Underwater acoustic signatures from recreational boats

Field measurement and guideline

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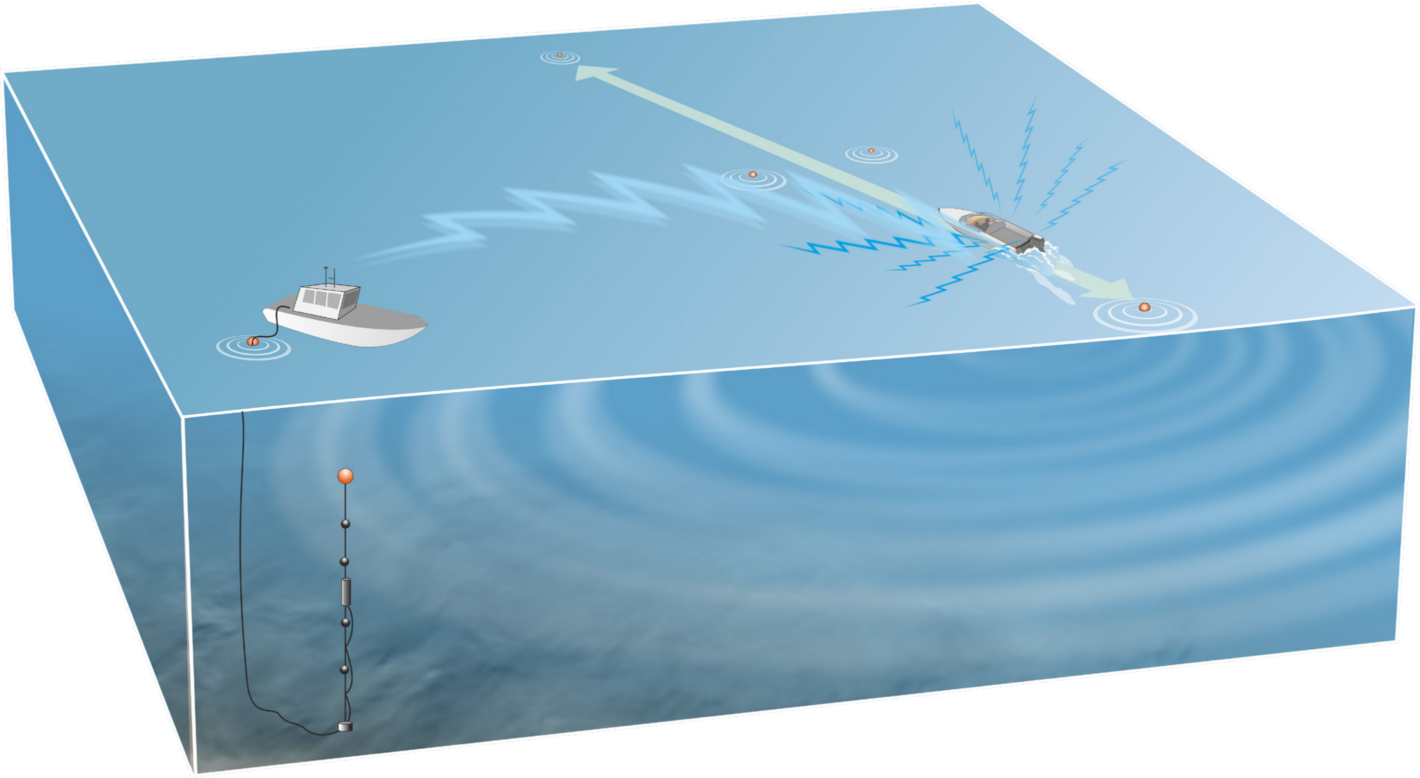

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Summary

The knowledge of the noise characteristics from recreational boats is scarce and there is little evidence to draw any conclusions on impact and recommend any measures. The first step to decrease this knowledge gap is to measure the underwater radiated noise (URN) from boats and calculate their source level.

This study aims to develop a methodology for source level estimations of recreational boats and test it in field trials, where the URN from three boats are recorded. Parameters such as speed, measurement depth, direction, distance and transmission loss estimations are varied, aiming to study their effect on the calculated source level. One field campaign was carried out in 2019 and one in 2020. By combining the boats' GPS position and a hydrophone system's sound data, successful measurements of the boats' URN and their source levels was estimated. The acoustic signatures of all boats showed clear tones, stemming from the engines' and propellers' rotational frequencies. The estimated source level error was about ±3 dB.

Finally, a measurement guideline was developed for the estimation of recreational boats' acoustic signature that can be used for comparison with published scientific studies, environmental impact studies and as input to source models.

Keywords: recreational boat, URN, acoustic signature, source level, measurement methodology.

Sammanfattning

Kunskapen om hur fritidsbåtar låter under vattnet är bristfällig och idag finns få studier för att dra några slutsatser om miljöpåverkan och ännu mindre för att rekommendera åtgärder. Det första steget för att minska denna kunskapslucka är att mäta deras utstrålade undervattensbuller (eng. underwater radiated noise, URN) och beräkna deras källnivå.

Denna studie syftar till att utveckla en metod för mätning av URN samt beräkning av källnivå från fritidsbåtar och att testa metoden i fältförsök där URN från tre båtar spelas in. Faktorer såsom hastighet, mätdjup, färdriktning, avstånd och skattningsmetoder för ljudutbredningsförluster varieras för att studera effekten på den beräknade källnivån. Två fältkampanjer utfördes: en under 2019 och en under 2020. Resultaten visar att genom att kombinera GPS-positionsdata för båtarna och inspelningar från hydrofonsystem kan framgångsrika mätningar av båtarnas URN uppnås. Källsignaturerna för alla båtar visade tydliga toner som härstammar från motorerna och propellerns rotationsfrekvenser och deras källnivå beräknas med ett uppskattat fel på ca ±3 dB i källnivå.

Slutligen utvecklas ett förslag på en mätguide för uppskattning av en akustisk signatur för fritidsbåtar som kan användas för jämförelse med vetenskapliga publicerade studier, miljökonsekvensstudier och som ingångsvärden för källmodeller.

Nyckelord: fritidsbåt, URN, akustisk signatur, källnivå, mätmetodik.

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1 Background

Underwater radiated noise (URN) from a recreational boat is generated by the rotation of the propeller and associated cavitation, the firing sequence of the engine(s), other moving parts of the propulsion system and the release of subsurface exhausts (Erbe et al., 2016; Matzner et al., 2010). The source level and frequency content of the URN define the acoustic signature, which depend on how the sound is generated, engine type (inboard and outboard), number of cylinders, propeller type and type of craft and its load (Erbe et al., 2016; Matzner et al., 2010). There are numerous variations and combinations of these parameters, making general conclusions of the acoustic signature a challenge (figure 1).

The large quantity of recreational boats in shallow water archipelagos has the potential to pollute sensitive biological areas with high levels of underwater noise, resulting in an environmental topic that urgently needs to be assessed (Moksnes et al., 2019). In contrast to commercial ships, the knowledge of noise characteristics from recreational boats is lacking and at present, there is little evidence to draw any firm conclusions on environmental impact and even less to recommend any measures.

The boat engine noise is commonly characterized by both broadband and narrowband (tonal) components below approximately 500 Hz, and mainly of tonal components above that frequency (Vieira et al., 2020). These tones have been shown to be speed dependent and related to the number of propeller blades, gear design, rounds per minute (RPM) and other engine characteristics (Matzner et al., 2010; Pollara et al., 2017). Propellers are known to produce amplitude modulated noise through cavitation mostly noted below 500 Hz (Pollara et al., 2017). The cavitation mainly depends on propeller design, speed and maintenance of the propeller. A damaged propeller can induce more cavitation than an undamaged one.

Vessels with water jets, such as a jet ski, have an impeller inside the hull instead of a propeller. This propulsion can create tones similar to a propeller, but might generate lower noise levels since it is enclosed (Erbe, 2013). However, more measurements are needed to verify the sound character in vessels with water jets, including jet skis, to conclude that they are less noisy than a propeller.

Electric motors are considered quieter underwater than gasoline and diesel engines, but at the time of writing there were no published studies of URN from recreational boats with electric motors. However, for larger commercial vessels, there are measurement showing electrical ships being less noisy than conventional ships (Parsons et al., 2020).

Figure 1. Two common type of recreational boats, left: a day cruiser with in inboard engine and right: a rib with outboard engine.

The speed and driving style with which the boat is driven has a large impact on how much noise a recreational boat generates. Lower speed and a more straight course generally results in lower noise levels in the sea (Matzner et al., 2010). At lower speed, however, the boat stays in the area for longer time, leading to prolonged elevation of noise levels in the area. In addition, most boats are optimized for higher speeds than e.g. 5 kn which is common speed limit close to harbours and shallow waters. If a boat is driven in a non-optimal speed, the radiated noise might potentially be higher.

1.1 Available standards for signature estimation

The starting point for understanding the underwater noise from recreational boats is to determine the URN in a standardized way. Currently, no such measurement standard exist for recreational boats. There are several different standards and notations, on measurement of the URN from commercial ships, e.g. (ANSI, 2009; Bureau Veritas, 2014; Det Norske Veritas AS, 2011; ISO, 2012). These standards and notations are used to classify a ship as silent in various categories depending on ship class. The standards have different kind of grades, representing different levels of accuracy in terms of estimated source level.

However, none of these standards or notations applies to recreational boats. These vessels are smaller and have less powerful engines, which most likely will result in lower source levels, and it is challenging to follow the standards and class notations measurement geometry. For example, many standards limit the measurement distance to a few hundred meters, which could decrease the signal-to-noise ratio of the measurement of a more silent, smaller, recreational boat. With a shorter measurement distances, the overall geometry of the measurement track will be affected, as well as the post-processing of data, as some standards divide the measurement into time segments corresponding to a certain distance covered by the boat. The measurements in this study were performed in partial compliance with the shallow water ship underwater radiated noise measurement standards of Bureau Veritas (Bureau Veritas, 2014), as well as with some inspiration of the above mentioned standards and notations. Deviations in the measurement setup in terms of measurement depth, distance and boat speed, which are varied in this study, were introduced to determine a suitable way to measure URN from small vessels in shallow water.

1.1.1 Level of uncertainty

In all above referenced methodologies for the estimation of a vessels URN, there are uncertainty at different levels related to the measurements, equipment and signal processing. The level of uncertainties in an URN estimation can be divided into different grades. The American National Standards Institute, Inc. (ANSI) offers three grades of measurement, each with a stated applicability, test methodology, system uncertainty and repeatability of the measurement. These grades are denoted A, B and C (table 1). The grades have different requirements on the hydrophone system, ranging accuracy, minimum number of runs per vessel and transmission loss estimation methodology. The transmission loss estimation can range from acoustic modelling to simple laws e.g. 18 $\log_{10}(R)$ (ANSI, 2009).

Table 1. Overview of the ANSI grades and uncertainties. Adapted from (ANSI, 2009).

Grade	**A**	**B**	**C**
Grade name	Precision method	Engineering method	Survey method
Measurement uncertainty	1.5 dB	3.0 dB	4.0 dB
Measurement repeatability	± 1.0 dB	± 2.0 dB	± 3.0 dB

1.1.2 Underwater noise class

For recreational boats, a separation into different noise classes based on boat type size or other parameters should be developed in order to make a relevant comparison between boats.

For commercial ships, the first silent noise class was published by International Council for the Exploration of the Sea (ICES) in 1995 for research vessels performing acoustical surveys to get comparable estimations of fish stocks (Mitson, 1995).

