TP XXXXXX

MMP3 Final Report

Prepared for

Transportation Development Centre
of
Transport Canada

by

JASCO Applied Sciences (Canada) Ltd

TP XXXXXX

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JASCO Applied Sciences (Canada) Ltd

February 2022

Prepared for:

Innovation Centre of Transport Canada
Contract T8009-190191/003/XLV

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P001556-003
Document 02616
Version 1.0

NOTICES

Suggested citation:

Martin, S.B., E.E. Maxner, and P. Borys. 2022. MMP3 Final Report. Document 02616, Version 1.0. Technical report by JASCO Applied Sciences for Innovation Centre of Transport Canada.

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Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP XXXXX	2. Project No. P001556-003	3. Recipient's Catalogue No.

4. Title and Subtitle MMP3 Final Report	5. Publication Date February 2022
	6. Performing Organization Document No. XXXX
7. Author(s) S. Bruce Martin, Emily E. Maxner, Pablo Borys	8. Transport Canada File No. XXXX
9. Performing Organization Name and Address JASCO Applied Sciences (Canada) Ltd. Suite 2305, 4464 Markham St. Victoria, BC V8Z 7X8 Canada	10. PWGSC File No. XXXX
	11. PWGSC or Transport Canada Contract No.
12. Sponsoring Agency Name and Address Transport Canada, Innovation Centre	13. Type of Publication and Period Covered
	14. Project Officer XXXX

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This is the final report for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. The project had four phases: developing the cavitation monitoring system (CMS) hardware, performing a Baseline Trial to collect cavitation and noise data, developing a cavitation detection algorithm and implementing it on the CMS hardware, and finally performing an Operational Field Trial to evaluate the utility of a CMS on a working commercial vessel. The trial vessel was the 187 m bulker M/V *Ferbec* owned and operated by Canada Steamship Lines (CSL). The CMS sensors were three pressure sensors and one accelerometer that were installed through and on the hull of the M/V *Ferbec* at substantial project expense. The results showed both sensor types measured a rapid change in levels over a small change in vessel speed, however, the onboard measures are not suitable as a means of predicting underwater radiated noise. With a cavitation onset as low as 6 knots, a vessel such as the *Ferbec* would have limited options for controlling underwater radiated noise (URN) by reducing speeds to stop cavitating. The CMS was integrated with the CSL O2 vessel management system for data logging and display to the bridge team, however, the vessel operators did not use the system to guide operations due to commercial requirements. The concept of real-time CMS system does not appear to be operationally feasible. It is recommended to develop a program to use autonomous data loggers to better understand the relationship between speed and cavitation for commercial vessels as input to future guidance on good ship and propeller design practices.

17. Key Words Underwater noise, cavitation monitoring, pressure sensors, commercial vessels	18. Distribution Statement Limited number of copies available from the Innovation Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xiii, 34, apps	23. Price Shipping/ Handling

CI/IC 79-005
Rev. 96

Canada

Transport Canada Transports Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. No de la publication de Transports Canada.
TP XXXXX

2. No de l’étude
P001556-003

3. No de catalogue du destinataire

4. Titre et sous-titre
XXXX

5. Date de la publication
février 2022

6. No de document de l’organisme exécutant
XXXX

7. Auteur(s)
S. Bruce Martin, Emily E. Maxner, Pablo Borys

8. No de dossier - Transports Canada
XXXX

9. Nom et adresse de l’organisme exécutant
JASCO Applied Sciences (Canada) Ltd.
Suite 2305, 4464 Markham St.
Victoria, BC V8Z 7X8 Canada

10. No de dossier - TPSGC
XXXX

11. No de contrat - TPSGC ou Transports Canada

12. Nom et adresse de l’organisme parrain
Transport Canada, Innovation Centre

13. Genre de publication et période visée

14. Agent de projet
XXXX

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

17. Mots clés

18. Diffusion
Le Centre de développement des transports dispose d’un nombre limité d’exemplaires.

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)
—

22. Nombre de pages
xiii, 34, ann

23. Prix
Port et manutent

CI/IC 79-005
Rev. 96

ACKNOWLEDGEMENTS

This project was possible thanks to the participation of Canada Steamship Lines, specifically the environmental, engineering and operational team of Caroline Denis, Yousef El Bagoury, Enzo Romano, and Sergiy Katayev as well as the ship's crew of the M/V *Ferbec* under the leadership of Captain Beaulne. JASCO greatly appreciates the advice and support from DW Ship Consult, specifically Max Schuster and Dietrich Wittekind. The project was supported by Transport Canada's Innovation Center, including Abigail Fyfe, Matthew Cooke, and Ali Faramarzifar.

EXECUTIVE SUMMARY

This report is the final deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project was supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board Cavitation Monitoring System (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA). The project was possible thanks to the participation of Canada Steamship Lines (CSL), who allowed JASCO to install sensors on the M/V *Ferbec*, provided the ship time to test the system, and implemented the CMS-O2 system.

The project had four phases: development of the CMS hardware, a Baseline Trial (documented in Martin et al. 2021), CMS Implementation (see Diggle and Maxner 2021), and a final Field Trial (see Maxner et al. 2022). During the Baseline Trial, sensors onboard the *Ferbec* simultaneously measured pressure and acceleration with underwater radiated noise (URN) measurements made on a vertical array of hydrophones along the *Ferbec's* route. Data were successfully obtained from all sensors during the Trial. During the Implementation Phase, a cavitation detection algorithm was developed and integrated into the data collection hardware and reinstalled in the *Ferbec* for the Field Trial. CSL implemented an interface between the CMS and their vessel management system that recorded the CMS data and provided the bridge crew with an indication of cavitation. Following the Field Trial, a modified cavitation detection algorithm using only acceleration levels was developed because of a failure of the CMS pressure sensors between the Baseline and Field Trials.

The Baseline Trial produced three important results. First, installing the sensors was challenging to arrange and a significant project cost. Second, the pressure and acceleration sensors both measured a rapid change in levels over a small change in vessel speed (4–6 knots), validating that cavitation is easily measurable using pressure sensors that penetrate the hull or acceleration sensors mounted inside the hull. However, the measurements are not 'subtle'; that is, they are better suited to a yes/no indication of cavitation and are ineffective as a calibrated measure of URN. Finally, with cavitation onset as low as 6 knots, a vessel such as the *Ferbec* would have limited options for controlling URN by reducing speed without also making the vessel unsafe for transits in a waterway like the St. Lawrence with current speeds as high as 3 m/s (~6 knots). Due to the low cavitation onset speed, a review of the *Ferbec*'s propeller design was performed. The design was found to be a relatively old design without trailing edge mitigations for reducing cavitation and increasing efficiency.

A major interest of this project was evaluating the usefulness of the CMS during operational field trials and obtaining feedback from the vessel operator. Every 10 seconds, the CMS output a cavitation indicator to the O2 vessel management system onboard the M/V *Ferbec*. The CMS did not function correctly in real-time, likely because the aft peak where the sensors were located was needed for sewage storage, resulting in damaged pressure sensors. Recorded data were analyzed with an accelerometer-only version of the Cavitation Detection Algorithm (CDA), which yielded cavitation indications as expected. The O2 Human Machine Interface operated as expected; however, vessel operators did not use the CMS-O2 system to guide operations due to commercial requirements. At the end of the Field Trial, the team met for an in-depth discussion with Captain Beaulne of the *Ferbec*. The *Ferbec*'s schedule is driven by two factors: (1) adhering to navigational speed limits and routes set by Transport Canada and (2) minimizing transit time between ports. To minimize transit times, the captain adjusts voyages so that the *Ferbec* arrives at Les Escoumins within 2 hours of high tide in order to safely transverse shallower areas leading into the port. Otherwise, the vessel would need to anchor until the next tidal window opens. In general, this means the *Ferbec* loads ore at Havre-Saint-Pierre until the last possible moment before departure, and voyages occur at the normal cruising speed or slightly faster. The captain could not see a scenario in which URN would become an operational consideration unless specifically mandated by Transport Canada.

We do not recommend further developing real-time cavitation monitoring for commercial vessels at this time. We recommend developing a peer-reviewed publication documenting the lessons learned from this project for reference by future researchers. We also suggest developing a program to use autonomous data loggers to better understand the relationship between speed and cavitation for commercial vessels to incorporate for future guidance on good ship and propeller design practices. Developing a project to replace the *Ferbec*'s propeller with a modern design to verify that such a change would reduce cavitation in overall vessel underwater radiated noise.

CONTENTS

APPENDICES

FIGURES

TABLES

GLOSSARY OF ABBREVIATIONS, ACRONYMS, SYMBOLS, AND SPECIAL TERMS

CDA	Cavitation Detection Algorithm
CMS	cavitation monitoring system
CPA	closest point of approach
CSL	Canada Steamship Lines
dB	decibel
dwt	deadweight tonnage
GIOPS	Global Ice-Ocean Prediction System
h	hour
HMI	human machine interaction
Hz	Hertz
IMO	International Maritime Organization
ISO	International Standards Organization
kn	knots
LCB	Longitudinal Center of Buoyancy
LTSA	Long-term Spectral Average
m	metre
M/V	merchant vessel
μPa^2	micropascal squared
min	minute
MMP	Marine Mammal Protection
MSL	monopole source levels
NARW	North Atlantic right whale
nm	nautical mile
PCA	principal component analysis
RNL	radiated noise levels
RPM	revolutions per minute
SARA	Species at Risk Act
SOG	speed over ground
SPL	sound pressure level
STW	speed through water
TC-IC	Transport Canada’s Innovation Centre
URN	underwater radiated noise

1. INTRODUCTION

This report is the final deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project was supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board Cavitation Monitoring System (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA). The project was possible thanks to the participation of Canada Steamship Lines (CSL), who allowed JASCO to install sensors on the M/V *Ferbec*, provided the ship time to test the system, and implemented an interface between the system and their vessel management system.

Appendix B includes the following reports that document the previous work performed during the MMP3 project:

- MMP3 – *Prototype Cavitation Monitoring System: Trials Plan* (Whitt et al. 2021, JASCO document 02216), which laid out the initial concepts for the project;
- *MMP3 April to June 2021 Field Trial and System Design Report* (Martin et al. 2021, JASCO document 02472);
- *MMP3 Integration and CMS Installation Test Report: Integration Test Description and Results* (Diggle and Maxner 2021, JASCO document 02543); and
- *MMP3 Field Trial Report: Data Logged and Analyzed during Field Trial* (Maxner et al. 2022, JASCO document 02617).

The current report is the final document from the project. It summarizes the MMP3 project and provides the project conclusions. This report includes the following:

- Section 2: An overview of the project,
- Section 3: A summary of the Baseline Trial results,
- Section 4: A summary of the final cavitation detection algorithm using only the accelerometer data; and
- Section 5: A discussion of the project and related conclusions.

2. PROJECT SUMMARY

This project, identified as MMP3, had four phases:

1. Developing the CMS hardware,
2. Performing a Baseline Trial to collect cavitation and noise data,
3. Developing a cavitation detection algorithm and implementing it on the CMS hardware, and
4. Performing an Operational Field Trial to evaluate the utility of a CMS on a working commercial vessel.

JASCO commenced the MMP3 project by delivering plans for the Baseline URN characterization of a trial vessel and a full field trial, which included designing the prototype CMS. The basic concept of the CMS was to measure pressure fluctuations above the propeller. These fluctuations were expected to increase with ship speed as the propeller changed from non-cavitating to cavitating, during which pulses of bubbles are released at each blade passage (Figure 1). For MMP3, the selected sensors were three pressure sensors mounted through the hull to measure the pressure fluctuations from cavitation and a 3-axis accelerometer mounted on the hull plates inside the trial vessel, above the propeller.

Figure 1. Visualization of cavitation shedding from the tips and face of a propeller (photo from: https://www.youtube.com/watch?v=SEvxngv-dkY).

The original project proposal was designed around instrumenting a research vessel based out of Halifax, the *Leeway Odyssey*. The *Odyssey* was chosen because it would be easy to instrument and operated regularly in areas with endangered North Atlantic right whales (NARW). However, the *Odyssey* is as a relatively small (33 m) vessel with dual propellers and is not representative of commercial vessels that generate the bulk of underwater radiated noise. After contacting different vessel operators, the project concept changed to focus on the M/V *Ferbec*, a 188 m single-screw bulker operated by Canada Steamship Lines (CSL; Figure 2). During summer, the *Ferbec* carries iron ore from Havre-Saint-Pierre to Sorel, QC (Figure 3). The *Ferbec*'s route passes through the critical habitat of endangered St. Lawrence Estuary beluga whales (~53 nm, 4 h 30 min transit), as well as the speed management zones in place during summer to protect NARW (~60 nm, 5 h 30 min transit).

Figure 2. Picture of the M/V *Ferbec*, a 187.5 m, 49500 deadweight tonnage (dwt) bulker operated by CSL.

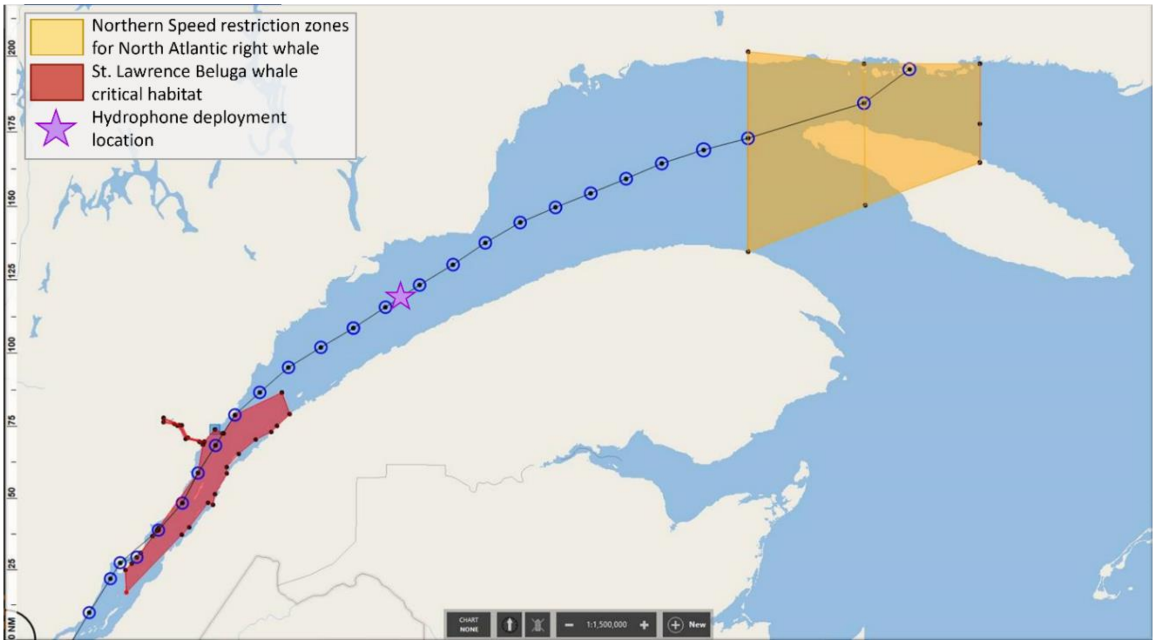

Figure 3. M/V *Ferbec* shipping route between Sorel, QC (south) and Havre-Saint-Pierre, QC (north). The *Ferbec* passes through two sensitive areas. Only the northern portion of the North Atlantic Right whale speed restriction zone that the *Ferbec* passes through is displayed on the map (yellow). The underwater radiated noise measurements during the Baseline Trial were performed off Baie Comeau (purple star).

The Baseline Trial occurred late April to early June 2021. A data collection system along with three pressure transducers and one accelerometer was installed in the aft peak of the *M/V Ferbec*. Because the aft peak could be flooded for ballast, the sensors were mounted in waterproof glands welded to the deck around the penetration holes (Figure 4). A vertical array of hydrophones (Figure 5) was simultaneously moored to the seabed in 300 m of water between Matane and Baie Comeau, QC, near shipping lanes used by the *Ferbec* (Figure 3)*.* The hydrophone array was designed to be compliant with the International Standards Organization (ISO) standard 17208-1 for measuring underwater radiated noise from vessels in deep water (ISO 2016). On-vessel and in-water data were collected during six passages of the *Ferbec* to compare underwater sound levels to on-board measured cavitation levels. Hydrophone data and data from three of four of the sensors on the *Ferbec* were successfully recorded and retrieved. One pressure sensor on the *Ferbec* failed; however, this did not affect our ability to develop the cavitation detection algorithm.

Figure 4. Installation of the sensors used to measure cavitation. (Left) Hole drilled through hull, and (right) pressure glands being installed around the sensors. Photos by Mount Royal Walsh installation team.

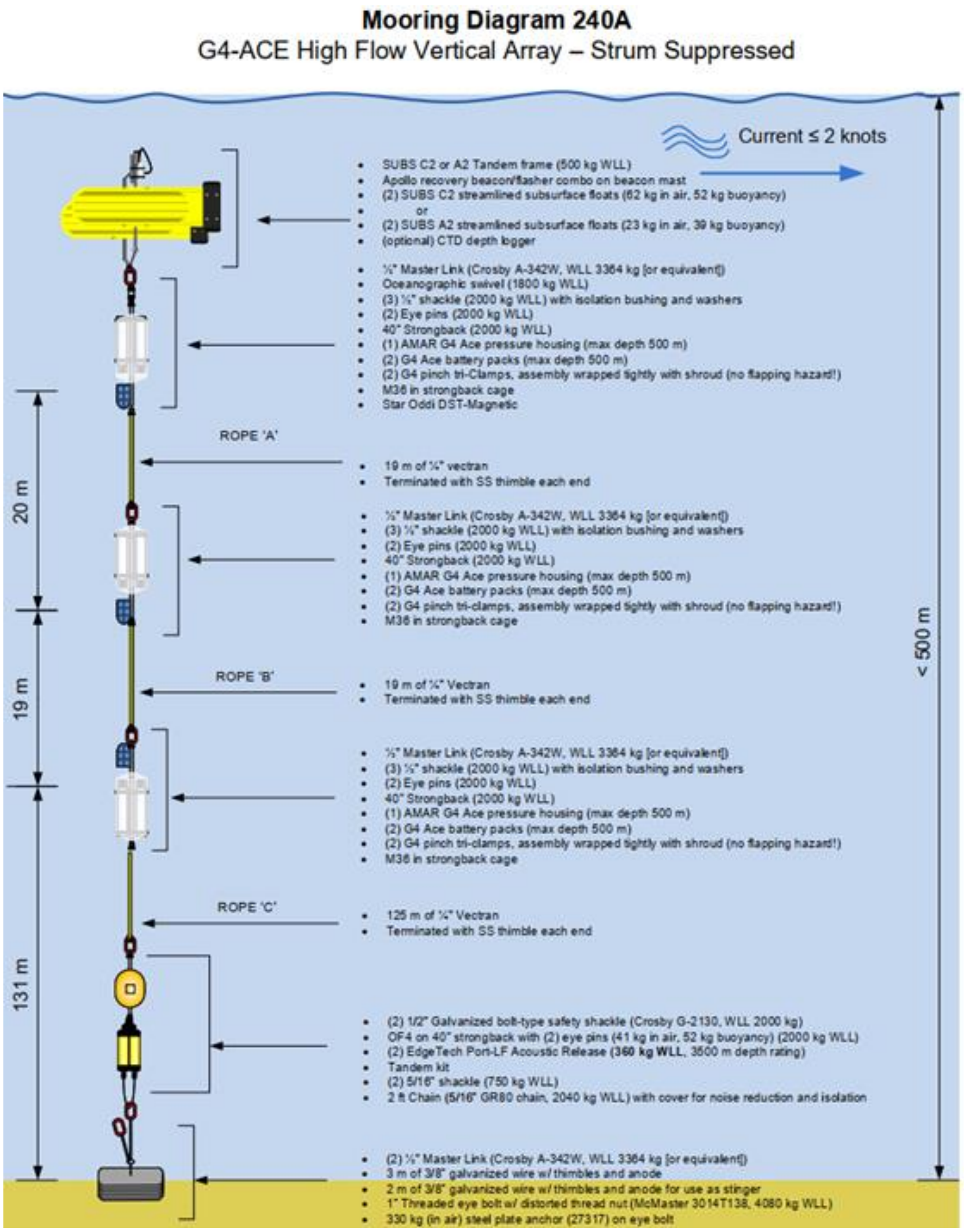

Figure 5. Mooring design diagram for the high-flow vertical line array used.

Analysis of the Baseline trial data demonstrated that when the ship was in ballast (from Sorel to Havre-Saint-Pierre), the hull area where the sensors were mounted was not underwater and, therefore, the cavitation state of the ship could not be determined. When the ship was loaded, the pressure and accelerometer data were highly correlated with the shaft revolution rate and speed through water. The speed through water was considered a more suitable predictor of the cavitation state and was used in the detection algorithm. The pressure and acceleration values varied exponentially up to 6.5 kn before entering a constant region for higher speeds, in which the pressure levels did not change more than 5 dB re 1µPa^2. Further details on the Baseline Trial results are provided in Section 3.

Results obtained from the Baseline Trial were used to develop a cavitation detection algorithm based on machine learning techniques to produce an alert of the cavitating state of the ship. This Logistic Regression Classification method was integrated into CMS hardware for the Field Trial on the *Ferbec*. The system analyzed the pressure and acceleration data every 10 s and output the current cavitation state to the CSL ‘O2’ vessel data management system. The data were transmitted to CSL headquarters in Montreal for logging and formatting for display (Figure 6). The display information was sent back to the *Ferbec* and presented to the captain and mates as an informational warning on the main O2 display (Figure 7), which could be selected to view as a pop-up ‘Tip’ that included a ‘Useful/Not Useful’ selection as well as space for a text comment (Figure 8).

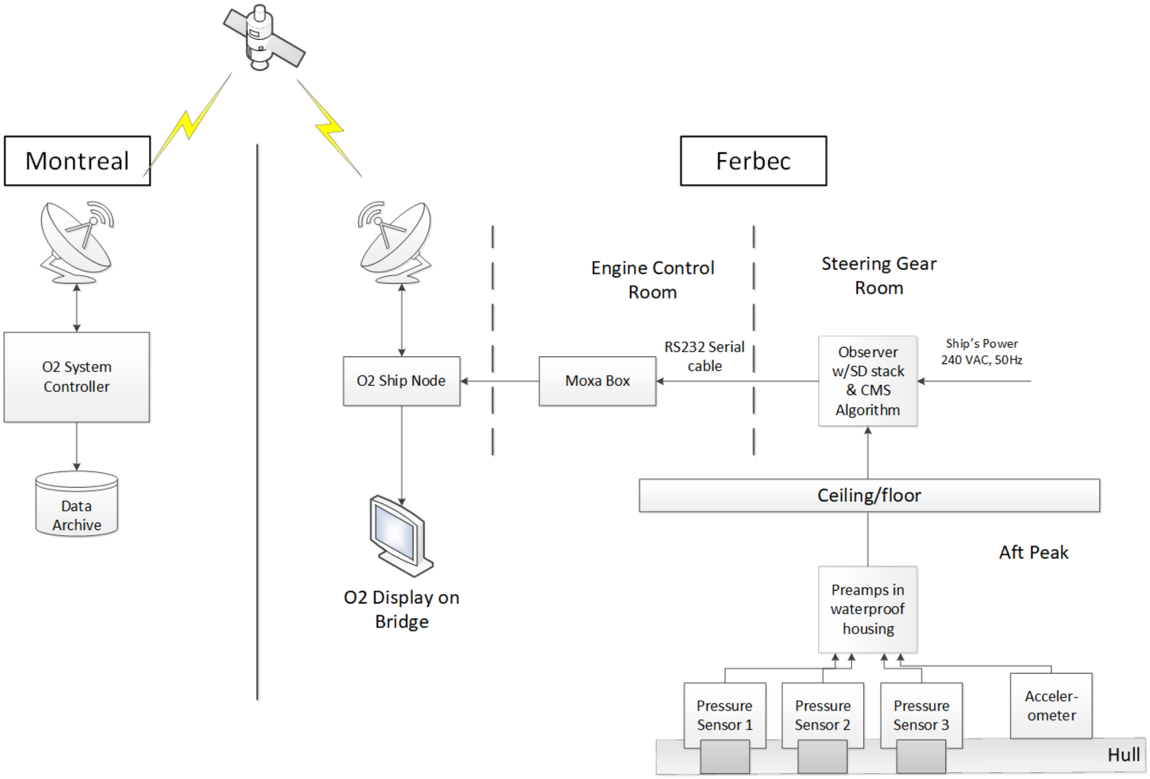

Figure 6. Block diagram for the operational evaluation of the cavitation monitoring system.

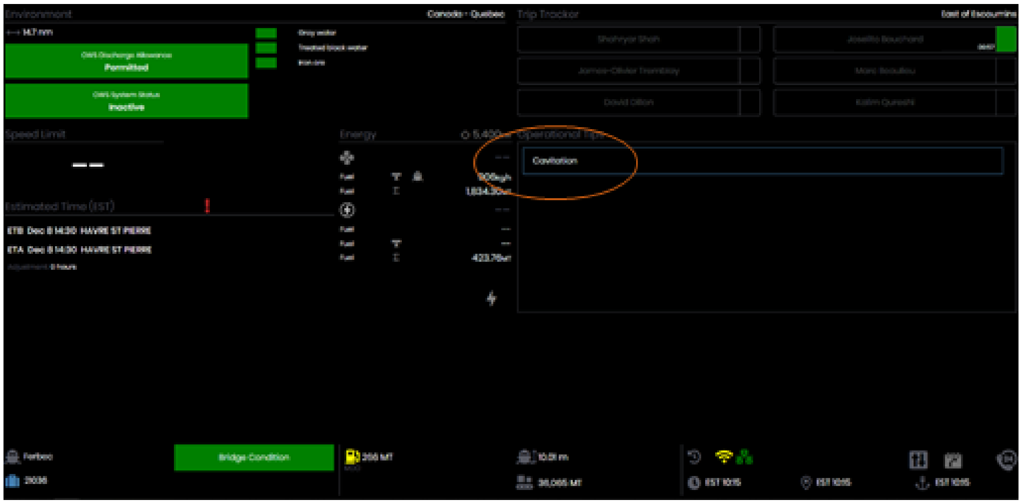

Figure 7. Main human machine interaction (HMI) display for the Canada Steamship Lines (CSL) O2 system. The ‘Cavitation’ informational message indicator is circled.

Cavitation Monitoring System

December 8th 2021 10:14 EST

Cavitation

Comments (Optional)

0/975

Figure 8. Example of a ‘Tip’ window used in the O2 system. The tips will stay active until either the user acknowledge the tips (if the tip is set to be acknowledgeable) or the condition generating the tip is no longer true.

The evaluation of the CMS-O2 system took place during the Field Trial from 26 Nov 2021 to 23 Dec 2021. The interface with the O2 system worked as intended and delivered data to the CSL operations centre in Montreal every 10 s. These data were provided to JASCO at the end of the trial and analyzed for this report. The recorded data showed that the accelerometers functioned as expected; however, the pressure sensor data was incorrect. As a result, the cavitation indicator was inaccurate during the Trial. CSL indicated that the aft peak was used as a sewage storage area during the Field Trial; however, how this may have impacted the pressure sensors has not been resolved. The sensors may have failed for other reasons, but this can not be determined. The sensors will be removed from the *Ferbec* during the next drydock period and discarded.

The accelerometer sensors performed as expected, with levels agreeing with those measured during the Baseline Trial, and effectively described the various stages during the trip of the vessel. The results from the accelerometer confirm the hypothesis presented in the Baseline Trial report: because pressure and acceleration are linearly dependent, it could be possible to rely solely on the accelerometer for the CMS. Appendix A outlines the modified algorithm using a logistic regression model that applies only the acceleration data to predict cavitation states.

The O2 HMI operated as expected; however, vessel operators did not use the CMS-O2 system to guide operations due to commercial requirements. An interview with the captain suggested that underwater radiated noise was unlikely to be a consideration for commercial operations unless specifically required by Transport Canada. The *Ferbec*, like most commercial vessels, is on a precisely planned schedule to maximize the revenue from its operations. For the *Ferbec*, commercial requirements for the transit(s) to be successful are dependent on timing of the ship. Section 5 outlines further factors to consider improving the CMS usability.

3. BASELINE TRIAL RESULTS SUMMARY

3.1. Sample Data

The average journey of the *Ferbec* between ports (Figure 3) takes approximately 40 h, with some time spent on either end to transfer cargo. The vertical line array of hydrophones was positioned along the Havre-Saint-Pierre to Sorel side of the route and were studied in detail (Table 1) because the sensors on the *Ferbec* were out of the water on the Sorel to Havre-Saint-Pierre voyages. Figure 9 provides an example time series of the key *Ferbec* parameters during the second transit between 7 May 2021 15:50:05 UTC and 9 May 2021 11:00:06 UTC.

At a standard through water cruising speed between 13 and 14 kn, there are two distinct main shaft revolutions per minute (RPM) regimes, 90–92 and 95–96 RPMs, respectively. Speed over Ground (SOG) and Speed through Water (STW) are generally similar in the first half of the transit. In the second half of the transit as the vessel entered the more constrained region of the St Lawrence River, the SOG was reduced while the STW remained the same as the vessel moved against the increasing current. On either end of the transit there were acceleration and deceleration periods lasting from 45 min to 1 h. During the main portion of transit, and as it passed the mooring, the *Ferbec's* STW remained relatively constant, except for when it changed course. An example of temporary speed reduction is visible on 8 May 2021 15:00:00 UTC, which occurred when the *Ferbec* took on a pilot at Les Escoumins.

Table 1. Passages of the M/V *Ferbec* past the vertical array.

Measurement date/ time (EDT)	Speed through water (kn)	CPA distance (m)	CPA slant distance to upper hydrophone (m)
2021 May 1 19:52	13 (cruising speed)	632	642
2021 May 8 04:52	13.9	571	585
2021 May 13 ~15:04	7.1	450	465
2021 May 19 17:12	13.8	1043	1049
2021 May 26 05:18	12.4	107	162
2021 Jun 1 21:35	9	558	570

Closest point of approach (CPA)

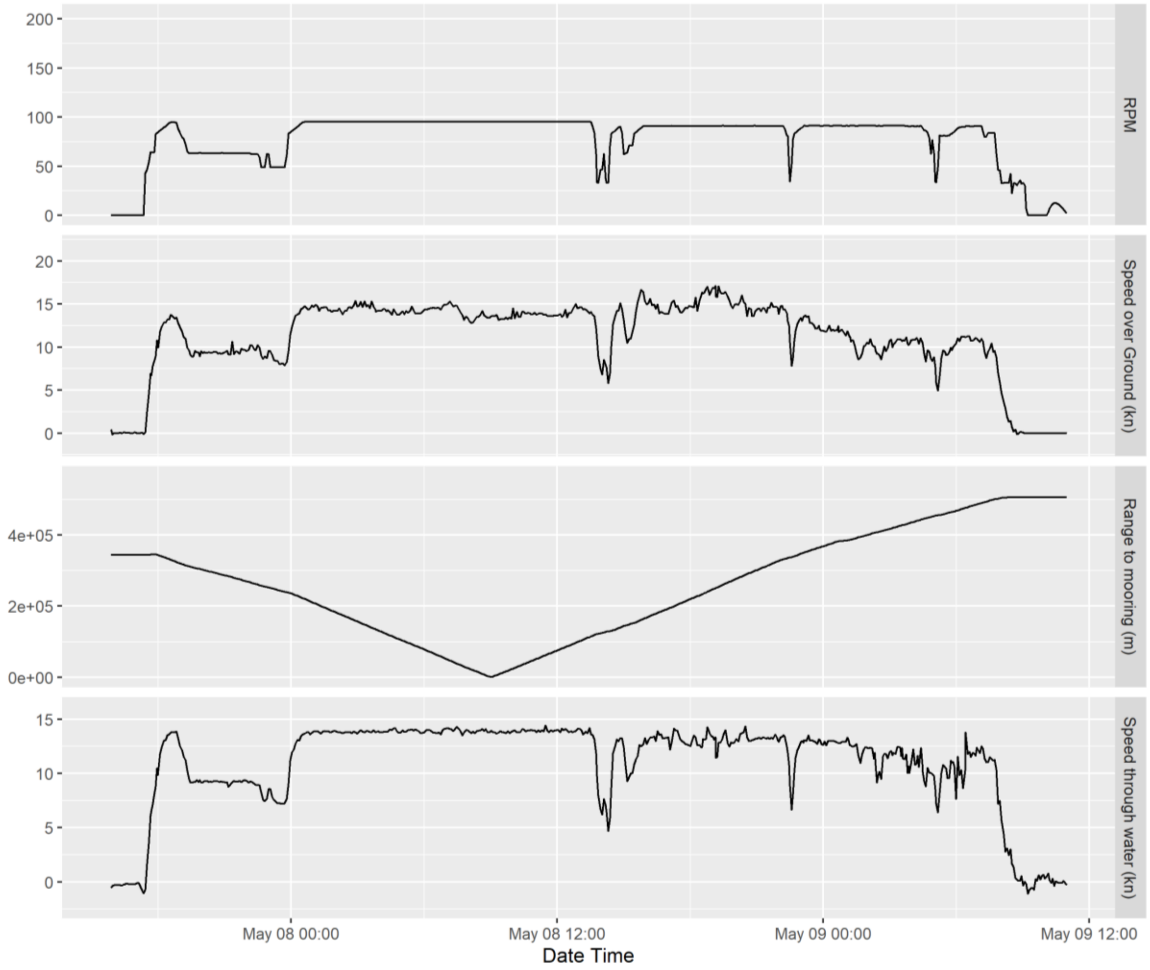

Figure 9. Engineering metrics of the M/V *Ferbec* during transit from Havre-Saint-Pierre to Sorel, QC, including main shaft RPM, speed over ground, range to mooring, and speed through water between 7 May 2021 15:50:05 UTC and 9 May 2021 11:00:06 UTC.

Figure 10 shows the pressure time series (top) and long-term spectral average (bottom) from the P2 pressure sensor during the voyage shown in Figure 9. There were three dominant regimes highlighted by annotations describing different cruising speeds, as well as a deceleration event. The frequency bands show very good correlation with the engineering metrics presented in Figure 9, suggesting that pressure and hull vibration are useful descriptive metrics of the vessel speed, shaft RPM, and ultimately cavitation on the screw.

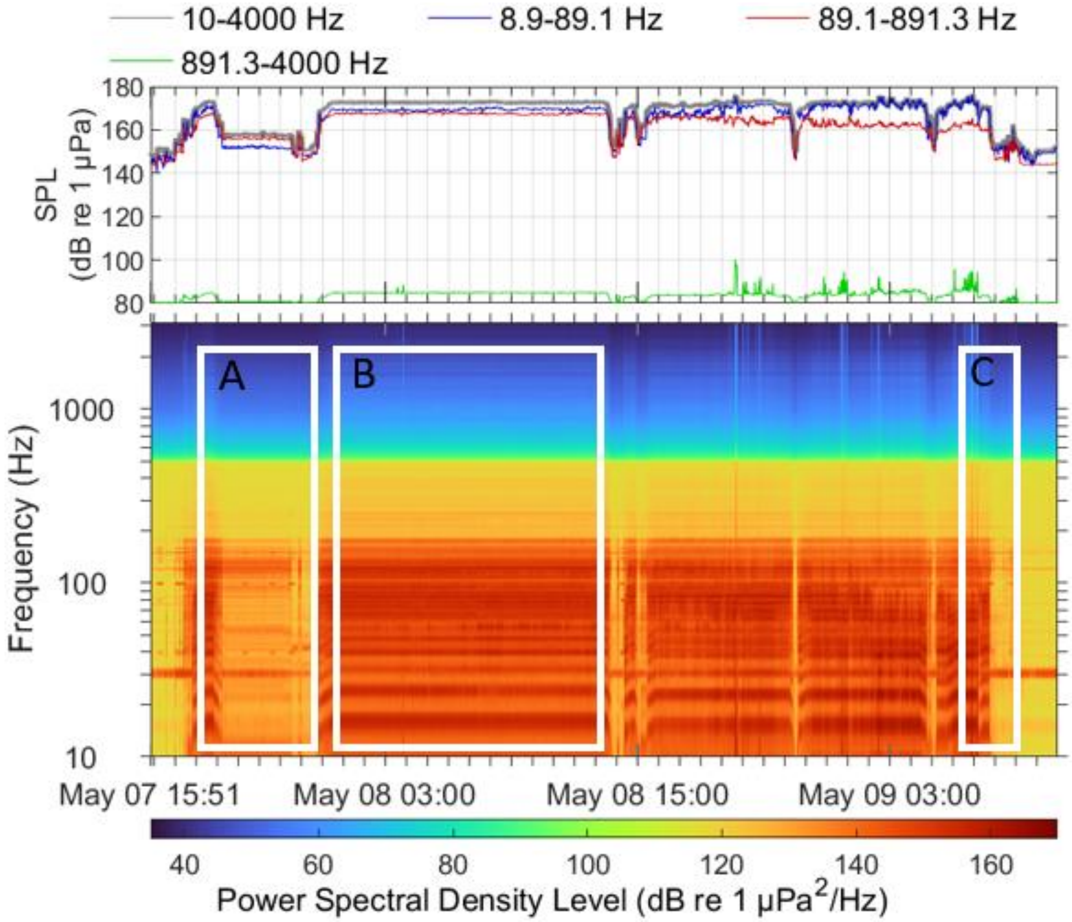

Figure 10. Onboard recorded pressure (Channel P2) during the transit on 7 May 2021 15:50:05 UTC to 9 May 2021 11:00:06 UTC. Annotations represent (A) lower cruising speed of approximately between 8 and 9 kn inside the North Atlantic right whale (NARW) speed zone, (B) higher cruising speed between 13 and 14 kn, and (C) deceleration at the termination of transit.

The vertical array (see Figure 5) was deployed and recording between 28 Apr and 6 Jun 2021. It provided complementary measurements to the onboard sensors on the *Ferbec.* In the recorded soundscape (Figure 11), the dominant source of energy was the passage of ships, including the *Ferbec*, accounting for the peak in levels slightly below 100 Hz. As this region is busy with shipping, other ships are identifiable in the LTSA plot as short-duration broadband peaks in energy. The CPAs made by the *Ferbec* are highlighted by the red arrows in Figure 11. There are also wind events visible as longer duration broadband sources increasing the spectral energy above 10 kHz, such as around 28 May 2021.

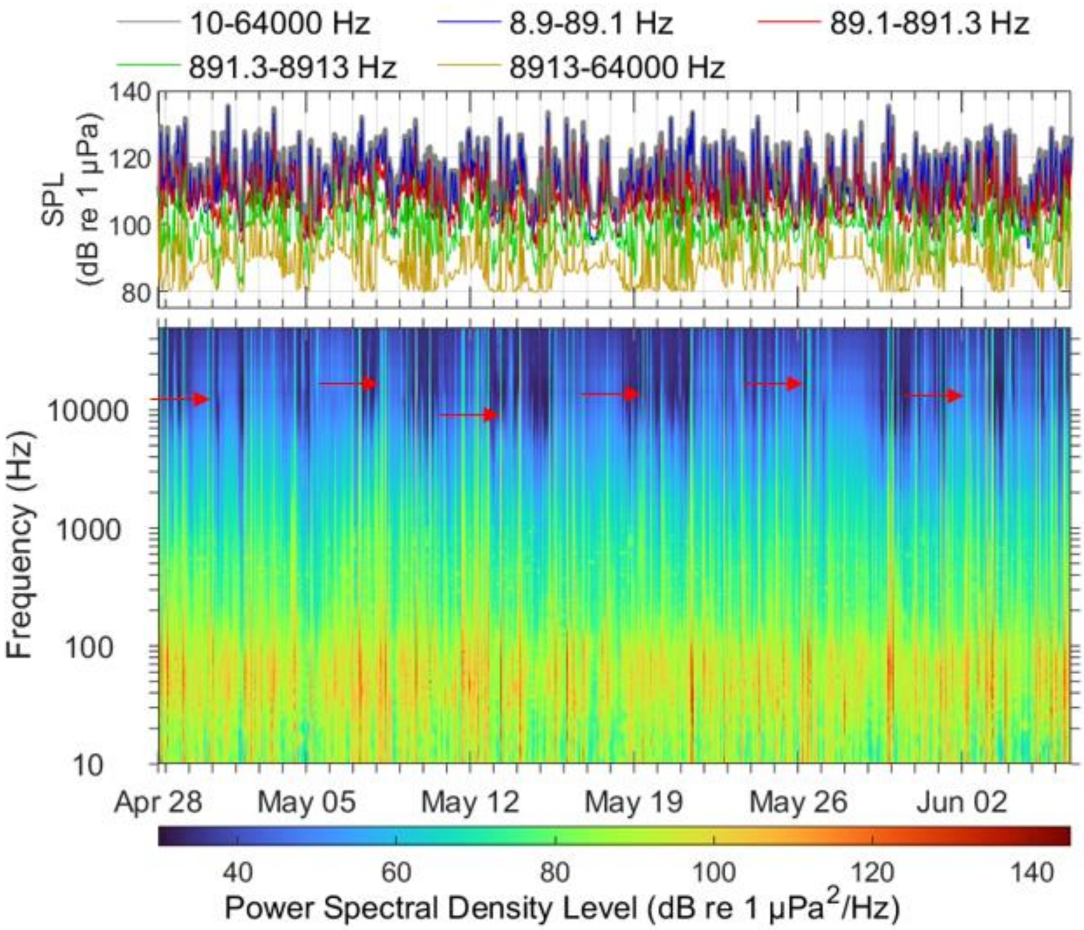

Figure 11.Selected band sound pressure level (SPL) and Long-term Spectral Average (LTSA) over the entire recording period for shallowest hydrophone (113 m). Red arrows highlight increased spectral average as M/V *Ferbec* passes. Other peaks are other vessels, with larger vessels generally accounting for louder signals.

3.2. Installation Costs

The overall installation procedure of the sensors was quite challenging and represented a significant percent of the total cost of the project. Installing three pressure sensors and the accelerometer in the Aft Peak required pressure glands (e.g., see Figure 4) because the space can be flooded for ballast or to hold sewage if necessary. The arrangement and installation of the exact sensor locations was a challenge because of the location of the ribs on the *Ferbec* and was further exacerbated by contractor installation error that switched the intended location of the accelerometer and one of the pressure sensors. The pressure sensors had to be mounted through the hull of the *Ferbec* to meet the water. At CAN$56,000, installing the through-hull pressure sensors was a substantial cost for the Baseline Trial. When added to the costs of the sensors and equipment, the full cost of this prototype was in excess of CAN$90,000, not including non-recurring engineering expenses. The installation costs included the design and build of the pressure glands to allow for installation in the aft peak, venting, and safety personnel so that work could be performed in that confined space. Additionally, costs of overtime because the work had to be done in a tight time window, at night over a weekend, while that section of the hull was out of the water in Sorel. The accelerometer did not require the through-hull installation, which would have reduced the costs for its installation if it were installed alone.

3.3. Results from Onboard Sensors

For the analysis, data was grouped in ballast and loaded scenarios. This was done using data from the sensors that were transformed into sound pressure levels and acceleration levels, and information provided by CSL. For the in-ballast scenario, the levels of the pressure channel remain almost constant, independent of the speed through water (STW), with a maximum change of around 5 dB re 1µPa^2 suggesting that the sensors were not underwater. No further effort was applied to these data. However, as the vessel travels in this condition half of its voyages, it indicates that the current design of the CMS is not effective for measuring cavitation for management purposes.

For the loaded scenario, Figure 12 shows median levels measured by pressure sensor 1 (P1) and the X-component of the 3-axis accelerometer as a function of the speed through water. The overall form of the pressure and acceleration curves is similar. In the region between 2 and 4 kn, the levels remain constant before increasing exponentially. The change in the pressure and accelerations levels in the 4–6.5 kn region is 20–35 dB depending on the frequency band and sensor. For speed values higher than 8 kn, the levels tend to remain within a band of 3–5 dB. Figure 12 shows a peak in pressure and acceleration at 6–7 kn. The *Ferbec*'s captain described this as critical speed at which the vessel has a resonant vibration that is extremely uncomfortable for the crew, and potentially dangerous for the ship if allowed to stay in this state for long. As a result, the vessel can not select this speed for any extended period of time. Each vessel has its own resonance speed, generally below cavitation, that must be avoided.

Figure 13 presents the 50 Hz decidecade band data whose median is shown in Figure 12. The scatterplot in Figure 13 shows the general trend observed in Figure 12; however, there was a wide range of pressure or acceleration levels that occur at each speed through water. As a result, it is not possible to reliably convert the pressure and acceleration levels to a speed through water, or to an underwater radiated noise level.

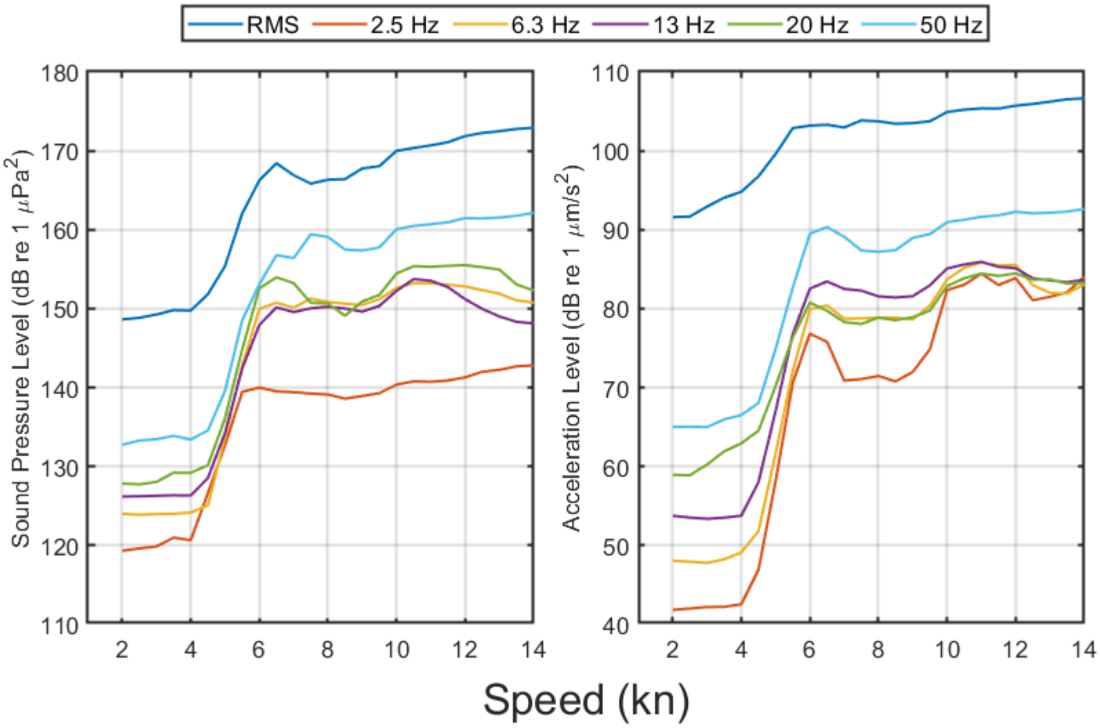

Figure 12. Median pressure sensor P1 (left) and accelerometer X-axis (right) levels as a function of M/V *Ferbec*'s speed through water (STW) when in the loaded state for several decidecade bands.

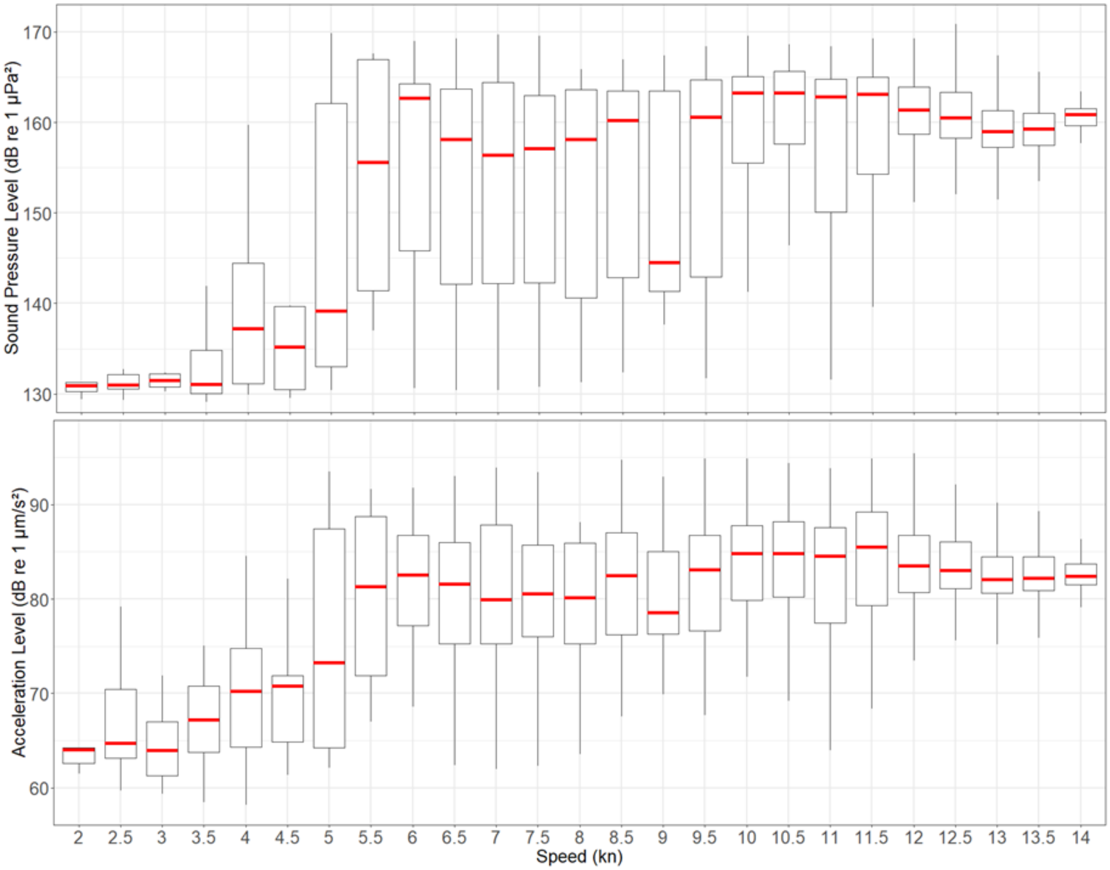

Figure 13. Box-and-Whisker plot of pressure sensor P1 (top) and accelerometer X-axis (bottom) levels as a function of M/V *Ferbec*'s speed through water (STW) when in the loaded state for the 50 Hz decidecade band.For each speed, the box shows the inter-quartile range of measurements, the red-line is the median, and the lines show the total range of measured levels.

3.4. Radiated Noise Levels from the Vertical Array

The vertical line array of hydrophones off Baie-Comeau allowed for an analysis of the underwater radiated noise (URN) as a function of speed (see Table 1 for the speeds measured). The URN metrics computed were the radiated noise level (RNL) assessed in accordance with ISO 17208-1, according to:

$$L_{RN} = L_R + 20\log_{10} R \tag{1}$$

and the monopole source level (MSL) computed in accordance with ISO 17208-2, according to:

$$L_S = L_{RN} + \Delta L \tag{2}$$

Where the change in level ΔL is

$$\Delta L = -10\log_{10}\left(\frac{14\eta + 2\eta^2}{14 + 2\eta + \eta^2}\right), \eta = k^2 d^2 \tag{3}$$

L_R is the received sound pressure level at a hydrophone *R* meters from the closest point of approach of the vessel, *d* is the source depth, *k* is the angular wavenumber ($2\pi f/c$), *f* is frequency and c is the speed of sound in water. Here we assume that the source depth is the depth at the upper 1/3 of the propeller depth, which for the *Ferbec* when loaded is 7.5 m. The sound speed for the period studied was obtained from the Global Ice-Ocean Prediction System (GIOPS, Environment and Climate Change Canada 2021). For May 2021, the sound speed from the sensor depth to the surface was 1455 m/s ±10 m/s; 1455 m/s was employed for this analysis.

Figure 14 contains the RNL and MSL measured for the *Ferbec*. These can be compared to a general model for vessel source levels based on an analysis of thousands of spectra measured using the Transport Canada commissioned underwater listening stations at the Vancouver Fraser Port Authority and Boundary Pass, supplemented by data collected by the European JOMOPANS project (for details on the data used in the model please refer to MacGillivray and de Jong 2021). The monopole source spectrum for a 187.5 m bulker as a function of vessel speed through water is shown in Figure 15. Note that the model has a standard deviation of ±6 dB. The measurements of the *Ferbec* show a number of features we expect: MSL levels within ~3 dB of the model MSL and an increase in source levels on the order of 10 dB for a speed change from 9 to 14 kn. The *Ferbec* source spectrum does not have the characteristic peak at 50–60 Hz that many commercial vessels have, rather it peaks in the 80–100 Hz range. This may be due to the *Ferbec* having a very low block coefficient, that is a long, sleek shape with an extended bow and stern compared to most bulkers, including all other bulkers in the CSL fleet. During discussions of the Baseline Trial with the Captain, he indicated that the *Ferbec* was gliding during the 7 kn measurements because she was at critical resonance when powered at 7 kn (see Section 3.3), however the levels compare well to the MacGillivray and de Jong (2021) model. The shift in spectral peak does not impact the generality of the cavitation detection algorithm. It would result in a small increase of the auditory frequency weighted sound exposure levels of the *Ferbec* when assessing possible effects on marine mammals.

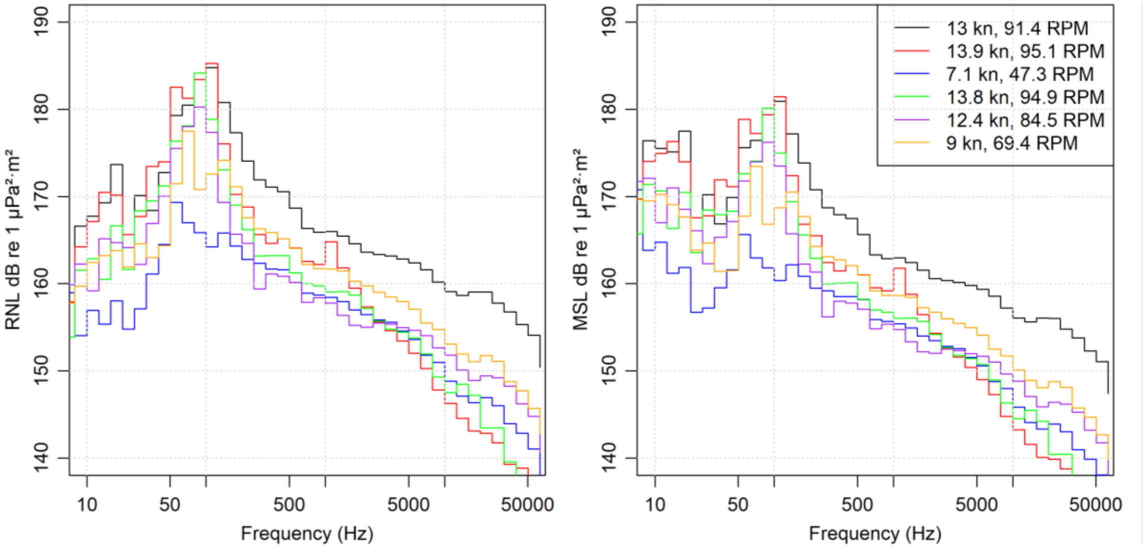

Figure 14. (Left) Radiated noise levels (RNL) and (right) monopole source levels (MSL) of the M/V *Ferbec* at different speeds through water as shown in the legend. The RNL results are the averages of the three hydrophones in the vertical array, as recommended by ISO 17208-1. The MSL results were computed from the RNL as recommended by ISO 17208-2.

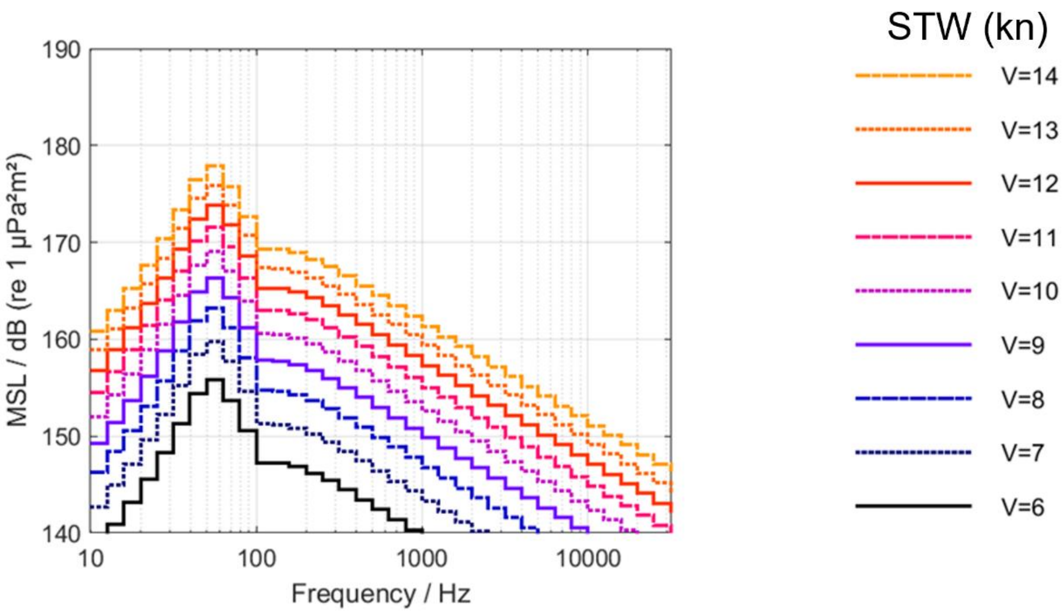

Figure 15. Decidecade band monopole source levels (MSL) for a 187.5 m bulker as a function of speed through water (STW)as predicted by the source model of MacGillivray and de Jong (2021).

3.5. Review of *Ferbec*'s Propeller Design

The *Ferbec* features design characteristics typical of a bulk carrier: is a typical 'big block' ship with a hull shape designed to carry high deadweight. The required displacement is generated by blunt ship lines that have significant impact on the wake field. This characteristic hull shape induces the following two challenges:

1. At slow speed, the maneuvering capabilities of big block ships can be very limited so that assistance by tugs is required. For the *Ferbec*, it is reported by the crew that speeds below 5 knots are avoided due to safety concerns linked to maneuverability.
2. The inflow of the *Ferbec's* propeller is heavily affected by the hull.

Both aspects are especially influenced by the hull shape in the aft part of the ship. The following discussion present working conditions of the *Ferbec*'s propeller and characteristics of the propeller itself.

3.5.1. Characteristics of M/V *Ferbec*'s Aft Ship

For big block ships with limited manoeuvrability at slow speed, modifying the aft ship can increase steering capabilities. This design is characterized in Figure 16, where two hull shapes of bulk carriers are compared:

1. Red is the hull shape of a modern bulk carrier, built in 2019. The bottom of this vessel is smoothly lifted as it approaches the propeller.
2. Blue illustrates *Ferbec*'s aft ship. It consists of a straight bottom line with a sharp aft edged skeg. This design increases directional stability and effects of the rudder at slow speed. However, the sharp edge obstructs inflow to the propeller.

The arrangement of the propeller in presence of this sharp edge is illustrated in Figure 17. The lower part of the propeller is especially prone to obstructing inflow.

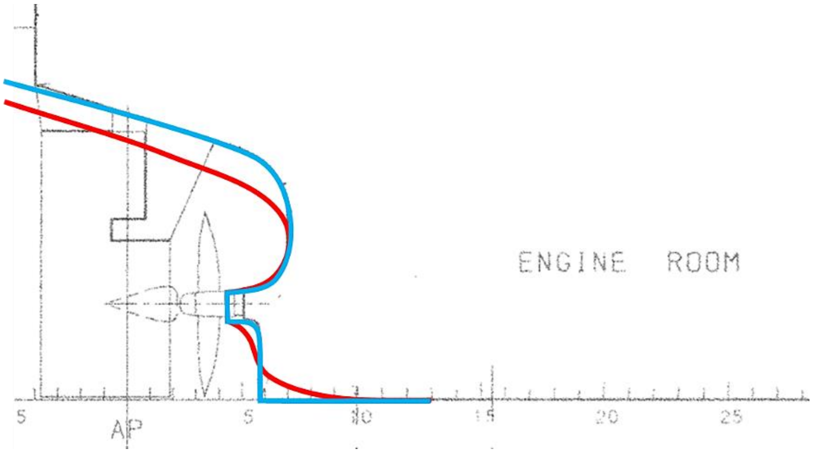

Figure 16. Comparison of a modern bulk carrier (red) with M/V *Ferbec*'s aft ship (blue).

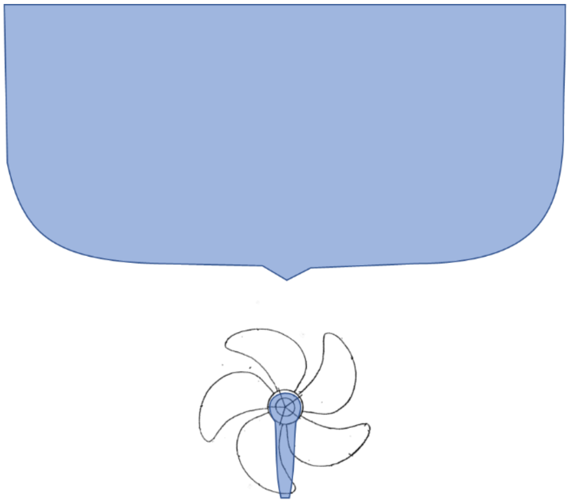

Figure 17. Position of the five-bladed propeller compared to *Ferbec*’s hull shape and skeg at frame 6.

3.5.2. Working Conditions of the Propeller

Propellers behind single screw ships are rotating in a highly inhomogeneous flow field. Flow in the upper section of the propeller inflow (12 o’clock position) is much slower than flow in other areas that are less affected by the hull. For large ships, this flow pattern is investigated in model tests and numerical simulations to be considered during design of the propeller. As illustrated in Figure 18 for two different ships, the propeller must be designed in a way that each blade is working properly while rotating through all angular sections of the inhomogeneous inflow. In Figure 18, purple sections indicate heavily obstructed flow with slow speed and green indicates undisturbed flow with high speed.

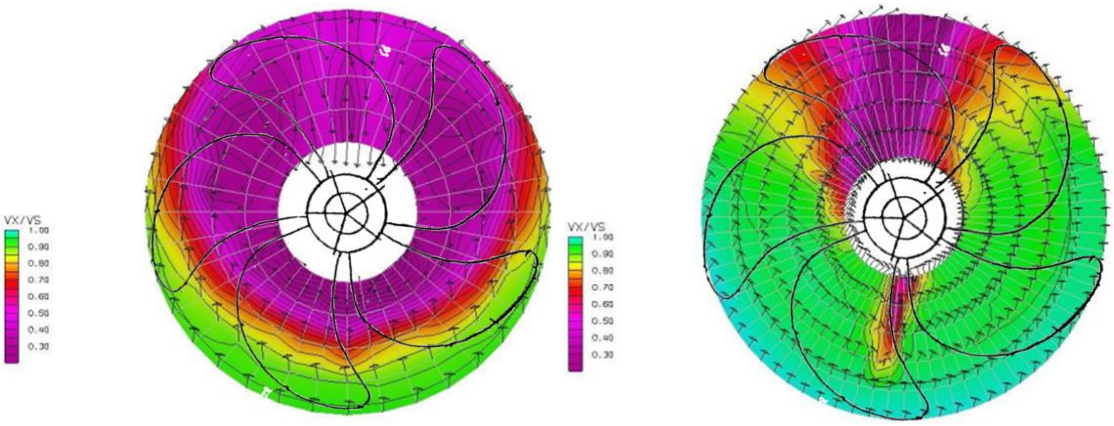

Figure 18. Comparison of axial wake velocity for (left) a single screw bulk carrier and (right) a slender ship with influence of the skeg.

A wake field as shown in Figure 18 is not available for *Ferbec*. However, it is expected that the big block hull as well as the sharp skeg will have significant impact on the pattern to which the propeller is exposed. This includes

1. Broad areas of decelerated inflow at the top position similar to the left graph of Figure 18.
2. A sharp area of decelerated flow in the lower area, similar to the right graph in Figure 18.

Low inflow velocity induces high dynamic angles of attack of the blade sections. Consequently, high lift with local low pressure is generated in areas of low inflow velocity, leading to a tendency for different types of cavitation in these areas.

3.5.3. Propeller Design

M/V *Ferbec* is driven by a fixed pitch propeller with a direct shaft connected to a two-stroke main engine. The five-bladed propeller has a 6 m diameter, which is assumed to be determined by ballast draft to avoid surface piercing of the propeller during voyage in unloaded condition. No information is available on other constraints of propeller diameter. Given the power of the main engine, the propeller is moderately loaded with approximately 240 kW/m², which is in the range of other bulk carriers. Due to the relatively small diameter, a large tip clearance of 42% diameter between upper propeller blades and hull is achieved. Typical values of cargo ships are below 30%.

However, compared to more recent designs the propeller turns fast with respect to ship speed. This results in a low coefficient of advance J, defined by ship speed divided by rotational speed. This is shown by propeller standard series such as the Wageningen B series that higher efficiency can be achieved higher coefficients of advance. In this respect, a propeller with the same power at lower rotational speed and higher torque would provide higher efficiency than the current propeller design. Possibly, the main engine cannot provide sufficient torque to accommodate a propeller with lower rotational speed.

Further investigation of the propeller data shows an efficiency reduction due to the low coefficient of advancing, which was partially compensated by a low value of blade area ratio. Efficiency increases with decreasing blade area ratio. The blade area ratio of *Ferbec*'s propeller is only 0.5, which is close to the lowest possible value. This measure increases propeller efficiency but alongside, it increases the propeller's overall sensitivity for cavitation.

The propeller is designed with almost constant pitch over the diameter and the tips are only slightly unloaded by 8% at the tips compared to pitch at half radius. Values of more than 10% are applied for other propellers of merchant ships to reduce hull pressure pulses that are generated by cavitation. The design feature of unloaded tips reduces cavitation while decreasing efficiency. Possibly, the high pressure amplitudes are partially attenuated by the large tip clearance so that cavitation reduction in the upper region of the propeller is not required to mitigate generation of excitation forces for vibration.

Overall, it seems that all main characteristics of the *Ferbec*'s propeller were optimized for efficiency except for rotational speed. Limitations for constraints of rotational speed are unavailable, so we can only speculate that torque of the main engine is a limiting factor for optimizing efficiency of this specific propeller. All optimization measures, such as low blade area ratio and almost constant pitch over the diameter, increase the propeller's general tendency to cavitate. This is supported by the observation that cavitation occurs in the full practical speed range above 5 knots. Cavitation inception speed is typically higher for other big block ships.

Cavitation can be further intensified by an inhomogeneous wake field that induces strong local loading in areas of low inflow velocity.

Note that much of this is speculative as we have no information of the wake field, engine selection, and principles of the particular propeller design. We also do no know the process of design. Usually, the hydrodynamic designer sacrifices some towing resistance against good working conditions for the propeller. A ship with minimized resistance irrespective of wake field is sharper at the bow and blunter at the stern, in a ship with good working condition for the propeller it is vice versa. A measure for this is longitudinal centre of buoyancy (LCB), which must be forward of the middle of the ship.

4. SUMMARY OF ALGORITHM

The Cavitation Detection Algorithm (CDA) was developed to provide the CMS with means to alert when the vessel is in a fully cavitating state. Using data obtained during the Baseline Trial, pressure and acceleration levels were calculated as a function of speed through water and shaft RPM, which in turn allowed a change point to be determined, i.e., a point at which the levels varied abruptly, indicating that full cavitation was occurring. Since data from all sensors yielded a very similar change point, it was possible to train a logistic regression machine learning model to classify real-time data into non-cavitating and fully cavitating states. Crucial steps in the algorithm include: (1) alerting the CMS in case the sensors were not underwater by requiring a minimum threshold of 140 dB re 1 µPa^2 before starting any calculation, and (2) using 10 s of real-time sensor data to calculate pressure or acceleration levels and feed them into the Logistic Regression model to get a prediction of the cavitation state.

The algorithm was designed to use data from all available sensors aiming to enhance the accuracy of the Logistic regression model. The drawback of this approach is that no calculation occurs if the pressure sensors do not operate properly as was the case during the Field Trial. However, during further analysis of the constructed Logistic regression model, it was determined that the levels from all sensors as a function of speed through water were linearly dependent, i.e., the cavitation state could be determined using data from just one of the sensors. To verify the linearly dependence of the levels a principal component analysis (PCA) was performed using the data from the Baseline trial and is presented in Appendix A. After determining that the variables are indeed linearly dependent, the CDA was modified so that the binary classification model was retrained with only data from the three components of the accelerometer during the Baseline trial. The first principal component was obtained using the PCA function from the Scikit Learn machine learning toolbox implemented in Python and fed into the Logistic Regression model for training. Then, data from the Field trial was reprocessed in a similar manner to be tested with the modified model. Figure 19 shows the prediction obtained with the modified algorithm together with the scaled values of the Z-component of the acceleration. It can be seen that higher values of acceleration result in a prediction of “1”, which corresponds to a fully cavitating state. The results validate the hypothesis that a CDA could be based solely on data retrieved from an accelerometer.

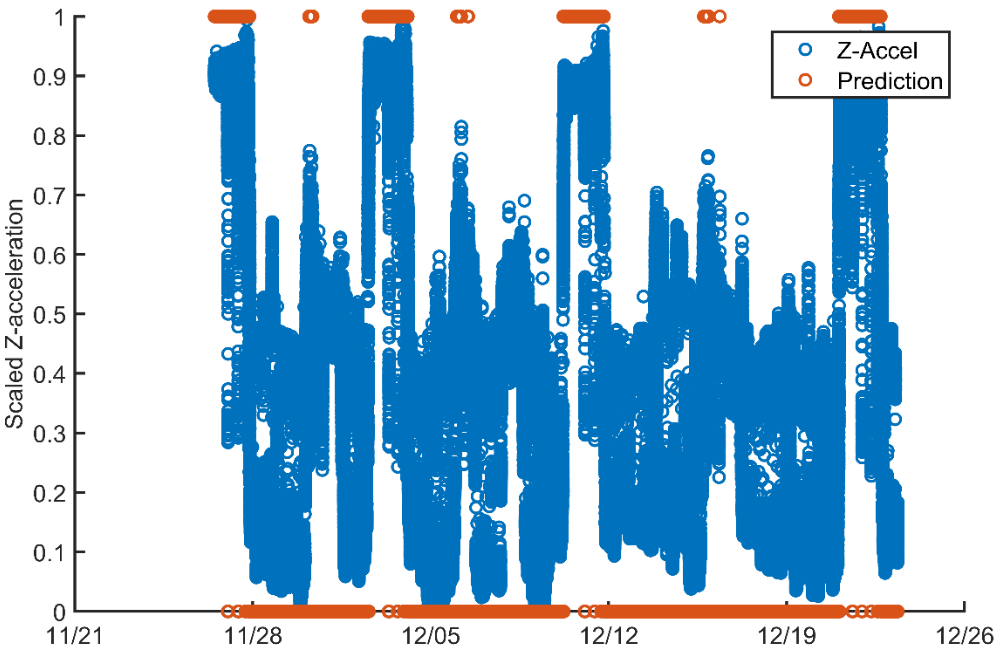

Figure 19. Predictions obtained using a modified version of the Cavitation Detection Algorithm (CDA), in which only acceleration levels were used to train the Logistic Regression model. Blue dots are the scaled acceleration levels from the Z-component for comparison.

5. CAPTAIN'S OBSERVATIONS

JASCO representatives had the pleasure of interviewing the captain of the *Ferbec* in coordination with staff from CSL's project management, environmental, and engineering teams. This allowed an evaluation of perspective from vessel operator on the usefulness of knowing their vessel's cavitation state. In general, commercial vessel operators are not concerned about the underwater sound signature of their vessel, rather the timing of their voyage. The following information was obtained from the interview with the captain.

Captain Beaulne has been the Master of many vessel types on routes through Canadian and international waters. During his long career, he has never considered underwater noise emissions while determining how to operate his vessels, although he is aware that it is increasingly of concern and is interested in how to mitigate URN. In almost all cases, determining how fast to sail a vessel is driven by minimizing the transit times while respecting the requirements of local regulations and conditions. For the *Ferbec*, regulations included respecting the 10 kn speeds limits in the Gulf of St. Lawrence and around the mouth of the Saguenay River. He also had to time his arrival at Les Escoumins while laden according to tide cycles to avoid running aground during low tide. While running other vessels, he had to adjust his speed to arrive in time for a scheduled berthing slot. Captains must adapt to changes in weather and local traffic and consider their crew's comfort and safety, all while arriving at their destination on time.

The captain spoke of his observations that the density of whales can be high in areas close to the coastline where there is a higher chance of greater densities of vessel traffic. Known marine mammal areas are typically governed by traffic lanes; however, vessels often seek permission to leave the traffic lanes. Areas such as the north shore in Quebec typically have vessels gaining permission to transit outside the traffic lanes to save time transiting along the shore or to avoid weather. Using the *Ferbec* as an example, the captain suggested that there can be very high noise levels around ports during berthing and departure. The noise is due to engine movements to bring the vessels alongside, whether using the ships own power or from tugs.

Captain Beaulne pointed out that the type of propulsion system on a vessel likely affects the noise it generates. Vessels like the *Ferbec* have a single engine directly coupled to a fixed pitch propeller. These vessels change speed by adjusting the engine speed and hence the shaft revolutions per minute. For pilots to communicate precisely with ships crews, all ships have standard engine settings of dead slow, slow, half ahead, and full ahead as their controls. Once at full ahead, the captain does have finer control over the RPM to adjust the speed slightly to account for currents, wind, local traffic, etc. For the *Ferbec*, the captain noted between slow and half ahead, the vessel reaches a critical resonant RPM where the vessel shudders violently but becomes comfortable again above this resonant RPM. Based on the results of the Baseline Trial, we believe that the cavitation inception speed for the *Ferbec* is around 6–7 kn, a speed too low for safely navigating in some areas of the St. Lawrence River.

During earlier discussions, the CSL headquarters staff noted that the captain has almost complete jurisdiction over a ship's schedule and safety during voyages.

6. DISCUSSION AND RECOMMENDATIONS

During the development of the MMP3 project, we identified two use cases for a CMS, each with an associated noise management plan (Figure 20). The first use case envisioned a real-time CMS where the onboard sensor levels would correlate with the vessel's URN. By controlling the vessel speed and observing the cavitation sensor levels, the vessel operators could maximize the speed through water at an allowed noise level in sensitive areas. In the second use case, a temporary cavitation monitoring system would be fit to the vessel to determine its cavitation versus speed profile. From this information, the vessel operators can be aware of the maximum speed at which cavitation does not occur, and thus could select an appropriate handle setting to reduce noise when transiting through sensitive areas without the need for a real-time system.

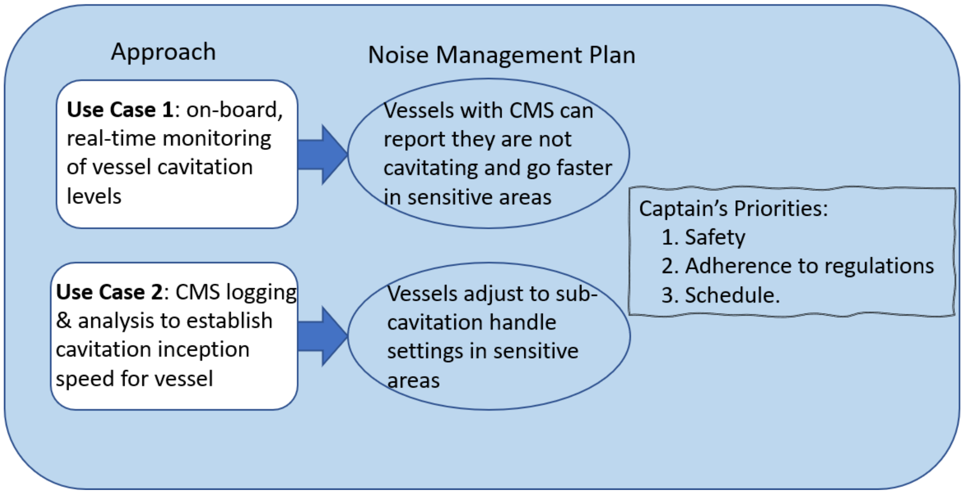

Figure 20. Potential use cases for cavitation monitoring systems on vessels.

This project demonstrated that the requirements needed for the first use case to be successful are not satisfied in the following realistic scenarios:

1. The pressure or acceleration levels measured on the vessel must be associated with a small window of URN levels. We already know that a vessel's speed is well correlated with URN, which was validated with the *Ferbec*'s measurements during the Baseline Trial (Figure 14). However, the onboard sensor values had an inter-quartile range on the order of 10–25 dB for speeds above 6 kn, with the ranges overlapping (Figure 13). This means once the *Ferbec* was fully cavitating, the sensors were not useful for assessing vessel speed, and hence URN.
2. The *Ferbec*'s cavitation onset occurred below 6 kn, which is below safe steerage speed for some areas of its voyage through the St. Lawrence River's currents. The *Ferbec* may be anomalous with a very low cavitation onset; however, this measurement raises concerns with the overall viability of using cavitation for speed regulation.

3. Interviews with the *Ferbec*'s captain revealed the types of considerations that are important for all vessels. Captains must safely maximize the ship's value to the owners by minimizing the overall cost of the voyage. The only way that URN will become a consideration for them is through regulation, similar to the speed management zones in place for the North Atlantic right whale.
4. Installing and maintaining a CMS must not be unduly expensive. The costs for the prototype installation on the *Ferbec* were likely anomalous, due to the need to install on an operational vessel. However, the costs of this project are indicative of possible costs for other vessels. The choice of sensors and their locations must also be carefully considered. The pressure sensors were installed above the propellers, as this is the location on the propeller with the highest exposure to fluctuating pressure. Consequently, the signal-to-noise ratio of cavitation-induced vibration is higher than in any other location on board, which results in good detection performance for the occurrence of propeller cavitation. However, for vessels that frequently travel in ballast, this is area is not always underwater. Installing in a location farther down the hull would likely be more difficult, as it would be in a confined (hazardous gases) space. The relationship between vibration and cavitation would need to be re-investigated in such an installation.

There are likely fewer impediments to adopting the second use case for the CMS. The MMP3 measurements demonstrated that an accelerometer attached to the hull of the ship by adhesive or magnetic connection will provide sufficient data to measure cavitation onset. A simple logging system could easily be developed and distributed to vessels to characterize them in a few voyages each. An extensive collection of these types of measurements will be needed to understand if most vessels are able to operate effectively at sub-cavitating speeds. This type of data will be necessary before deciding if it is reasonable to invoke cavitation-based speed limits in some sensitive areas.

Analysis of the *Ferbec*'s propeller characteristics indicated that its efficiency is below achievable values, probably due to the engine being unable to deliver enough torque. Other design features of the propeller to increase efficiency, such as low blade area ratio and low unloading of the tips, increase the propeller's tendency to cavitate. This tendency of the propeller in the presence of a wake field, with presumably highly inhomogeneous flow, leads to cavitation inception at untypically low speed. It seems likely that a sharp skeg which is possibly introduced for increased directional stability induces additional inhomogeneity of the wake field, resulting in additional cavitation in the lower section of the propeller. Measurements of cavitation onset speeds for many vessels will reveal how common this type of system is in Canadian and global fleets. Such data could lead to a mandate from regulators and/or the International Maritime Organization (IMO) to increase cavitation onset speeds through better propeller and hull designs (Büchler et al. 2020).

The following activities could be further investigated following the MMP3 project:

- Conduct and analyze the accelerometer data that were collected during MMP2 onboard a BC Ferries vessel to see if the same conclusions can be drawn as with the *Ferbec*.
- Develop a peer-reviewed journal article documenting the results and lessons learned from MMP3. This would likely be well received by Marine Pollution Bulletin.
- Create a new project to develop an autonomous accelerometer logger that can be installed for short periods of time on a wide variety of ships to assess the prevalence of low-cavitation onset speeds in Canadian and global fleets.
- Consider developing a project to evaluate replacing the *Ferbec*'s propeller with an optimized design to improve the cavitation inception and underwater radiated noise.
- Investigate the potential of installing an energy saving device such as a Mewis duct, which can be used to smooth out sharp inhomogeneous sections of the wake field. This measure has the potential to reduce cavitation and increase efficiency at the same time.

7. CONCLUSIONS

The onboard pressure and acceleration measurements made on the M/V *Ferbec* both showed a rapid change in levels as the vessel speed increased from 4 to 6 kn, which validated that the cavitation was easily measurable using onboard sensors. The in-water measurements found that the *Ferbec* had typical URN for a bulker of its size. However, the onboard measurements were not unique in that there was substantial overlap in measured levels for all speeds above the cavitation onset. Thus, the onboard sensors are better suited to a yes/no indication of cavitation and are ineffective as a calibrated measure of URN. The CMS was integrated with the CSL O2 vessel management system for data logging and display to the bridge team; however, the vessel operators did not use the system to guide operations due to commercial requirements. The concept of real-time CMS system does not appear to be operationally feasible. Development of a peer-reviewed publication to document these results is suggested. It is recommended to develop a program to use autonomous data loggers to better understand the relationship between speed and cavitation for commercial vessels as input to future guidance on good ship and propeller design practices. Transport Canada could also consider developing a project to evaluate how replacing the *Ferbec*’s propeller with an optimized design improves the cavitation inception and underwater radiated noise.

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APPENDIX A. ALGORITHM DETAILS

It is possible to determine the linear dependency of the sounds levels as a function of the speed through water via many methods. In this section, a principal component analysis (PCA) is presented to demonstrate that it is accurate enough to only use data from the accelerometer. PCA is a technique widely used in machine learning algorithms to reduce the dimensionality of large data sets, increasing interpretability while minimizing information loss. It does so by creating new uncorrelated variables, called the principal components, that successively maximize the variance. In this case, the maximum dimensionality of the system was five because the model was trained using data from the five sensors during the baseline trial. Using the Scikit Learn toolbox implemented in Python programming, it was possible to determine the accuracy of several classification models when using a different number of principal components. Figure A-1 presents different binary classification methods applied to different combinations of channels. The first row corresponds to combining pressure channel 1 with pressure channel 2. The following rows are different combinations of accelerometer sensors, where blue dots indicate a fully cavitating state and red dots no cavitating state. The first column is the input data fed into the different machine learning techniques whose output is presented in columns 2–12: Nearest Neighbors, Linear Support Vector Machine, Radial Basis Function Support Vector Machine, Gaussian Process Regression, Decision Tree, Random Forest, Neural Network, Adaptive Boosting, Naïve Bayes, Quadratic Classifier, and Logistic Regression. Within each subplot, there is a score from 0–1, with 0 being no accuracy and 1 perfect accuracy. All obtained accuracy scores were above 0.9, regardless of the classification method or the combination of sensors used to train the model. This result suggests it is possible to reduce the system's dimensionality.

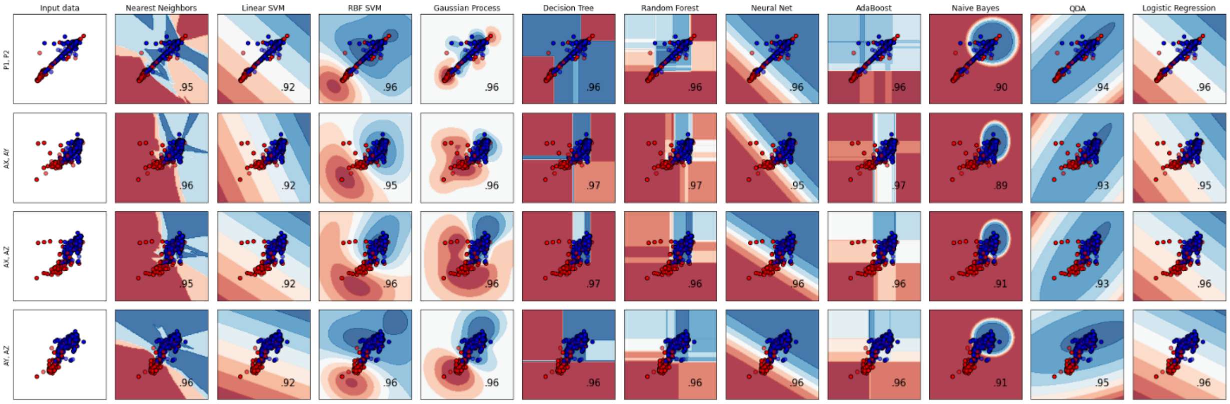

Figure A-1. Different machine learning classification techniques applied to different combinations of channels. The first column shows the input data where blue dots indicate the system was fully cavitating and red dots indicate it was not. The corresponding score of the technique is indicated within each subplot. The rows are different combinations of sensors (P1 or P2) corresponding to pressure channels 1 and 2, or AX, AY, or AZ corresponding to the X, Y, and Z accelerometer channels.

Figure A-2 presents a result similar to Figure A-1. In Figure A-2, a PCA was applied to the input data. The pressure and acceleration levels were standardized, i.e., the values were centred around the mean with a unit standard deviation, and then the new uncorrelated dimensions with the highest variance, the principal components, were calculated. Unlike Figure A-1, in Figure A-2 the first row corresponds to “pressure a” and “pressure b”, which indicates that the values were different and were not expressed using the same units. For the acceleration levels, the dimension was reduced to two, A1 and A2, from Ax, Ay, and Az. While the accuracy for the pressure levels was expected to remain the same because no dimensionality reduction was applied, the score obtained from the acceleration levels remained above 0.94 for all classification models after the dimensionality was reduced.

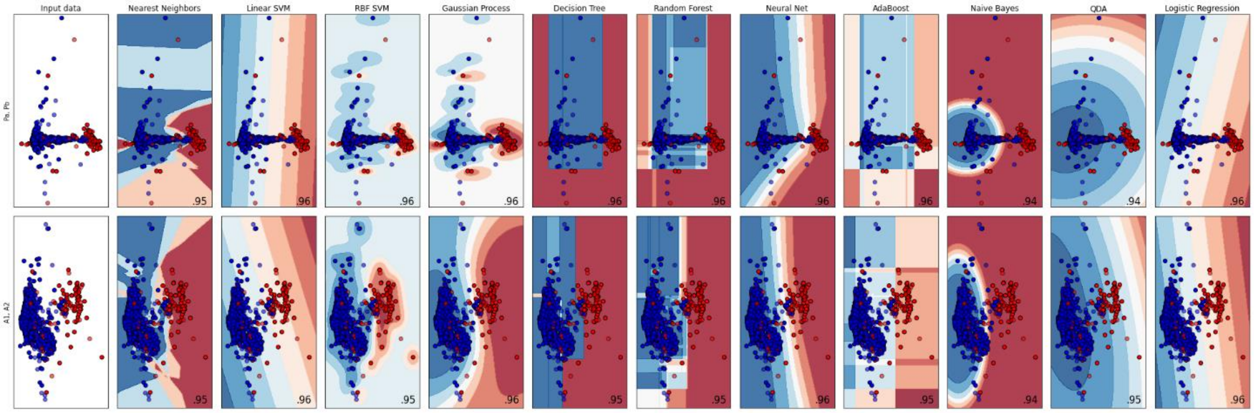

Figure A-2. Different machine learning classification techniques applied to different combinations of channels. The first column shows the input data where blue dots indicate the system was fully cavitating and red dots indicate it was not. The corresponding score of the technique is indicated within each subplot. The rows are the pressure and acceleration levels after a principal component analysis (PCA) was performed on the original data.

It is possible to go further by reducing the dimensionality to one, i.e., only the first principal component that corresponds to the one with the highest variance. Since a Logistic Regression model was used in the CDA, Figures A-3 and A-4 show the probability obtained after applying the model to the principal component of the pressure and acceleration respectively, compared with the Logistic function. While the pressure principal component follows very closely the Logistic function, the acceleration principal component also agrees well. Note that the units in the x axis of the figures are not represented by a physical unit since there is not a physical quantity related to these values.

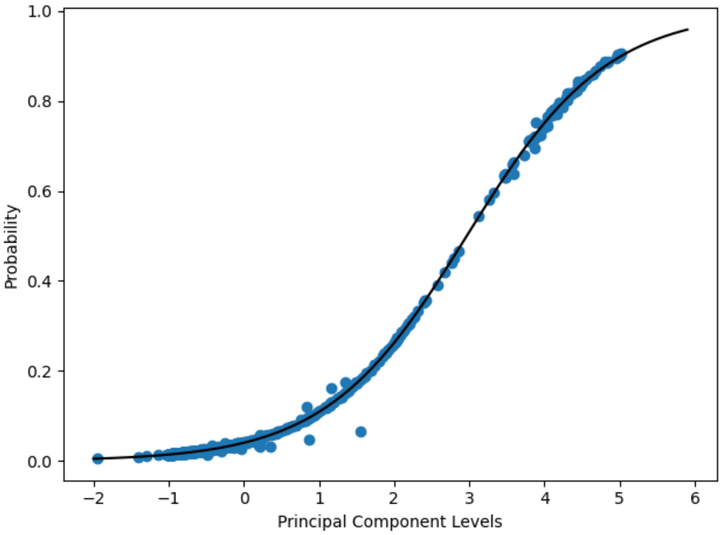

Figure A-3. Probability obtained after applying a Logistic Regression model to the principal component of the pressure.

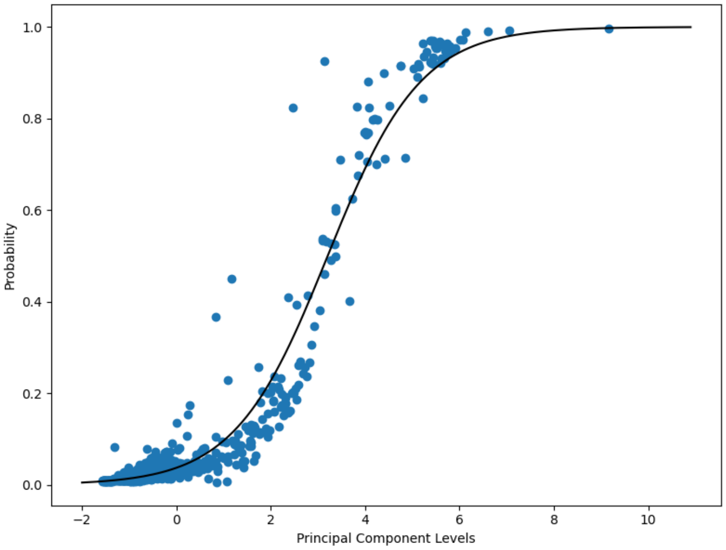

Figure A-4. Probability obtained after applying a Logistic Regression model to the principal component of the acceleration.

Finally, the PCA function in Scikit Learn, allows the calculation of the explained variance for the different principal components obtained. Figure A-5 shows the percent of the variance that is explained by each of the principal component variables. The blue line corresponds to the case when all sensors are considered, the maximum number of principal components is 5 corresponding to 2 pressure channels and 3 acceleration coordinates. The first principal component explains above 95% of the variance, the second 3% and the rest of the components the remaining 2%. This kind of behaviour is expected when all variables are linearly dependent. The orange and green lines corresponding to considering only the acceleration or only the pressure data exhibit a similar result as is expected which demonstrates that it is plausible to train the CDA using only one channel from the pressure or acceleration sensors.

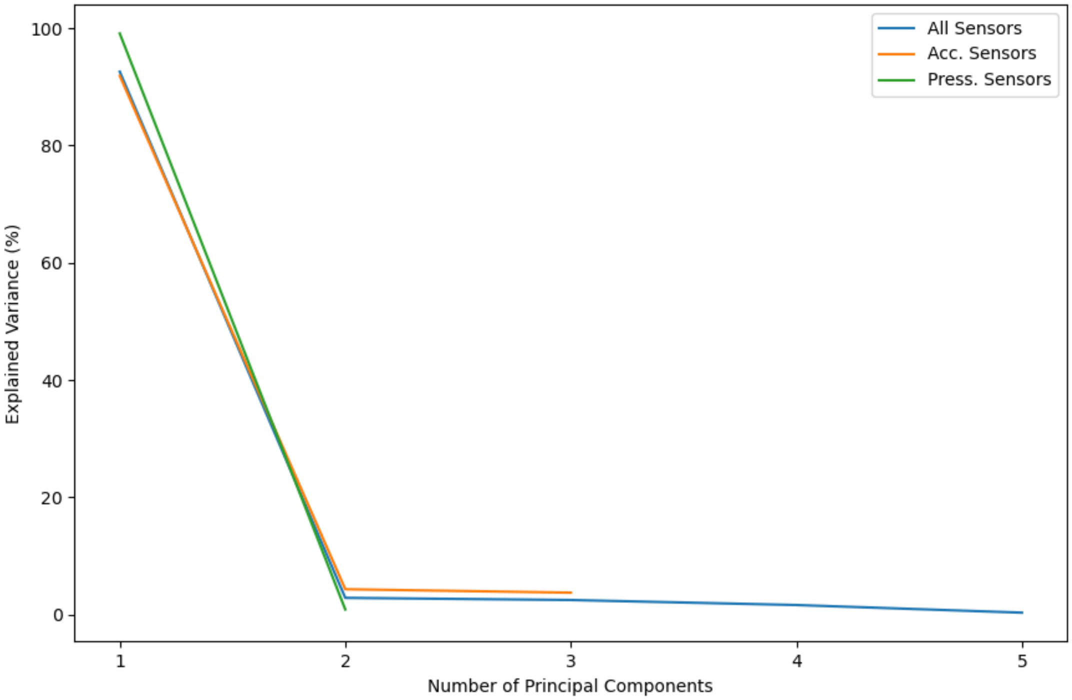

Figure A-5. Percent of the variance that is explained by the different principal components. Blue, orange, and green lines correspond to the case where all sensors, only acceleration sensors, and only pressure sensors are considered respectively. The x axis indicates the order of the principal component with 1 being the first principal component.

APPENDIX B. PREVIOUS REPORTS

This appendix contains the following MMP3 reports, which were previously delivered to Transport Canada in advance of this final report:

- MMP3 – *Prototype Cavitation Monitoring System: Trials Plan* (Whitt et al. 2021, JASCO document 02216),
- *MMP3 April to June 2021 Field Trial and System Design Report* (Martin et al. 2021, JASCO document 02472),
- *MMP3 Integration and CMS Installation Test Report: Integration Test Description and Results* (Diggle and Maxner 2021, JASCO document 02543), and
- *MMP3 Field Trial Report: Data Logged and Analyzed during Field Trial* (Maxner et al. 2022, JASCO document 02617).

