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Report 2/1455-00

Contribution Agreement No. 164624:

Development of Noise Reduction Measures for Conventionally Propelled Whale Watching Vessels

Customer:

Transports Canada   Transport Canada

Provided by:

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Document Control Sheet

Customer	Transport Canada
Project	Quiet Vessel Initiative - Development of Noise Reduction Measures for Conventionally Propelled Whale Watching Vessels
Report No.	Report 2/1455-00
Report Title	Noise Analysis

Rev. No.	Date	Reason for Issue	Prepared by	Checked by	Approved by
00	30.09.2024	Initial release	Sebastian Sturm	Thomas Büchler	Max Schuster

Keywords

The four investigated whale watching vessels had four different propulsion concepts. Together they represent the vast majority of propulsion concepts of small vessels all over the world and across many different applications. Therefore, the results of this study can be applied to other whale watching vessels as well as other boats with similar configurations.

The major results of this study are:

1. Speed matters! If a vessel operates below its cavitation inception speed, the RNL stays relatively low. Individual RNL versus speed diagrams show that every vessel has speed ranges in which the RNL barely increases. Beyond such a range, the RNL “jumps” to the next level. It is recommended that every whale watching boat undergoes a systematic URN measurement at different speeds in order to obtain its individual speed/RNL chart. Such a chart would provide scientific basis for a proper speed vs. noise management.
2. Engine foundations should be designed as stiff as feasible. Elastic engine mounts should be selected as soft as feasible. Those two measures would reduce the engine’s SBN contribution to the RNL considerably.
3. Wherever possible, the propeller shall not only be designed or selected regarding highest efficiency but also with regard to low URN emissions. Several design recommendations were given.
4. A new vessel design would provide the best opportunities to implement low noise features. Hull lines and appendages should be designed in a way to avoid cavitation. A conventional, big propeller with a good inflow operating at slow to medium speed likely provides the quietest and most efficient result.
5. If high speed of more than 20 kts is of the essence, a surface piercing propeller is the quietest propulsion system.

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Abbreviations

ABN	Airborne Noise
BAR	Blade Area Ratio (total propeller blade area/propeller disc area)
BSH	Bundesamt für Seeschifffahrt und Hydrographie
DNV	Det Norske Veritas
MSL	Monopole Source Level
NOAA	National Oceanic and Atmospheric Administration
RNL	Radiated Noise Level
SBN	Structure-Borne Noise
TC	Transport Canada
URN	Underwater Radiated Noise

1 Executive Summary

In October 2022, four whale watching vessels of Eagle Wing Tours, Victoria B.C. were measured for Underwater Radiated Noise at the Underwater Listening Station in Boundary Pass, British Columbia, Canada.

These four vessels featured different propulsion systems:

- "Conventional propulsion" with screw-type propulsors
  - fixed pitch propeller with inboard engine
  - Outboard engines with fixed pitch propeller
  - Surface piercing fixed pitch propeller
- Waterjet (pump type propulsor)

All vessels were systematically analyzed for their ship noise particularities and equipped with a variety of different onboard sensors, including noise and vibration measurement devices. These onboard measurements were conducted in parallel to the URN measurements.

The combination of the different measurement results and information allowed an assessment of the noise reduction potential of the investigated boats in particular and small vessels in general.

The major results of this study are:

1. Speed matters! If a vessel operates below its cavitation inception speed, the Radiated Noise Level (RNL) remains at a level that is rather independent on speed. Individual RNL versus speed diagrams show that every vessel has speed ranges in which the RNL barely increases. Beyond such a range, the RNL "jumps" to the next level. It is recommended that every whale watching boat undergoes a systematic URN measurement at different speeds in order to obtain its individual speed/RNL chart. Such a chart would provide scientific basis for a proper speed vs. noise management.
2. Engine foundations should be designed as stiff as necessary to keep the resilient mounting effective. Elastic engine mounts should be selected as soft as feasible. Those two measures would reduce the engine's SBN contribution to the RNL considerably.
3. Wherever possible, the propeller shall not only be designed or selected regarding highest efficiency but also with regard to low URN emissions. Several design recommendations were given.
4. A new vessel design would provide the best opportunities to implement low noise features. Hull lines and appendages should be designed in a way to avoid cavitation. A conventional, big propeller with a good inflow operating at slow to medium speed likely provides the quietest and most efficient result.
5. If high speed of more than around 20 kts is of the essence, a surface piercing propeller has been found to be the quietest propulsion system.

As the four investigated whale watching vessels had four different propulsion concepts, they represent the vast majority of propulsion concepts of small vessels all over the world and across many different applications. Therefore, the results of this study can be applied to other whale watching vessels as well as other boats with similar configurations.

2 Introduction

The project "Development of Noise Reduction Measures for Conventionally Propelled Whale Watching Vessels" was initiated by Transport Canada's Contribution Agreement No. 164624.

The partners involved are:

1. DW-ShipConsult, GERMANY
   A JASCO Applied Sciences Company
   Lead Partner
   Responsible for:
   - Onboard noise and vibration measurements
   - Investigation of main noise contributors
   - Noise analysis
   - Data merging
   - Development of recommendations

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2. JASCO Applied Sciences, CANADA
   Responsible for:
   - Underwater Radiated Noise measurements
   - URN data analysis

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3. Eagle Wing Tours (EWT), Victoria B.C., CANADA
   Responsible for:
   - Providing the analysis objects (boats)
   - Boat operation
   - Providing technical and operation data

EAGLE WING WHALE WATCHING TOURS

The aim of the project was to analyse causes and effects of underwater radiated noise by conventionally propelled whale watching vessels and develop recommendations for reducing their URN by:

- Operational means
- Retrofit measures
- Newbuildings

3 Purpose

URN is recognized by government regulatory frameworks such as Transport Canada (TC) of Canada, National Oceanic and Atmospheric Administration (NOAA) of the USA or Bundesamt für Seeschifffahrt und Hydrographie (BSH) of Germany as a marine pollutant which can cause permanent or temporary threshold shifts in marine species' ability to hear (Southall, et al., 2007). Additionally, higher levels of vessel noise can cause sufficient disturbance to marine species to negatively impact essential behaviours such as foraging, navigating or mating (Wisniewska, et al., 2018). Consequently, efforts to reduce URN are increasingly seen as an essential component of any environmental impact assessment for marine activities.

The operation of whale watching boats is only one of many small boat operations in vicinity of marine mammal habitats. Comparable boat operations can be found with Crew Transfer Vessels (CTVs) in Offshore Wind Farms (OFW), pilot boats in every port approach or pleasure crafts for recreational use. Therefore, the results of this study also help to understand causes, effects and available remedial measures for similar vessels in other use cases as well.

Figure 1: CTV approaching a monopile in an offshore wind farm (source: DW-ShipConsult)

4 Scope of Investigations

To gain insights in the URN regime of typical whale watching boats, a measurement campaign has been conducted with the whale watching boats of Eagle Wing Tours. The URN of the three conventionally propelled boats and one waterjet-propelled boat were measured at the Transport Canada Underwater Listening Station (ULS) located south of Saturna Island in Boundary Pass at various boat speeds, during acceleration and during turning. Parallel to the URN measurements, DW-ShipConsult GmbH measured the onboard noise and vibration levels of the propulsion system components and at locations on board which were found to be relevant. The measurement locations were selected depending on accessibility, possibility of mounting a sensor and relevance for the evaluation of noise sources.

4.1 URN measurements

The measurements were performed during passes of the ULS along a defined track as shown in Figure 2 during October 2022.

Recorded data of both tetrahedral arrays as illustrated in Figure 3 was processed and analyzed by JASCO (Li & Demers, 2023).

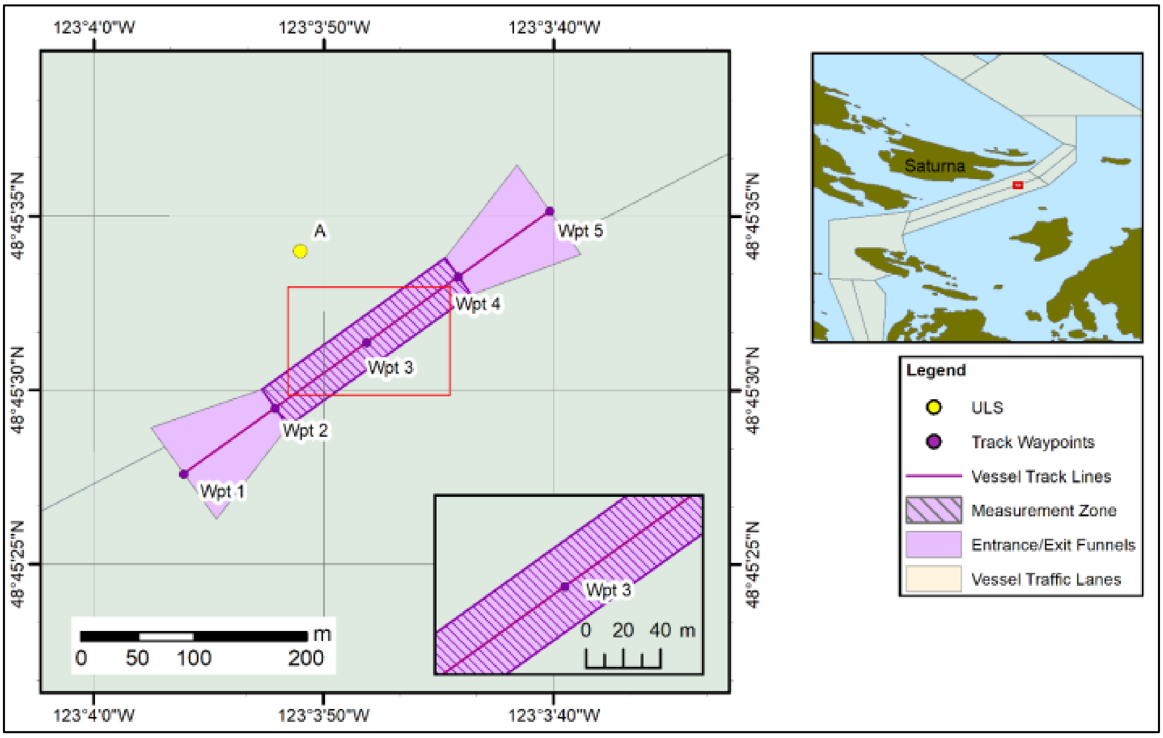

Figure 2: ULS and measurement track

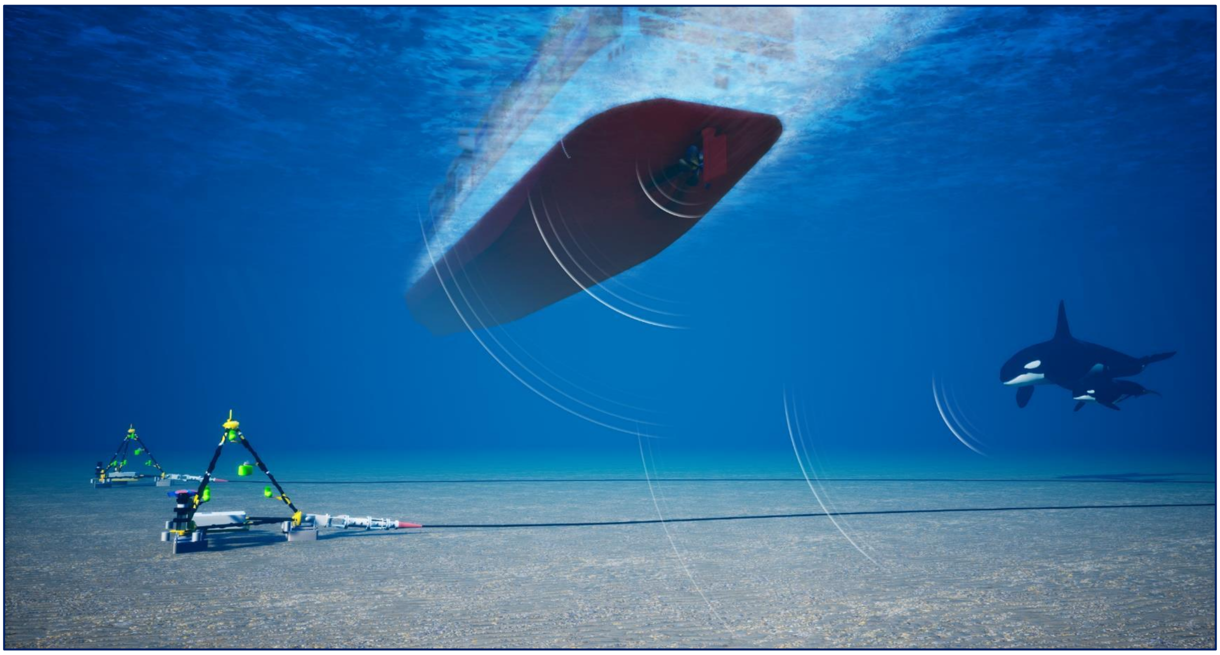

Figure 3: rendering of the ULS (© JASCO)

4.2 Onboard Measurements

During the passages above the ULS the following data as summarized in Figure 4 was recorded on board the vessels to allow all necessary analysis.

- Structure-borne noise (SBN)
  - Above resilient mounts of engines and gearbox ('source level')
  - Below resilient mounts ('foundation level')
  - Above propellers or on housing of water jets
- Airborne noise (ABN)
  - In engine room
- Inclination (dynamic trim)
- Video of bow wave and stern wave

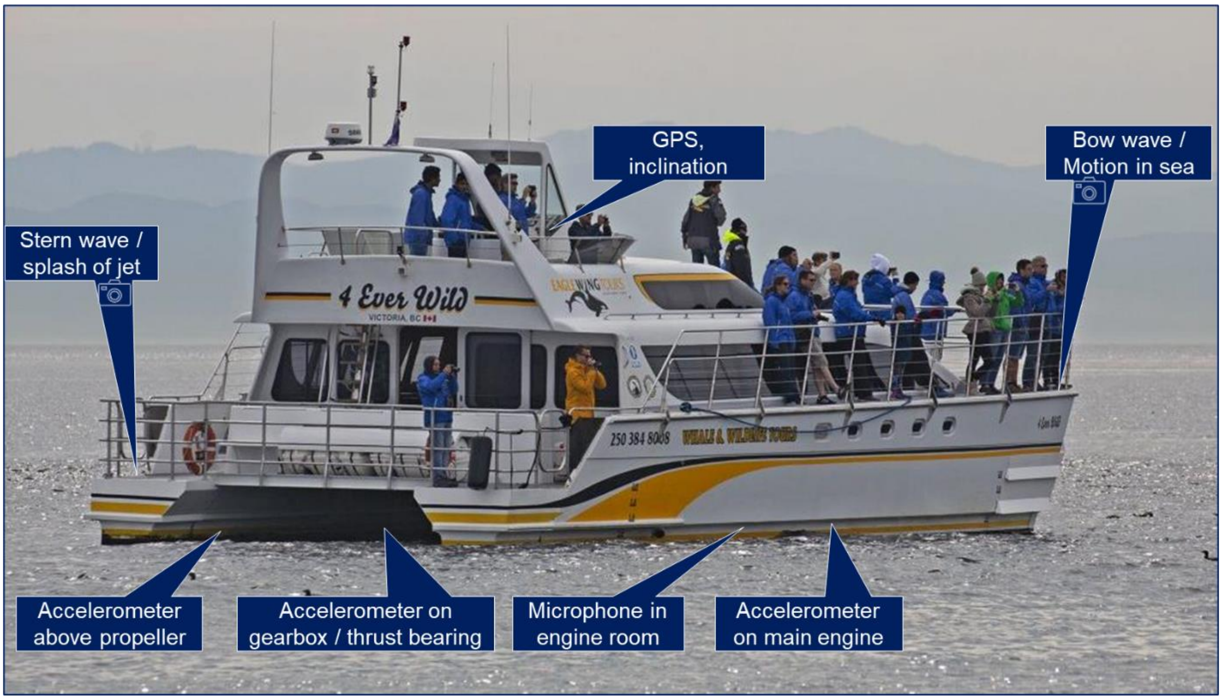

Figure 4: sensors used during onboard noise and vibration measurements

4.3 Investigated Whale Watching Vessels

For the investigation three different conventionally propelled and one waterjet propelled whale watching vessel were provided by Eagle Wing Tours, Victorica B.C.:

	4 Ever Wild (4EW)	Goldwing (GW)	Serengeti (SE)	Wild4Whales (W4W)
Length [m]	17.36	15.51	11.58	18
Engines	2 x 320 kW @3450 rpm Diesel	2 x 460 kW @2450 rpm Diesel	3 x 220 kW @5800 rpm Gasoil	2x515 kW @2300 rpm Diesel
Propulsion System	2 x shaft and 5-bladed fixed pitch propeller	2 x shaft and surface piercing propellers	3 x outboard engines with 3-bladed fixed pitch propellers	2 x Waterjet
Top Speed [kts]	~26	~40	~40	~27

Table 1: main data and propulsion system of the boats

The four systems show significant differences. This is a big advantage to this project as these systems cover typical propulsion concepts used on the majority whale watching boats and other small crafts operating in coastal waters. Typical integration of noise sources is sketched in Figure 5.

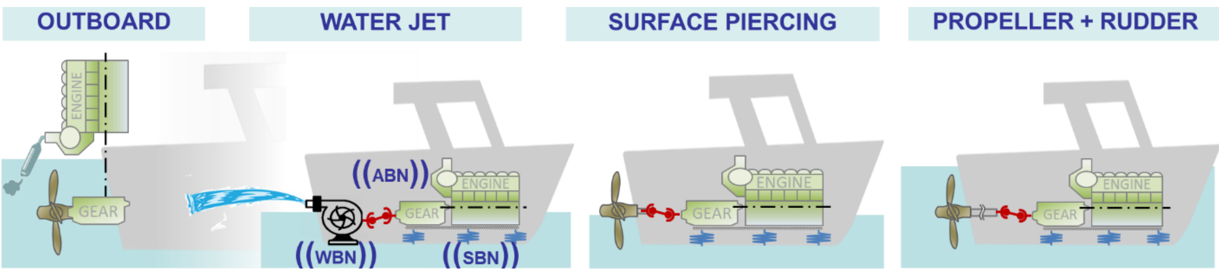

Figure 5: principle for integration of noise sources for each investigated propulsion system

4.3.1 4 Ever Wild (4EW)

Figure 6:4 Ever Wild (© EWT)

4EW is a catamaran boat made of GRP, propelled by two fixed pitch propellers. Each propeller is connected to a resiliently mounted engine with gearbox by a cardan shaft. Steering is done by a rudder behind each propeller. This kind of propulsion configuration is common for medium sized whale watching vessels.

4EW is one of the two bigger whale watching vessels and accommodates 50 guests plus crew.

The top speed is slower than the other two smaller vessels.

4.3.2 Goldwing (GW)

Figure 7: Goldwing (© EWT)

GW is a small, high-powered monohull boat for 26 guests. It features a surface piercing propeller. During higher speeds the boat planes and the propeller is trimmed in a way that only the lower half of the propeller is still submerged. This propeller creates the unique high splash (“rooster tail”) in the air behind the boat which can be seen in the picture above.

Figure 8: Goldwing’s surface piercing propeller in port (left) and during high-speed transit (right)

4.3.3 Serengeti

Figure 9: Serengeti (© EWT)

Serengeti is the smallest investigated boat and accommodates 12 guests. It is propelled by three Suzuki outboard engines with fixed pitch propellers. This type of propulsion is likely the most common for small whale watching vessels and private boats. Outboard motors are usually off-the-shelf items with a very limited capacity for customization. There is usually a selection of propellers which are chosen according to the size of the boat.

Figure 10: outboard engines of Serengeti (© DW)

4.3.4 Wild 4 Whales (W4W)

Figure 11: Wild 4 Whales (© EWT)

W4W is the biggest of EWT's boats with a capacity of 63 passengers plus crew. The catamaran is propelled by two onboard engines driving two waterjets. Such waterjets are not uncommon for vessels of this size. Especially in crew transfer vessels (CTV) operating in offshore wind parks and a growing fraction of whale watching boats, this propulsion system is quite attractive for its efficiency at high speeds.

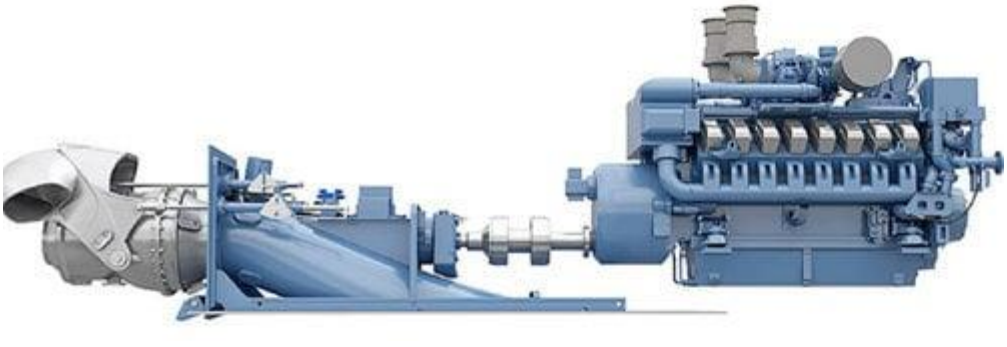

Figure 12: waterjet with coupling and engine. (© Kongsberg Maritime)

4.4 Biological Relevance

Marine mammals can be classified by different auditory groups. In the Salish Sea the Humpback Whale and the Killer Whales (SWRCs and Transient) reflect two different auditory groups: the low frequency and the high frequency group. Another very prominent high frequency group member is the Harbor Porpoise which is seen as the critical species in most European wind park projects. Some American windfarm projects on the west coast are located in habitats of Right Whales which belong to the LF hearing group.

The investigations in this project therefore cover both low and high frequency content of the vessels URN.

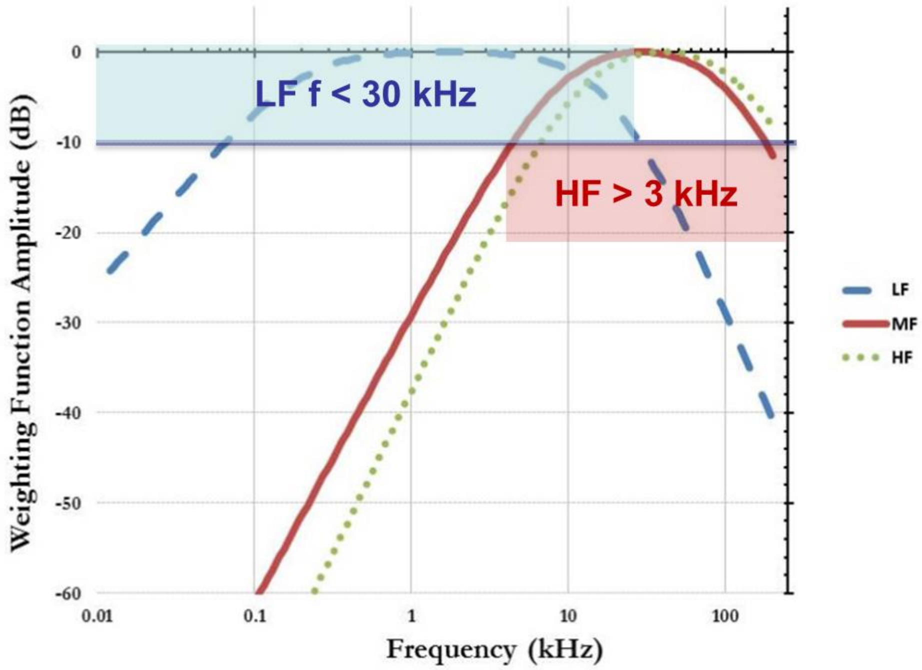

Figure 13: hearing sensitivity for low (LF), medium (MF) and high frequencies (HF) (© NOAA)

Currently there are only non-mandatory limit values available for thresholds of disturbance and injury. All values describe received levels at the animal's ear.

There is no internationally recognized mandatory URN limit for source levels of vessels that defines above which level an adverse effect for marine life in general of the specific species in particular is considered. In absence of such a mandatory limit we compare the measured levels with two different URN class notations by DNV (DNV, 2022). These provide an orientation for comparison with radiated noise of other ships. DNV is an arbitrary choice in this case, any other class notation for underwater radiated noise could be applied.

The first notation is DNV SILENT(E) (Environmental). Compliance of any vessel with this notation shall indicate that the vessel has been designed in a way that design features are avoided which would result in increased radiated noise levels. This notation is applied for the operating condition "transit speed" which is either 85% of maximum continuous engine power or contractually defined service speed. For big ocean-going vessels this transit speed can be different than for smaller crafts. In our analysis we compare the limit with the high speed transits of our whale watching boats. The reduced RNL limits of DNV Silent (E) quiet cruise are compared to measurement results at slow speed.

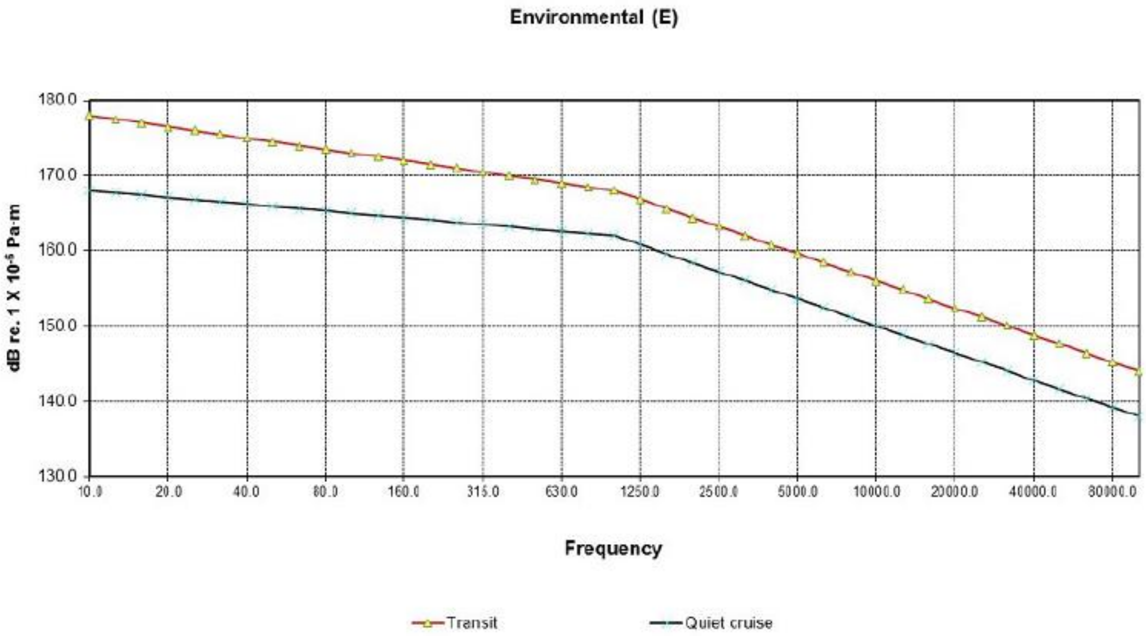

Figure 14: extract from the DNV-RU-SHIP Pt.6 Ch.7: DNV SILENT(E) limit curve

The second notation is DNV SILENT(R) (Research). This notation is the strictest DNV Silent notation of all. The intention of this notation is to give fishery research vessels a realistic limit in the low frequency range below which it is unlikely that the research target species are disturbed in such a way that they would either flee from the vessel or stop their current activity such as foraging. The high frequency part of the limit curve is restricted to ensure proper function of all hydroacoustic equipment such as fish finding sonar, multibeam echo sounder and others. In that respect it is plausible to assume that a vessel which complies with the DNV SILENT(R) notation is unlikely to disturb marine life within a certain radius. In our analysis we compare the SILENT(R) notation with the slow speed operations which are conducted by the whale watching vessels in proximity of the animals.

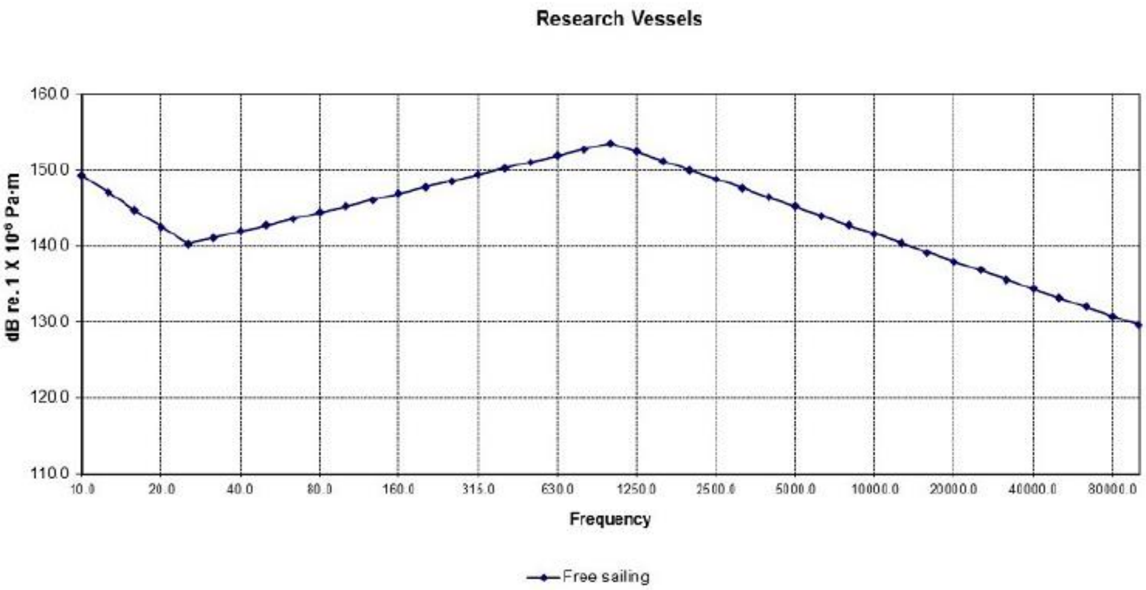

Figure 15: extract from the DNV-RU-SHIP Pt.6 Ch.7: DNV SILENT(R) limit curve

When looking at the figures and diagrams in our analysis below it is important to know that source levels in 1 m distance of the vehicle are described, therefore an exceedance of the limit does not necessarily lead to an acoustic disturbance of an animal. Vice-versa, the full compliance with those limits does not necessarily mean that all animals remain acoustically unaffected by the vessel. This is especially true as the distance between a vessel and an animal is not defined in the Silent notations.

Nevertheless, these limit curves are internationally recognized as a suitable label to show that control of underwater radiated noise was considered in all stages of ship design.

5 URN Results

Figure 16 and Figure 17 show spectra of the Radiated Noise Level of all three boats in comparison to the different DNV Silent notations. The spectral display of the results allows to identify in which frequency bands the boats radiate more or less acoustic energy, thus enable biologists to assess the acoustic impact on different species.

5.1 Slow Speeds

When approaching whales, whale watching vessels reduce their speed significantly to avoid strikes and high URN emissions. There is no international exact definition of a slow speed. Typically, 5 knots shall not be exceeded during paralleling. Therefore, the boats vary slightly in the speeds under which they were measured. Nevertheless, the speed range between 3 kts and 6 kts can be considered as slow speed as the engines are all running just slightly above idle, and the propellers do not show any cavitation.

The scatter of the levels is about 10 dB.

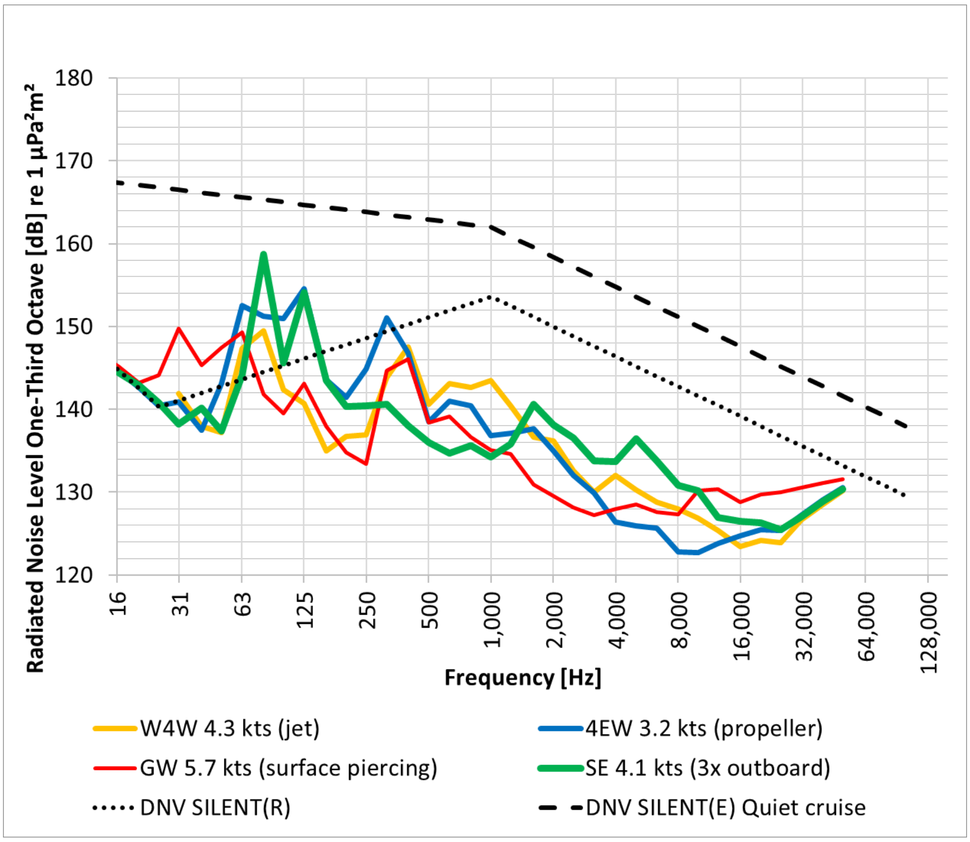

Figure 16: RNL of the boats at low speed; DNV Silent (E) Quiet Cruise and Silent (R) curves

The comparison with the DNV SILENT(E) [Quiet Cruise] notation shows that all vessels stay well below the limit when operating at a slow speed. This does not necessarily mean that the vessels do not have any biological relevant impact on any species in vicinity but the significant distance to this benchmark curve indicates that these whale watching vessels are part of the quieter group of vessels when operating at these slow speeds.

The second limit applied to these spectra is the DNV SILENT(R) notation. That notation is the most stringent Class Notation and is intended for fishery research vessels. Those vessels shall not bias biological investigations due to disturbance of marine species by self-made underwater radiated noise. It is therefore plausible to argue that a ship compliant with the SILENT(R) limit curve does not pose a significant disturbance of marine life compared to other vessels without underwater noise class notation. The biological effect needs to be evaluated by experts for the respective species and strongly depends on distance between vessel and animal. But these three vessels seem to introduce a comparatively low amount of acoustic energy in the water at frequencies above 250 Hz when operating with a slow STW (Speed through water). The cause of the spikes which lead to an exceedance of the DNV Silent (R) curve in the frequencies below 250 Hz will be explained in chapter 6.

5.2 High Speeds

Whale watching vessels operate at medium to high speeds when transiting to an area of interest. A boat operator would not be interested to have maximum available power applied on his propulsion system. Environmental concerns, reduced passenger comfort, safety matters and significantly increased fuel consumption would keep any captain from going that fast without a very good reason.

Nevertheless, the top speeds of the three boats were measured and compared to a DNV Silent notation. Therefore, these RNLs can be seen as upper limits of possible levels. All regular transit speeds would be quieter than those shown in Figure 17. The applied Silent notation is the DNV SILENT(E) [Transit]. That limit curve is 5-10dB higher than the DNV SILENT(E) [Quiet Cruise] and intended for commercial ships operating at their typical transit speed.

The scatter in the levels is now larger amounting to 15 to 20 dB which is not too surprising as the designs are very different together with the top speed between 24 and 38 knots.

The increase of the URN level at high frequencies amounts to up to 30 dB compared to low speed.

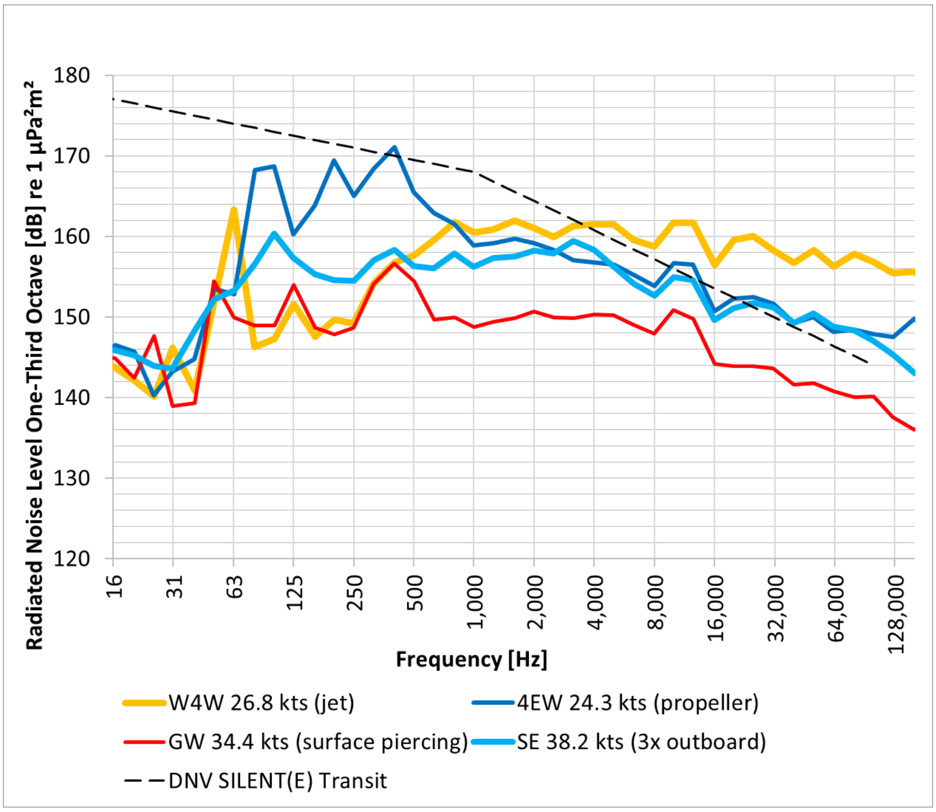

Figure 17: RNL of the boats at high speed; SILENT(E) curve

Although GW is the fastest boat, it is the only vessel which complies with the SILENT(E) Transit curve. The other two show exceedances of some dB at the higher frequencies. The non-compliance of the three vessels in the higher frequencies is not unexpected. At these very high speeds, way above the typical operating speed, extensive cavitation occurs at the propellers. That effect causes a significant increase of high frequency noise. Therefore, Figure 17 does not show that the investigated vessels are comparatively loud in general but that a very high speed increases the RNL to a significant level which is nearly comparable to an oceangoing commercial ship in the higher frequency bands.

The reasons for the compliance of GW and non-compliance of 4EW, W4W and SE will be described in detail in chapter 6.

5.3 Comparison with Other Small Crafts

Figure 18 and Figure 19 show RNL of comparable small crafts at slow and high speeds. The data was taken from a measurement campaign for the ECHO program (Wladichuk, Hannay, MacGillivray, & Li, 2018).