Since then, several classification societies have published different notation classes for a vessel fulfilling the requirements of a silent class. These classes are often separated depending on vessel type, e.g. cargo, tanker, which have different thresholds. American

Bureau of Shipping (ABS) divide the underwater noise notation (UWN) classes into below sub categories (American Bureau of Shipping, 2018).

UWN T	Underwater noise criteria for Transit condition.
UWN Q	Underwater noise criteria for Quiet Operation condition.
UWN R	Underwater noise criteria for Research Vessels.

Den Norske Veritas (DNV) has slightly different classes and a vessel has a combination of qualifiers, e.g. SILENT-AE denotes an underwater noise class for acoustical operations as well as having a controlled environmental noise emission (Det Norske Veritas AS, 2011). Below is a list of available classes from DNV.

SILENT-A	Vessel using hydro-acoustic equipment.
SILENT-S	Vessel engaged in seismic research activities.
SILENT-F	Vessel performing fishery activity.
SILENT-R	Vessel engaged in research or other noise critical operations.
SILENT-E	Any vessel wanting to demonstrate a controlled environmental noise emission.

1.2 Aims

The study has four overall aims:

1. Develop a methodology for acoustic signature estimation of recreational boats based on existing standards for commercial ships.
2. Test of the methodology in field trials where the URN from three boats are recorded.
3. Study the effect of speed, measurement depth, direction, distance and transmission loss estimations on the acoustic signature.
4. Develop a measurement guideline for the acoustic signature estimation for recreational boats which shall be based on the above input from 1-3.

2 Measurement setup and signal processing

The design of the measurement track and test procedure were modified from the previously mentioned notation societies and standards, see section 1.1. The standard that had the most impact on the methodology developed in this study was the shallow water ship URN measurement standards of Bureau Veritas grade B1 (Bureau Veritas, 2014).

Two measurement campaigns where carried out with the purpose of estimating the acoustic signature from recreational boats. These campaigns were conducted one day in December 2019 and two days in June 2020. In total, three boats were studied at varying vessel speed, direction of motion and distance to the hydrophone system. On the receiver end, the hydrophone system used included four hydrophones at different depths.

2.1 Trial site

The trial site Djupviken is located in the southern part of Stockholm archipelago in eastern Sweden (figure 2). The area is a shallow water bay (< 50 m depth), with muddy sediments and in general a flat topography in the middle of the bay. The area is generally unaffected by maritime traffic resulting in a low level of ambient noise.

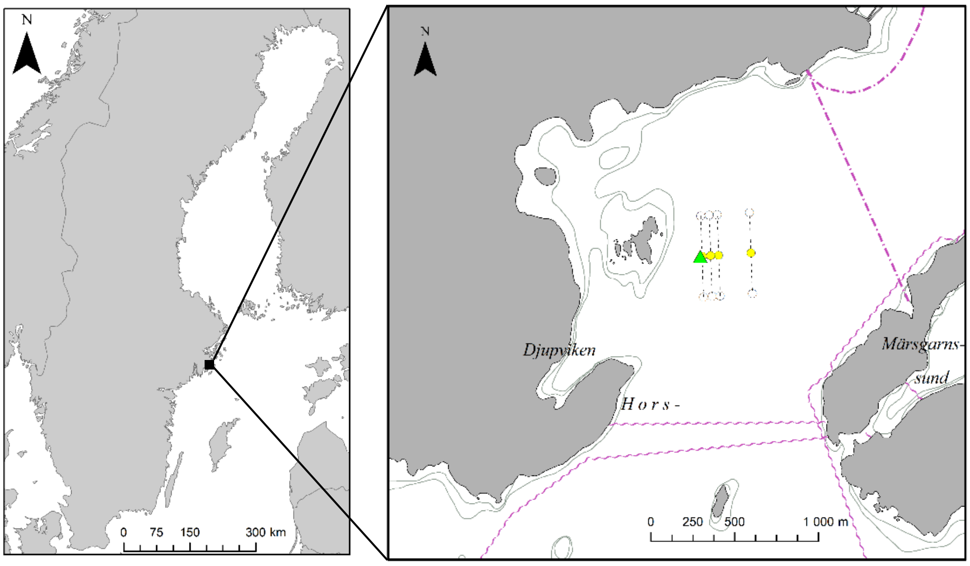

Figure 2. Left: Map of Sweden. Right: The location of the test site Djupviken with the test track marked.

2.2 Instrumentation

Salinity, temperature and sound speed in the water column were measured three times each day with a Sound Speed Profiler, SWiFT SVP, from Valeport.

URN from a selected boat was measured with a four-channel instrument, an RTsys, SDA014, deployed at 32 m depth. The system had four hydrophones located at different depths creating a vertical line array (table 2 and figure 3). The array of hydrophones was mounted on a vertical rig with a bottom weight of 20 kg at 30 m depth and a subsurface buoy at 5 m depth in order to keep the array vertical as well as minimizing the influence from surface waves. The RTsys was powered by internal batteries and a 100 m LAN cable connected the system to a computer in the measurement platform, an anchored boat, in order to control the system. Data were recorded with a sampling speed of 78 125 Hz, 24-bit, and stored internally on a SD card and a hard drive. Data was downloaded to a computer at regular intervals to check the ambient noise levels and to assure that the signal to noise ratio was not too low, during the boat's passages.

Table 2. Hydrophone specifications for the RTsys system.

Channel	Hydrophone brand	Sensitivity	Water depth
A	Reson TC4032	-164 dB re 1 V/µPa, 15 dB gain	25.5 m
B	HTI-96-MIN	-164 dB re 1 V/µPa, 15 dB gain	8.3 m
C	HTI-96-MIN	-164 dB re 1 V/µPa, 15 dB gain	19.7 m
D	CO.L.MAR GP090	-174 dB re 1V/µPa, 1 dB gain	13.3 m

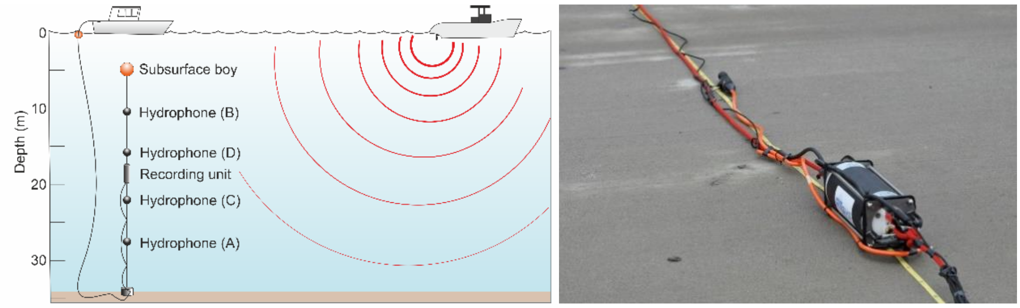

Figure 3. Left: Drawing of the RTSys array setup and suspension in the water. There was a 100 m cable connecting the array to the measurement platform. Right: The RTsys array and system on land before deployment. The data-recording unit is seen to the right and one of the four hydrophones at the top.

Pressure pulses and noise from the Eelex 8000 was measured in one pressure sensor mounted directly above the propeller (figure 4). The pressure sensor was a PCB Piezotronics, Model 112M336 flush mounted sensor. A NI9234 CompactDAQ data logger from National instruments with a sampling speed of 51 200 Hz was used. The bandwidth was 23 kHz and the resolution 24-bit. This work where carried out by Kongsberg and more details are found in their report (Kämpeskog and Wenneberg, 2020).

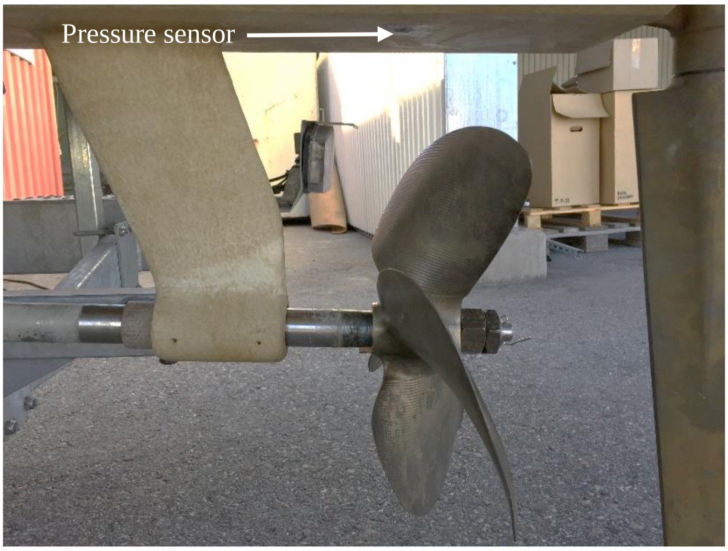

Figure 4. Pressure sensor in the hull of Eelex 8000 above the propeller, see white arrow.
Photo © Kongsberg.

2.2.1 Transmission loss estimation

Transmission loss for the trial area was estimated by undertaking transmission loss measurement employing acoustic pulses transmitted at a number of locations in the vicinity to the boat tracks. The receiving equipment was the same as during the URN measurements. The measurements were performed using a workboat, Targa 23, which was set drifting with the current across the boat tracks while a handheld GPS receiver continuously recorded the positions for each transmission. The transmitter, of type LL-1424HP, was suspended from a boat at a depth of 5 m. In addition, an active reference hydrophone of type Neptune D/70/H was positioned at the same depth and 6 m horizontal distance from the transmitter. The complete reference hydrophone system was calibrated a priori down to 100 Hz.

Linear frequency modulated pulses, spanning 100 Hz to 12 kHz, were used during the transmission loss measurements. By match-filtering the received signal with appropriate segments of the emitted signal, the sound pressure level in a given frequency band was obtained. Under the assumption of spherical spreading from the source to the reference hydrophone, the source level was estimated. Finally, combined with data from the RTsys, the transmission loss in the specified frequency bands was then obtained.

2.3 Trial procedure

Several surface buoys were used to mark the closest point of approach (CPA) to the sensors, indicating the distances 10, 50, 100 and 300 m (figure 5). These distances were selected based on the measurement geometry found the in the standards from commercial ships, but the 10 and 50 m distance was added due to the smaller size of the recreational boats in this study.

The start and end of the track were marked with virtual waypoints in a GPS receiver in order for the boat to keep a straight course. Each track ran in parallel to each other and with the CPA to the RTsys position in the centre of the track. The length of the track was 500 meters where the water depth varied between 30-40 m.

One run was quantified as a completed passage at a fixed speed between the virtual waypoints marking the start and end, passing the CPA buoys. The boats performed several runs for the speeds 5, 10 and 20 knots. On occasion, a run was repeated when other vessels passed the area, increasing the ambient noise above background level and as a result disturbing the recordings.

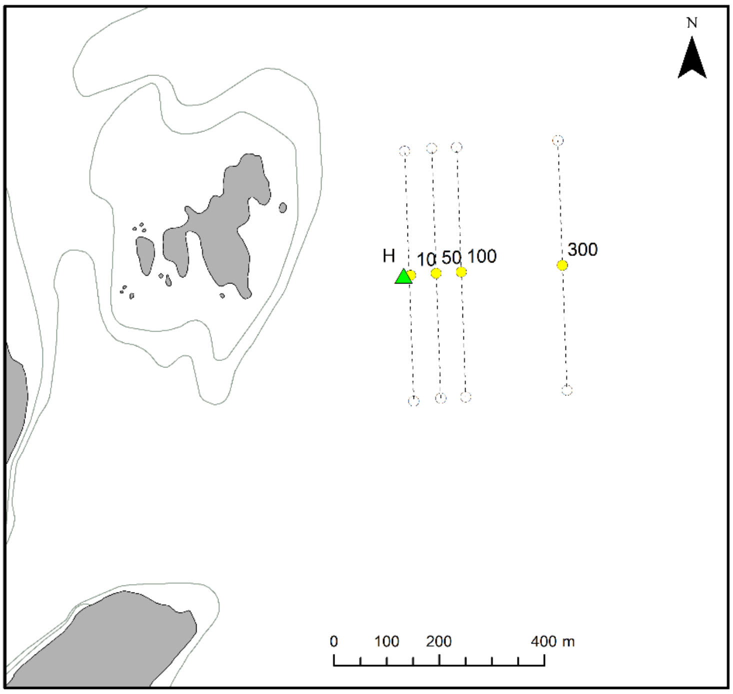

Figure 5. Overview of the measurement's tracks at the test site with the hydrophone location (green triangle), CPA buoys (yellow circles) at different distance to the hydrophone and end way points for the 500 m test track (open circles).

Three different kinds of boats were used in this trial ranging from an open boat with a 4-stroke outboard engine, Örnvik 540, a day cruiser with in inboard diesel engine, Targa 23, and finally a day cruiser with an electric inboard engine, Eelex 8000 built 2019. The Eelex 8000 was a prototype with an experimental hull and propeller (table 3, figure 6). The boats was of different age and built 1988, 1997 and 2019, respectively.

Table 3. Overview of the test boats and their technical specifications.

Boat type	**Length (m)**	**Draught (m)**	**Weight (kg)**	**Fuel**	**Engine type**	**Engine power (hp/kW)**	**Propulsion**
Örnvik 540	5.4	0.4	300+108 (engine)	Petrol	Outboard, Yamaha, 4 cylinders (Year 1999)	50 hp/ 37 kW	Single prop, 4 blades
Targa 23	7.6	0.9	2300	Diesel	Inboard, Volvo Penta AD31P-A, 6 cylinders	150 hp/ 110 kW	Duo prop, 3+4 blades
Eelex 8000	8	0.8	2600	Electric	Inboard, electric	300 hp/ 225 kW	Single prop, 4 blades

Figure 6. Boats participating in the trial from left: Örnvik 540, Targa 23 and Eelex 8000.

2.4 Signal processing

In this work, the signals from the hydrophones were processed in several sequential steps, based on the guidelines from Bureau Veritas (Bureau Veritas, 2014), but with some adjustments to better fit the recreational boat measurements. The guidelines treats the boat under study as an omnidirectional source, that is, the sound pressure levels measured in different directions from the boat are treated equally and averaged to form the final acoustic signature of the boat. The signal processing steps can be summarized as follows:

1. Combine GPS and hydrophone data.
2. Divide each run into 19 dataset time segments.
3. Calculate 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 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).

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

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

2. Each run was divided into 19 time segments, centred on a given set of angles between the boat and the hydrophone system. The set of angles was given in steps of 5°, depending on angle of the boat facing the hydrophone, from 45° to 135° or from -45° to -135°, as exemplified in figure 7. In order for the time segments to contain a certain amount of data, the time segments correspond to 50 m long distances.

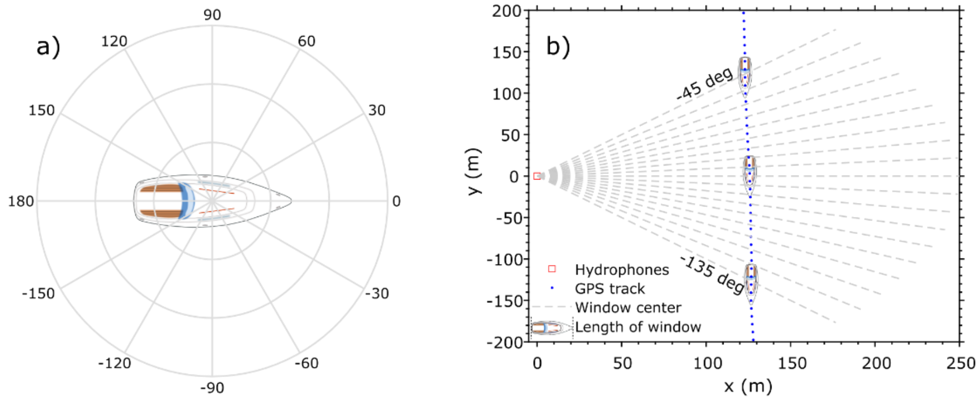

Figure 7. The boat angle and data window definitions. a) The boat angle is defined from the source centre to the hydrophone(s) and, therefore, b) varies as the boat passes through the measurement area. In this case, a southbound route yields negative angles, while a northbound route results in positive angles. The centre of each data window is given by the angles ±45° to ±135° in 5° steps and the width is 50 m, as indicated by the boat cartoon length.

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

4. For 1/3 octave band analysis, the narrow band spectrum was converted into 1/3 octave bands by taking the mean narrow band value in each band. Note, that this procedure is different from a natural conversion into 1/3 octave bands, as there is no correction for the bandwidth of the 1/3 octave bands.

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 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 $TL = A \cdot log_{10}(R)$ formula was used.

7. After the transmission loss correction, all time segments were averaged in the linear domain to create a single spectrum for the run. This averaging method is recommended by Bureau Veritas and treats the boats as omnidirectional sources instead of focusing on the maximum levels radiated in a specific angle. For example, the sound pressure spectral density level measured by hydrophone *h*, is $L_h = 10 \cdot log_{10} \frac{\sum_t 10^{L_t/10}}{n_t}$, where $L_t$and n_t are the sound pressure spectral density level of time segment *t*, and the number of time segments, respectively.

8. If several hydrophone channels were used, the spectra from each hydrophone was combined and averaged in the linear domain. As described above, this implies $L_r = 10 \cdot log_{10} \frac{\sum_t 10^{L_h/10}}{n_h}$, where n_h is the number of used hydrophones.

9. If several runs were made with equivalent running conditions (route, speed etc.), the runs were averaged in the linear domain to create a single spectrum for the boat. For clarity, the spectrum is $L_b = 10 \cdot log_{10} \frac{\sum_t 10^{L_r/10}}{n_r}$, where n_r is the number of runs.

3 Results and discussion

In this section, the results of the two measurement campaigns are presented using the post-processing steps in section 2.5. With the aim to produce a measurement guideline, various factors that may influence the measured noise levels are presented and analysed. The analysis sections include both general and experimental examples providing a basis for the guideline. When the findings of this study has led to a certain recommendation related to the proposed measurement guideline, see section 4, this is written in a text box in this chapter. Finally, recreational boat acoustic signatures are presented at two speeds, including both narrow band and 1/3 octave band spectra. The boat acoustic signatures are compared and discussed.

3.1 Sound speed profile

The sound speed profile of the first measurement campaign 2019-12-04 was almost constant, varying from 1434 m/s at the surface to 1436 m/s at the bottom (figure 8). During the second campaign 2020-06-24, the situation was different, with a clear thermocline in the profile at 17-20 m depth and a much larger variation of speed spanning from 1440-1490 m/s. Transmission loss measurements, as described in sections 2.2.4 and 3.2.3, were conducted on 2020-06-23, with similar characteristics in the sound speed profile as during the measurement campaign conducted on 2020-06-24.

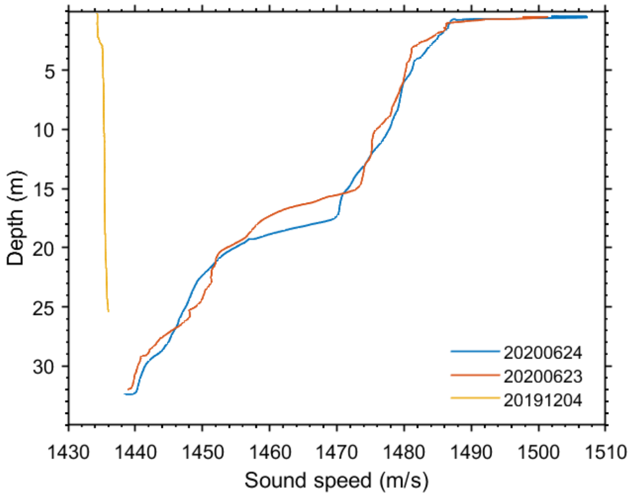

Figure 8. Sound speed profiles for the measurement campaigns 2020-06-24 and 2019-12-04, as well as during the transmission loss measurements 2020-06-23.

3.2 Factors influencing estimated source levels

Measurement parameters that could influence the estimated source levels include the distance between the boat and the hydrophones, the boat speed, portside/starboard facing the hydrophones or other directional effects, the depth and location of the hydrophones, the transmission loss estimation, and the boat GPS location precision.

3.2.1 Measurement depth

The depth position of the hydrophone(s) could lead to a relative change in the measured sound pressure levels, but could also make the channels more or less sensitive to other sources. For example, figure 9a shows the sound pressure spectral density level for a boat run with a CPA ~20 m. However, the measured total levels vary with as much as 4 dB, with tonal components varying up to 7 dB. One reason for this difference could be the sound speed profile, shown in figure 9b, where the sound speed is causing refraction towards the bottom. The deepest positioned hydrophone channels also show higher sound pressure levels.

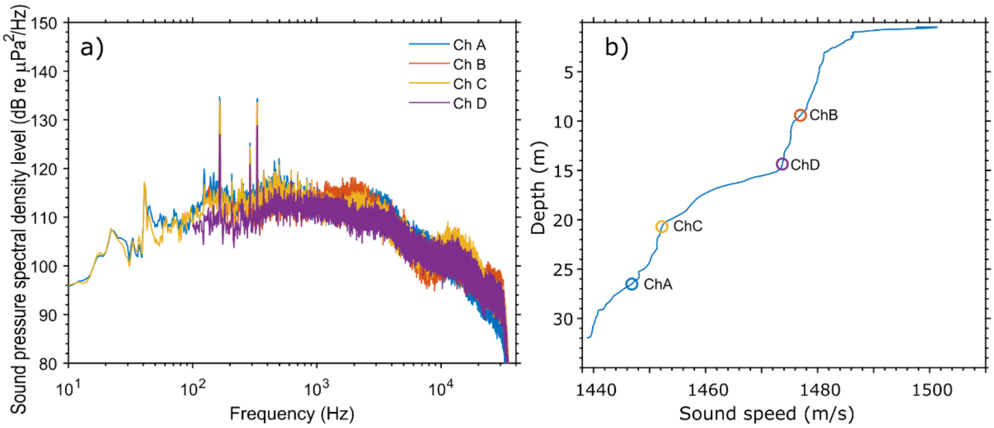

Figure 9. Hydrophone position and the dependence of depth. a) Sound pressure spectral density level from four hydrophone channels. b) The sound speed profile as a function of water depth. The depth of the hydrophone channels in a) are indicated with their respective coloured circle.

During the measurement campaigns, it was noted, that a hydrophone closer to the water surface will possibly be more influenced by the measurement platform, reflections from floating buoys, waves and other sound sources located near the surface (figure 10). For a hydrophone located near the seabed other effects can influence the result. It is therefore a good practice not to be closer than 1 m from the seabed (Gassmann et al., 2017; ITTC, 2017; Jensen et al., 2011).

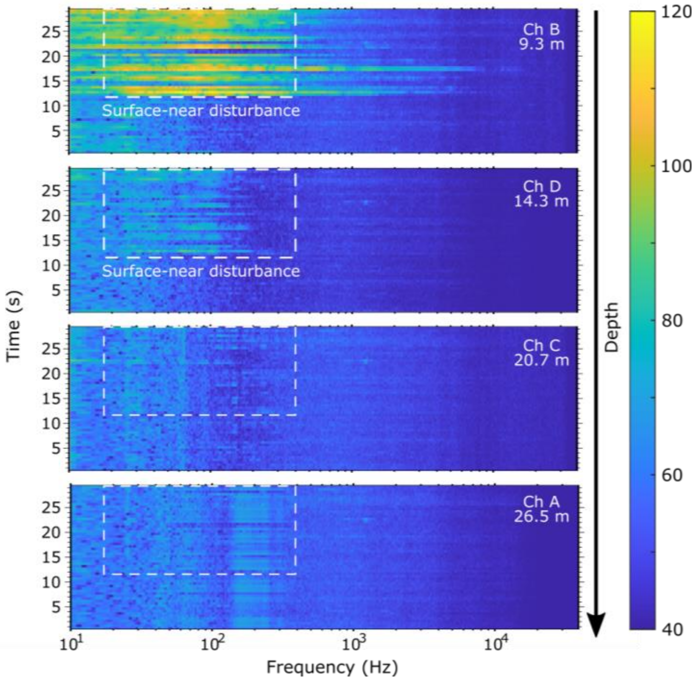

Figure 10. Time/frequency diagrams of four hydrophones arranged from top to bottom with the top diagram being the closest hydrophone to the water surface. The white square indicates a disturbance, coming from somewhere close to the water surface. The disturbance is clear in the two top-most diagrams, but much less pronounced in the two bottom channels. Locations of the channels are the same as in figure 9b.

We recommend that the hydrophone(s) should be positioned in the bottom half of the water column in order to avoid disturbances associated with the sea surface, provided that the sound energy is not significantly directed to another depth layer by the sound speed profile. The sound speed profile should always be consulted.

3.2.2 Boat speed

The boat speed is a parameter that effects the source level. As the speed increases, cavitation may occur at or near the boat propeller leading to increased source levels. A naïve assumption may be that increased boat speed directly leads to increased source levels. However, the noise from the propeller depends largely on the propeller design and condition. For example, figure 11 shows the sound pressure spectrum levels for three speeds with the same boat, all measured at a similar distance. Surprisingly, the boat Eelex 8000 in this example, is producing most noise at around 10 kn. High-speed camera measurements of the propeller revealed that the cavitation was the largest at this speed, as the propeller was designed for speeds above 20 kn (Kämpeskog and Wenneberg, 2020).

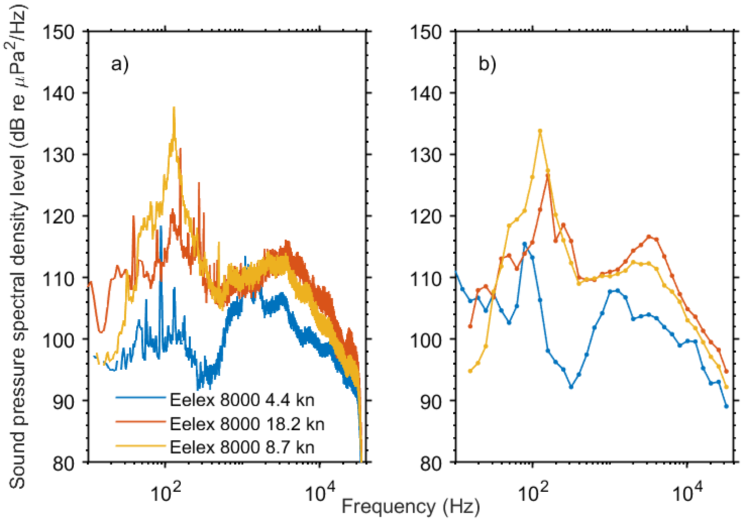

Figure 11. Boat speed influence on the measured sound pressure spectral density level. a) Narrow band and b) 1/3 octave band spectra for Eelex 8000 runs at 4.4, 8.7 and 18.2 kn.

> *We recommend that at least two boat speeds should be studied, to cover both conditions with and without propeller cavitation.*

3.2.3 Transmission loss estimation

One of the largest sources of error in source level measurements is the TL of acoustic waves travelling from the source to the receiver. One of the best practices is to measure TL with calibrated sources and receivers. This is, for practical reasons, not always possible. A second approach is to use the boats under investigation to measure and retrieve information on the transmission loss. Another alternative is to numerically model TL based on known parameters of the bottom layer(s) and sound speed profile. Often, the same measurement location is used repeatedly, and knowledge of the expected TL can be gained with time.

Each of the classification society's guidelines for noise measurements of larger vessels have a slightly different approach to handle the estimation of TL, as seen in table 4.

Table 4. TL-estimation methods for different classification guidelines.

Society classification	Det Norske Veritas Silent-E	Bureau Veritas URN	American Bureau of Shipping UWN	Rigistro Italiano Navale Dolphin	Lloyd's Registers ShipRight
TL-estimation method	$18log_{10}(R)$	Acoustic modelling methods	$20\log_{10}(\mathrm{R})$	$20\log_{10}(\mathrm{R})$	Measured or modelled TL in shallow waters and $20\log_{10}(R)$ in deep water

In short, there are different approaches, each with different pros and cons in terms of time, resources and accuracy. A measurement will always contain some level of error or uncertainty, but the results may still describe the actual situation better compared to modelling efforts that use some more or less known inputs for the final TL estimation. Building knowledge about the measurement area is important, but the underwater acoustic environment can none the less change with time.

Based on experiences in shallow water in the Baltic Sea, made by FOI, a good estimate for these conditions is $TL = 17 \cdot log_{10}(R)$, which could be used if none of the above methods are applicable (Johansson and Andersson, 2012). However, this might introduce an error and should be noted in the measurement report.

Since modelling TL was not applicable during these measurements, TL measurements was conducted based on two methods: 1. using a known source (sonar) to generate sound at different positions and distances from the receiving hydrophones and 2. to use the boat runs themselves as a source.

1. TL can be measured by drifting through the measurement area with a known calibrated source (as described in section 2.2.3), which creates known sound levels that are measured by the hydrophone(s). The difference between source levels and received levels are then used to estimate TL using GPS location data (figure 12). Only data in the far field regime of the reference hydrophone was evaluated, resulting in a conservative limit of measured data to frequencies above ~500 Hz. Considering all the data points, the average A estimate was 19.8±1.8, 18.4±3.7, 20.0±2.2 and 18.1±3.2 for channels A-D, respectively.
2. TL-formulas can also be fitted to measurements of the boats during the noise measurement campaign of the recreational boats. This approach is more uncertain, as the directivity and stability of the source is unknown, but the approach is efficient in time and resources. If similar measurement tracks are used during the measurement campaign, the runs can be treated individually and then combined to increase the precision of the track TL estimate (figure 13). Different tracks, at different CPA, can yield different TL estimates depending on the bottom layers, water depth and sound speed profile. In the specific case illustrated in figure 13, a simple $TL = A \cdot log_{10}(R)$ formula was used to fit *A*. The parameter A was found to increase with distance for the four characteristic tracks with CPA 20, 70, 100 and 300 m. Note that the results are vastly different from the measured TL in figure 12, which may be due to the nature of the source. The boat is a broadband source and have an unknown three dimensional directivity. It is possible that tracks with small CPA detect noise that is not detectable at larger distances. Along those lines, it may very well be the data shown in figure 13 is not a true TL estimation, but rather an indication of the directivity of the boat itself.

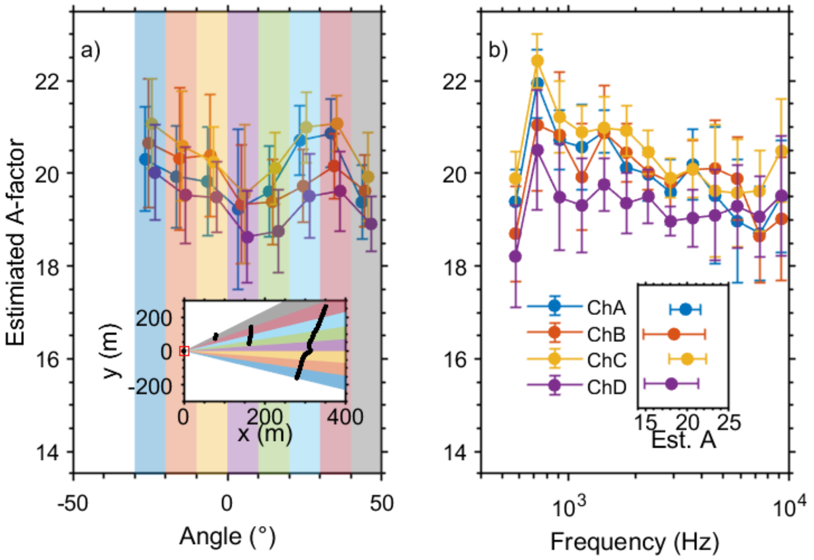

Figure 12. Direct measurement of TL. Using a known source, the transmission loss in a) an angle range and b) 1/3 octave bands is calculated and fitted to a $TL = A \cdot log_{10}(R)$-formula. The colours of the colour-shaded areas in a) correspond to different angle ranges indicated in the inset, where the position of the source throughout the measurement campaign (black) with respect to the hydrophones (red square) define the angle. The inset in b) shows the average A estimation for the four hydrophone channels, for all source positions and including 1/3 octave bands above 500 Hz.

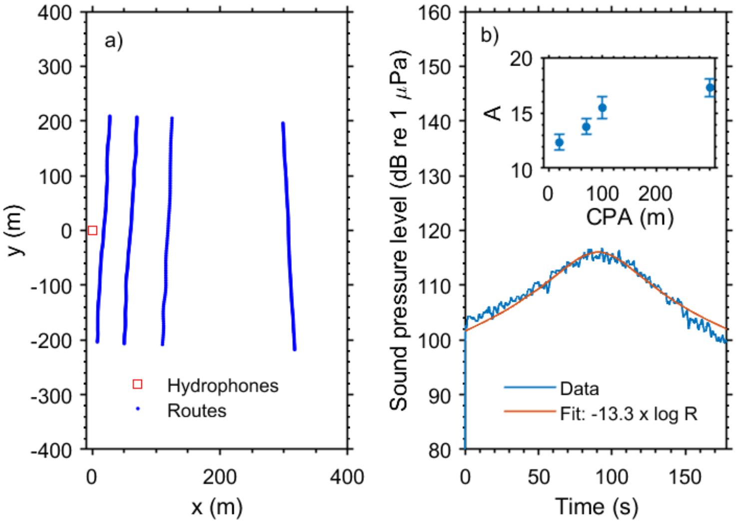

Figure 13. CPA dependent TL model measurement. a) Several runs were conducted at different CPA and b) the sound pressure level measured from the hydrophones was fitted to a $TL = A \cdot log_{10}(R)$ formula, illustrated here with channel A data. The inset in b) shows the average values of A, as retrieved from 26 runs for channel A. The error bars correspond to the data included in the analysis only.

As can be seen in figure 14, the distance dependent TL-estimates based on the measurement tracks perform rather well over-all, but in some frequency bands it results in 2-4 dB separation of the signatures from tracks at small and large CPA. Around 20 Hz there is a clear tone in the 310 m CPA data, which is more smeared out in the 120 m CPA case, yielding ~8 dB difference, likely due to other factors than the transmission loss compensation. The TL-estimates based on a known source were performed one day before the boat measurements and showed a relatively small distance variation in the fitted TL-estimation. The estimates based on a known source varied ±0.8 dB, compared to ±2.5 dB for the measurements based on boat routes. As a conclusion in line with these results, it is important to conduct routes with different CPA to verify the TL model used.

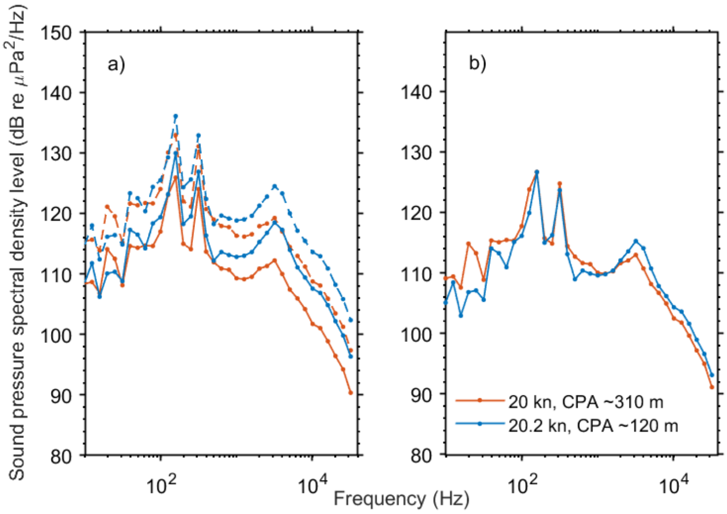

Figure 14. Example of TL-implementations. Two runs at similar speeds, but at a CPA of 310 and 120 m are compared using a) a flat TL = 19.8 log R and TL = 17 log R formula used throughout the measurement area and b) a distance varying TL model, as described in figure 13.

As mentioned above, the background knowledge of the shallow water measurements are in line with a $TL = 17 \cdot log_{10}(R)$ correction. As shown in figure 14a, it performs reasonably well compared to measurements with a known source. Knowledge of the measurement area is thus beneficial when it comes to these types of measurements.

We recommend that the transmission loss (TL) is estimated using the following prioritized order:

1. *TL measurement.*
2. *TL modelling.*
3. *Based on previous knowledge of TL in the area.*
4. *Using* $TL = 17 \cdot log_{10}(R)$.

3.2.4 Distance and GPS precision

As implicated above and in figure 15, the sound wave decreases in amplitude further from the source, resulting in negligible (relative to the background) sound levels far from the source. It is therefore important to be certain that the signal-to-background level is large enough for the measurement to be successful. For example, the measurements at CPA = 300 m were, on average, 4.5 times more likely to have data points below the background level as compared with CPA = 100 m measurements.

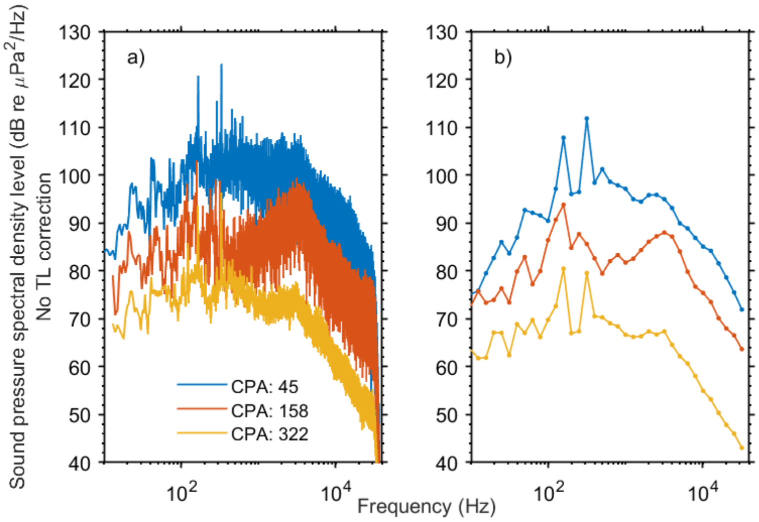

Figure 15. The effect of distance between the hydrophones and the boat on the measured sound pressure spectral density level. a) Narrow band and b) 1/3 octave band spectra of the Eelex 8000 boat running at approximately 20 kn at different distances. Note that the boat had slightly different engine rpm for the three spectra shown here.

However, there are several factors that come into play when selecting at what distance to undertake the URN measurement. As discussed in section 3.1.3, when TL is not very well known, the estimated source level error becomes larger the further away we measure (see figure 16).

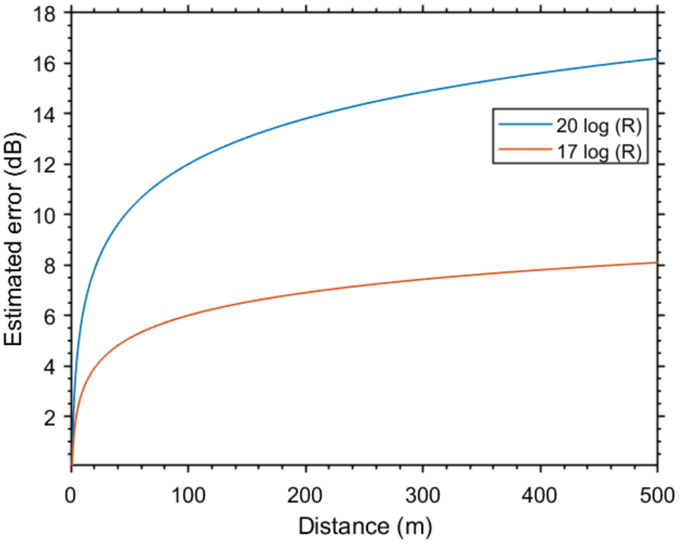

Figure 16. Transmission loss error as a function of distance for $TL = A \cdot log_{10}(R)$, where *R* is the distance, and *A* is set to 14, but *A* = 20 or 17 is assumed.

Finally, the GPS precision may influence the position error. Generally, today's GPS transceivers have a precision of a few meters. Such errors will have a larger impact at close range. At 100 m distance, the effect is significantly smaller compared to the TL-error estimates, as shown in figure 17.

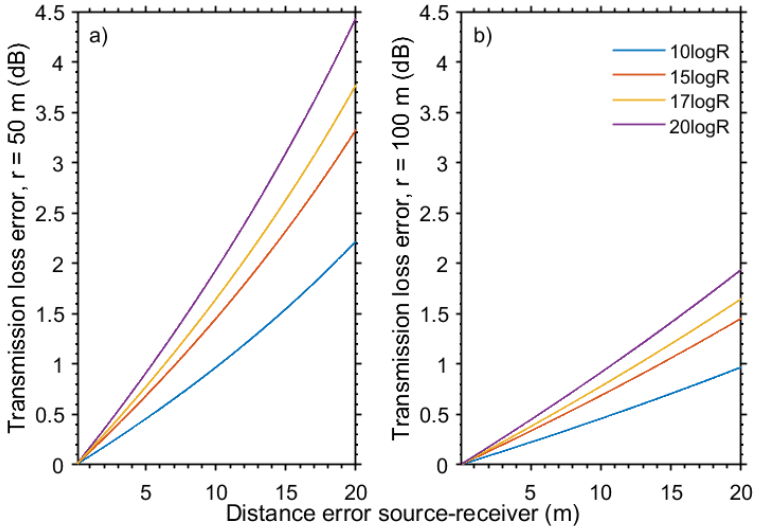

Figure 17. Transmission loss error depending on erroneous range data at different actual range as function of A, in $TL = A \cdot log_{10}(R)$.

We recommend that the boats CPA is more than 100 m and less than 300 m from the hydrophone(s), to balance the possible TL-estimate errors, GPS-position errors and signal-to-background levels for less noisy boats. At least two runs with different CPA should be conducted if possible.

3.2.5 Starboard/portside runs and directivity

Depending on the design of the hull and propeller(s), the boat constitutes a directional source. For a complete coverage of angles between the hydrophone and the boat, it is important to include both starboard and portside runs (figure 18). Capturing directivity in a measurement implies that the runs should be long enough such that a large boat-to-hydrophone angle is both obtained and measured accurately.

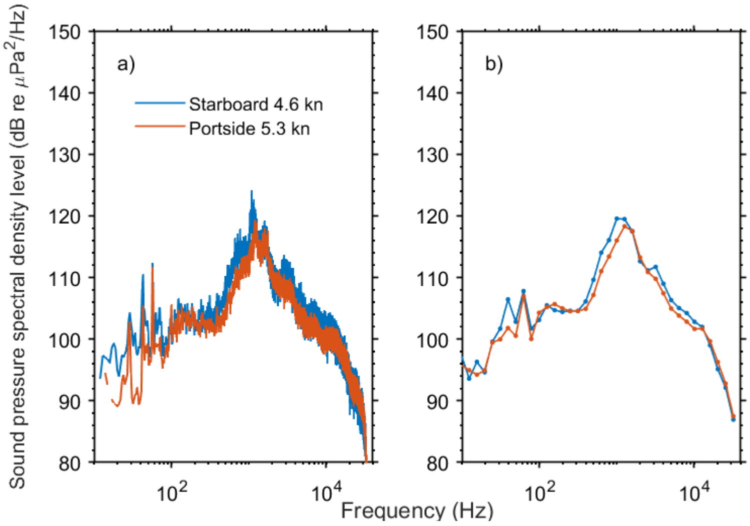

Figure 18. Starboard/portside passage and the influence on the measured sound pressure spectral density level. a) Narrow band and b) 1/3 octave band of two passages in different directions, with either starboard or portside facing the hydrophones.

In other words, the boat should not be too far from the hydrophones both due to signal-to-background limitations, but also in order to maintain feasible run times. A 500 m long track results in a maximum distance of 270 m to the hydrophones and about ±70° in angle for 100 m CPA. Increasing the covered angles to ±80°, would be equivalent to 1200 m long tracks, that is, more than double the distance for a limited amount of data.

From the directivity in figure 19, the sound pressure levels seem to drop at angles far from the CPA located at ±90°. The data suggest that the main angles to take into account indeed are within the ± (45°-135°)-range.

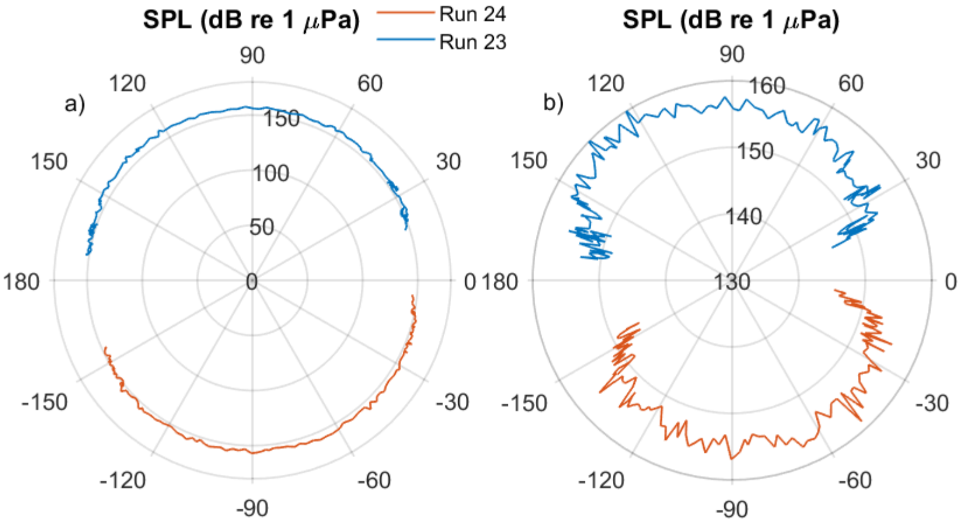

Figure 19. Directivity of Eelex 8000, with the origin at a) 0 dB and b) 130 dB. See figure 7 for angle definition.

We recommend both portside and starboard side runs and that runs are sufficiently long to cover angles ±70° between the boats and the hydrophone(s).

3.3 Boat signatures

In this section, the noise level signatures are presented for the three recreational boats Örnvik 540, Targa 23 and Eelex 8000. In line with the post-processing in section 2.5 we perform both narrow band (bandwidth 1 Hz) and 1/3 octave band analysis. However, the 1/3 octave bands spectra are merely a representation of the mean narrow band noise levels of the specific band, not to confuse with a regular 1/3 octave band spectrum. Therefore, both the narrow band and the broadband spectra have the unit dB re 1 $\mu Pa^2/Hz$.

3.3.1 Örnvik 540

Örnvik 540 showed interesting characteristics as it was louder running at 5 kn compared to 20 kn, in the 62-125 Hz range (figure 20). However, from 125 Hz and upwards, the 20 kn speed showed a higher noise level, likely due to an increased cavitation.

The main tones at 5 kn speed correlates well with the engine rpm, which measured about 32-33 Hz. Overtones 2, 3, 6, 8, 10, and so on, times the engine rotational frequency are clearly visible in the spectra. With a documented downshift rate of 2.33, several propeller frequency overtones are also visible. For the 20 kn case, the engine was running at around 90 Hz, with the first tones showing up at 38 (90/2.33 Hz) and 44 Hz (cylinder firing), with a multitude of overtones of these frequencies showing up for several hundred Hz. Additionally, there is a distinct tone at 2105 Hz, about 24 times the engine rpm.

The 1/3 octave band spectra in tabulated form are shown in table 6 in the Appendix.

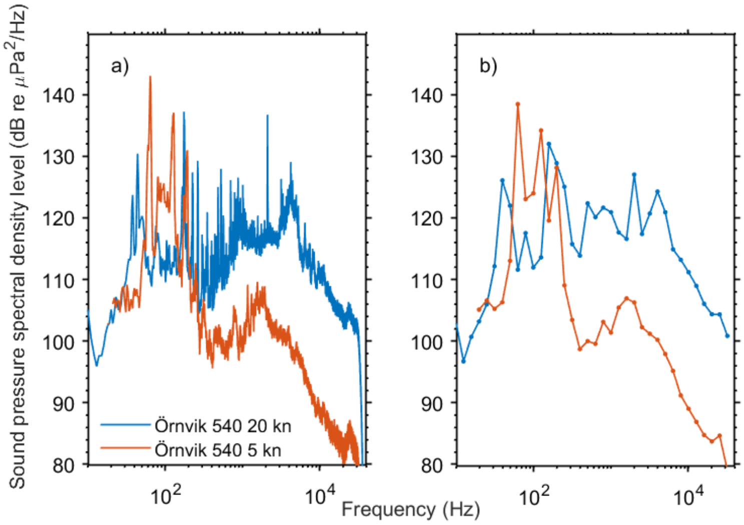

Figure 20. Sound pressure spectral density level from boat Örnvik 540. a) Narrow band and b) 1/3 octave band spectra for the 20 kn and 5 kn cases, respectively.

3.3.2 Targa 23

The Targa 23 boat had a higher noise level at lower frequencies in the 5 kn case, compared to 20 kn, as shown in figure 21. This range was, however, limited to 32-78 Hz before the increased cavitation lead to higher measured levels for the 20 kn runs.

The downshift ratio of the boat was specified as 2.3. At 5 kn, the engine was running at a rotational frequency of around 20-21 Hz, giving a propeller rotational frequency 8.7-9.1 Hz. The sound pressure spectrum levels had clear tones at 36 Hz (~4 x propeller frequency) , 42 Hz (~2 x engine frequency), 51 Hz (~6 x propeller frequency), 84 Hz (~4 x engine frequency), 126 Hz (~6 x engine frequency), and many more. Furthermore, at 20 kn, the engine was running at 58-60 Hz, with the acoustic data showing tones at 73 Hz, and then every 23-27 Hz up to 830 Hz. This would correspond to a downshift ratio rate of ~2.4.

The 1/3 octave band spectra in tabulated form is shown in table 6 in the Appendix.

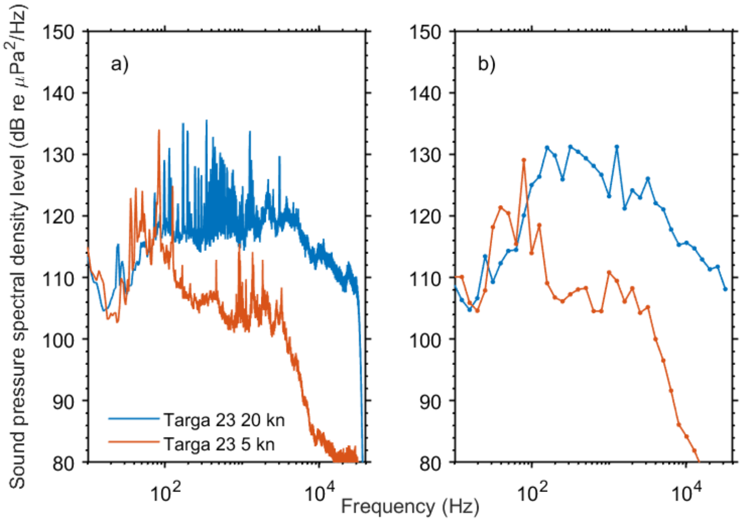

Figure 21. Sound pressure spectral density level from the Targa 23. a) Narrow band and b) 1/3 octave band spectra for the 20 kn and 5 kn cases, respectively.

3.3.3 Eelex 8000

In contrast with the results in 3.3.1-2, Eelex had lower levels throughout the spectrum when running at 5 kn compared to the 20 kn case. Overall, there are distinctive tones in the narrow band spectrum that correlate with the engine and propeller speeds. However, there were some runs, or part of runs, with tones slightly offset from the expectations from the propeller frequency data retrieved. For example, the propeller frequency should be around 14-15 Hz, with a fourth overtone at 57 Hz, but in some cases this peak was overshadowed by a tone at 66 Hz. One potential reason for the 66 Hz peak is that the propeller speed was not completely constant during the entire run but varied slightly. It is also possible that nearby boats could have affected the measurements, as indicated in the measurement protocol. These runs are not included to calculate the spectra in figure 22. Furthermore, some hydrophone channels yielded an artificially higher level in the low frequency range, and therefore only one channel (Channel A) was used for this analysis. Even so, not all peaks in the 5 kn spectrum can easily be explained from the propeller speed data provided, for example the prominent 106, 190 and 252 Hz lines.

At 20 kn, the Eelex 8000 ran with engine speeds at 6800 – 7100 rpm. With a downshift ratio rate of ~2.85 this results in a propeller speed of ~40 Hz. As the propeller has four blades, the blade frequency of the propeller was ~160 Hz. These tones are clearly present in the Sound pressure spectral density level plots (see figure 23).

The 1/3 octave band spectra in tabulated form is shown in table 6 in the Appendix.

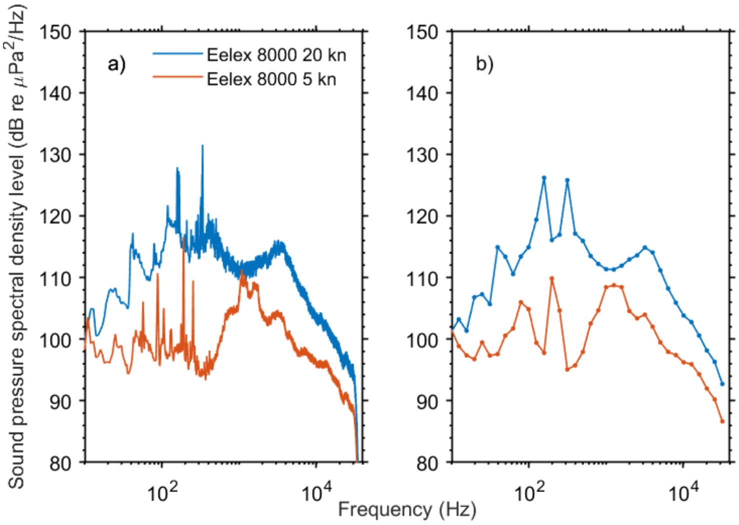

Figure 22. Sound pressure spectral density level from boat Eelex 8000. a) Narrow band and b) 1/3 octave band spectra for the 20 kn and 5 kn cases, respectively.

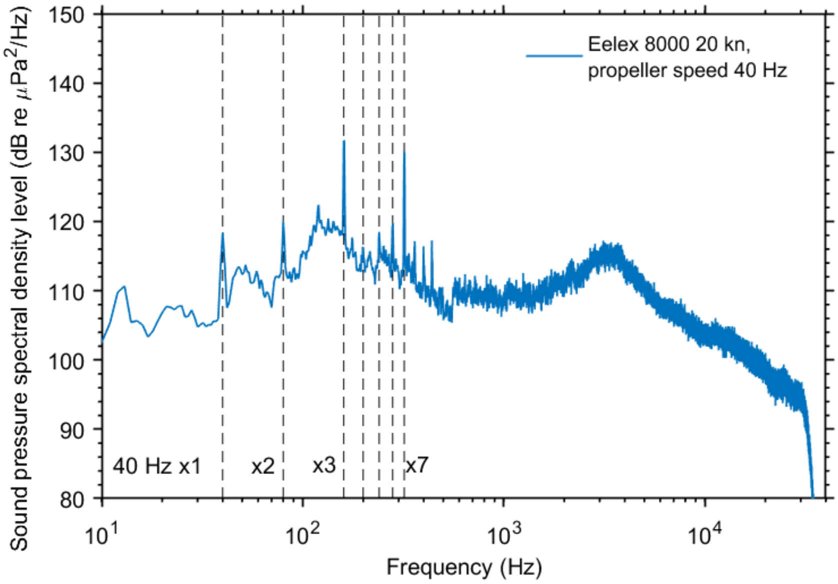

Figure 23. Tone origins from Eelex 8000 from a single run, marked as dashed lines. The propeller rotated with a rotational frequency of 40 Hz, which yields overtones throughout the spectrum.

3.3.3.1 Pressure pulse comparison

The hull of Eelex 8000 was equipped with a pressure sensor, which logged pressure pulses during a 7 s period near the CPA of each run. As the pressure sensor was positioned close to the source (in the near field of the propeller), these pressure levels cannot be directly compared with measurements hundreds of meters away in the far field. Additionally, for frequencies below 3 kHz, the sensor is within one wavelength of separation from the source, well within a point-source near field condition making interpretations even more challenging. However, the pressure sensor gives important information regarding the pressure levels in the vicinity of the propeller and could possibly serve as an intermediate calibration between these full-scale measurements and scaled-down measurements in water tunnels (Kämpeskog and Wenneberg, 2020).

Figure 24 shows a comparison between the hydrophone and pressure sensor data for three speeds: ~5, ~10 and ~20 kn. The hydrophones have decreased performance below ~100 Hz making the main tones of the propeller difficult to measure directly, but these are clearly found in the pressure sensor data.

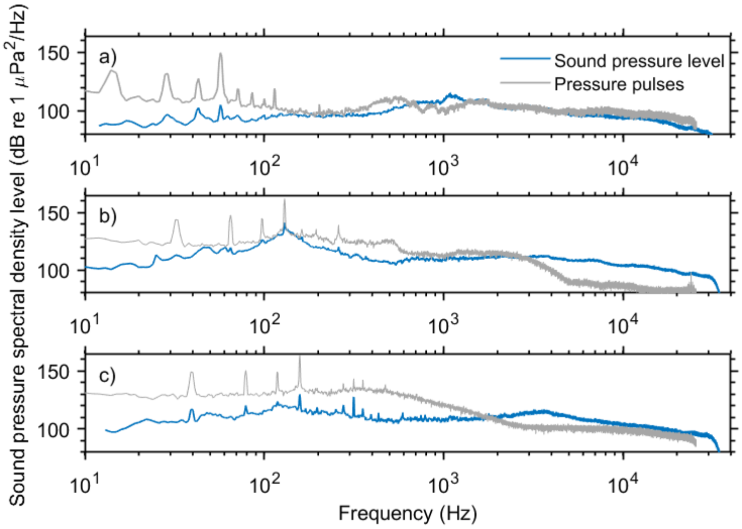

Figure 24. Comparison of far-field sound pressure measurements and pressure pulses from a meter on the hull of Eelex 8000. Single run spectra from hydrophones (blue) and a pressure sensor (grey) for a) 4.5 kn, b) 9.6 kn and c) 19.6 kn.

3.3.4 Acoustic signature comparisons of trial boats

The three boats constitute a set with different engine, propeller and fuel types. It is therefore interesting to compare their acoustic signatures, as shown in figure 25 and figure 26. At 5 kn, Örnvik 540 has the highest levels, both in maximum tone levels found in the narrow band spectrum and in the 1/3 octave spectrum. In the range 60-200 Hz, this boat is louder than the other two. Furthermore, Eelex 8000 stands out as the quieter at lower frequencies but experiencing higher levels at higher frequencies.

The situation is different at 20 kn, however, where Targa 23 over-all seems as the boat with slightly higher levels except for the strong tones near 40 Hz of the Örnvik 540. However, the 1/3 octave band spectra indicate that the three boats are relatively comparable throughout the measurement frequency range.

Table 5 shows the source levels for the boats over the frequency band 10 Hz- 30 kHz, as calculated from narrow band spectra. Comparing with figure 25, Eelex 8000 has lower levels up to ~600 Hz, but is noisier above 4 kHz, which makes it comparable to Targa 23. The opposite trend is found in figure 26, where the levels are comparable for the three boats up to 1 kHz, but then Eelex 8000 is quieter, resulting in a lower over-all sound pressure level. The calculated source levels in this study are difficult to compare to other studies due to the lack of standardization but are in the same range as published studies (Erbe et al., 2016; Matzner et al., 2010).

Table 5. Source levels re 1 μPa @ 1 m for boats Örnvik 540, Targa 23 and Eelex 8000 in the spectral range 10 Hz - 30 kHz.

Speed\Boat	**Örnvik 540**	**Targa 23**	**Eelex 8000**
5 kn	148	145	144
20 kn	158	161	153

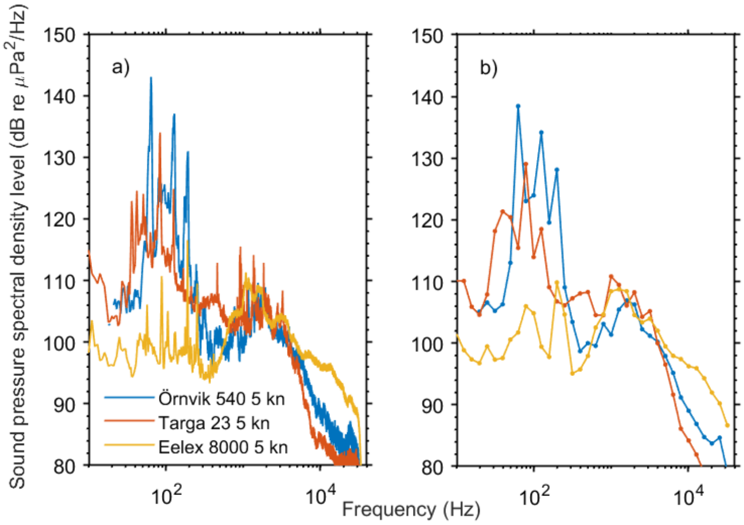

Figure 25.Comparison of the three recreational boats at 5 kn. a) Narrow band and b) 1/3 octave band spectra retrieved from sections 3.2.1-3.

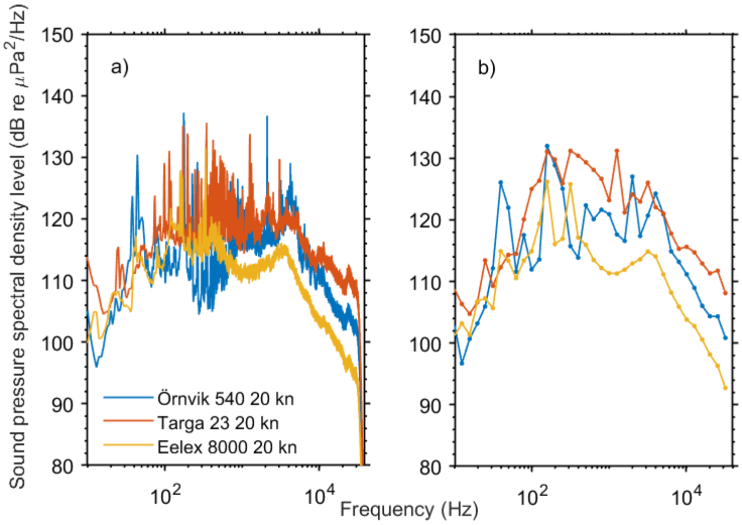

Figure 26. Comparison of the three recreational boats at 20 kn. a) Narrow band and b) 1/3 octave band spectra retrieved from sections 3.2.1-3.

3.4 Uncertainties in acoustic signature estimations

As described in the section 3.3, there are several terms that add up to the measurement uncertainty. We may write the measured sound pressure level, SPL, measured from an omnidirectional source with source level SL as:

$$SPL = 20\log_{10}(a) - R_r = SL - TL + NL, \qquad (1)$$

where a is the measured voltage amplitude of the hydrophone, R_r is the hydrophone sensitivity, TL is the transmission loss and NL is the background noise level. Assuming that NL is small, we may rewrite eq. (1) as

$$SL = 20\log_{10}(a) - R_r + TL. \qquad (2)$$

Thus, there are uncertainties in all terms of the measured amplitude, the hydrophone sensitivity calibration and the transmission loss. Here we note that the post-processing method used herein, specifically the averaging of spectra in different time-segments, treats the boat as an omnidirectional source. This may not always be the case, which could introduce additional uncertainty, if the directionality is not fully captured by the measurement geometry. The assumption is commonly used in ship radiation models found in the literature. The close to symmetric curve in the right pane of figure 13 suggests that a point source assumption is rather accurate, at least for the broad-band source level.

The measured amplitude error is typically lower than the other terms, and the uncertainty in R_r is most often written in the calibration report, typically around 0.7-0.5 dB, but varies with frequency. The main measurement uncertainty, as mentioned in sections 3.2.3 and 3.2.4 is TL estimation errors. In this report, this uncertainty has been partly handled by measuring the TL using a controlled source. To further control such errors, more elaborate methods such as seismic exploration including sediment sampling combined with inverse estimation of the sediment properties could be employed. This is however a laborious task and beyond the scope of this report.

The narrow-band TL is typically rapidly oscillating function of both frequency and range. For broad-band signals, the TL can however often be approximated with reasonable accuracy as $TL = A \cdot log_{10}(R)$ where A is constant. Even though there is no formal upper limit on A, it typically has a value between 10 and 20. For example, the broadband TL estimate in figure 12 suggests A is around 19 with a standard deviation of ~3, when combining all channels and source positions in the measurement area. The standard deviation of the A estimations increased with distance. For example, considering distances ranging from 100-125 m, 160-225 m and 290-440 m the standard deviation for channel A was 1.1, 1.33 and 1.9, respectively. Applying the same ranges for channel B, which had the largest standard deviations over-all, resulted in standard deviations 1.1, 2.3 and 4.0, respectively. The trend is the same even though only single angle ranges are considered.

The standard variation of A estimated from fits to sound pressure level measurements from boat runs, shown in figure 13, was found to be 1 or below 1 for all tracks. In the acoustic signature estimations presented in this report, assuming a sensitivity uncertainty of 0.7 dB and an estimated $TL = (15.5 \pm 1)\,\log_{10}(R)$ for the 100 m tracks, the uncertainty is around 3 dB.

To study the repeatability of signatures, one example is the measured signatures from Eelex 8000 at 20 kn speed at 100 m CPA, a track that was covered with four runs. The average standard deviation of the 1/3 octave band signatures was 1 dB. Comparing the 100 m CPA track signature with the 300 m CPA track, which was covered with two runs, yields a standard deviation of 0.4 dB.

4 Measurement guideline for recreational boats

There is a lack of measurements standards for the radiated underwater noise from recreational boats as mentioned in section 1.1. The experiences and results from the two measurement campaigns in this study (see section 3.2), together with the Bureau Veritas grade B1 standard (Bureau Veritas, 2014), were used to develop a practical measurement guideline for the estimation of the acoustic signature from recreational boats in shallow waters. For more details of the Bureau Veritas measurement and signal processing methodology, see Bureau Veritas (2014).

The scope of this guideline is to assess the underwater sound pressure levels normalized at a distance of 1 m from a recreational boat. The measured quantity is the sound pressure level radiated by the recreational boat considered as a monopole source, measured at a certain position in the water. The source sound pressure level is normalized to the level at 1 m from the source, using the measured distance from the hydrophone position. The resulting quantity is expressed in terms of spectral density of the sound pressure level (in dB re 1 $\mu Pa^2/Hz$).

The section 4.1-4.3 below, describes in detail, the general requirements (Req) for the test site, the measurement and post processing procedure and how to present the results.

By following this guideline, the estimation of a recreational boat's acoustical signature can be used for comparison with scientific published studies, environmental impact studies, and mitigation measure calculations and as input to source models.

4.1 Setup and procedures

4.1.1 Test site and measurement conditions

Req TS1. The measurement area shall be as quiet as possible, such that the vast majority of boat runs have sound levels at least 10 dB above the background level. Note: It is recommended that the area should be at least 3 km away from commercial vessels and other boats. Wave height should be as low as possible, preferable < 0.5 m, as this affects both the boat's driving and the background noise levels. Avoid areas with strong currents, which may affect the recording and the position of the hydrophone in the water. Do not perform the measurement in rain as this raises the ambient noise level.

Req TS3. The area should have a size to allow the boat to run in a straight course at the target speed for at least 500 m.

Req TS4. The seabed should be as smooth and homogeneous as possible to minimize the influence of varying transmission loss.

Req TS5. The water depth should be at least 20 meters. The actual water depth should be measured in the area and especially along the test track and at the hydrophone position.

Req TS6. The sound speed profiles shall be measured before and after the test runs.

Req TS7. The result of the first sound speed profile shall be taken into consideration regarding where in the water column the hydrophone should be placed to have the most predicable transmission loss. Note: The second measurement is to detect changes in the sound speed profile during the course of the measurement and may affect measurement uncertainties.

Req TS8. The background noise shall be recorded at least 30 min before and after the measurement starts, and two minutes before each run, but preferably longer.

Req TS9. The signal stability shall be checked every 15 minutes in order to ensure the reliability of the measurement.

4.1.2 Instrumentation

Req I1. At least one hydrophone shall be used.

Req I2. The hydrophone should have a known response in the frequency range 20 Hz to 50 kHz.

Req I3. The hydrophone should be omnidirectional, i.e. have a directivity of <2 dB.

Req I4. The hydrophone should have been calibrated (uncertainty ±2 dB) together with the entire system (hydrophone, cable and data collection system) prior to the measurement.

Req I5. The system should record with at least 50 kHz sampling frequency and have a dynamic range of at least 80 dB.

4.1.3 Deployment

Req D1. The hydrophone shall be placed at least one meter from the bottom and in the bottom half of the water column in order to avoid disturbances associated with the sea surface. Note: If the sound speed profile suggest that the sound energy is significantly directed to another depth layer, the hydrophone may be placed accordingly. If not, the hydrophone should be placed below the middle of the water column (e.g. at a depth of 15-29 m if it is 30 m deep at the site).

Req D2. The hydrophone shall be disconnected from wave motions (figure 27). Note: The hydrophone can be anchored either at the bottom or suspended from the surface. If the hydrophone is close to the surface, the measurement has a higher risk of being disturbed by wave motion and rig noise. Note the importance of knowing the sound speed profile, which can effect transmission loss.

Req D3. There should be no air-filled buoy or similar air-filled cavity such as an autonomous logger unit, within three meters of the hydrophone, as this may interfere with recording.

Req D4. If the hydrophone is mounted on a line between the bottom weight and the buoy, this shall be kept vertical in the water, and thus not tilted due to currents or waves. Note: If the line is assumed vertical but is not, the hydrophone is not where it is expected to be, which means that distance estimates and depth values are incorrect.

Req D5. Data recording shall be synchronized with a GPS clock prior to measurements. Note: The data recording can be done either via a cable to land or to a boat or in an autonomous unit in the water.

Req D6. The position of the surface buoys and the hydrophone positions shall be measured with a GPS receiver.

Req D7. The error margin of the hydrophone positions should be < 5 m.

Req D8. If a boat is used as measurement platform, it should be anchored at least 100 m from the hydrophone to minimize wave induced noise when they hit the boat hull.

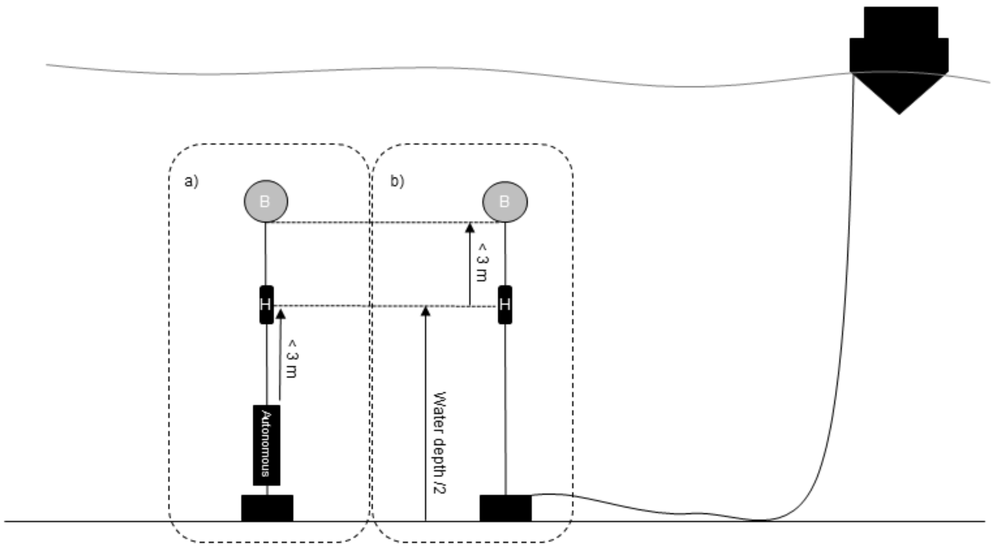

Figure 27. Illustration of two examples of the setup of a hydrophone (H), suspended from the bottom to reduce the impact from the surface. It should be at least 3 m to the nearest buoy (B) or air-filled body to minimize acoustic reflection. Data recording can be done either a) in an autonomous unit on the bottom or b) via a cable up to a boat.

4.1.4 Test track

Req T1. The start, closest point of approach (CPA) and end point of the course should be marked with surface buoys for easier navigation.

Req T2. Each run should be at least 500 m long.

Req T3. There should be two tracks, with the second CPA 1.5 – 2.5 times further away compared to the first track's CPA. If only one track is used, the measurement uncertainty shall be increased considering the lack of TL-estimation verification.

Req T4. The primary tracks CPA should be 100-200 m away from the deployed hydrophones position.

4.1.5 Test procedure

Req TP1. If a run is disturbed by another boat nearby, this run shall be repeated.

Req TP2. A GPS receiver shall be positioned at the stern of the boat, set to record the position every second to get an accurate recording to the boats position and speed during the runs.

Req TP3. The boat should have a straight course and even speed/rpm throughout the run.

Req TP4. The designated speed should have been reached before entering the track.

Req TP5. The course shall be repeated at least two times (figure 28). Note: It is recommended to avoid driving so that the boat hits any wind driven waves or from the boats own wake.

Req TP6. The measurement shall be repeated for at least two different speeds: 5 kn and one more speed. Note: Preferable, these speeds should be one without cavitation and one with cavitation. The 5 kn is a common speed into harbour and in sensitive areas. The other speed should be chosen based on a typical speed the boat is designed for. Boats that are driven in a non-optimal way can be very noisy, which results in an uneven comparison if this source level is compared to other boats at optimal speeds.

In some areas, other speed limits can occur and these speeds are worth testing at as well.

Req TP7. Before testing, engine, propeller type, number of blades and location in the boat, draught, boat size and type should be noted in the protocol.

Req TP8. During the measurement, the speed, power, engine rpm and run number shall be noted in the protocol.

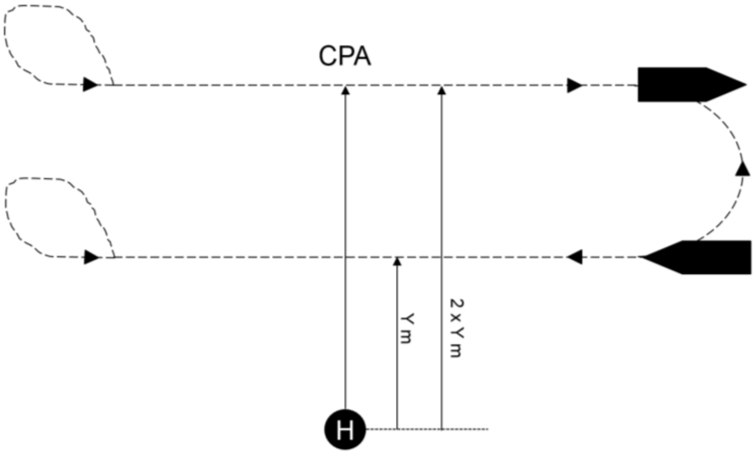

Figure 28. Outline of a test track where the hydrophones (H) positons in relation the track is marked.

4.2 Post processing

As a first step, GPS tracks are extracted and combined with acoustic data.

Req PP1. The run shall be segmented into 19 segments, centred on a given set of angles between the boat and the hydrophone system. Note: The set of angles is exemplified in figure 7 and defined as ±45° to ±135° in 5° increments.

Req PP2. In order for the segments to contain a certain amount of data, the segments should have a length of 50 m.

4.2.1 Data segments

Req PP3. For all 19 segments, a PSD shall be calculated using the Welch method, with 1 s time segments and a 50% overlap, yielding a PSD with a bandwidth of 1 Hz.

Req PP4. For 1/3 octave band analysis, the narrow band spectrum shall be converted into 1/3 octave bands by *taking the mean narrow band value* in each band.

Req PP5. The calculated spectrum, whether it is narrow band or 1/3 octave band, shall be compared to a corresponding background spectrum.

Req PP6a. If the signal-to-background is above 6 dB, the data point shall be used directly without any modifications. b. For a signal-to-background of 3-6 dB, the background shall be subtracted from the signal. c. If the signal-to-background is less than 3 dB, this data point shall be removed from further analysis.

Req PP7. The transmission loss shall be corrected for in each of the 19 time segments, by taking into account the distance from the hydrophones to the centre of each time segment.

Req PP8. The estimation of A should be done using the following priority order:
1. TL measurement, based on separate calibrated source or boat runs.
2. TL modelling.
3. Based on previous knowledge of TL in the area.

4. Using $\mathrm{TL} = 17 \cdot \log_{10}(\mathrm{R})$.

Req PP9. After the transmission loss correction, all data time segments shall be averaged in the linear domain to create a single spectrum for the run. Thus, the sound pressure spectral density level measured by hydrophone h, is $L_h = 10 \cdot log_{10} \frac{\sum_t 10^{L_t/10}}{n_t}$, where $L_t$and n_t are the sound pressure spectral density level of time segment *t*, and the number of time segments, respectively.

Req PP10. When multiple hydrophone channels are used, their spectra of each run shall be averaged in the linear domain. The measured sound pressure spectral density level of the run is $L_r = 10 \cdot log_{10} \frac{\sum_t 10^{L_h/10}}{n_h}$, where n_h is the number of used hydrophones.

Req PP11. When multiple runs have been conducted with equivalent running conditions, the spectra of the runs shall be averaged in the linear domain. Portside and starboard side passages are then averaged in a similar manner to create a single spectrum for the specific running condition. Therefore, the boat spectrum is $L_b = 10 \cdot log_{10} \frac{\sum_t 10^{L_r/10}}{n_r}$, where n_r is the number of runs.

4.3 Presentation of results

Req PR1. The protocol shall contain one page identifying the boat to be measured, the location, time and date of the measurements and the measurement leader, whom is responsible for the implementation of these guidelines.

Req PR2. The second page shall clearly state the boat characteristics, measurement-specific data, the transmission loss estimation model used and the sea state. Note: The boat characteristics include engine type, fuel type, propulsion type (e.g. propeller type), and design speed (if known). The measurement data form include the measured boat speeds in knots and the engine rpm for these speeds, the date from the GPS and the GPS time as well as the recording time.

Req PR3. The measured sound pressure spectrum levels should be presented in 1 Hz spectrum and a 1/3 octave band spectrum, for each running speeds.

Req PR4. The main tones of the narrow band spectrum should be noted in a table and identified.

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Appendix

Table 6. Sound pressure spectrum levels per 1/3 octave band re 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ @ 1 m, from the Örnvik 540, Targa 23, and Eelex 8000 for runs at 5 and 20 kn, respectively.

Frekvens (Hz)	Örnvik 540 5 kn	Örnvik 540 20 kn	Targa 23 5 kn	Targa 23 20 kn	Eelex 8000 5 kn	Eelex 8000 20 kn
6	-	105	117	111	113	-
8	-	104	114	110	-	95
10	-	103	110	109	102	101
12	-	97	110	106	99	103
16	-	101	106	105	97	101
20	105	103	105	107	97	107
25	107	106	108	113	99	107
31	105	112	118	109	97	106
39	106	126	121	112	98	115
50	113	122	120	114	101	113
63	138	112	115	114	102	111
79	123	118	129	120	106	113
99	124	112	114	125	105	115
125	134	114	118	126	99	119
157	120	132	109	131	98	126
198	128	129	107	130	110	116
250	109	125	106	126	105	117
315	103	116	107	131	95	126
397	99	114	108	130	96	117
500	100	122	108	129	98	116
630	100	120	105	128	103	113
794	103	122	105	127	105	112
1000	101	121	111	123	108	111
1260	105	118	109	131	109	111
1587	107	117	106	121	108	112
2000	106	127	108	124	105	113
2520	102	117	104	123	103	114
3175	101	121	105	126	104	115
4000	100	124	100	122	102	114
5040	98	121	97	121	99	111
6350	95	115	92	118	98	108
8000	91	113	86	115	97	106
10079	89	111	84	116	96	104
12699	87	109	82	115	96	103
16000	85	106	79	113	94	101
20159	84	104	77	111	92	98
25398	85	104	76	112	90	96
32000	79	101	74	108	87	93
40317	-	-	-	-	-	-

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