MMP3 – Prototype Cavitation Monitoring System

Trials Plan

Submitted to:
Abigail Fyfe
Transport Canada Innovation Center
Contract: T8009-190191/003/XLV

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3 March 2022

P001556-003
Document 02216
Version 2.0

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Suggested citation:

Whitt, C.J., Martin, B., and C.B Lawrence. 2022. *MMP3 – Prototype Cavitation Monitoring System: Trials Plan*. Document 02216, Version 2.0. Technical report by JASCO Applied Sciences for Transport Canada Innovation Center.

Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Contents

Figures

Tables

1. Summary

This plan describes the Marine Mammal Protection Project 3 (MMP3) Cavitation Monitoring System measurement trials planned by JASCO Applied Sciences for Transport Canada Innovation Center (TC-IC). Two trials are planned: A baseline data collection trial in May/June 2021 and an Operational Trial in Sept/Oct 2021 (Figure 1). This document provides the details of the system installation and baseline trials plan as well as vessel and equipment requirements. Detailed scheduling for the trials will take place in spring of 2021 once the vessel schedule is known.

The goal of this project is to provide an assessment of possible operational benefits of using a cavitation monitoring system to modify vessel operations in areas around species at risk, based on real vessel data. The concept is to provide vessel masters with an indication of the vessel's radiated noise, based on measurements made using sensors onboard the vessel. During the operational trial we will evaluate how masters employ this information.

To convert on-board sensor readings to underwater radiated noise (URN) levels, simultaneous measurements on the vessel and in the water are required. The baseline trial will characterize the URN produced by the bulk carrier *Ferbec* (Figure 2) and at the same time measure pressure and vibration above the propellers. Prior to the trial, the *Ferbec* will be outfitted with pressure transducers and accelerometers that are proposed for the prototype cavitation monitoring system (CMS). These sensors will collect data over a 1-2 month period, with an expected start of ~1 May 2021. Once the on-board sensors are in place, JASCO will deploy a moored vertical array of Autonomous Multichannel Acoustic Recorder (AMARs) along the route of the *Ferbec* to measure her URN. The AMARs will be installed and deployed as close as reasonably practical to the start of the *Ferbec* operating season, likely around 1 May. The AMARs will be retrieved when sufficient passes have been collected. A different operating state will be captured on each pass, most likely different speeds on the fully-loaded transits and different trims on the ballast return transits. A minimum of five fully-loaded passes is needed (see Section 2.4.3).

The URN measurements will be made with a vertical array that is compliant with ISO Standards 17208-1/-2 for the measurements of vessel underwater radiated noise. The URN data will be analyzed using JASCO's ShipSound software that has been demonstrated on numerous projects, including for the Vancouver-Fraser Port Authority's ECHO program.

A correlation of the URN data and the on-board data will allow the CMS to predict the URN based on the on-board sensors throughout the remainder of the transits. The long-term record from the on-board sensors and our correlation with the URN will also provide an indication of how the URN changes during the voyages. The knowledge gained by analyzing data will be incorporated into the prototype CMS and tested in 2021 during the operational trial. The operational trial will also use the *Ferbec* for consistency between the baseline and operational trials.

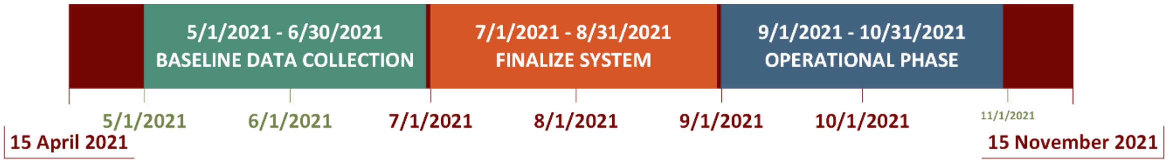


Figure 1. Baseline Data Collection, System Completion, and Operational Trials timeline.

Figure 2. Bulk carrier Ferbec. Taken from: https://www.cslships.com/sites/default/files/ferbec_-_new_version_2017.07_0.pdf

Table 1. Technical Specifications of the bulk carrier *Ferbec.*

Technical specifications		
Length Overall (m)	187.5	
Breadth Moulded (m)	31.0	
Dead Weight Tonnes	49,502	
Draft (m)	Summer	12.071
	Winter	11.820
Cruising Speed (kts)	13.4	
Engine Size	6880 kW	
Propeller Diameter	6 m	

2. Baseline Trial

2.1. Vessel Route

The *Ferbec*'s route begins in Havre-Saint-Pierre, QC and ends in Sorel-Tracy, QC. Based on bathymetry and maneuverability requirements of the monitoring operation, the ideal location for the trial is an area with water depth 180-250 m and with sufficient space that the trial vessel can adjust speed for the various operating states that will be measured. The measurements would be on the vessel's route between Havre-Saint-Pierre and Rivière-du-Loup (Figure 3). As the *Ferbec* is an active bulk carrier, measurements will need to be collected underway to minimize schedule impacts.

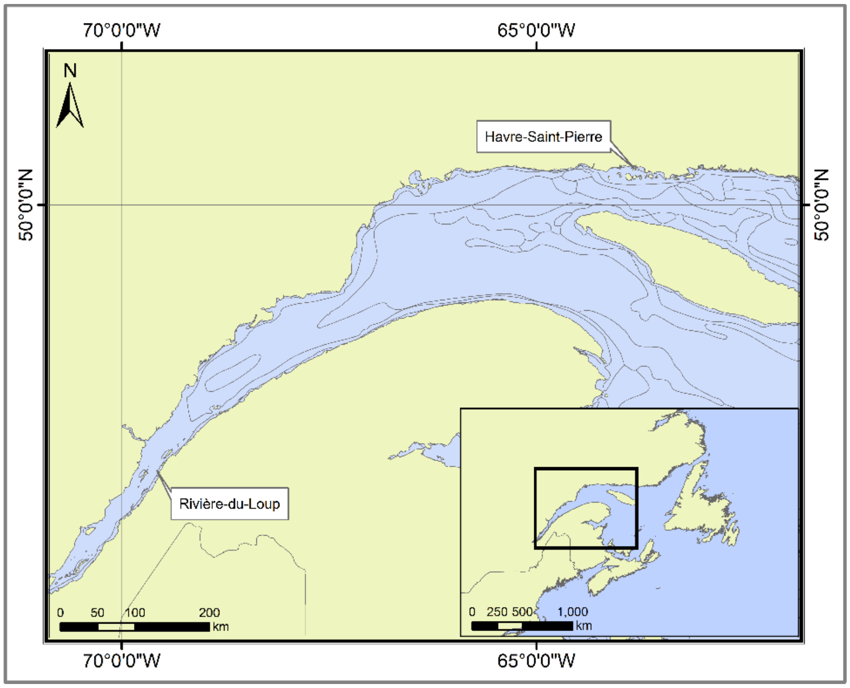


Figure 3. Planned measurement area on the route of the bulk carrier *Ferbec*, between Havre-Saint-Pierre and Rivière-du-Loup.

2.2. Ship Schedule

The *Ferbec* operates on an approximately 6-day cycle of loading in Havre St. Pierre and unloading in Sorel. Typical departure times from Havre St. Pierre are late afternoon or late evening. At least 20 return trip voyages are planned for 2021; the exact starting date is not yet determined.

2.3. Cavitation Monitoring System

2.3.1. System Architecture

The overall architecture for the MMP3 system in shown in Figure 4. Three pressure sensors and an accelerometer are mounted on the ship's hull using the mechanical design proposed by the vessel operator or their chosen subcontractor. Appropriate approvals by the Class Society will be obtained. The power/signal cables from each of the sensors will be routed to a waterproof box in the same compartment, that contains pressure sensor preamps. Locating the pressure sensor preamps close to the sensors is necessary to maximize data quality.

A signal/power cable would then run from this wet/dry compartment into a dry compartment. The vessel operator will be responsible for contracting this penetration (the costs for the modifications will be paid by the project). The CMS electronics (a JASCO Observer system and supporting electronics) will be in the dry compartment, and sample all required channels at 8 kHz. The Observer would initially be programmed to record all data to SD cards – in a subsequent update it will be retrofitted with software capable of processing the sensor data in real time and transmitting its processed results to the ship's '02' information management system. The Observer will be powered by ship's power (240 VAC, 50 Hz), and connect to the ship's LAN via WiFi. The WiFi capability on Observer will be provided by a Bullet radio with an external antenna or a consumer Ethernet router.

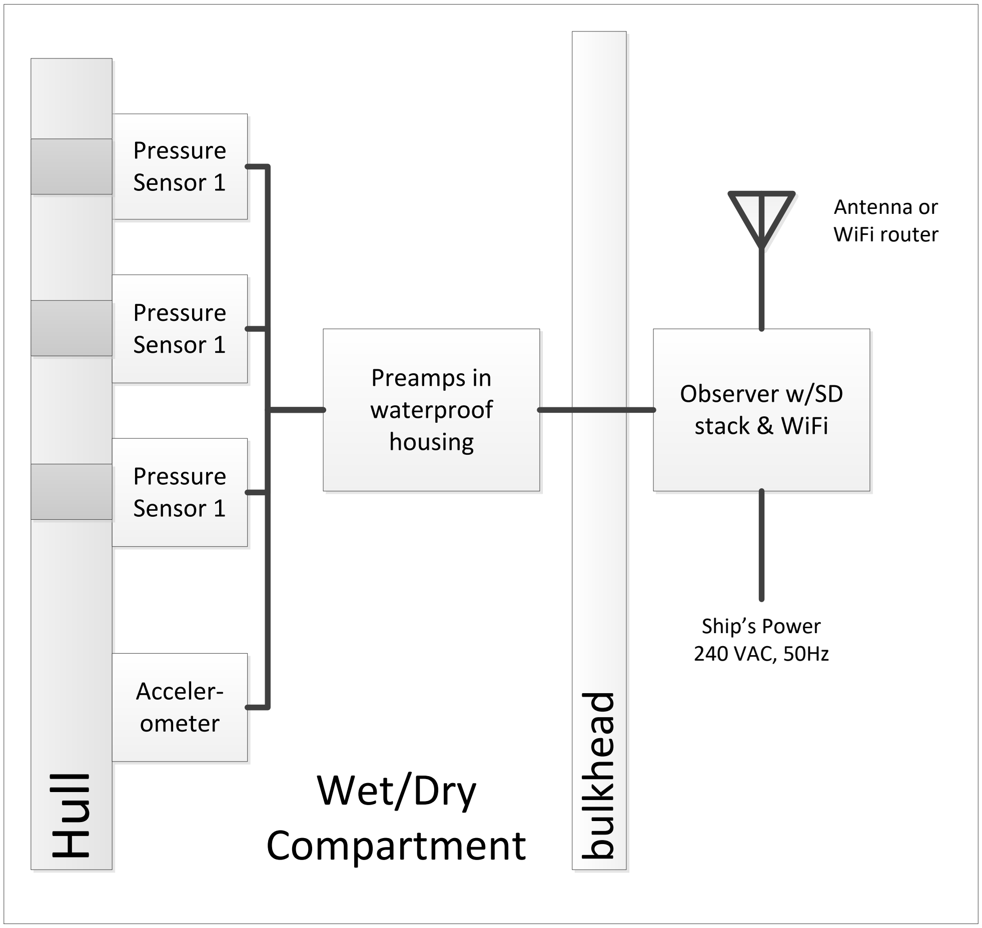
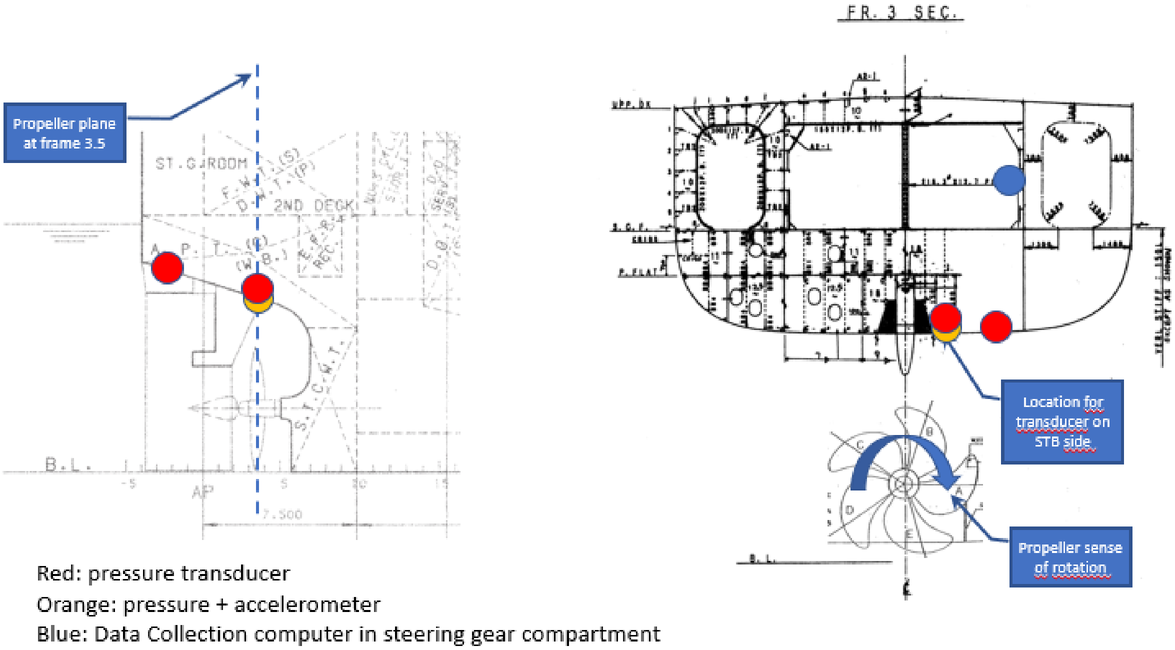


Figure 4. Cavitation Monitoring System architecture.

2.3.2. Transducers and Data Collection

Three Kyowa PGMC-A-200KP pressure transducers will be employed to measure the onset and full spectrum of cavitation. The transducers will be installed in the aft peak, which on the *Ferbec* is also a ballast tank. The transducers will be in propeller plane just to the starboard of the propeller, on the centreline 1 m behind the propeller (or as close as practical given the aft peak structural limitations), and in the propeller plane 1 m to starboard of the centreline, as shown in Figure 5. The three locations ensure different cavitation types can be distinguished and allow for averaging.



Red: pressure transducer
Orange: pressure + accelerometer
Blue: Data Collection computer in steering gear compartment

Figure 5. Transducer installation locations.

A PCB 356B18 accelerometer will be installed with the pressure transducer closest to the centerline above the propeller.

As described in Section 2.3.1, the data collection system will be installed in the steering gear compartment above the aft peak. The sampling rate will be set at 8 kHz or higher. 8 kHz is recommended since the PCB 356B18 has an upper frequency limit of 3 kHz and PGMC-A-200KP has an upper limit of 500 Hz.

2.3.3. Installation

For the CMS to effectively monitor the full spectrum of propeller sound, pressure transducers will be installed above the *Ferbec's* propeller and connect to a data acquisition system placed inside the vessel. This will require the *Ferbec* to be in an unballasted condition in port for about a day for the installation of the through-hull components. This installation will occur in Montreal.

The through-hull installation will be performed by a contractor outside of JASCO and arranged by CSL. The outline of the installation requirements is described in Appendix A. The specific plans for the installation will be determined during the winter of 2020-21 for installation before the *Ferbec* returns to service in April 2021.

2.4. URN Measurements

2.4.1. Measurement Plan

URN measurements will be made using a moored vertical array that is compliant with the ISO 17208-1/-2 Standard (Figure 7). This system will be deployed and retrieved by JASCO field staff and vessel crew. JASCO will coordinate with the *Ferbec* ahead of time the location and description of operating states.

Each measurement pass will consist of the vessel reaching the required operating state, then maintaining it through a period of approximately 1km (500 m before and 500 m after closest point of approach (CPA)). The measurement system will be positioned approximately 200-250 m off the vessel track, at a point perpendicular to CPA.

The planned deployment vessel is the STELSEA workboat (Figure 6). This boat can be trailered and deployed from an opportune location. Matane is likely where we will work from.

Figure 6. STELSEA workboat operated by COB Marine from Saint-Flavie PQ.

2.4.2. Moored Hydrophones

The moored vertical arrays of hydrophones will use the high-flow array mooring (Figure 7).

All moored hydrophones will be sampled continuously by an AMAR G4 (JASCO Applied Sciences) at 128 kHz for a maximum duration of 12 weeks. All hydrophones will be GeoSpectrum M36-V35 with a nominal sensitivity of −164 dB re 1 V/µPa. The hydrophones will be calibrated on deck prior to deployment and on retrieval using a G.R.A.S 42AC pistonphone calibrator at 250 Hz.

The real-time clocks on the AMAR G4s will be synchronized with GPS time prior to deployment. The maximum clock drift for deployment period is 52 s.

The deployment and retrieval procedures for the mooring array are given in Appendix B.

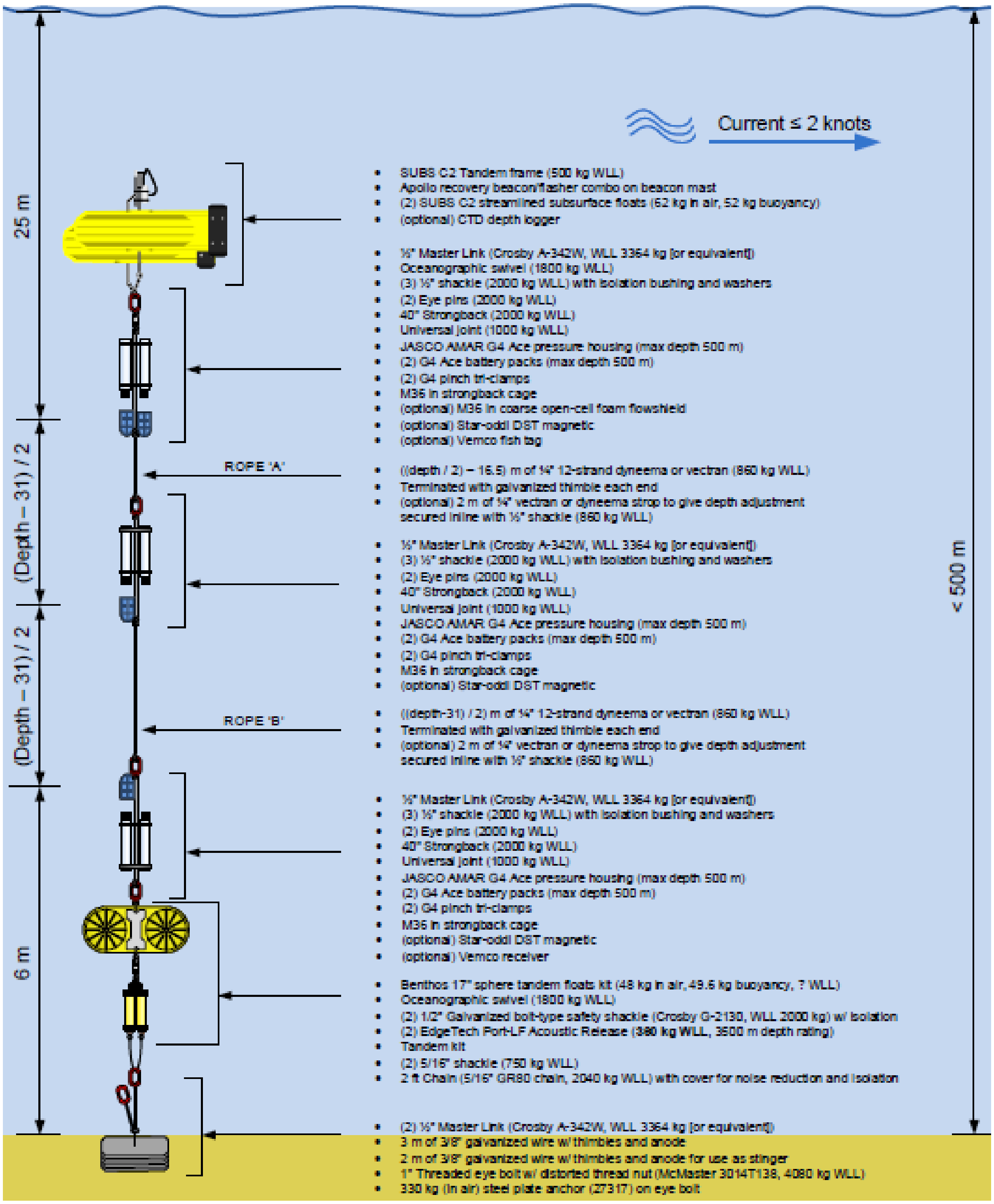


Figure 7. Mooring diagram for the bottom mounted vertical arrays that will be employed for the source level measurements.

2.4.3. Vessel Operating States

To characterize the vessel cavitation onset and related underwater radiated noise (URN), a range of operating states must be measured. These should include both cavitating and non-cavitating operation.

We propose to measure 5 states including 13, 11, 9, 7, 5 kts. The vessel should be normally loaded for these measurements. Summer deadweight is 49,500 tonnes. If possible, we may also choose to make a set of measurements with the vessel in its ballasted condition during transit from Sorel to Havre St. Pierre. Ideally, measurements will be made with trim varying by 0.5 m from one transit to another. The propellers and rudder are fully submerged while ballasted.

2.4.4. Data Analysis

The objective of the baseline trial is to correlate the pressure pulses and vibrations measured with the sensors inside the hull to the underwater radiated noise. This section provides an overview of the planned data analysis.

2.4.4.1. Data Recorded on the Vessel

The primary data of interest from the onboard data are the minutes associated with the speeds / times during which recordings were made with external, in-water sound measurement system. These minutes will be extracted from all recorded channels from the on-board system and processed using JASCO's PAMLab acoustic analysis software to quantify the sound pressure levels and acceleration levels as a function of decidecade frequency bands. The same setting employed for the off-board data using ShipSound will be employed for the on-board data.

The full data set from the onboard system will also be analyzed in detail to determine how the recorded signatures change as the vessel speed increases. Vessel operating conditions will be provided via a data download from CSL's O2 system. We want to determine which sensor's signals contain the onset of cavitation most clearly. We also want to determine if adequate information can be obtained from the accelerometer alone as it will be much easier to install in other vessels in the future.

2.4.4.2. Data Recorded on the In-Water Measurement System

The data from the in-water hydrophones will be processed using JASCO's ShipSound software. Each hydrophone will be individually processed to determine the received sound pressure levels as a function of decidecade frequency band for the duration of the CPA (see Appendix C). The received sound pressure levels will be added to the modelled acoustic propagation loss to determine the radiated noise level and the source level. The results from all three hydrophones will be averaged to reduce variability (as per ISO 17208-1 & -2). Details on the ShipSound analysis, include a typical ShipSound noise report is shown in Appendix C.

2.4.4.3. Development of a Shipboard Sensor – Radiated Noise Level Transfer Function

The ratio of the radiated noise level to the acceleration or pressure levels collected onboard the Ferbec define a transfer function, which once computed, can be employed to then convert the measured on-board sensor levels to a radiated noise estimate. JASCO will employ the same methods as the Signature Management Group at Defence Research and Development Canada to compute a transfer function for the *Ferbec*, and will then compare the function obtained to the functions they have obtained on smaller vessels.

2.5. Data Requirements

JASCO will record the following information during the URN measurements:

- Position of the measurement array every 10 seconds (or faster)
- Depth of the hydrophones

- Sound speed profile.
- Calibration of each hydrophone

The CSL O2 system will provide:

- Main Engine Power (kW)
- Main Engine Fuel consumption per unit of time (kg/hr or MT/day)
- Main Engine Fuel consumption per unit of distance (kg/nm)
- Speed over ground and through water (knots)
- Trim angle
- Draft
- Water temperature
- Position

3. Operational Trial Overview

Once the in-water AMAR and baseline *Ferbec* data are collected and analysed, they will be used to finalize the operational analysis algorithms of the CMS. The CMS will interpret accelerometer and pressure sensor data and infer the radiated noise level (RNL) of the vessel (see Section 2.4.4.3). If the interface is available, the RNL and cavitation state will be fed to the CSL O2 system for display on the bridge and transmission to CSL operations center. Alternately a computer display provided by JASCO will be added on the *Ferbec*'s bridge providing the crew with a prediction of their noise levels in real time to see if it influences vessel operations.

Once the CMS installed on the *Ferbec*, the vessel will continue its normal operations for the remainder of the 2021 season, approximately late summer to early November 2021. During this time, vessel parameters (e.g., Section 2.5) will be measured and provided to JASCO, as well as the raw data collected by the CMS. A questionnaire or similar tool will be used to obtain the vessel master's input to determine how the CMS was employed for mitigating the potential effects of high sound levels produced by large vessels. It will also be informative to see how different vessel master's methods of driving the ship affect radiated noise levels.

The collected data will be post-analyzed to look for changes in the cavitation onsets throughout the season, if there are differences associated with fresh or salt water, weather conditions, draft, trim, vessel master or any other operating condition.

All methods and analysis results will be presented to CSL and Transport Canada in Q1 of 2022 and documented in the project final report.

Literature Cited

[ISO] International Organization for Standardization. 2016. *ISO 17208-1:2016. Underwater acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes*. https://www.iso.org/standard/62408.html.

Appendix A. Cavitation Monitoring System Transducer Installations

A.1. Introduction

The following is a short introduction of the procedure to perform cavitation measurements on board.

The idea is to measure water pressure fluctuations in direct vicinity of the propeller, typically in the propeller plane vertically above the propeller using a pressure pickup.

A.2. Procedure

- Outline the installation of a measuring system and present to classification society, get permission by ship owner and class for onboard sensor installation
- Outline the permanent condition onboard after measurements are finished, get certification by classification society
- Prepare drawings and installation procedure onboard, select pickup
- Install onboard. Involves welding from the inside and drilling holes into bottom plating above propeller
- Install transducer and connect to data acquisition
- Perform measurements
- Convert to permanent condition. Involves welding from inside and outside and coating.
- Get certification of class

A.3. Material needed and work onboard

The following is based on a measurement project previously done on a container vessel which aimed at classical cavitation observation according to ITTC (International Towing Tank Conference) standard.

In the current project we deem visual observation not necessary. According to ITTC 5 pressure pickups are recommended: 3 of them in the propeller plane. In this project we suggest 2 to 3 in the propeller plane.

Material needed is:

- Flanges welded to the hull around the bore holes for the pickups
- Plugs for sealing bore holes
- Pressure pickups
- Plugs for accepting pickup

A.3.1. Flange and sealing plug

A flange of 20 mm thickness with an M24 thread is welded to the shell plating all around. An insert with thread M24 outside and a hole with the diameter of the hole into the shell is prepared. This can be used to guide the drill.

The flange facilitates handling of the installation. Connection holes can be provided for a drill stand or a borescope if visual cavitation observation is considered at a later stage.

A bolt is made with a M24 thread which seals the hole when no transducer is mounted. The part below the thread has a length of the thickness of the hull plating.

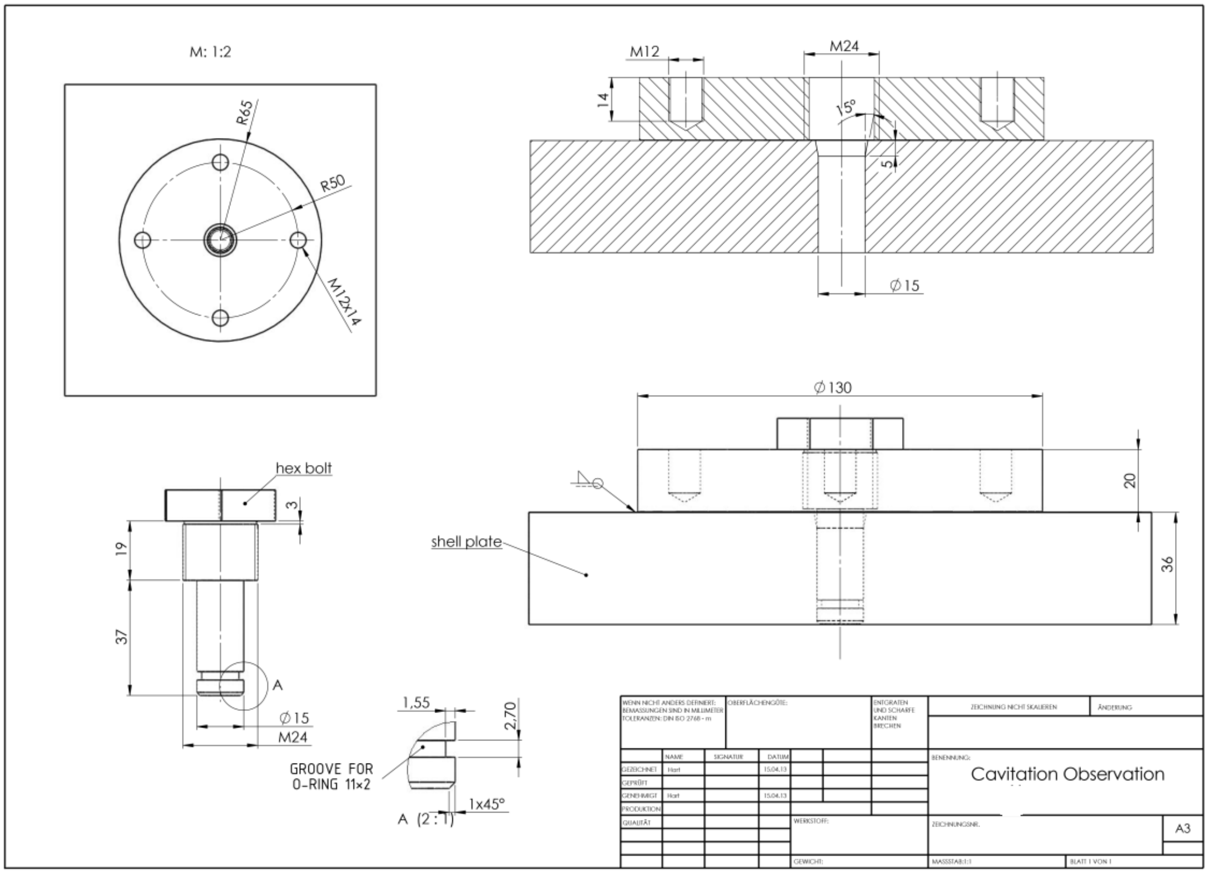
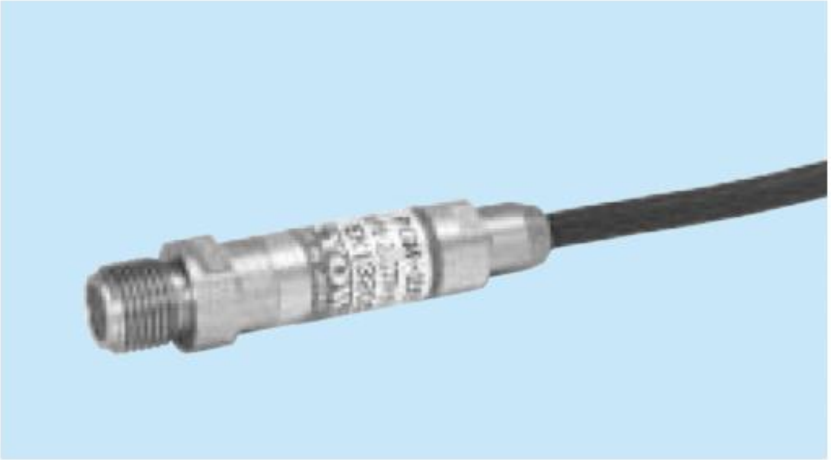


Figure A-1. Mounting flange and plug

A.3.2. Pickup and mounting plug

A pickup (Figure A-2) shall be fitted to the hole and thread with a plug according to Figure A-3. The pickup is mounted to the plug and sealed before the plug is mounted to the flange. The length of the plug is selected such that the pick-up is flush with the shell.

The Transducer used for pressure fluctuation measurement is KOYAWA PGMC_A as follows:



Dimensions:

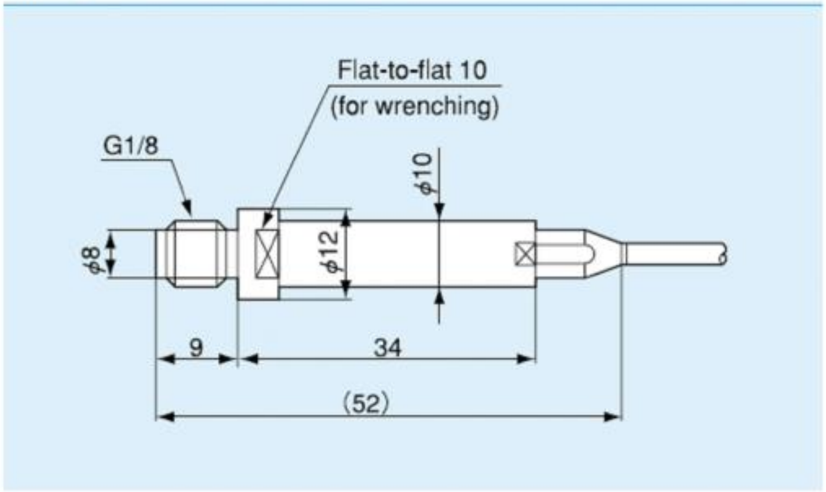


Figure A-2. Transducer (pickup)

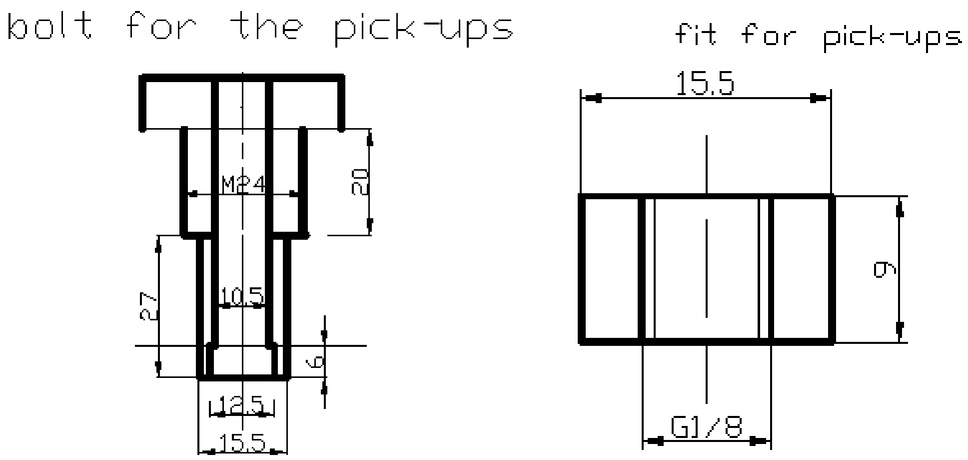


Figure A-3. Plug for pickup

A.4. Aftertreatment

It is possible to do the mounting with the plating submerged. It can also be sealed afterwards with the plug, but class may require that the hole be welded shut to the outside. This could be done in the following docking period. The exact sealing and coating procedure must be agreed with class beforehand.

A.5. Remarks

The exact procedure and parts preparation depend on the situation onboard, plate thickness, sensor selection and class requirement. The sensor suggested above is suitable (should be checked for upper frequency limit and dynamic range with respect to expected pressure pulses) and available also in the US.

Appendix B. Mooring Deployment and Retrieval Instructions

This operations plan covers the deployment and retrieval procedures planned for field deployments for the baseline trial. This plan summarizes JASCO's operational requirements, the long-term mooring that will be employed, and the deployment and retrieval methods for that equipment.

B.1. Vessel Requirements

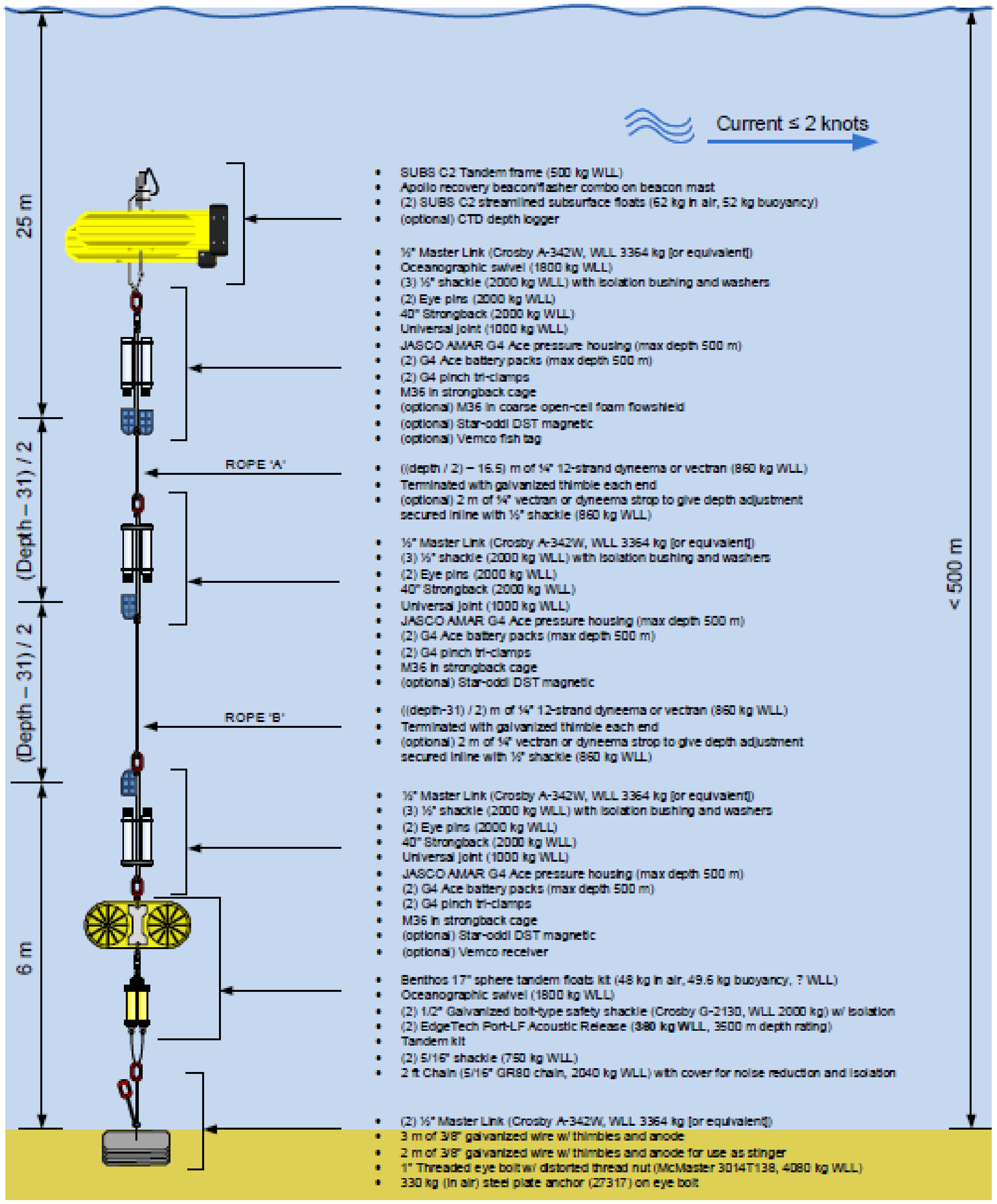
The following resources are required from the vessel to complete the deployments/retrievals:

A hydraulic articulating boom (HIAB or similar) working load limit (WLL) of at least 1.5 tonnes at 7 feet,
A hydraulic davit rated for 2 tonnes*,*
Captain,
One deckhand/capstan/winch/boom operator,
Communications between JASCO lead, captain, and operator, and
The planned deployment vessel is the STELSEA workboat (Figure 6). This boat can be trailered and deployed from an opportune location. Matane is likely where we will work from.

Figure 8. STELSEA workboat operated by COB Marine from Saint-Flavie PQ.

B.2. Moorings and Locations

One vertical line arrays (VLAs, Figure 9) will be deployed in the study area.



- SUBS C2 Tandem frame (500 kg WLL)
- Apollo recovery beacon/flasher combo on beacon mast
- (2) SUBS C2 streamlined subsurface floats (62 kg in air, 52 kg buoyancy)
- (optional) CTD depth logger

- ½" Master Link (Crosby A-342W, WLL 3364 kg [or equivalent])
- Oceanographic swivel (1800 kg WLL)
- (3) ½" shackle (2000 kg WLL) with isolation bushing and washers
- (2) Eye pins (2000 kg WLL)
- 40" Strongback (2000 kg WLL)
- Universal joint (1000 kg WLL)
- JASCO AMAR G4 Ace pressure housing (max depth 500 m)
- (2) G4 Ace battery packs (max depth 500 m)
- (2) G4 pinch tri-clamps
- M36 in strongback cage
- (optional) M36 in coarse open-cell foam flowshield
- (optional) Star-oddi DST magnetic
- (optional) Vemco fish tag

- ((depth / 2) – 16.5) m of ¼" 12-strand dyneema or vectran (860 kg WLL)
- Terminated with galvanized thimble each end
- (optional) 2 m of ¼" vectran or dyneema strop to give depth adjustment secured inline with ½" shackle (860 kg WLL)

- ½" Master Link (Crosby A-342W, WLL 3364 kg [or equivalent])
- (3) ½" shackle (2000 kg WLL) with isolation bushing and washers
- (2) Eye pins (2000 kg WLL)
- 40" Strongback (2000 kg WLL)
- Universal joint (1000 kg WLL)
- JASCO AMAR G4 Ace pressure housing (max depth 500 m)
- (2) G4 Ace battery packs (max depth 500 m)
- (2) G4 pinch tri-clamps
- M36 in strongback cage
- (optional) Star-oddi DST magnetic

- ((depth-31) / 2) m of ¼" 12-strand dyneema or vectran (860 kg WLL)
- Terminated with galvanized thimble each end
- (optional) 2 m of ¼" vectran or dyneema strop to give depth adjustment secured inline with ½" shackle (860 kg WLL)

- ½" Master Link (Crosby A-342W, WLL 3364 kg [or equivalent])
- (3) ½" shackle (2000 kg WLL) with isolation bushing and washers
- (2) Eye pins (2000 kg WLL)
- 40" Strongback (2000 kg WLL)
- Universal joint (1000 kg WLL)
- JASCO AMAR G4 Ace pressure housing (max depth 500 m)
- (2) G4 Ace battery packs (max depth 500 m)
- (2) G4 pinch tri-clamps
- M36 in strongback cage
- (optional) Star-oddi DST magnetic
- (optional) Vemco receiver

- Benthos 17" sphere tandem floats kit (48 kg in air, 49.6 kg buoyancy, ? WLL)
- Oceanographic swivel (1800 kg WLL)
- (2) 1/2" Galvanized bolt-type safety shackle (Crosby G-2130, WLL 2000 kg) w/ isolation
- (2) EdgeTech Port-LF Acoustic Release (380 kg WLL, 3500 m depth rating)
- Tandem kit
- (2) 5/16" shackle (750 kg WLL)
- 2 ft Chain (5/16" GR80 chain, 2040 kg WLL) with cover for noise reduction and isolation

- (2) ½" Master Link (Crosby A-342W, WLL 3364 kg [or equivalent])
- 3 m of 3/8" galvanized wire w/ thimbles and anode
- 2 m of 3/8" galvanized wire w/ thimbles and anode for use as stinger
- 1" Threaded eye bolt w/ distorted thread nut (McMaster 3014T138, 4080 kg WLL)
- 330 kg (in air) steel plate anchor (27317) on eye bolt

Figure 9. Transport Canada high-flow vertical array.

B.3. Additional Equipment

JASCO will provide the following additional equipment:

Hand-held GPS logger,
Field team will keep a GPS log throughout the deployment.

B.4. Schedule of Operations

The planned schedule of operations for the deployment of the recording equipment is shown in Table 2. The planned schedule for equipment retrieval operations is shown in Table 3.

Table 2. Schedule of operations for the baseline trial deployment. Weather permitting, the deployment dates will be 3/4 May 2021.

Time	Activity
Day 1	
07:00	Load mooring into van
08:00	Depart for *Stelsea* dock
08:30	Load *Stelsea*
09:30	Depart docks
12:00	Deploy mooring
16:30	Secure at docks

Table 3. Schedule of operations for the baseline trial retrieval. Weather permitting the dates will tentatively be 28/29 Jun 2021.

Time	Activity
Day 1	
07:30	Depart for *Stelsea* dock
08:00	Depart docks
10:30	Retrieve Mooring
15:00	Secure at docks

B.5. Procedures

The following procedures outline the steps required to deploy and retrieve the mooring. These steps correlate to the Job Safety Analysis (JSA) form inserted. The JSA will be reviewed and adjusted prior to operations by all individuals involved in the recovery effort.

Following initial review, the JSA will be reviewed when the activity and personnel involved change, or lessons learned or circumstances require adjustments to the procedure.

Retrieval operations will be performed using the vessel *Stelsea* (Figure 8). In addition to the vessel master, one winch operator/deck crew will be onboard as per the vessel charter agreement.

Sea state and the decision to proceed with the operations outlined in this JSA will be determined by the vessel captain/crew and JASCO. Personal protective equipment (PPE) worn for all deck-based activities will be determined based on the hazards assessed in the JSA meeting but are generally anticipated to include auto-inflate PFD, steel toed boots, gloves, hard hat with chin strap, and eye protection. Other PPE required to mitigate a specific hazards are documented on each line item in JSAs.

B.5.1. Communications

Communication during activities onboard the vessel with the vessel master or skipper will be done by JASCO crew and deck hands through VHF, hand signals, and ship's radio. VHF radio channel 16 for emergency communications and cell phones by the JASCO team. VHF channel 14 will be the working channel. Table 4 lists the check in procedure.

Table 4. Check-in procedure for JASCO field staff.

Primary check-in (Christopher Whitt)	**Secondary check-in (Bruce Martin)**
Cell phone (call or text)	Cell phone (call or text)
Check-in will occur every 2 h, as well as prior to and after boarding the vessel. Additional check-in procedures will be implemented as needed.	Check-in will occur if the primary check-in is missed. This should happen immediately if the primary check-in is missed or has a delayed response.

B.5.2. Deployment Procedure – High-Flow Vertical Array

Vessel to maintain minimum steerage way with bow into the seas. Sea states ≥ SS3 will be no-go limit for this vessel. To be assessed by JASCO and crew once on-site. Favourable weather days will be monitored.

1. JASCO team with assistance from crew to ready top float assembly, tandem SUBS C2, for deployment including turning on Apollo beacon.
2. Team will affix a pass-through tagline through the masterlink at the bottom of the strongback and hold to vessel's side after deployment via cleat.
3. Crane operator will lift entire top float assembly over the side while the team maintains the pass-through tagline. Crane hook will be removed by crew from top float D-ring.
4. Once the top float assembly is floating alongside the team will affix the first recorder package via masterlink and crane will overboard. This step will be repeated for the next two recorder packages while the crew holds the mooring alongside via masterlink and pass-through tag line.
5. Once the third recorder package is secured to a hard point on the vessel and secured alongside, the crane operator will pick the anchor stinger with a TR-7 affixed to the crane hook, lifting the anchor, releases and tandem Benthos floats over the gunnel. Mooring will be held in place by the crane.
6. The bottom masterlink below the third recorder package will be affixed to the Benthos tandem floats and lowered to the surface of the water via pass-through tagline and cleat for holding in place.
7. Once the entire array is overboard, JASCO to confirm position with the captain and, if necessary, tow the mooring to the way point provided under minimum steerageway.
8. Once on top of way point JASCO will trigger the TR-7 or sacrificial deployment line and release.
9. Team to take way point and box-in releases at each cardinal point at 200 m.
10. Debriefing meeting to capture lessons learned.
11. Vessel's crane will be used for off-loading the equipment. JASCO will assist with taglines only and not be directly involved in transfers from vessel to truck.

B.5.3. Retrieval Procedure – High-Flow Vertical Array

Vessel to maintain minimum steerage way with bow into the seas. Sea states ≥ SS3 will be no-go limit for this vessel. To be assessed by JASCO and crew once on-site. Favourable weather days will be monitored for retrieval.

1. Vessel will close way point to 200 m and de-clutch.
2. JASCO will enable releases and confirm range.
3. Vessel to be positioned down wind at 200 m once range verified.
4. Once satisfied with the position JASCO will send the release code to one release and conduct a 360º surface search for SUBS. Assent should not take more than 30–40 s.
5. After tandem SUBS have surfaced, vessel will gaff the D-ring and place crane hook on lifting D-ring and crane the SUBS and first recorder package over the gunnel.
6. JASCO will secure the second masterlink with a pass-through tagline and secure while the SUBS and top recorder package are dissembled on deck.
7. Crane will then hook the subsequent masterlinks and repeat this process until the Benthos floats are alongside.
8. Crew will gaff the masterlink above the Benthos floats and place crane hook on the masterlink and hoist onboard. Taglines will be used to ensure the mooring does not swing.
9. Debriefing meeting to capture lessons learned.
10. Vessel’s crane will be used for off-loading. JASCO will assist with taglines only and not be directly involved in transfers from vessel to truck.

Appendix C. Underwater Radiated Noise Estimation

C.1. ShipSound Analysis

Radiated Noise Level (RNL) and source level (SL) will be calculated using JASCO's ShipSound software, which is the same software employed for vessel source level analysis on projects such as the Boundary Pass Underwater Listening Station.

Data from the CSL O2 vessel management system will be used to obtain the vessel speed, and CPA to the recorders.

C.1.1. Quality Assurance

Manual Quality Assurance (QA) will be performed on individual passes to ensure the measurements fit established criteria; for example, if the speed of the vessel varied by more than 3 kn within the measurement window, the pass will be discarded. Other criteria for exclusion of the measurements included the presence of other vessels within a detectable distance (i.e., 6 × CPA, as determined by the AIS tracks or other observations collected at the measurement location) or poor signal to noise ratio in many frequency bands.

C.1.2. Propagation Loss Calculation

ShipSound corrects the sound pressure level measured at a recorder when the vessel is at its CPA to obtain the for RNL and SL. The RNL, equal to the measured sound pressure level back-propagated from the measuring device to the acoustic source, is computed in ShipSound using the ANSI/ASA S12.64 Grade-A method (2009), which requires use of the spherical spreading conversion:

$$\mathrm{RNL} = \mathrm{SPL} + 20\log_{10} R \text{ dB}\,,$$

where $R = s/r_0$ is the ratio of the slant range, s, between the source and the recorder and the reference distance $r_0 = 1$ m. The frequency-dependent attenuation of acoustic energy by molecular absorption in seawater is accounted for through an absorption coefficient, computed as a function of water temperature, salinity, and depth using the formulae by François and Garrison (1982):

$$\mathrm{RNL}_{\mathrm{ShipSound}} = \mathrm{RNL} + \alpha R\,.$$

RNL does not account for reflections off the sea surface and the bottom, which can have a significant effect particularly at lower frequencies and in shallow waters. These are accounted for when computing the SL.

ShipSound computes the SL as the measured sound pressure level plus the propagation loss over the source-recorder path, estimated by a model that accounts for the effects of the local environment on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and bottom loss). The parabolic equation model RAM, modified to treat shear wave reflection losses, is used to compute the PL in decidecade bands up to 4 kHz; at higher frequencies, an image reflectivity model is used. At the shortest ranges, given the limitations of the parabolic-equation approach, the PL is estimated using VSTACK, a code implementing the wavenumber-integration numeric solution of the full wave equation.

In the case of the parabolic equation model, the compressional sound-speed gradient will be incorporated into the environmental characterization, while the other compressional properties will be the average over the layer thickness. Only a single value for the shear properties can be specified in order to preserve the stability of the algorithm. The shear-wave sound speed will be limited to 250 m/s, corresponding to an attenuation of 0.88 dB/wavelength. The wavenumber-integration model (VSTACK) only supports constant properties in each layer. The single value for shear sound speed and attenuation will be set equal to the ones in the parabolic-equation model.

At frequencies up to 4000 Hz, the PL will be computed using VSTACK for distances up to 30 m in horizontal range r from the source. The results produced by CRAM will be used at ranges greater than 80 m. Between 30 and 80 m, at each depth the results of the two codes will be a weighted sum $\mathrm{PL}(r,z) = w_1(r)\mathrm{PL}_{\mathrm{VSTACK}}(r,z) + w_2(r)\mathrm{PL}_{\mathrm{CRAM}}(r,z)$. The weights at 30 m start as $w_1 = 0.923$ and $w_2 = 0.077$. With increasing range, w_1 decreases linearly and w_2 increases by the opposite amount, so that a smooth transition leads to the threshold of r = 80 m, beyond which only the CRAM PL are used.

For intermediate frequencies in the frequency range of 4–10 kHz, ShipSound computes the frequency-domain transfer function for a Pekeris waveguide, using a geometrical approximation based on the method of images and plane-wave reflection coefficients. Beyond 10 kHz, a simple formula of PL = 20*log(*R*) dB + α**R* - 3.01 is used, where α is the volumetric absorption coefficient in dB/m, *R* is the range, and −3.01 accounts for energy reflected back at the water-air interface.

Combining the models described above, ShipSound computes the PL as a function of frequency, range, and source depth.

C.1.3. Correction for Vessel Speed Through Water

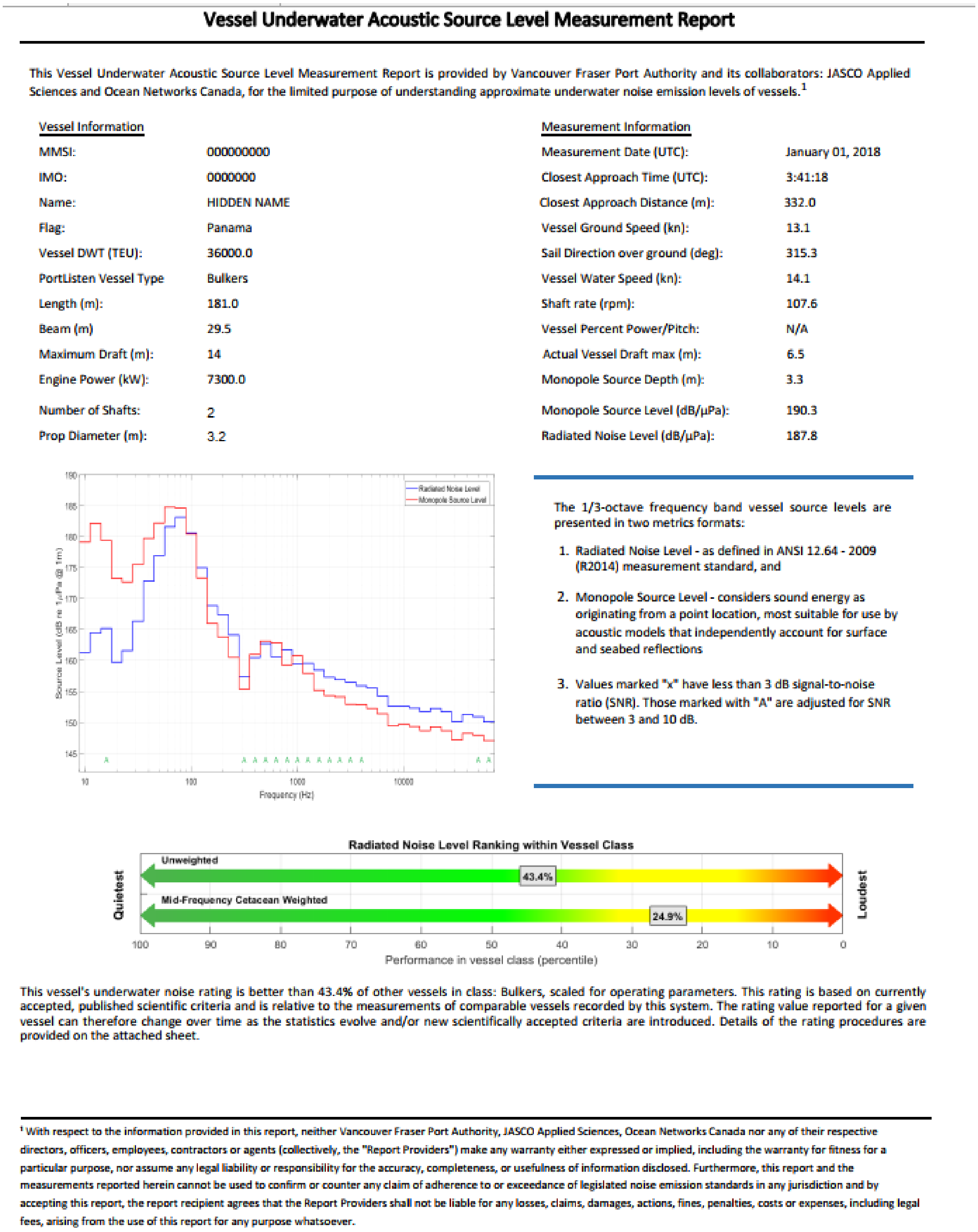
RNL and SL measurements will be obtained at a range transit speeds. Speed through water (STW) for each pass was calculated from speed over ground (from AIS), corrected according by the direction and speed of water currents at the time of measurement. To quantify trends of RNL (or SL) with speed through water, a power law model (Ross 1976) of the following form will b fit to the data:

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

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

where, Cv is the slope of increase in RNL (or SL) with speed through water, v, measured in knots. $\mathrm{RNL}_{\mathrm{ref}}$ or $\mathrm{SL}_{\mathrm{ref}}$ (dB re 1 µPa m) is defined here as the reference source level, representing the RNL or MSL at the reference speed through water v_{ref} of 10 kn.

C.1.4. Sample Ship Sound Report



Vessel Underwater Acoustic Source Level Measurement Report

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

Vessel Information		Measurement Information	
MMSI:	000000000	Measurement Date (UTC):	January 01, 2018
IMO:	0000000	Closest Approach Time (UTC):	3:41:18
Name:	HIDDEN NAME	Closest Approach Distance (m):	332.0
Flag:	Panama	Vessel Ground Speed (kn):	13.1
Vessel DWT (TEU):	36000.0	Sail Direction over ground (deg):	315.3
PortListen Vessel Type	Bulkers	Vessel Water Speed (kn):	14.1
Length (m):	181.0	Shaft rate (rpm):	107.6
Beam (m)	29.5	Vessel Percent Power/Pitch:	N/A
Maximum Draft (m):	14	Actual Vessel Draft max (m):	6.5
Engine Power (kW):	7300.0	Monopole Source Depth (m):	3.3
Number of Shafts:	2	Monopole Source Level (dB/µPa):	190.3
Prop Diameter (m):	3.2	Radiated Noise Level (dB/µPa):	187.8

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 43.4% of other vessels in class: Bulkers, 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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[1] With respect to the information provided in this report, neither Vancouver Fraser Port Authority, JASCO Applied Sciences, Ocean Networks Canada 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.

VFPA Vessel Underwater Noise Rating - Additional Information

Underwater Noise from vessels has the potential to disturb marine mammals, fish and other marine fauna. Vancouver Fraser Port Authority (VFPA) wishes to assist the shipping industry reduce its noise footprint in the marine environment. With this goal in mind, we have developed a vessel noise measurement system and a comparative noise ranking method that allows vessel noise emissions to be characterized relative to those of other vessels of the same class and similar size. The acoustic measurement approach conforms approximately with the protocol defined in ANSI standard 12.64-2009 Grade C, with exceptions as outlined below.

Vessel underwater noise emissions vary with vessel class, size, tonnage, speed, loading and other parameters. The rating system implemented here applies scaling to account for important variables such as speed and vessel dimensions. The rating also considers that different marine species have different hearing acuities. For example, humpback whales are believed to be more sensitive to low-frequency sounds than killer whales. To account for these differences, the system calculates frequency-weighted noise metrics based on functions adopted by U.S. National Oceanic and Atmospheric Administration (NOAA) and published in their Marine Mammal Acoustic Technical Guidance[2]. The VFPA listening station calculates frequency-weighted noise levels for: Low Frequency Cetaceans (LFC), Mid-Frequency Cetaceans (MFC), and High-Frequency Cetaceans (HFC), Phocid Pinnipeds (PPW) and Otariid Pinnipeds (OPW). The actual rating value is the percentile of the vessel's adjusted and frequency-weighted noise level relative to all vessels of the same class. The overall performance rating therefore ranges from 0 to 100, with 0 representing the loudest and 100 representing the quietest vessel relative to all vessels of the same class, accounting for influencing parameters. A vessel's rating for different species groups may be different as it depends on the frequency distribution of its emitted noise.

RNL with Marine Mammal Weightings (NOAA 2016):

Low Frequency Cetaceans (LFC):	179.9	LFC Rank:	30.0
Mid-Frequency Cetaceans (MFC):	161.1	MFC Rank:	24.9
High-Frequency Cetaceans (HFC):	160.0	HFC Rank:	25.7

Additional Information for this Vessel Measurement:

Name of Vessel:	NEW INSPIRATION
Measurement ID:	sog-echoarray1-3-372688000201801010341
Date of Measurement:	January 01, 2018

Environmental Information:

Closest Point of Approach location (WGS 84):	49°02'044"N, -123°18'051"W		
Hydrophone location (WGS-84):	49°02'036"N, -123°19'003"W		
Water Depth (m):	166.0		
Hydrophone Depth (m):	163.5	Wind Speed (kn):	11.3
Speed of Current (kn):	1.0	Wind Direction (deg):	320.0
Current Direction (deg):	150.7	Sea State Code (WMO):	N/A

Conformance with Standard

The vessel source measurements reported here were acquired using procedures conforming approximately with Grade C - Survey Method - ANSI 12.64-2009 (R2014) Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements. Notable conformance exceptions are:

1. The standard requires 4 vessel passes, while this measurement is of a single pass.
2. The standard requires vessel Closest Point of Approach (CPA) of the greater of 100 m or one vessel length. This system may admit measurements at other distances.
3. The standard requires the hydrophone subtend depression angles relative to the ship of 20° ± 5° below horizontal, while this system permits angles from 10° to 60°.

Vessel name and dimension information is obtained from Automatic Identification System (AIS) records sent from the vessel at time of measurement and from MarineTraffic.com. Fields not transmitted by these services are marked as N/A in the report. Frequency bands marked with "X" or "A" in the source level graphs are respectively invalid or adjusted, due to being insufficiently above background noise levels as described in the standard.

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[2] 2016 Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (NOAA Technical Memorandum NMFS-OPR-55)

C.2. Adjusted Radiated Noise Level and Adjusted Source Level Analysis

C.2.1. Adjusted RNL

The RNL computed by ShipSound is calculated as (which is equivalent to the RNL equation showed earlier):

$$L_{\mathrm{RN},\theta_1}(x,z) = L_{p,M}(x,z) + 10\log_{10}\frac{x^2+z^2}{1\ \mathrm{m}^2}\ \mathrm{dB}\,. \tag{1}$$

where *x* is the horizontal distance between the vessel and recorder, *z* is the vertical distance, and $L_{p,M}$ is the sound pressure level measured at the recorder. The angle θ_1 is determined by the measurement geometry:

$$\theta_1 = \operatorname{asin}\frac{z}{(x^2+z^2)^{1/2}}\,. \tag{2}$$

For a given vessel, RNL varies with the value of θ_1, and this angle dependence needs to be removed to ensure a like-with-like comparison. To compute the adjusted RNL, we first convert the RNL to a common angle of 30°, chosen for compatibility with ISO 17208:

$$L_{\mathrm{RN,30}} = L_{\mathrm{RN},\theta_1} + 10\log_{10}\frac{\sigma(\pi/6)}{\sigma(\theta_1)}\mathrm{dB}\,, \tag{3}$$

where the value of $\sigma(\theta)$ (the ratio of dipole source factor to monopole source factor) is (combining equations 8.188 and 8.190 from Ainslie (2010); see also de Jong et al. (2010) and Ainslie et al. (2020a))

$$\sigma(\theta) \approx \left(\frac{1}{2} + \frac{c^2}{(4\pi d f_M \sin\theta)^2}\right)^{-1}. \tag{4}$$

Where *d* is the source depth, and f_M is the measured frequency.

To calculate aRNL, we use Ainslie et al. (2020a):

$$L'_{\mathrm{RN}} = L_{\mathrm{RN,30}} + \Delta L_H + \Delta L_\alpha \tag{5}$$

where

$$\Delta L_\alpha = \alpha(x^2+z^2)^{1/2} \tag{6}$$

and

$$\Delta L_H = -10\log_{10}\left(1 + \frac{\psi(x^2+z^2)^{1/2}}{H}\right)\mathrm{dB}\,, \tag{7}$$

where ψ is the critical angle and H is the water depth.

C.2.2. Adjusted SL

The adjusted source level is computed on a per-frequency basis, where the frequency steps analyzed are typically decidecades (ddec). The ddec SL is estimated by ShipSound using:

$$L_{\mathrm{S},M}(x,z) = L_{p,M}(x,z) + \Delta L_{\mathrm{PL}}(x,z)\,, \tag{8}$$

where ΔL_{PL} is PL at each decidecade centre frequency in the spectrum of the vessel.

Adjusted source level (abbreviation aSL, symbol L'_S) is calculated from the decidecade SL (L_S) using:

$$L'_{S,M}(x,z) = L_{S,M}(x,z) + 10\log_{10}\overline{\sigma_M}\ \mathrm{dB}\,, \tag{9}$$

where $\overline{\sigma_M}$ is (following Ainslie et al. 2020a):

$$\overline{\sigma_M} \approx \frac{14(k_M d)^2 + 2(k_M d)^4}{14 + 2(k_M d)^2 + (k_M d)^4}\ , \tag{10}$$

where d is the source depth and

$$k_M = \frac{2\,\pi f_M}{c}\ . \tag{11}$$

The aSL is the dipole source level evaluated at a grazing angle of 30°.

TP XXXXXX

MMP3 April to June 2021 Field Trial and System Design Report

JASCO Applied Sciences (Canada) Ltd

3 March 2022

Prepared for:

Abigail Fyfe
Innovation Centre of Transport Canada
Contract T8009-190191/003/XLV

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P001556-003
Document 02472
Version 1.0

NOTICES

Suggested citation:

Martin, S.B., P. Borys, C. Robinson, J.P. Sharman, and J.J.-Y. Delarue. 2022. MMP3 April to June 2021 Field Trial and System Design Report. Document 02472, Version 1.0. Technical report by JASCO Applied Sciences for Innovation Centre of Transport Canada.

This report reflects the views of the JASCO Applied Sciences and not necessarily those of the Innovation Centre of Transport Canada.

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The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP XXXXX	2. Project No. P001556-003	3. Recipient's Catalogue No.

4. Title and Subtitle MMP3 April to June 2021 Field Trial and System Design Report	5. Publication Date Aug 2021
	6. Performing Organization Document No. 02472
7. Author(s) S. Bruce Martin, Pablo Borys, Calder L. Robinson, Joe P. Sharman, Julien J.-Y. Delarue	8. Transport Canada File No. XXXX
9. Performing Organization Name and Address JASCO Applied Sciences (Canada) Ltd. 32 Troop Ave, Suite 202 Dartmouth, NS, B3B 1Z1, Canada	10. PWGSC File No. XXXX
	11. PWGSC or Transport Canada Contract No.
12. Sponsoring Agency Name and Address Transport Canada, Innovation Centre	13. Type of Publication and Period Covered
	14. Project Officer XXXX

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This is the Baseline Trials and System Design Report for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. The Baseline Trial occurred April to June 2021 and involved installing a cavitation monitoring system (CMS), including three pressure transducers and one accelerometer on *M/V Ferbec*, operated by Canada Steamship Lines (CSL), in the Saint Lawrence Seaway. A vertical array of three hydrophones was simultaneously moored to the seabed near shipping lanes used by *Ferbec.* On-vessel and in-water data were collected during six passages of *Ferbec* to compare underwater sound levels to on-board measured cavitation levels. Hydrophone data and data from three of four of sensors on *Ferbec*, were successfully recorded and retrieved. CMS sensor data showed *Ferbec* developing cavitation by 9–10 kn and fully cavitating at 13 kn. Underwater noise data showed noise levels increased by ~15 dB at 9 kn and an additional 6–8 dB at 13 kn. Results were used to develop a cavitation detection algorithm that will be integrated into hardware for the Operational Trial on *Ferbec*, displaying real-time CMS results on the vessel's bridge. Results will be used to assess the utility of a CMS.

17. Key Words Cavitation monitoring, underwater noise, marine mammal protection	18. Distribution Statement Limited number of copies available from the Innovation Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xiii, 34, apps	23. Price Shipping/ Handling

CI/IC 79-005
Rev. 96

Transport Canada Transports Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. No de la publication de Transports Canada.
TP XXXXX

2. No de l’étude
P001556-003

3. No de catalogue du destinataire

4. Titre et sous-titre

5. Date de la publication
Aout 2021

6. No de document de l’organisme exécutant
XXXX

7. Auteur(s)
S. Bruce Martin, Pablo Borys, Calder L. Robinson, Joe P. Sharman, Julien J.-Y. Delarue

8. No de dossier-Transports Canada
XXXX

9. Nom et adresse de l’organisme exécutant
JASCO Applied Sciences (Canada) Ltd.
32 Troop Ave, Suite 202
Dartmouth, NS, B3B 1Z1, Canada

10. No de dossier-TPSGC
XXXX

11. No de contrat-TPSGC ou Transports Canada

12. Nom et adresse de l’organisme parrain
Transport Canada, Innovation Centre

13. Genre de publication et période visée

14. Agent de projet
XXXX

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

17. Mots clés

18. Diffusion
Le Centre de développement des transports dispose d’un nombre limité d’exemplaires.

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)
—

22. Nombre de pages
xiii,

23. Prix
Port et manutent

CI/IC 79-005
Rev. 96

EXECUTIVE SUMMARY

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board cavitation monitoring system (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern, such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA). This project, dubbed MMP3, has three phases: developing the CMS, a Baseline Trial to collect cavitation and noise data, and an Operational Trial to evaluate the utility of a CMS on a working commercial vessel. This report is the Baseline Trials and System Design Report, describing the trial and the cavitation detection algorithm developed from the collected data.

The Baseline Trial occurred from late April to early June 2021. Four sensors were installed on M/V *Ferbec*, a bulker owned by Canada Steamship Lines (CSL). The *Ferbec* transits a regular route carrying iron ore from Harve-Saint-Pierre to Sorel, QC. The sensors on the *Ferbec* measured pressure fluctuations and accelerations at the hull plates above the propeller. It was expected that the pressure and accelerations would change substantially between the cavitating and non-cavitating states. At the same time, a vertical array of hydrophones was moored to the seabed between Matane and Baie Comeau, QC, near the shipping lanes followed by the *Ferbec.* The hydrophones were used to measure underwater sound levels from the *Ferbec* at 7, 9, 11, and 13 kn. The onset of cavitation was expected at 8–10 kn.

All hydrophone data were successfully recorded and retrieved, and data from three of four sensors on the *Ferbec* were properly recorded. One pressure sensor failed; however, this did not affect our ability to develop the cavitation detection algorithm.

The pressure and accelerometer data were separated into two situations depending on the direction of navigation, the ship was in ballast, or the ship was loaded. Data analysis demonstrated that when the ship is in ballast, the sensors were not underwater and therefore the cavitation state of the ship can not be determined. When the ship was loaded, the pressure and accelerometer data were highly correlated with the shaft revolution rate and speed through water. The speed through water is considered a more suitable predictor of the cavitation state and was employed in the detection algorithm. The pressure and acceleration values vary exponentially up to 6.5 kn before entering a constant region for higher speeds in which the pressure levels do not change more than 5 dB re 1μPa^2. Analysis of the propeller characteristics indicates that the efficiency is low and leads to a fast spinning probably due to the engine not being to deliver enough torque, all of which results in a heavily cavitating system. Using the analysis of the propeller together with the pressure and acceleration curves as a function of speed through water, the system is expected to always exhibit some level of cavitation and achieve full cavitation at 6.5~7 kn.

The underwater radiated noise level of the *Ferbec* is typical for vessels of its size and type. Noise levels increased by ~15 dB between the low-cavitating state at 4 kn to the fully cavitation state at 7 kn. They increased a further 6–8 dB for speeds higher than 7 kn.

The cavitation algorithm is based on a machine learning technique to produce an alert of the cavitating state of the ship. A Logistic Regression Classification method is trained using the data presented in this report in order to obtain a model that enables the prediction of the cavitating states using live data.

The cavitation detection algorithm will be integrated into the data collection hardware and reinstalled in the *Ferbec* in September 2021 for the Operational Trial, which will occur throughout September, October, and November 2021. The system will analyze the pressure and acceleration data every 10 s and output the current cavitation state to the CSL O2 vessel data management system. This data will be presented to the Captain and Mates as ‘pop-up’ information that they will identify as ‘Useful/Not Useful’. The utility of the CMS will be derived from captain and mate logs of ‘Useful/Not Useful’ as well as interviews with Transport Canada, CSL, and potentially other vessel operators with experience with CMS data.

Further analysis of the data from the Baseline trial will be performed to determine if the accelerometer alone could be used to determine the cavitation state. The in-water hydrophone data will also be further analyzed to determine the monopole source level (MSL) of the *Ferbec*. The final report for this project will be delivered by 31 Mar 2022.

CONTENTS

Appendices

FIGURES

TABLES

GLOSSARY OF ABBREVIATIONS, ACRONYMS, SYMBOLS, AND SPECIAL TERMS

AMAR	Autonomous Multichannel Acoustic Recorder
ANSI	American National Standards Institute
CDA	Cavitation Detection Algorithm
CMS	cavitation monitoring system
CPA	closest point of approach
CSL	Canada Steamship Lines
FFT	fast Fourier transform
HMI	human machine interaction
IMO	International Maritime Organization
LAN	Local Area Network
LTSA	Long-term Spectral Average
MD	Mahalanobis distance
MMP	Marine Mammal Protection
MSL	Monopole Source Level
NMEA	National Marine Electronics Association
PK	peak sound pressure level (zero-to-peak sound pressure level)
PL	propagation loss
PSD	Power Spectral Densities
QA	Quality Assurance
RAM	Range-dependent Acoustic Model
RNL	Radiated Noise Level
RPM	revolutions per minute
SARA	Species at Risk Act
SD	Secure Digital (memory card)
SEL	sound exposure level
SOG	speed over ground
SPL	sound pressure level
STW	speed through water
TC-IC	Canada’s Innovation Centre
URN	Underwater Radiated Noise
VAC	Volts Alternating Current
VLA	vertical line array

1. INTRODUCTION

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board cavitation monitoring system (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modification of operating states in areas of concern, such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA).

Previously, JASCO delivered plans for the Baseline Underwater Radiated Noise (URN) characterization of a trial vessel as well as a full field trial, including designing the prototype CMS to be used in the field trial. A Baseline Trial occurred from late April to early June 2021. Four sensors were deployed on M/V *Ferbec*, a bulker owned by Canada Steamship Lines (CSL). The *Ferbec* transits a regular route between Harve-Saint-Pierre and Sorel, QC. The sensors on the *Ferbec* measured pressure fluctuations and accelerations at the hull plates above the propeller. It was expected that the pressure and accelerations would change substantially between the cavitating and non-cavitating states. At the same time, a vertical array of hydrophones was deployed along the transit route of the *Ferbec* to measure underwater sound levels. The correlation of these on-board and in-water sensors is expected to allow for the prediction of the underwater radiated noise level based on the on-board measurements.

This report is the next project deliverable that documents the details of the Baseline Trials, summarizes the results obtained through analysis of the data, and provides an overview of the full system design and installation process for the CMS used for the Operational trial.

2. METHODS

2.1. Data Collection

2.1.1. In-water Data Collection

JASCO deployed a vertical line array (VLA; Figure 1) consisting of three Autonomous Multichannel Acoustic Recorders Generation 4 (AMAR G4s; manufactured by JASCO) equipped with M36-V35-100 hydrophones (manufactured by GeoSpectrum Technologies Inc). All AMARs were calibrated before deployment and again after retrieval to assess any changes in recorder's sensitivity during the recording period (none observed; see Appendix A). Each AMAR recorded continuously at a sampling rate of 128 kHz, yielding an effective recording bandwidth of 64 kHz.

The VLA was deployed from 28 Apr to 7 Jun 2021 in the St. Lawrence Estuary, approximately 295 m from the centre of the inbound shipping lane at a water depth of approximately 290 m (Figure 2). The 45 ft fishing vessel *L'Anse aux Basques* was used for the deployment operations (Figures 3 and 4). Table 1 lists the latitude and longitude of the deployment location derived via acoustic triangulation. The depth of the top AMAR in the VLA was obtained using a depth logger mounted on the instrument. The mean depth during the deployment was 117.8 m. Depth ranged from 113.4 to 147.2 m (Figure 5). Depth of the middle and bottom AMAR were derived based on the spacing between each instrument in the VLA (see Figure 1 and Table 1).

The vertical array of three hydrophones was designed so that the measurements are as closely compliant with ISO 17208-1 (2019) for the measurement of the radiated noise level (RNL) of a vessel in deep water as possible, in particular regarding the depth of the three hydrophones (Figure 6). Last-minute changes to the cables linking the different AMARs (an addition of fairing to minimize flow noise and improve data quality) resulted in the hydrophones being closer together than is recommended ISO 17208-1 (2019). The effect of the change in spacing on our ability to average the results across hydrophones to eliminate the effects of multipath interference is discussed in Section 5.

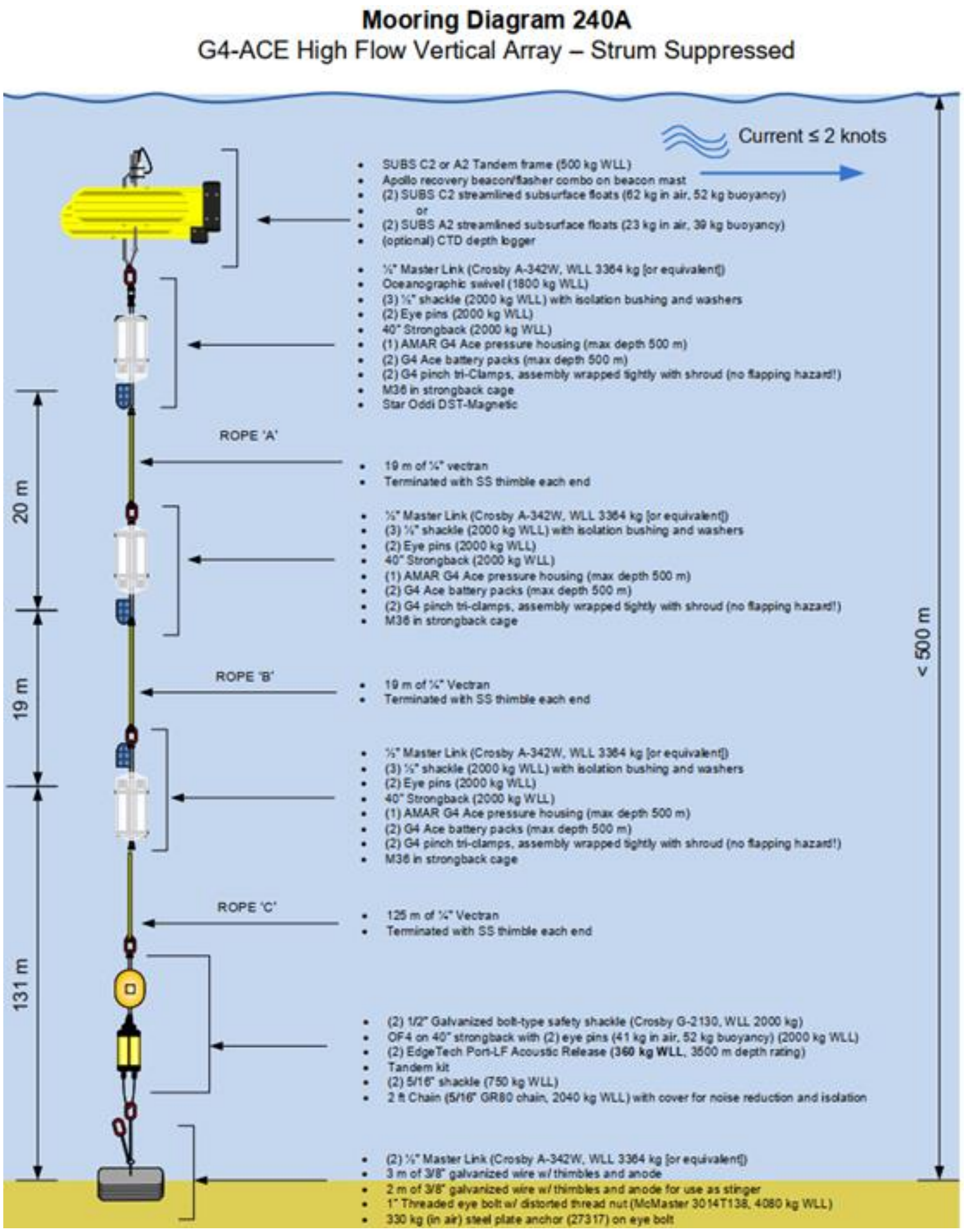


Figure 1. Mooring design diagram for the high-flow vertical line array used.

Table 1. MMP3 mooring location and approximate depth of each Autonomous Multichannel Acoustic Recorder (AMAR).

AMAR	Latitude	Longitude	Depth (m)
Top	48.968871 N	67.967936 W	113
Middle			133
Bottom			152

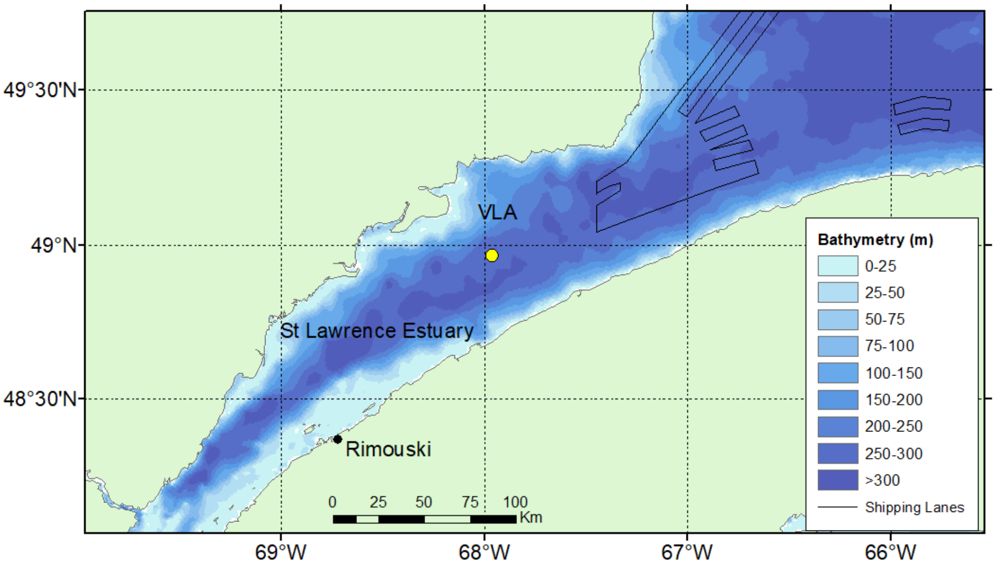


Figure 2. Map of the study area for the MMP3 2021 field trials. The yellow dot shows the location of the vertical line array (VLA) mooring.

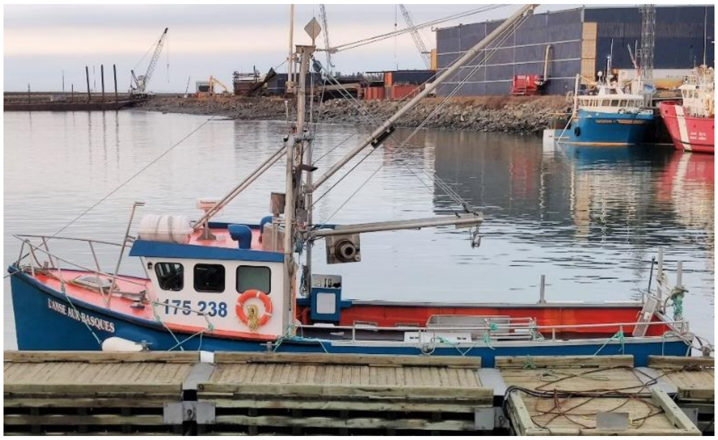


Figure 3. *L'Anse aux Basques*, 45' fishing vessel used for the deployment. Photo by Julien Delarue.

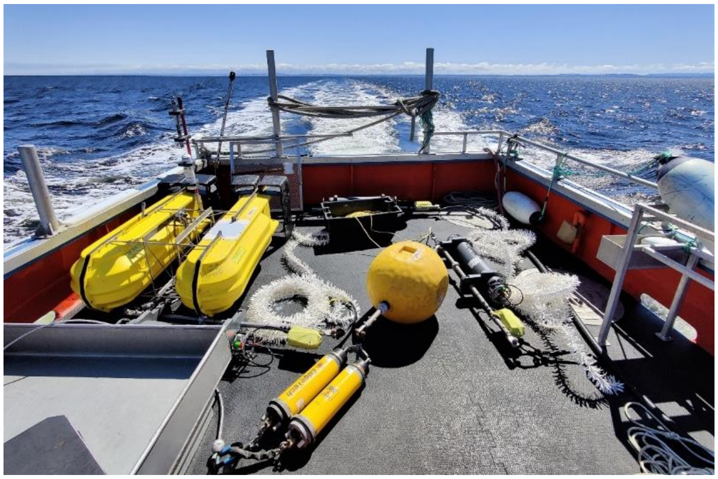


Figure 4. Mooring ready for deployment on the aft deck of *L'Anse aux Basques.* Photo by Julien Delarue.

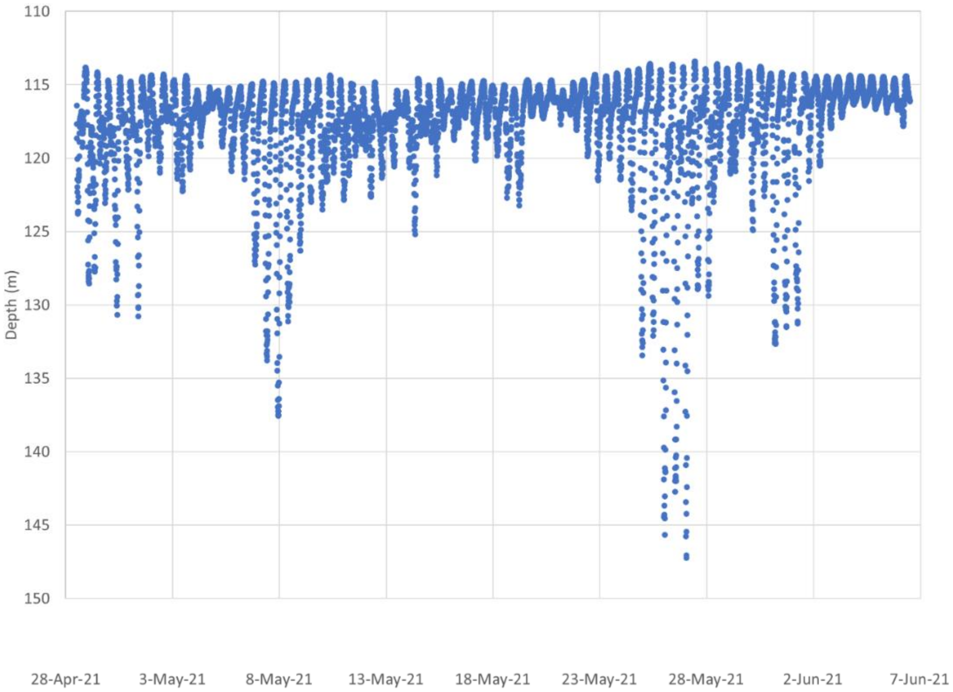


Figure 5. Depth of the top Autonomous Multichannel Acoustic Recorder (AMAR) of the vertical line array as recorded by a depth logger mounted on the unit.

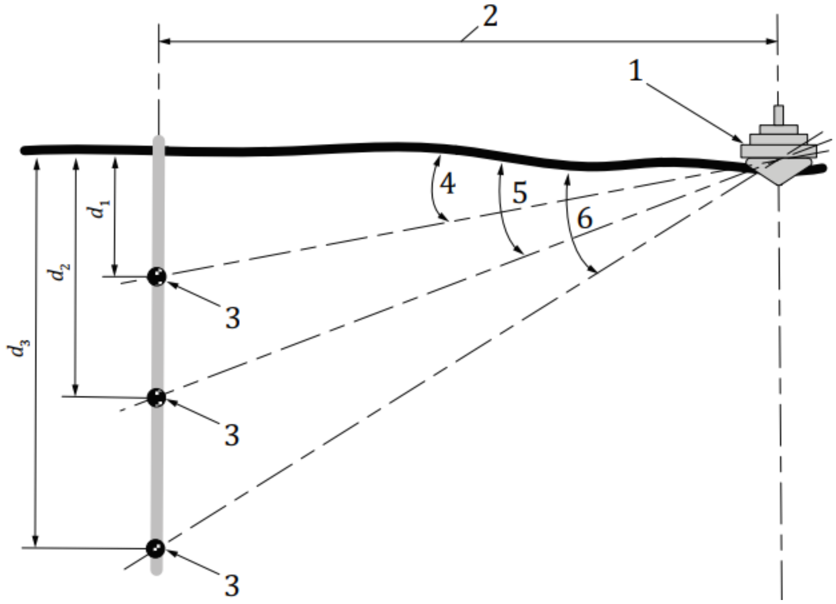


Figure 6. Recommended geometry for measuring underwater radiated noise. (1) The vessel; (2) the closest point of approach (CPA) distance, which should the longer of 100 m or the vessel length; (3) hydrophones; and (4, 5, 6) angles to the hydrophones with target angles of 15, 30, and 45°. The water depth should be greater than the CPA distance or 150 m for this geometry. From ISO Standard 17208-1 (2016).

2.1.2. Data Collection on M/V *Ferbec*

The block diagram of the MMP3 on-board data collection system during the Baseline Trial is shown in Figure 7. Three pressure sensors and an accelerometer (see Section 2.1.3) were mounted on the ship's hull in the aft peak, a space that can be flooded for ballast if necessary. The power/signal cables from each of the sensors were routed to a waterproof box in the same compartment, that also contained the sensor preamps (Figure 8). Locating the pressure sensor preamps near the sensors was necessary to maximize data quality.

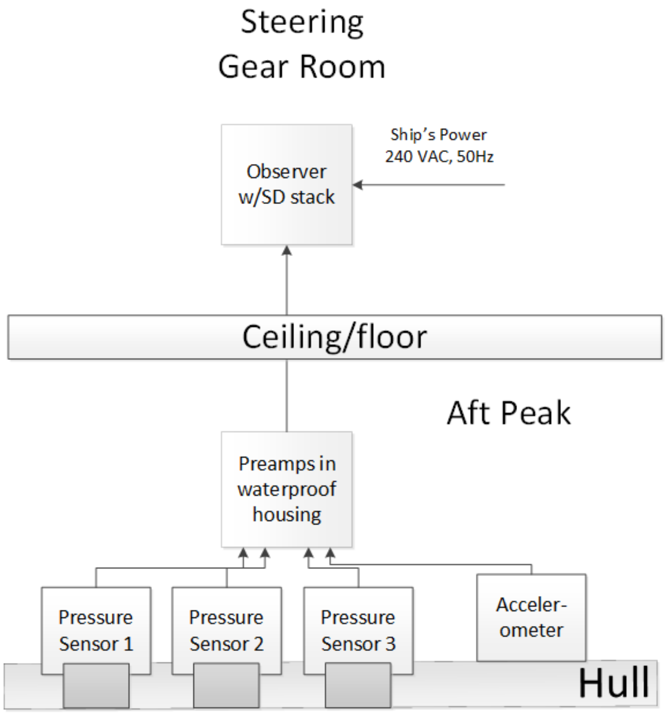


Figure 7. Cavitation monitoring system architecture from the Baseline Trial.

Figure 8. Preamplifier conditioning enclosure located in M/V *Ferbec*'s aft peak. Photo by Art Cole.

A signal/power cable was then run from this wet/dry compartment into the dry steering gear compartment above the aft peak. The CMS electronics (Figure 9), containing a JASCO Observer system and supporting electronics, were mounted in the dry compartment. The Observer sampled all sensors at 8 kHz, which was chosen because the PCB 356B18 accelerometer has an upper frequency limit of 3 kHz and PGMC-A-200KP pressure sensors have an upper limit of 500 Hz.

Figure 9. JASCO Observer enclosure located in the steering gear compartment. Photo by Art Cole.

The Observer was programmed to record all data on Secure Digital (SD) memory cards for the Baseline Trial. The Observer was powered by the ship’s power (240 VAC, 50 Hz), and can connect to the ship’s local area network (LAN) via Wi-Fi, or via a serial interface cable.

2.1.3. Transducers

Three Kyowa PGMC-A-200KP pressure transducers were employed to measure the onset and full amplitude of cavitation. The transducers were installed in the aft peak, which on the *Ferbec* is also a ballast tank. The desired location for the transducers were in the propeller plane starboard of the propeller, on the centreline 1 m behind the propeller (or as near as practical given the aft peak structural limitations), and in the propeller plane 1 m to starboard of the centreline (approximately the red, green, and yellow ‘x’s in Figure 10). To compare sensor performance, a PCB 356B18 accelerometer was intended to be installed with the pressure transducer nearest to the centerline above the propeller (blue cross in Figure 10). Due to the location of the ribs of the *Ferbec*, the exact dimensions locations were not possible, and the best available sites were chosen (see Figure 10 for dimensions). Due to a contractor installation error, the accelerometer was installed at the yellow ‘x’, and two pressure sensors installed at the red and blue symbols in Figure 10. The pressure sensor at the blue ‘+’ did not function properly.

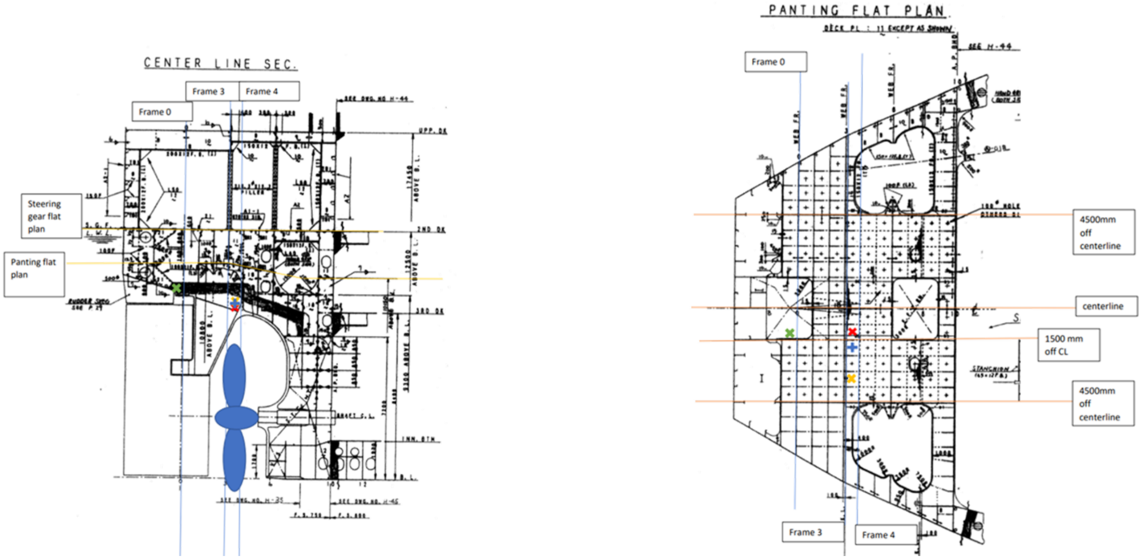


Figure 10. Transducer installation locations on M/V *Ferbec* as part of the Baseline Trial.

The pressure sensors were mounted through the hull of the *Ferbec* to come into contact with the water. This required the *Ferbec* to be in an unballasted condition in port for about a day for the installation of the through-hull components. The through-hull installation was performed by a contractor outside of JASCO and arranged by CSL. The outline of the installation requirements was described in the MMP3 Prototype Cavitation Monitoring System Trials Plan.

Figure 11. Location and installation of the sensors used to measure cavitation. Photos by Mount Royal Walsh installation team.

2.1.4. Passages of M/V *Ferbec* by the Vertical Array

The M/V *Ferbec* sailed past the Vertical Array on six occasions (Table 2), which provided four speeds that could be compared to the on-board measurements: 7, 9, 11, and 13 kn. Cavitation was expected to occur in the 8–10 kn range (speed through water).

Table 2. Passages of the M/V *Ferbec* past the vertical array.

Measurement time (EDT)	Speed through water (kn)	Closest point of approach (CPA) distance (m)	CPA slant distance to upper hydrophone (m)
2021 May 1 19:52	13 (cruising speed)	632	642
2021 May 8 04:52	13.5	571	585
2021 May 13 ~15:04	7	450	465
2021 May 19 17:12	Unknown	1043	1049
2021 May 26 05:18	11	107	162
2021 Jun 1 21:35	9	558	570

2.1.5. Data Provided by CSL

CSL provided JASCO with an export from their O2 data management system that included the following:

- Latitude and Longitude.
- Speed over ground (SOG) and heading.
- Speed through water (STW) and heading.
- Wind speed and direction.
- Shaft revolutions per minute (RPM).
- Forward port draft.
- Aft port draft.

Each variable had its own time base. Variables were updated in the data file whenever there was a significant change to the value.

2.2. Data Analysis: Long-term Recording Sound Level Analysis

Both the on-board and in-water sensors were initially analyzed using JASCO's automated bulk processing tools to find the sound pressure and acceleration levels. The basic unit of analysis is the per-minute power spectral density of the measured data. It is computed by averaging the output 120 fast Fourier transform (FFT), each 1-s long, overlapped by 50%, with a Hann window applied to each data block. This data is then presented as:

1. **Band-level plots**: These strip charts show the averaged received sound levels as a function of time within a given frequency band. We show the total sound level (10 Hz to 64 kHz) and the decade bands for 10–64000, 10–100, 100–1000, 1000–10000, and 10–64 kHz. For the in-water data, the 10–100 Hz band is associated with fin, sei, and blue whales, large shipping vessels, seismic surveys, and mooring noise. The 100–1000 Hz band is generally associated with wind and wave noise, but can include minke, right, and humpback whales, nearby vessels, dynamic positioning sound, and seismic surveys. Sounds above 1000 Hz include humpback whales, pilot whales, dolphin whistles, wind and wave noise, and close-range human sources. For the on-board sources, a band of 1–1000 Hz was employed.
1. **Long-term Spectral Averages (LTSAs)**: These color plots show power spectral density levels as a function of time (*x* axis) and frequency (*y* axis). The LTSAs are excellent summaries of the temporal and frequency variability in the data.
2. **Distribution of decidecade-band sound pressure level (SPL)**: These box-and-whisker plots show the average and extreme sound levels in each decidecade band. The decidecade bands represent the hearing bands of many mammals. They are often used as the bandwidths for expressing the source level of broadband sounds such as shipping and seismic surveys. The distribution of decidecade sound levels can be used as the noise floor for modelling the detection of vessels or marine mammal vocalizations.
3. **Power Spectral Densities (PSDs)**: These plots show the statistical sound levels in 1 Hz frequency bins. These levels can be directly compared to the Wenz curves (NRC Wenz 1962, 2003). We also plot the spectral probability density (Merchant et al. 2013) to assess whether the distribution is multi-modal.

For this project, the objective of the ambient noise analysis depended on the sensors. For the in-water sensors, the results were employed to verify the recording data quality. For the on-board sensors, the per-minute decidecade sound levels were regressed against the vessel speed to determine the relationship with pressure or vibration levels.

2.3. Monopole Source Level and Radiated Noise Level Using ShipSound (To Be Completed)

The source level of a vessel is computed by adding the propagation loss between the vessel and recorder to the measured sound pressure levels. There are two approaches to computing the propagation loss that yield different underwater radiated noise metrics – the radiated noise level (RNL) or the monopole source level (MSL). In both cases the analysis begins by using the vessels GPS track to compute the distance between recorder and vessel at the closest point of approach (CPA) as well as the approximate CPA time. To account for unknowns in the vessel GPS antenna location as well as clock drifts, the acoustic CPA time is then determined from the data, and the distance at CPA is set to the CPA distance derived from the GPS data. In accordance with the ISO 17208-1 standard, the time taken for the vessel to pass through a ±30-degree arc is the window that is averaged to determine the received sound pressure level. For this analysis we set that duration to 1 min.

The RNL is equal to the measured sound pressure level back-propagated from the measuring device to the acoustic source using the spherical spreading law:

$$\mathrm{PL} = 20\log_{10} R, \tag{1}$$

where $R = s/r_0$ is the ratio of the *slant range* s between the source and the recorder and the reference distance $r_0 = 1\ \mathrm{m}$.

The RNL therefore does not account for reflections off the sea surface and the bottom, which can have a significant effect, particularly at lower frequencies and in shallow waters. These reflections are considered when computing the MSL. By not including the surface reflections, the RNL at different depths may have constructive and destructive interference patterns (i.e., Lloyd’s mirror) which affects the RNL. To reduce this effect the ISO standards recommend averaging over three hydrophones, which has been done here (Figure 1).

3. RESULTS

3.1. On Board Measurements

3.1.1. M/V *Ferbec* Transits

The *Ferbec* is a bulk carrier delivering iron ore between Sorel (south) and Havre-Saint-Pierre (north), Quebec (Figure 12). An average journey takes approximately 40 h with some time spent on either end to transfer cargo. The Havre-Saint-Pierre to Sorel transits pass closer to the mooring, and are the passes considered in this report. Figure 13 provides an example breakdown of the transit between 7 May 2021 15:50:05 UTC and 9 May 2021 11:00:06 UTC through time, while Figure 14 is a collection of histograms offering insight to the amount of time spent in different transit states.

At a standard through water cruising speed between 13 and 14 kn, there are two distinct main shaft RPM regimes, 90–92 and 95–96 RPMs, respectively. Speed over Ground (SOG) and Speed through Water (STW) are generally similar in the first half of the transit. In the second half of the transit as the vessel enters the more constrained region of the Saint Lawrence, the SOG is reduced while the STW remains the same as the vessel moves against the increasing current. On either end of the transit is an acceleration and deceleration period lasting between 45 min and 1 h. During the main portion of transit, and as it passes the mooring, the *Ferbec* STW remains relatively constant, save for when it changes course. An example of temporary speed reduction is visible on 8 May 2021 15:00:00 UTC.

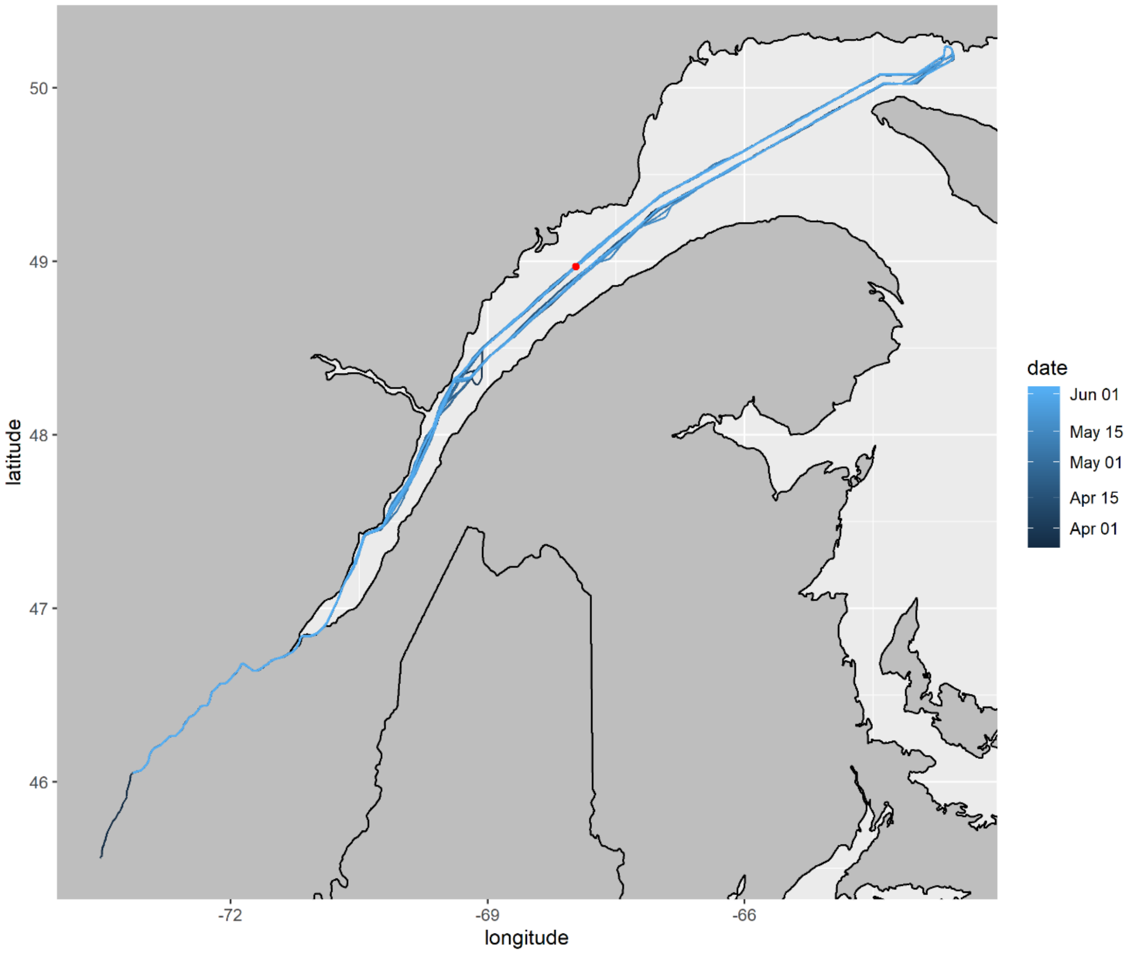


Figure 12. M/V *Ferbec* shipping route between Sorel (south) and Havre-Saint-Pierre (north), QC.

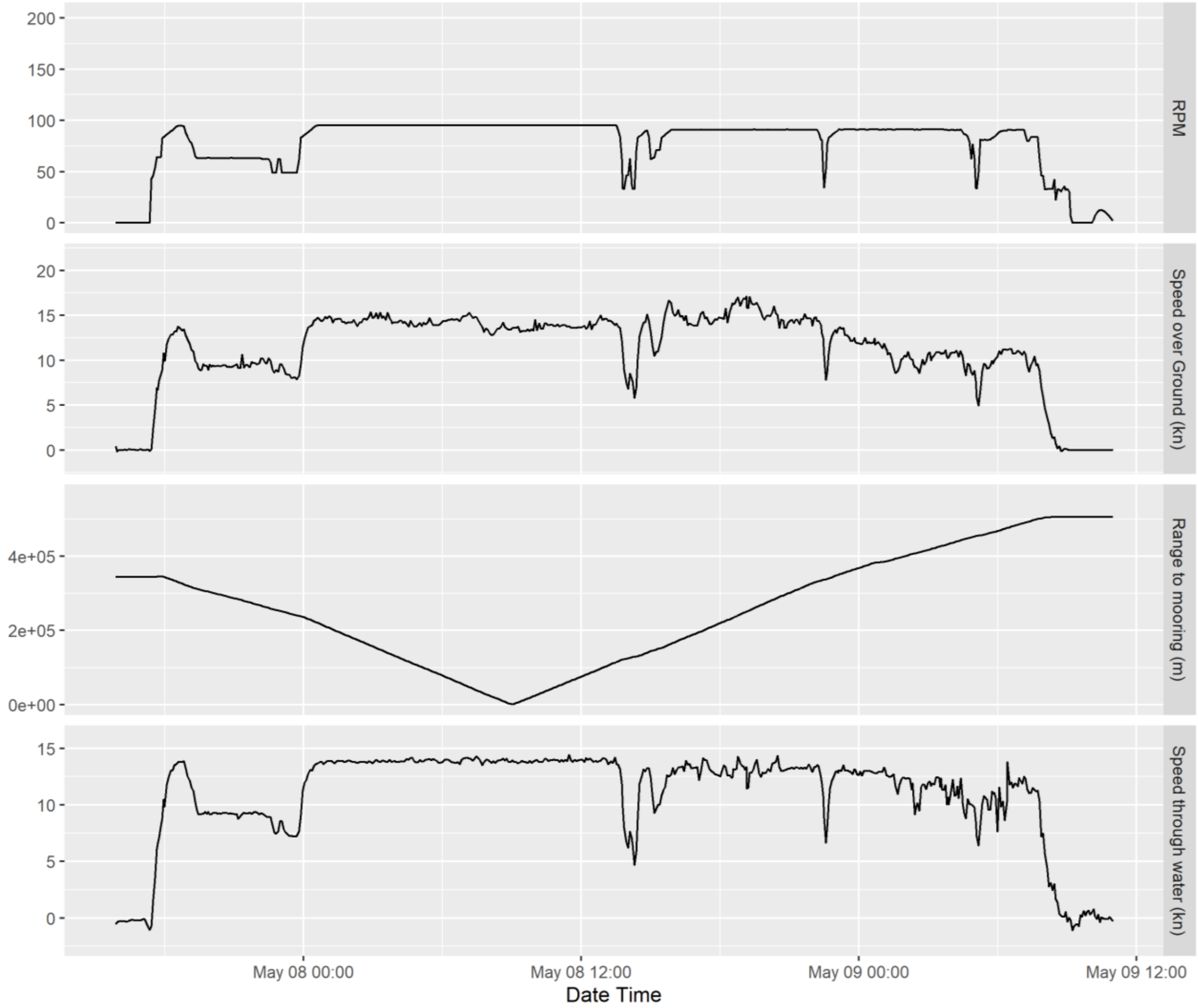


Figure 13. Engineering metrics M/V *Ferbec* during transit from Havre-Saint-Pierre to Sorel, QC, including main shaft RPM, speed over ground, range to mooring, and speed through water between 7 May 2021 15:50:05 UTC and 9 May 2021 11:00:06 UTC.

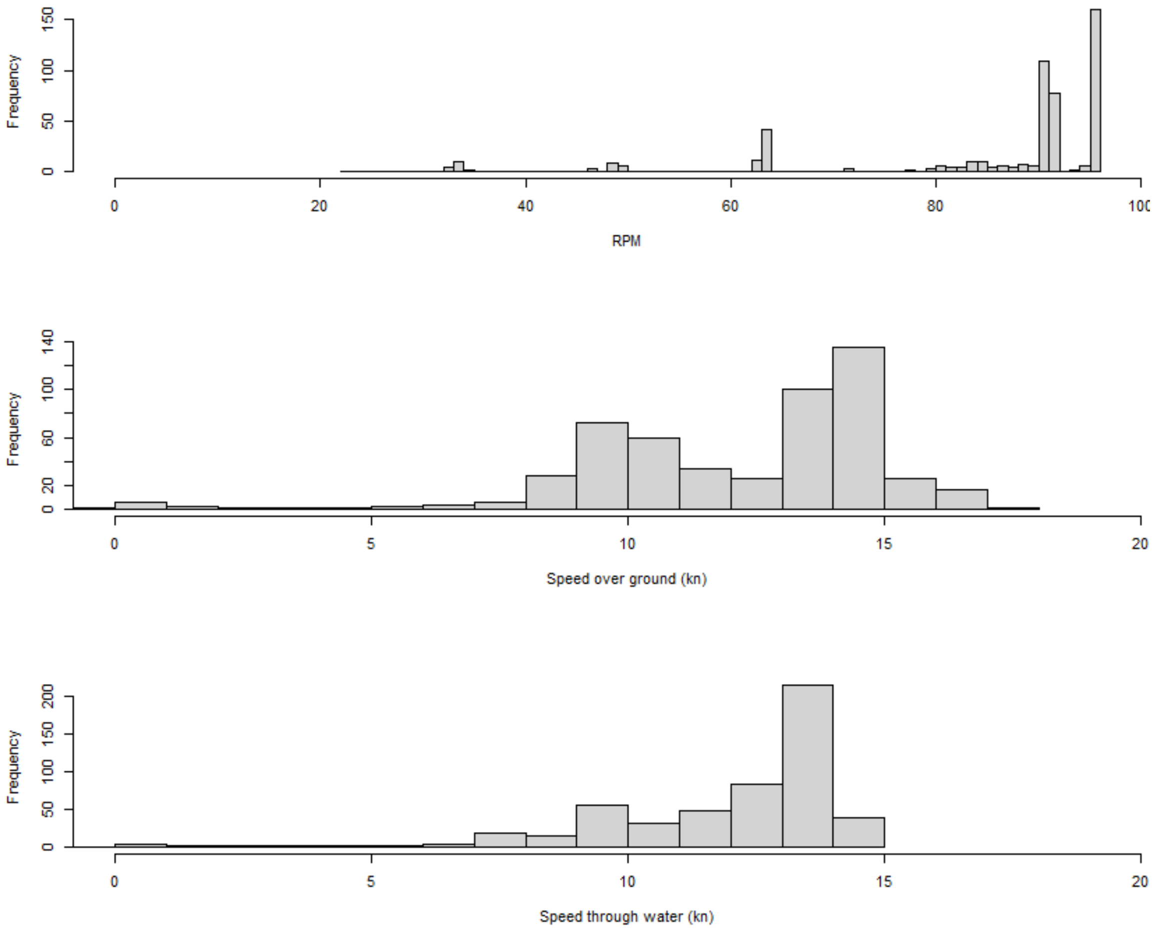


Figure 14. Histograms of vessel recorded metrics during the 7 May 2021 15:50:05 UTC to 9 May 2021 11:00:06 UTC transit. (Top) main shaft RPM, (middle) vessel speed over ground in knots, and (bottom) vessel speed through water.

Figures 15 and 16 represent the time and frequency components of the onboard pressure and y-axis accelerometers, respectively, for the passage 7–9 May 2021 discussed above. There are three dominant regimes highlighted by annotations describing different cruising speeds as well as a deceleration event. The frequency bands show very good correlation with the engineering metrics presented in Figure 13 suggesting that pressure and hull vibration are useful descriptive metrics of the vessel speed, shaft RPM, and ultimately cavitation on the screw.

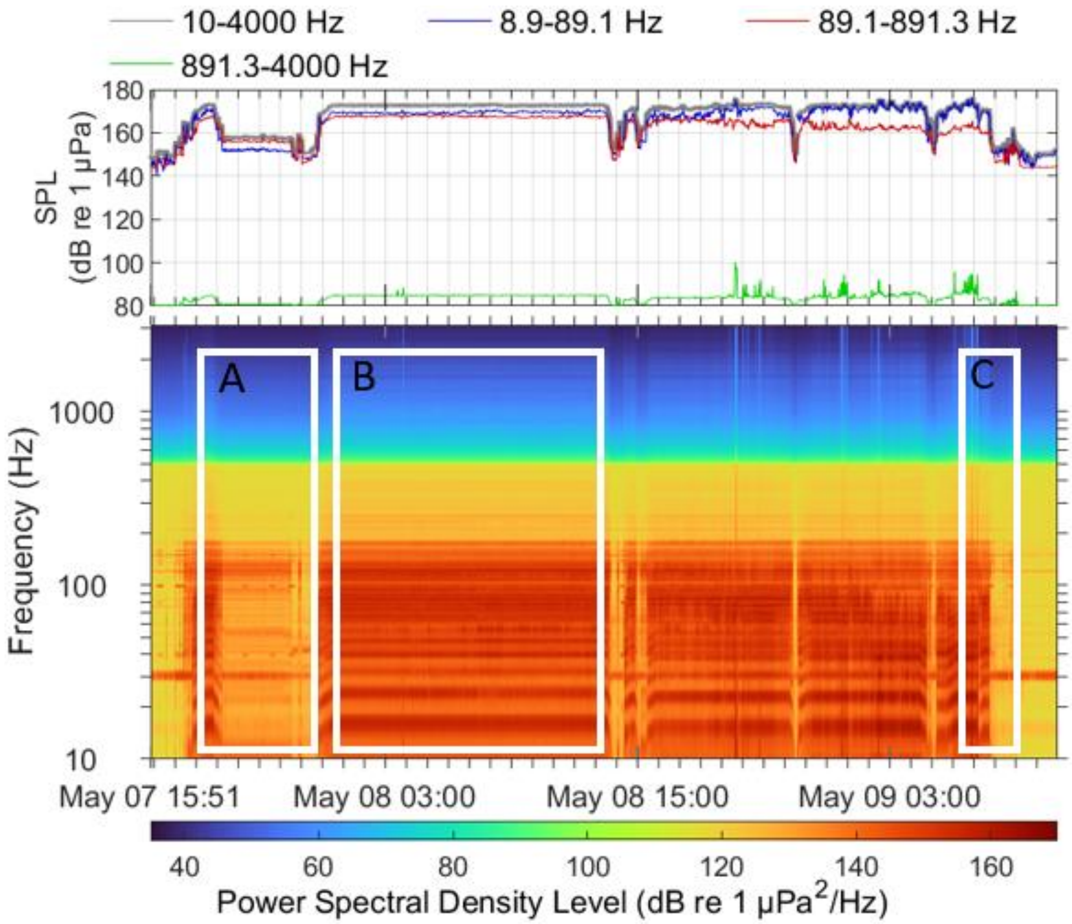


Figure 15. Onboard recorded pressure (Chanel A2) during the transit on 7 May 2021 15:50:05 UTC to 9 May 2021 11:00:06 UTC. Annotations represent A) lower cruising speed of approximately between 8 and 9 kn, B) higher cruising speed between 13 and 14 kn, and C) deceleration at the termination of transit.

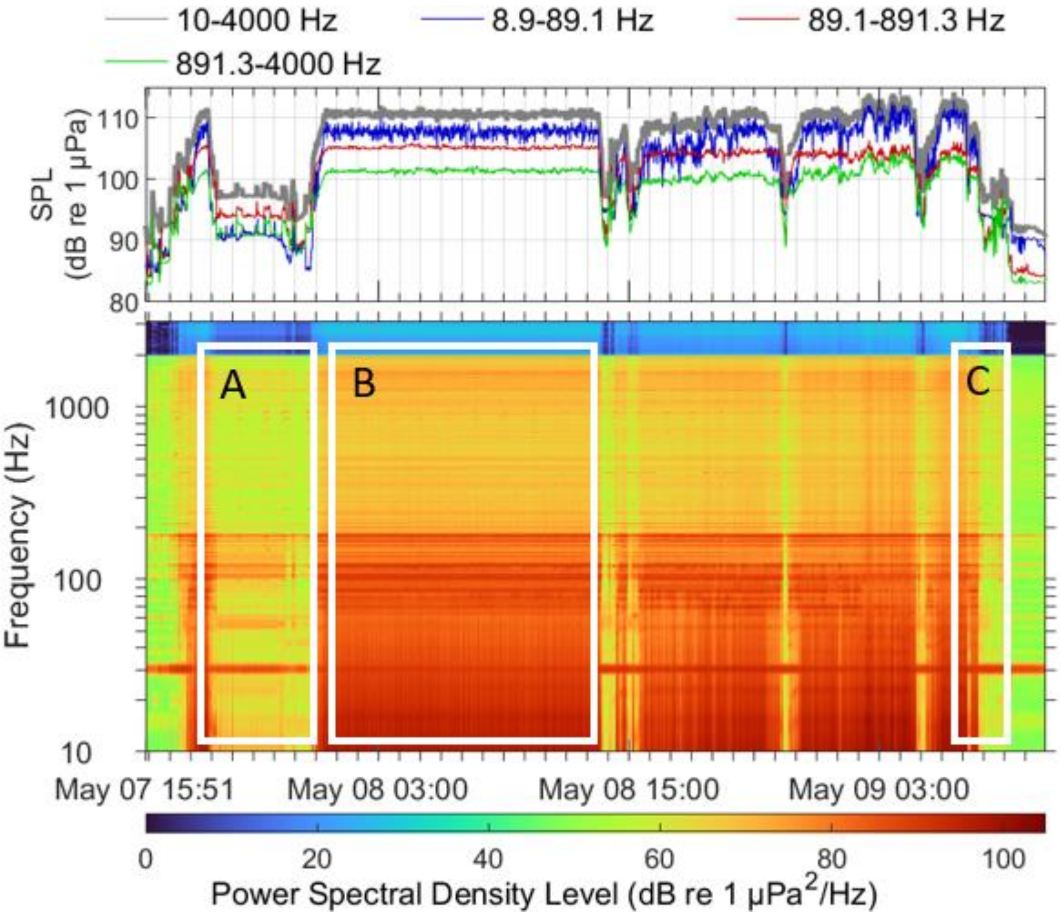


Figure 16. Onboard recorded y-axis acceleration from the accelerometer Z-axis for the duration of the transit on 7 May 2021 15:50:05 UTC to 9 May 2021 11:00:06 UTC. Annotations represent A) lower cruising speed of approximately between 8 and 9 kn, B) higher cruising speed between 13 and 14 kn, and C) deceleration at the termination of transit.

3.1.2. Speed Through Water Versus On-Board Measurements

Data from the three pressure sensors (Channels 1–3) and the accelerometer (Channels 5–7, three coordinates) were used to calculate the corresponding levels as $10\,log_{10}(X_T)$ with $X_t = \frac{1}{T_0 p_0^2}\int^T x^2(t)dt$ where *x(t)* is the pressure or acceleration data, T_0 is 1 sec, and p_0 is $1\mu\mathrm{Pa}$ or 1 μm/s², depending on the sensor. To gain more insight, data were analyzed in the frequency domain and summed over frequency so that the resulting levels are given for each decidecade-band. For the pressure sensors, decidecades in the frequency band from 1–500 Hz and for the accelerometer 1–2000 Hz were analyzed. Based on the recorded data and further analysis, Channel 3, corresponding to one of the pressure sensors, had a malfunction.

As described in Sections 2.1.5 and 3.1.1, CSL provided the speed through water (STW) and the RPM of the vessel’s shaft. Importantly, the CSL logs also provides information about the sailing direction of the ship, allowing to account for the effect of the ship being in ballast or not on the data analysis. The STW and RPM data are grouped into two situations based on the direction: *in-ballast* or *loaded*. It is possible then to match the dates and times of the calculated levels with the STW to determine the levels as a function of speed. Figures 17 and 18 present data from Channel 1, pressure and Channel 5, X-coordinate in the accelerometer for the loaded and in-ballast situation, respectively. Figures for the rest of the channels can be found in Appendix D.2. The curves are smoothed for an easier inspection by using a rolling average of 1.5 kn and correspond to the median values of the levels for the RMS and five different representative frequencies at each speed where the speed step is 0.5 kn. That the median and not the mean value of the levels is used in the calculation is based on the skewness of the data at each speed.

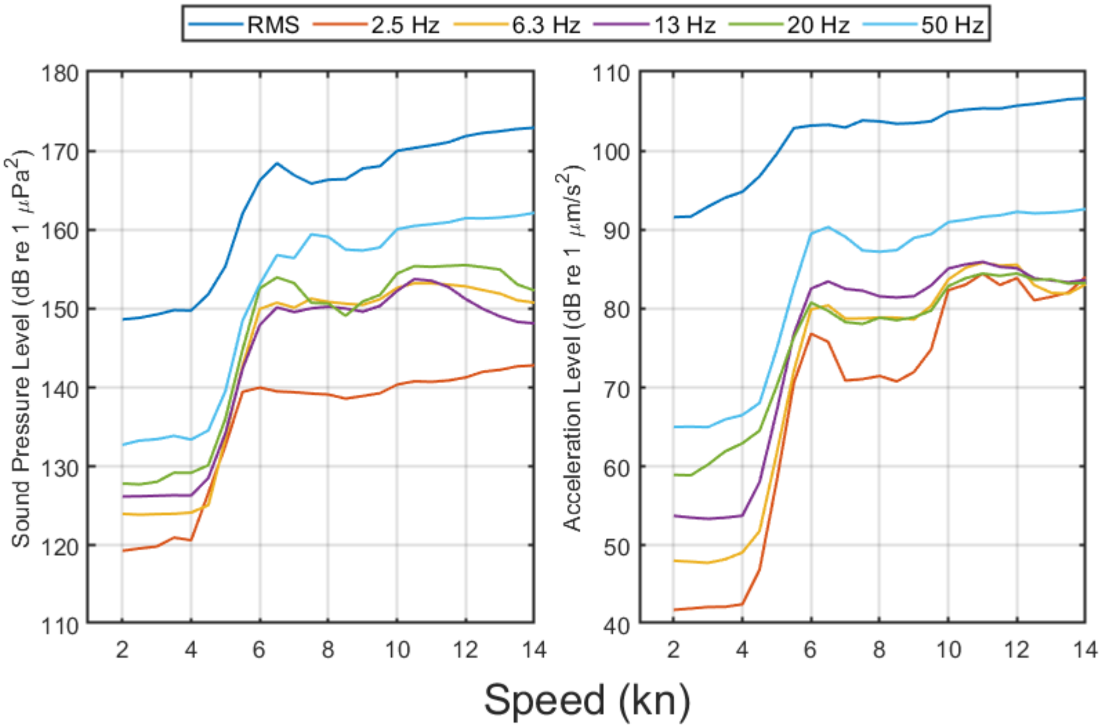


Figure 17. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) for several decidecade bands. The curves present the median values of the calculated levels for the loaded case.

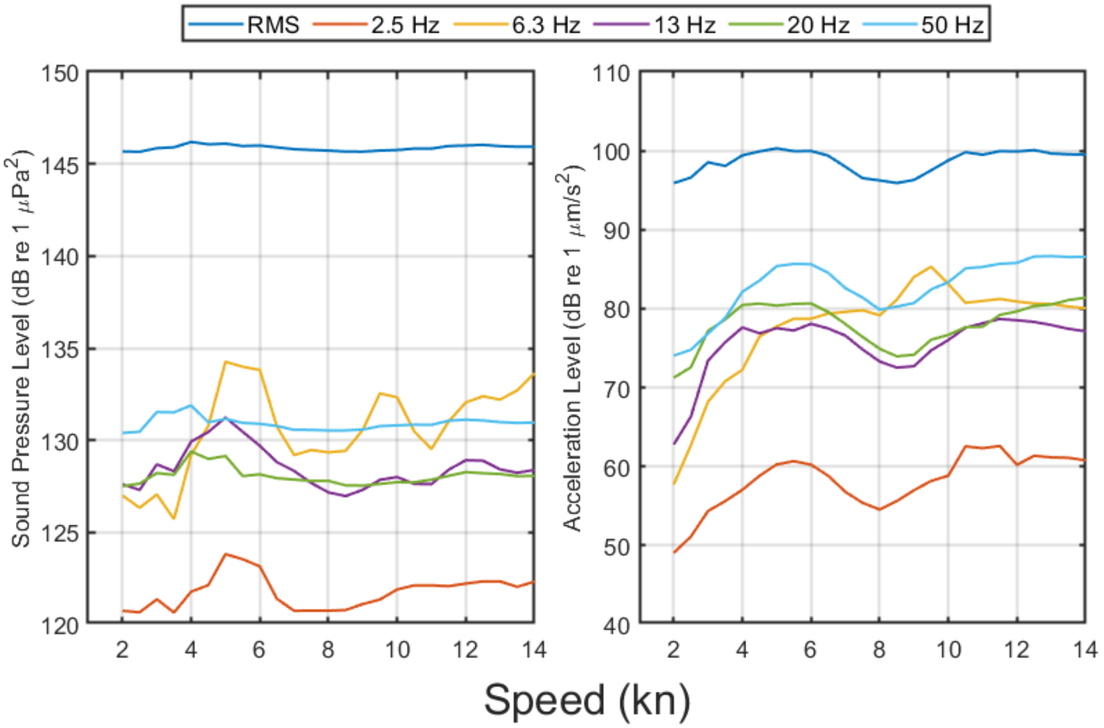


Figure 18. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) of the vessel for several decidecade bands. The curves present the median values of the calculated levels for the in-ballast case.

For the *loaded* scenario: While the overall form of the curves is not identical for pressure and acceleration, both sensors exhibit similar features. There is a region from 2-4 kn in which the levels remain constant, before increasing exponentially. The total change in the pressure levels in the 4-6.5 kn region is 20 dB for the decidecade frequency bands and 18 dB for the RMS level, while for the acceleration channel the change is 35 dB for the lower frequency bands, 25 dB for the higher frequency presented, and 13 dB for the RMS acceleration. This trend continues for higher frequencies (not shown), i.e., levels tend to stay flatter throughout the whole speed range. Finally, for speed values higher than 6.5 kn the levels tend to remain constant, this can be easily observed in the 2.5 Hz decidecade band in the pressure channel and in the RMS level of the acceleration channel.

For the *in-ballast* scenario: The levels of the pressure channel remain almost constant, independent of the STW, with a maximum change of around 5 dB as can be observed in the 20 Hz, 50 Hz, and RMS curves. The acceleration channel exhibits more variation, with a maximum 10 dB change, but not comparable to the loaded situation. These results suggest that the sensors were not underwater while the ship was in ballast. To further verify, a similar analysis is done using the RPM data. First, Figure 19 shows that the STW and the RPM are linearly correlated for both possible situations. This result discards the possibility that a foul hull is responsible for the discrepancy in the levels' rate of change in both scenarios.

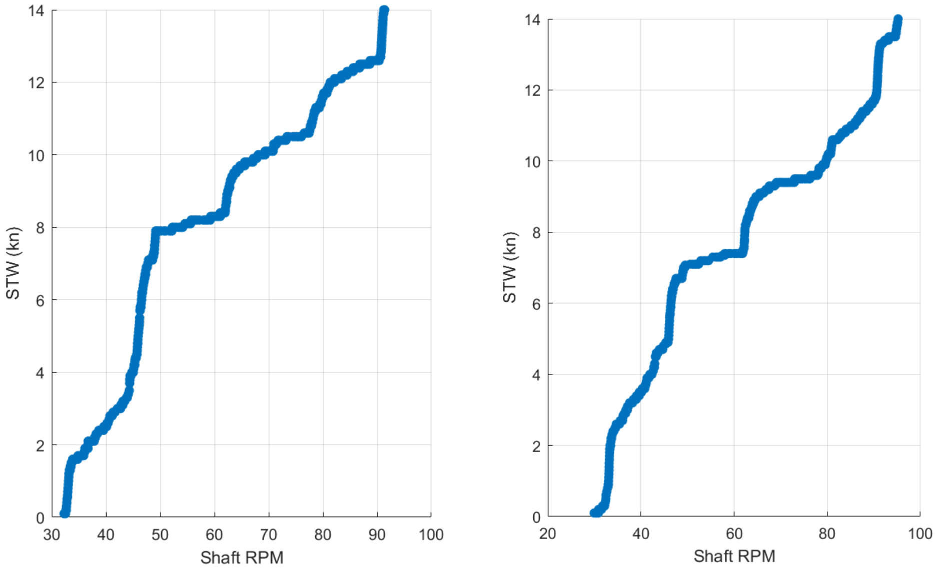


Figure 19. Speed through water (STW) as a function of revolutions per minute (RPM) (Left) in-ballast and (right) the loaded cases.

Figure 20 presents data from Channel 1, pressure, and Channel 5, X-coordinate in the accelerometer when the ship is in ballast. Like the levels vs STW case, the pressure channel remains constant, and the acceleration channel shows less than 10 dB variation.

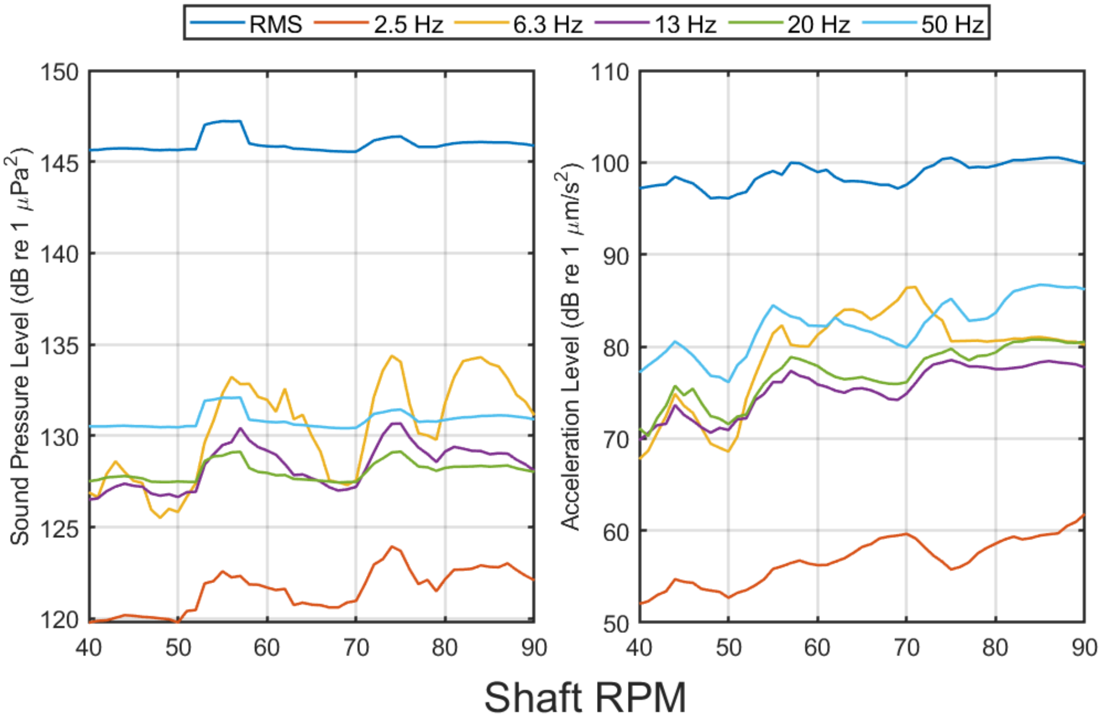


Figure 20. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec*'s revolutions per minute (RPM) for several decidecade bands. The curves present the mean values of the calculated levels for the in-ballast case.

The loaded situation is presented in Figure 21. While the curves are not as smooth as in the STW case, regions are clearly identified. First, from 40-50 RPM there is an increase in the levels that match the 4-6.5 kn region in the STW figure as can be verified in Figure 19. Then from 50-70 RPM the levels stay constant before a change of around 10 dB after which the levels remain constant again. A more rigorous method will be used in Section 4.1 to determine the regions.

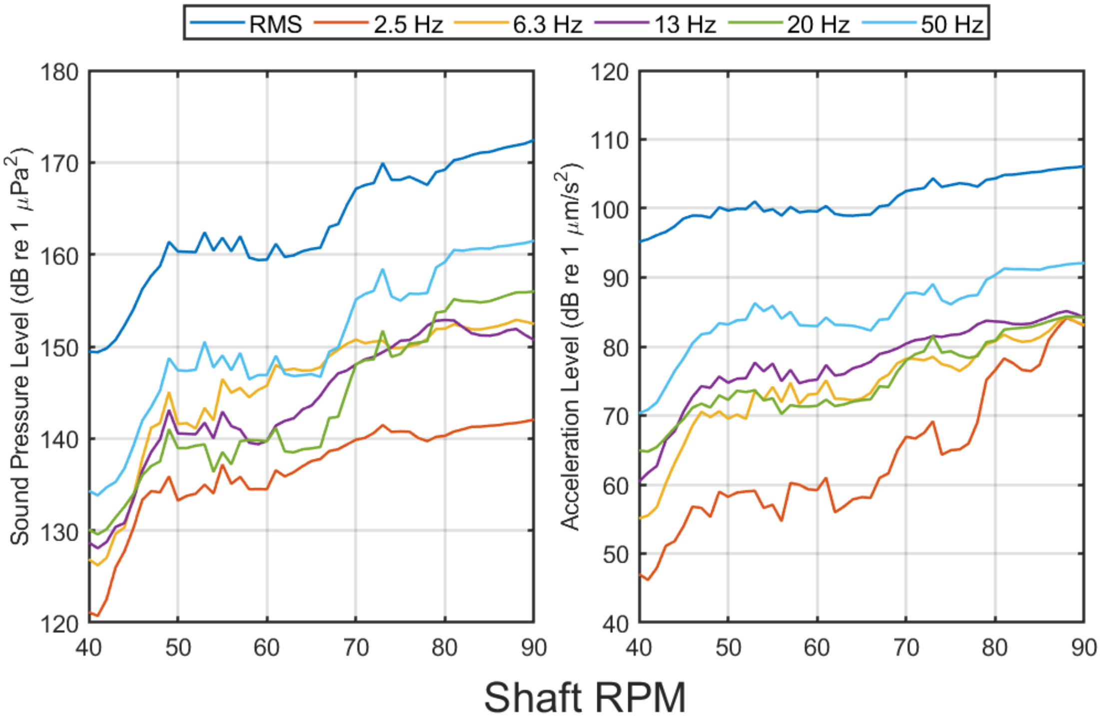


Figure 21. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec*'s revolutions per minute (RPM) for the RMS and several decidecade bands. The curves present the mean values of the calculated levels for the loaded case.

The RPM and the STW analyses demonstrate two main points. One, the sensors were not underwater while the ship was in-ballast. Two, the levels as a function of STW are mores suitable for further analysis. The most significant agreement between the STW and the RPM occur in the 40-50 RPM and the 4-6.5 kn which is also verifiable via Figure 19. The above conclusions will play a key role while developing the cavitation detection algorithm

3.2. In Water Measurements

3.2.1. Vertical Array Data

The vertical array (Figure 1) was deployed and recording between 28 Apr and 6 Jun 2021 and offered complementary measurements to the onboard sensors on the *Ferbec* All figures use data collected from the uppermost hydrophone of the mooring at a nominal depth of 113 m (Figure 5). Long term spectral averages (LTSA) and band level plots (Figure 22) aid in describing and evaluating the soundscapes change in time, while decidecade and percentile plots (Figure 23) allow dominant sources of energy to be identified by frequency. In the recorded soundscape, the dominant source of energy is the passage of ships, including the *Ferbec*, accounting for the peak in levels just below 100 Hz. As this is region is busy with shipping, other ships are identifiable in the LTSA plot as short duration broadband peaks in energy. The CPAs made by the *Ferbec* are highlighted by the red arrows. There are also wind events visible as longer duration broadband sources increasing the spectral energy above 10kHz, as seen around 28 May 2021. In the Percentiles plot, flow noise is attributed to the slight peak in level around 10Hz.

It is also often useful to visualize received levels in higher time resolution to identify the key features of a passing vessel, and get good estimates of Radiated Noise Level (RNL). Figure 24 represents 10 min of received pressure time series and spectrogram at the top hydrophone of the VLA mooring during the CPA of the *Ferbec* on 1 May 2021. Lloyds mirror is visible below 130 Hz, as the vessel pulls away from the mooring. Increasing and subsequent decreasing of broadband noise at CPA is a result of the interaction of frequency dependent attenuation and the vessel transiting through the listening area of the mooring increasing and decreasing the received noise levels.

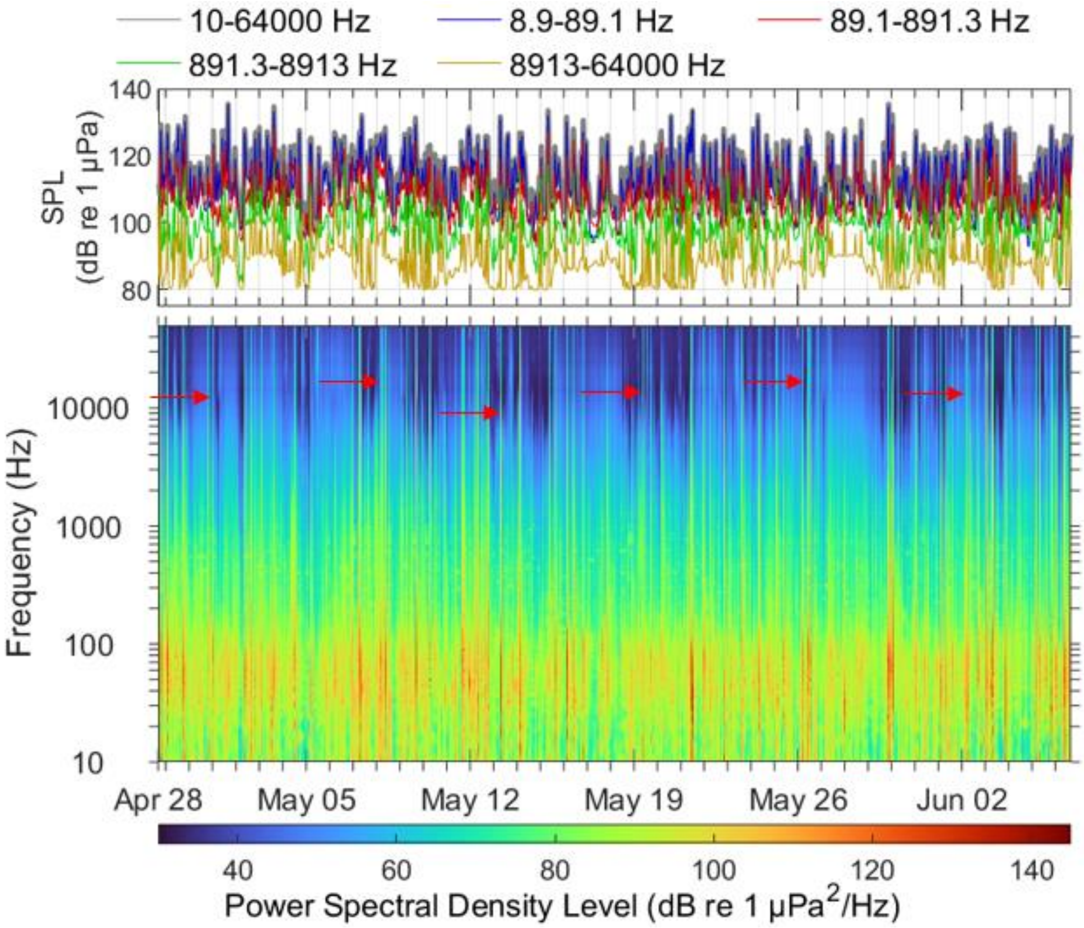


Figure 22.Selected band sound pressure level (SPL) and Long-term Spectral Average (LTSA) over the entire recording period for shallowest hydrophone (128 m). Red arrows highlight increased spectral average as M/V *Ferbec* passes. Other peaks are other vessels, with larger vessels generally accounting for louder signals.

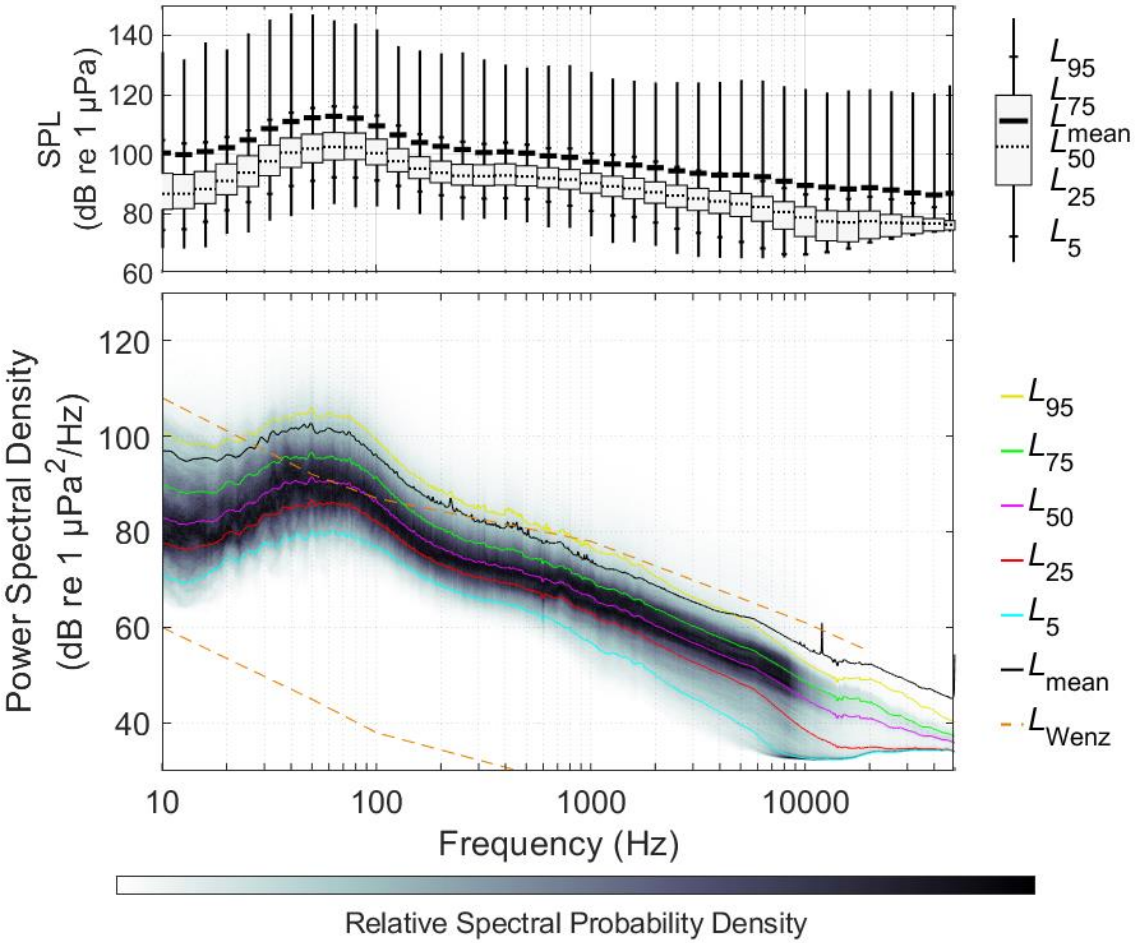


Figure 23. Decidecade boxplots with percentiles and power spectral density percentiles for the shallowest hydrophone on the mooring (128 m).

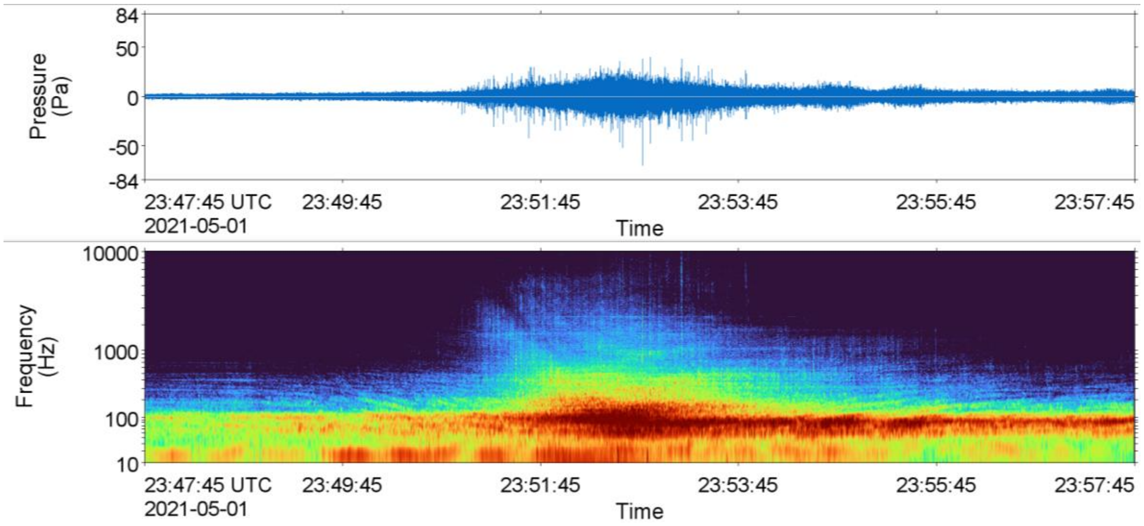


Figure 24. Snapshot of top hydrophone (128 m depth) timeseries and spectrogram of M/V *Ferbec* passing the mooring on 1 May 2021, with a slant range closest point of approach (CPA) of 671 m.

3.2.2. M/V *Ferbec* RNL

The computed RNL for the *Ferbec* are shown for reach passage in Figure 25 through Figure 30, and summarized in Figure 31. At higher speeds (>9 kn), the RNL was above the ambient noise in the 40 or 50 Hz decidecade and higher, with a peak in the 100 and 125 Hz decidecades. The peak frequency was 50 Hz at 7 kn (Figure 27) and 80 Hz at 9 kn (Figure 30). The data for the planned passage at 11 kn (26 May 2021, Figure 29) is anomalous with peaks at multiple times in the data (Figure 32), and a speed from the track of 12.4 kn. This data was removed from further analysis.

The noise levels for the 7 kn data are far below those for the other speeds (Figure 31), however, the analysis of the cavitation pressure and acceleration sensors strongly indicated that the vessel should be fully cavitating by 7 kn. It is suspected that the vessel was idling while transiting at 7 kn rather then being driven by the propeller. Thus, the 7 kn result is likely more representative of the vessel at speeds below 4 kn.

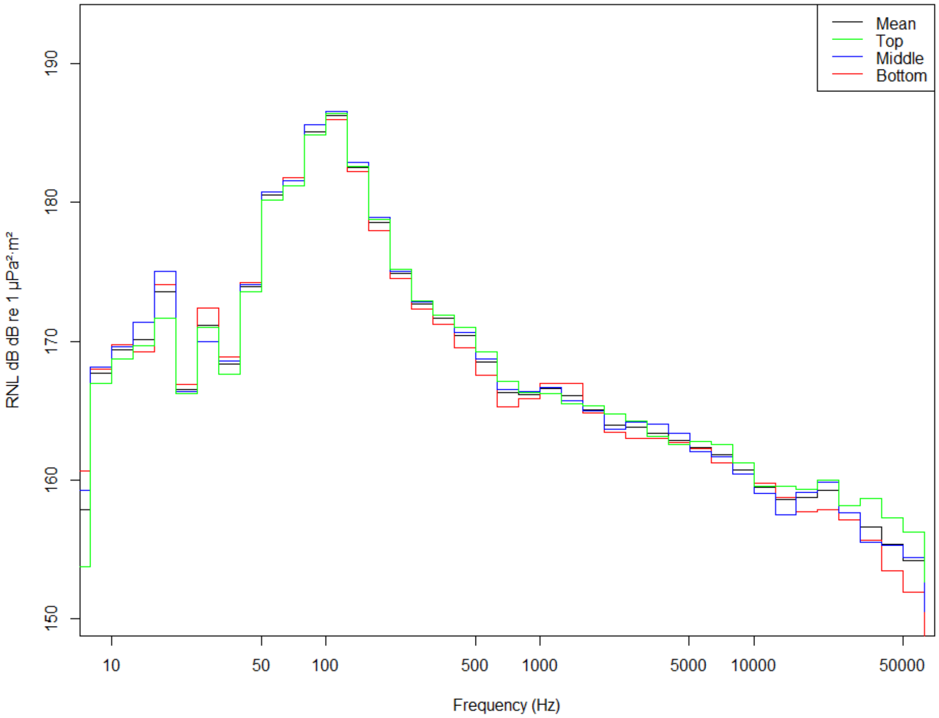


Figure 25. Radiated noise level (RNL) at closest point of approach (CPA) on 1 May 2021 23:52:32 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 13.0 kn at a shaft revolutions per minute (RPM) of 91.3.

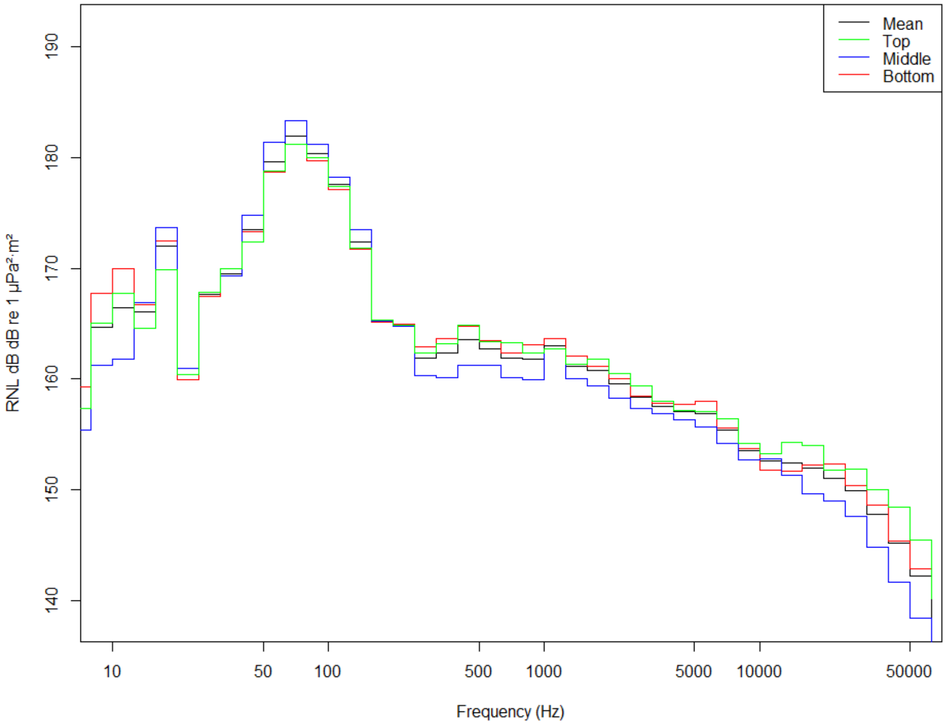


Figure 26. Radiated noise level (RNL) at closest point of approach (CPA) on 8 May 2021 08:59:47 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 13.9 kn at a shaft revolutions per minute (RPM) of 95.4.

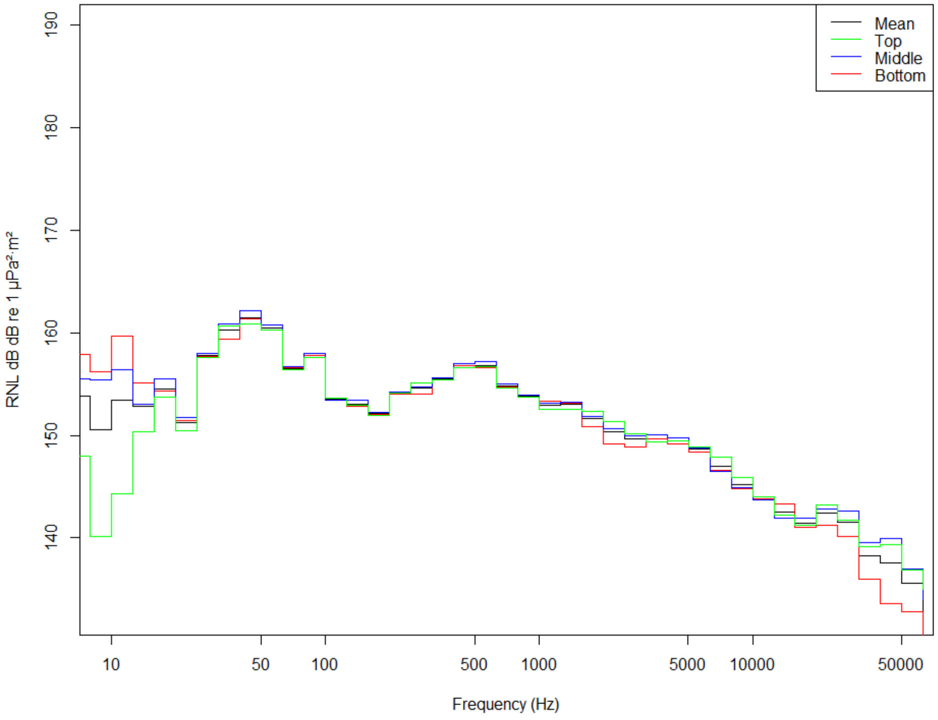


Figure 27. Radiated noise level (RNL) at closest point of approach (CPA) on 13 May 2021 19:09:23 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 7.1 kn at a shaft revolutions per minute (RPM) of 48.

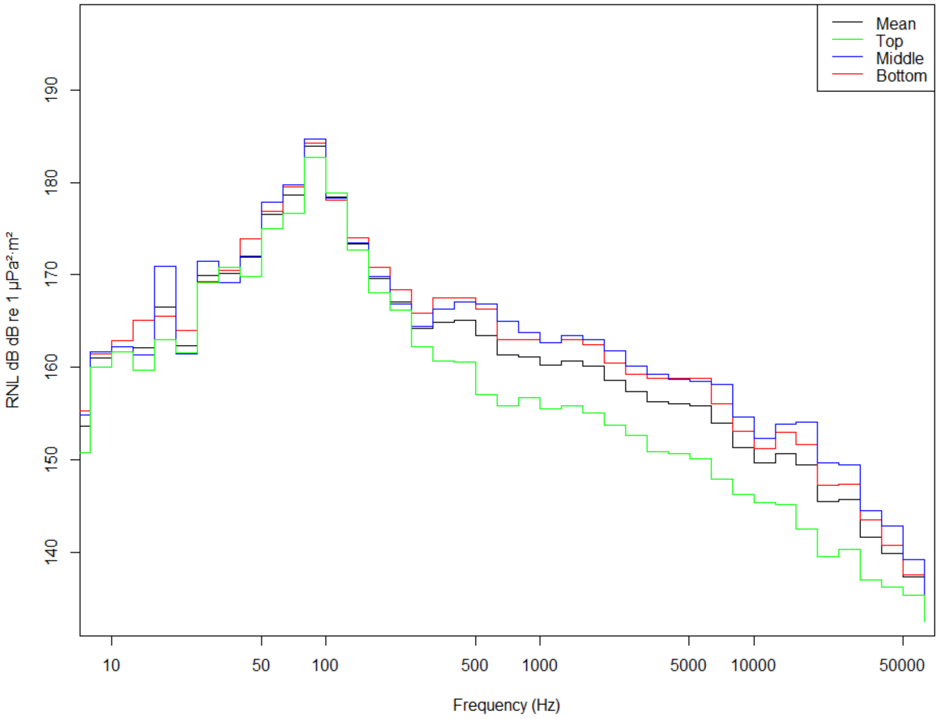


Figure 28. Radiated noise level (RNL) at closest point of approach (CPA) on 19 May 2021 21:15:46 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 13.8 kn at a shaft revolutions per minute (RPM) of 95.

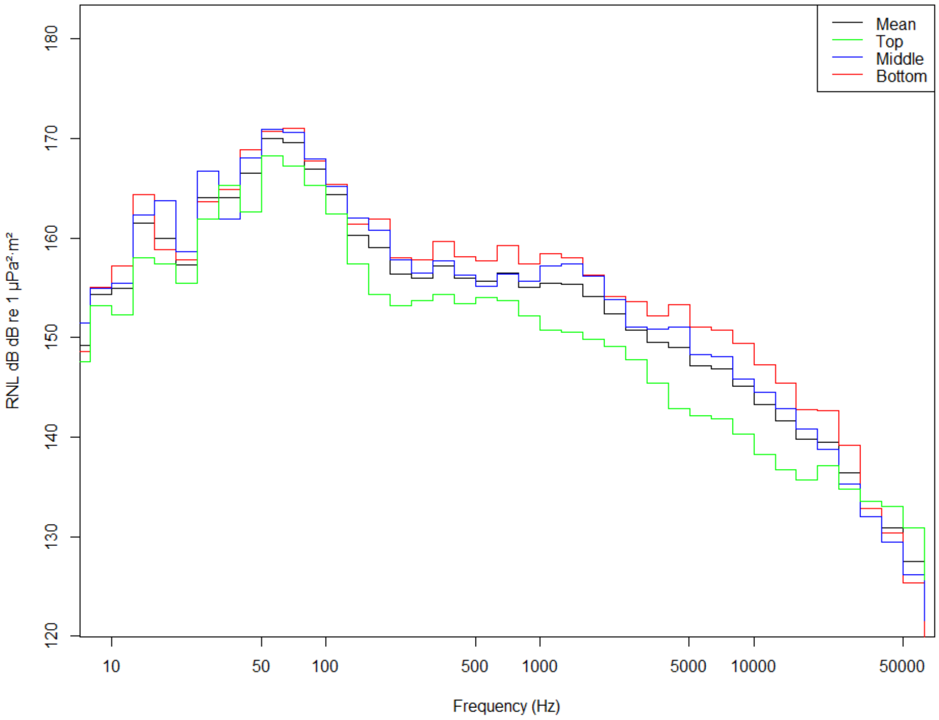


Figure 29. Radiated noise level (RNL) at closest point of approach (CPA) on 26 May 2021 09:16:41 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 12.4 kn at a shaft revolutions per minute (RPM) of 86.

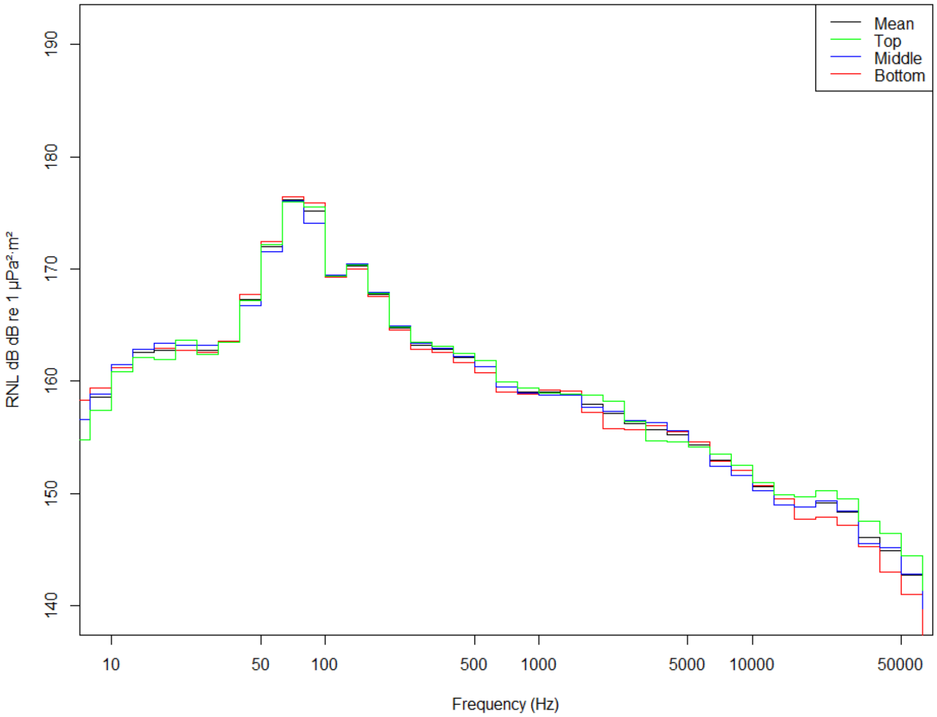


Figure 30. Radiated noise level (RNL) at closest point of approach (CPA) on 2 Jun 2021 01:36:27 UTC, estimated from the three hydrophone locations on the mooring. Cruising speed through water was 9.0 kn at a shaft revolutions per minute (RPM) of 71.5.

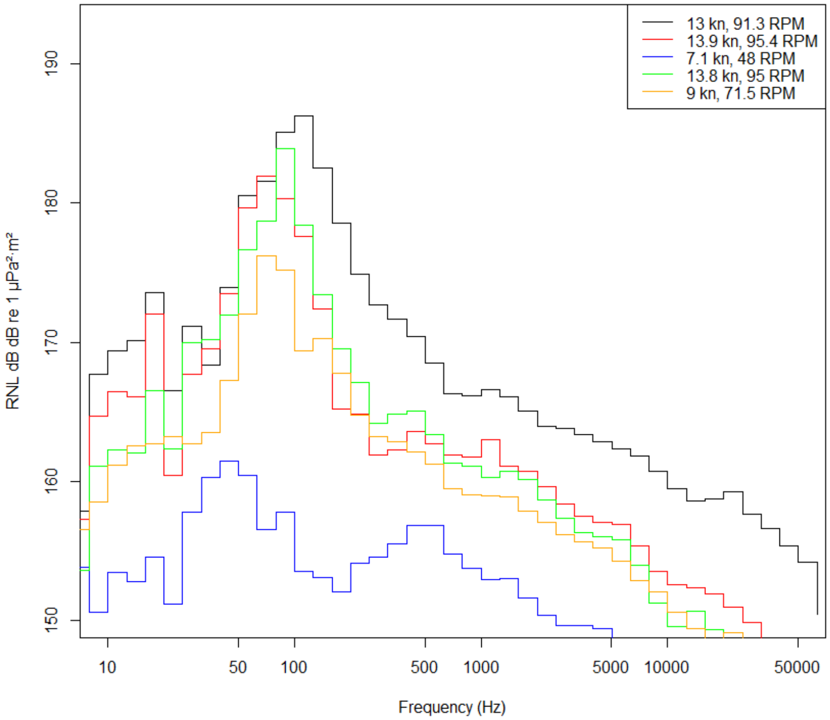


Figure 31. Average radiated noise level (RNL) by vessel speed through water (STW), plot is a composite of the mean values from each transit, visible in the previous figures.

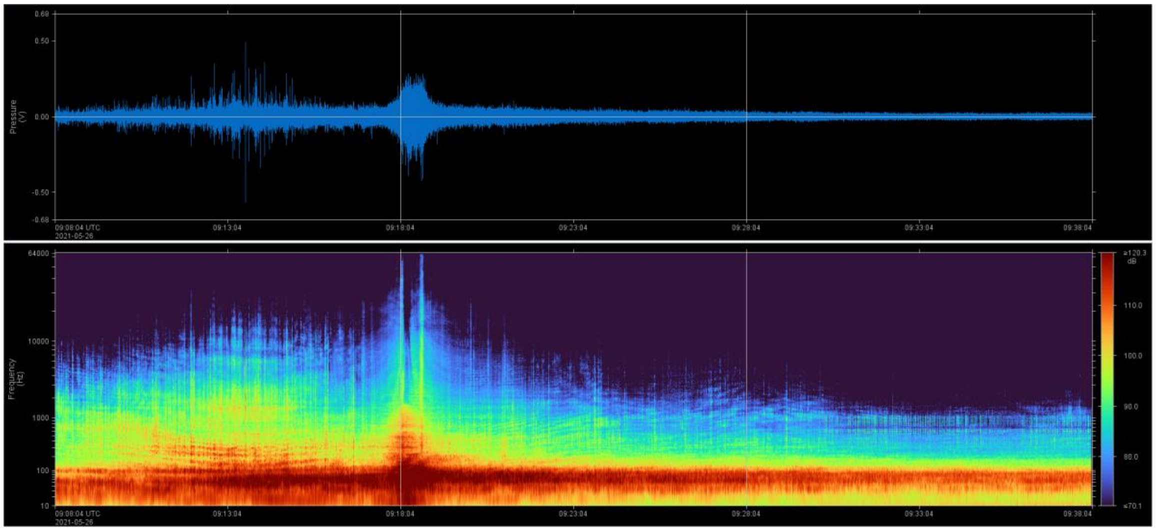


Figure 32. 30 min spectrogram and time series indicating multiple events associated with the passage of M/V *Ferbec* on 26 May 2021.

4. CAVITATION MONITORING SYSTEM DESIGN AND TESTING

4.1. Cavitation Detection Algorithm

The Cavitation Detection Algorithm (CDA) aims to provide the Cavitation Monitoring System with means to alert when the system is in a fully cavitating state. To this end, the CDA uses live data coming from the pressure and accelerometer sensors together with information presented in Figures 17 and 18. Before describing the algorithm and the data pipeline, two pre-processing steps are made. First, the state of the system is classified using a change point function included in the Signal Processing Toolbox of Matlab 2021a that detects changes in mean and slope by comparing signal values with predictions obtained through a least-squares linear fit. Figure 33 presents the calculated changing points for channel 1, pressure, and channel 5, X-coordinate acceleration, using the RMS curve and the 50 Hz decidecade band, respectively. In both curves, the changing point is found at 6.5 kn and agree with what the visual inspection inferred. The same process is repeated for the rest of the available channels. The changing points are the same or very close for both the pressure and acceleration sensors, allowing for a clear classification of the system in either no cavitating or fully cavitating state.

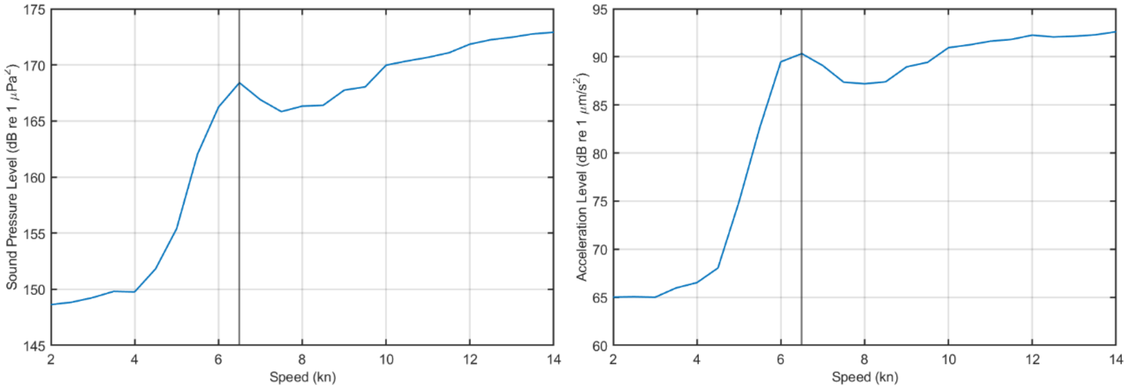


Figure 33. Calculation of the changing points on the pressure and acceleration levels curves as a function of speed through water (STW).

Second, the data presented in this report is used in a machine learning technique to construct a model that can predict the cavitating state with the live data. Figure 34 presents different binary classification methods applied to different combinations of the channels. For example, the first row corresponds to the RMS level of the combination: pressure, channel 1 with pressure channel 2 where the blue dots indicate a fully cavitating state and the red dots a no cavitating state. The first column is the input data fed into the different machine learning techniques: Nearest Neighbors, Linear Support Vector Machine, Radial Basis Function Support Vector Machine, Gaussian Process

Regression, Decision Tree, Random Forest, Neural Network, Adaptive Boosting, Naïve Bayes, Quadratic Classifier, and Logistic Regression whose output is presented in columns 2-12. Within each subplot there is a score that goes from 0-1 with 0 being no accuracy and 1 perfect accuracy. While each classifier has advantages and disadvantages that include faster processing times, better accuracy, and better handling of outliers, in this work a Logistic Regression Classification will be used to determine the cavitating state since it results in a 95% accuracy on the testing dataset, it requires fewer lines of code to be implemented and a lower workload for the hardware.

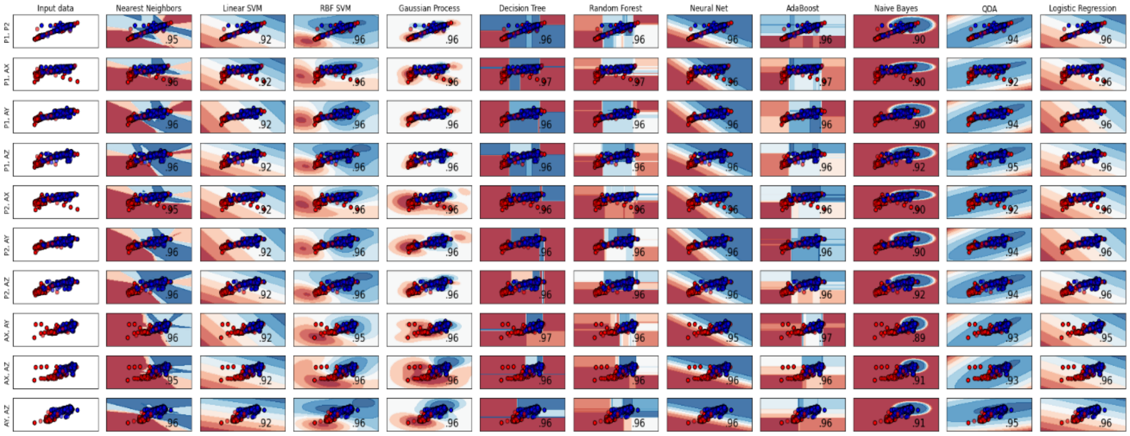


Figure 34. Different machine learning classification techniques applied to different combinations of channels. The first column shows the input data where the blue (red) dots indicate that the system is fully (not) cavitating. The corresponding score of the technique is indicated within each subplot. The rows are different combinations of sensors, which could be P1 or P2, corresponding to pressure channels 1 and 2, or AX, AY or AZ, corresponding to the X, Y and Z accelerometer channels.

Once it was determined that the boundary between cavitating states is at 6.5 kn it was possible to set a binary classification method using several machine learning techniques from which Logistic Regression was chosen, now the algorithm is outlined.

The first step in the algorithm is to verify that level calculated with live data from the pressure sensor is above 147 dB re 1μPa^2 that corresponds to the constant value found when the sensors are not underwater (see Figure 18). If the condition is not fulfilled, the algorithm alerts that it is impossible to determine a cavitation state. If the condition is met, the next step of the CDA occurs: ten seconds of live data from the pressure and acceleration sensors will be used to calculate the levels in dB, similar to what is described in Equation (1). Data points corresponding to one minute, i.e., six SPL points, are stored and outliers are replaced using a linear interpolation. This step does not tamper the data since the levels and hence the developing of the cavitation state are expected to vary smoothly. Then, features are built by pairing the levels from the different channels which are plugged in the Logistic model. The model yields a value of 0 if the system is predicted to be in a no-cavitating state and 1 if it is fully cavitating. The prediction is used in the CMS to produce the corresponding alert.

The classification is performed by considering data from two different channels, the combinations may result in one pressure channel with one acceleration channel or two pressure channels or two acceleration channels. It was expected that by considering as variables two different physical quantities (pressure and acceleration) the robustness of the algorithm would be enhanced, however, the classification score is similar if only acceleration channels are considered (only the score of the combination acceleration X, acceleration Y drops to 95%). This demonstrates the feasibility of only using acceleration sensors which would be less invasive to the hull of the vessel. Finally, it is worth noting that because of the way the levels are calculated, it is irrelevant that the live data points are calculated using 10 s of data while the classification used 1 min of data.

4.2. Cavitation System Architecture

The block diagram for the CMS that will be deployed for the September to November 2021 evaluation is shown in Figure 35. The data collection and analysis hardware will be the same as was employed for the Baseline Trial. For the Operational Trial, the Observer hardware will also be running the cavitation detection algorithm described in Section 4.1. The algorithm will output the cavitation state every 60 s using a National Marine Electronics Association (NMEA) compliant message over an RS-232 serial connection to the CSL O2 data system. The physical interface to the O2 system will be a Moxa junction box located in the engine room.

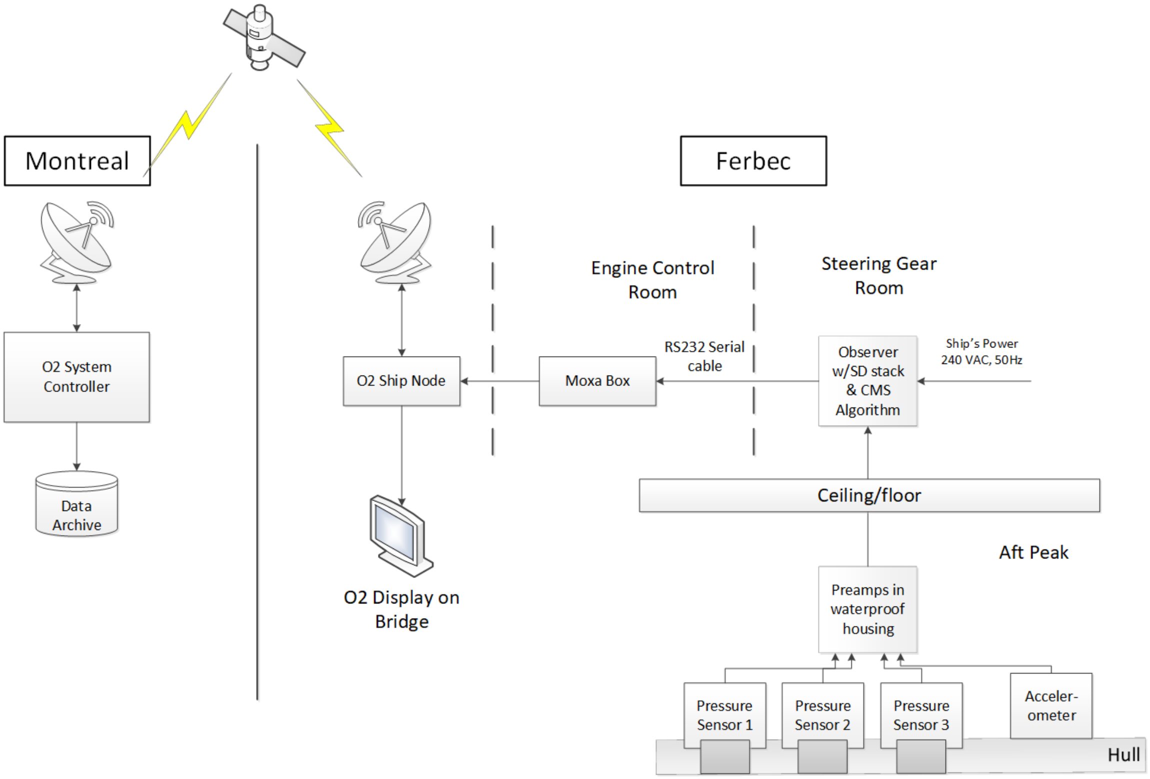


Figure 35. Block diagram for the operational evaluation of the cavitation monitoring system.

The NMEA compliant message has nine data fields and the required checksum field. The nine data fields are: a timestamp, an indication of high/med/low cavitation state, an estimate of the current underwater radiated noise, and the current root means square signal level for each of the sensors as a system health indication. Details of the RS-232 interface and NMEA message string are contained in Appendix A.

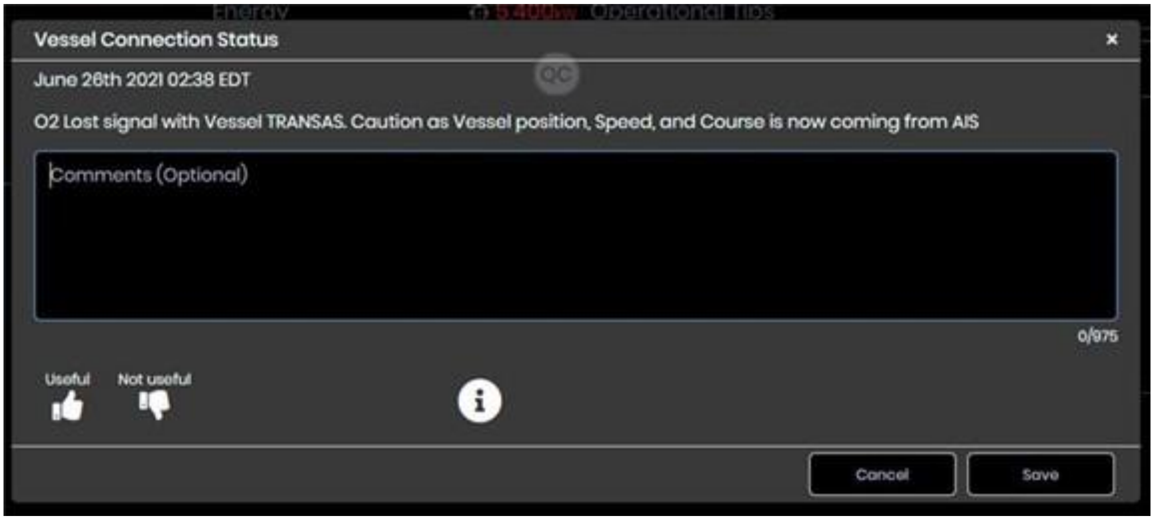
The CSL O2 system gathers a variety of data on board the vessel and transmits it via satellite to CSL Headquarters in Montreal, where the data is archived and processed. The processed data is formatted for presentation to the Captain/Mates and transmitted back to the vessels. The display on the Bridge has a main page that presents critical vessel information in a format that has been standardized for all CSL vessels (Figure 36). Ship and voyage specific information is presented using 'Tip' (popup) messages that are acknowledged by the Bridge team (Figure 37). As shown in Figure 37, the "Tip' Messages may include a 'Useful/Not Useful' option that will be employed to assist with the Operational Evaluation of the CMS. The CSL O2 team releases new versions of the system every 6–8 weeks, which is greatly simplified because of the centralized design. This may allow for an update to the CMS 'Tip' message during the Operational Trial to evaluate the usefulness of different message content.

ETB Jun 26 14:12 WINDSOR

ETA Jun 23 15:25 St. Lambert Locks

O2 lost signal with Vessel TRANSAS. Caution as Vessel ...

Figure 36. Main human machine interaction (HMI) display for the Canada Steamship Lines (CSL) O2 system. This version is shown without colors as it is a "test" screen.



Vessel Connection Status

June 26th 2021 02:38 EDT

O2 Lost signal with Vessel TRANSAS. Caution as Vessel position, Speed, and Course is now coming from AIS

Figure 37. Example of a ‘Tip’ window used in the O2 system. The tips will stay active until either the user acknowledge the tips (if the tip is set to be acknowledgeable) or the condition generating the tip is no longer true.

4.3. Cavitation Monitoring System Test Plan

4.3.1. System Deployment

The next phase of the project will be the re-deployment of the full CMS (see Section 4.2) for the Operational Trial in fall 2021. Equipment for the Operational Trial will be shipped to CSL around 9 Sep 2021, for installation of the CMS on the *Ferbec* and two months of evaluation until roughly the end of November 21. Installation will not require the *Ferbec* to be unballasted as the through-hull components are already installed from the Baseline Trial. As the sensors and preamps are still in place on the *Ferbec*, only the observer system will be shipped back as part of the equipment for the Operational Trial. The CMS will then collect data throughout the voyage season up to the end of November 2021, when the CMS and associated data will be recovered for analysis by JASCO.

4.3.2. CMS Data Collection

Data will be collected by the CSL O2 system during the Operational trial. Changes of cavitation state will be presented to the Captain/Mate using the ‘Tip’ feature (see Section 4.2), which they will acknowledge as useful/not useful. Alongside this, operational state and navigation data will also be logged to provide contextual information (as was done during the Baseline trial, see Section 2.1.5). Secondly, raw data will simultaneously be collected and stored by the data acquisition system (observer) built into the onboard CMS (see Section 4.2).

4.3.3. CMS Usage Evaluation

A major interest of this project is to evaluate how useful the CMS was during the Operational Trial. As part of this goal, a social science component to the project will evaluate perspectives from vessel operators as to whether it is useful for them to have cavitation information provided on the bridge through the O2 HMI system. This will be conducted in two parts, the first being the use of a pop-up ‘Tips’ window on the O2 system, which will be used to display a ‘useful’ or ‘not useful’ button option (Figure 37). Cavitation levels will be displayed on the O2 system as a color-coded level of red (high cavitation), yellow (medium cavitation), and green (low cavitation). Vessel operators can then choose either the ‘useful’ or ‘not useful’ option when cavitation level is indicated, providing data on usefulness of displayed information.

The second part will likely take the form of a survey or interview conducted with CSL after or near the end of the field trial during 2021. BC Ferries will also potentially be involved in this discussion due to having utilized a similar CMS on their vessel as part of MMP2. Results from such a survey will mark an important end point for the current project and will directly inform the next stage of usage of this technology and its integration into adaptive noise management plans through understanding the potential use-cases for the technology.

While working with the vessel operators in the development of the CMS and during the Baseline trial, we consistently found two use cases for a CMS, each with an associated noise management plan (Figure 38). In the first use case, a real-time CMS would provide the vessel operators with an indication of the level of cavitation, which would corelate with the vessel’s URN. By controlling the cavitation level, the vessel operators could maximize the speed through water at an allowed noise level in sensitive areas. In the second use case a temporary CMS is fit to the vessel to determine the cavitation versus speed profile of the vessel. By comparing to the known noise for vessels of the class (MacGillivray and de Jong 2021), the cavitation versus noise level can be determined. From this information, the vessel operators can be aware of the noise emitted versus speed and could select an appropriate handle setting to reduce noise when transiting through sensitive areas without the need for a real-time system.

The survey will also investigate the perspectives and opinions of industry on how this technology could be implemented and regulated in Canadian waters, and how this might impact vessel operators and companies. Comparisons to other cavitation noise mitigation methods will also be investigated including physical design features such as propeller changes and spatial slow downs. The current requirement to reduce speed to 10 kn throughout sections of the Gulf of St. Lawrence was implemented through a change to Regulations, with a trickle-down effect on vessel schedules that required adjustment of expectations by shippers and receivers throughout the East Coast. It resulted in the cancellation and rerouting of cruises. To add a CMS into vessel operations would require Canada’s marine regulator, Transport Canada, to either mandate or at least incentivize its use. Transport Canada likely can not broadly mandate the use of a CMS since many of the vessels calling at Canadian ports have international registrations – it would require adoption by the International Maritime Organization (IMO). Without operational, proven cavitation monitoring systems it will not be possible to influence the IMO to require their use. From another point of view, either use case for a CMS could be viewed as means for establishing a quiet vessel operations certification, and hence could cross into the domain of the Classification Societies who must also be consulted on the role and implementation of the CMS.

Understanding the suitability of these different use cases from both the industry perspectives will be valuable information to regulators and will aid in facilitating the most successful integration of CMS into future adaptive noise management plans.

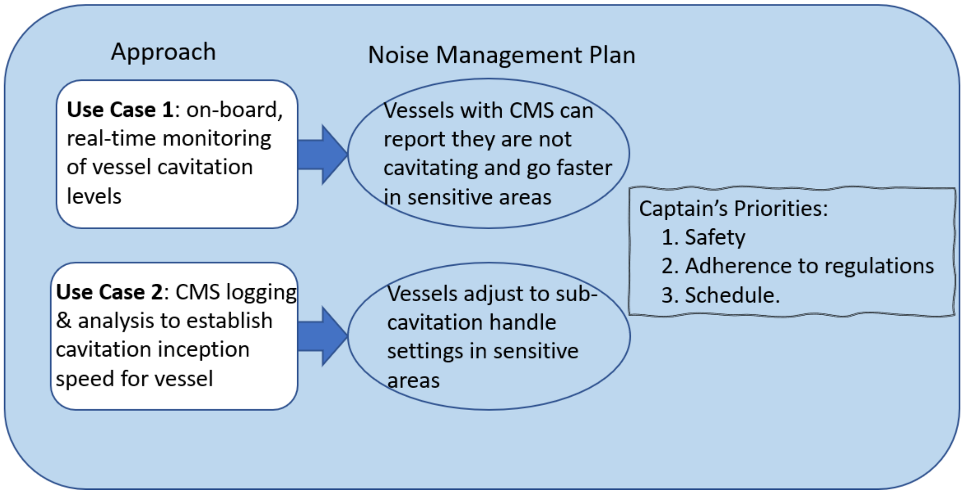


Figure 38. Potential use cases for cavitation monitoring systems on vessels.

5. DISCUSSION AND RECOMMENDATIONS

The sensor placements on M/V *Ferbec* and the hydrophones spacing on the vertical line array (VLA) were not in accordance with the original Baseline Trial plans. However, neither of these potential issues compromised the value of the Baseline Trial. Onboard the *Ferbec*, the signals on the two functioning pressure transducers and the accelerometer all provided similar data. The data allowed for the development of a robust algorithm for predicting the shaft rate from the sensor values, which was the goal of the Baseline Trial data collection. For the in-water measurements, in four out of six passes of the *Ferbec* the data on the three hydrophones were within 2–3 dB of each other, indicating that any of the three would have yielded the same results. For two of the passages, the top hydrophone predicted a source level several decibels below the others, demonstrating the value in having multiple hydrophones to average across.

The analysis in this report only determined the radiated noise level (RNL) of the *Ferbec*. Detailed analysis of the monopole source level (MSL) will be included in the final report and will employ the most current methods being developed by JASCO as part of the MMP2 project, *Support to the International Standards Organization for the Development of a Shallow Water Vessel Source Level Measurement Standard.*

At $56,000, installing the through-hull pressure sensors was a substantial cost for the Baseline Trial. Added to the costs of the sensors and equipment, the full cost of this prototype was in excess of $90,000, without non-recurring engineering expenses. The installation costs included the design and build of the ‘paint cans’ to allow for installation in the aft peak, venting, and safety personnel so that work could be performed in that confined space, and costs of overtime because the work had to be done at night over a weekend while that section of the hull was out of the water in Sorel. The accelerometer did not require the through-hull installation, which would have reduced the costs for its installation if it were installed alone. Data analysis suggests that the acceleration data alone could be employed for the cavitation detection algorithm. This possibility will be investigated as part of the project final report.

The imperatives of the vessel schedule impacted our ability to make the in-water source level measurements. The *Ferbec*, like most commercial vessels, is on a precisely planned schedule to maximize the revenue from its operations. Like many ports where vessel arrival or departure is timed around the tides, the *Ferbec’s* arrival at Les Escoumis is timed to occur near high tide. Two of the source level measurements were made at full cruising speed, rather than the desired speeds of 5 and 9 kn to stay on schedule. Vessel scheduling must be kept in mind when developing noise management plans that include voluntary slow downs based on cavitation monitoring.

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APPENDIX A. RECORDER CALIBRATIONS

Each AMAR was calibrated before deployment and upon retrieval (battery life permitting) with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S; Figure A-1). The pistonphone calibrator produces a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space with known volume. The recorded level of the reference tone on the AMAR yields the system gain for the AMAR and hydrophone. To determine absolute sound pressure levels, this gain was applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure.

Figure A-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone.

APPENDIX B. MMP3 MESSAGE ICD

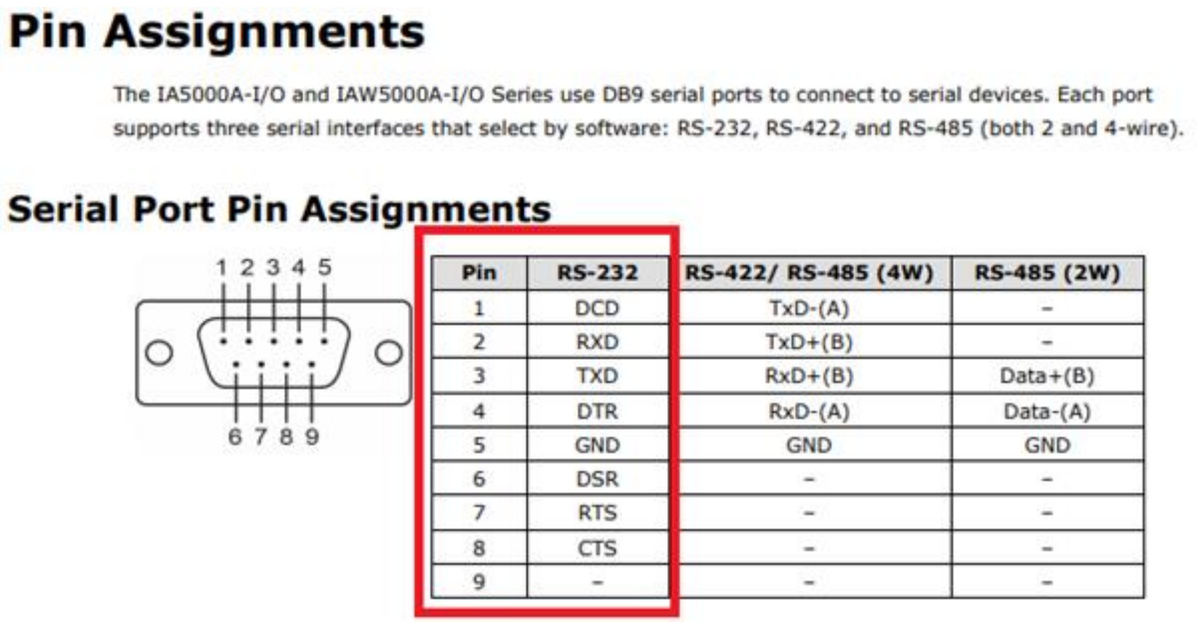
This appendix outlines the serial communication interface control design. The physical connection is described, as well as the definition of the NMEA 0183.

B.1. RS232 Connection Information

As the communications standard will be NMEA 0183, the serial settings are:

- Baud rate: 4800
- Data bits: 8
- Parity: None
- Stop bits: 1
- Handshake: None

The serial connector pinout for the MOXA NPort IA5250A-6I/O is shown below. The MOXA has a male DB9 port; therefore, the serial cable from the system requires a DB9 female connector.



Pin Assignments

The IA5000A-I/O and IAW5000A-I/O Series use DB9 serial ports to connect to serial devices. Each port supports three serial interfaces that select by software: RS-232, RS-422, and RS-485 (both 2 and 4-wire).

Serial Port Pin Assignments

Pin	RS-232	RS-422/ RS-485 (4W)	RS-485 (2W)
1	DCD	TxD-(A)	–
2	RXD	TxD+(B)	–
3	TXD	RxD+(B)	Data+(B)
4	DTR	RxD-(A)	Data-(A)
5	GND	GND	GND
6	DSR	–	–
7	RTS	–	–
8	CTS	–	–
9	–	–	–

Figure B-1. Pin-out diagram for the RS-232 cables that will transport data from the Observer to the CSL MOXA box.

B.2. Message Format

The message will be an NMEA 0183, in the following format:

$PJASS,1624364224,1,125.26,134.56,135.4,133.45,12.34,8.98,7.65*45

Table B-1. Message format for the NMEA cavitation message.

Field	Meaning
0	Timestamp of message (Unix Epoch, seconds since 00:00:00 1 Jan 1970)
1	Cavitation indicator: 0. Processing not running. 1. SPL too low to determine cavitation status 2. No cavitation 3. Cavitation
2	Root-mean-squared sound pressure level (RMS SPL, Source Level), dB re 1 µPa²
3	Pressure Sensor 1 RMS SPL, dB re 1 µPa²
4	Pressure Sensor 2 RMS SPL, dB re 1 µPa²
5	Pressure Sensor 3 RMS SPL, dB re 1 µPa²
6	Accelerometer X-Channel RMS Accel, m/s²
7	Accelerometer Y-Channel RMS Accel, m/s²
8	Accelerometer Z-Channel RMS Accel, m/s²
9	The checksum data, always begins with *

The message will be sent once every 10 seconds.

APPENDIX C. SOUND PROPAGATION MODELS

C.1. Propagation Loss

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss: a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, as well as absorbed, scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed, as its value changes with frequency.

If the acoustic source level (SL), expressed in dB re 1 µPa²m²s, and propagation loss (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 µPa²s by:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{PL} \tag{C-1}$$

C.2. Parabolic-equation Model: CRAM

Underwater sound propagation (i.e., propagation loss) at frequencies of 10 Hz to 4 kHz was predicted with JASCO's CRAM, an implementation of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), modified to treat shear-wave reflection loss.

The model computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996) because it accounts for the additional reflection loss at the seabed resulting from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces. It also includes wave attenuations in all layers. The following site-specific environmental properties are required in input: underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor. The implementation adapted for the particular purposes of ShipSound assumes the bottom depth and geoacoustic properties to be independent between the source and the receiver. CRAM computes PL at 50 evenly spaced frequencies in each 1/3-octave-band; the PL within each band is averaged to reduce narrowband interference effects.

C.3. Ray-Tracing Model: Bellhop

Noise Model (MONM). This model computes sound propagation from highly-directional, high-frequency acoustic sources via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994). This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is important for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as *N*×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (Figure C-1). The angular step size of the radials is chosen to sufficiently sample the source beam pattern. MONM accounts for the variability of the sound level of the emitted pulse with both azimuth and depression angles according to the 3-D beam pattern of the source and estimates sound levels at various horizontal distances from the source as well as at various depths.

The received sound level at a sampling location is taken as the maximum value that occurs over all samples within the water column below, i.e., the maximum-over-depth received sound level (Figure C-1). These maximum-over-depth levels are then presented as colour contours around the source (e.g., Figure C-2).

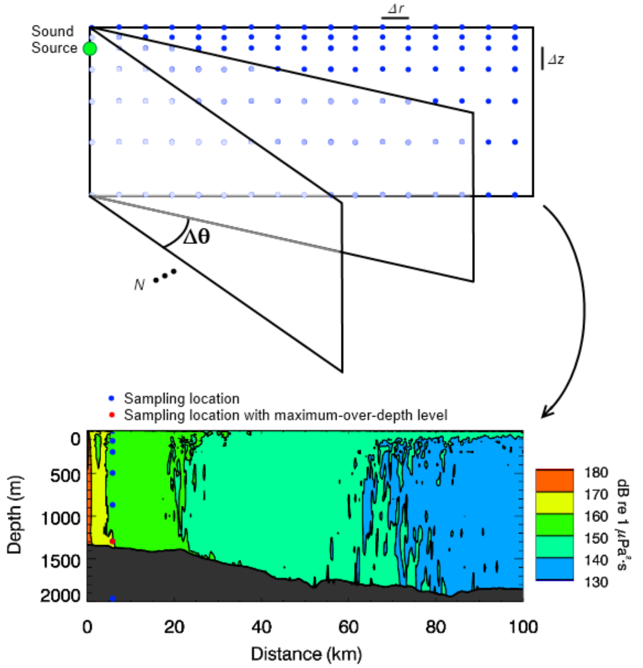


Figure C-1. Representation of *N*×2-D and maximum-over-depth approaches.

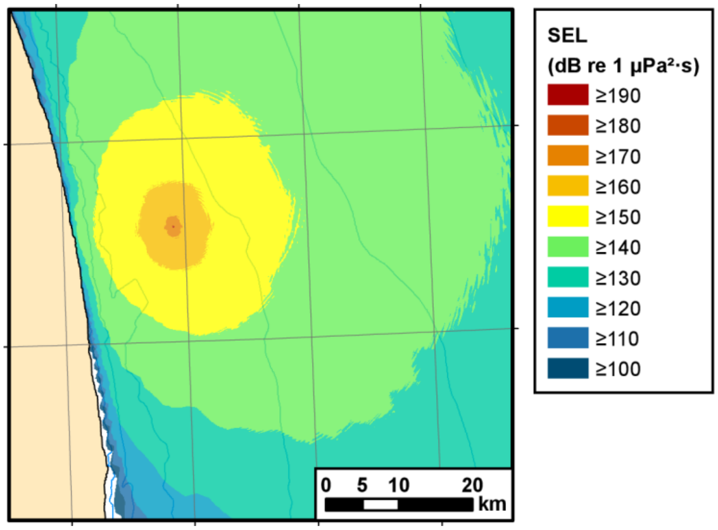


Figure C-2. Example of a maximum-over-depth SEL colour contour map for an unspecified source.

C.4. Wavenumber Integration Model: VSTACK

Sound pressure levels near the source were modelled using JASCO's VSTACK wavenumber integration model. VSTACK computes synthetic pressure waveforms versus depth and range for arbitrarily layered, range-independent acoustic environments using the wavenumber integration approach to solving the exact (range-independent) acoustic wave equation. This model is valid over the full angular range of the wave equation and can fully account for the elasto-acoustic properties of the sub-bottom. Wavenumber integration methods are extensively used in the fields of underwater acoustics and seismology, where they are often referred to as reflectivity methods or discrete wavenumber methods.

VSTACK computes sound propagation in arbitrarily stratified water and seabed layers by decomposing the outgoing field into a continuum of outward-propagating plane cylindrical waves. Seabed reflectivity in the model is dependent on the seabed layer properties: compressional and shear wave speeds, attenuation coefficients, and layer densities. The output of the model can be post-processed to yield estimates of SEL, SPL, and PK.

VSTACK accurately predicts steep-angle propagation in the proximity of the source but is computationally slow at predicting sound pressures at large distances due to the need for smaller wavenumber steps with increasing distance. Additionally, VSTACK assumes range-invariant bathymetry with a horizontally stratified medium (i.e., a range-independent environment) that is azimuthally symmetric about the source. VSTACK is thus best suited to modelling the sound field in close proximity to the source.

APPENDIX D. LONG-TERM ACOUSTIC DATA RESULTS

D.1. In-Water Results

Figures D-1 to D-4 represent the long-term spectral averages and percentiles of the lower two hydrophones on the mooring.

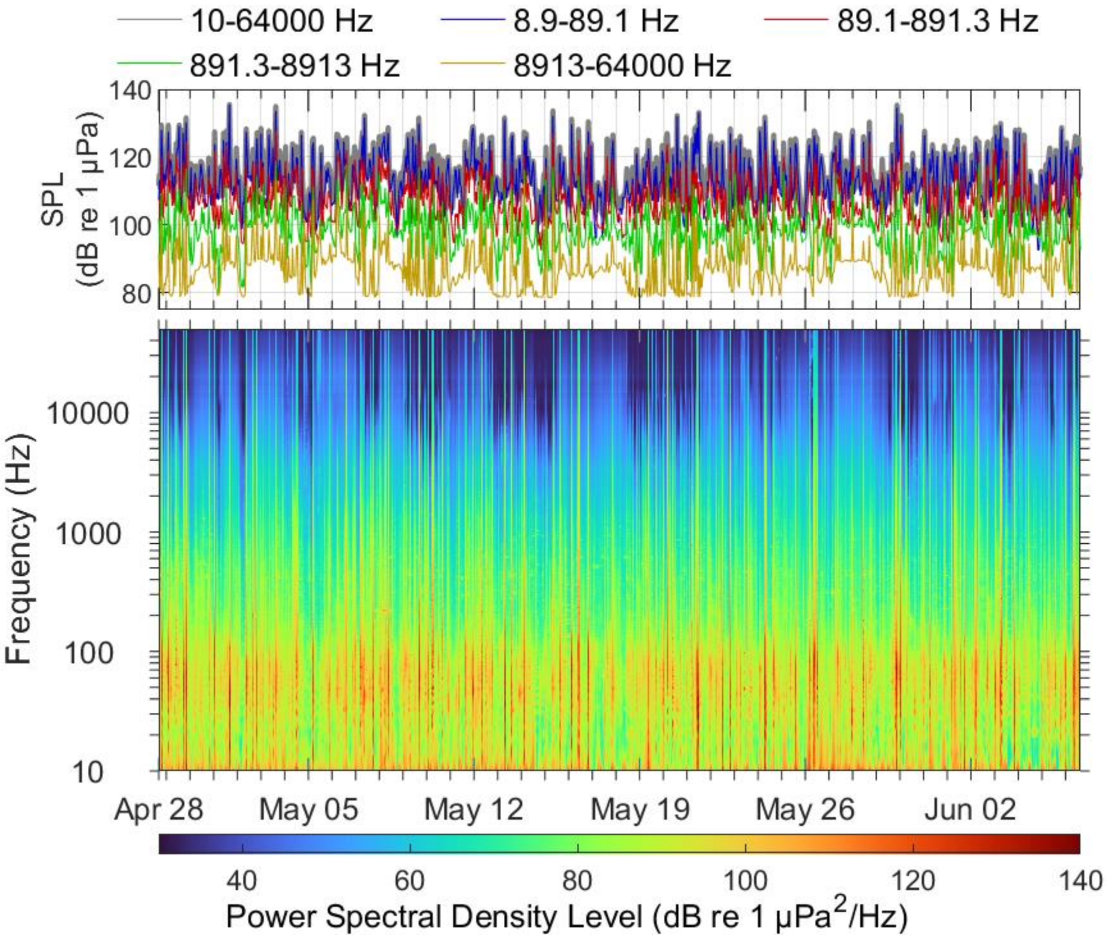


Figure D-1. Long term spectral averages for the mid depth hydrophone (146 m) throughout the deployment period. High intensity broadband noise spikes represent the passage of ships, including the M/V *Ferbec*.

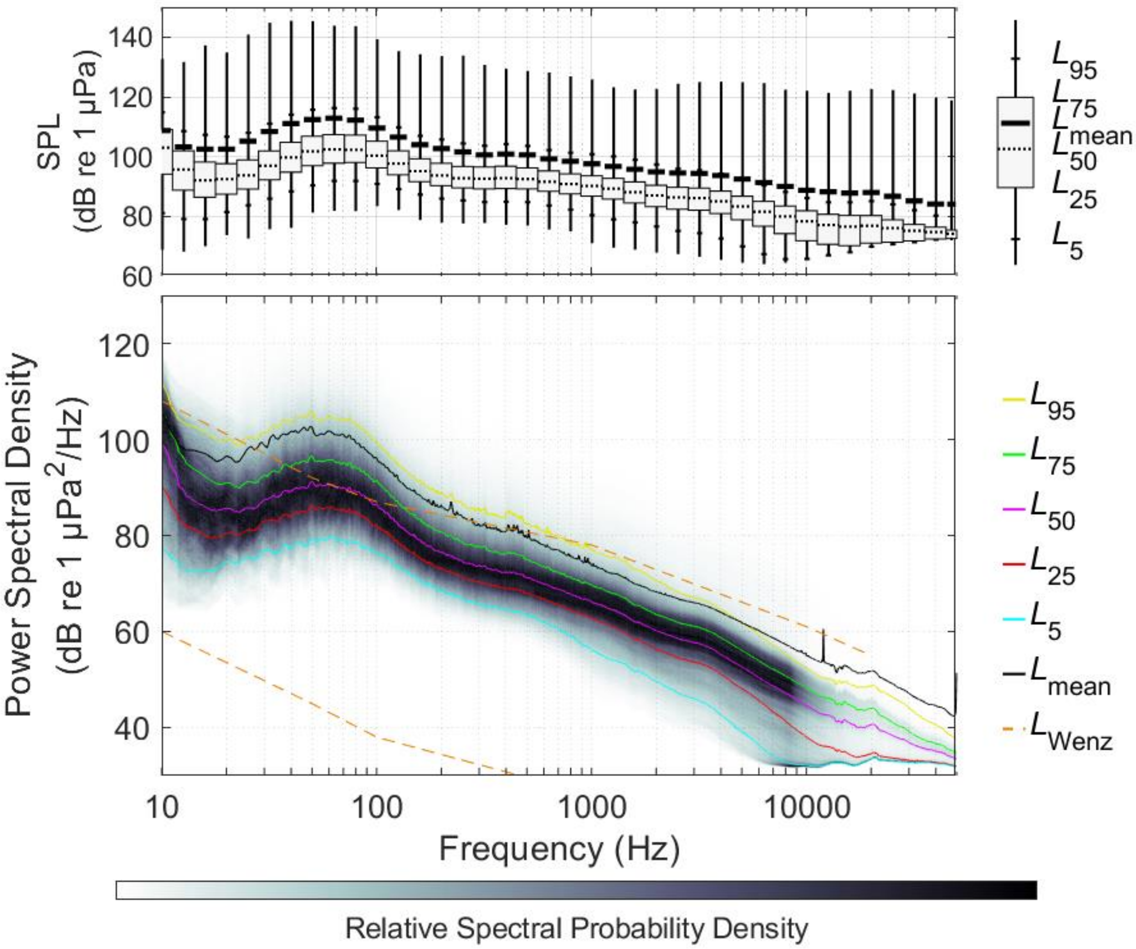


Figure D-2. Decidecade boxplot and percentiles for the mid depth hydrophone (146 m) throughout the deployment period. The peak just below 100 Hz is attributed to shipping, while the very low frequency energy is attributed to flow noise.

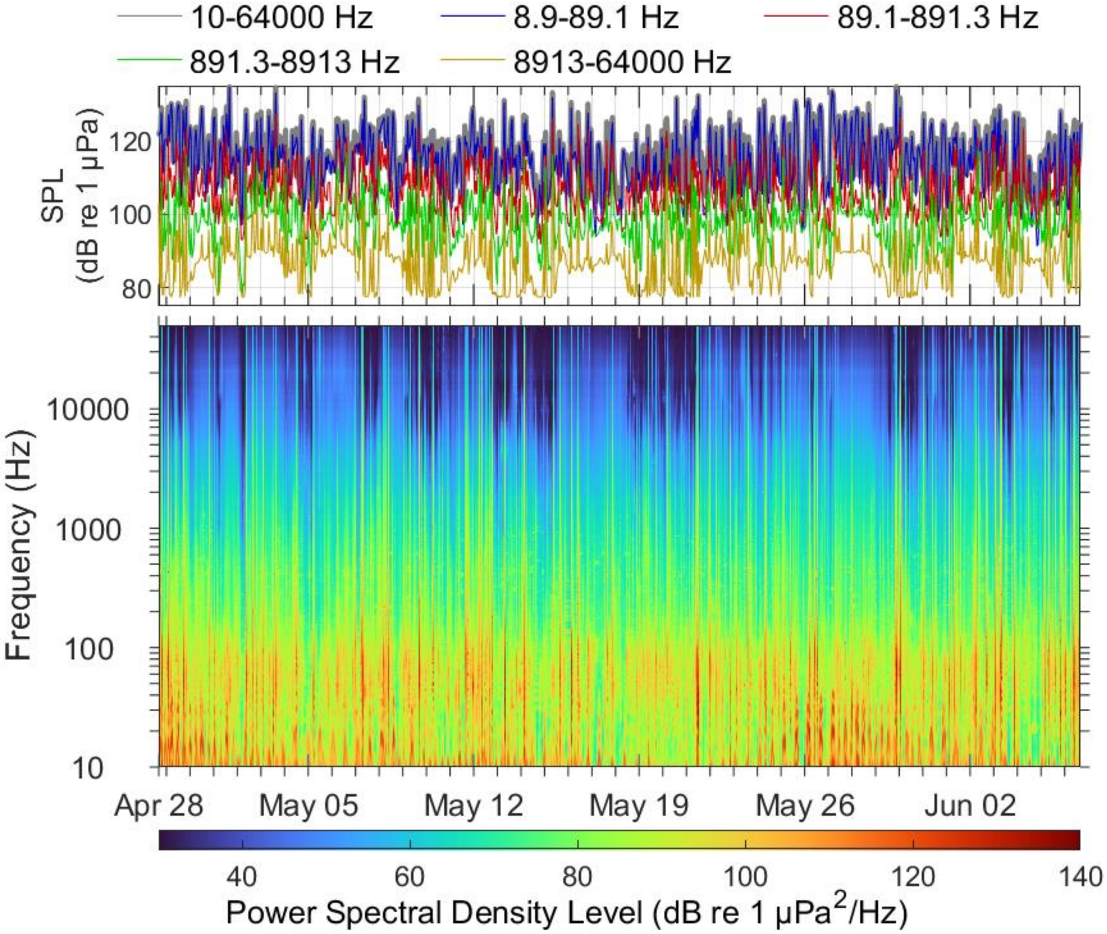


Figure D-3. Long term spectral averages for the deep hydrophone (166 m) throughout the deployment period. High intensity broadband noise spikes represent the passage of ships, including M/V *Ferbec*.

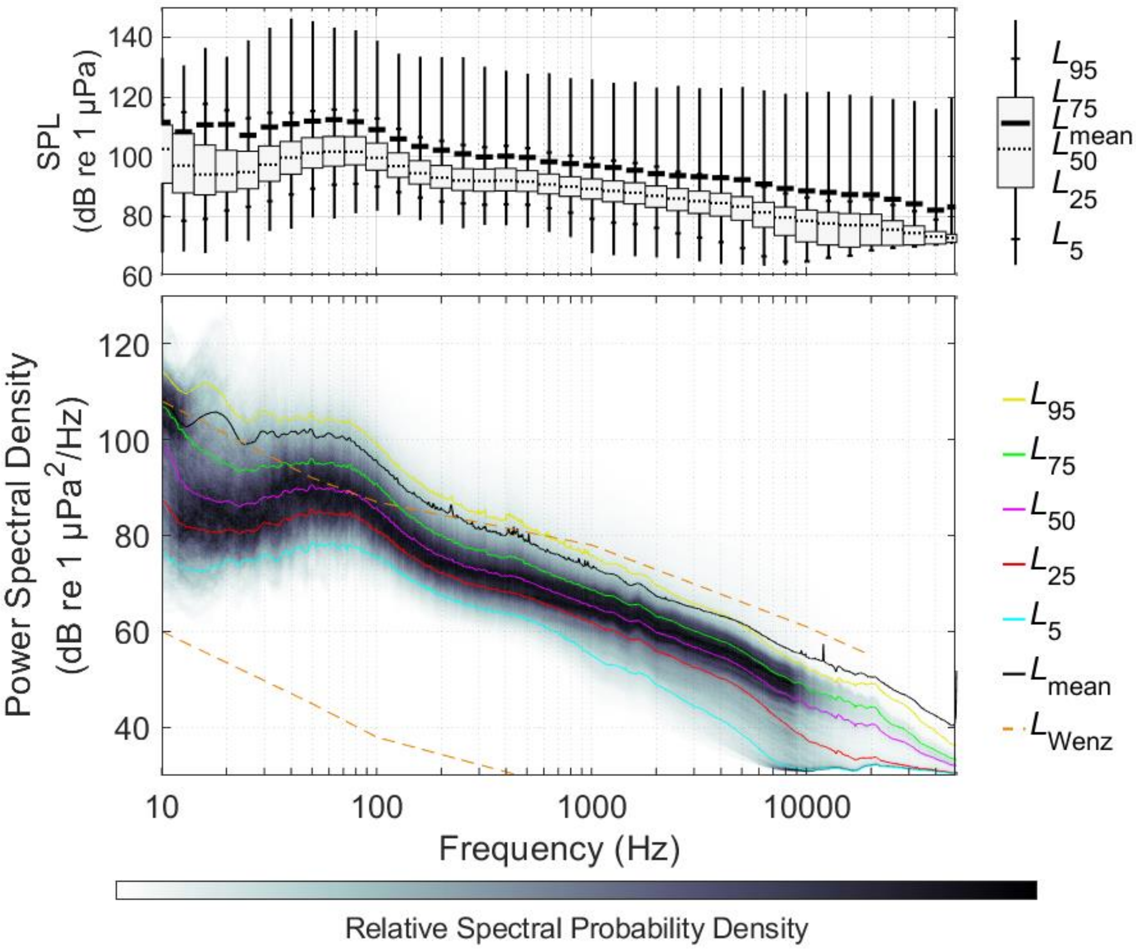


Figure D-4. Decidecade boxplot and percentiles for the deep hydrophone (166 m) throughout the deployment period. The peak just below 100 Hz is attributed to shipping, while the very low frequency energy is attributed to flow noise.

D.2. On-Board Results

Figures D-5 to D-8 present the calculated levels as a function of speed through water.

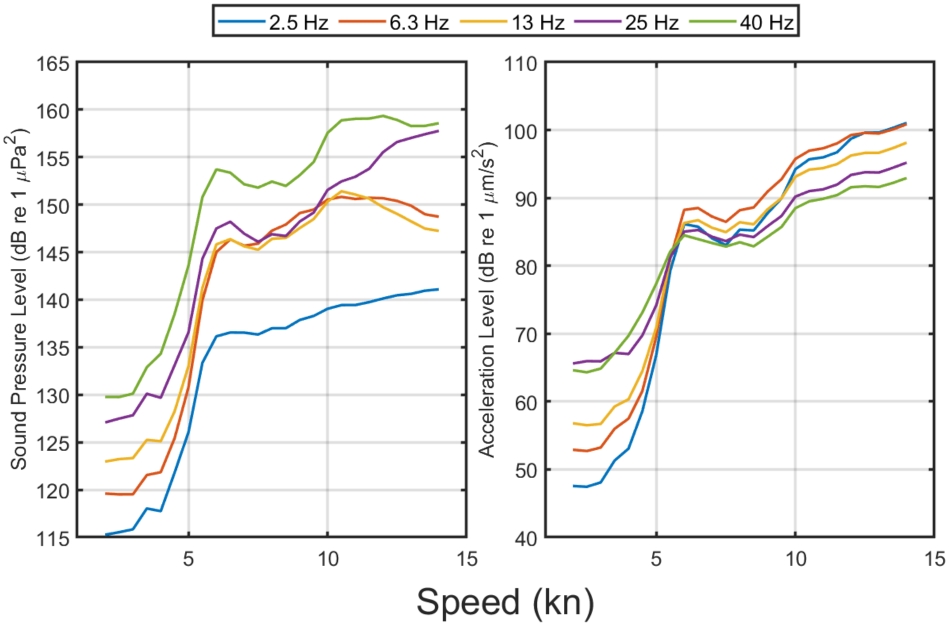


Figure D-5. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) of the vessel for several decidecade bands. The curves present the mean values of the calculated levels for the loaded case. Channel 2, pressure and Channel 6, y coordinate of the accelerometer.

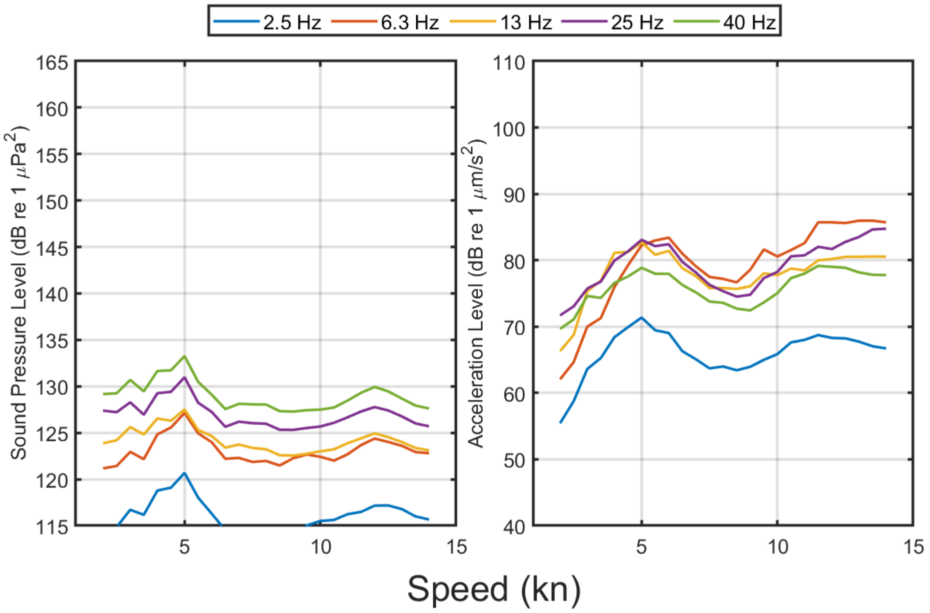


Figure D-6. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) of the vessel for several decidecade bands. The curves present the mean values of the calculated levels for the in-ballast case. Channel 2, pressure and Channel 6, y coordinate of the accelerometer.

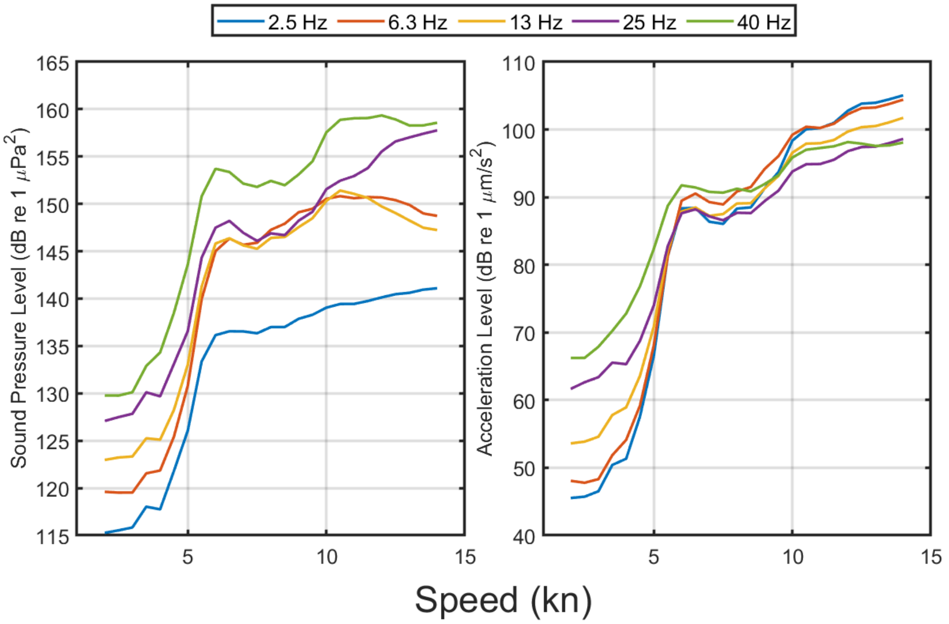


Figure D-7. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) of the vessel for several decidecade bands. The curves present the mean values of the calculated levels for the loaded case. Channel 2, pressure and Channel 7, z coordinate of the accelerometer.

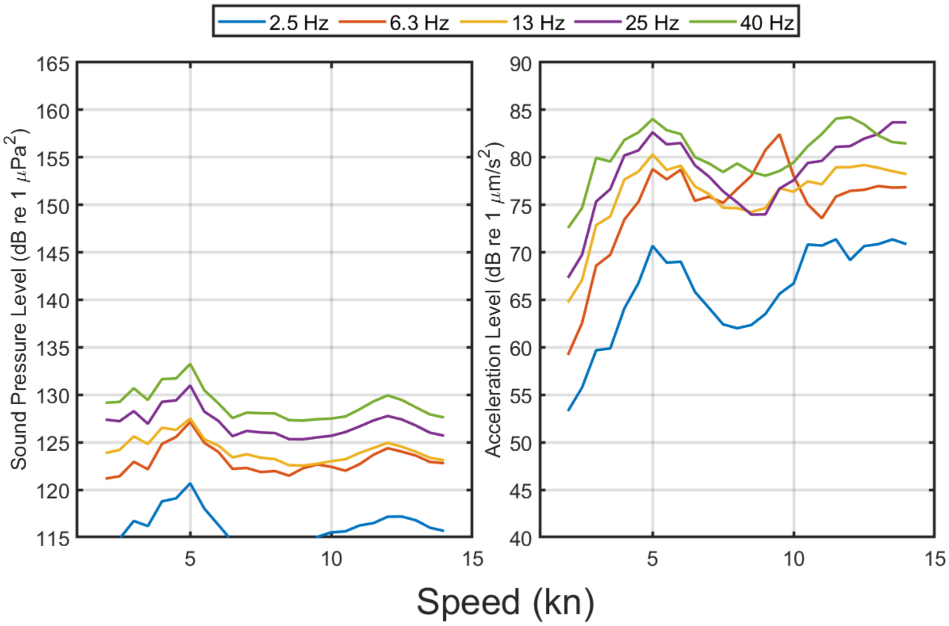


Figure D-8. Levels calculated from the pressure and accelerometer sensors as a function of M/V *Ferbec's* speed through water (STW) of the vessel for several decidecade bands. The curves present the mean values of the calculated levels for the in-ballast case. Channel 2, pressure and Channel 7, y coordinate of the accelerometer.

TP XXXXXX

MMP3 Integration and CMS Installation Test Report

Integration Test Description and Results

JASCO Applied Sciences (Canada) Ltd

17 December 2021

Prepared for:

Matthew Cooke
Innovation Centre of Transport Canada
Contract T8009-190191/003/XLV

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P001556-003
Document 02543
Version 2.0

NOTICES

Suggested citation:

Diggle, N.P. and E.E. Maxner. MMP3 Integration and CMS Installation Test Report: Integration Test Description and Results. Document 02543, Version 2.0. Technical report by JASCO Applied Sciences for Innovation Centre of Transport Canada.

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Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.

TP XXXXX

2. Project No.

P001556-003

3. Recipient's Catalogue No.

4. Title and Subtitle

MMP3 Integration and CMS Installation Test Report

5. Publication Date

December 2021

6. Performing Organization Document No.

XXXX

7. Author(s)

Nicholas Diggle, Emily Maxner

8. Transport Canada File No.

XXXX

9. Performing Organization Name and Address

JASCO Applied Sciences (Canada) Ltd.
Suite 2305, 4464 Markham St.
Victoria, BC V8Z 7X8 Canada

10. PWGSC File No.

XXXX

11. PWGSC or Transport Canada Contract No.

12. Sponsoring Agency Name and Address

Transport Canada, Innovation Centre

13. Type of Publication and Period Covered

14. Project Officer

XXXX

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This is the Integration and Operational Trial for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. The integration testing occurred end of September 2021 and the operational trial implementing the CMS-O2 system onboard the *Ferbec*, operated by Canada Steamship Lines (CSL) begun early November. Troubleshooting connection issues on the serial ports crated unexpected delays. Following troubleshooting by CSL and JASCO, the integration of the cavitation detection algorithm was successfully performed in-house and confirmed on *Ferbec* in November 2021. CSL confirmed successful implementation of the O2 vessel data management system; however, intermittent data issues were pending the display of real-time CMS results on the vessel's human machine interaction (HMI). Ongoing troubleshooting by CSL and remote assistance from JASCO resulted in a full CMS-O2 system implementation.

17. Key Words

Cavitation monitoring system, integration testing, O2 system

18. Distribution Statement

Limited number of copies available from the Innovation Centre

19. Security Classification (of this publication)

Unclassified

20. Security Classification (of this page)

Unclassified

21. Declassification (date)

—

22. No. of Pages

xiii, 34, apps

23. Price

Shipping/ Handling

CI/IC 79-005
Rev. 96

Canada

Transport Canada Transports Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. No de la publication de Transports Canada. TP XXXXX	2. No de l'étude P001556-003	3. No de catalogue du destinataire
4. Titre et sous-titre XXXX		5. Date de la publication Month 2021
		6. No de document de l'organisme exécutant XXXX
7. Auteur(s) Nicholas Diggle, Emily Maxner		8. No de dossier - Transports Canada XXXX
9. Nom et adresse de l'organisme exécutant JASCO Applied Sciences (Canada) Ltd. Suite 2305, 4464 Markham St. Victoria, BC V8Z 7X8 Canada		10. No de dossier - TPSGC XXXX
		11. No de contrat - TPSGC ou Transports Canada
12. Nom et adresse de l'organisme parrain Transport Canada, Innovation Centre		13. Genre de publication et période visée
		14. Agent de projet XXXX

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

17. Mots clés	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xiii,	23. Prix Port et manutent

CI/IC 79-005
Rev. 96

Canada

EXECUTIVE SUMMARY

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board cavitation monitoring system (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modification of operating states in areas of concern, such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA). This project, dubbed MMP3, has three phases: developing the CMS, a Baseline Trial to collect cavitation and noise data, and an Operational Trial to evaluate the utility of a CMS on a working commercial vessel. This report covers the preparation required for the Operational Trial, describing the installation and integration of the CMS system and the implementation of the human machine interface (HMI) Tip.

The integration test was successfully performed in the Halifax JASCO office to validate the cavitation detection and simultaneous recording abilities of Observer 977 (OBS-977) on 28 Sep 2021.

The CMS system connection and implementation was performed by CSL onboard the *Ferbec* as COVID restrictions did not allow JASCO to participate in person. Serial connection issues between the OBS-977 and Moxa Box created delays but were dealt with through remote assistance from JASCO. CSL confirmed the system connection on Nov 9, receiving data output every 10 s. The data was first being evaluated by CSL before implementing a Tip on the captain's HMI. On 24 Nov 2021, CSL confirmed successful implementation of the O2 vessel data management system and the full CMS-O2 system was implemented on 26 Nov 2021.

JASCO will meet with CSL to discuss the value of CMS-O2 system given the cost and installation efforts. This information will be outlined in the final report. Further analysis on the data from the Baseline trial will be performed to determine if the accelerometer alone could be used to determine the cavitation and included in the final report, delivered by 31 Mar 2022.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects, with the goal of assessing the possible operational feasibility of using an on-board cavitation monitoring system (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern, such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA).

JASCO previously a) delivered plans for the Baseline Underwater Radiated Noise (URN) characterization of a trial vessel, b) designed the prototype CMS used in the field trial, and c) submitted a report summarizing the analysis and results obtained (Martin et al. 2021). The summary report included an overview of the full system design and installation process for the CMS used for the Operational Trial.

This report is the next project deliverable. It documents the test description and results for the integration testing performed on Observer 977 (OBS-977), as well as the connection and implementation of the CMS-O2 system onboard the *Ferbec*. The integration test was performed in the JASCO Halifax facility to validate the cavitation detection and simultaneous recording abilities on OBS-977. The CMS-O2 system connection and implementation was performed by CSL, as COVID restrictions did not allow JASCO to participate in person.

1.1. System Overview

The purpose of the MMP3 system is to monitor for cavitation onboard the *Ferbec*. The system uses three pressure sensors and one accelerometer to monitor for conditions that could indicate propeller cavitation. The pressure sensors require hull penetrations, while the accelerometer is attached firmly inside the hull. The system is designed to ingest and process data in real time, with the results being sent to the vessel's O2 information system in real time.

The overall architecture for the MMP3 system in shown in Figure 1. Three pressure sensors and an accelerometer are mounted inside the ship's hull using specialized housings, designed in cooperation with CSL. Unlike the pressure sensor housing, the accelerometer housing does not have a hull penetration. The power and signal cables from each sensor are routed to a waterproof enclosure in the aft peak, which contains pressure sensors' preamps. The preamps have been placed inside the aft peak to minimize the cable distance between the sensors and the preamps, reducing the risk of contaminating signals due to electromagnetic interference and degrading signals due to cabling resistance.

A signal/power cable runs from the aft peak into the steering gear room though the room's floor. In the steering gear room, there is another housing containing Observer electronics. The Observer samples the analogue data from the preamps, processes the data in real time to detect indicators of cavitation, and transmits these results to the bridge via an RS422 serial connection output.

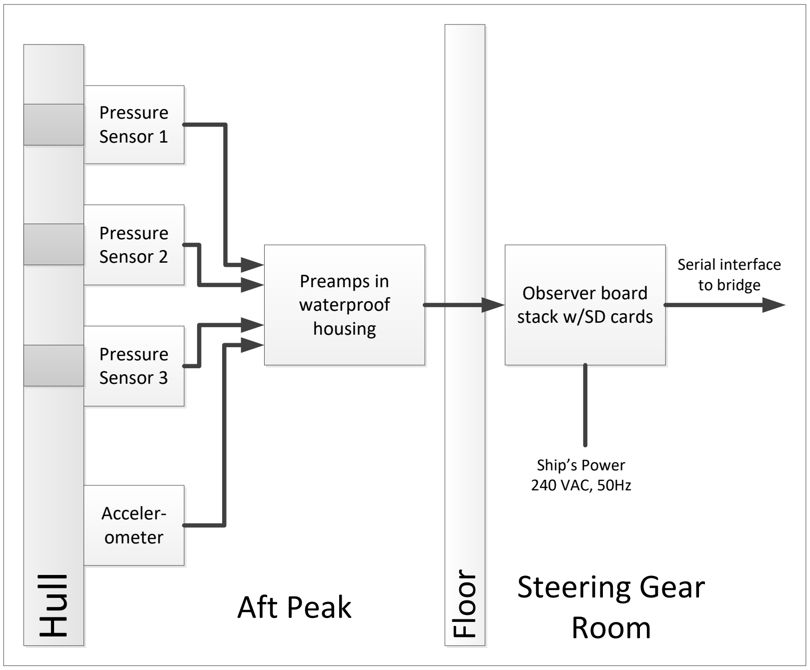

Figure 1. System overview.

The format, content, and frequency of the output from the system is defined in the MMP3 Interface Control Document (ICD). As per the ICD, the output is in National Marine Electronics Association (NMEA) 0183 format. NMEA-formatted strings are commonly used by devices such as GPS and AIS units to output data and for marine systems such as radars and chart plotters to ingest data from sensors and to exchange data with each other. Fields within the messages are comma-delimited, and there are standardized fields such as headers and checksums, along with custom fields that depend upon the type of information being output. This system outputs the following custom information at ten-second intervals within its single NMEA message:

- Time
- Cavitation status: One of four possible values:
    a. Not operating (value 0)
    b. Sound pressure level (SPL) too low to determine cavitation status (value 1)
    c. Not cavitating (value 2)
    d. Cavitating (value 3)
- Pressure sensor SPLs
- Accelerometer X, Y, and Z readings.

2. INTEGRATION TESTING IN HALIFAX

2.1. Test Objective

The objective of this test was to verify the end-to-end functionality of the Observer, which was configured to detect cavitation through its sensor data input. A test WAV file was played into the Observer to validate the long-term stability of the Observer while it was simultaneously processing sensor data, generating output cavitation messages in NMEA 0183 format, and recording the raw data to SD cards (via its Stream Repeater software). The PAMlab software component was installed and modified on the Observer to process the sensor data to determine the cavitation status. The test WAV file contained data that caused PAMlab to report all four possible cavitation states and to report these states via its NMEA output message.

The test validation objectives were to verify the following:

- The system outputs cavitation messages in NMEA 0183 format via its serial port.
- The cavitation status message conforms with the NMEA message format defined in the ICD.
- PAMlab properly detects cavitation when sensor data containing cavitation noise is played into the Observer.
- PAMlab properly indicates no cavitation occurring when recorded data containing no cavitation noise is played into the Observer.
- The SPL within the output message are constant values when the sensor channels associated with those fields are fed with constant amplitude and frequency input.
- Recorded data was continuous with no time gaps.

2.2. Test Preconditions

The following were the required hardware:

- OBS-977 Box:
    - 2021.09.28-CMS-1.4 software release installed via AMARlink.
    - SD card storage installed.
    - Ethernet connected to a network switch.
- Interface computer, set up as follows:
    - Interface connected to same network as OBS-977's Ethernet connection.
    - RS232 serial cable connected to OBS-977's RS-422 serial connection via an RS-232/USB converter and Black Box IC1473A-F-ET RS-232/RS-422 converter.
    - JASCO AMARlink 4.11.5 installed.
    - JASCO DataSummary Tool installed.
    - PuTTY installed.
    - Audacity installed.
    - Focusrite Scarlet Solo audio interface connected over USB. This audio interface played audio into the Observer to validate PAMlab's cavitation detection. This was achieved by a connection of the left channel balanced audio output to OBS-977 ADC channel 1, and the right channel balanced audio output to OBS-977 ADC channel 2. The master volume knob on the interface was set to 75% of full volume. A 1.0 amplitude sine wave (in a 32-bit floating point WAV file) was produced on the interface computer to correspond to a 1-Vpp sine wave on the audio interface's balanced audio outputs.
- Function generator outputting 1-Vpp/1.6-kHz sine wave, HIZ drive strength.
    - Function generator output connected to OBS-977 ADC channels 3, 5, 6, and 7.
- 500 GB hard drive to download SD card data to connect the test hardware as shown in Figure 2.[1]

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[1] Note that the Ethernet connection is not shown Figure 2, but both the OBS-977 Box and Interface computer are connected to the same network via Ethernet.

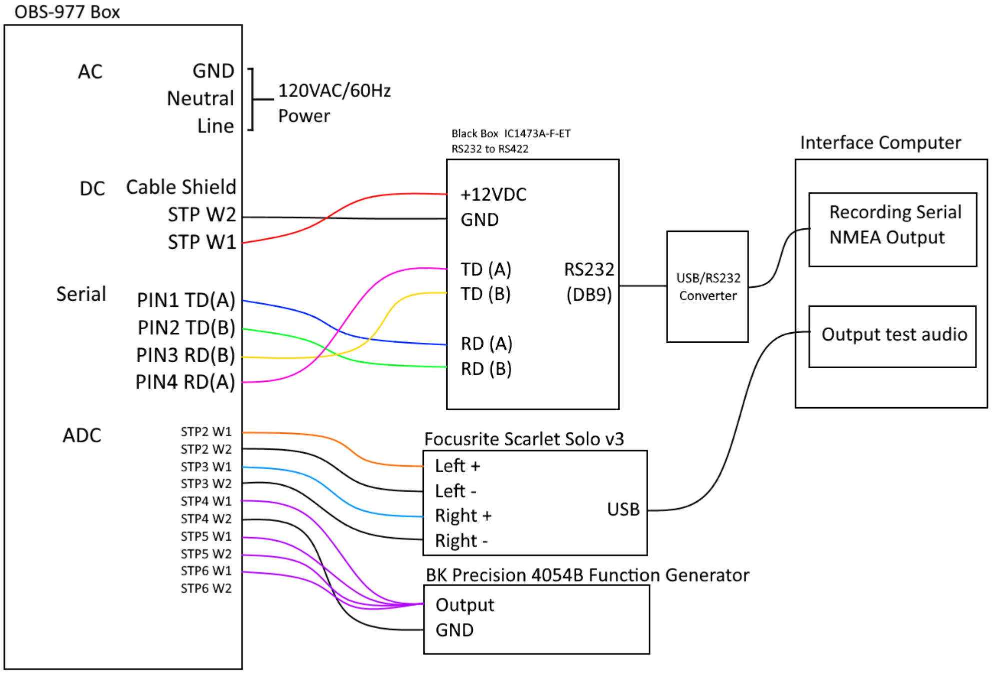


Figure 2. Integration test hardware setup.

2.3. Test Data

A copy of the observer-cavitation-test.WAV was added to the interface computer. The file was 3 h long, and when played back on a loop, it resulted in the cavitation indication values shown in Figure 3. For integration testing purposes, this file was only played back once. Note that during software testing, however, a more extensive ‘dry-run’ test was performed where the system was run for over 18 hours to verify its readiness for long-term vessel operation, and the test file was played into the system multiple times.

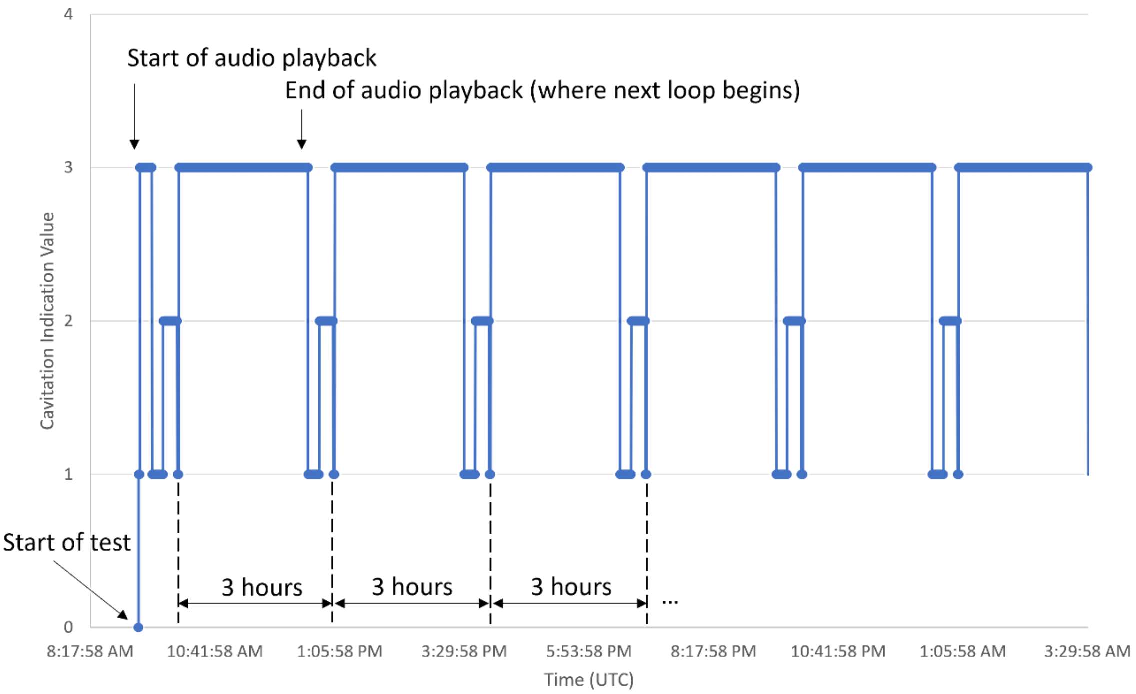


Figure 3. Expected National Marine Electronics Association (NMEA) string cavitation indication values.

2.4. Test Steps

The integration test procedure as described in Table 1 was followed.

Table 1. Integration Test Procedure.

Instruction	Expected results
Step 1	
Ensure power is not connected to the OBS-977 power supply.	
Step 2	
Open *PuTTY* on the interface computer. Configure *PuTTY*: • Serial line: COM port of serial adapter connected to serial IO board H3 • Speed (baudrate): 4800 • In *Session>Logging*, under *Session Logging*, select *All session output*. Click *Browse,* and select location to save log on interface computer. Click *Open* button to connect.	
Step 3	
Record the time.	
Step 4	
Connect power to OBS-977 box.	
Step 5	
Once Observer is powered on, it should begin recording to its SD card within ~2 min. Verify that files are recording to *Observer* SD card and are increasing in size. Open SSH connection to Observer, and issue command `$ ll /mnt/extstorage/*` two or more times. Checking file sizes and verify WAV/CSV files exist and are increasing in size.	Observer is connectable over SSH. One folder exists for each channel, and each WAV/CSV file is increasing in size.
Step 6	
Open *Audacity* on interface computer. Select *Focusrite Scarlet Solo* audio interface as output device. Enable stereo output. Start playback of *observer-caviation-test.WAV*.	Audio begins playing back
Step 7	
While test is running, verify Observer is outputting cavitation NMEA strings over serial port.	NMEA messages are received every 10 s.

Instruction	Expected results
Step 8	
Allow recording to run for 3.5 h while *observer-caviation-test.WAV* finishes playing back.	
Step 9	
In *AMARlink*, connect to the *Observer* and stop recording.	
Step 10	
In *AMARlink,* download all recorded data from *OBS-977*. Save these files to hard drive.	
Step 11	
Download all logs files and configuration files from *Observer*. Save these files to hard drive.	
Step 12	
Remove wall power from *OBS-977*. Wait 20 s for it to shut down.	
Step 13	
Save cavitation NMEA serial data captured by PuTTY to hard drive. Make copy of serial data capture. Rename it to have "`.CSV`" extension. Open this file in a text editor, and find/replace all "`*`" characters with "`,`" so last SPL value column can be treated as its own column.	
Step 14	
Execute *JASCO DataSummary Tool* on downloaded SD card data to produce `parse-summary.txt` file with recorded data.	Expected parse-summary output: • No gaps present in recording • Non-acoustic channel values for battery current is 0.1~0.5-A. • Non-acoustic channel values for battery voltage on the power input that was supplying power is 11~12-V.
Step 15	
Review cavitation NMEA string data CSV file and verify timestamp values (field 0).*	The first timestamp matches the date and time that the test was started. Subtracting each timestamp from the one previous to it, all timestamp values are all 10 s apart. Note that the first 10–20 timestamps may have some variance from 8–10 s, but the rest that follow should be 10 s apart.

Instruction	**Expected results**
Step 16	
Review cavitation NMEA string data CSV file. Verify cavitation indication values (field 1).* Plot cavitation indication column vs. timestamp column as scatter plot.	Sequence of cavitation matches what is shown in Figure 3.
Step 17	
Review cavitation NMEA string data CSV file. Verify SPL values corresponding to channels connected to function generator.*	Excluding first entries where cavitation indication value is 0 (as PAMlab is starting cavitation detector), SPL is constant (±1%) on following columns (fields 5, 6, 7, 8): • Field 5: Pressure Sensor 3 RMS SPL, dB re 1 μPa² • Field 6: Accelerometer X-Channel RMS Accel, m/s² • Field 7: Accelerometer Y-Channel RMS Accel, m/s² • Field 8: Accelerometer Z-Channel RMS Accel, m/s²

* Refer to MMP3 Message ICD document for full description of cavitation NMEA string protocol.

2.5. Test Results

Integration Test Result: Pass

Date run: 28 Sep 2021 (15:41–19:12 ADT)

Notes:

- NMEA strings were produced by OBS-977 throughout the entire test.
- The first timestamp value of 1632843719 (28 Sep 2021 3:41:59 PM) agrees with the start time of the test.
- The first cavitation indication of “1” was sent 9 s after the previous NMEA message. All that followed were 10 s apart until the end of the test.
- The cavitation indication values were as expected (see Figure 4).
- The SPL values on channels connected to the function generator were constant and within ±1% for the test duration.
- The DataSummary Tool’s output indicated no gaps were present in the recording on acoustic and non-acoustic channels.

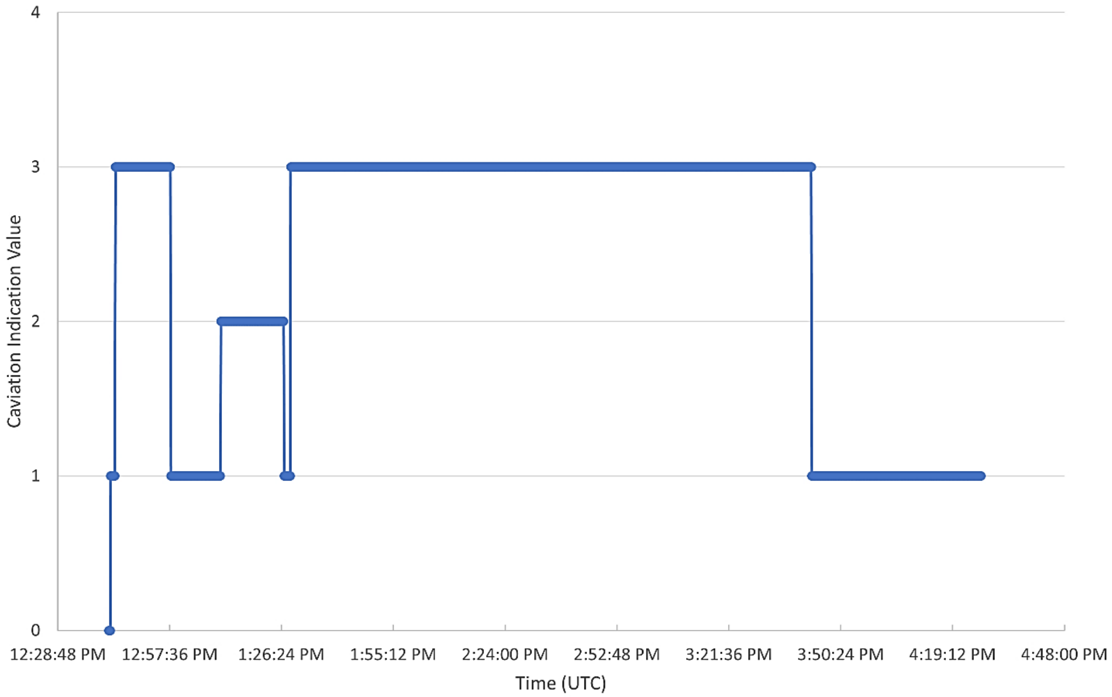


Figure 4. Plot of the OBS-977 integration test cavitation indication value.

3. INSTALLATION SET TO WORK

Following the successful integration test performed in Halifax, the CMS installation was performed onboard the *Ferbec.* Delays occurred when trying to correctly wire the Observer to the Moxa Box and during further connection troubleshooting (see Figure 5). The CMS installation and HMI implementation was performed by CSL. JASCO was unable to participate (in person) in the connection troubleshooting due to COVID protocols, but remote assistance and troubleshooting were provided.

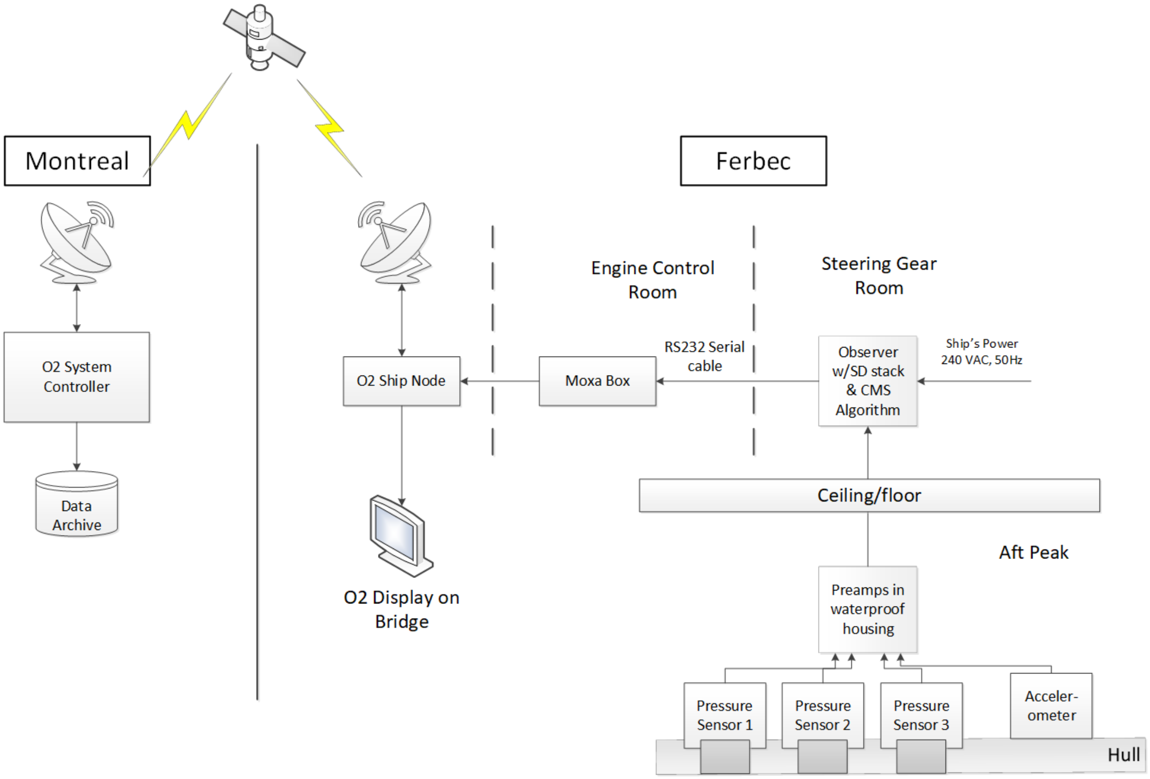


Figure 5. Block diagram for the operational evaluation of the cavitation monitoring system.

3.1. Troubleshooting

The following troubleshooting steps were provided to CSL. JASCO advised starting directly at the Observer box and working away from it (one device at a time) to solve a connection issue with a serial line:

1. The box is not powered. When it is powered on, there will be a green light lit inside the Observer box.
2. The wiring is incorrect. Tx/Rx and A/B.
3. The Moxa converter is configured incorrectly (RS422 on one side, RS232 on the other). No handshaking signals, wrong baud rate, etc.

4. A connection upstream of the Moxa box is wired incorrectly. Possibly the RS232 side of the Moxa box needs a null modem.

Troubleshooting options:

1. Open the Observer box, and ensure the power supply has a green light.
2. Only connect the Tx lines from the JASCO box (pins 1 and 2). Try connecting to the Rx and then the Tx lines on the Moxa box. Try to get anything showing up every 10 s, and then troubleshoot from there.
3. Connect a laptop with an RS422 directly to the output of the Observer box to ensure RS422 traffic is coming out of it.
4. Connect a laptop with an RS232 directly on the *output* of the Moxa box
5. Connect a laptop with an RS422 directly on the *input* of the Moxa box to see if typed characters are being received properly at the far end.

On 9 Nov 2021, CSL confirmed the CMS-O2 connection was successfully established. The data were first evaluated by CSL before implementing a Tip on the captain’s human machine interaction (HMI). The cavitation detection algorithm output data every 10 s as expected.

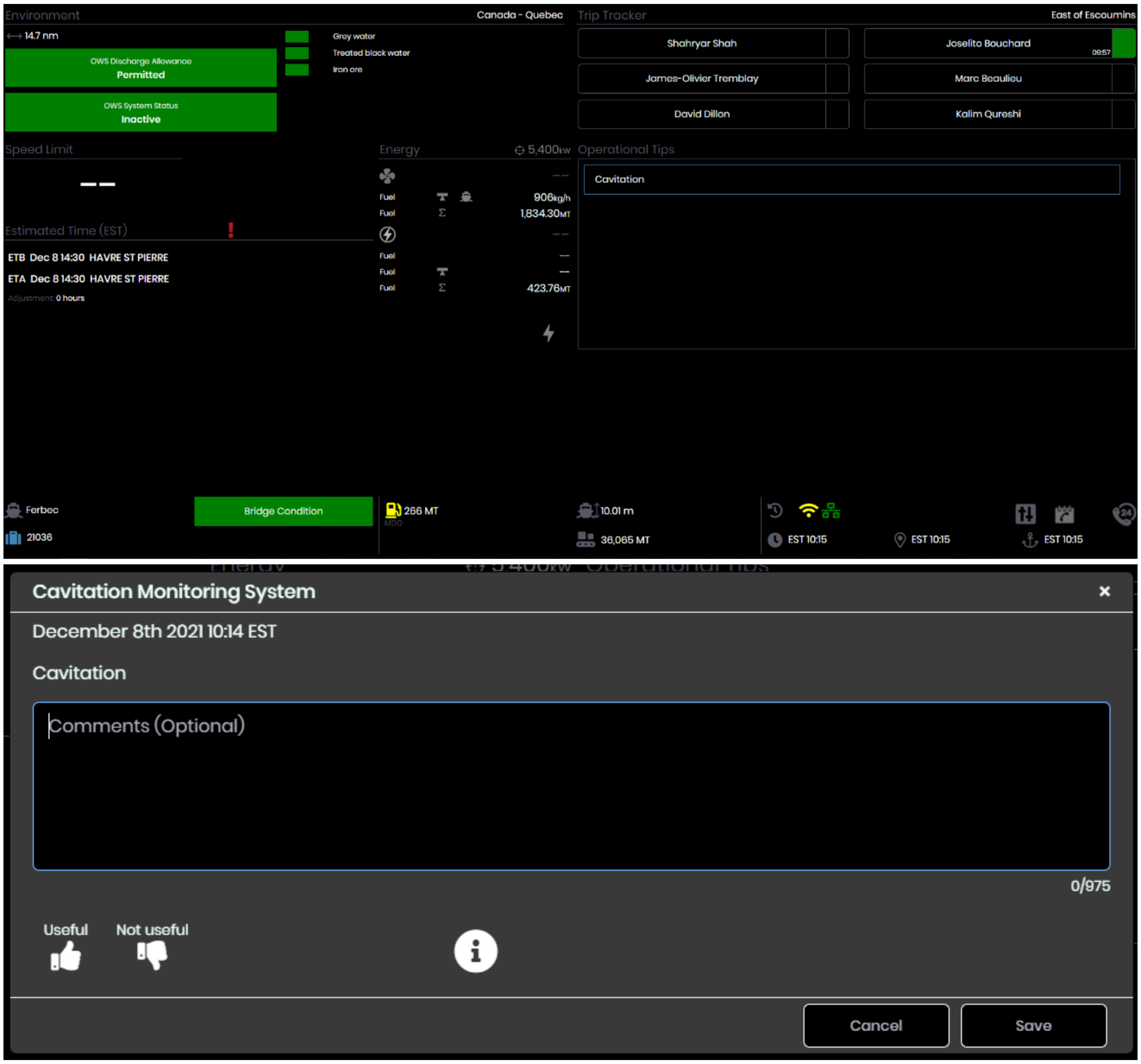
3.2. CMS-O2 Connection and Troubleshooting

On 24 Nov 2021, CSL confirmed that the HMI Tip development was complete and implementation of the CSM-O2 system was successful. However, intermittent data issues followed, which warranted further investigated by CSL with the following assistance from JASCO:

- The data coming through every 10 s indicated the system was running and producing output. The serial data was completely incorrect, which indicates that there was a wiring (or wiring connection) problem, or something was configured incorrectly, perhaps the MOXA box. The output switched between working and non-working a few times, which would also indicate a hardware issue. JASCO suggested connecting a computer with an RS232 port directly to the output of the Observer inside the JASCO enclosure, and then working upstream (RS422 output of the enclosure, then at the MOXA box). If this was not possible, then every serial wire in the serial path should be disconnected and reconnected as follows:
    - Serial connector on Observer board (very prone to damage by an untrained or inexperienced person). JASCO only recommends this after trying all connections below and after getting more detailed instructions from JASCO.
    - Wires on the RS232/422 converter and terminal block inside the JASCO enclosure.
    - Junction box connections.
    - MOXA box connection.

  - Check all cable connectors and pins for open paths.
- If none of those troubleshooting options were successful, then possibly replace the RS232-to-RS422 converter inside the JASCO enclosure.

On 26 Nov 2021, CSL confirmed that the CMS-O2 system was fully operational. The Tips implemented on the HMI have a section for the captain to make comments and to select if the Tip was useful (Figure 6). CSL does not currently have procedures in place to influence the vehicle operation based on Tips. More details on this will be provided in the final report.



ETB Dec 8 14:30 HAVRE ST PIERRE
ETA Dec 8 14:30 HAVRE ST PIERRE
Adjustment: 0 hours

Cavitation Monitoring System
December 8th 2021 10:14 EST
Cavitation

Figure 6. (Top) The human machine interaction (HMI) onboard the *Ferbec* and (bottom) a Tip implemented.

LITERATURE CITED

Martin, S.B., P. Borys, C. Robinson, J.P. Sharman, and J.J.-Y. Delarue. 2021. *MMP3 April to June 2021 Field Trial and System Design Report*. Document 02472, Version 1.0. Technical report by JASCO Applied Sciences for Innovation Centre of Transport Canada.

TP XXXXXX

MMP3 Field Trial Report

Data Logged and Analyzed during Field Trial

JASCO Applied Sciences (Canada) Ltd

28 January 2022

Prepared for:

Matthew Cooke
Innovation Centre of Transport Canada
Contract T8009-190191/003/XLV

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P001556-003
Document 02617
Version 2.0

NOTICES

Suggested citation:

Maxner, E.E., S.B. Martin, and P. Borys. 2022. MMP3 Field Trial Report: Data Logged and Analyzed during Field Trial. Document 02617, Version 2.0. Technical report by JASCO Applied Sciences for Innovation Centre of Transport Canada.

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Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.
TP XXXXX

2. Project No.
P001556-003

3. Recipient's Catalogue No.

4. Title and Subtitle
MMP3 Field Trial Report

5. Publication Date
January 2022

6. Performing Organization Document No.
XXXX

7. Author(s)
Emily Maxner, S. Bruce Martin, Pablo Borys

8. Transport Canada File No.
XXXX

9. Performing Organization Name and Address
JASCO Applied Sciences (Canada) Ltd.
32 Troop Ave, Suite 202
Dartmouth, NS, B3B 1Z1, Canada

10. PWGSC File No.
XXXX

11. PWGSC or Transport Canada Contract No.

12. Sponsoring Agency Name and Address
Transport Canada, Innovation Centre

13. Type of Publication and Period Covered

14. Project Officer
XXXX

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This is the Field Trial for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. The Field Trial occurred from end of November 2021 to end of December 2021. A Cavitation Monitoring System (CMS) was installed on board and interfaced to pressure sensors and accelerometers. Every 10 seconds, the CMS output a cavitation indicator to the O2 vessel management system onboard the M/V *Ferbec*, operated by Canada Steamship Lines (CSL). The CMS did not function correctly in real-time, likely because the Aft Peak where the sensors were located was needed for sewage storage, resulting in damaged pressure sensors. Recorded data were analyzed with an accelerometer-only version of the Cavitation Detection Algorithm (CDA), which yielded cavitation indications as expected. The O2 Human Machine Interface operated as expected; however, vessel operators did not use the CMS-O2 system to guide operations due to commercial requirements. An interview with the captain indicated that underwater radiated noise was unlikely to ever be a consideration for commercial operations unless specifically required by Transport Canada.

17. Key Words
Cavitation monitoring, accelerometer, pressure sensors

18. Distribution Statement
Limited number of copies available from the Innovation Centre

19. Security Classification (of this publication)
Unclassified

20. Security Classification (of this page)
Unclassified

21. Declassification (date)
—

22. No. of Pages
xiii, 34, apps

23. Price
Shipping/Handling

CI/IC 79-005
Rev. 96

Canada

Transport Canada Transports Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. No de la publication de Transports Canada.
TP XXXXX

2. No de l'étude
P001556-003

3. No de catalogue du destinataire

4. Titre et sous-titre
XXXX

5. Date de la publication
janvier 2022

6. No de document de l'organisme exécutant
XXXX

7. Auteur(s)
Emily Maxner, S. Bruce Martin, Pablo Borys

8. No de dossier - Transports Canada
XXXX

9. Nom et adresse de l'organisme exécutant
JASCO Applied Sciences (Canada) Ltd.
32 Troop Ave, Suite 202
Dartmouth, NS, B3B 1Z1, Canada

10. No de dossier - TPSGC
XXXX

11. No de contrat - TPSGC ou Transports Canada

12. Nom et adresse de l'organisme parrain
Transport Canada, Innovation Centre

13. Genre de publication et période visée

14. Agent de projet
XXXX

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

17. Mots clés

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)
—

22. Nombre de pages
xiii,

23. Prix
Port et manutent

CI/IC 79-005
Rev. 96

Canada

EXECUTIVE SUMMARY

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board Cavitation Monitoring System (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA). This project, dubbed MMP3, has three phases: developing the CMS, performing a Baseline Trial to collect cavitation and noise data, and performing an Operational Field Trial to evaluate the utility of a CMS on a working commercial vessel. This report covers the results of the Field Trial, describing the pressure sensor and accelerometer outputs and feedback from the vessel operators on the CMS-O2 system.

The Field Trial occurred from 26 Nov to 23 Dec 2021 on board the M/V *Ferbec* operated by Canada Steamship Lines (CSL). The CMS system did not function as expected due to the failure of the pressure sensors. Further analysis was performed on comparing sensor data obtained from the Baseline Trial that resulted in all sensors being linearly dependent, allowing the accelerometer data alone to be used for determining cavitation state. Details on the changes warranted to the Cavitation Detection Algorithm (CDA) will be included in the draft final report, to be delivered by 1 Feb 2022.

The overall CMS-O2 system performed as expected. When 'Tips' were implemented on the vessel's Human Machine Interface (HMI), operators could choose either the 'useful' or 'not useful' option when cavitation level is indicated or add notes during that time. The *Ferbec* crew did not use the CMS-O2 system to guide operations due to commercial requirements. The captain also provided feedback on situations involving marine mammals and vessel cavitation and their limitations, which is further discussed in this report. Due to commercial requirements to maximize vessel revenue, it will likely be very difficult to limit vessel operations to sub-cavitating conditions.

CONTENTS

FIGURES

1. INTRODUCTION

This report is a deliverable for JASCO Applied Sciences' project MMP3 Stream 2: 2A2: *Feasibility of Real-Time Shipboard Cavitation Monitoring and Management*. This project is supported by Transport Canada's Innovation Centre (TC-IC) under the Marine Mammal Protection (MMP) umbrella of projects with the goal of assessing the possible operational feasibility of using an on-board Cavitation Monitoring System (CMS). Such a system could provide vessels with real-time data on propeller cavitation levels, facilitating modifying operating states in areas of concern such as critical habitat of at-risk whale species identified as endangered under the Canadian federal Species at Risk Act (SARA).

JASCO previously a) delivered plans for the Baseline Underwater Radiated Noise (URN) characterization of a trial vessel (Martin et al. 2022), b) designed the prototype CMS used in the Baseline Trial , c) submitted a report summarizing the analysis and results obtained (Martin et al. 2021), and d) submitted a report on the integration (Diggle and Maxner 2021) and CMS installation (Martin et al. 2021).

A major interest of this project was evaluating the usefulness the CMS during operational field trials. The trials were conducted in November and December 2021, in a partnership with Canadian Steamship Lines (CSL) using their vessel M/V *Ferbec*, which transports iron ore from Havre-Saint-Pierre, QC, to Sorel, QC. A social science component to the trials evaluated perspectives from vessel operators as to whether it is useful for them to have cavitation information provided on the bridge through the vessel management system. This was conducted in two parts: 1) using a pop-up 'Tips' window for the bridge crew to show cavitation state and 2) interviewing the vessel operator, in particular the captain. This report is the next project deliverable that documents the details of the Field Trial, summarizes the results obtained, and provides a summary of feedback from the vessel operator.

2. METHODS

2.1. Cavitation Monitoring System Design

The CMS block diagram for the November to December 2021 Field Trial is shown in Figure 1. The data collection and analysis hardware were the same as employed for the Baseline Trial. For the Field Trial, the Observer hardware was running the cavitation detection algorithm described below. The algorithm outputs the cavitation state every 60 s using a National Marine Electronics Association (NMEA) compliant message over an RS-232 serial connection to the CSL O2 data system. The physical interface to the O2 system was a Moxa junction box located in the engine room.

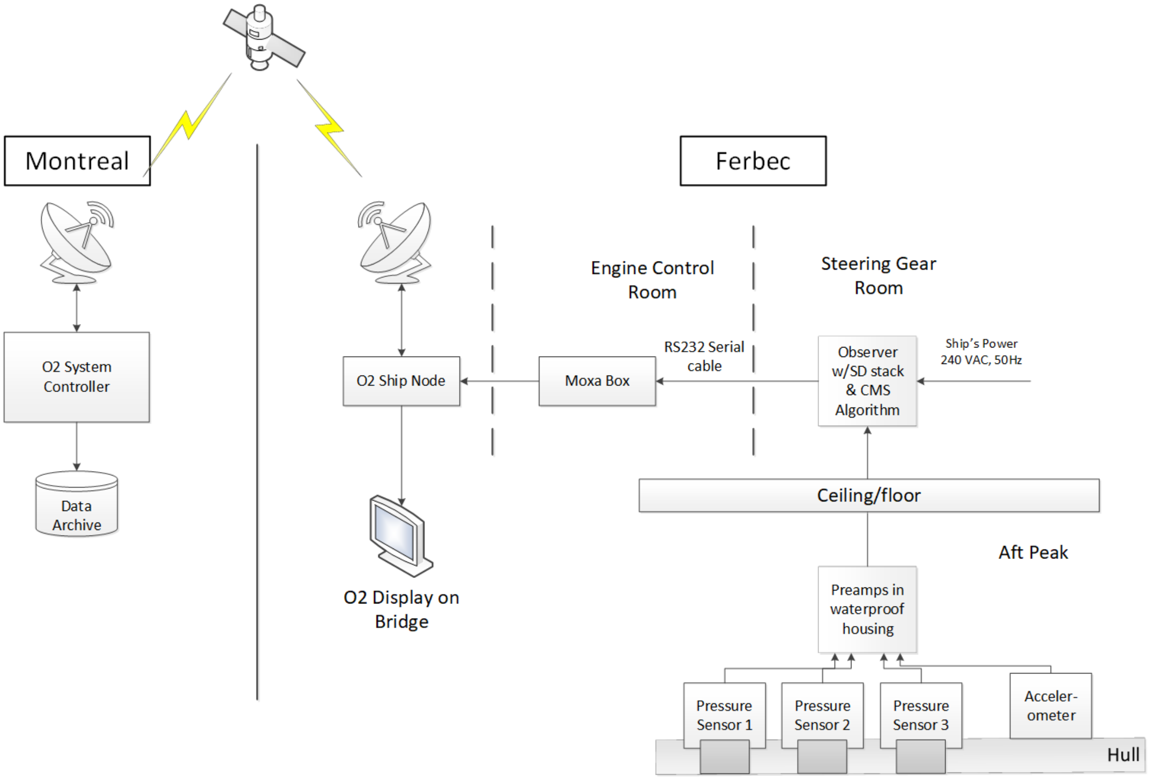

Figure 1. Block diagram for the operational evaluation of the cavitation monitoring system.

The NMEA-compliant message has nine data fields and the required checksum field. The data fields are: a timestamp, an indication of high/med/low cavitation state, an estimate of the current underwater radiated noise, and the current root mean square signal level for each sensors as a system health indication.

The Cavitation Detection Algorithm (CDA) aims to provide the CMS with means to alert when the vessel is in a fully cavitating state. Data obtained during the Baseline Trial were used to calculate pressure and acceleration levels as a function of speed through water, which in turn allowed a change point to be determined, i.e., a point at which the levels varied abruptly, indicating that full cavitation was occurring. Since data from all sensors yielded a very similar change point, it was possible to train a logistic regression machine learning model to classify real-time data into non-cavitating and fully cavitating states. The steps in the algorithm allow: 1) alerting the CMS in case the sensors were not underwater and 2) using 10 s of real-time sensor data to calculate pressure or acceleration levels and feed them into the Logistic Regression model to get a prediction of the cavitation state. Notably, during the construction of the Logistic regression model, it was determined that the levels from all sensors as a function of speed through water were linearly dependent. This would allow the using of only an accelerometer to determine the cavitation state—this possibility is discussed in the project's Final Report.

The CSL O2 system gathers various data on board the vessel and transmits them via satellite to CSL Headquarters in Montreal, QC, where the data are archived and processed. The processed data are formatted for presentation to the captain/mates and transmitted back to the vessels. The display on the Bridge has a main page that presents critical vessel information in a format standardized for all CSL vessels (Figure 2). Ship- and voyage-specific information is presented using 'Tip' (popup) messages that are acknowledged by the Bridge team (Figure 3). As shown in Figure 3, the Cavitation 'Tip' Messages displayed a 'useful' or 'not useful' button option (Figure 3). Cavitation levels were displayed on the O2 system as colour-coded levels of red (high cavitation), yellow (medium cavitation), and green (low cavitation). Vessel operators could then choose either the 'useful' or 'not useful' option when cavitation level is indicated, providing data on usefulness of displayed information. Room was provided also for the bridge crew to enter a comment or observation about the cavitation message.

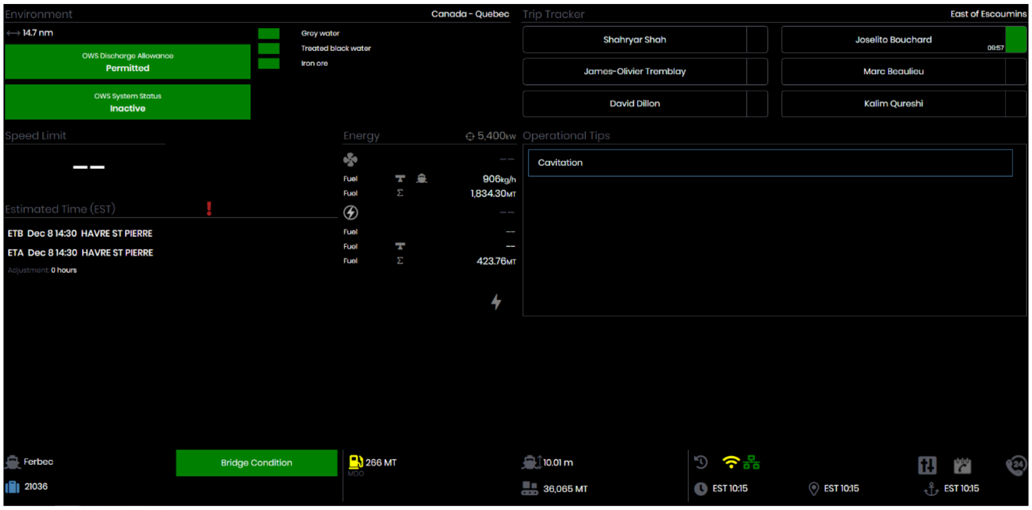

Figure 2. Main human machine interaction (HMI) display for the Canada Steamship Lines (CSL) O2 system.

Cavitation Monitoring System

December 8th 2021 10:14 EST

Cavitation

Figure 3. Example of a ‘Tip’ window used in the O2 system. The tips will stay active until either the user acknowledge the tips (if the tip is set to be acknowledgeable) or the condition generating the tip is no longer true.

CSL provided JASCO with an export from their O2 data management system that included the following:

- Latitude and longitude,
- Speed over ground (SOG) and heading,
- Wind speed and direction,
- Shaft revolutions per minute (RPM),
- Forward port draft.
- Aft port draft,
- Cavitation Detection Algorithm output, and
- Root-mean-square (rms) pressure and acceleration levels from the CMS sensors.

2.2. Field Trial Equipment Overview

Three pressure sensors and a 3-axis accelerometer were mounted inside the ship's hull using specialized housings, designed in cooperation with CSL. Unlike the pressure sensor housing, the accelerometer housing does not have a hull penetration. The CMS electronics contained a JASCO Observer system and supporting electronics, which were mounted in the dry compartment. The Observer was returned to the JASCO Dartmouth facility following the Baseline Trial, and a system integration test occurred on 28 Sep 2021. Following Observer testing, the unit was returned to Quebec and reinstalled on the *Ferbec* in the steering gear room in November 2021 (Figure 4). The Observer was operational for the duration of the Field Trial, starting 26 Nov 2021, and removed once the trial was completed on 24 Dec 2021.

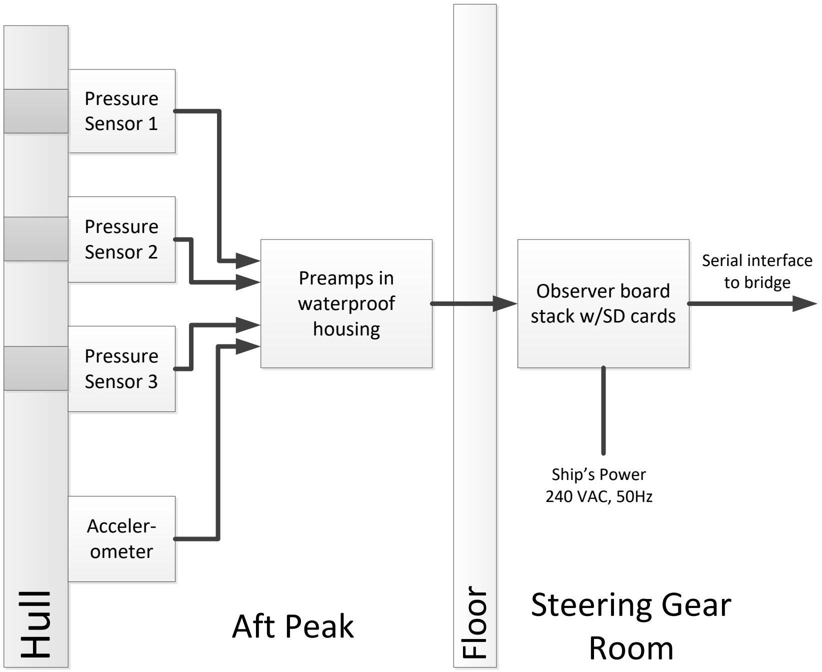

Figure 4. System overview.

2.2.1. M/V *Ferbec* Transits

The *Ferbec* is a bulk carrier delivering iron ore between Havre-Saint-Pierre (north) and Sorel (south), Quebec (Figure 5). An average journey takes approximately 40 h, including some time spent on either end to transfer cargo. At a standard through water cruising speed between 13 and 14 kn, there are two distinct main shaft RPM regimes, 90–92 and 95–96 RPMs. Speed over Ground (SOG) and Speed through Water (STW) are generally similar in the first half of the transit. In the second half of the transit, as the vessel enters the more constrained region of the Saint Lawrence, the SOG decreased while the STW remained the same as the vessel moved against the increasing current. On either end of the transit, there was an acceleration and deceleration period lasting between 45 min to 1 h. During the main portion of transit and when changing course, the *Ferbec* STW remained relatively constant.

During the Field Trial period, four laden voyages from Havre-Saint-Pierre to Sorel occurred, with arrivals in Sorel on 28 Nov, 4 Dec, 11 Dec, and 23 Dec 2021. It was determined during the Baseline Trial data analysis that the during the voyages in the ballast condition from Sorel to Havre-Saint-Pierre, the CMS sensor were not in the water, and hence the cavitation state could not be determined.

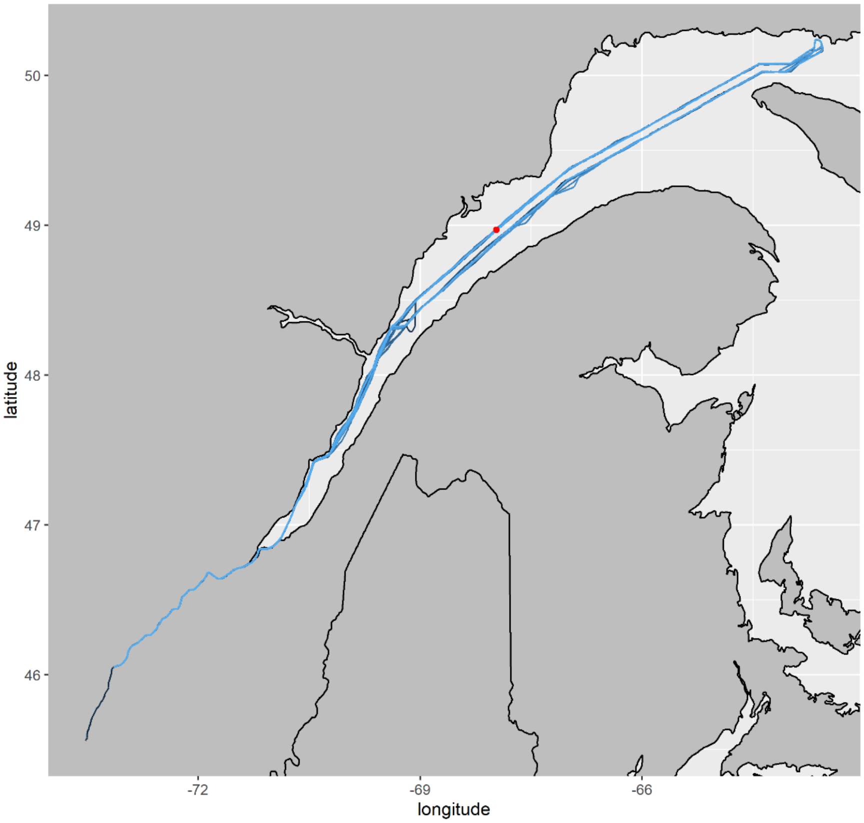

Figure 5. M/V *Ferbec* shipping route between Sorel, QC (south) and Havre-Saint-Pierre, QC (north). The red dot indicates the AMAR location during the Baseline Trial.

2.2.2. M/V *Ferbec* Operator Feedback

On 24 Nov 2021, CSL confirmed that the HMI Tip development was complete and implementation of the CMS-O2 system was successful. However, intermittent data issues followed, which warranted further investigations by CSL and remote assistance from JASCO. On 26 Nov 2021, CSL confirmed that the CMS-O2 system was fully operational and waiting to receive feedback from the captain before implementing Tips. Tips were live from 6 Dec 2021 to 23 Dec 2021. An interview with the *Ferbec* captain occurred on 9 Dec 2021, providing details on the vessel constraints and a summary of the CMS-O2 feedback (see Section 3.3).

2.3. Data Analysis

On completing the field trial, the CMS system data logged in the CSL O2 system were provided to JASCO and analyzed for this report. The analysis occurred in two steps. First, a quality review of the O2 data and CMS data. Second, determining if the CMS system indicated that the *Ferbec* was cavitating at the same shaft RPMs and/or speed over ground like we expected as a result of our analysis of the Baseline Trial data.

3. RESULTS

3.1. Cavitation System Performance

To assess the performance of the CMS, the relationship between different recorded variables and the resulting cavitation state predictions were analyzed. In Figure 6, the shaft RPM, pressure from Channel 1, and the Z component of the acceleration are shown together with the cavitation flag for 26 Nov to 24 Dec 2021. The shaft RPM and the Z-acceleration are highly correlated. During the southbound laden voyages, the accelerations were approximately 130 dB re 1 μm/s^2, matching the corresponding maxima in the shaft RPM panel. The rest of the RPM maxima correspond to regions in the Z acceleration with values of around 110 dB re 1 μm/s^2, which occurred during the northbound ballast voyages.

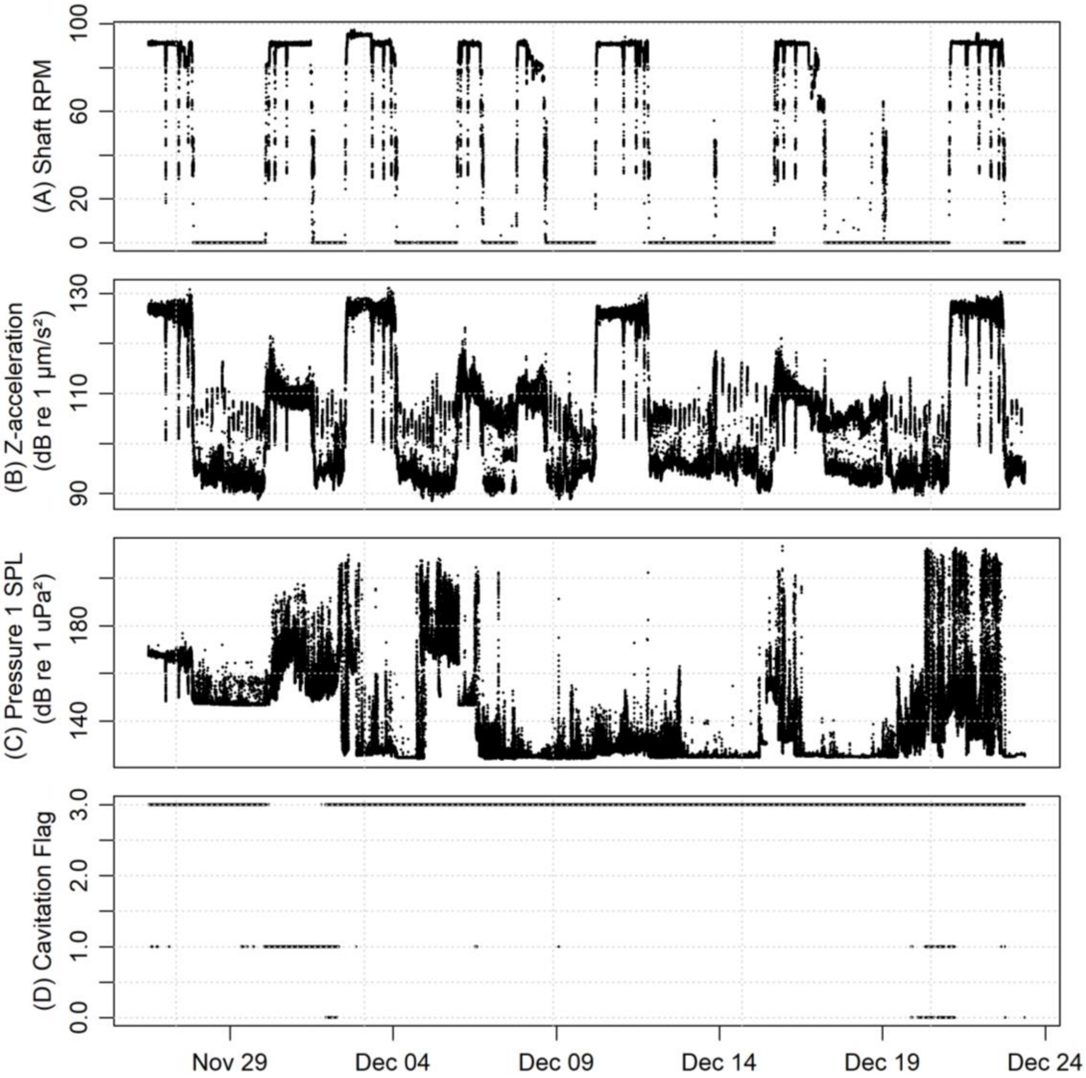

Figure 6. Summary of key CMS data from the *Ferbec's* Field Trial. (A) Shaft revolutions per minute (RPM). (B) Levels calculated from the Z-axis of the accelerometer. (C) Pressure levels calculated from Channel 1 of the pressure sensor. (D) The Cavitation Flag, where (0) indicates no cavitation, (1) indicates cavitation, and (3) indicates the pressure levels were too low for cavitation to be detected.

From the analysis presented in the Baseline Trial report, we expected the pressure levels to be correlated with the acceleration levels and consequently with the RPM. The pressure levels appear to match the acceleration levels up until 1 Dec, 2021 after which the pressure levels are mostly below the 160 dB re 1 µPa^2 until 20 Dec, 2021 when the levels vary abruptly between 130 and 180 dB re 1 µPa^2 To analyze the situation closer, Figure 7 shows all the pressure channels from where it is clear that Channel 2 also exhibits a strange pattern, and Channel 3 was not operational, which we had also noted during the Baseline Trial. A plausible explanation for the malfunction of the pressure sensors 1 and 2 is that the aft peak was used for sewage storage during the trial, which may have flooded the sensor housing or pre-amplifier housing. The pressure sensors use the atmospheric pressure at the back of the sensor as a reference pressure. Thus, they may also have been affected by having a higher 'backing' pressure due to the sewage than during the Baseline Trials. