per day at Böttö and 1.3 times per day at Lurö.

Eel predation risk was shown to increase at levels of 148-149 dB re 1 µPa. Such levels do not occur at Lurö, but levels above 150 dB re 1 µPa occur approximately 0.44 times per day at Böttö.

<u>Invertebrates</u> are less sensitive to noise than fish. At noise levels of 148-155 dB, it was shown that shore crab feeding behaviour was affected and there is an increased risk of predation. These levels do not occur at Lurö, but levels above 150 dB re 1 µPa occur approximately 0.44 times per day at Böttö. Blue mussel filtration

decreased at 150 to 160 dB. Again this is not likely at Lurö but such levels occur 0.44 times per day at Böttö.

5.2 Environmental impact of underwater noise – a short summary focused on Swedish species

The ocean is full of noise and the ocean underwater soundscape is a complex mixture of sounds from various natural and anthropogenic sources, with different frequencies, sound levels and duration. Natural sounds are produced by for example wave motions, wind, rain and ice but also different organisms, including sound signals for biological communication. Underwater noise from shipping lanes causes more or less continuous noise pollution in areas near shipping lanes. In order for underwater noise to have an environmental impact, the sound has to spread from the source through the environment and reach an organism, where it may cause a response or an effect. Generally, sound propagates five times faster and much further in water than in air and sound also propagates farthest in the sea compared to other sensory cues. Indeed, many marine animals use acoustic cues for a wide range of behaviours essential for their life functions, including communication, identification of other animals of the same species, orientation, navigation, locating food, avoiding predators and other dangers, finding and choosing reproductive partners, and finding suitable habitats for settling [Bass and McKibben 2003, Simpson et al 2004, Egner and Mann 2005, Slabbekoorn 2010, Radford 2014]. Both continuous and temporary anthropogenic noise may disturb or disrupt the ability of marine animals to perform these sound-dependent behaviours, for example by masking sounds used for communication. Noise pollution may also affect animals' physiology and induce general stress responses, and in extreme cases loud noise may induce temporary or permanent physical damage and hearing loss, or even be lethal (Popper 2009; Shannon, 2016 Nedelec, 2017; Popper and Hastings 2009, Slabbekoorn et al 2010, Tyack and Janik 2013].

A major contributing factor to underwater noise pollution in the sea is transportation [Hildebrand 2009, Andersson and Sigray 2017]. It has been estimated that the increased shipping over the past 50 years has contributed to a 32-fold increase in low-frequency noise along high-traffic shipping lanes. In such areas, marine organisms are likely to be chronically exposed to noise all year round. The frequent use of recreational boats during spring and summer means that noise exposure can become constant even in areas outside the shipping lanes during the boating season [Haviland-Howell et al 2007, Moksnes et al 2019]. In coastal archipelagos and other shallower areas, the biological diversity is often very high, and shallow bays with eelgrass and soft bottom habitats function as nurseries for numerous fish and invertebrates (Moksnes, 2019). The environmental impacts of underwater noise from shipping and boating activity on marine organisms in these areas/habitats can be great, especially if the exposure occurs during sensitive periods such as the mating season. A good environmental status with respect to underwater noise pollution requires that the level and distribution of anthropogenic sounds should not cause negative impacts on marine life. Although the impact of underwater noise on marine animals has received more attention in recent times [Shannon et al 2016], there is still much we do not know about how marine animals perceive sound and what effect noise can have on them.

It is problematic to generalise regarding vulnerability to noise pollution since different species perceive different kinds of sounds in different ways and are thus sensitive to different kinds of noise [Popper et al 2019, Ladich and Fay 2013]. The vulnerability depends on whether the sound overlaps in frequency with the hearing ability of the animal and whether the noise reaches levels above the animal’s hearing threshold [Popper et al 2019]. This hearing threshold varies depending on the level of background noise and sounds must be more intense at higher levels of background noise in order to be detected [popper and Hastings 2009]. Thus, it is important to also measure the amount of background noise when examining the effects of noise.

Underwater noise produced by ships and leisure boats is primarily of relatively low frequency (typically from 10 Hz to several hundred Hz) but may range from a few Hz to over 10 000 Hz [Radford et al 2014]. This overlaps with the hearing range of a wide range of taxa, including mammals, fish and invertebrates. In contrast, high-frequency sounds from for example sonars (1 to 100 kHz) and echo-sounders (30 to 200 kHz) mainly affect mammals, such as harbour porpoises and seals (Kastelein, 2010). In general, **fish** can hear mainly low-frequency sounds up to ca. 1000 Hz and also hear these frequencies better than marine mammals. For example, for Atlantic cod the hearing range is 30-500 Hz, herring can detect sounds up to 1000 Hz and haddock up to 2000 Hz, while some freshwater species like goldfish can detect up to 5000 Hz (Popper et al 2019). A few species like European eel are also sensitivity to infrasound (<20 Hz). **Mammals** have broader hearing ranges. Pinniped grey seal for example hear sounds between ca. 75-75000 Hz, while cetaceans may hear sounds over 100 kHz. The harbour porpoise is among the animals with the broadest hearing range and specialises in detecting high- rather than low frequency sounds with an estimated hearing range of 100-160 000 Hz. (Hermannsen et al. 2014; Hermannsen et al. 2015). Sound occurs both as pressure changes and particle motion/vibration and marine animals have different organs to register these. Mammals perceive sound pressure, while all fish species studied can perceive sound through particle motion/vibration (Popper 2010), either via the inner ear or via the lateral line. Some fish species can also perceive sound pressure e.g. via the swim bladder [Popper et al 2019].

Relatively few studies have examined the hearing ability of marine **invertebrates** and we know relatively little about how invertebrates perceive sound, but they seem to perceive sound through particle motion/vibrations, also via the seabed [Popper et al 2001, Zhadan 2005, Kaifu et al 2008, Charifi et al 2017, Roberts et al 2016, Lovell et al 2005). A few recent audiogram studies investigating sound-detection abilities in invertebrates like cephalopods (Samson et al., 2014) and decapod crustaceans like crabs, prawns and lobsters (Lovell et al., 2005; Radford et al., 2016), have shown that they mainly detect low frequencies below 1000 Hz (up to 3000 Hz in crabs and prawn), with best sensitivity around 100 Hz. Recently, even jellyfish were described to possess sensitivity to low frequency sound (Solé et al., 2016). Marine invertebrates show a great variety of sensory organs and hydrodynamic receptors (mechanoreceptors) supposedly able to detect particle motion, including hair-like cells on the body or antennae, chordotonal organs on appendages. Moreover, octopuses and some crustaceans, echinoderms and mussels have ear-like statocyst organs (Roberts et al., 2016, Popper et al., 2001, Montgomery et al., 2006, André et al., 2016). Thus, also animals that cannot hear sounds in the classic manner may detect and/or be disturbed by noise. There is a lack of threshold studies for many marine species and most threshold studies report sound pressure and not particle motion that fish and invertebrates are sensitive to.

There are a number of recent and comprehensive review articles summarising the current state of knowledge on impacts of noise pollution, e.g. Shannon et al., 2016, Durate et al., 2021, Chahouri et al., 2022) and some more specific on marine mammals (Erbe et al., 2019), fish (Slabbekoorn et al., 2010, Popper and Hawkins 2019) and invertebrates (Soto et al 2016, Wale et al., 2021). In a recent article, Duarte et al (2021) reviewed over 500 published studies that attempted to quantify the effects of anthropogenic noise on marine animals and found strong evidence of significant impact on mammals (85-94% of all studies), fishes and invertebrates (>80% of studies). It should be noted however, that there may be a strong bias that studies showing significant effects are published to a greater extent compared with those presenting no effects.

The following sections summarise known effects of underwater noise on different animal groups.

Harbour porpoise

The harbour porpoise (*Phocoena phocoena*) is the most common cetacean in Swedish waters and is considered one of the species most sensitive to noise pollution. It has a unique, highly sensitive hearing ability (hearing range 100 Hz - 160 000 Hz), detecting mainly high frequency sounds. The relevant research papers on cetaceans and shipping noise include endpoints such as foraging disruption, triggering of specific swimming/escape behaviour (so called porpoising) and temporary hearing loss. Harbour porpoises, like other toothed whales, rely on echolocation for foraging, communication and navigation. Shipping noise may affect the species negatively by disturbing (masking) the perception of echolocation. Among the effects that have been observed are disrupted foraging with a significant decrease in prey capture attempts after exposure to live vessel noise (Wisniewska et al. 2018). Unfortunately this study only reported sound pressure levels in a frequency band centered at 16 kHz; total noise levels will have been much higher. Porpoising relates to specific swimming behaviour of mammals like porpoises, dolphins and pinnipeds (but also birds like penguins), where long jumps are alternated with swimming near the sea surface to maintain respiration and energy efficiency. The behaviour can be referred to as the marine mammal equivalent of running and is used when in pursuit of prey or escaping from a threat. Porpoising behaviour was triggered by vessel noise from passing vessels from a distance as far as 1 km from the source with an estimated threshold of ca. 110-140 dB re 1 µPa (Dyndo et al. 2015). Furthermore, no clear habituation to the noise exposure was found over longer periods of time. Temporary hearing loss, or temporary threshold shifts (TTS), may be caused by moderate to high levels of noise for longer periods of time. Results from TTS experiments and field studies of behavioural reactions to noise have shown harbour porpoises to be more sensitive to sound compared to other smaller toothed whales like dolphins, and response thresholds critically depend on the stimulus sound frequency (reviewed by Tougaard et al. 2015). There have been no TTS experiments with ship noise, but Kastelein et al, 2013, reported significant TTS after exposure to pure tones of 1.5 and 2 kHz at levels of 154 dB re 1 µPa.

Pinniped seals

The hearing range of pinnipeds in Swedish waters is estimated to about 100-22 500 Hz for harbour seal (Phoca vitulina) 100-25 000 Hz for ringed seal (Pusa hispida) to

75-75 000 Hz for grey seal (Halichoerus grypus). The relevant research papers on seals and shipping noise included endpoints such as masking of calls, reduced haul-out behaviour and temporary hearing loss. Seals use vocalisation calls as an important recognition cue between mothers and pups and as complex threat calls between males (Insley et al. 2003). These social calls dominate in low frequency bands within the frequency range of 100–5000 Hz, centre frequencies 250–1300 Hz, at average power spectral density levels of 52–71 dB re 1 μPa^2/Hz, with considerable overlaps with shipping noise and thus potential masking consequences (Bagočius 2014). Noise from vessels can be audible for seals at up to 1 km distance, shortening their communication distance (Blundell & Pendleton, 2015). Haul-out behaviour refers to periods when pinnipeds temporarily leave the water for a range of land-based activities, including reproduction and nursing and tending of pups. Presence of vessels, particularly cruise ships and other large vessels (of unknown frequencies and levels) has shown to reduce haul-out behaviour in harbour seals, which may lead to reduced fitness associated with loss of resting-time. Seals are not as sensitive to hearing damage as other marine mammals (see eg Southall et al, 2021). Kastelein et al, 2019, showed TTS in harbour seals occurring at levels of 171-177 dB re 1 μPa for tones at frequencies of 6.5 kHz.

Fish

Among the fish species considered relevant to Swedish waters, the estimated hearing ranges range from 50-200 Hz (gilthead sea bream (*Sparus aurata*)) to 10-5000 Hz (roach (*Rutilus rutilus*)). The commercially important Atlantic cod (*Gadus morhua*) has a relatively short estimated hearing range of 30-500 Hz also compared to the closely related Haddock (Melanogrammus aeglefinus) with a hearing range of 100-2000 Hz. Identified effects from relevant studies include numerous behavioural parameters, masking, elevated stress response, developmental or reproductive disturbances and temporary hearing loss. Generally, fish seem to be affected by strong low frequency sounds at 50-1 000 Hz, but this depends on whether a species is an auditory generalist or specialist. Noise pollution from shipping and motorboats has been shown to affect several important behaviours in fish, either by direct disturbance or by masking acoustic signals that fish produce and use in a variety of contexts. Fish can react to the presence of ships and boats by escape or avoidance behaviour. For example, cod (G. morhua) changed its natural movement pattern when ships passed by [Anderson et al 2015] and schools of tuna (Thunnus thynnus) changed swimming direction and tended to disperse when vessels were nearby [Sara et al 2007]. In net-caged Pacific herring (Clupea pallasii), avoidance behaviour was induced by noise from large vessels approaching at a constant speed and smaller vessels approaching at an accelerating speed. The authors estimated that 50 % of the fish reacted at noise levels of 123 dB re 1 µPa (herring) and 140 dB re 1 µPa (salmon). In contrast, the herring showed no visible response to sonar, echo sounders, or recordings of natural sounds from rain, gulls, killer whales, sea lions or self-produced chirps and whistles (Schwarz and Greer, 2011), indicating higher sensitivity to low frequency noise emitted from ships than high frequency sound from sonar and echo sounders. Noise can also lead to reduced foraging when fish switch from foraging to other behaviours, as seen in common minnow (Phoxinus phoxinus) exposed to playback of noise originally recorded from ships in an aquarium experiment [Voellmy et al 2014]. The levels in the aquarium were not given, but can be estimated as 155 dB re 1 mPa (Figure 2; Voellmy et al 2014). Increased noise levels may affect the predator-prey relationship either by disturbing the predators or by making it more difficult for prey to detect predators that may lead to increased mortality for preys, but may also makes it easier for predators to catch their prey. In juvenile European eels (Anguilla anguilla), acoustic disturbance by playback of shipping noise (100-5000 Hz at 148-149 dB) comprised several antipredator behaviours with direct consequences for survival likelihood [Simpson et al 2015]. Decreased foraging efficiency has been shown in aquarium studies with stickleback (Gasterosteus aculeatus) that more often failed to catch their prey when exposed to playback of ship noise compared to natural sound conditions [Voellmy et al 2014]. The same species also showed a shift in attention and foraging efficiency by impaired food-handling and decreased discrimination of food items, and more attacks were needed to consume the same number of prey, when exposed to short-term playback of white noise between 100 and 1000 Hz (Purser and Radford, 2011). Important parental care behaviours may also cease in noisy environments. Largemouth bass (Micropterus salmoides) reduced their guarding behaviour and defence of eggs and fry against predators during playback of noise from a passing motorboat [Bruintjes and Radford 2013). In worst case, this can lead to lower survival of the offspring. Masking of acoustic signals as suggested for the common goby is likely to cause behavioural disruption in many cases, although the mechanisms are often unknown. Masking of species-specific signals may decrease the effective sound range for communication, as shown for cod (G. morhua) and haddock (M. aeglefinus) during times of high vessel activity [Stanley et al., 2017]. The peak in acoustic energy for vocalisation in these two species lies in the 50-260 Hz frequency band and overlaps with that of shipping noise. As a consequence, the fish would have to swim closer together to be able to communicate. This raises concerns that communication between conspecifics, and thereby mating success, may be comprised in areas and periods with near constant high levels of low frequency shipping noise, such as near larger shipping lanes or during high boating activity. Noise from vessels may also cause physiological disturbances and increased general stress responses, especially if exposure occurs during sensitive life stages. In a study assessing elevated stress response in the gilthead sea bream (Sparus aurata) after 10 days playback of shipping noise 62.5 - 16 000 Hz at approximately 165 dB re 1 µPa, found all nine evaluated stress parameters measured to be significantly affected (Celi et al. 2016). In the worst case, such stress responses can lead to altered developmental rate, morphological changes, immunological deficiencies or increased mortality [Fakan and McCormick 2019]. Reproductive success has been shown to be affected, as in a cod broodstock population exposed for two weeks to artificial noise consisting of a daily randomized 1-hour linear sweep from 100 to 1000 Hz (at 132 dB re 1 µPa) during the spawning period. This resulted in reduced egg production and fertilization rates, reducing the total number of viable embryos by over 50% compared to a control (Sierra-Flores *et al.*, 2015). To our knowledge, **temporary hearing loss** has not been investigated for any Swedish fish species.

Invertebrates

More recently, it has been more and more evident that anthropogenic noise also affects different invertebrates. The extent of these effects and which species are affected are still however poorly understood. With their great diversity in morphology and life history, responses among different invertebrates are unpredictable and generalisations are difficult if not impossible. Therefore, several species also from outside Swedish waters have been included here to give a more comprehensive overview of possible effects and only about half of the studies represent species found in Swedish waters (see Table 1). Sound-detection abilities of marine invertebrates are mostly unknown, but the estimated hearing range for the commercial decapod species European lobster (*Homarus gammarus*; estimation based on the closely related American lobster (*H. americanus*)) and Norway lobster (*Nephrops norvegicus*) are 80-250 Hz (possibly up to 5000 Hz, as measured by Pye and Watson, 2004, using a different method) and 20-180 Hz, respectively and the blue mussel (*Mytilus edulis*) and Pacific oyster (Crassostrea gigas) are 10-1000 Hz and 30-1000 Hz, respectively. The effects identified include impacts on larvae settling and numerous other behavioural parameters, masking, morphological changes, reproductive disturbances and effects on development and growth as well as elevated stress response and temporary hearing loss. Generally, invertebrates seem to be affected by low frequency sounds, but effect thresholds are mostly unknown. Many invertebrates use sound cues to locate appropriate habitats to settle and ship noise has been shown to induce larvae settlement in a wide range of animals native to Swedish waters, including the bivalves blue mussel (M. edulis) and Pacific oyster (C. gigas), sea squirt (Ciona intestinalis) and polychaetae (Pomatoceros sp.), and in non-native bryozoans (Bugula neritina, Watersipora sps.) [McDonald et al 2014, Stanley et al 2014, Jolivet et al 2016]. Noise from ships and boats can also affect other types of behaviour in marine invertebrates. In a tank-based experiment, playback of ship noise at levels of 148 to 155 dB re 1 µPa did not impair the ability of shore crab (Carcinus maenas) to find food, but crabs that were feeding were more likely to stop feeding (Wale et al. 2013a). Besides disrupted foraging, shore crab exposed to ship noise also showed impaired antipredator behaviour, with longer time for shelter retreat at a simulated predator attack compared to those experiencing ambient noise playback (Wale et al., 2013a). Ship noise playback may also have a negative impact on behaviours that are important for the whole ecosystem, such as reduced filtration in blue mussels (M. edulis), reported at sound pressure levels of approximately 150 to 160 dB re 1 µPa [Wale et al 2019] and reduced bioturbation of sea sediment in Norway lobster (N. norvegicus) and in a non-native venous mussel (Ruditapes philippinarum) [Solan et al 2016].

6 Discussion

In the project SHIPNOISE we have developed a measurement station for both airborne and underwater noise from ships underway. The airborne noise levels indicate that there is a risk to exceed recommended indoor low-frequency noise limits for dwellings positioned up to several hundred meters from the passing ships. It is still unclear how to properly evaluate the effect to public health of low frequency noise from ships under way. More research is needed to determine limits for equivalent and maximum low-frequency noise levels, and a simple low-frequency noise level measure corresponding to the a-weighted SPL used for broad band noise sources would be useful for making simple evaluations.

The present report has also assessed the environmental impact of the underwater noise levels at the SHIPNOISE recording sites near Böttö and Lurö. Several types of impact have been shown to be likely. In order to gain further understanding of the environmental impact of underwater noise near Swedish waterways, several avenues for future research are of interest.

SHIPNOISE only characterized the noise at its two recording locations. With more recording sites and underwater noise propagation modelling, it would be possible to create underwater noise maps such as has been done eg in the BIAS and JOMOPANS projects. Then one would be able to judge the environmental impact of underwater noise in a large area. Underwater noise mapping in open sea areas is an established methodology, but in the coastal regions studied in SHIPNOISE, it is an area that requires more research in order to construct sufficiently accurate prediction methods that consider shallow and rapidly varying depths as well as the occurrence of islands and archipelagos. Accurate prediction of the environmental impact of underwater noise would also require more experiments; representative species would need to be subjected to relevant noise samples and the reactions observed. Such experiments would need to consider both short- and long-term effects, and also the natural variations in time of the noise near a shipping lane.

Ships are a dominant source of underwater noise, and there are models predicting the levels of noise emitted by a given ship based on its characteristics. However there is a lack of information on effective measures of decreasing the radiated underwater noise at the source. In the Silent@Sea project, the effect of the propulsion method on the radiated noise under water and in air is investigated using dedicated measurements. Such approaches promise more data in this area and more research of this type is needed in order to develop effective methods of decreasing ship underwater noise.

It would be possible to cross-compare tones found in airborne and underwater noise and identify sources. This would be an interesting avenue for future research.

The SHIPNOISE measurement station records noise continuously. Integrating an AIS receiver into the station would allow it to start recording when a ship approaches. This would offer considerable power and memory savings, permitting far longer data recording sessions.

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