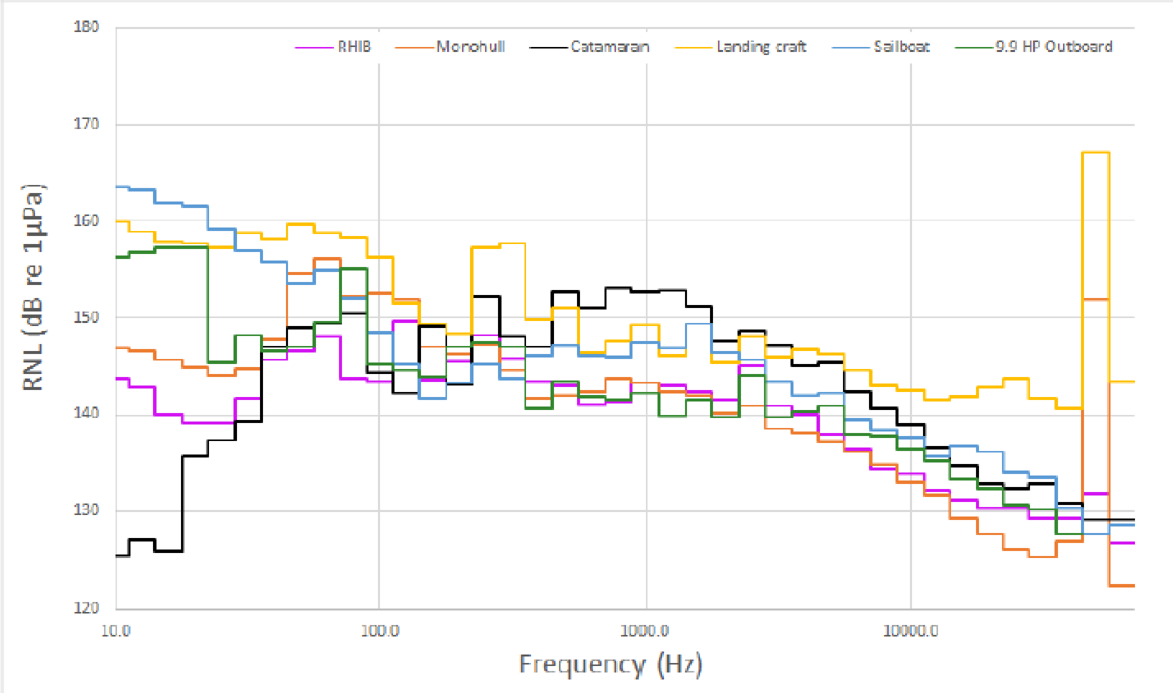

Figure 17. Mean one-third octave band RNL for each vessel type for the slow speed (≤ 7 kts STW) passes.

Figure 18: slow speed passages of other small crafts

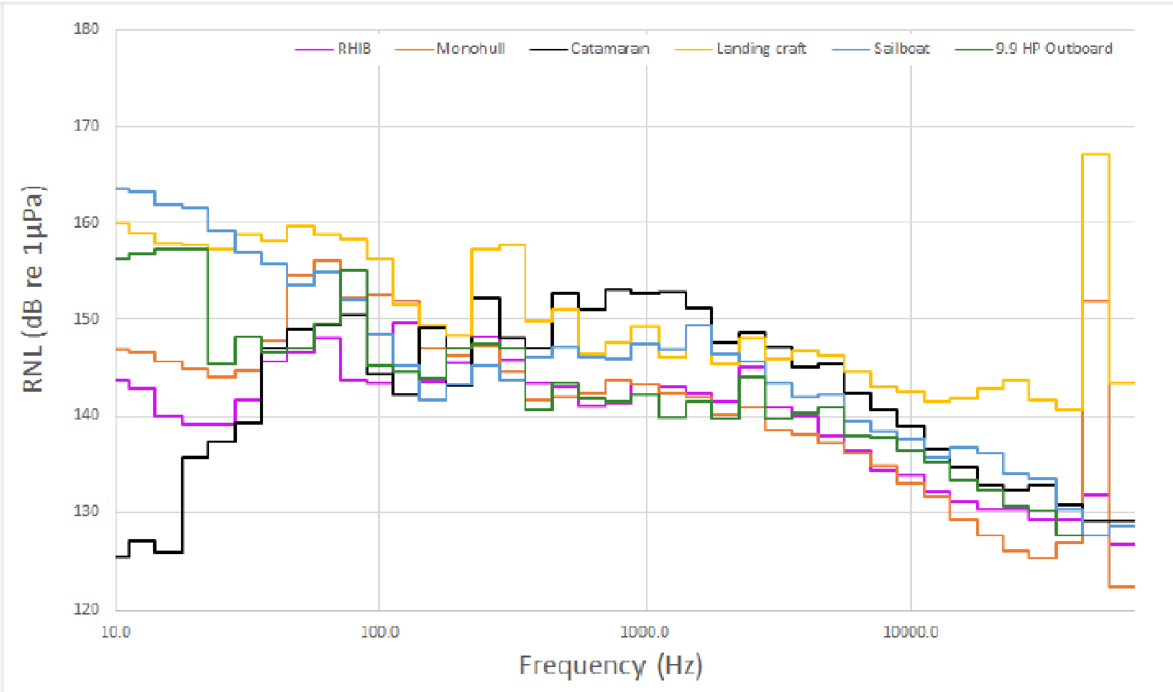

Figure 17. Mean one-third octave band RNL for each vessel type for the slow speed (≤ 7 kts STW) passes.

Figure 19: high-speed passages of other small crafts

The data of the small craft measurements have been converted to an acoustic model for such craft which allows a better comparison of the boats investigated here to the average small craft. The model includes parameters depending on size, powering and speed.

For the waterjet propelled ship, a conventional propeller was assumed as the model does not cover jet propulsion.

It can be seen in Figure 20 that the measured data of two catamarans 4Ever Wild and Wild 4 Whales substantially exceeds the model spectrum which indicates potential for quieting.

The data to calculate the monopole level has been taken from the URN measurements and the associated geometry except that the vertical down angle is always 61° and the source depth is 0.75 m rather than 2.8 m as indicated in the measurement reports of Jasco.

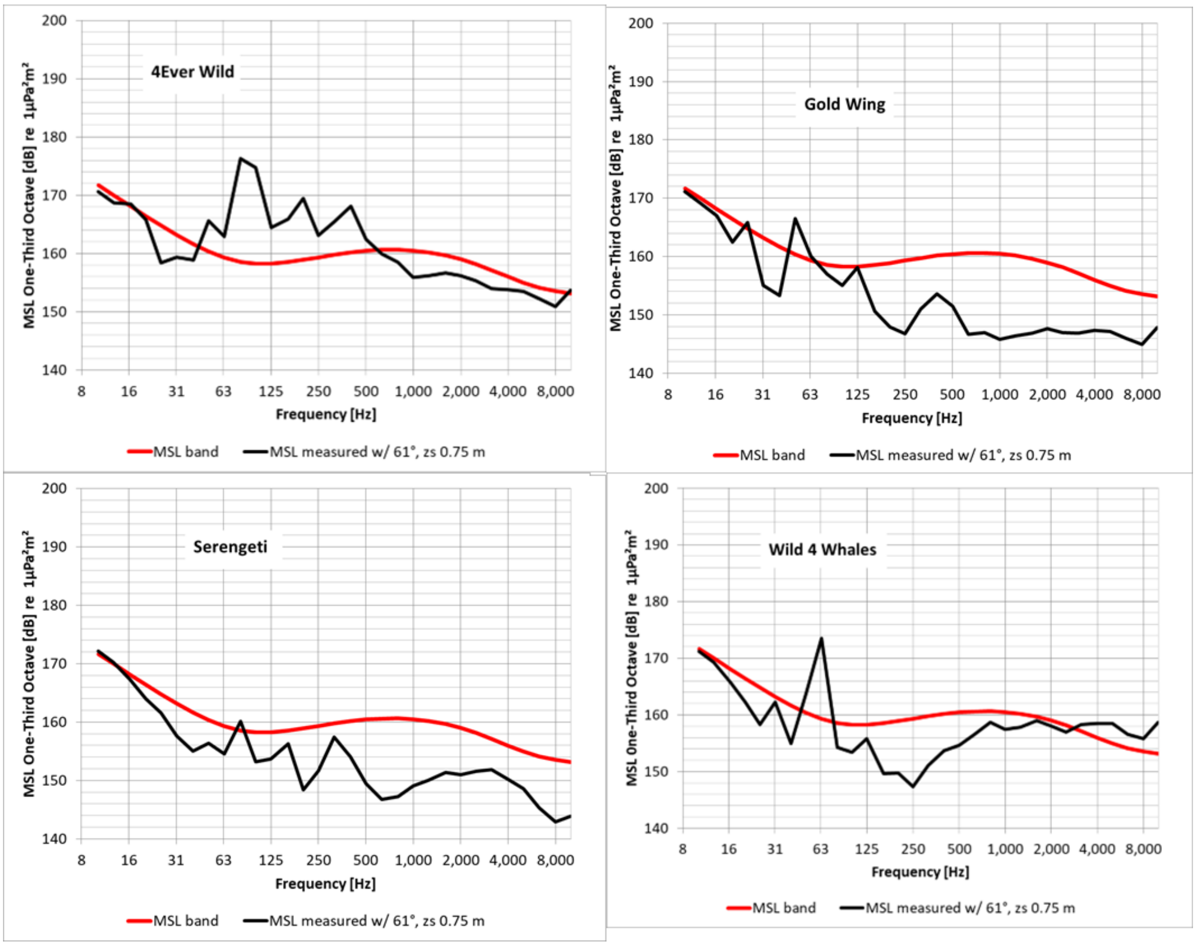

Figure 20: comparison with acoustic model for high speed condition

In the following chapter reasons of the noise and effect on radiated noise are discussed for each boat.

6 SBN Analysis

Key feature of this project was the opportunity to install a variety of sensors on board during the URN measurements (see Figure 4) and to document the operational status of all running equipment for any given time. This dynamic information paired with the static technical information on the vessels and their equipment enables a proper cause and effect analysis for the URN signature. The URN spectrum of every vessel is the combination of several different sources. The most dominant sources on the investigated whale watching vessels are:

1. Cavitation noise at the propeller
2. Structure borne noise (SBN) from the propulsion engine and shaft coupling, transferring through the foundation, exciting the hull and radiating into the water
3. Airborne noise (ABN) from the propulsion engine, exciting the engine room's floors and walls and radiating through the hull into the water
4. Exhaust gas noise
5. Gear noise

The different noise sources will be described in more detail in the following chapters.

6.1 4 Ever Wild (4EW)

On 4 Ever Wild, the 12 locations shown in Table 2 have been equipped with acceleration sensors. Figure 21 and Figure 22 show examples of sensors in place. The sensor signals have been tracked and processed with IMC Wave 2022 and IMC Studio 2022.

Table 2: 4EW: Sensor Naming and LocationChannel	Location (, Direction)
PS_prop	shell above portside propeller
eng_PS_fore_ z	portside engine: fore mounting
eng_PS_fore_y	portside engine: fore mounting
bow_shell_SB_ y	shell at the bow of the starboard
SB_prop	shell above starboard propeller
eng_SB_aft_y	starboard engine: aft mounting
floor_guest_saloon	on the floor in the passenger
fndt_SB_aft_z	engine foundation starboard:
fndt_SB_aft_y	engine foundation starboard:
fndt_SB_fore_y	engine foundation starboard:
fndt_SB_fore_z	engine foundation starboard:
eng_SB_fore_z	starboard engine: fore mounting

Figure 21: SBN sensors at engine mounting of 4EW, attached with magnet above resilient mount, attached with plate and adhesive below resilient mount

Figure 22: SBN sensor above propeller of 4EW

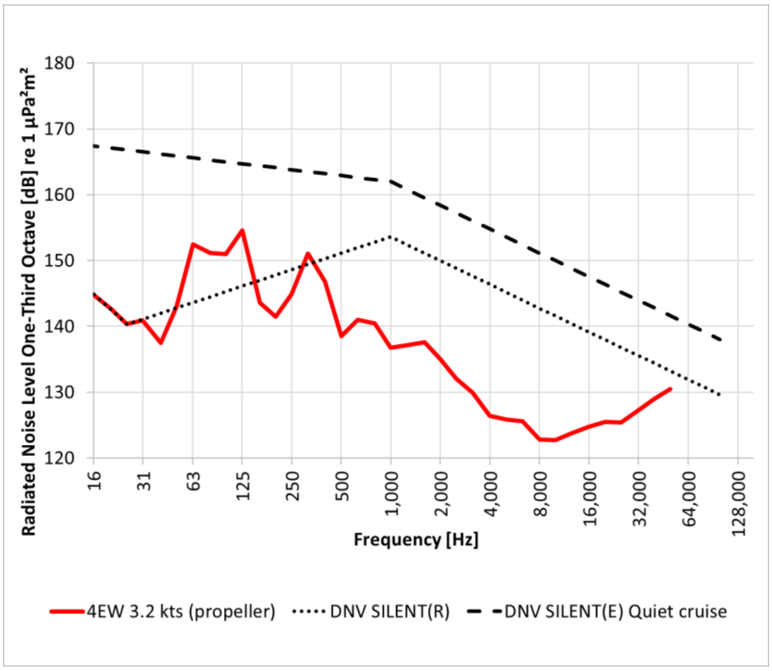

Figure 23: RNL of 4EW at a slow speed in comparison to DNV SILENT(R) and E (Quiet Cruise)

As mentioned in chapter 5, at slow speeds 4EW's URN spectrum shows significant tones in the lower frequency bands, particularly at 63 Hz and 125 Hz 1/3 octave bands (Figure 23).

Figure 24 shows the signals of the relevant SBN sensors for URN, the RNL (bold red) and the ABN level (bold brown) of 4EW when sailing eastwards on the test track at 600 rpm with 4.9 kts. The dominating peaks of slightly more than 150 dB in the RNL curve are located in the 63, 125 and 315 Hz band. All SBN sensors show a significant peak at 31 Hz and smaller peaks at 16 and 63 Hz. However, despite its magnitude, the peak at 31 Hz does not generate intense underwater noise.

At 600 rpm, 30 Hz equals the ignition frequency of the 6-cylinder Diesel engines and 60 Hz equals the 2nd order of the ignition frequency. 90/120/150 Hz are the 3rd/4th/5th order of it. 16 Hz corresponds with the propeller blade frequency when the engines run at 600 rpm. 32/48/64 Hz are the higher orders of the blade frequency. These relations indicate that the peaks in the shown SBN signals in Figure 24 and Figure 28 are generated by the engine ignition frequency and/or the propeller blade frequency.

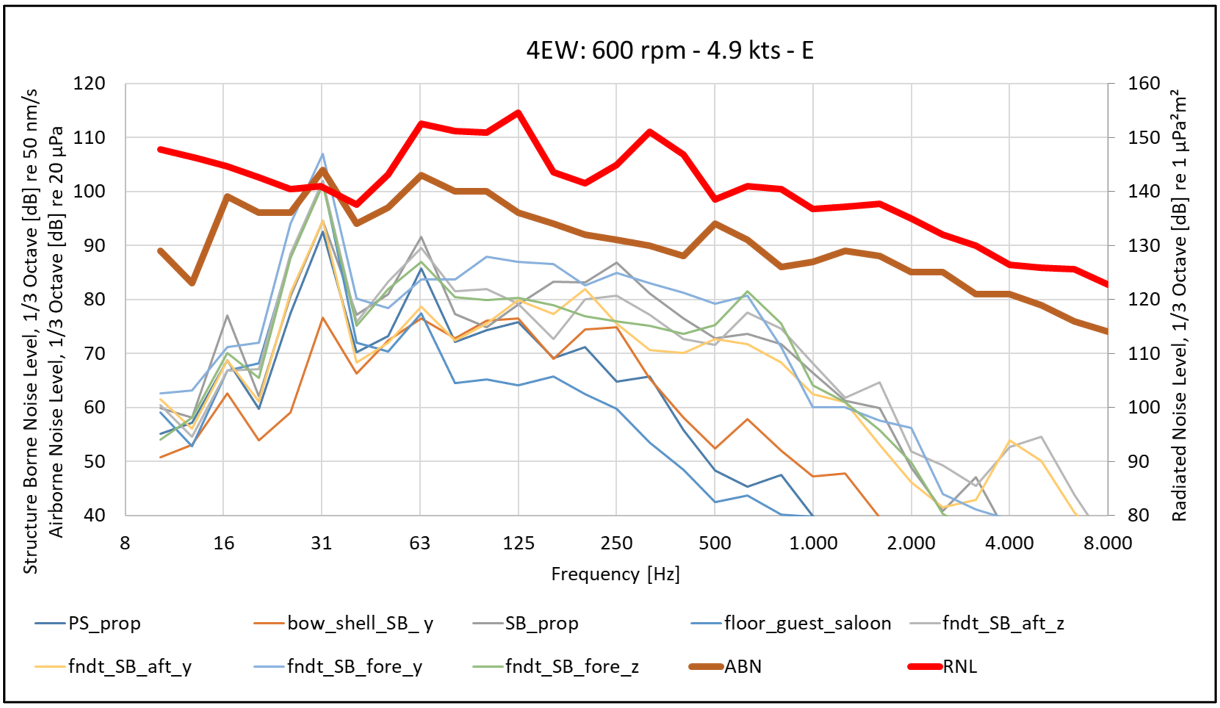

Figure 24: 4EW: Selected Sensor Data, RNL, ABN; 1/3 Octave at 600 rpm and 4.9 kts. SBN and ABN relate to left y-axis, RNL related to right y-axis

For a more detailed view of the frequency range below 500 Hz, the SBN and RNL data for the 600 rpm eastwards operation point is shown as narrow band data up to 500 Hz in Figure 25. The overall level of SBN on engine foundation is approximately 10 dB higher compared to other installations of single resiliently mounted high speed engines.

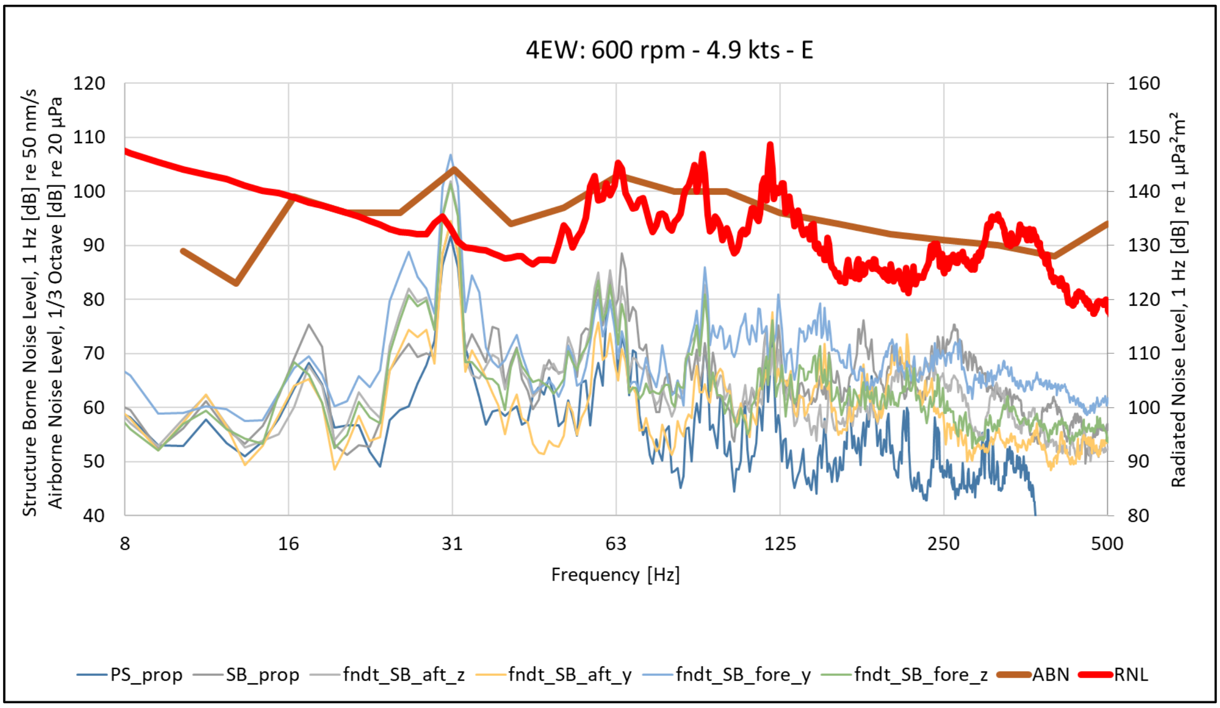

Figure 25. 4EW: Selected Sensor Data, RNL; 1 Hz at 600 rpm and 4.9 kts

With the higher resolution of the 1 Hz representation, one can see that the RNL peaks around 63, 90 and 120 Hz correspond with peaks in one of the signals taken at the engine foundations or at the shell above the propellers, these frequencies are clearly radiated into the water. However, the high SBN levels at 30 Hz are picked up with low intensity by the hydrophones which can be attributed to strong downward directivity (Lloyd mirror of shallow sources at low frequencies) or to poor radiation efficiency of the hull in this frequency range. Note that SBN levels on SB forward foundation are higher than 100 dB which is uncommon for resiliently mounted engines.

The results of the ABN measurements in vicinity of the engine showed no levels which would be high enough to cause the RNL in the lower frequency bands. Direct ABN transmission into the water dominates the levels between 1.5 kHz and 8 kHz but in those frequency bands the overall level is particularly low.

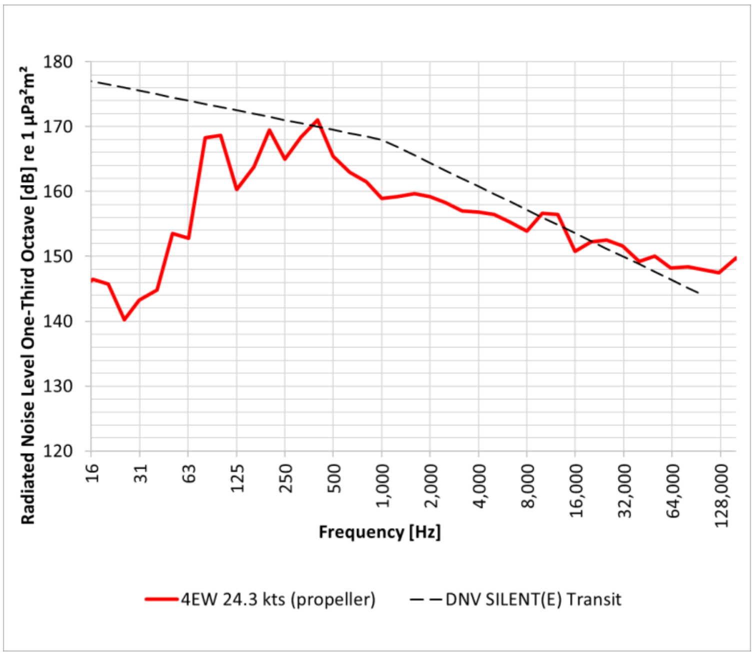

Figure 26: RNL of 4EW at high speed in comparison to DNV SILENT(E) (Transit)

The analysis of the high speed passage shows that the whole spectrum is dominated by the propeller (Figure 26). The lower frequencies clearly show the blade rate (five blades * rotational frequency).

For the detailed review, Figure 28 shows the signals of the relevant sensors for SBN, the RNL (bold red) and the ABN level (bold brown) of 4EW when sailing eastwards on the test track at 3300 rpm and 24.5 kts, which is close to the maximum speed of the boat. A comparison of slow speed and high speed in Figure 27 shows that radiated noise increases over the full frequency range. While radiated noise levels are fully dominated by machinery noise at slow speed, significant contribution from the propeller is identified for high speed condition. The magnitude of structural vibration with more than 110 dB re 50 nm/s above the propeller (Figure 29) is an indication that the propellers heavily cavitate.

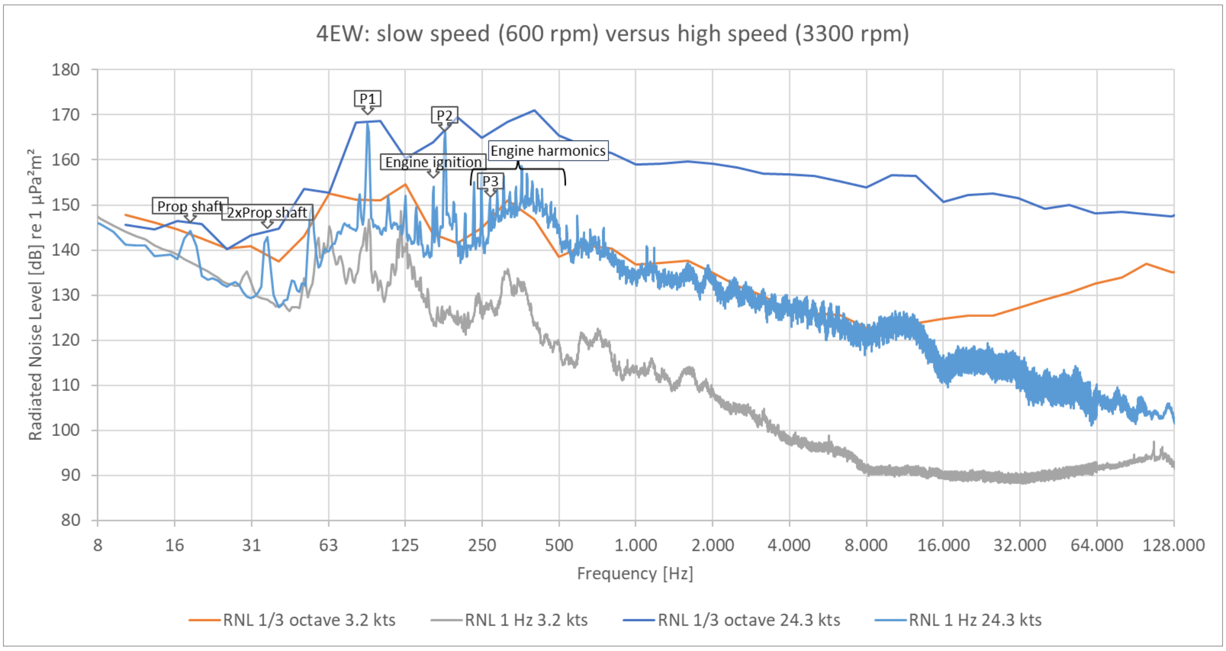

Figure 27: 4EW, comparison of RNL for slow speed and high speed. P1, P2 and P3 indicate propeller blade frequency harmonics

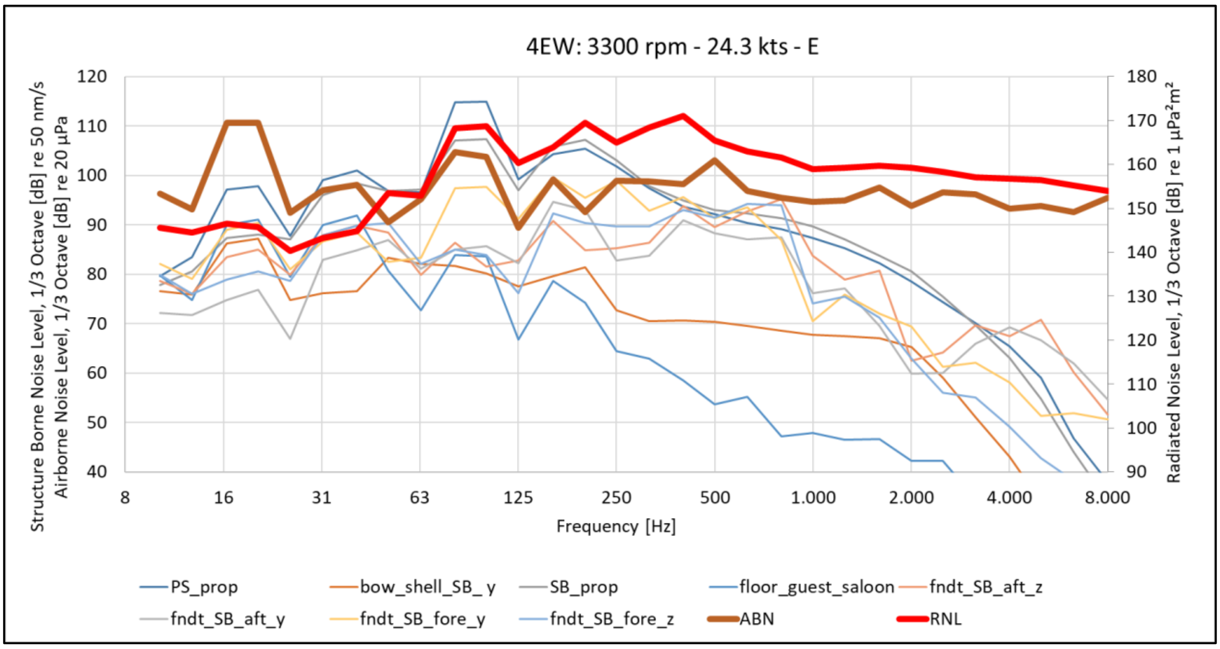

Figure 28: 4EW: Selected Sensor Data, RNL; 1/3 Octave at 3300 rpm and 24.5 kts

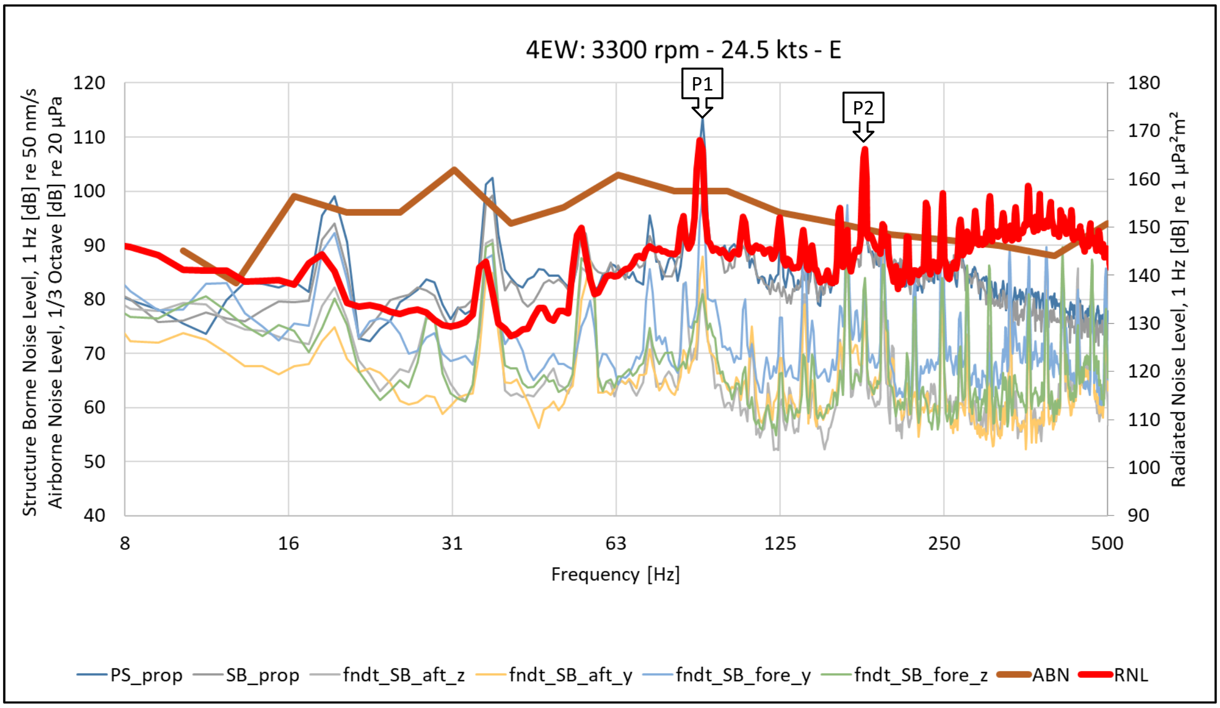

Figure 29: 4EW: Selected Sensor Data, RNL; 1 Hz at 3300 rpm and 24.5 kts. P1 and P2 indicate propeller blade frequency harmonics

Cavitation is the process of vapour bubbles forming in a fluid medium in areas of low pressure. On ships, cavitation is generated by the lifting surfaces of a propeller moving through the water or by appendages such as rudders. For a commercial vessel, cavitation occurs in different forms that radiate broadband noise and tonal noise to varying extents (Carlton 2007), as shown in Figure 30.

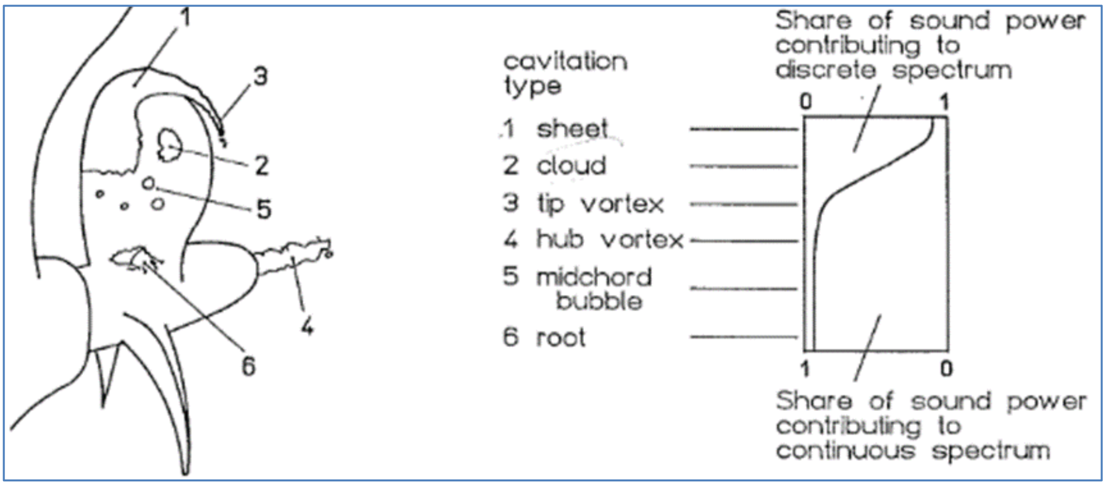

Figure 30: cavitation types on a propeller and their contributions to frequency components of the spectrum (source: Carlton 2007)

On 4EW at the top speed of 24.3 kts, it is concluded from SBN and URN measurements that both propellers show fully developed cavitation. Their noise contributions at this speed clearly dominates the spectrum above 250 Hz. At frequencies above 64 kHz the level is even constant or increasing although typical cavitation spectra would show a slight decrease of level per 1/3 octave.

Figure 31 shows the relationship between speed and band level above 15 kHz relevant for high frequency sensitive species. The rise in level is moderate.

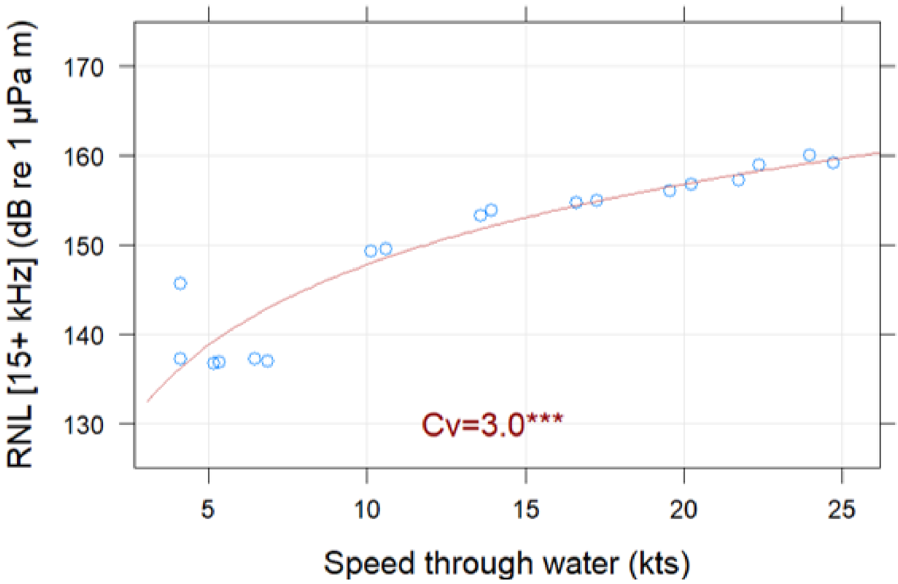

Figure 31: 4EW RNL > 15 kHz versus speed

Figure 31 shows 4EW's RNL versus speed and allows a comparison of the noise emissions at slow speed with those at high speed. As the URN measurements incorporated several passages at different speeds over the ULS, this figure also provides information on how the noise level increases with speed over the whole operational range.

The most significant change in level happens between 7 kts and 10 kts. Between those two speeds, the RNL increases by 13 dB, while the level increase between 10 kts and 25 kts is 10 dB.

Reason for this significant change is the cavitation inception which happens between 7 kts and 10 kts. This speed is called cavitation inception speed. Each combination of propeller and hull has an individual cavitation inception speed which also depends on current amount of marine growth on surfaces of hull and propeller. A higher cavitation inception speed would shift the curve of Figure 31 to the right.

Therefore, a reduction of cavitation noise can be achieved by operating at slower speeds or an increase of the cavitation inception speed. The technical solutions are described in Chapter 7.

To find the reason for the high SBN levels at the engine foundations in the region of 30 Hz (Figure 24) and the higher harmonics (Figure 25, Figure 29), the effectiveness of the elastic mounting of the engine is evaluated and the structure of the foundation is reviewed based on the pictures which were taken during the measurement campaign.

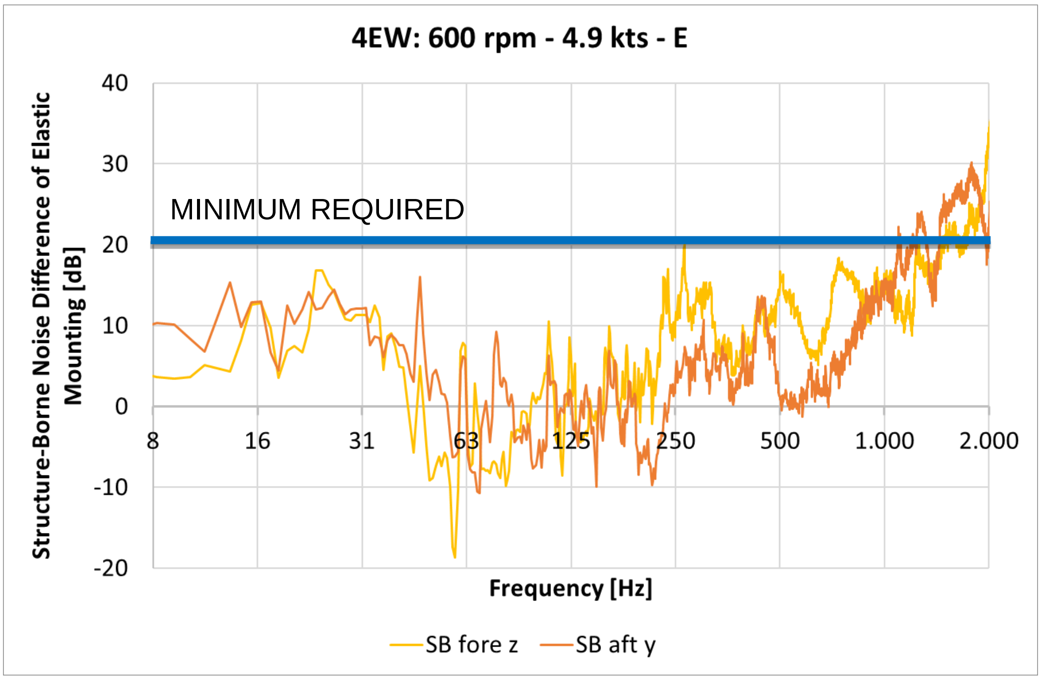

Figure 32: SBN difference above and below the flexible engine mounts on 4EW at slow speed.

For this analysis, the measured SBN level below the mounts was subtracted from the measured SBN level above the mount. The resulting level difference is shown in Figure 32 for vertical and lateral direction. An elastic mount (see example in Figure 33) is intended to reduce the engine's dynamic forces on the foundation. A properly working elastic decoupling of engine and foundation by such rubber mounts provides a level difference of at least 20 dB. On 4EW the elastic mounting system provides such a level difference only at frequencies above 2 kHz. Especially in the frequency ranges of concern (63 and 125 Hz), the mounting system does not work properly. Reason for this is either a low foundation impedance (=foundation is not stiff enough), too stiff rubber mounts or a combination of both. Flanking path transmission by the cardan shaft to connect resiliently mounted engine with rigidly mounted shaft bearing can also be a relevant transmission path. The technical analysis and recommendations for remedial measures is given in Chapter 7.

Figure 33: Example of an elastic engine mount. Picture taken on GW.

6.2 Goldwing (GW)

On Goldwing, the 9 locations shown in Table 3 have been equipped with acceleration sensors. The sensor signals have been tracked and processed with IMC Wave 2022 and IMC Studio 2022.

Table 3: GW: Sensor Naming and Location

Channel	Location (, Direction)
eng_PS_aft_ z	portside engine: aft mounting bracket, vertical
eng_SB_aft_y	starboard engine: aft mounting bracket, horizontal
eng_SB_aft_z	starboard engine: aft mounting bracket, vertical
eng_SB_fore_y	starboard engine: fore mounting bracket, horizontal
fndt_SB_aft_z	engine foundation starboard: below aft elastic mounting element, vertical
fndt_SB_aft_y	engine foundation starboard: below aft elastic mounting element, horizontal
fndt_SB_fore_z	engine foundation starboard: below fore elastic mounting element, vertical
fndt_SB_fore_y	engine foundation starboard: below fore elastic mounting element, horizontal
eng_SB_fore_z	starboard engine: fore mounting bracket, vertical

Since the propellers are placed behind the hull on Goldwing, it was not possible to place a sensor in the hull close to them, thus their influence on the URN could not be measured by SBN measurement.

Similar to 4EW, GW also features an engine which is installed onboard on flexible engine mounts. The two resiliently mounted engines drive the two propellers via a short cardan shaft. The most significant difference to 4EW is the propeller type, which is surface piercing. Furthermore, GW is a monohull made of aluminum, has a smaller draft and carries less passengers than 4EW. This allows it to perform considerably higher speeds of up to 35 kts.

Surface piercing propellers are suitable for very high speed ships up to and beyond 60 knots. The propellers are steerable by a hydraulic mechanism. In low speed they are fully submerged, at high speed they are steered such that only the lower half of the propeller is submerged so that only the pressure side of the blades is in contact with water.

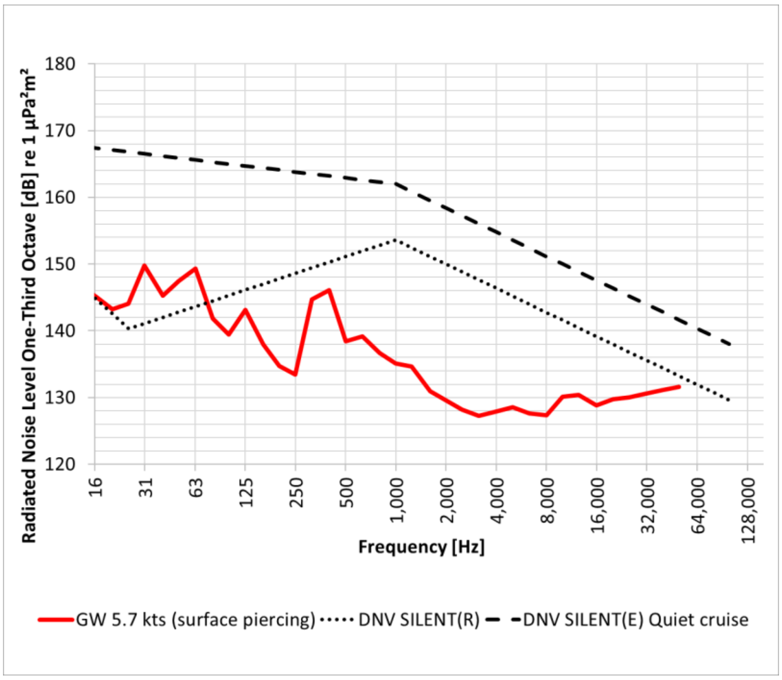

Figure 34: RNL of GW at a slow speed in comparison to DNV SILENT(R) and E (Quiet Cruise)

The slow speed URN spectrum shows that GW also exceeds the SILENT(R) limit curve in some lower frequency bands but stays compliant with SILENT(E) (Quiet Cruise) (Figure 34).

Figure 35 shows the signals of the relevant SBN sensors for URN, the RNL (bold red) and the ABN level (bold brown) of GW when sailing westwards on the test track at 650 rpm with 6.0 kts. The dominating peaks of approximately 150 dB in the RNL curve are in the 31.5 and 63 Hz band. All SBN sensors show a significant peak at 32 Hz and smaller peaks at 63 Hz.

At 650 rpm, 32 Hz equals the ignition frequency of the 6-cylinder Diesel engines and 64 Hz equals the 2nd order of the ignition frequency. 32 Hz also corresponds with the propeller blade frequency when the engines run at 650 rpm. 64 and 96 Hz are the 2nd and 3rd order of the blade frequency. The observations in Figure 42 indicate that the peaks at 32 Hz in the shown SBN signals in Figure 35 are generated by the engine ignition frequency.

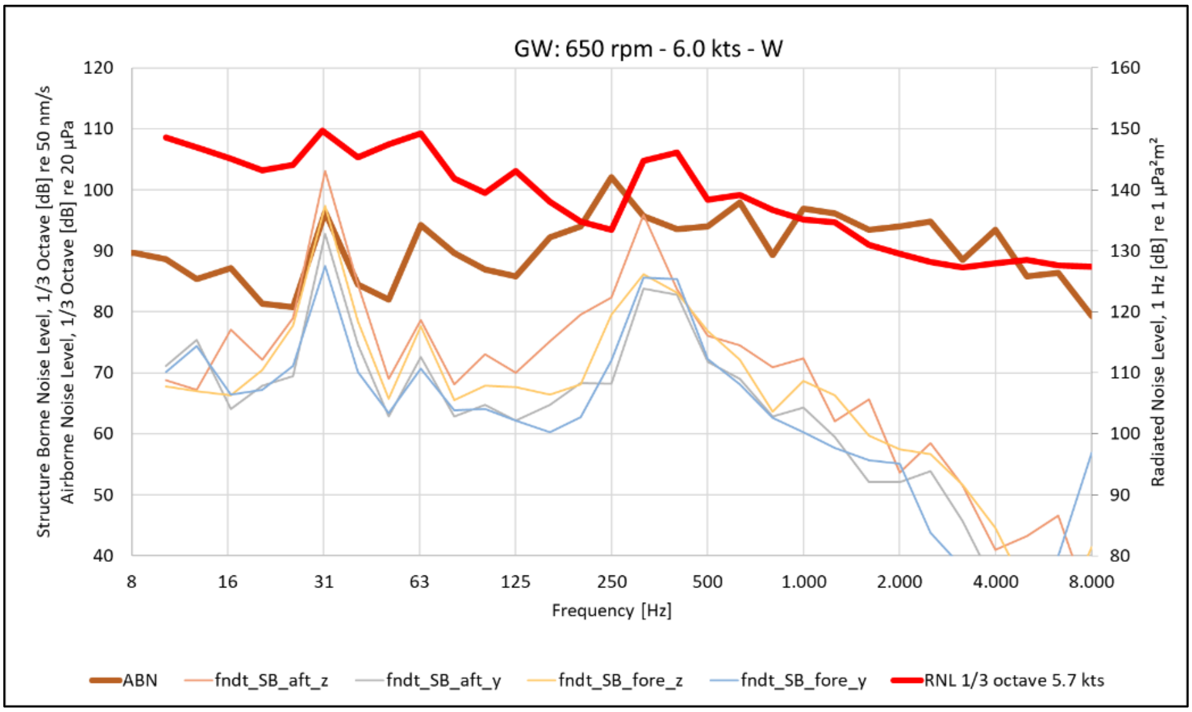

Figure 35: GW: Selected Sensor Data, RNL, ABN; 1/3 Octave at 650 rpm and 6.0 kts

For a more detailed view of the frequency range below 500 Hz, the SBN and RNL data for the 650 rpm westwards operation point is shown as narrow band data up to 500 Hz in Figure 36.

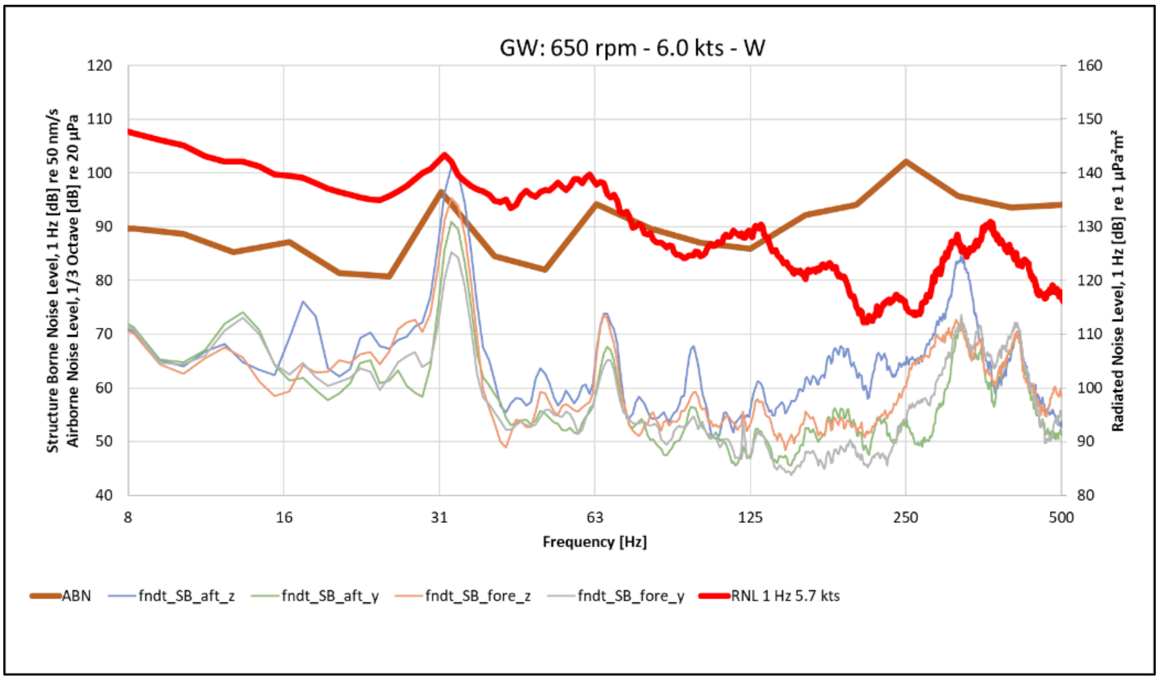

Figure 36: GW: Selected Sensor Data, RNL; 1 Hz at 650 rpm and 6.0 kts

Frequencies below around 750 Hz are dominated by the engine. The analysis of onboard sensors provides very similar results as for 4EW: The engine's SBN is transmitted through the elastic engine mounts, through the foundation into the structure and radiates through the hull into the water.

URN contributions above 750 Hz can be attributed to the propeller. The level of those emissions is quite low and does not raise any concerns.

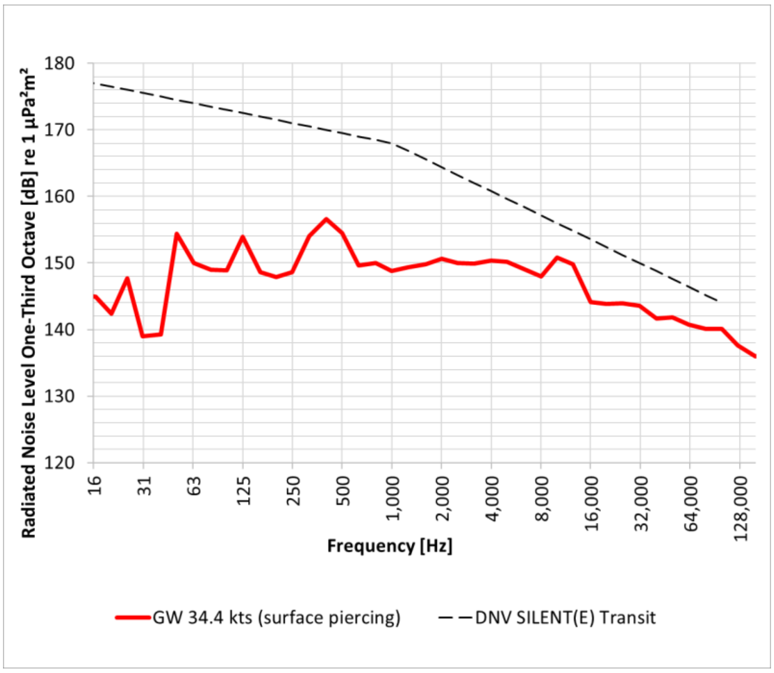

Figure 37: RNL of GW at a high speed in comparison to DNV SILENT(E) (Quiet Cruise)

GW's URN emissions at high speed are the lowest of all three vessels (Figure 37). This is the only signature which complies with the DNV SILENT(E) (Transit) at high speeds, even though GW's measured speed was 34.4 kts.

Figure 38 shows the signals of the relevant SBN sensors for URN, the RNL (bold red) and the ABN level (bold brown) of GW when sailing westwards on the test track at 2460 rpm and 34.5 kts, which is the maximum speed of the boat. Compared to the 650 rpm operation point (Figure 35), the RNL has increased at frequencies higher than 50 Hz. The same applies for the ABN level. The SBN signals show a significant peak at 25 Hz, which is close to the propeller frequency of 23.8 Hz. The SBN peak at 31 Hz (low speed) does not occur at high speed. The SBN level has increased over the whole frequency range.

As can be seen in the more detailed 1 Hz representation in Figure 39, the SBN and ABN curve run quite parallel above 63 Hz.

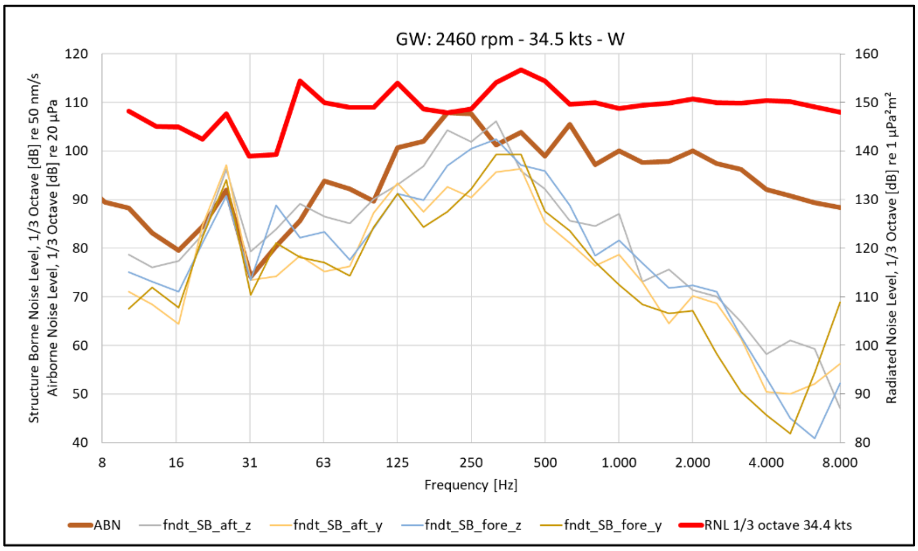

Figure 38: GW: Selected Sensor Data, RNL, ABN; 1/3 Octave at 2460 rpm and 34.5 kts

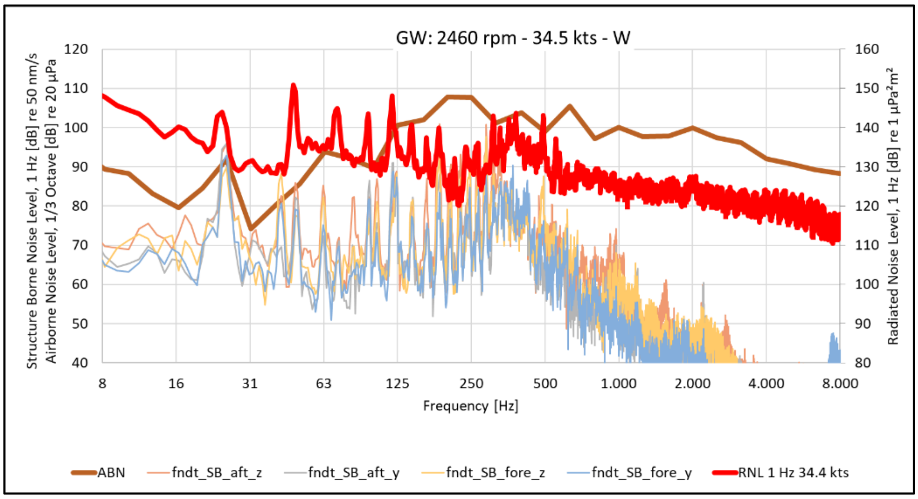

Figure 39: GW: Selected Sensor Data, RNL, ABN; 1 Hz at 2460 rpm and 34.5 kts

The reason for the comparatively low levels at high speed is likely to be found in the propulsion concept. GW is the only vessel with surface piercing propellers.

Figure 40: GW's surface piercing propeller

As can be seen in Figure 40, the propeller operates right at the water surface. This results in three different effects which contribute to a lower RNL:

1. Sources high in the water column do not propagate as effectively as sources in the middle of the water column. Due to waves and wind, the water in vicinity of the surface is filled with more air bubbles than deeper water. Even tiny air bubbles have an effect on the water's acoustic absorption capability. Therefore, the sound propagation at the water surface is impeded.
   In addition to that, a source directly at the surface underlies the Lloyd-Mirror-Effect which makes noise radiation appear as a dipole, i.e., vertically directed. The lower the source depth the more significant is this effect. This geometrical effect is also responsible for the reduced RNL.
2. A surface piercing propeller mixes a significant amount of air with the water. These air bubbles around the noise source act as a kind of silencer and absorb a part of the generated noise.
3. A surface piercing propeller does not show suction side cavitation as the suction side and the upper half of the propeller are completely ventilated.
4. Figure 41 shows the relationship between speed and band level above 15 kHz relevant for high frequency sensitive species. The rise in level is low, however, with a steeper rise above 30 knots

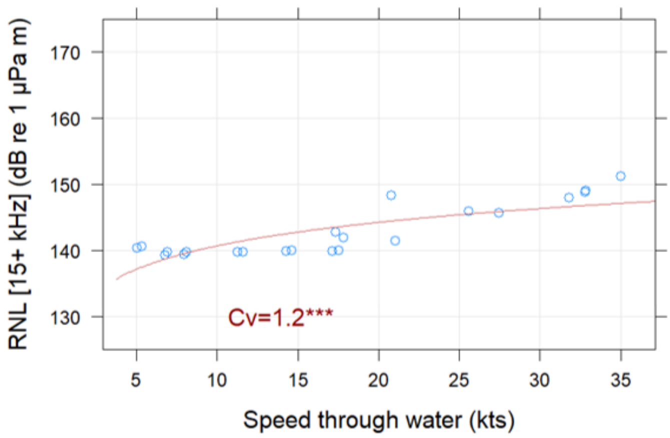

Figure 41: RNL versus speed of GW

A look at the RNL versus speed plot shows how unsusceptible this vessel is to higher speeds. The RNL stays nearly constant between 5 kts and 20 kts. Just above 20 kts, a small increase in level is observed.

Due to the high SBN peaks at 31 Hz (low speed) and 25 Hz (high speed) at the engine foundations a review of the elastic mounting and the foundations of the engines is performed.

Figure 42 shows the mean SBN levels above and below the resilient mounts, measured at 2460 rpm and the level difference between engine and foundation, which equals the attenuation of the elastic mounting. Additionally, the expected attenuation of an elastic mounting is shown. As can be seen, the attenuation is below the expected value over a wide range of the considered frequency region.

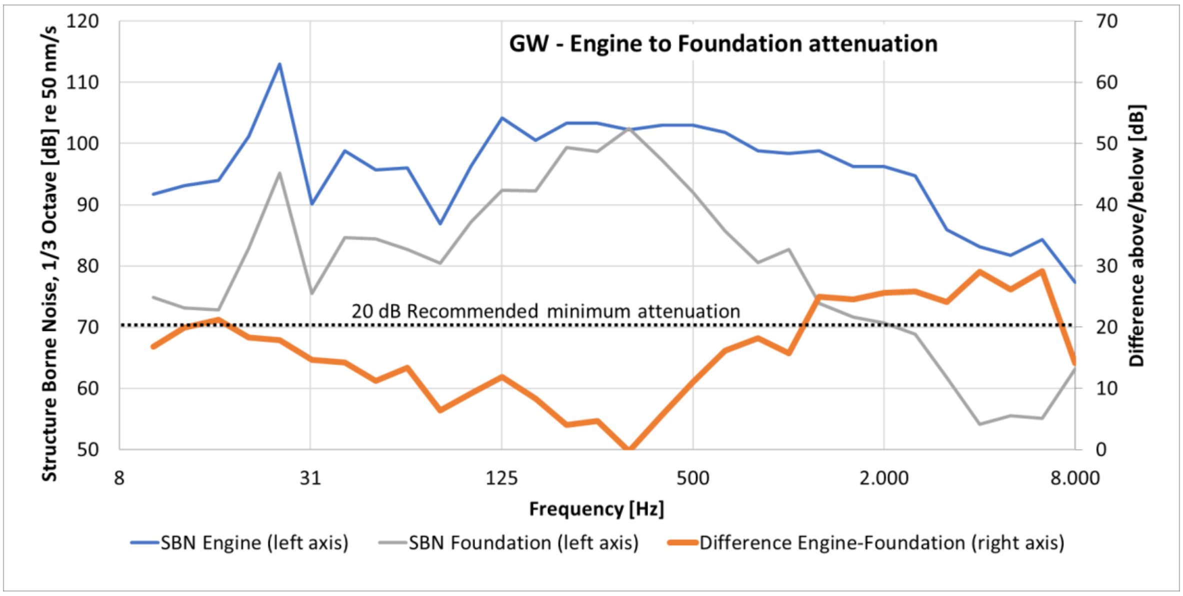

Figure 42: GW: Attenuation of Elastic Mounting: Mean SBN levels at 2460 rpm and 34.5 kts

Figure 44 and Figure 43 show a view in the engine room of GW and one of the aft engine mountings. The engines are mounted on longitudinal web frames with significant cutouts. In cross direction, the lonituginal frames are stiffened by one frame approximately in the middle between the forward and aft engine mountings, the photograph of Figure 44 stands on another cross frame. In addition to the standard Volvo Penta mounting elements (Figure 43, right) one element per side is installed at the power take off side and mounted to the gearbox which is flanged to the engine. The standard mounting element in Figure 43 is placed above a large cutout.

Figure 43: GW: Engine Mounting

Figure 44: GW: Engine Room

Another investigation on all four vessels aimed at a comparison between the low speed voyages in hydrostatic displacement condition and the planing condition. During planing a vessel faces a reduced drag compared to the displacement condition.

Analysing the URN data, it was seen that this drag reduction did not lead to a reduction of URN.

Figure 45 shows the angular signal around the cross direction over time. In the left part of the figure, the trim angle varies around a rather constant value; the boat is displacing. In the right part, the trim angle follows a periodic shape which is explained in the zoom of the red framed part (Figure 46). In Figure 46, a typical run across the ULS track is shown. The trim angle decreases first, then it increases, followed by a constant part and then in increases again. This shape matches the acceleration phase, the measurement period and the following deceleration phase.

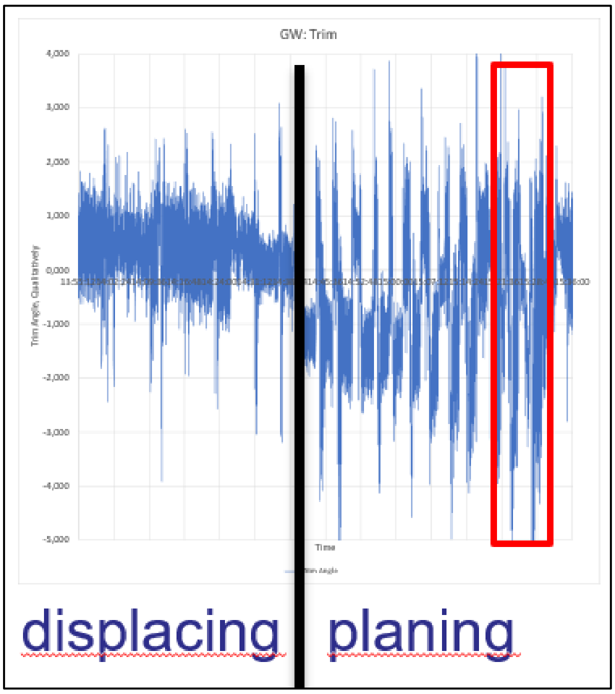

Figure 45: GW: Trim Angle vs Time; Detail Shown in Figure 46

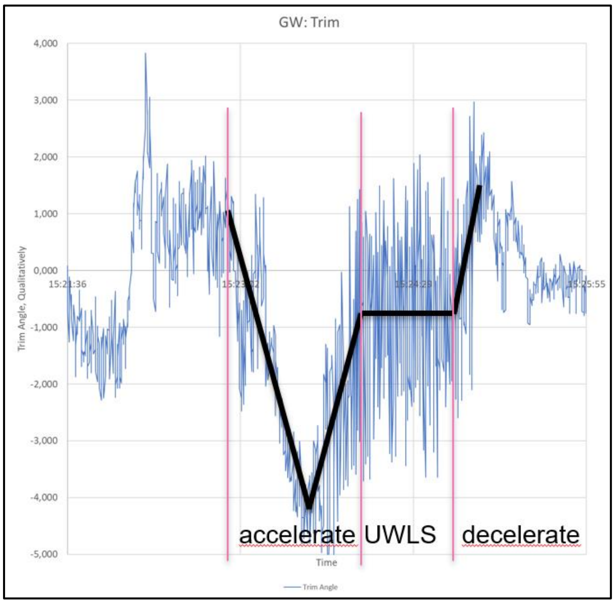

Figure 46: GW: Trim Angle During Run when Planing

The evaluation of the trim angle data and the logsheet of the runs shows that the boat is displacing at speeds below 11 kts. Between 11 and 20 kts it is semi-planing, above 20 kts it is planing. No clear dependency from displacing or planing can be found; the development of the RNL over speed appears to be more likely related to the boat speed.

6.3 Serengeti (SE)

Serengeti is equipped with outboard engines which don't allow SBN measurements at the engine foundations or close to parts of the propulsion drive line. Since the propellers work behind the hull and due to a necessary change in the measurement equipment which can deal with four channels only, it was decided to place an acceleration sensor at each engine and one at the hull bottom close to the stern. Figure 47 shows the sensor position at the PS engine exemplarily. The sensor signals have been tracked and processed with LabView and NI Sound and Vibration Assistant.

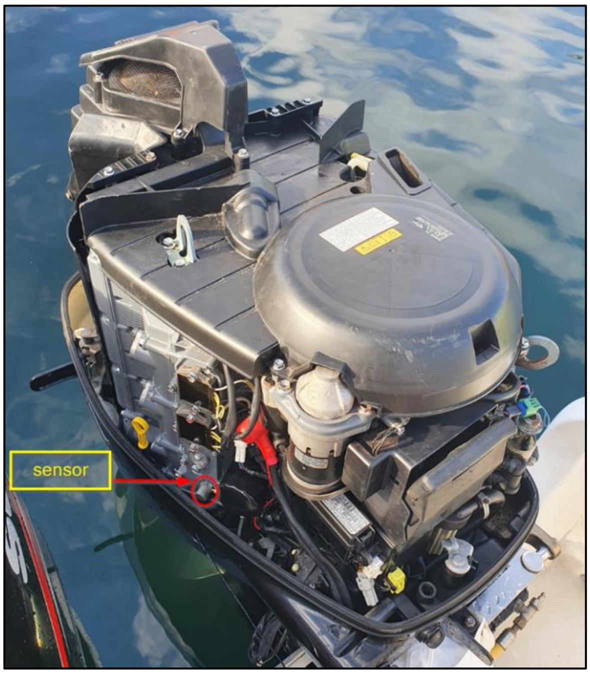

Figure 47: SE: Sensor Position at Engines; PS Engine Shown

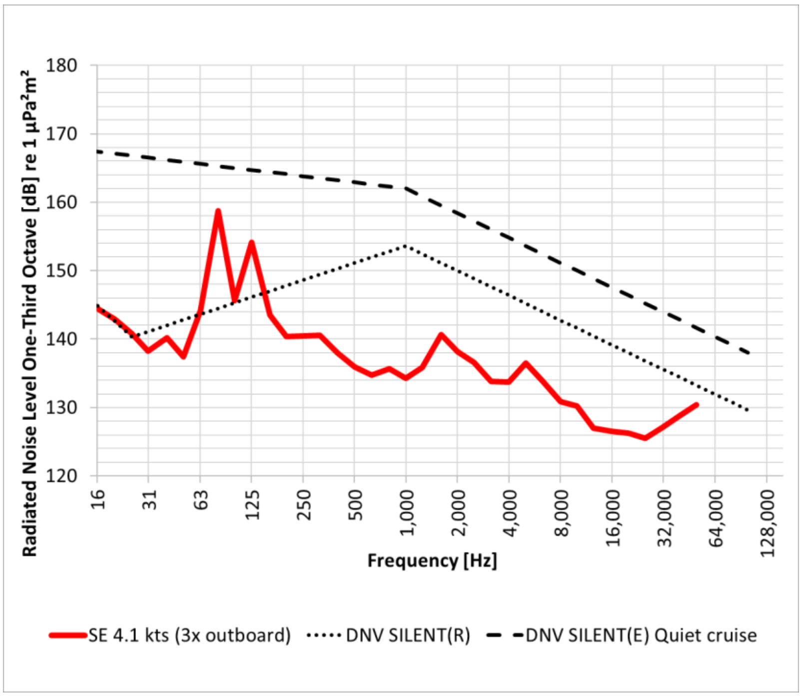

Figure 48: RNL of SE at a slow speed in comparison to DNV SILENT(R) and E (Quiet Cruise)

In comparison to the other vessels, SE features the highest spikes in the lower frequencies during the slow speed transit (Figure 48).

Figure 49 shows the SBN, ABN and RNL when sailing at 844 rpm and 4.1 kts. The smaller peaks of the SBN signals correspond with half engine speed orders, the higher peaks show the noise caused by the propeller blades. The URN is dominated by a mix of the 6th and 9th order of the engine rotation frequency and the 3rd and 4th order of the propeller blade frequency.

The analysis shows that the low frequencies below 100 Hz are dominated by exhaust gas noise because overall SBN levels are low but 6th order RNL is high which corresponds to the number of cylinders. This is plausible as the exhaust gas outlets are located below the waterline (see Figure 50). The clear distinguishable tone is caused by the engine's ignition frequency and transferred into the water via the exhaust gas.

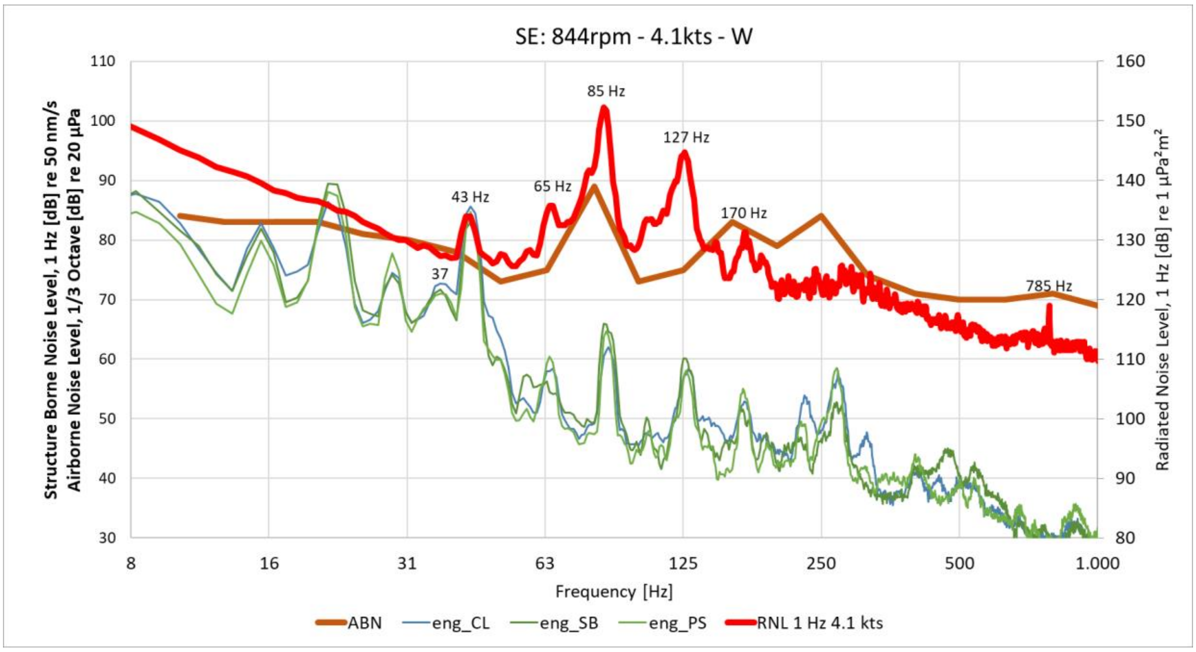

Figure 49: SE: SBN, ABN and RNL at 844 rpm and 4.1 kts

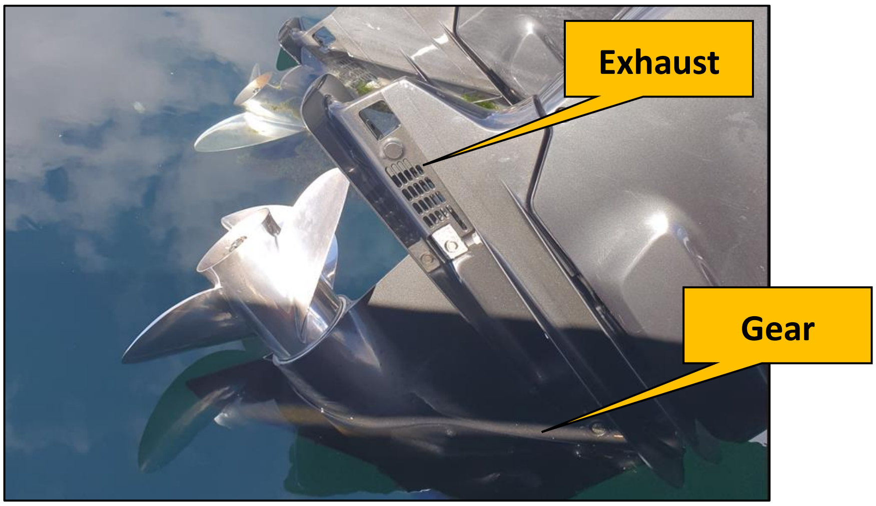

Figure 50: One of the three SE's Suzuki outboard motors. Picture was taken with the motors in retracted position.

Other spikes are observed at 127 Hz and 170 Hz. These are also attributable to an individual feature of outboard motors which have a bevel gear in the gondola directly in front of the propeller and below the waterline. This gear transfers the vertical shaft rotation from the engine into a horizontal shaft rotation for the propeller. The very small installation room for the gearbox allows for a very effective coupling to the surrounding water medium, thus enabling the sound transmission from the gearbox into the water. Above 1 kHz the spectrum is dominated by the propeller.

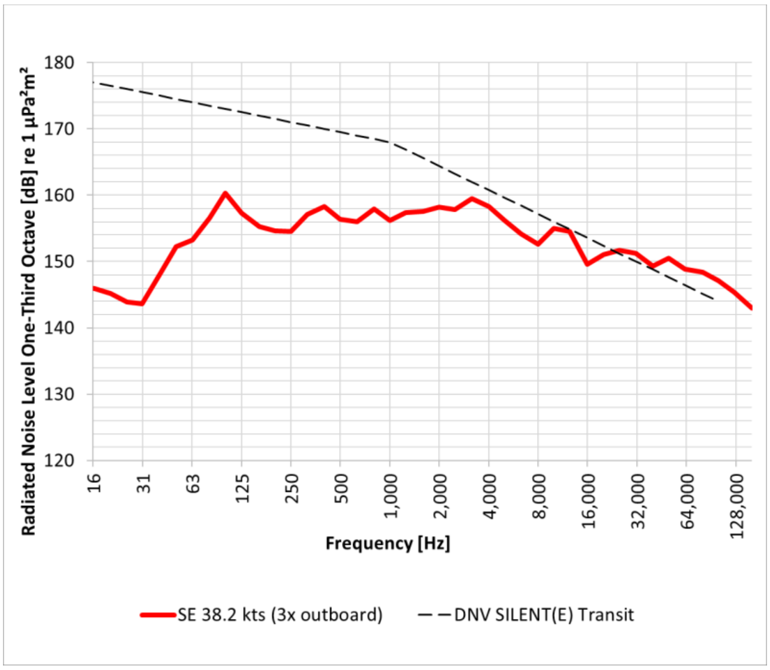

Figure 51: RNL of SE at a high speed in comparison to DNV SILENT(E) (Quiet Cruise)

At SE's top speed of 38.2 kts the engine noise is visible in all frequencies below 500 Hz (Figure 51).

Due to a sensor overload at full speed, the maximum speed that can be evaluated for SBN is 26.0 kts at 3350 rpm. Figure 52 shows the SBN and RNL at this operation point. ABN is excluded as signals from the microphone were dominated by wind noise.

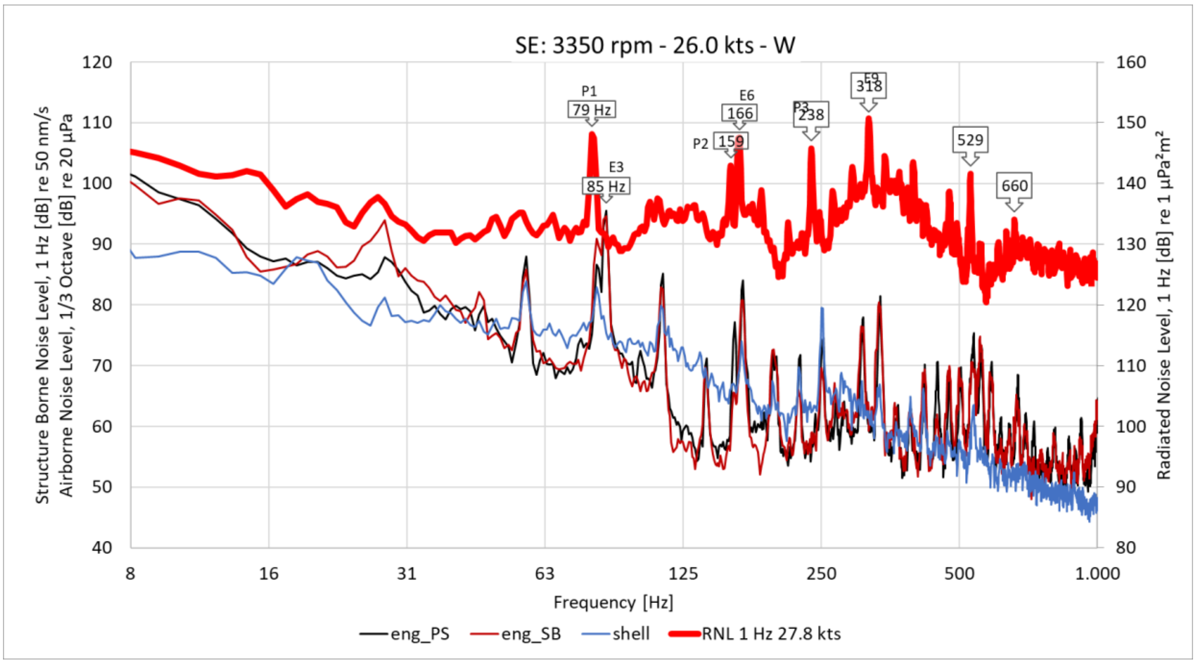

Figure 52: SE: SBN and RNL at 3350 rpm and 26.0 kts. "E" indicates multiples of engine speed, "P" multiples of propeller blade frequency

The URN is dominated by the propeller blade frequency of 79 Hz, the 3rd order of the engine rotation frequency (166 Hz) and most probably by a tone generated by the pair of bevel wheels in the submerged part of the outboard engine shaft at 318 Hz. It seems to be a combination of exhaust gas noise, gear noise and SBN from the engine. It is remarkable that these lower frequencies show only a very minor increase in level compared to the idle speed.

This is all the different for the cavitation noise which contributes to the level between 500 Hz and 1 kHz and clearly dominates the spectrum above that.

Figure 53 shows the relationship between speed and band level above 15 kHz relevant for high frequency sensitive species. The rise in level is still low, however, with a steeper rise above 30 knots.

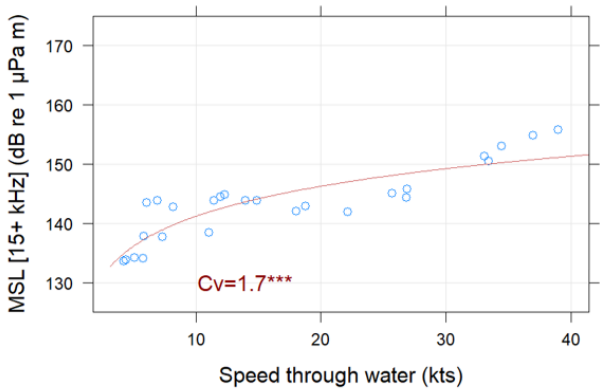

Figure 53: RNL versus speed of SE

Another remarkable observation is that SE shows two "steps" in its RNL versus speed plot. The first speed after idle already shows a significant increase in level. But between 5 kts and 28 kts this level barely increases. Only the speed level above 32 kts shows an increase.

6.4 Wild 4 Whales (W4W)

On Wild 4 Whales, the 14 locations shown in Table 4 have been equipped with acceleration sensors. The sensor signals have been tracked and processed with IMC Wave 2022 and IMC Studio 2022.

Channel	Location (, Direction)
jet_PS_pump	PS jet: close to pump
eng_PS_aft_z	PS engine: aft bracket, vertical
eng_PS_aft_y	PS engine: aft bracket, horizontal
foil_PS	near foil mounting in PS hull
eng_STB_aft_z	SB engine: aft bracket, vertical
eng_STB_aft_y	SB engine: aft bracket, horizontal
jet_SB_intake	SB jet: close to intake
jet_SB_pump	SB jet: close to pump
eng_SB_fore_z	SB engine: fore bracket, vertical
fndt_SB_aft_y	SB engine foundation: below aft elastic mounting element, horizontal
fndt_SB_aft_z	SB engine foundation: below aft elastic mounting element, vertical
fndt_SB_fore_y	SB engine foundation: below fore elastic mounting element, horizontal
fndt_SB_fore_z	SB engine foundation: below fore elastic mounting element, vertical
eng_SB_fore_y	SB engine: fore bracket, horizontal

Table 4: Sensor Naming and Location

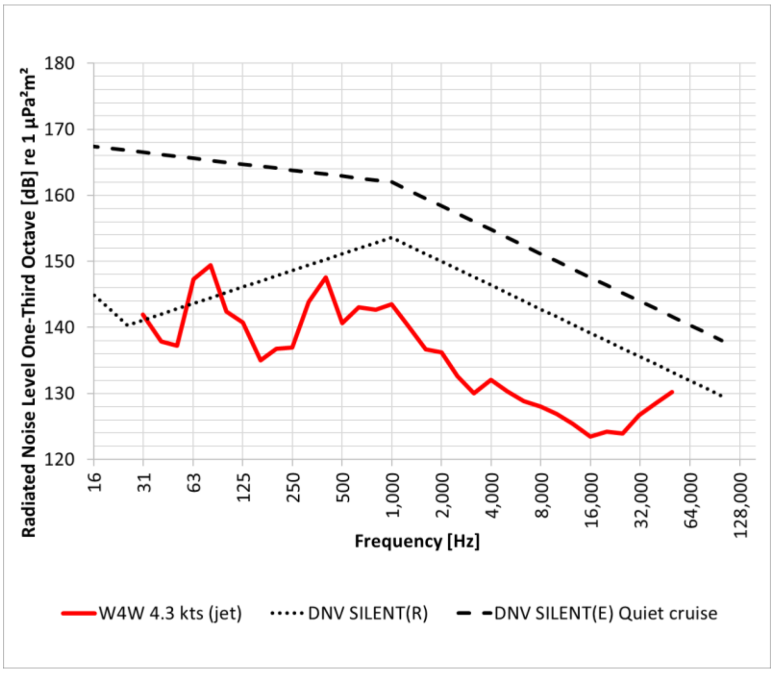

Figure 54: RNL of W4W at a slow speed in comparison to DNV SILENT(R) and E (Quiet Cruise)

At a slow speed W4W shows only slight exceedances of DNV's SILENT(R) limit curve around 63 to 100 Hz (Figure 54). It is the quietest of the analysed vessels at this speed.

Figure 55 shows the signals of the relevant SBN sensors for URN, the RNL (bold red) and the ABN level (bold brown) of W4W when sailing eastwards on the test track at 600 rpm with 4.2 kts. The dominating peaks of almost 150 dB in the RNL curve are located in the 80 and 400 Hz band. All SBN sensors show a significant peak at 31 and 63 Hz. The 63 Hz peak might partly cause the RNL peak at 80 Hz; the narrow band data will show this more clearly.

At 600 rpm, 30 Hz equals the ignition frequency of the 6-cylinder Diesel engines, the higher orders value 90, 120 and 150 Hz. 50 Hz corresponds with the propeller blade frequency when the engines run at 600 rpm, its higher orders value 100, 150, and 200 Hz. These relations indicate that the peaks in the shown SBN signals at 30 and about 60 Hz in Figure 55 are generated by the engine ignition frequency.

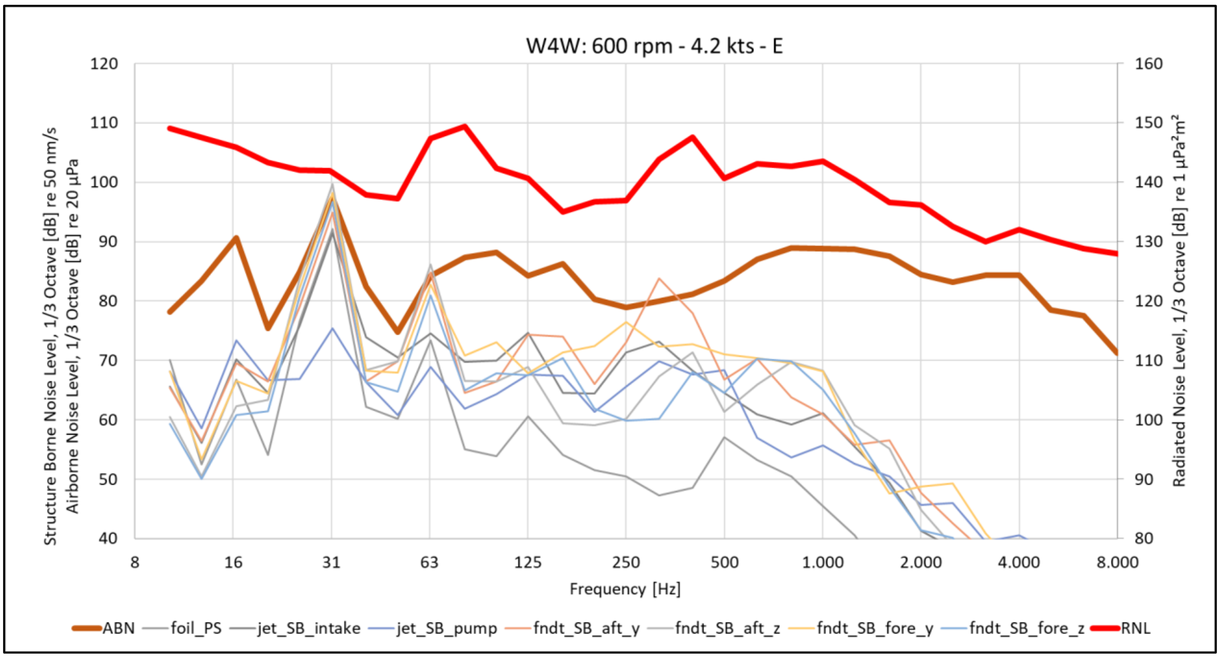

Figure 55: W4W: Selected Sensor Data, RNL, ABN; 1/3 Octave at 600 rpm and 4.2 kts

For a more detailed view of the frequency range below 500 Hz, the SBN and RNL data for the 600 rpm eastwards operation point is shown as narrow band data up to 500 Hz in Figure 56. The sensor at the foil is not dominating, thus its signal is not shown in Figure 56.

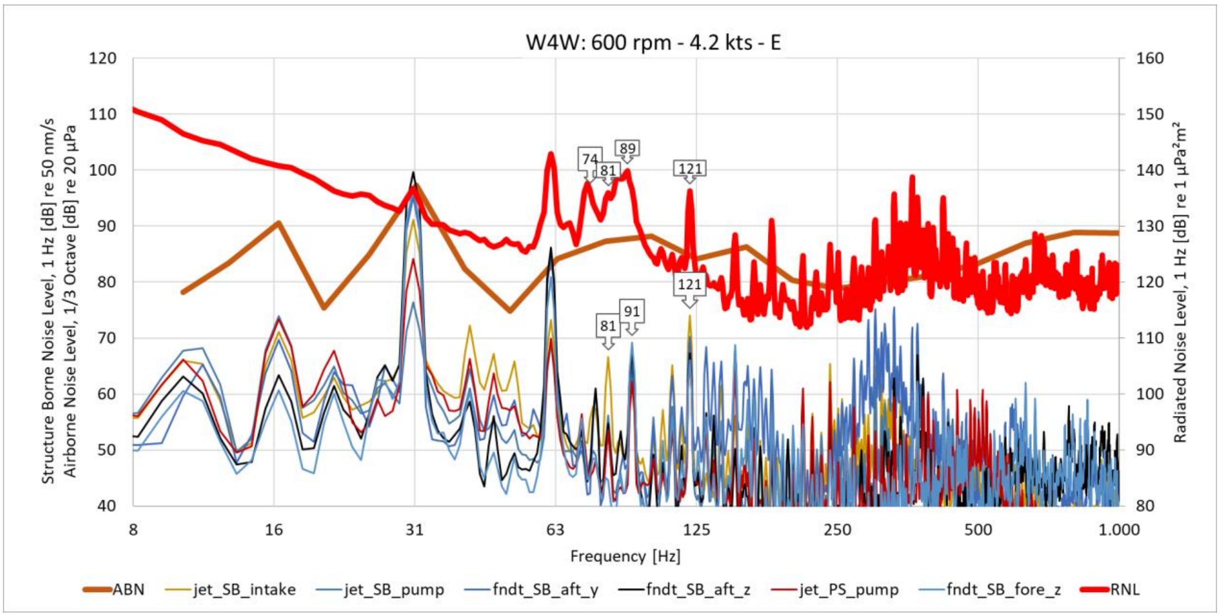

Figure 56: Selected Sensor Data, RNL; 1 Hz at 600 rpm and 4.2 kts

The narrow band data shows that the SBN peaks at 31 Hz (ignition frequency) virtually match the small peak in the RNL data at 30 Hz. The higher orders of the ignition frequency cause RNL peaks at 60, 90 and 120 Hz of which the 60 and 90 Hz peaks dominate the RNL signal with 142 and 137 Hz.

Above 250 Hz, the RNL curve shows peaks in 10 Hz steps with eye-catching regularity which are accompanied by respective peaks in the SBN sensors at the engine foundations. This phenomenon will be discussed in chapter 7.3. At frequencies below 2 kHz, the recorded noise was transmitted through the structure. Above it, ABN transmission prevails. The propulsors are not recognizable at all at this speed.

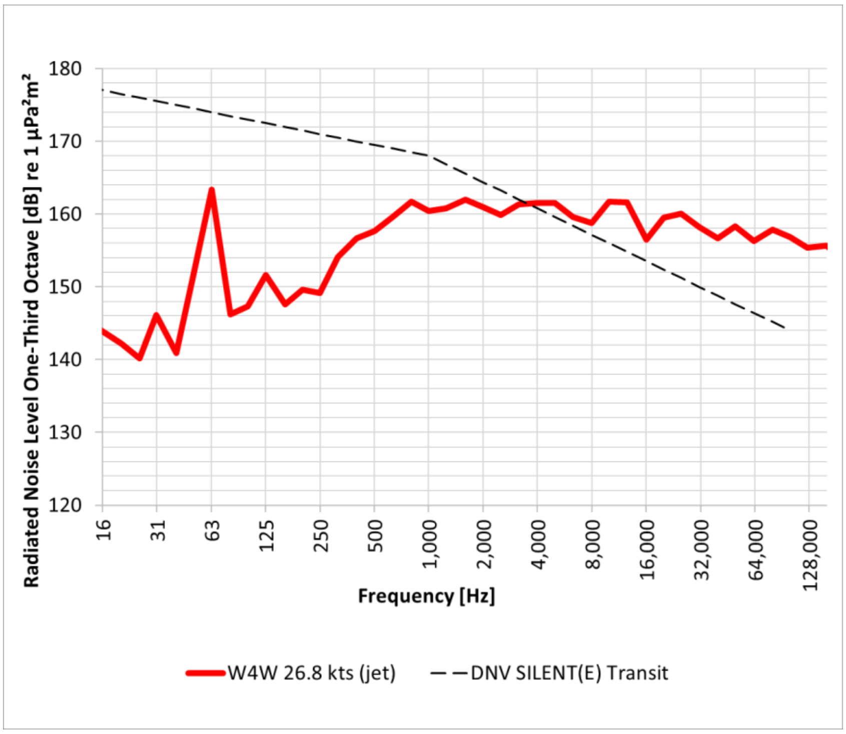

Figure 57: RNL of W4W at a high speed in comparison to DNV SILENT(E) (Quiet Cruise)

W4W's URN spectrum at top speed shows a completely other result (Figure 57). Engine SBN goes up by 15 dB.

At high speed, the SBN, ABN and RNL situation results as shown in Figure 58. As expected, significantly higher SBN levels have been measured compared to the low-speed case. The ABN level increased a little, the RNL shows a peak of 163 dB at 63 Hz and increases up to a plateau of about 160 dB at 800 Hz and above. The source for the peak at 63 Hz cannot be identified in the SBN data in the 1/3 octave representation, thus the data is plotted as narrow band up to 500 Hz in Figure 59 and Figure 60.

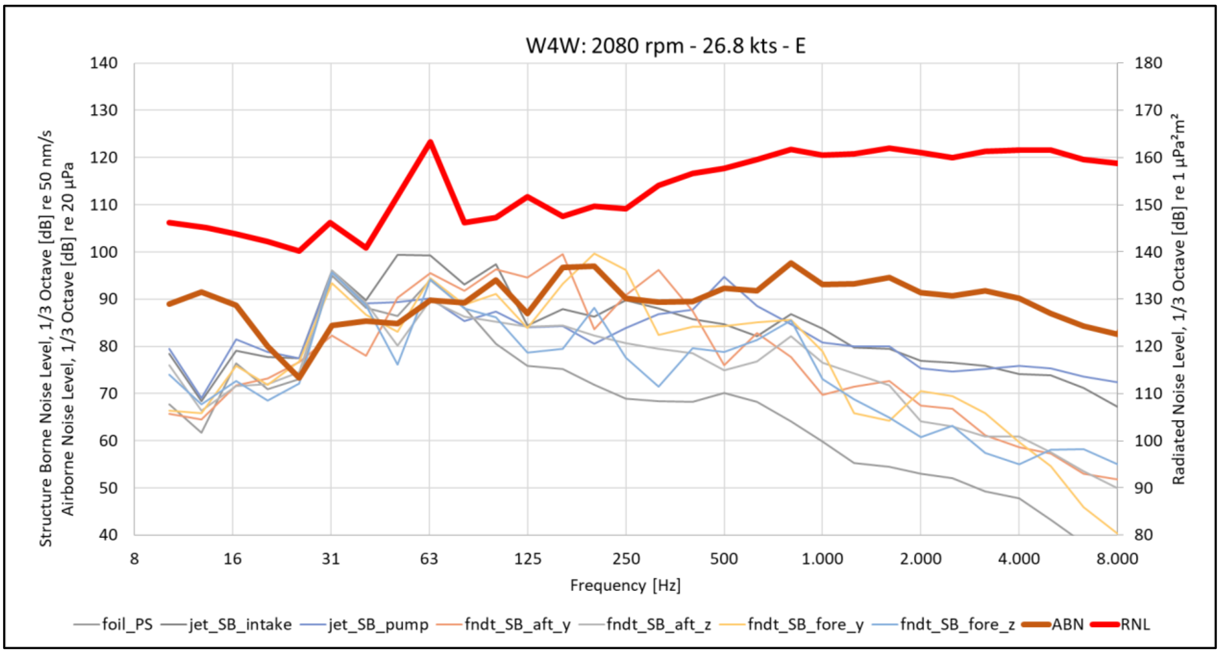

Figure 58: W4W: Selected Sensor Data, RNL, ABN; 1/3 Octave at 2080 rpm and 26.8 kts

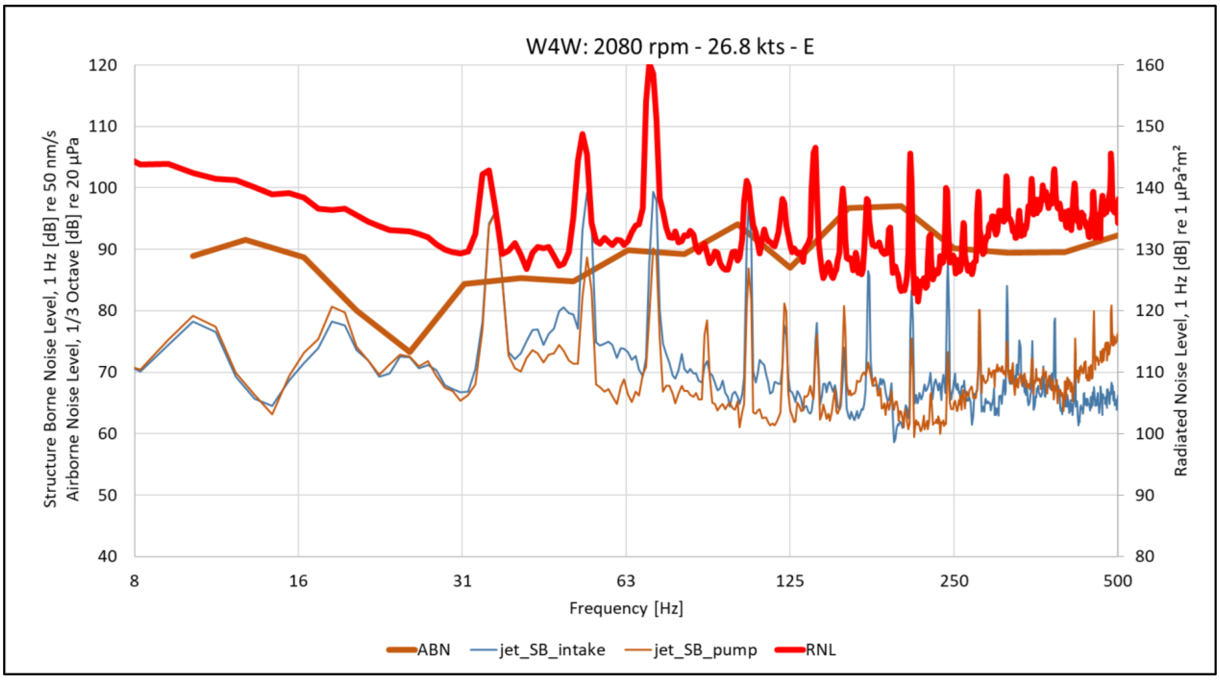

Figure 59: W4W: Jet Sensor Data, RNL, ABN at 2080 rpm and 26.8 kts

The narrow band analysis up to 500 Hz shows SBN peaks of the sensors at the SB jet intake and SB jet pump at 35, 52, 70 and 105 Hz which equals the 1st, 1.5th, 2nd and 3rd order of the engine frequency and, due to the gear ratio of 1:1, the same orders of the waterjet frequency (Figure 59). The SBN data of the engine and foundations, shown in Figure 60, also shows peaks at the orders of the engine frequency at similar levels up to 105 Hz and at higher levels than the sensors at the jet locations above 105 Hz. At the aft foundation, the horizontal direction dominates the vertical direction, at the fore foundation it is vice versa.

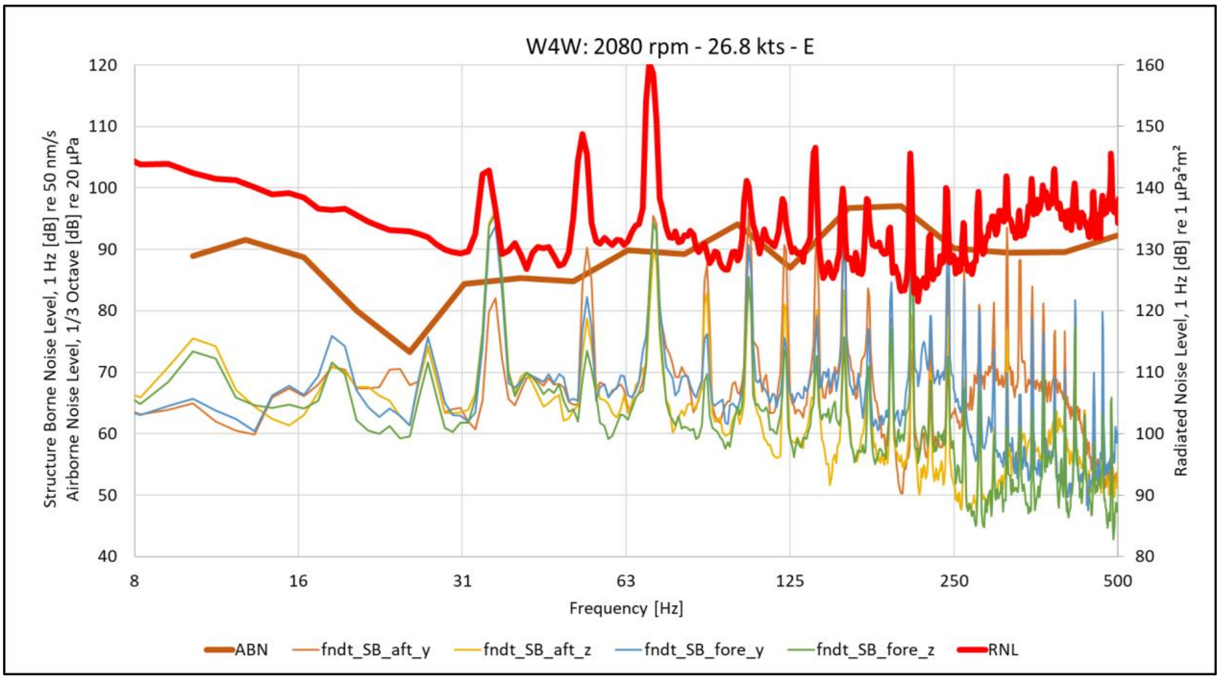

Figure 60: W4W: Engine and Foundation Sensor Data, RNL, ABN at 2080 rpm and 26.8 kts

The waterjets become the dominant noise source above 250 Hz and raise the noise level in these frequencies by 30 dB. This extensive cavitation noise at the waterjets makes W4W the loudest of the analysed vessels with a clear exceedance of the DNV SILENT(E) (Transit) curve. A later onboard investigation revealed that the portside shaft showed a minor imbalance with a huge effect. The starboard jet was 10 dB quieter. The repair of the PS jet was done directly after the measurements. It can be expected that the RNL of this vessel would be 5-7 dB lower if measured again. This needs to be taken into account when analysing the results.

Figure 61 shows the relationship between speed and band level above 15 kHz relevant for high frequency sensitive species. The rise in level is very steep over the whole speed range.

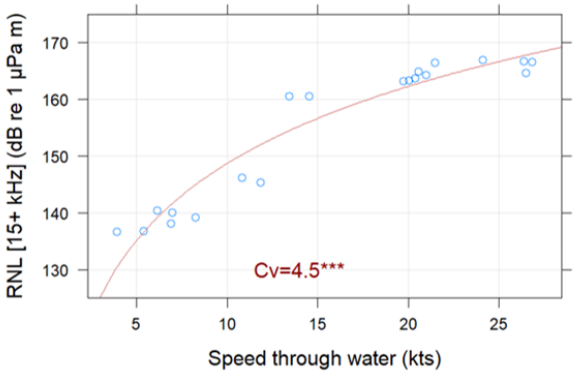

Figure 61: RNL versus speed of W4W

W4W also shows the highest Cv value. This means that the RNL is very susceptible to speed increases. A quite significant jump in level can be observed around 12 kts.

To find the reason for the high SBN levels at the engine foundations at ignition frequency (low-speed) and engine frequency (high speed) and their higher harmonics, the effectiveness of the elastic mounting of the engine is evaluated and the aluminium structure of the foundation is reviewed based on the pictures which were taken during the measurement campaign.

Figure 62 shows the SBN levels up to 1 kHz at 600 and 2080 rpm at the SB aft engine brackets, at the respective engine foundations and the level difference between bracket and foundation, which equals the attenuation of the elastic mounting. Additionally, the expected attenuation of an elastic mounting is shown.

As can be seen in Figure 62, the attenuation is below the expected value over a wide range of the considered frequency region, and it becomes negative in horizontal direction in both operation points.

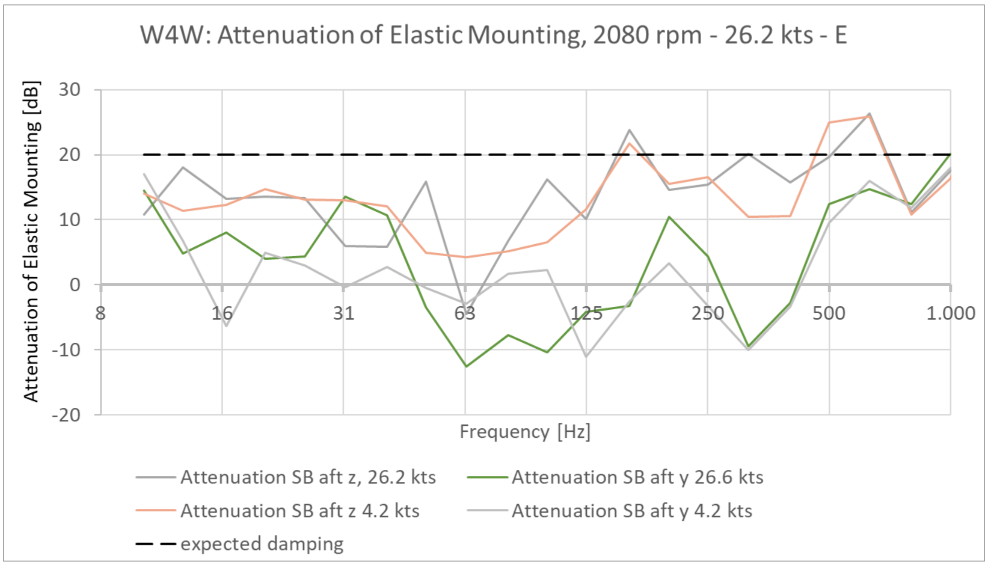

Figure 62: Attenuation of Elastic Mounting at 2080 rpm and 26.2 kts

Figure 63 shows a view along the PS of one of the W4W engines to visualize its installation in the hull. The red arrows point to the fore and aft mounting element at portside. The engine is mounted in the same way at its starboard side.

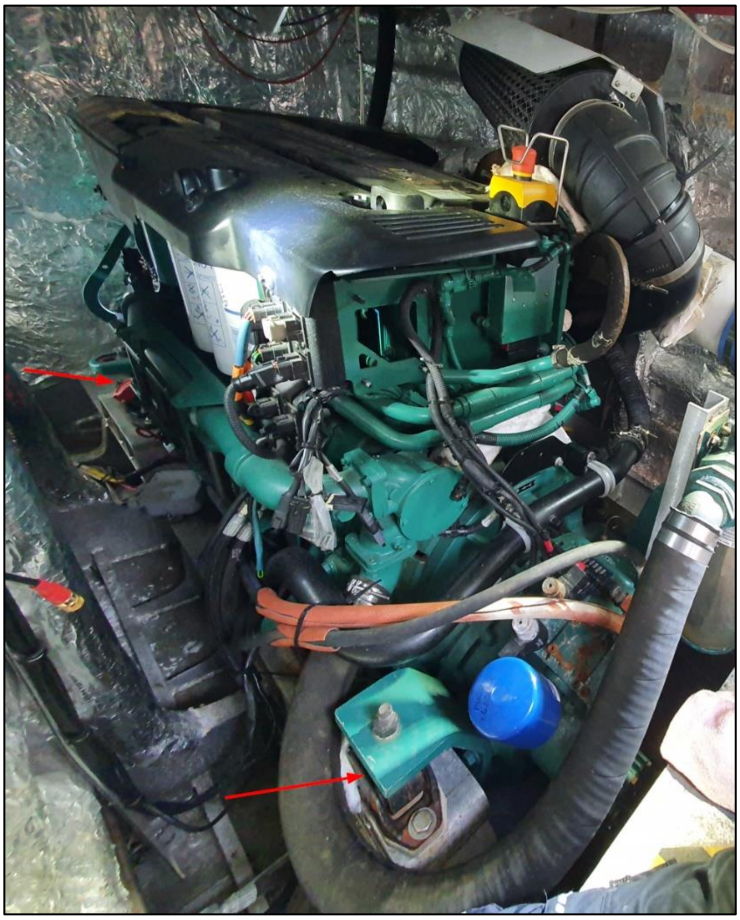

Figure 63: Engine Installation Situation

Figure 64 depicts the PS aft mounting bracket (1) and the elastic mounting element (2), both partly hidden by the black hose. The elastic element is bolted on the elevated engine foundation (3) via another elevation (4). The two additional elevations on the structural web frame (5) result in a rather large height of the foundation top plate (top of 4) above the floor plates (6). Compared to other engine foundations, the execution on W4W appears to be stiffened too little in lateral direction. However, a minimum foundation stiffness is fundamental for the proper functioning of an elastic mounting.

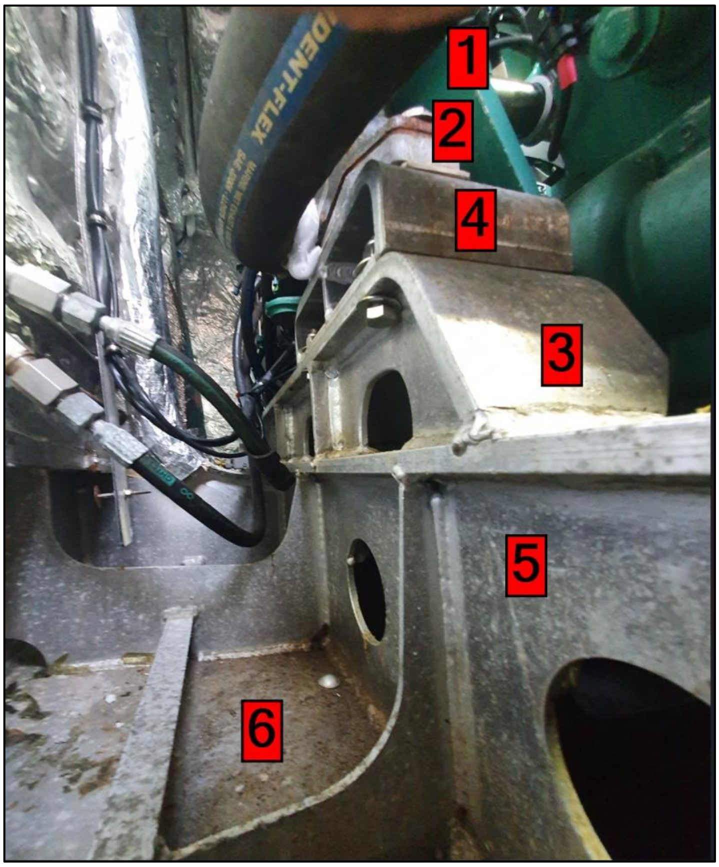

Figure 64: Detail of Engine Mounting

In Figure 65 the SBN data at the SB jet pump and at the SB fore foundation is shown. Between 34 Hz (ignition frequency) and 200 Hz, the jet pump data has peaks at the same frequency as the foundation data. Although some of the jet pump peaks dominate, this noise likely is caused by the engine vibrations via the foundations and the hull structure to the jet pump. Above 250 Hz, the jet pump data changes to a narrow band shape which is typical for cavitation noise.

The installation situation of the waterjet unit (Figure 66) indicates that the structure around the jets might have too little stiffness which would promote the noise transmission both from and to the waterjet unit.

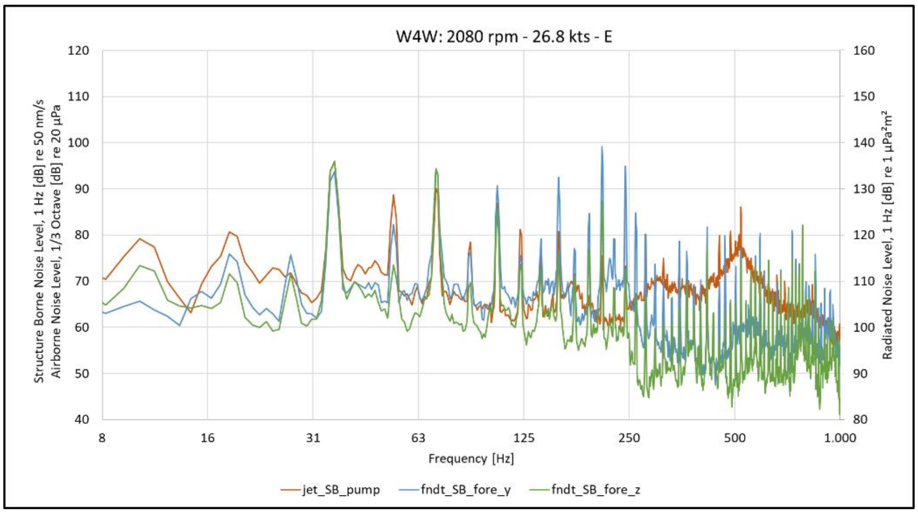

Figure 65: W4W: SBN Data at SB Jet Pump and SB Fore Foundation

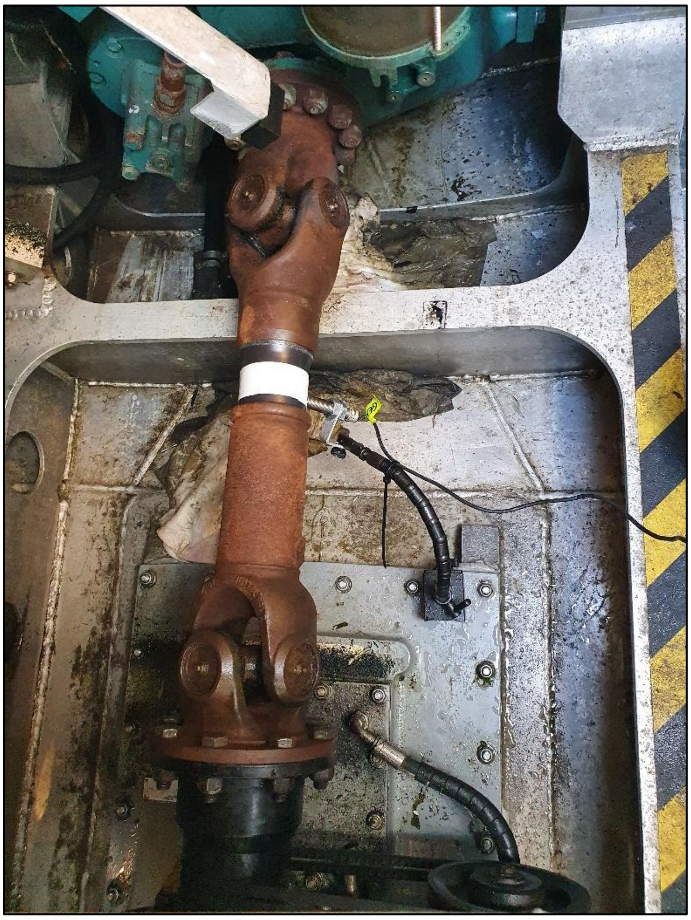

Figure 66: W4W: Waterjet Installation Situation

In the frequency range above 250 Hz, the narrow band noise of the jet intake and pump locations, indicating presence of cavitation, dominate except for the periodically occurring significant peaks of the signals from the foundations (Figure 67).

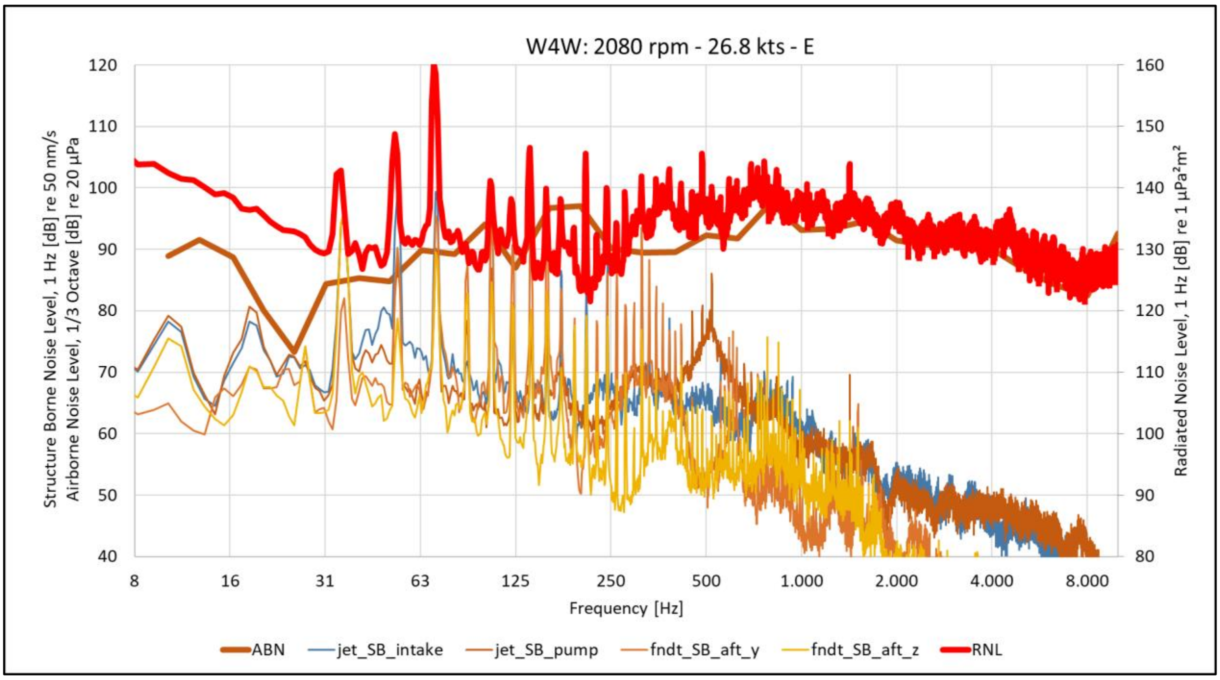

Figure 67: W4W: Selected Sensor Data, ABN, RNL at 2080 rpm and 26.8 kts

7 Technical Solutions

This chapter describes the typically observed contributors for the URN signature, causes of possibly unintended high noise emissions and advise on what to consider to reduce their contribution or avoid it at all. These takeaways can be applied to every kind of vessel of similar type.

7.1 Propeller Cavitation Noise

The RNL versus speed graphs indicated how a reduction of speed is an easy way to reduce propeller cavitation noise at higher frequencies. Nevertheless, it is not always an option to go slow. Especially in a commercial context, where transportation time is an integral part of any business consideration.

As shown in chapter 6.1, the URN of conventional propelled vessels like 4EW at high speed is dominated by propeller noise, more specifically by the contribution of the blade frequency at lower frequencies and by blade cavitation at high frequencies. To get an impression of the effect of modifications at the propellers, several calculations have been performed and are presented subsequently. Since the available data of the propellers, the installation situation and the flow around the boat is very basically, the shown results must be understood as estimations with qualitative character.

As the low frequent noise contribution of a propeller, the pressure pulses on the hull when a propeller blade passes the 12 o’ clock position has been indirectly determined on 4EW by the acceleration measurements at the hull shell. In non-cavitating condition, this vibration of the hull shell is mainly governed by the distance between the blade tip and the hull (tip clearance) and by the tip thickness of the propeller blade: a larger distance leads to smaller pressure pulses and a smaller tip thickness results in less displacement by the blade tip and consequently also in smaller pressure pulses on the hull. However, we expect that in non-cavitating condition this effect is masked by other noise emissions.

The typical high frequent broad band noise contribution of a propeller is blade cavitation. Cavitation occurs when vapor bubbles collapse after the pressure on the blade had undercut the vapor pressure of water and the water had begun to bubble. Figure 68 shows a model propeller in a test basin with cavitation at the blade in 12 o' clock position.

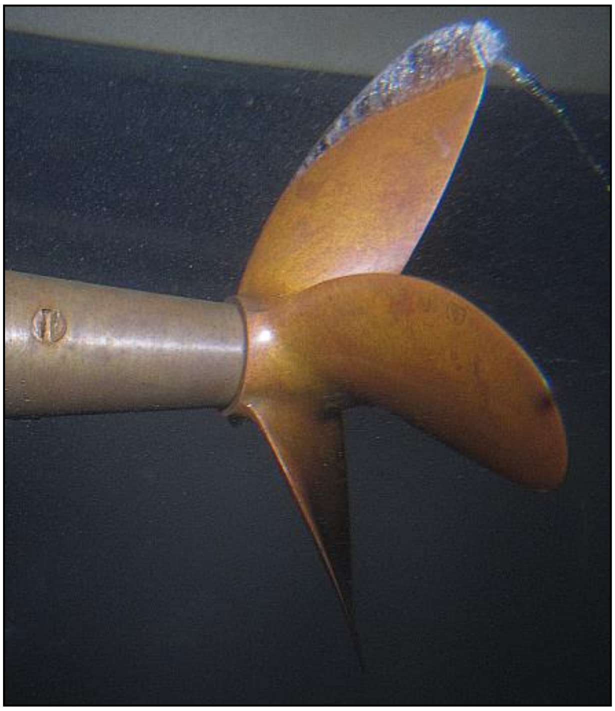

Figure 68: cavitating model propeller during model tests showing sheet and tip vortex cavitation (Source: DW-ShipConsult)

The extent of propeller cavitation can be influenced by the following parameters:

1. Flow homogeneity in front of the propeller: A homogeneous flow to the propeller is equivalent with little velocity variation over the propeller disc area and leads to a smaller extent of cavitation.
2. Propeller diameter and BAR: a high load per area results in a larger extent of cavitation, thus the propeller diameter and the BAR shall be chosen with regards to the required minimum propeller blade area.
3. Type of profile sections: the available profile section types for propellers have different sensitivities for the risk of occurring cavitation.

It is rather obvious that these parameters can hardly be influences with a standard outboard motor like on SE. Those motors are standardized, and vendors would hardly agree on changing their propeller design for one boat operator. A boat operator can only look into alternative vendors.

On 4EW or on vessels with a comparable propulsion system, a variation of the diameter and the BAR are the parameters that can be changed with appropriate effort. As the most promising option to decrease the cavitation volume, an increase of the propeller diameter is discussed subsequently.

A diameter increase results in a pitch decrease to compensate the higher power demand of the larger propeller. From practical experience we know that with small changes, the pitch shall be decreased by the same value as the diameter is increased. Thus, the relevant data of the existing and the alternative propeller are determined as shown in Table 5.

	Existing	Alternative
Diameter [mm]	700	762
Pitch [mm]	840	777
P/D [-]	1,20	1,02

Table 5: data of existing and alternative propeller

Based on the recorded boat data during the measurement campaign, with an estimation for the propeller thrust, propeller inflow velocity and with the propeller data of Table 5, an estimation of the cavitation performance of the propellers has been performed based on the series data of the Wageningen B Propeller Series. The results are shown in Figure 69 and Figure 70 for a diameter of 700 mm and 762 mm. Each dot in the diagrams, marked with the boat speed, shows the cavitation number σ_0 and the thrust coefficient c_T of the propeller at the respective operation point, defined by boat speed, propeller rpm and propeller thrust. Without any further explanation of the physical background of these coefficients, a propeller shows cavitation in a certain operation point if it is located below the red lines in the diagram. In Figure 69, the estimation gives that the propeller does not cavitate at 4.9, 5.8, and 7.1 kts. From 10.8 to 19.9 kts, the propeller works slightly above the limit for cavitation occurrence, and at 22 and 24.5 kts it clearly cavitates.

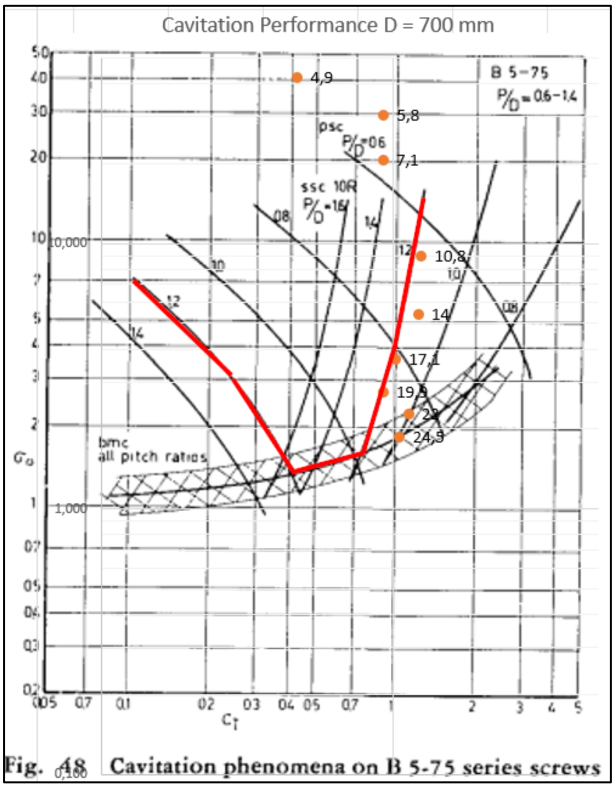

Figure 69: cavitation performance D = 700 mm

In Figure 70, the case with increased diameter, reduced pitch and thus reduced pitch-diameter-ratio P/D is shown. With the different limit curve and slightly differently located points in the diagram, all operation points are located in the “no cavitation”- region and only the operation points 22 and 24.5 kts show a risk of cavitation due to their proximity to the limit curve.

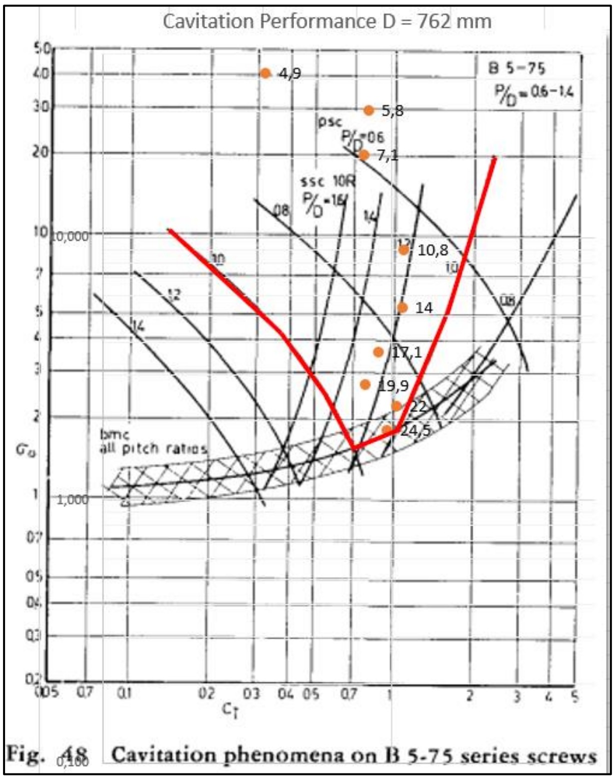

Figure 70: cavitation performance D = 762 mm

The shown estimation of the cavitation performance of the existing and an alternative propeller indicates that with a larger propeller with reduced pitch, less cavitation can be expected. However, it must be considered that the pressure pulses on the hull shell will increase with a larger propeller diameter. This effect cannot be evaluated within this study due to the lack of input data.

The herein described possibilities to reduce cavitation noise do not apply to a surface piercing propeller like on GW. Such a propeller works in a completely different way. But as shown in chapter 0, a surface piercing propeller at high speed seems to be generally quieter than others.

7.2 Waterjet Noise

Waterjets work with an impeller and a stator in a duct. The impeller is driven by a shaft which is connected to an engine via a coupling. Aft of the impeller the water flows through a nozzle and exits as a jet with a very high velocity of about twice the ship speed. In technical terms the system works like an axial pump with the thrust generated in the shaft being used for propulsion, Figure 71.

Waterjets are employed typically at ship speeds above 30 knots where cavitation in propellers leads to unacceptable cavitation and thrust breakdown.

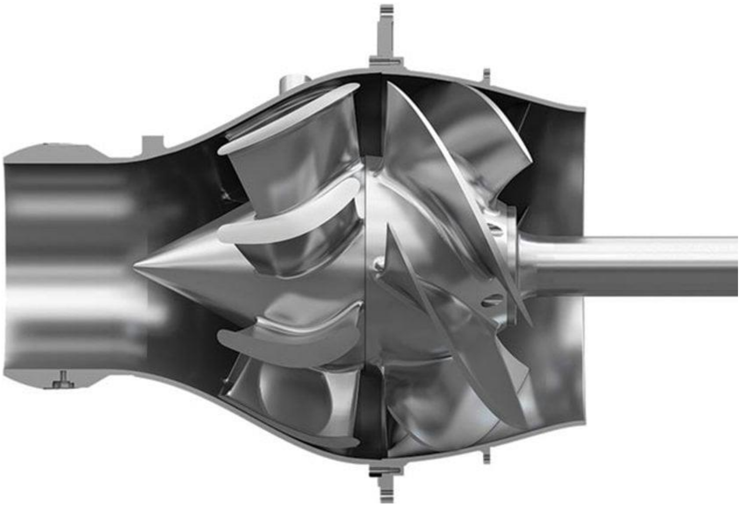

Figure 71: Cut-away illustration of a waterjet. Water enters from the right-hand side into the shaft-driven impeller. The stator behind the impeller removes the swirl and guides the water flow towards the nozzle at the left. (© Kongsberg Maritime)

There are four different types of noise generating mechanisms at a waterjet:

1. Cavitation at the impeller
2. Cavitation at the inlet
3. Impingement noise where the waterjet hits the surface behind the boat

Figure 72: waterjets hitting the surface in the wake of the boat

The first noise generating effect would be distinguishable in onboard as well as URN measurements. Those blade passing frequencies show tones which can be calculated by the number of impeller blades and rotational frequency. In this particular case this noise was not a dominant source.

At a certain speed cavitation develops at a waterjet impeller as it also does at a conventional propeller. There are some differences, especially regarding the inflow characteristics but the principle that cavitation develops at locations where the water pressure drops below vapor pressure, remains the same.

But cavitation does not only happen at the impeller. At the inlet the surrounding water is sucked into the pipe leading to the impeller. Especially at the inlet edges the water is accelerated highly and sees a steep pressure decrease which may cause cavitation. To avoid cavitation at the waterjet pump which would lead to breakdown of thrust, the inlet itself and the surrounding hull need to be designed accordingly. At the maximum ship speed considered here we find severe cavitation on impeller blades at the inlet not likely to occur. However, cavitation in the gap between blades and tunnel emerges at lower speed, therefore it is possibly included in the investigated speed range.

Impingement noise caused by the waterjet hitting the surface in the wake of the boat is a noise source which is not investigated well enough yet. There is only very limited literature available for this noise generating mechanism. During this project, the measurement setup did not allow an in-depth analysis of this phenomenon. However, measurement data from onboard noise and vibration measurements in the vicinity of the waterjet proved helpful in the assessment of this noise. Figure 55 and Figure 58 show the RNL of W4W at slow and fast speed (red line). When looking at the frequencies dominated by the propulsion noise (>250 Hz) and comparing both speeds, we see how the red line rises by up to 30 dB.

The thin lines show the SBN levels at various locations around the jet. These lines also increase in level. Most of them even more than the RNL. It is therefore plausible to say that the RNL increase is mostly caused by cavitation effects at the waterjet.

Impingement noise contributions cannot be ruled out completely but there is no indication that this had any relevant effect during this measurement. It is observed that at the lower speed the transom of the ship is submerged so the jet discharges directly into the water with no impingement. At the higher speed the transom is dry and the jet hits the water surface at ship speed which is likely to give rise to considerably higher noise levels which as discussed above is not possible to quantify with current knowledge.

7.3 Structure-Borne Noise (SBN) of Propulsion Engines

Vessels with a propulsion engine installed on board like GW, W4W or 4EW may transfer engine noise through the structure into the water. This SBN emission dominates the spectra in the lower frequencies both at slow and high speeds. In these particular cases it was also the only noise contributor causing the vessels to exceed the DNV SILENT(R) limit curve. A reduction of SBN noise transmission would therefore have a distinctive effect.

Figure 32 showed as an example of 4EW that the noise attenuation by the elastic engine mounts does not work properly. In transverse directions vibration level below maybe the same above and below mounts which means that engine and hull vibrate together with no mitigating effect of the resilient mounts The cause for that was either a too stiff elastic mounts, a foundation which is not stiff enough or a combination of both. A further analysis including a comparison of vertical and transverse attenuation revealed that especially the transverse attenuation was lower than anticipated.

Onboard investigations of the structure support the measurement data: The engine foundations lack sufficient stiffness (see Figure 73) for GW.

Figure 73: engine foundation on GW

It is plausible to assume that the foundation design was based on weight saving considerations and space limitations. Similar foundations can be found on a variety of small vessels.

The most effective technical solution to reduce SBN would be to provide a higher stiffness to the foundation. This can be done as a retrofit measure. Well-designed stiffeners can be welded on the foundation below the mounts. Those stiffeners should particularly increase the lateral stiffness. Figure 74 gives an example.

It may also be possible to change the engine mounts and select a softer type of mount. This exchange requires some more extensive work and a discussion with the engine manufacturer, which usually provides the mounts with together with the engines.

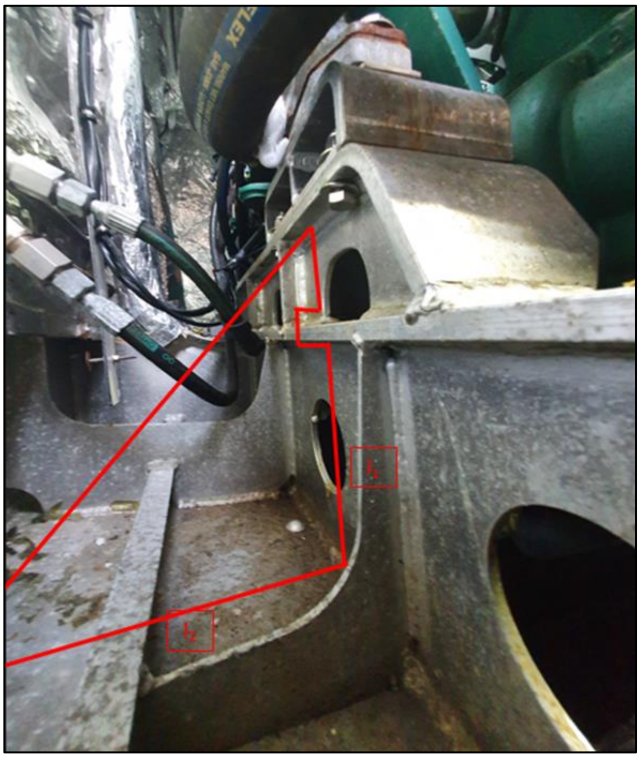

Figure 74: Engine mount and foundation. Red: possible design for a stiffener.

If it is intended to build a new vessel, the shipyard should pay attention to select a very soft engine mount and to design the foundation very stiff. The higher the difference of stiffness between those two elements, the better the noise attenuation from the engine into the structure and thus, into the water.

Figure 75 gives an example of a well-designed and stiff engine foundation. That particular foundation is found on somewhat bigger vessels, but it shows some key takeaways for foundation design:

- Use a frame construction, which is supported below the deck plating
- Use stiffeners in small spacing
- Pay attention to the transverse direction first

Figure 75: example of a stiff engine foundation

7.4 Engine Airborne Noise (ABN)

ABN was not a dominant contribution of the investigated vessel's URN signatures. It is therefore not necessary to reduce this noise transmission path.

But if any other small vessel shows a problem with this ABN transmission path it is recommended to look at the walls, floors and ceilings of the engine room. Additional absorbing material on uncovered structures as deck head, bulkheads and ship sides may be helpful gut the effect practically amounts to maximum 3 dB improvement Absorption material can consist of mineral wool which is only covered by a thin foil or glass cloth for water protection. Maybe a perforated metal shield may also be applied in front of it to avoid mechanical damages.

7.5 Exhaust Gas Noise

With regard to URN it is generally recommended to avoid exhaust gas outlets below the water. On SE the exhaust gas of the three outboard motors emitted more noise than the SBN of the other two vessel's onboard engines.

But with regard to outboard motors, a boat operator has only limited means of changing the motor design. Those outboard motors are commercial of the shelf products which are usually not adapted to individual requests. It is rather worth a consideration to investigate different outboard motors for their URN signatures. With that information, boat operators may make a better based decision on the motor selection.

7.6 Gear Box Noise

The observed gear box noise in this project was also only attributable to the boat with the outboard motors. As for the exhaust gas noise, this noise can only be influenced by another design. But those outboard motors are unlikely to be designed differently if there is no significant demand from the boat operator industry. The suggestion to measure different outboard motors from different manufacturers is also valid in this case.

8 Recommendations how to Reduce the URN of Whale Watching Boats

The following recommendations aim to provide guidance on how to reduce the URN of small vessels by operational means, by retrofit measures or with a new design. The different vessel and propulsion concepts need to be taken into account as not every recommendation fits to a certain vessel type. The recommendations are given in a general way. Some may apply to the particular vessels at hand but most of them are valid to all small vessels of similar type.

8.1 Operation

The measurements at different speeds showed a significant correlation between speed and RNL of every boat. But although this is a rather obvious result, the comparison of the many different speeds showed, that every vessel has one or two particular speed ranges in which the RNL increases significantly (see Figure 76).

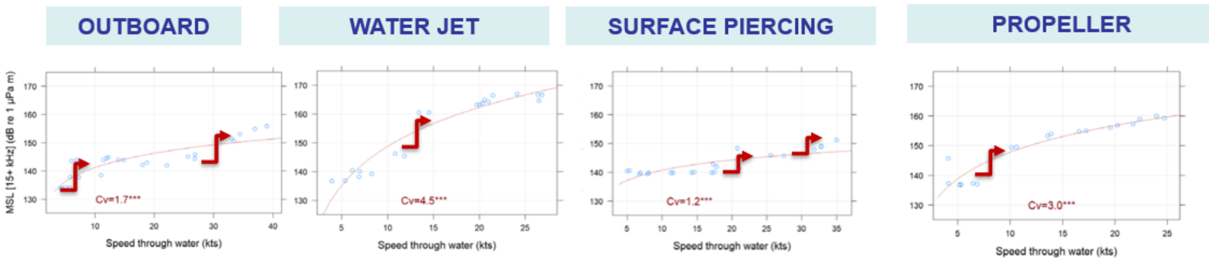

Figure 76: RNL versus speed diagrams of investigated boats

Although every vessel shows this clear jump of RNL, the extent and the particular speed at which this happens is individual.

If keeping a low URN is crucial for a certain vessel, it is therefore recommended that it receives a systematic URN and onboard measurement at different speeds. The resulting RNL versus speed diagram would show the individual vessel's jump in level. This information allows the boat operator to choose a certain speed range for each purpose (e.g. quiet cruise, transit).

When accelerating a boat operator should always aim for a slow acceleration. Too quick speed increases would cause the propeller to work in an inhomogeneous and too slow wake field, resulting in unnecessarily high cavitation. This can be avoided if the speed is increased smoothly.

8.2 Retrofit

8.2.1 Inboard Engine Noise

SBN transmission from the engine into the water was shown to be the dominant noise contributor for the low frequencies at slow and high speeds. All investigated vessels which had their engines installed in the boat showed similar effects in their URN signatures and similar causes for this effect.

It is recommended that boat operators pay attention to their engine foundations and improve the lateral and vertical stiffness of it. Especially the structure below any elastic mount needs to be designed rigidly. Such additional brackets or girders can be welded into the foundation during a retrofit. It does not require any discussions with other vendors and in many cases does not require a shipyard or external ship designer.

The second recommendation to reduce SBN transmission is the choice of soft flexible engine mounts. As this is often a standard part within the delivery scope of an engine manufacturer and requires the engine to be lifted off it's feet, such a measure is connected to more effort and costs.

The basic rule for an acoustically well designed engine bed should be:

Elastic engine mount: as soft as feasible

Foundation: as stiff as feasible

8.2.2 Cavitation by Conventional Propellers

The extent of propeller cavitation can be influenced by different parameters detailed in chapter 7.1.

During a retrofit some things cannot be changed:

- The hull lines of the vessel (to allow a better flow to the propeller)
- The distance between the center of the propeller and the hull above the propeller (To allow for a bigger propeller tip clearance)

That limits the possible measures to a change of the propeller.

When considering a new propeller with e.g. a higher cavitation inception speed, a bigger propeller diameter and BAR would have advantages. The boat's hull lines, the typical operational profile and the propulsion train need to be taken into account when selecting another propeller. It is therefore not possible to suggest one solution fitting all.

At least one propeller manufacturer promises a revolutionary new design with big advantages in efficiency and URN emissions over the conventional propellers. If such a revolutionary propeller design is considered it is recommended to insist on seeing technical data like an open water diagram first.

8.2.3 Outboard Motors

As outboard motors are commercials off the shelf, it is hard to influence the design of the whole product or the propeller design. The investigated motor showed a propeller with potential for improvement, a gear box and an exhaust gas outlet below the waterline. All three aspects were noticeable in the URN signature. If a retrofit is envisaged, it might be worth looking for an outboard motor vendor who can present URN measurements of its systems. Furthermore, we see a comparison of different outboard motor's URN emissions as a potential research ambition.

It could also be worthwhile to investigate better outboard motor propellers in general. One design of parameter of propellers is skew, Figure 77.

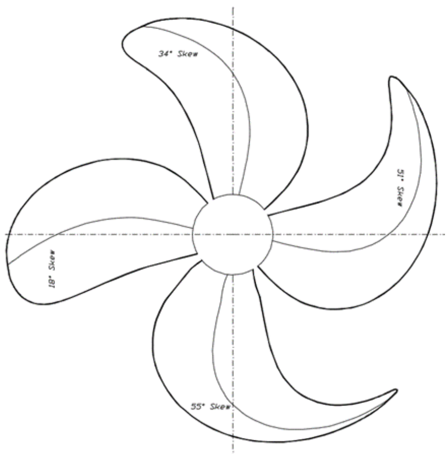

Figure 77: skew variations with low skew (9 o'clock) to high skew (6 0'clock)

Figure 78: Standard outboard propeller with low skew, few blades (source: Mercury), left, and multiblade high skew propeller (source: Torqeedo) as proposed for silent propulsion, right

8.2.4 Hydrofoils

Hydrofoil boats sail with the hull out of the water at high speed. In this condition, they are quieter as concerns machinery noise and likely also quieter in regards of propeller noise because power requirements are lower than in a conventional ship of same capacity and speed but would not be expected to be quieter at low speed in non-foiling condition.

In which cases a hydrofoil boat is feasible would require URN measurements of such a boat and an analysis by operators whether the concept suits the business case.

8.3 Newbuild

For newbuild projects, we recommend giving the acoustic performance of the boat and the critical components a higher priority than it is usual on boats of this size. Especially the mutual influence of light weight building and acoustics should be made aware of.

The comparison of the four tested boats showed that the surface piercing propulsion system generates the lowest URN level of these boats. We see significant noise reduction potential on 4EW and expect that a well-designed boat with conventional shafts and propellers generates less noise than 4EW and SE.

For a low noise level at low frequencies, it must be ensured that the foundations of the engine and the gearbox provide the minimum necessary stiffness in all directions and the elastic mounting of the engine and gearbox must be designed appropriately. Furthermore, the propeller blade impact must be kept low by ensuring a propeller tip clearance to the hull of at least 0.2 x propeller diameter.

To ensure a low noise level at high frequencies, the extent of cavitation at a propeller, a waterjet inlet and at appendages like rudder or a shaft bracket must be minimized. Ideally, the occurrence of cavitation can be avoided. A basic requirement to achieve this is that the hull design ensures a smooth flow along itself to the propeller. Regarding the propeller, its thrust loading shall be chosen low. This can be achieved by a large propeller diameter and a large BAR. The absolute necessary value depends on the quality of the flow to the propeller. Chapter 7.1 might help as basic information here.

9 Conclusion

The four investigated whale watching vessels had four different propulsion concepts. Together they represent the vast majority of propulsion concepts of small vessels all over the world and across many different applications. Therefore, the results of this study can be applied to other whale watching vessels as well as other boats with similar configurations.

The major results of this study are:

1. Speed matters! If a vessel operates below its cavitation inception speed, the RNL stays relatively low. Individual RNL versus speed diagrams show that every vessel has speed ranges in which the RNL barely increases. Beyond such a range, the RNL "jumps" to the next level. It is recommended that every whale watching boat undergoes a systematic URN measurement at different speeds in order to obtain its individual speed/RNL chart. Such a chart would provide scientific basis for a proper speed vs. noise management.
2. Engine foundations should be designed as stiff as feasible. Elastic engine mounts should be selected as soft as feasible. Those two measures would reduce the engine's SBN contribution to the RNL considerably.
3. Wherever possible, the propeller shall not only be designed or selected regarding highest efficiency but also with regard to low URN emissions. Several design recommendations were given.
4. A new vessel design would provide the best opportunities to implement low noise features. Hull lines and appendages should be designed in a way to avoid cavitation. A conventional, big propeller with a good inflow operating at slow to medium speed likely provides the quietest and most efficient result.
5. If high speed of more than 20 kts is of the essence, a surface piercing propeller is the quietest propulsion system.

10 Final remark

Eagle Wing Tours provided their own vessels for this URN study. The vessels have been intensely investigated by our Naval Architect and Ship Acoustic Consultant. Many technical drawings and information were analyzed, close up pictures were taken from locations which have not seen sunlight in many years. The many different sensors on board provided even more insight into the vessel's particularities. Finally, every vessel was systematically analyzed for their URN signature in various operating conditions.

Such an extensive investigation uncovers nearly every detail of a vessel. Even those the typical boat operator would be unaware of. Sharing this intimate information with the public is something only very few vessel operators would do. Therefore, we are very thankful that we found a company which agreed on doing this analysis.

Due to the results, EWT was able to execute several ad-hoc measures to improve their URN footprint, both in terms of operation and structural adaption. As these measures were all taken after this investigation, the results are not part of this report.

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12 Appendix: Report on Underwater Radiated Noise Measurements

Underwater Radiated Noise (URN) Measurements of Whale Watch Vessels

Quantifying Noise Reduction Measures for Whale-watching Vessels

JASCO Applied Sciences (Canada) Ltd

4 April 2023

Submitted to:

Thomas Buechler
DW-Ship Consult GMBH
Purchase order DW-23002-QVI and DW-23003-QVI

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P001719-000
Document 03062
Version 1.0

Suggested citation:

Li, Z. and K. A. Demers. 2023. Underwater Radiated Noise (URN) Measurements of Whale Watch Vessels: Quantifying Noise Reduction Measures for Whale-watching Vessels. Document 03062, Version 1.0. Technical report by JASCO Applied Sciences for DW-Ship Consult GMBH.

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1. Overview

This report presents acoustic radiated noise level and source level measurements of four whale watch vessels: *WILD 4 WHALES*, *4EVER WILD*, *GOLDWING*, and *SERENGETI* (Figure 1), operated by Eagle Wing Tours Ltd., Victoria B.C.. The measurements performed at the Transport Canada Underwater Listening Station (ULS) located south of Saturna Island in Boundary Pass. The present study of underwater radiated noise was performed in concert with a simultaneous study by DW ShipConsult GmbH, that measured on-board vibration levels of several of the mechanical components of these vessels.

Measurements of underwater noise emissions of the vessels were made during planned passes of these vessels at various speeds and operating conditions past the ULS. The passes were made along a pre-defined measurement track (see Figure 2 and Table 1). Table 2 shows the physical and nominal operating characteristics of the participated whale watch vessels. Table 3 presents the vessel operating parameters, such as setting and RPM, logged by the vessel operators.

Figure 1: Whale watch vessels *WILD 4 WHALES* (top left), *4EVER WILD* (top right), *GOLDWING* (bottom left), and *SERENGETI* (bottom right).

The sound recordings were analyzed with ShipSound™, a vessel noise measurement software system within JASCO's PortListen® application and database (see Appendix A), to obtain the radiated noise level (RNL) and Source Level (SL) of the vessels. PortListen automatically tracked the identity, position, and speed over ground of vessels transiting the ULS on the Automated Identification System (AIS). Environmental conditions (wind speed, current speed) were also recorded for each pass. Source level reports were produced for each valid pass using the hydrophone and vessel tracking data collected by PortListen.

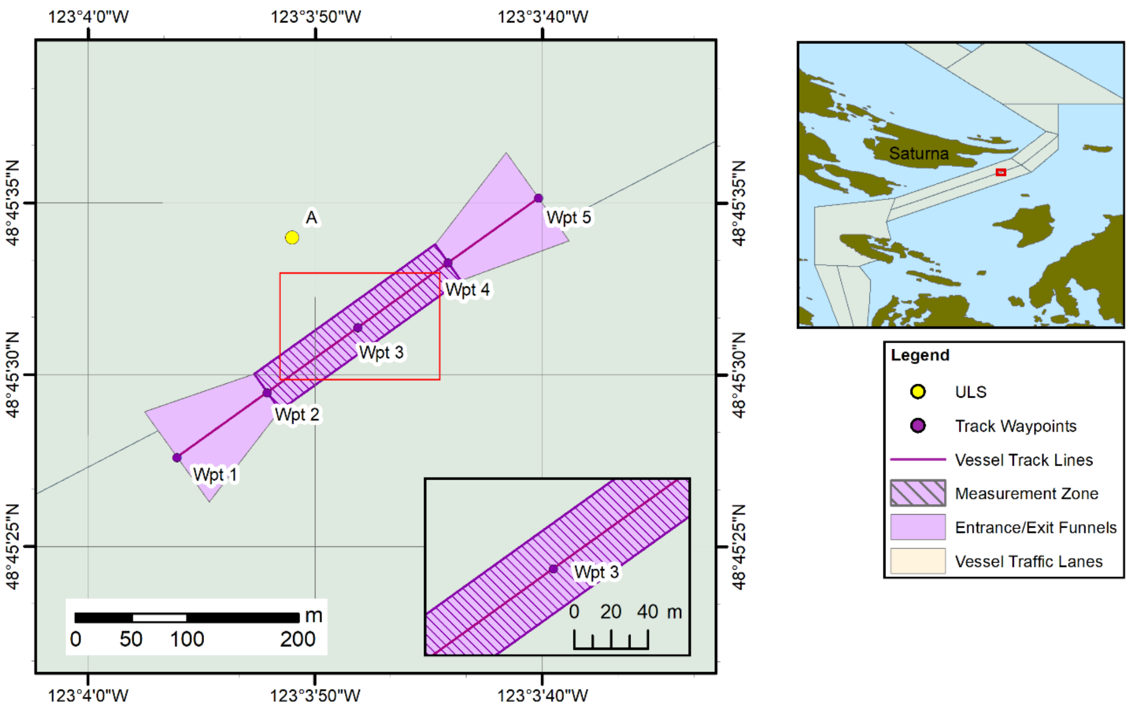


Figure 2. Map of measurement track waypoints (purple dots) and entrance/exit funnels relative to the Underwater Listening Station (ULS) hydrophones (yellow dots). The ULS lies on the commercial shipping lanes to/from Vancouver, BC. Inbound (north-east direction) traffic travels in the southern lane, while outbound (southwest direction) traffic passes in the north lane. The ULS hydrophones are situated between the lanes to measure traffic from both directions.

Table 1. Underwater listening station measurement funnel coordinates in UTM Zone 10 coordinates and latitude/longitude.

Waypoint	WGS84 UTM Zone 10		WGS84 geographic coordinates	
	Easting (m)	Northing (m)	Latitude	Longitude
A	495284.00	5400717.01	48° 45.56672' N	123° 3.85011' W
Wpt 1	495180.18	5400519.68	48° 45.46016' N	123° 3.93474' W
Wpt 2	495261.44	5400577.90	48° 45.49162' N	123° 3.86844' W
Wpt 3	495342.69	5400636.12	48° 45.52308' N	123° 3.80215' W
Wpt 4	495423.95	5400694.34	48° 45.55455' N	123° 3.73585' W
Wpt 5	495505.20	5400752.57	48° 45.58601' N	123° 3.66956' W

Table 2. Specifications of the whale watch vessels involved in this study, and number of measurements for each.

Item	Details			
	WILD 4 WHALES	*4EVER WILD*	*GOLDWING*	*SERENGETI*
Year built	2017	2000 (Retrofitted in 2015)	2005	1989 (Retrofitted in 2008)
IMO No.	840774	838199	827860	C12122BC
MMSI	316034816	316028179	316007107	316008468
Length (m)	18	17	18	11.5
Nominal Draft (m)	1.60	2.06	1.83	1.00
Propulsion Power (kW)	1044	648.7	932	671
Drive	Ultrajet drives with ZF transmission	Straight shaft, V-drive transmission ZF drive, prop, rudder	Arneson Drive propulsion system, ZF transmission	Outboard Suzuki DF 300hp
Style	Catamaran semi-displacement hull	Catamaran-twin hull-full displacement	Custom monohull design	Monohull
Propellers	N/A	2	2	3
Diameter (m)	N/A	0.71	0.71	0.62
Blades	5	5	5	3
Max Engine RPM	2300	3600	3300	5800
Cruise RPM	1850–2050 RPM (Speed 24–27 kts)	2950–3050 RPM (Speed 22–24 kts)	2750–2850 RPM (Speed 32+ kts)	3800–4000 RPM (Speed 32–35 kts)
Cylinders	6	6	6	6
Engines	1450 HP Volvo diesel	435 HP Volvo marine diesel = 870 HP	1250 HP Volvo diesel	750 HP Suzuki 4-stroke
Number of accepted passes	20	18	20	26
Number of rejected passes	0	0	2	0

Table 3. *WILD 4 WHALES*: Details of the measurements at the ULS. All measurements were made on Station 1. MSL source depth is 2.8 m. STW = speed through water. SOG = speed over ground.

Pass	CPA Time (UTC)	CPA distance (m)	SOG (kn)	STW (kn)	QC Status	RPM	Notes
1	2022-10-17 21:54:35	94	4.1	3.9	Accepted	600	At 5th wp – .50 kn; 68 LPH
2	2022-10-17 22:01:39	101	5.2	5.4	Accepted	600	
3	2022-10-17 22:07:51	91	7.2	7.0	Accepted	1100	32 LPH
4	2022-10-17 22:19:46	100	8.2	8.3	Accepted	1100	32 LPH
5	2022-10-17 22:24:03	80	13.5	13.4	Accepted	1750	113 LPH; interceptors 50%
6	2022-10-17 22:28:24	104	14.5	14.6	Accepted	1750	113 LPH
7	2022-10-17 22:36:15	70	26.4	26.5	Accepted	2080	196 LPH
8	2022-10-17 22:38:46	93	26.8	26.9	Accepted	2080	196 LPH
9	2022-10-17 22:42:06	77	19.8	19.7	Accepted	1870	136 LPH; Cost Guard 2.5 km away
10	2022-10-17 22:44:23	76	21.5	21.5	Accepted	1870	136 LPH; Cost Guard 2.1 km away
11	2022-10-18 00:35:00	97	6.0	6.2	Accepted	950	22 LPH
12	2022-10-18 00:38:49	111	7.1	6.9	Accepted	950	22 LPH
13	2022-10-18 00:43:04	96	10.7	10.8	Accepted	1610	91 LPH
14	2022-10-18 00:46:26	105	12.0	11.9	Accepted	1610	91 LPH
15	2022-10-18 01:18:55	118	26.2	26.4	Accepted	2040	183 LPH; interceptors on 100%
16	2022-10-18 01:21:26	96	24.3	24.1	Accepted		183 LPH; interceptors off 0%
17	2022-10-18 01:23:35	59	20.8	21.0	Accepted		
18	2022-10-18 01:26:05	144	20.6	20.4	Accepted	1880	140 LPH; interceptors off 0%
19	2022-10-18 01:28:43	73	19.8	20.0	Accepted	1830	Interceptors on 100%
20	2022-10-18 01:31:08	113	20.7	20.6	Accepted	1830	138 LPH; interceptors on 100%

Table 4. *4EVER WILD*: Details of the measurements at the ULS. All measurements were made on Station 1. MSL source depth is 2.8 m. STW = speed through water. SOG = speed over ground.

Pass	CPA Time (UTC)	CPA distance (m)	SOG (kn)	STW (kn)	QC Status	RPM	Notes
1	2022-10-19 20:57:26	99	5.0	4.1	Accepted	600	Just in gear; 0.6 LPN; 2.7 LPH
2	2022-10-19 21:04:01	94	3.2	4.1	Accepted	600	Just in gear; 0.9 LPN; 2.6 LPH
3	2022-10-19 21:44:15	100	5.9	5.2	Accepted	800	
4	2022-10-19 21:49:38	106	4.6	5.3	Accepted	800	1.1 LPN; 4.9 LPH
5	2022-10-19 21:55:17	107	7.1	6.4	Accepted	1040	0.9 LPN; 6.2 LPH
6	2022-10-19 21:59:57	100	6.2	6.9	Accepted	1040	1 LPN; 6.1 LPH
7	2022-10-19 22:05:12	104	10.7	10.1	Accepted	1750	2.8 LPN; 29 LPH
8	2022-10-19 22:08:44	96	10.0	10.6	Accepted	1750	3 LPN; 30 LPH
9	2022-10-19 22:12:36	105	14.1	13.6	Accepted	2200	3.9 LPN; 55 LPH
10	2022-10-19 22:15:28	91	13.4	13.9	Accepted	2200	4.1 LPN; 55 LPH
11	2022-10-19 22:19:46	101	17.2	16.6	Accepted	2500	4.3 LPN; 74 LPH
12	2022-10-19 22:22:42	103	16.8	17.3	Accepted	2500	4.4 LPN; 73 LPH
13	2022-10-19 22:26:23	92	20.0	19.6	Accepted	2800	5.2 LPN; 103 LPH
14	2022-10-19 22:29:49	98	19.8	20.3	Accepted	2800	5.2 LPN; 101 LPH
15	2022-10-19 22:32:56	85	22.2	21.7	Accepted	3040	5.7 LPN; 127 LPH
16	2022-10-19 22:36:03	104	22.0	22.4	Accepted	3040	5.7 LPN; 125 LPH
17	2022-10-19 22:39:10	104	24.4	24.0	Accepted	3300	Full speed
18	2022-10-19 22:41:35	86	24.3	24.7	Accepted	3300	6.7 LPN; 162 LPH

Table 5. *GOLDWING*: Details of the measurements at the ULS. All measurements were made on Station 1. MSL source depth is 2.8 m. STW = speed through water. SOG = speed over ground. LNM = litres per nautical mile, LHR = litres combined per hour.

Pass	CPA Time (UTC)	CPA distance (m)	SOG (kn)	STW (kn)	QC Status	RPM	Notes
1	2022-10-20 20:58:10	94	3.9	5.0	Accepted	600	Port engine only; 1.8 LNM; 7.2 LHR
2	2022-10-20 21:14:33	112	6.4	5.4	Accepted	600	Port engine only; 1.8 LNM; 7.2 LHR
3	2022-10-20 21:20:34	93	5.7	6.8	Accepted	650	Both engines; 2.1 LNM; 12.0 LHR
4	2022-10-20 21:24:47	114	7.9	6.9	Accepted	650	Bothe engines; 1.5 LNM; 11.5 LHR
5	2022-10-20 21:34:38	100	7.1	8.1	Accepted	920	3.0 LNM; 22.0 LHR
6	2022-10-20 21:37:52	104	8.9	8.0	Accepted	920	2.5 LNM; 22.2 LHR
7	2022-10-20 21:42:28	88	10.7	11.6	Accepted	1480	5.4 LNM; 59.3 LHR
8	2022-10-20 21:45:39	105	12.2	11.3	Accepted	1480	4.7 LNM; 58.8 LHR
9	2022-10-20 21:49:47	79	13.8	14.6	Accepted	1620	5.5 LNM; 75 LHR
10	2022-10-20 21:54:15	102	15.2	14.3	Accepted	1620	4.9 LNM; 75 LHR
11	2022-10-20 21:57:35	84	16.7	17.5	Accepted	1730	5.2 LNM; 87.5 LHR
12	2022-10-20 22:00:31	103	17.9	17.1	Accepted	1730	4.7 LNM; 87 LHR
13	2022-10-20 22:04:10	93	20.3	21.1	Accepted	1860	5.3 LNM; 105 LHR
14	2022-10-20 22:07:55	119	21.6	20.8	Accepted		Possible RCMP boat in shore; 4.9 LNM; 105 LHR
15	2022-10-20 22:12:16	86	26.7	27.5	Accepted	2070	5.1 LNM; 140 LHR
16	2022-10-20 22:15:38	110	26.3	25.6	Accepted	2070	4.8 LNM; 136 LHR
17	2022-10-20 22:20:54	93	32.1	32.8	Accepted	2310	5.5 LNM; 177 LHR
18	2022-10-20 22:24:24	86	33.5	32.8	Accepted	2310	5.1 LNM; 173 LHR
19	2022-10-20 22:29:19	107	34.4	35.0	Accepted	3460	5.91 LNM; 206 LHR
20	2022-10-20 23:03:55	106	17.8	17.4	Rejected	N/A	Ø -> full throttle
21	2022-10-20 23:06:39	66	17.4	17.8	Rejected	N/A	Ø -> ease into throttle
22	2022-10-20 23:10:23	268	31.5	31.8	Accepted	N/A	Test overtop waypoints farthest away from hydrophone

Table 6. *SERENGETI*: Details of the measurements at the ULS. All measurements were made on Station 1. MSL source depth is 2.8 m. STW = speed through water. SOG = speed over ground. LNM = litres per nautical mile, LHR = litres combined per hour.

Pass	CPA Time (UTC)	CPA distance (m)	SOG (kn)	STW (kn)	QC Status	RPM	Notes
1	2022-10-24 21:03:09	101	4.2	5.1	Accepted	844	3 engines; 2.5 LNM
2	2022-10-24 21:07:06	93	5.3	4.4	Accepted	844	2.05 LNM
3	2022-10-24 21:14:20	98	4.8	5.8	Accepted	1030	Engines trimmed up; 3 LNM; 1 tanker ship at 3 nm
4	2022-10-24 21:47:47	87	5.3	4.2	Accepted	880	2 engines trimmed down port/starboard
5	2022-10-24 21:53:02	108	5.0	6.1	Accepted	1590	1 engine trimmed down center
6	2022-10-24 22:20:02	108	11.2	12.3	Accepted	2156	4.04 LNM
7	2022-10-24 22:21:57	114	12.2	11.1	Accepted	2156	3.6 LNM
8	2022-10-24 22:24:11	116	13.8	14.9	Accepted	2390	4.05 LNM
9	2022-10-24 22:26:41	78	15.0	14.0	Accepted	2390	3.68 LNM
10	2022-10-24 22:51:17	115	17.7	18.8	Accepted	2700	3.85 LNM
11	2022-10-24 22:53:36	80	19.1	18.0	Accepted	2700	3.60 LNM
12	2022-10-24 22:58:07	109	6.3	7.3	Accepted	1200	2.85 LNM
13	2022-10-24 23:01:14	97	6.9	5.9	Accepted	1200	2.70 LNM
14	2022-10-24 23:04:35	110	7.2	8.2	Accepted	1420	3.30 LNM
15	2022-10-24 23:07:42	97	7.9	6.9	Accepted	1420	3.08 LNM
16	2022-10-24 23:10:16	113	11.0	12.0	Accepted	N/A	
17	2022-10-24 23:12:37	92	12.4	11.5	Accepted	2156	3.6 LNM
18	2022-10-24 23:15:42	100	21.2	22.1	Accepted	3250	3.5 LNM
19	2022-10-24 23:21:46	79	26.6	25.7	Accepted	3250	3.2 LNM
20	2022-10-24 23:25:17	98	25.9	26.8	Accepted	3350	3.4 LNM
21	2022-10-24 23:30:58	87	27.8	26.9	Accepted	3350	3.22 LNM
22	2022-10-24 23:33:30	106	32.6	33.4	Accepted	3900	4.05 LNM
23	2022-10-24 23:36:45	69	35.3	34.5	Accepted	3900	3.90 LNM
24	2022-10-24 23:39:49	80	38.2	39.0	Accepted	4500	4.7 LNM
25	2022-10-24 23:41:48	81	37.8	37.0	Accepted	4500	4.3 LNM
26	2022-10-25 00:21:25	282	33.5	33.1	Accepted	3850	400 m line: speed run

1.1. Underwater Listening Station

All measurements discussed here were acquired using the Boundary Pass ULS, consisting of sea-bed mounted hydrophone arrays that are cabled to shore to allow for real-time measurements. This ULS has two tetrahedral-shaped frames (Frames A and B) that support 8 hydrophones each (two arrays of 4 elements, with one set for redundancy). Figure 3 shows the deployed shore-cabled compact tetrahedral hydrophone arrays.Ror this study, only Frame A was used and the hydrophone model was a

GeoSpectrum Technologies Inc (GTI) M35-V35-100. The ULS frames are deployed on the seabed between the inbound and outbound international shipping lanes in Boundary Pass. Table 7 lists the deployment locations and hydrophone information of each recorder. The hydrophone arrays were mounted on the tetrahedral ULS frames, with the top hydrophone (channel 1) 2.2 m above the seafloor and the bottom three hydrophones (channels 2–4) 0.9 m above the seafloor (Figure 3). Each channel of the activated ULS arrays recorded at 512,000 samples per second (10 Hz to 256 kHz recording bandwidth) with 24-bit resolution. For this study, ULS sound levels in this report are from channel 1 of Frame A2 (channel A2.1), and are accessible through ShipSound, a component of JASCO’s online PortListen® sound measurement system.

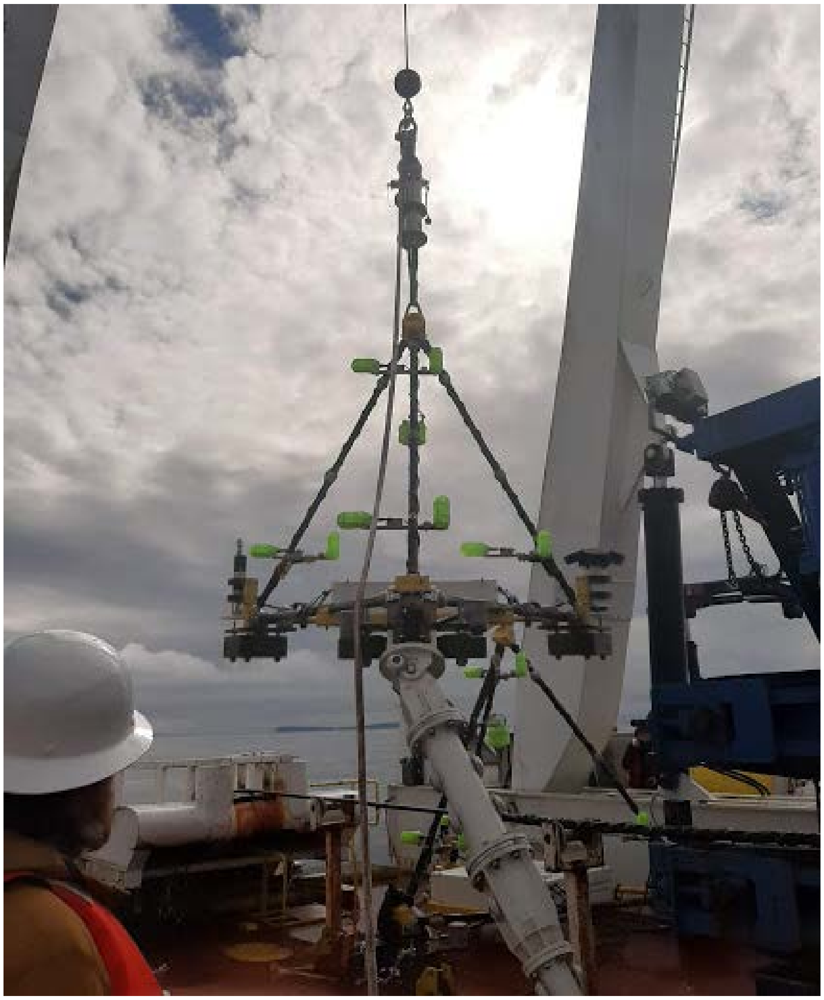


Figure 3. Boundary Pass Underwater Listening Station (ULS) mooring: deployed shore-cabled compact tetrahedral hydrophone array

Table 7. Recorder deployment locations and periods in 2022 (Year 4). The deployment locations are also shown in Figure 2.

Recorder	Latitude (N)	Longitude (W)	Water depth (m)	Active hydrophone array	Hydrophone model
Frame A	48°45.56672'	123°3.85010'	193	Frame A2.1	HTI 99-HF
Frame B	48°45.65731'	123°3.65912'	195	Frame B1.1	GTI M36-V35-100

2. Results

The results presented in this section are broadband radiated noise levels (RNL) as defined in ANSI S12.64-2009 and a second metric known as monopole source levels (MSL), for the frequency range 10 Hz to 250 kHz. MSL as calculated here is closely related to the ISO 18405 definition of source level (SL).

2.1. Vessel Noise Emissions

The source levels (RNL and MSL) of all passes were summarized in a box-and-whisker plot that shows the range of all accepted ULS measurements (see Figures 4–7 and Tables 8–11).

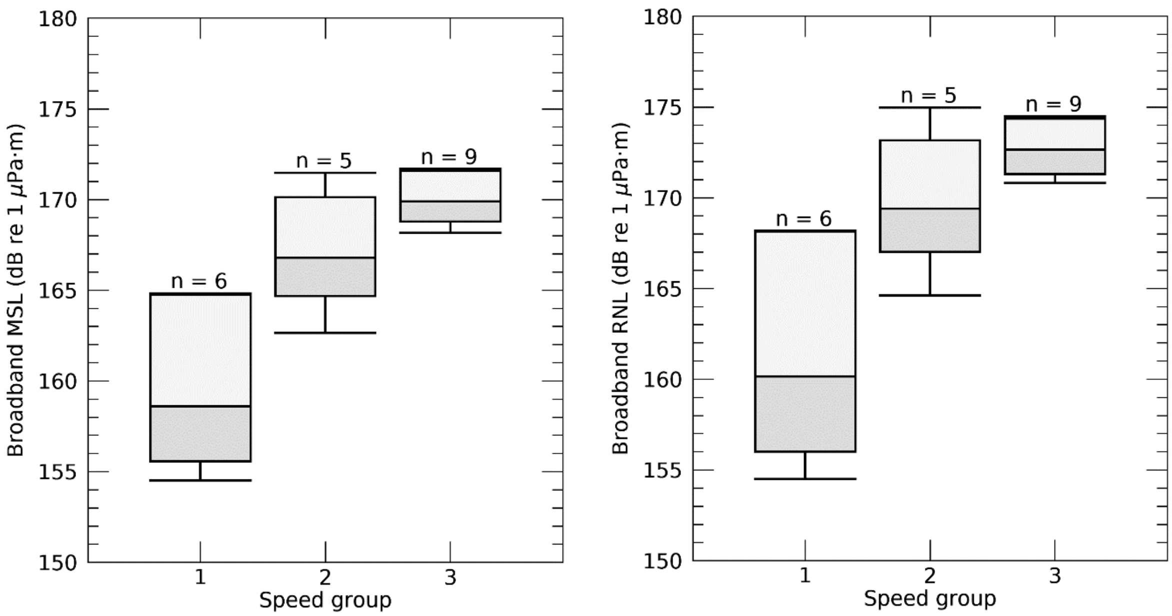


Figure 4. *WILD 4 WHALES*: Box-and-whisker plot summarizing source level (left: RNL and right: MSL) for all accepted measurements on the ULS Station 1. Speed group 1 = less than 10 kts, speed group 2 = 10–20 kts, and speed group 3 = greater than 20 kts.

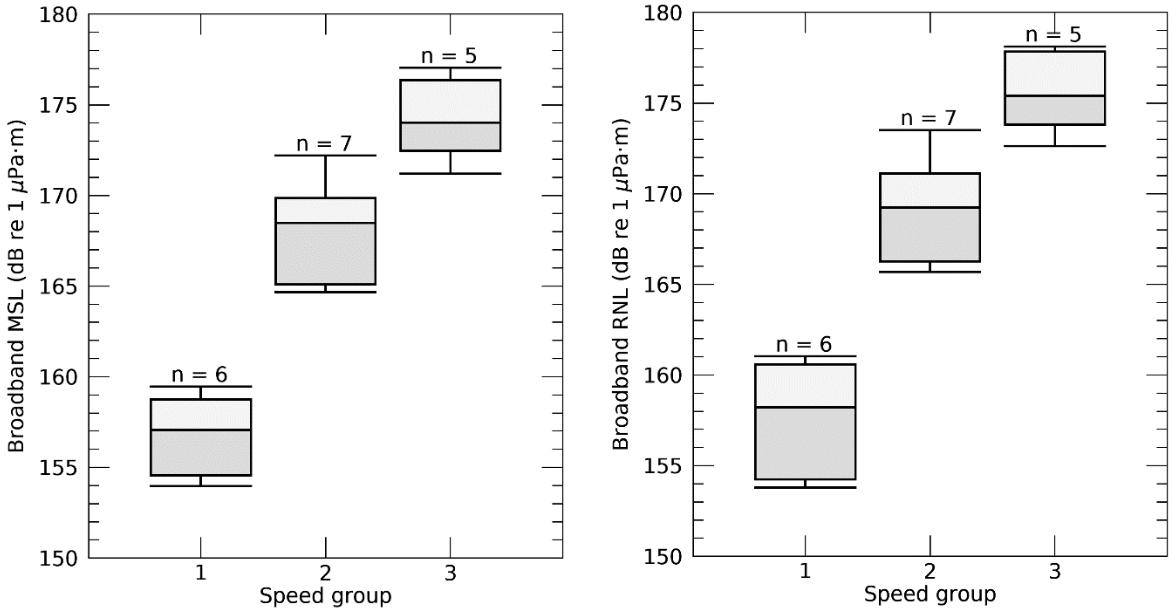


Figure 5. *4EVER WILD*: Box-and-whisker plot summarizing source level (left: RNL and right: MSL) for all accepted measurements on the ULS Station 1. Speed group 1 = less than 10 kts, speed group 2 = 10–20 kts, and speed group 3 = greater than 20 kts.

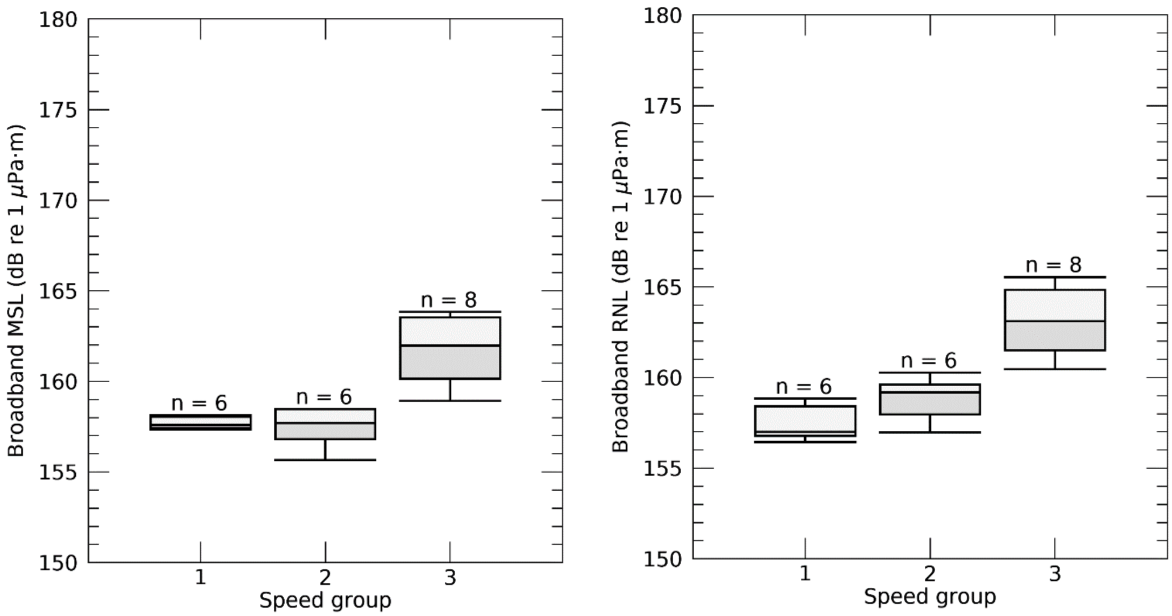


Figure 6. *GOLDWING*: Box-and-whisker plot summarizing source level (left: RNL and right: MSL) for all accepted measurements on the ULS Station 1. Speed group 1 = less than 10 kts, speed group 2 = 10–20 kts, and speed group 3 = greater than 20 kts.

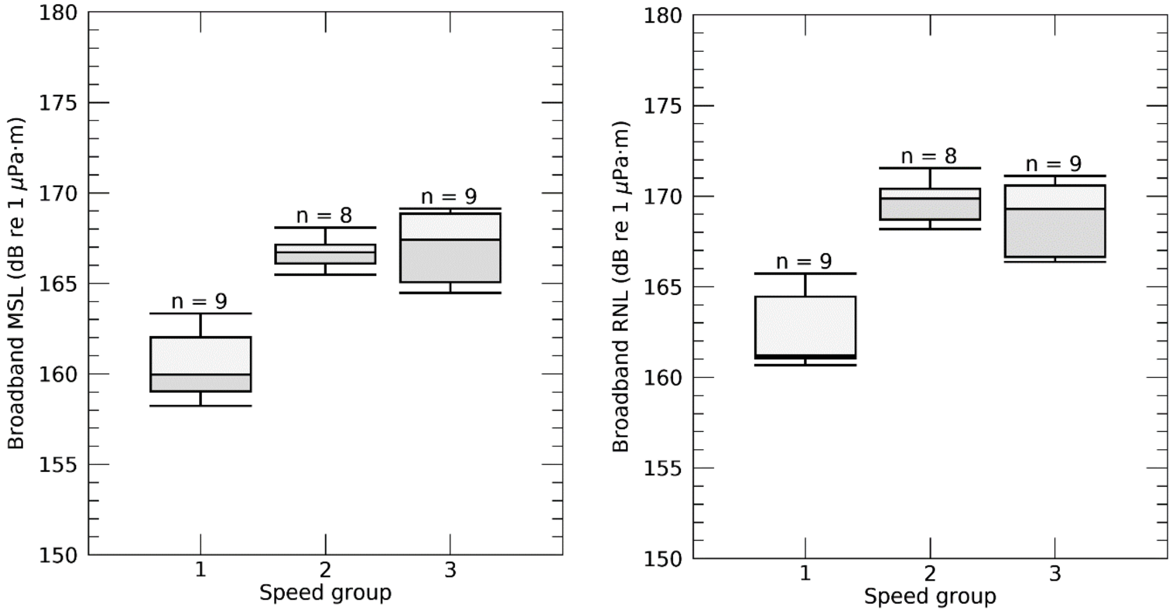


Figure 7. *SERENGETI*: Box-and-whisker plot summarizing source level (left: RNL and right: MSL) for all accepted measurements on the ULS Station 1. Speed group 1 = less than 10 kts, speed group 2 = 10–20 kts, and speed group 3 = greater than 20 kts.

Table 8. *WILD 4 WHALES*: Five-number summary (minimum, lower quartile, median, upper quartile, maximum) of accepted measurements (RNL and MSL, dB re 1 µPa^{2}m^2).

Statistic	RNL (Broadband)			MSL (Broadband)		
	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts
Maximum	168.2	175	174.5	164.8	171.5	171.7
Upper quartile	168.1	173.2	174.4	164.8	170.1	171.6
Median	160.2	169.4	172.7	158.6	166.8	169.9
Lower quartile	156	167	171.3	155.6	164.7	168.8
Minimum	154.5	164.6	170.8	154.5	162.7	168.2

Table 9. *4EVER WILD*: Five-number summary (minimum, lower quartile, median, upper quartile, maximum) of accepted measurements (RNL and MSL, dB re 1 µPa^{2}m^2).

Statistic	RNL (Broadband)			MSL (Broadband)		
	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts
Maximum	161	173.5	178.1	159.5	172.2	177
Upper quartile	160.6	171.1	177.8	158.8	169.8	176.4
Median	158.2	169.2	175.4	157.1	168.5	174
Lower quartile	154.2	166.3	173.8	154.6	165.1	172.5
Minimum	153.8	165.7	172.6	154	164.7	171.2

Table 10. *GOLDWING*: Five-number summary (minimum, lower quartile, median, upper quartile, maximum) of accepted measurements (RNL and MSL, dB re 1 µPa²m²).

Statistic	RNL (Broadband)			MSL (Broadband)		
	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts
Maximum	158.8	160.3	165.5	158.1	158.5	163.8
Upper quartile	158.4	159.6	164.8	158	158.5	163.5
Median	157	159.2	163.1	157.6	157.7	162
Lower quartile	156.8	158	161.5	157.4	156.8	160.1
Minimum	156.5	157	160.5	157.3	155.7	158.9

Table 11. SERENGETI: Five-number summary (minimum, lower quartile, median, upper quartile, maximum) of accepted measurements (RNL and MSL, dB re 1 µPa²m²).

Statistic	RNL (Broadband)			MSL (Broadband)		
	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts	Speed < 10 kts	Speed 10–20 kts	Speed ≥ 20 kts
Maximum	165.7	171.5	171.1	163.3	168.1	169.1
Upper quartile	164.4	170.4	170.6	162	167.1	168.8
Median	161.2	169.9	169.3	160	166.7	167.4
Lower quartile	161.1	168.7	166.7	159	166.1	165.1
Minimum	160.7	168.2	166.4	158.2	165.5	164.5

2.2. Vessel Speed Analysis

RNL and MSL measurements were made at several transit speeds. Speed through water (STW) for each pass was calculated from speed over ground (from AIS), corrected according by the direction and speed of water currents at the time of measurement. The time-dependent ocean current estimates for the measurement site were obtained from the Webtide current model from Fisheries & Oceans Canada. To quantify trends of RNL or MSL with STW, a power-law model of the following form was fit to the data:

$$\mathrm{RNL} = C_v \times 10\log_{10}\left(\frac{v}{v_{\mathrm{ref}}}\right) + \mathrm{RNL}_{\mathrm{ref}}\,,$$

$$\mathrm{MSL} = C_v \times 10\log_{10}\left(\frac{v}{v_{\mathrm{ref}}}\right) + \mathrm{MSL}_{\mathrm{ref}}\,,$$

where, Cv is the slope of increase in RNL (or MSL) with STW, v, measured in knots. $\mathrm{RNL}_{\mathrm{ref}}$ or $\mathrm{MSL}_{\mathrm{ref}}$ (dB re 1 µPa) is defined here as the reference source level, representing the RNL or MSL at the reference STW v_{ref} of 10 knots. This linear regression was performed for three different frequency bands: Southern Resident Killer Whale (SRKW) communication band (0.5–15 kHz), SRKW echolocation band (>15 kHz), and the broadband (20 Hz to 250 kHz). Table 12 shows the best-fit trend line parameters for all vessels, while Figures 8 to 11 show the trend-lines plotted against the STW data. The analysis shows that the trend of RNL and MSL with speed was statistically significant (positive) in all frequency bands. Negative trends represent decreasing RNL with increasing speed, while positive trend represent increasing RNL with speed.

Table 12. RNL and MSL versus STW data: Best-fit trend line parameters as determined by linear regression analysis. C_v is the best-fit slope of trend line, and SL_{ref} is the intercept. The coefficient of determination (r^2) indicates the strength of correlation between SL and STW (0 = no correlation, 1 = total correlation). Significance indicates whether the observed trend could have occurred by chance with greater than a 5% probability (p-value).

Fit parameter	RNL			MSL		
	Broadband	0.5–15 kHz	>15 kHz	Broadband	0.5–15 kHz	>15 kHz
WILD 4 WHALES						
C_v	1.98	2.78	4.51	1.81	2.75	10.06
SL_{ref} (dB re 1 µPa m)	166.00	161.08	148.71	163.84	158.28	145.71
V_{ref} (knots)	10	10	10	10	10	10
Coefficient of determination (r^2)	0.69	0.96	0.91	0.74	0.96	0.91
Significant ($p < 0.05$)	Yes	Yes	Yes	Yes	Yes	Yes
4EVER WILD						
C_v	2.61	3.42	2.99	2.57	3.42	11.49
SL_{ref} (dB re 1 µPa m)	165.59	157.21	147.81	164.53	154.43	144.81
V_{ref} (knots)	10	10	10	10	10	10
Coefficient of determination (r^2)	0.84	0.94	0.86	0.88	0.94	0.86
Significant ($p < 0.05$)	Yes	Yes	Yes	Yes	Yes	Yes
GOLDWING						
C_v	0.89	1.59	1.18	0.69	1.59	12.58
SL_{ref} (dB re 1 µPa m)	158.80	150.34	140.69	158.28	147.60	137.68
V_{ref} (knots)	10	10	10	10	10	10
Coefficient of determination (r^2)	0.65	0.70	0.61	0.52	0.72	0.61
Significant ($p < 0.05$)	Yes	Yes	Yes	Yes	Yes	Yes
SERENGETI						
C_v	0.83	2.19	1.69	0.89	2.20	12.43
SL_{ref} (dB re 1 µPa m)	165.80	156.15	144.19	163.49	153.19	141.18
V_{ref} (knots)	10	10	10	10	10	10
Coefficient of determination (r^2)	0.51	0.84	0.73	0.66	0.84	0.73
Significant ($p < 0.05$)	Yes	Yes	Yes	Yes	Yes	Yes

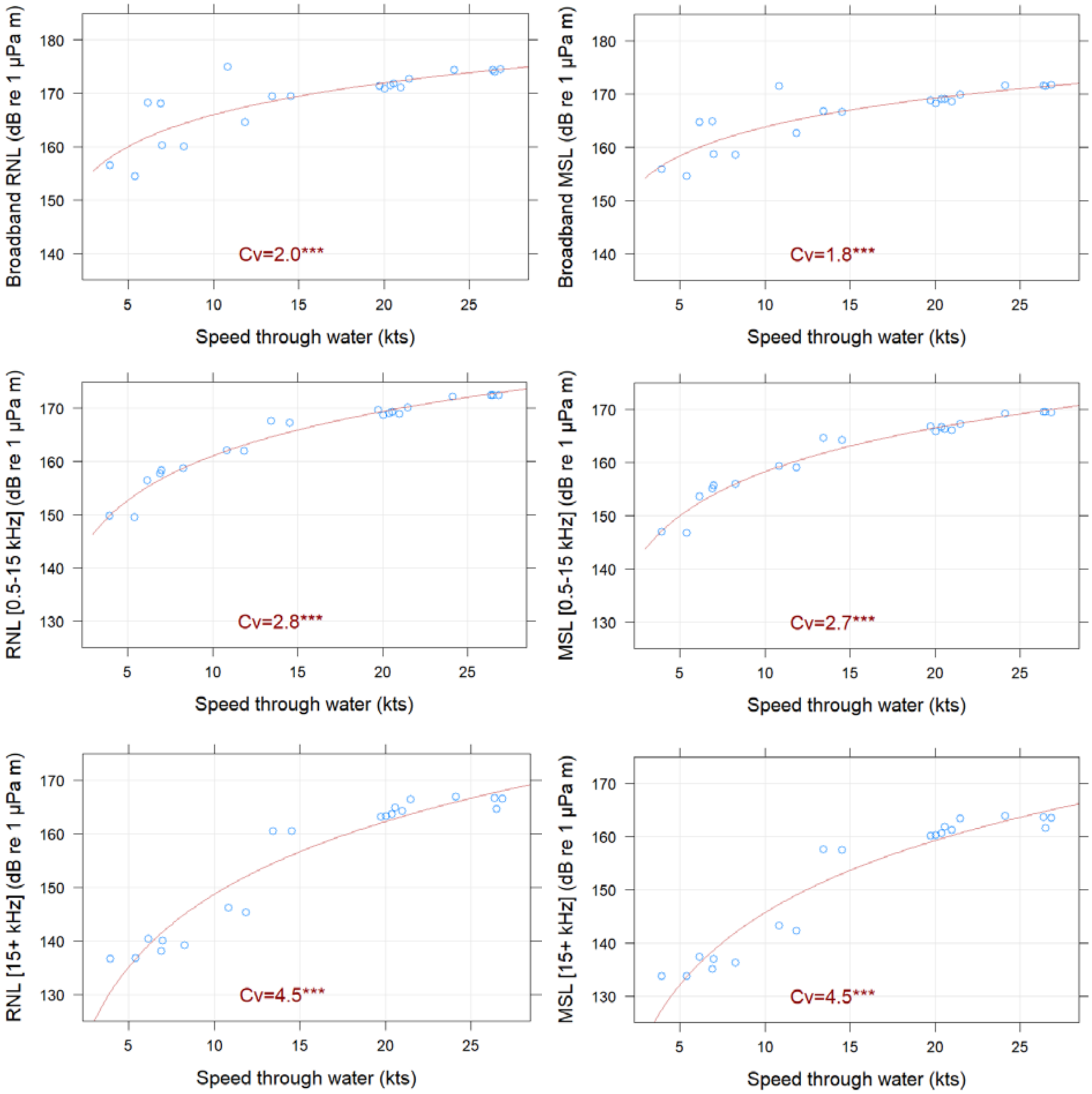


Figure 8. *WILD 4 WHALES*: Top: Scatter plot of broadband source level (left: RNL, right: MSL) versus STW; Center: Scatter plot of source level for SRKW communication band (0.5–15 kHz) (left: RNL, right: MSL) versus STW; Bottom: Scatter plot of source level for SRKW echolocation band (>15 kHz) (left: RNL, right: MSL) versus STW. The red lines show the best-fit trend lines. See Table 12 for line parameters.

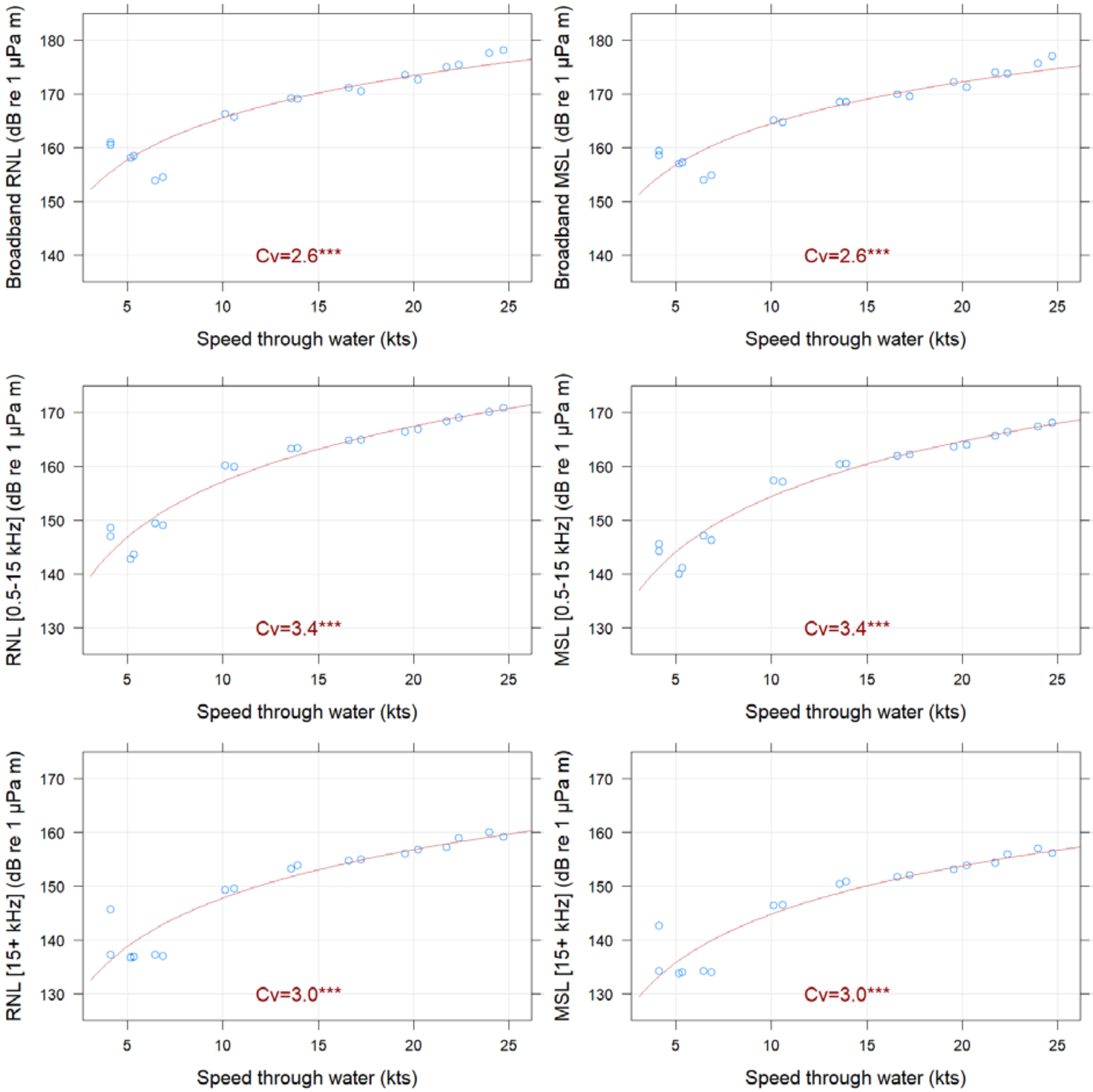


Figure 9. *4EVER WILD*: Top: Scatter plot of broadband source level (left: RNL, right: MSL) versus STW; Center: Scatter plot of source level for SRKW communication band (0.5–15 kHz) (left: RNL, right: MSL) versus STW; Bottom: Scatter plot of source level for SRKW echolocation band (>15 kHz) (left: RNL, right: MSL) versus STW. The red lines show the best-fit trend lines. See Table 12 for line parameters.

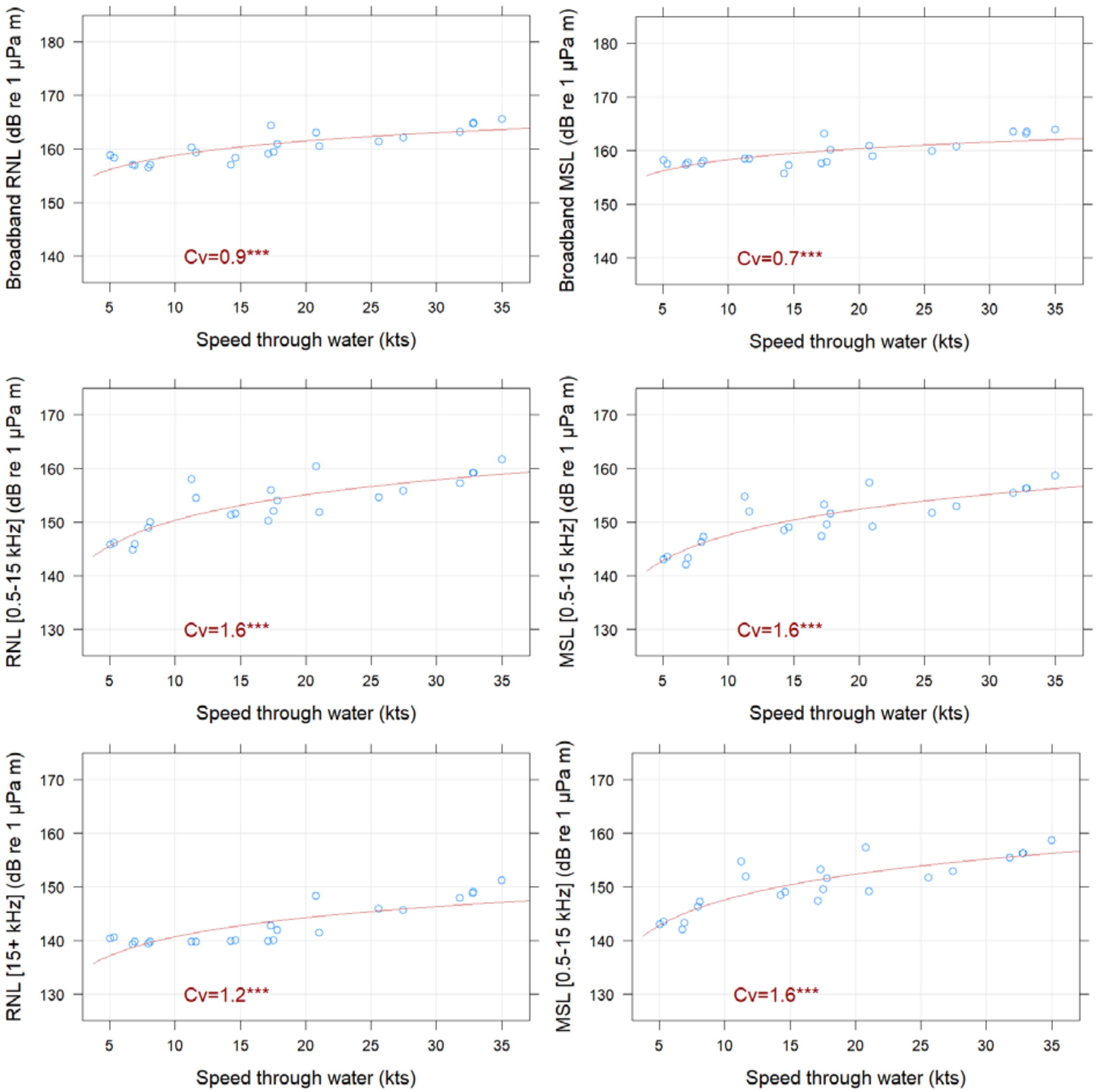


Figure 10. *GOLDWING*: Top: Scatter plot of broadband source level (left: RNL, right: MSL) versus STW; Center: Scatter plot of source level for SRKW communication band (0.5–15 kHz) (left: RNL, right: MSL) versus STW; Bottom: Scatter plot of source level for SRKW echolocation band (>15 kHz) (left: RNL, right: MSL) versus STW. The red lines show the best-fit trend lines. See Table 12 for line parameters.

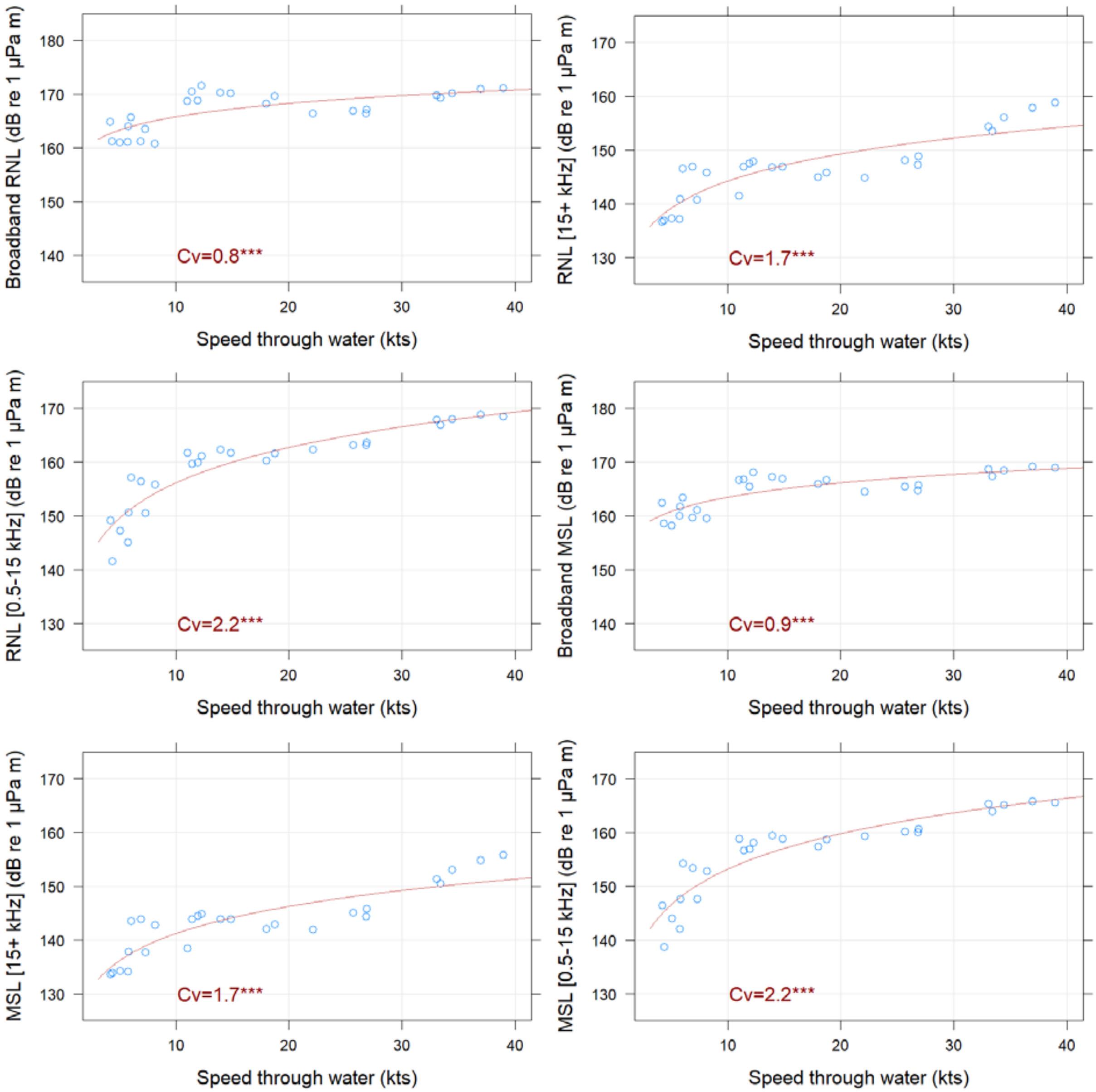
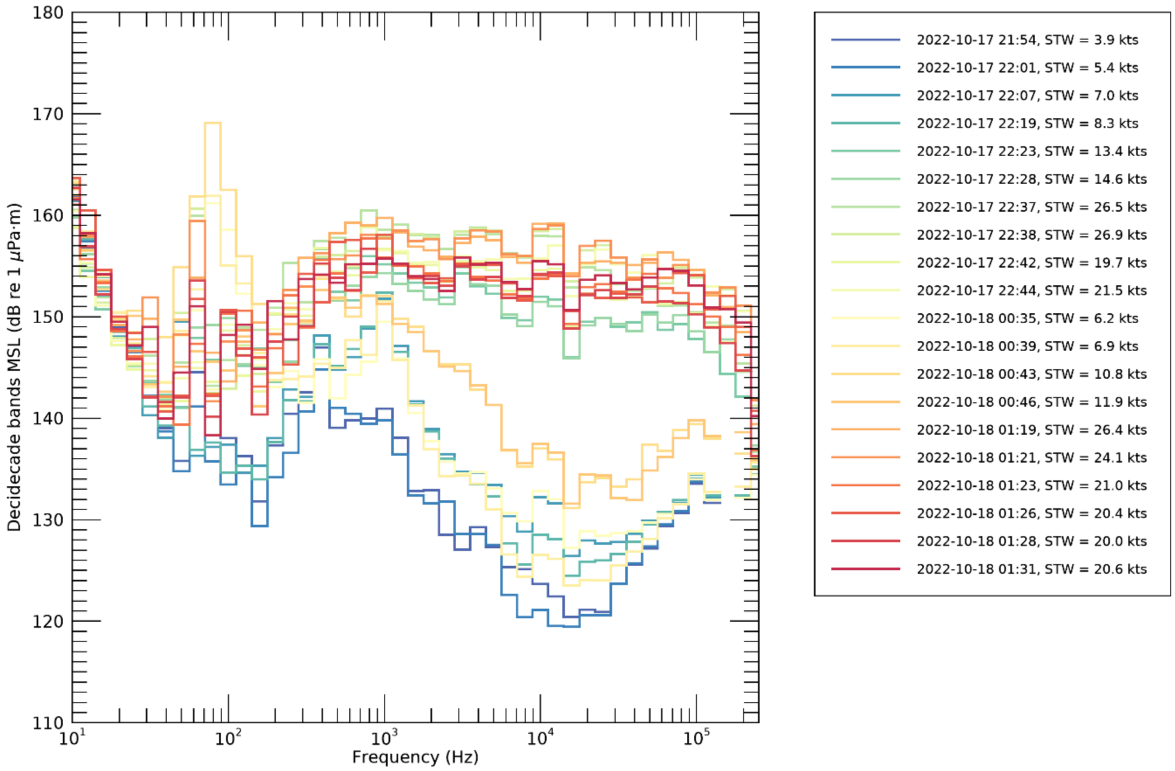


Figure 11. *SERENGETI*: Top: Scatter plot of broadband source level (left: RNL, right: MSL) versus STW; Center: Scatter plot of source level for SRKW communication band (0.5–15 kHz) (left: RNL, right: MSL) versus STW; Bottom: Scatter plot of source level for SRKW echolocation band (>15 kHz) (left: RNL, right: MSL) versus STW. The red lines show the best-fit trend lines. See Table 12 for line parameters.

2.3. Band Level Analysis

Analysis of RNL and MSL in decidecade bands were used to determine how vessel noise emissions varied with frequency (Figures 12–15). A high-resolution spectrum analysis is presented in Section 2.4.



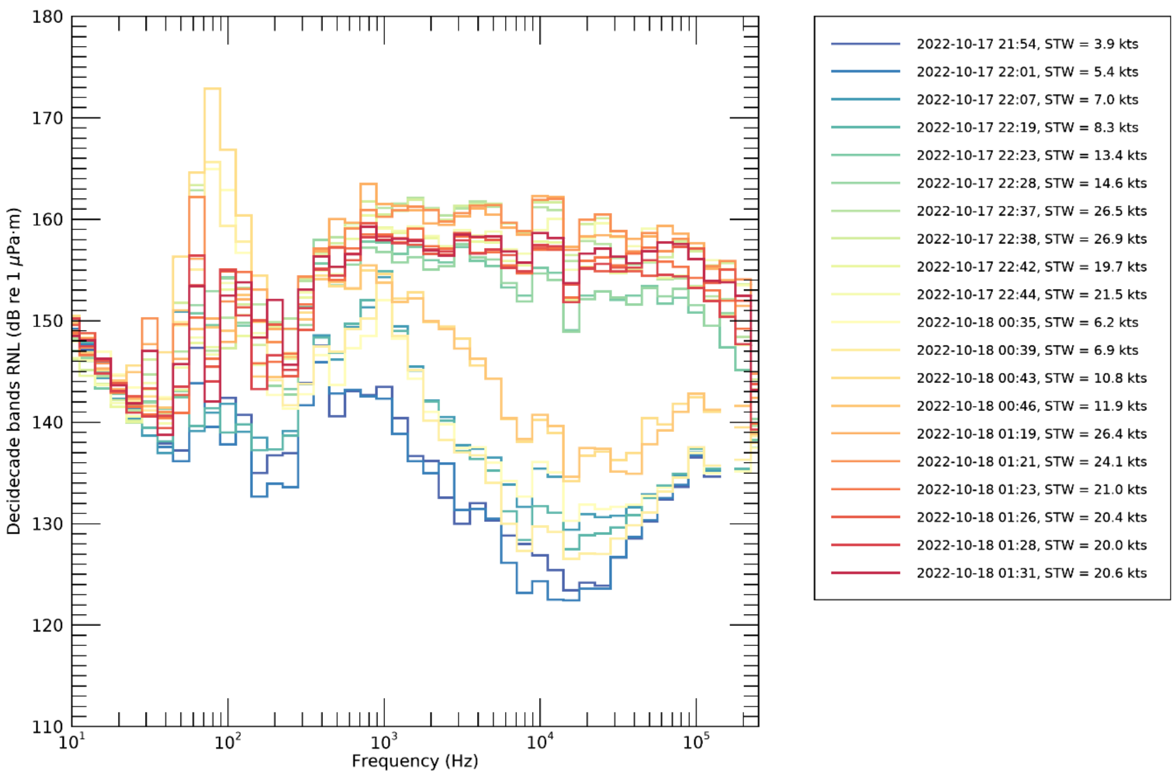


Figure 12. *WILD 4 WHALES*: Decidecade band RNL (top) and MSL (bottom) versus frequency at ULS Station 1. STW is speed through water.

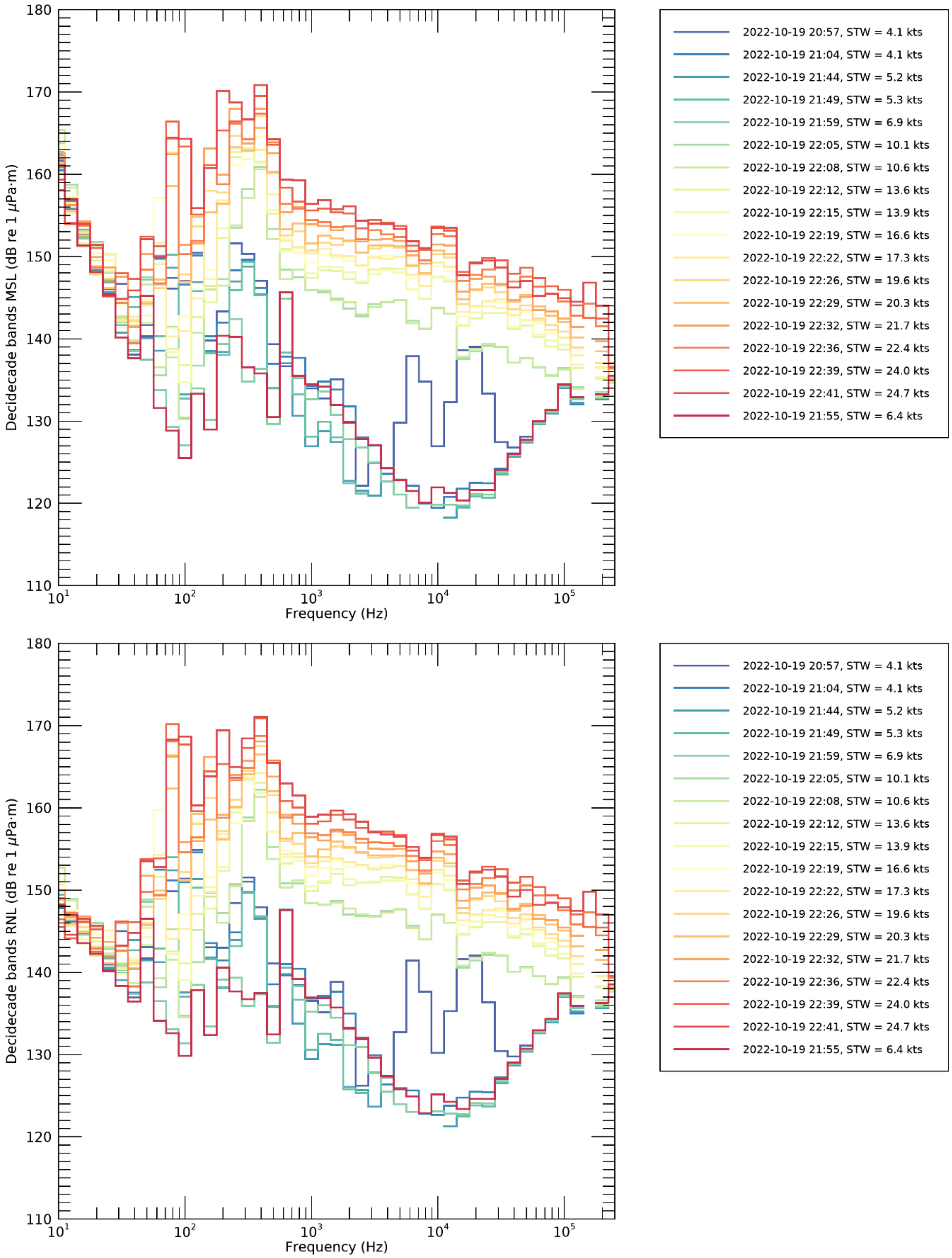


Figure 13. *4EVER WILD*: Decidecade band RNL (top) and MSL (bottom) versus frequency at ULS Station 1.STW is speed through water.

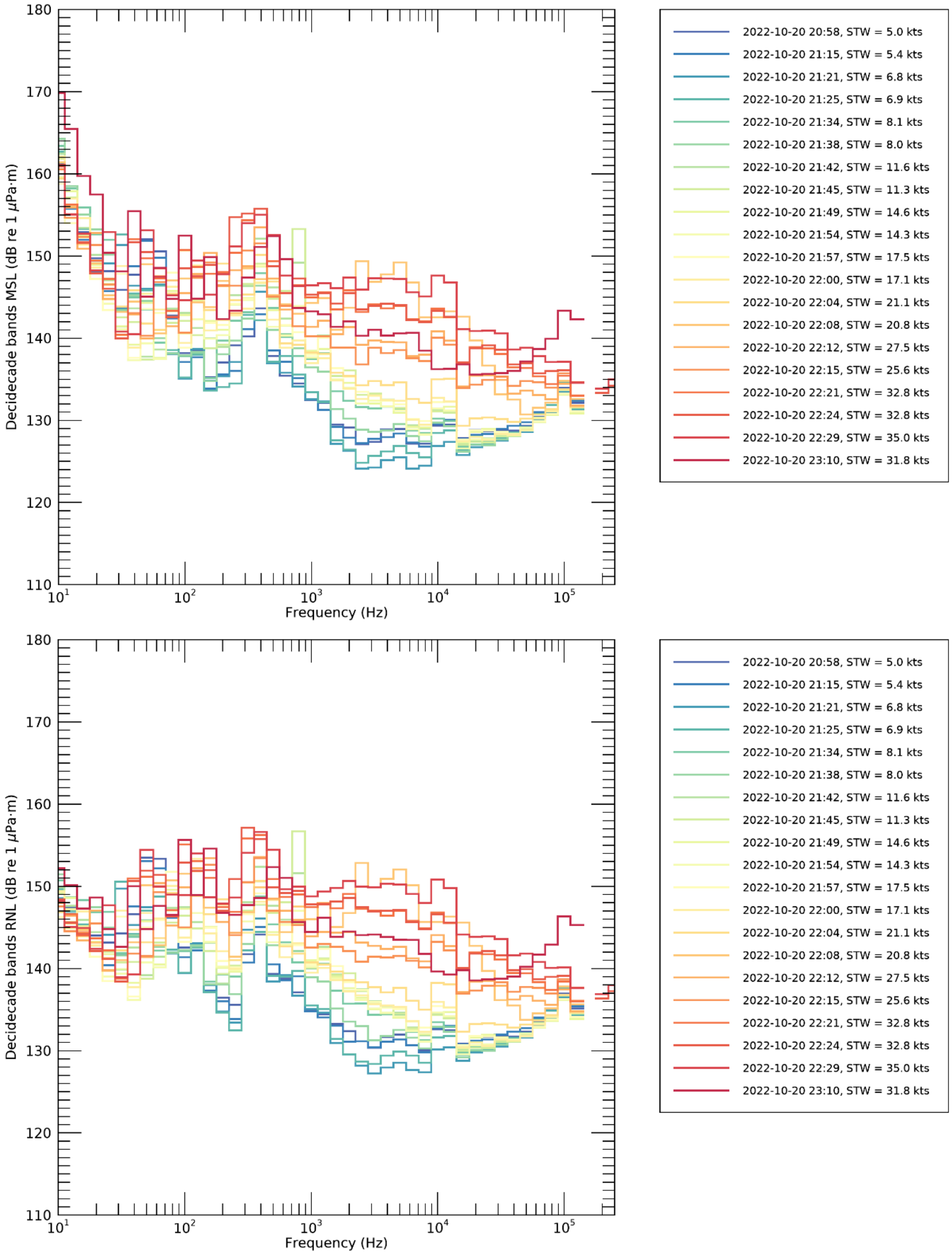


Figure 14. *GOLDWING*: Decidecade band RNL (top) and MSL (bottom) versus frequency at ULS Station 1.STW is speed through water.

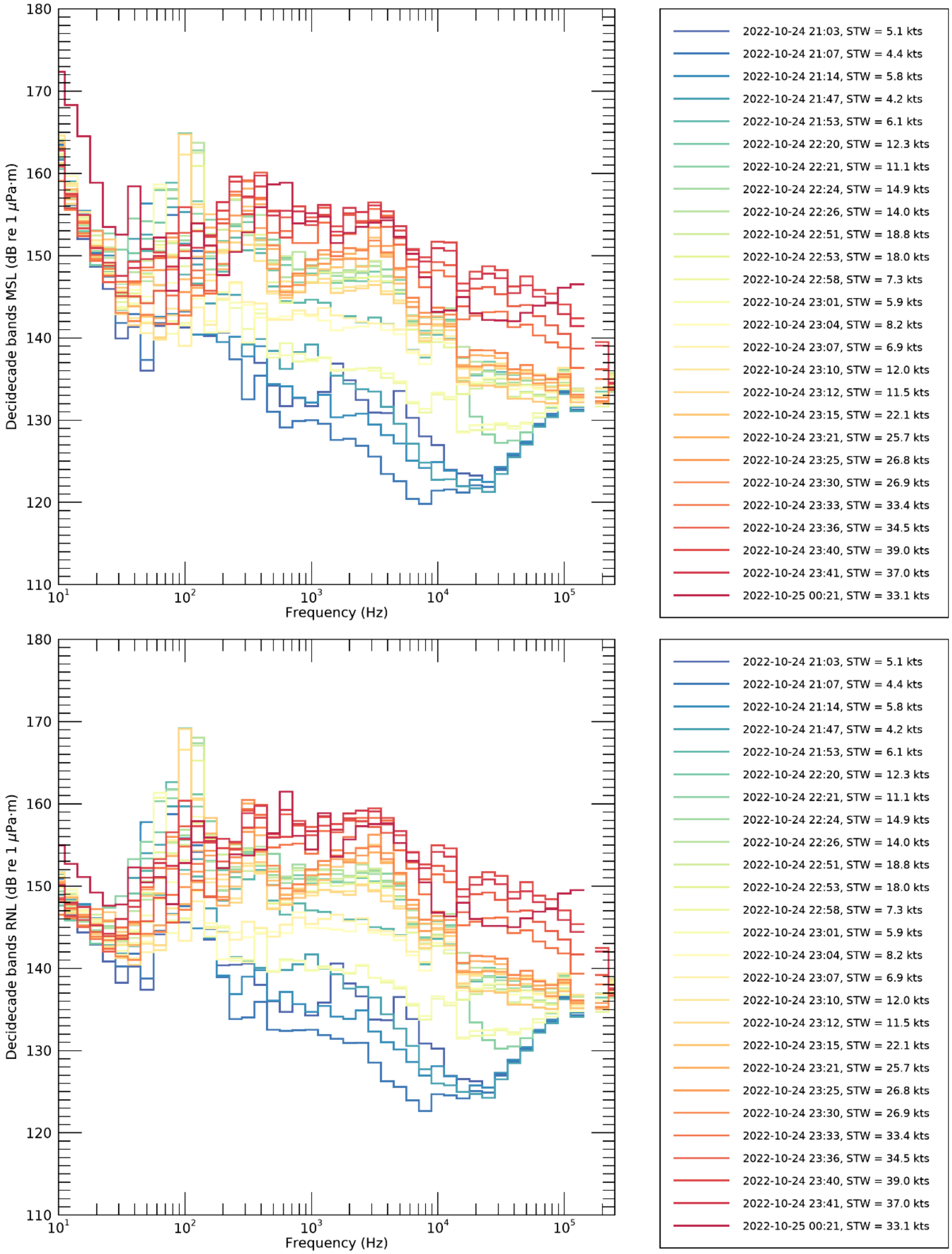


Figure 15. *SERENGETI:* Decidecade band RNL (top) and MSL (bottom) versus frequency at ULS Station 1.STW is speed through water.

2.4. Spectrum Analysis

Section 2.3 presented decidecade band source levels. A spectral analysis was applied below 2000 Hz to identify low-frequency tone noise, such as would be typically associated with propeller rotation and machinery vibration (Figures 16 to 19). Each spectrum was calculated from the mean power spectral density level during a single vessel pass, averaged between ±30° azimuth angle surrounding the vessel CPA, and backpropagated to obtain the source spectral levels. The spectrum plots show several individual tones generated by the vessel. These tones are generally associated with either propeller blade rate cavitation or vibrations from engines and other rotational machinery.

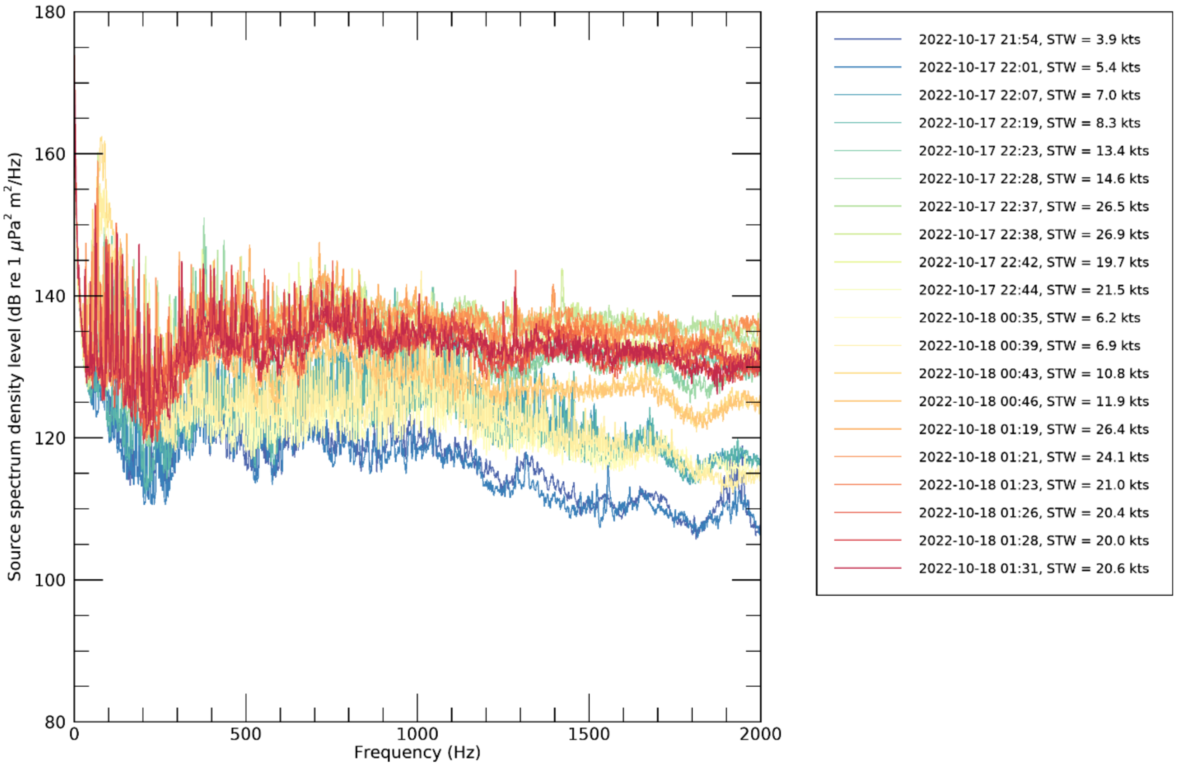


Figure 16. *WILD 4 WHALES*: Source spectral levels at ULS Station 1.

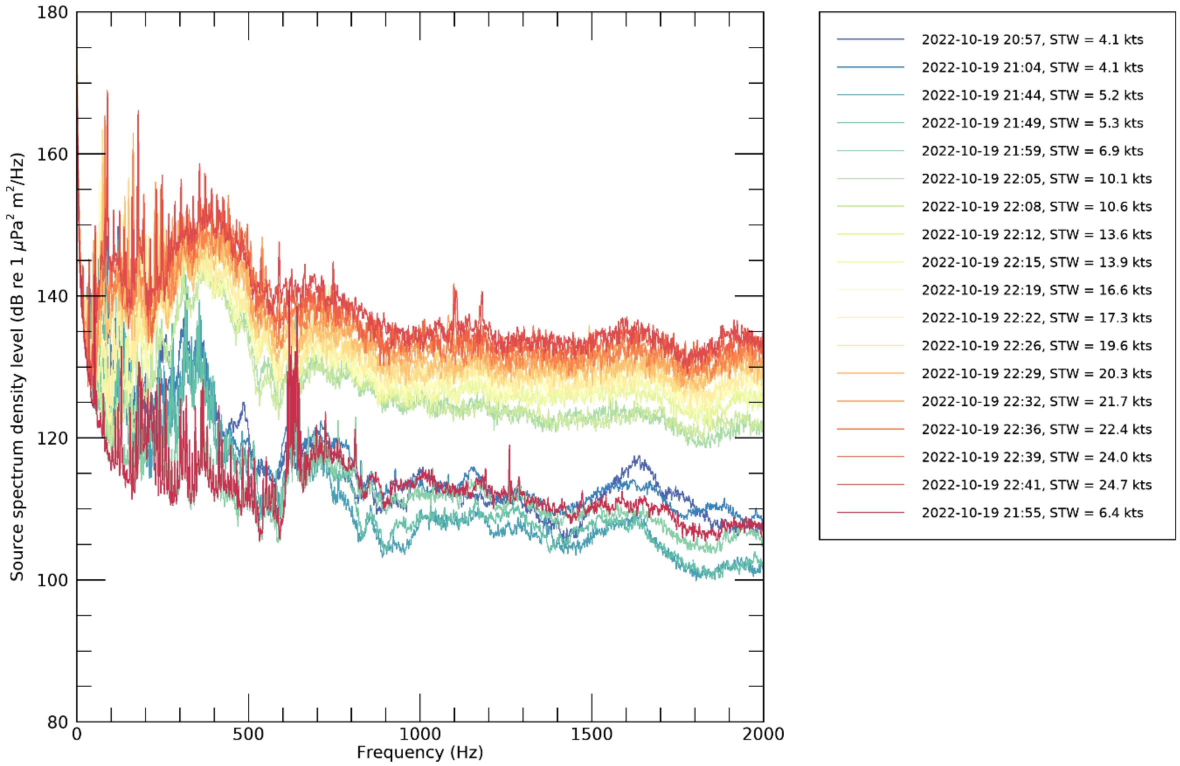


Figure 17. *4EVER WILD*: Source spectral levels at ULS Station 1.

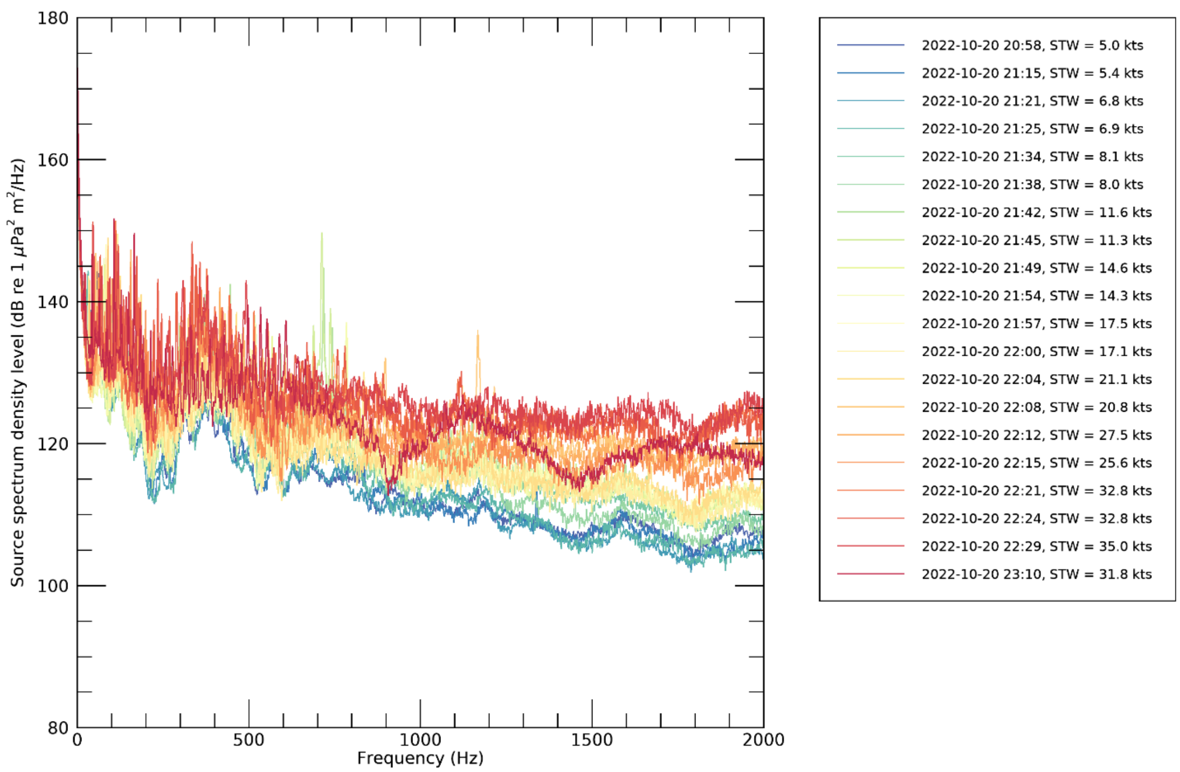


Figure 18. *GOLDWING*: Source spectral levels at ULS Station 1.

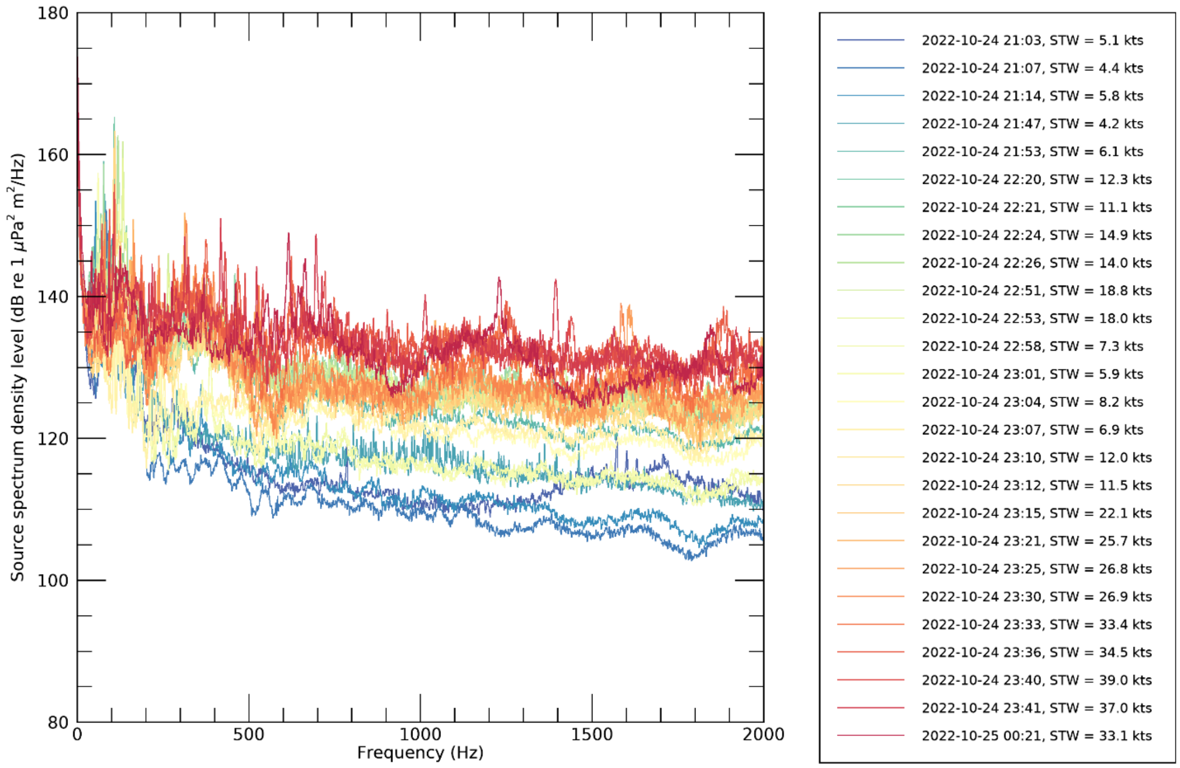


Figure 19. *SERENGETI*: Source spectral levels at ULS Station 1.

2.5. Spectrogram

Figures 20 to 23 present some examples of spectrogram for *WILD 4 WHALES*, *4EVER WILD*, *GOLDWING*, and *SERENGETI* measurements (accepted measurements only) for ULS Station 1. Corresponding reports are presented in Appendix B.

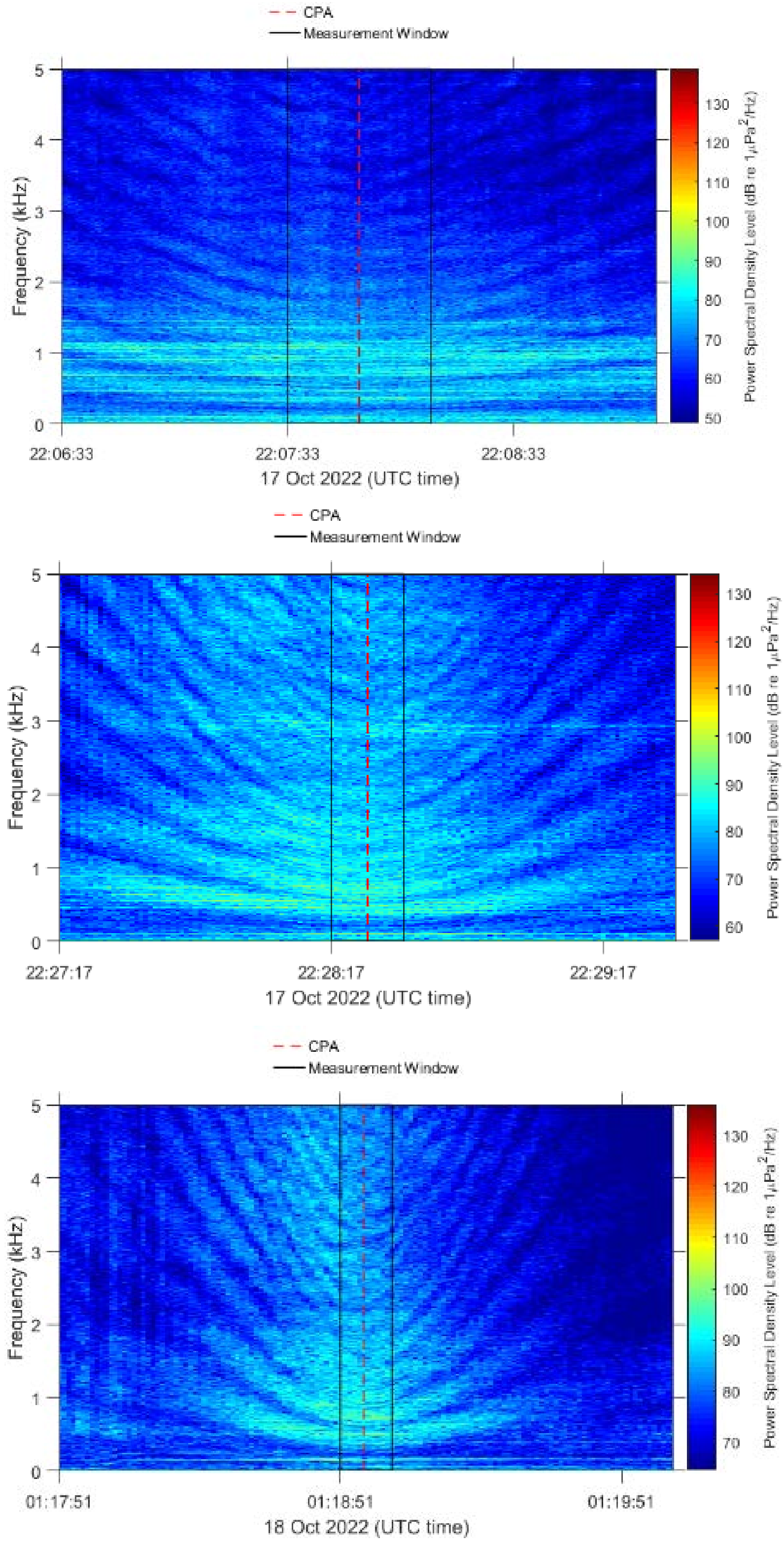


Figure 20. *WILD 4 WHALES*: Spectrogram for transits with speed through water of 7.0 kts (top), 14.6 kts (center), and 26.4 kts (bottom) for ULS Station 1. All measurements are accepted.

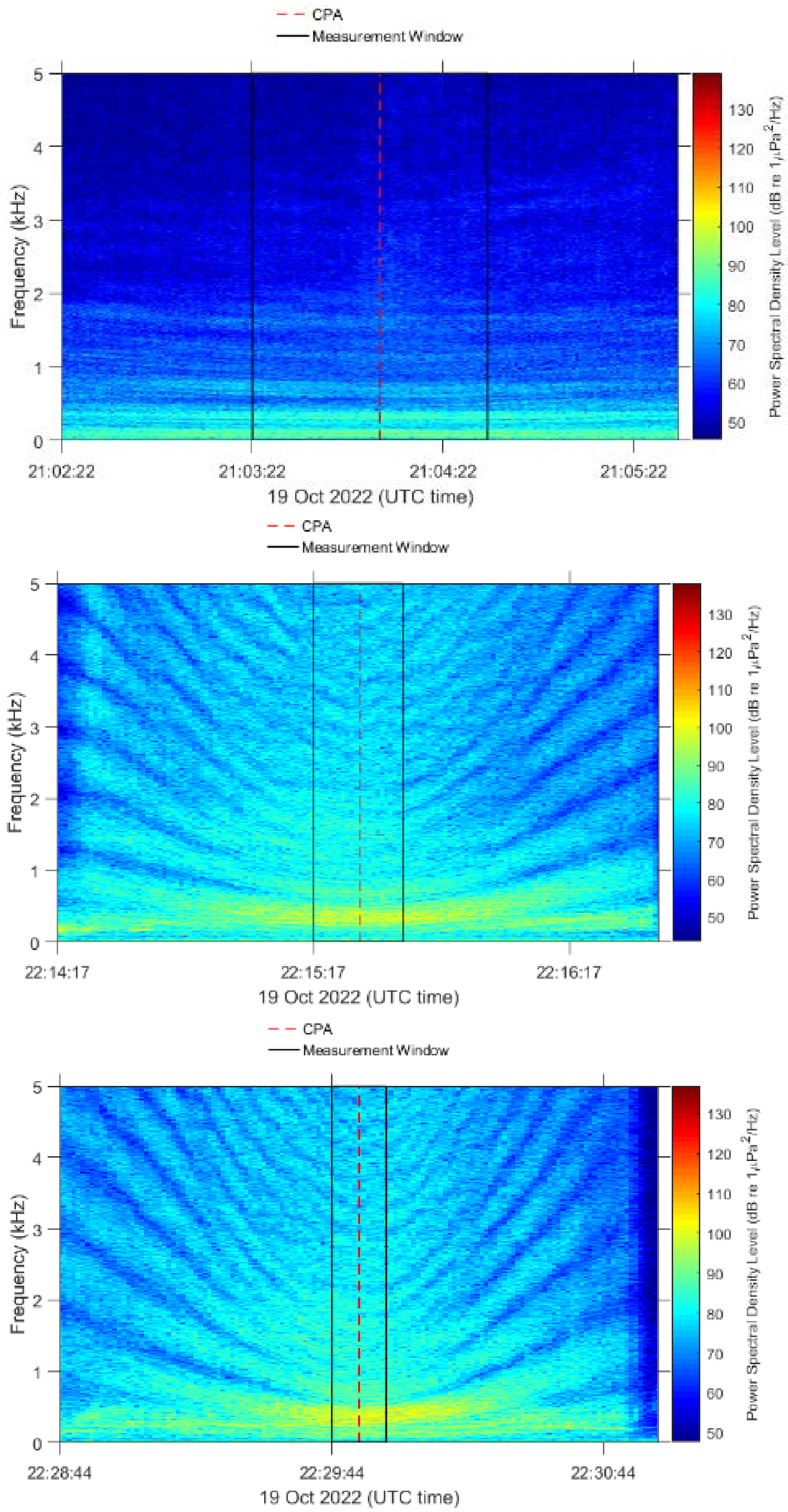


Figure 21. *4EVER WILD*: Spectrogram for transits with speed through water of 4.1 kts (top), 13.9 kts (center), and 20.3 kts (bottom) for ULS Station 1. All measurements are accepted.

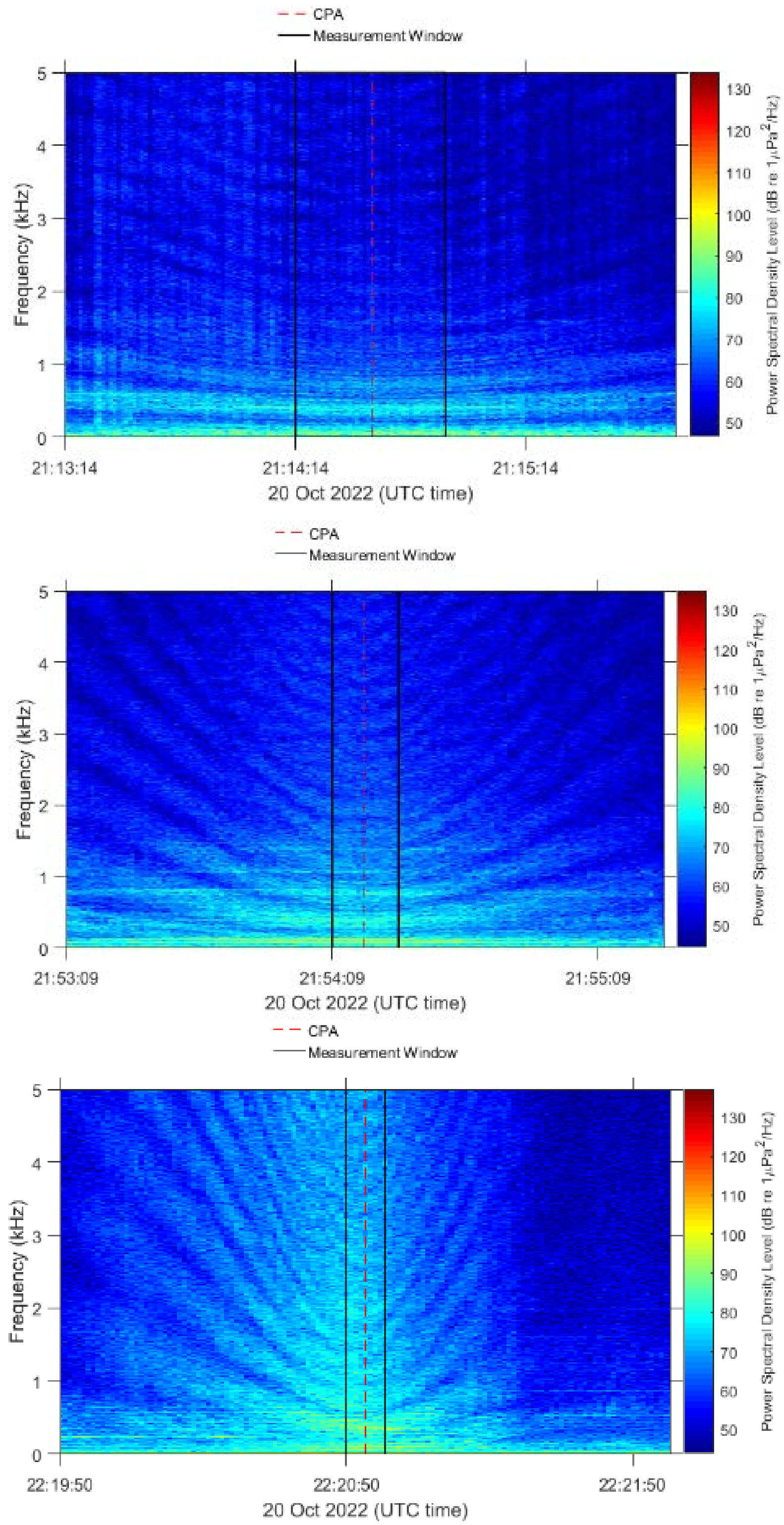


Figure 22. *GOLDWING*: Spectrogram for transits with speed through water of 5.4 kts (top), 14.3 kts (center), and 32.8 kts (bottom) for ULS Station 1. All measurements are accepted.

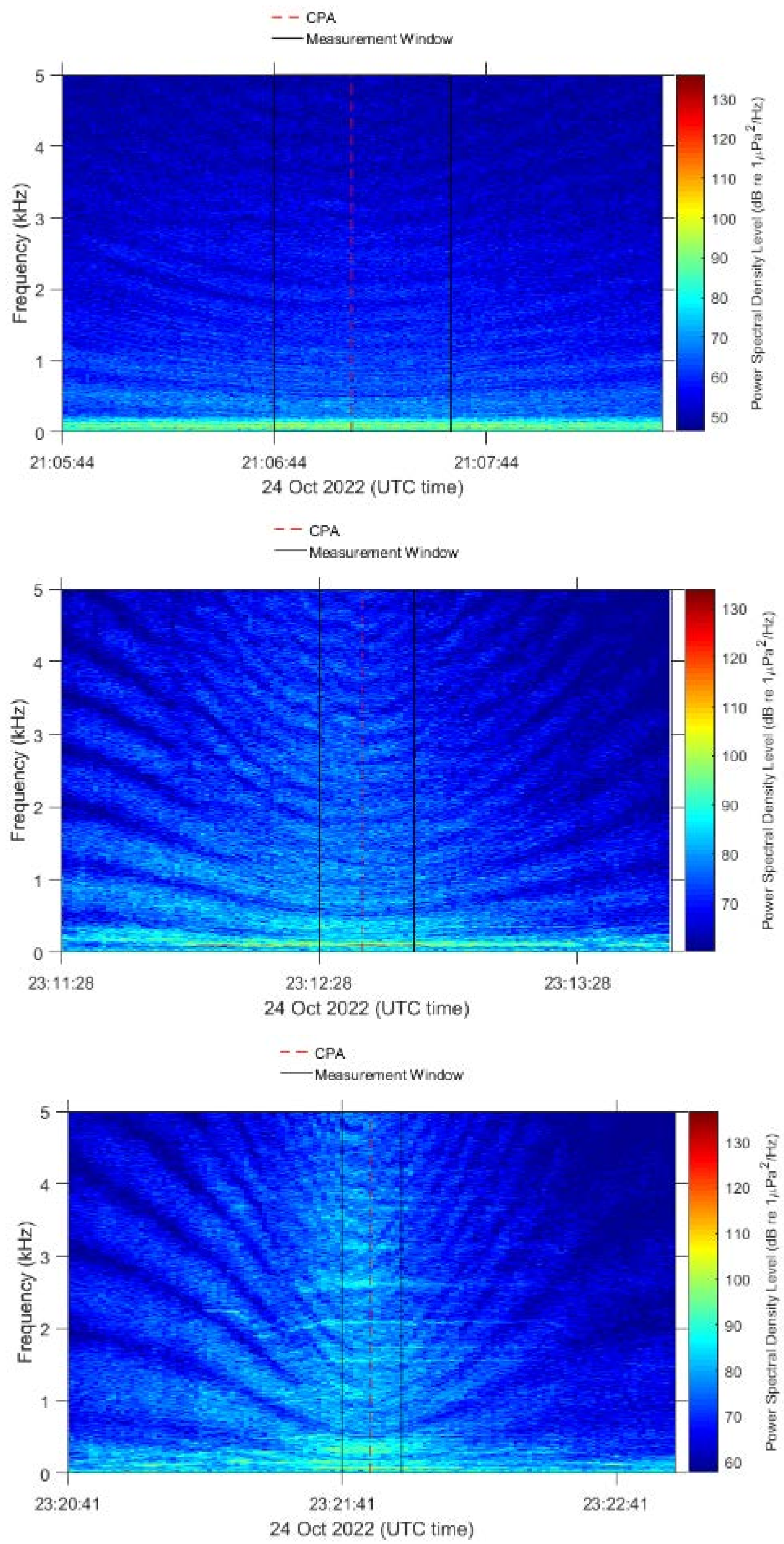
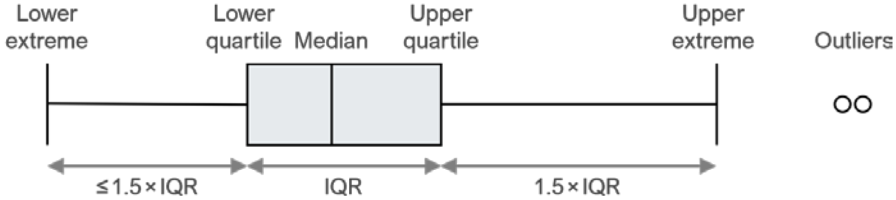


Figure 23. *SERENGETI*: Spectrogram for transits with speed through water of 5.1 kts (top), 11.5 kts (center), and 25.7 kts (bottom) for ULS Station 1. All measurements are accepted.

Glossary

box-and-whisker plot

A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The box is the interquartile range (IQR), which shows the middle 50 % of the data—from the lower quartile (25th percentile) to the upper quartile (75th percentiles). The line inside the box is the median (50th percentile). The whiskers show the lower and upper extremes excluding outliers, which are data points that fall more than 1.5 × IQR beyond the upper and lower quartiles.



broadband level

The total level measured over a specified frequency range.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

frequency

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hertz (Hz)

A unit of frequency defined as one cycle per second.

hydrophone

An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

monopole source level (MSL)

A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point-like (monopole) sound source. See related term: radiated noise level.

power spectral density

Generic term, formally defined as power in a unit frequency band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared sound pressure. ratio of Error! Reference source not found., E_f, to time duration, Δt, in a specified temporal observation window. In equation form, the power spectral density P_f is given by:

$$P_f = \frac{E_f}{\Delta t}.$$

Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

power spectral density level

The level ($L_{P,f}$) of the **power spectral density** (P_f). Unit: decibel (dB).

$$L_{P,f} := 10 \log_{10}\left(P_f / P_{f,0}\right) \text{ dB} .$$

The frequency band and integration time should be specified.

As with **power spectral density**, power spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($P_{f,0}$) for power spectral density level depends on the nature of field variable.

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure.
Unit: pascal (Pa).

radiated noise level (RNL)

A source level that has been calculated assuming sound pressure decays geometrically with distance from the source, with no influence of the sea-surface and seabed. See related term: monopole source level.

received level

The level measured (or that would be measured) at a defined location. The type of level should be specified.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound pressure level (rms sound pressure level)

The level ($L_{p,\text{rms}}$) of the time-mean-square sound pressure (p_{rms}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 µPa^2.

$$L_{p,\text{rms}} := 10 \log_{10}(p_{\text{rms}}^2 / p_0^2) \text{ dB } = 20 \log_{10}(p_{\text{rms}} / p_0) \text{ dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

source level (SL)

A property of a sound source obtained by adding to the sound pressure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 µPa^{2}m^2.

spectrum

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

Appendix A. PortListen

The acoustic recordings from the ULS were analyzed using JASCO's custom vessel noise measurement system, PortListen. This system implements the Grade C (Survey Method) for Underwater Radiated Noise Level Measurements per ANSI S12.64-2009 Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements.

The acoustic data were analyzed in 1/3-octave frequency bands from 10 Hz to 250 kHz. Each sound recording was processed using 1-s sliding Fast Fourier Transforms (FFTs) applied with a power-normalized Hanning window, with 50% overlap, to obtain power spectral density (PSD) levels versus time. Vessel track information was obtained from Automatic Identification System (AIS) data. Since the AIS transmitter/receiver was not necessarily coincident with the vessel's acoustic source, the acoustic closest point of approach (CPA) was determined by tracking the range and speed of the source using an automated tracking algorithm based on the image symmetry detection by gradient polarity method, and the cepstrogram method. The background noise levels (NL) were computed by averaging noise levels over two one-minute intervals—1 min just before the vessel entered the entrance funnel and 1 min after it left the exit zone. Measured RLs were compared with the NLs in 1/3-octave-band frequencies and were adjusted as needed based on the method prescribed in ANSI S12.64-2009.

The source levels were computed along the track with a ±30° azimuth angle centered from the acoustic CPA. Source levels are reported referenced to a nominal range of 1 m from the source, under the standard assumption that all the noise energy originates from a single point source (i.e., the far-field approximation). The computation of source levels requires analyzing the measurements made over a small range of distances, typically of a few hundred metres away from the vessel, and scaling them to account for the reduction in level that occurs as the sound propagates from the reference range (1 m) to the receiver location. The scaling is often referred to as back-propagation. PortListen calculates both Radiated Noise Levels (RNL) and Monopole Source Levels (MSL). A back-propagation that applies a spherical spreading loss 20log(R), where R is the measurement distance in metres, is used to calculate RNL. The RNL back-propagation method of ANSI S12.64-2009 neglects sound reflections off the sea surface and the seabed. Those reflections introduce important propagation effects, especially for sound frequencies below approximately 250 Hz. The backpropagation for MSL accounts for these reflection effects and is computed using JASCO's Marine Operation Noise Model (MONM).

MONM computes sound propagation in range-varying acoustic environments through a wide-angle parabolic equation (PE) solution to the acoustic wave equation[1]. MONM accounts for the environmental parameters including water depth, seabed geoacoustic parameters, and water sound speed profile (SSP). For both RNL and MSL, the attenuation of acoustic energy by molecular absorption in seawater was also considered and computed using the formulae of François and Garrison.[2,3]

The RNLs and MSLs (broadband and 1/3-octave-band) were computed in decibels as a linear average from the RNLs and MSLs from all 1-s sample locations along the vessel track within the ±30° data window as defined in ANSI S12.64-2009.

[1] Collins, M.D. 1993. A split-step PadÂsolution for the parabolic equation method. Journal of the Acoustical Society of America 93: 1736-1742.
[2] François, R.E. and G.R. Garrison. 1982. Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. Journal of the Acoustical Society of America 72(3): 896-907.
[3] François, R.E. and G.R. Garrison. 1982. Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America 72(6): 1879-1890.

Appendix B. Accepted Measurement PortListen Report

The following Appendix contains automatically generated PortListen reports, which contain relevant information about the measurement conditions, vessel characteristics, and acoustic noise results, for all the accepted measurements discussed in this document. All selected reports were from ULS Station 1.

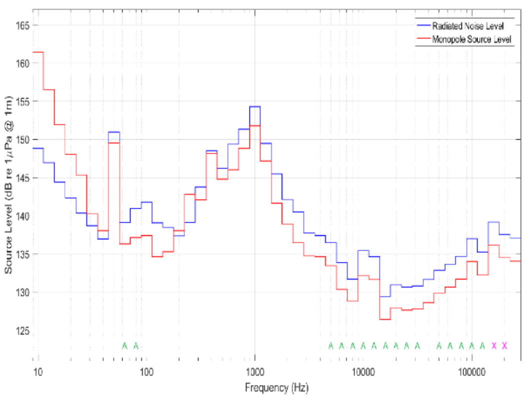
B.1. *WILD 4 WHALES*

Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

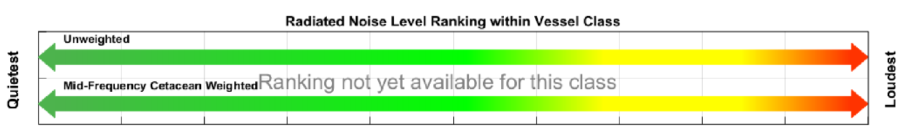
Vessel Information	
MMSI:	316034816
IMO:	
Name:	WILD 4 WHALES
Flag:	Canada
Vessel DWT (TEU):	N/A
PortListen Vessel Type	Whale Watch
Length (m):	0.0
Beam (m)	0.0
Maximum Draft (m):	N/A
Engine Power (kW):	N/A
Number of Shafts:	N/A
Prop Diameter (m):	N/A

Measurement Information	
Measurement Date (UTC):	October 17, 2022
Closest Approach Time (UTC):	22:07:51
Closest Approach Distance (m):	91.1
Vessel Ground Speed (kn):	7.2
Sail Direction over ground (deg):	55.1
Vessel Water Speed (kn):	7.0
Shaft rate (rpm):	34.2
Vessel Percent Power/Pitch:	N/A
Actual Vessel Draft max (m):	0.0
Monopole Source Depth (m):	2.8
Monopole Source Level (dB/µPa):	158.7
Radiated Noise Level (dB/µPa):	160.3



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



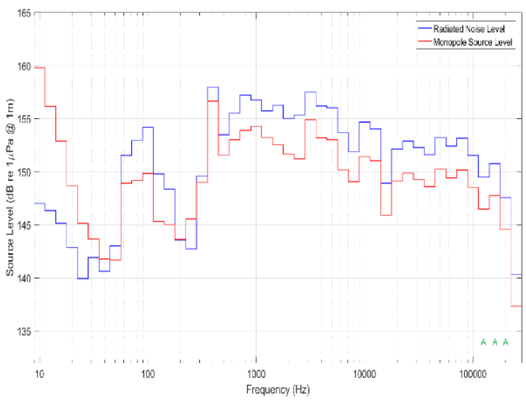
This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

[1] With respect to the information provided in this report, neither Vancouver Fraser Port Authority, JASCO Applied Sciences nor any of their respective directors, officers, employees, contractors or agents (collectively, the "Report Providers") make any warranty either expressed or implied, including the warranty for fitness for a particular purpose, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of information disclosed. Furthermore, this report and the measurements reported herein cannot be used to confirm or counter any claim of adherence to or exceedance of legislated noise emission standards in any jurisdiction and by accepting this report, the report recipient agrees that the Report Providers shall not be liable for any losses, claims, damages, actions, fines, penalties, costs or expenses, including legal fees, arising from the use of this report for any purpose whatsoever.

Vessel Underwater Acoustic Source Level Measurement Report

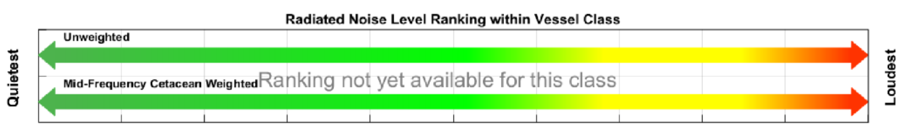
This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316034816	Measurement Date (UTC):	October 17, 2022
IMO:		Closest Approach Time (UTC):	22:28:24
Name:	WILD 4 WHALES	Closest Approach Distance (m):	103.8
Flag:	Canada	Vessel Ground Speed (kn):	14.5
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	234.5
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	14.6
Length (m):	0.0	Shaft rate (rpm):	60.6
Beam (m)	0.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	166.7
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	169.4



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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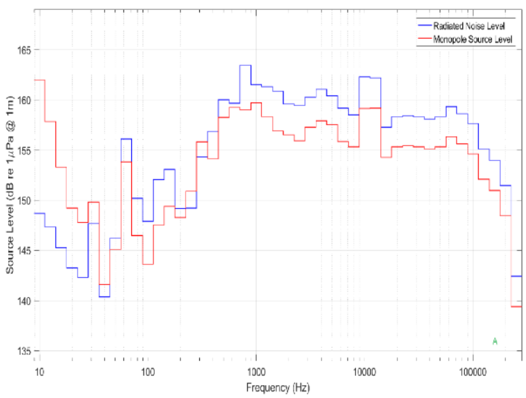
Vessel Underwater Acoustic Source Level Measurement Report

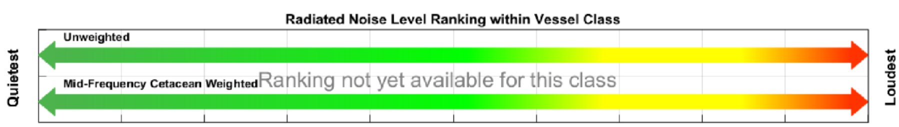
This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316034816	Measurement Date (UTC):	October 18, 2022
IMO:		Closest Approach Time (UTC):	1:18:55
Name:	WILD 4 WHALES	Closest Approach Distance (m):	117.7
Flag:	Canada	Vessel Ground Speed (kn):	26.2
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	47.8
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	26.4
Length (m):	0.0	Shaft rate (rpm):	-6000.0
Beam (m)	0.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	171.6
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	174.3



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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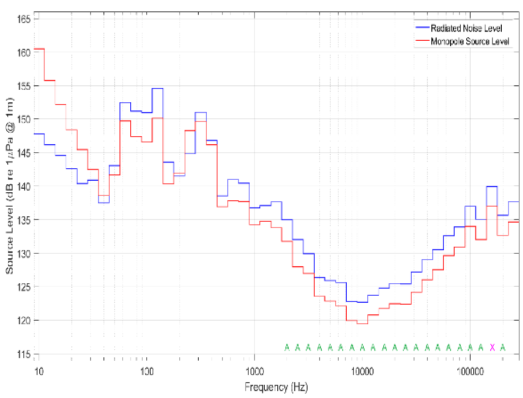
B.2. 4EVER WILD

Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316028179	Measurement Date (UTC):	October 19, 2022
IMO:		Closest Approach Time (UTC):	21:04:01
Name:	4 EVER WILD	Closest Approach Distance (m):	94.3
Flag:	Canada	Vessel Ground Speed (kn):	3.2
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	233.5
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	4.1
Length (m):	25.0	Shaft rate (rpm):	75.6
Beam (m)	7.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	158.5
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	160.4



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.

This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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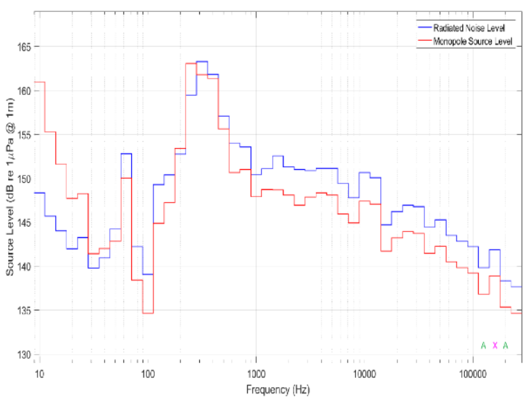
Vessel Underwater Acoustic Source Level Measurement Report

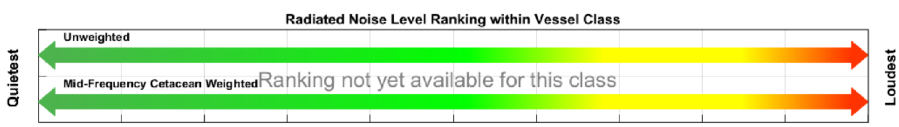
This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316028179	Measurement Date (UTC):	October 19, 2022
IMO:		Closest Approach Time (UTC):	22:15:28
Name:	4 EVER WILD	Closest Approach Distance (m):	91.2
Flag:	Canada	Vessel Ground Speed (kn):	13.4
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	231.2
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	13.9
Length (m):	25.0	Shaft rate (rpm):	77.4
Beam (m)	7.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	168.4
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	169.0



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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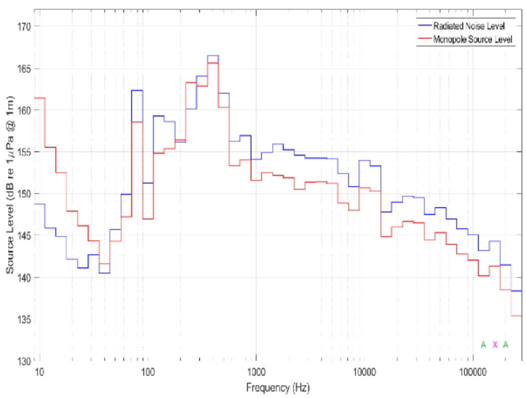
Vessel Underwater Acoustic Source Level Measurement Report

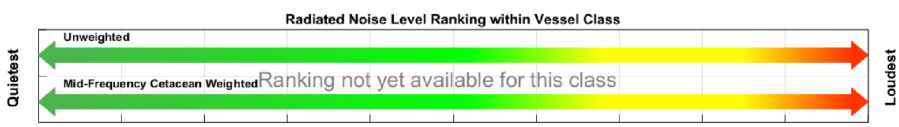
This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316028179	Measurement Date (UTC):	October 19, 2022
IMO:		Closest Approach Time (UTC):	22:29:49
Name:	4 EVER WILD	Closest Approach Distance (m):	98.0
Flag:	Canada	Vessel Ground Speed (kn):	19.8
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	234.1
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	20.3
Length (m):	25.0	Shaft rate (rpm):	64.2
Beam (m)	7.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	171.2
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	172.6



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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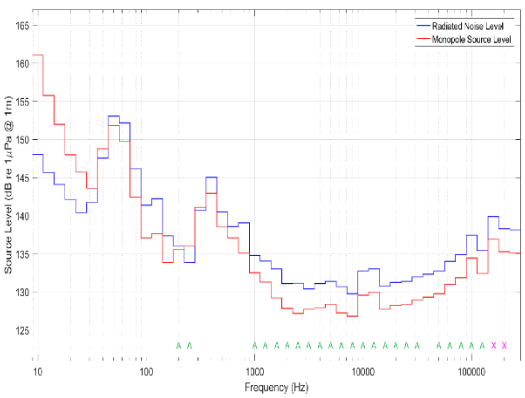
B.3. GOLDWING

Vessel Underwater Acoustic Source Level Measurement Report

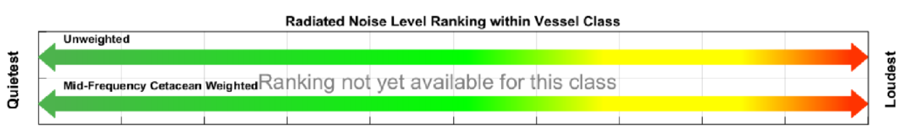
This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316007107	Measurement Date (UTC):	October 20, 2022
IMO:		Closest Approach Time (UTC):	21:14:33
Name:	GOLDWING	Closest Approach Distance (m):	112.0
Flag:	Canada	Vessel Ground Speed (kn):	6.4
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	57.0
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	5.4
Length (m):	0.0	Shaft rate (rpm):	60.0
Beam (m)	0.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	157.5
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	158.3



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.



This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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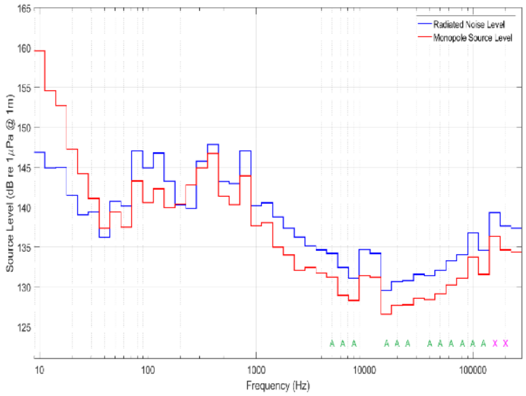
Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316007107	Measurement Date (UTC):	October 20, 2022
IMO:		Closest Approach Time (UTC):	21:54:15
Name:	GOLDWING	Closest Approach Distance (m):	101.8
Flag:	Canada	Vessel Ground Speed (kn):	15.2
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	54.3
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	14.3
Length (m):	0.0	Shaft rate (rpm):	70.2
Beam (m)	0.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	155.7
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	157.0



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.

This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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Vessel Underwater Acoustic Source Level Measurement Report

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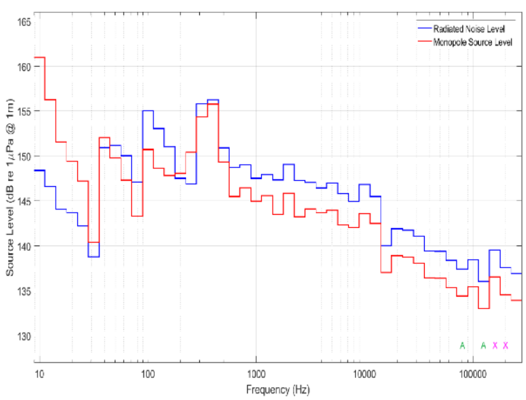
Vessel Information		Measurement Information	
MMSI:	316007107	Measurement Date (UTC):	October 20, 2022
IMO:		Closest Approach Time (UTC):	22:20:54
Name:	GOLDWING	Closest Approach Distance (m):	92.7
Flag:	Canada	Vessel Ground Speed (kn):	32.1
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	240.1
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	32.8
Length (m):	0.0	Shaft rate (rpm):	-6000.0
Beam (m)	0.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	163.2
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	164.8



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.

This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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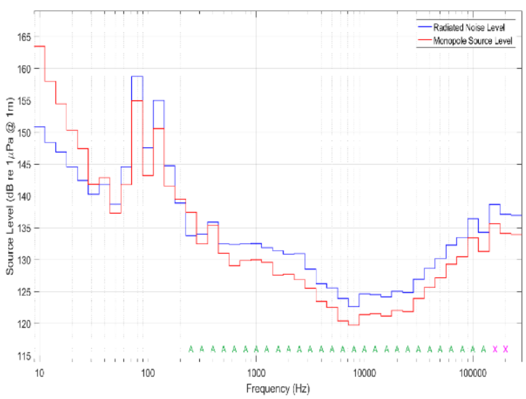
B.4. SERENGETI

Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information	
MMSI:	316008468
IMO:	
Name:	SERENGETI
Flag:	Canada
Vessel DWT (TEU):	N/A
PortListen Vessel Type	Whale Watch
Length (m):	40.0
Beam (m)	8.0
Maximum Draft (m):	N/A
Engine Power (kW):	N/A
Number of Shafts:	N/A
Prop Diameter (m):	N/A

Measurement Information	
Measurement Date (UTC):	October 24, 2022
Closest Approach Time (UTC):	21:07:06
Closest Approach Distance (m):	93.1
Vessel Ground Speed (kn):	5.3
Sail Direction over ground (deg):	55.9
Vessel Water Speed (kn):	4.4
Shaft rate (rpm):	97.8
Vessel Percent Power/Pitch:	N/A
Actual Vessel Draft max (m):	0.0
Monopole Source Depth (m):	2.8
Monopole Source Level (dB/µPa):	158.6
Radiated Noise Level (dB/µPa):	161.2



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.

This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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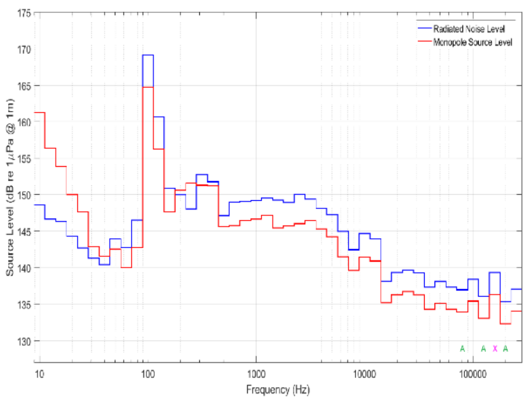
Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316008468	Measurement Date (UTC):	October 24, 2022
IMO:		Closest Approach Time (UTC):	23:12:37
Name:	SERENGETI	Closest Approach Distance (m):	92.2
Flag:	Canada	Vessel Ground Speed (kn):	12.4
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	51.0
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	11.5
Length (m):	40.0	Shaft rate (rpm):	72.6
Beam (m)	8.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	166.8
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	170.5



The 1/3-octave frequency band vessel source levels are presented in two metrics formats:

1. Radiated Noise Level - as defined in ANSI 12.64 - 2009 (R2014) measurement standard, and
2. Monopole Source Level - considers sound energy as originating from a point location, most suitable for use by acoustic models that independently account for surface and seabed reflections
3. Values marked "x" have less than 3 dB signal-to-noise ratio (SNR). Those marked with "A" are adjusted for SNR between 3 and 10 dB.

This vessel's underwater noise rating is better than N/A% of other vessels in class: Whale Watch, scaled for operating parameters. This rating is based on currently accepted, published scientific criteria and is relative to the measurements of comparable vessels recorded by this system. The rating value reported for a given vessel can therefore change over time as the statistics evolve and/or new scientifically accepted criteria are introduced. Details of the rating procedures are provided on the attached sheet.

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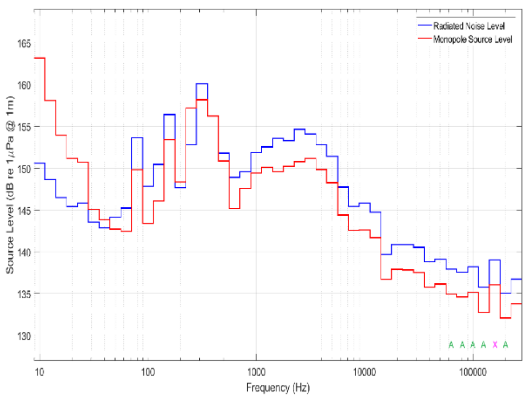
Vessel Underwater Acoustic Source Level Measurement Report

This Vessel Underwater Acoustic Source Level Measurement Report is provided by Vancouver Fraser Port Authority and its collaborator: JASCO Applied Sciences, for the limited purpose of understanding approximate underwater noise emission levels of vessels.[1]

Vessel Information		Measurement Information	
MMSI:	316008468	Measurement Date (UTC):	October 24, 2022
IMO:		Closest Approach Time (UTC):	23:21:46
Name:	SERENGETI	Closest Approach Distance (m):	78.9
Flag:	Canada	Vessel Ground Speed (kn):	26.6
Vessel DWT (TEU):	N/A	Sail Direction over ground (deg):	56.0
PortListen Vessel Type	Whale Watch	Vessel Water Speed (kn):	25.7
Length (m):	40.0	Shaft rate (rpm):	71.4
Beam (m)	8.0	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	N/A	Actual Vessel Draft max (m):	0.0
Engine Power (kW):	N/A	Monopole Source Depth (m):	2.8
Number of Shafts:	N/A	Monopole Source Level (dB/µPa):	165.5
Prop Diameter (m):	N/A	Radiated Noise Level (dB/µPa):	166.9



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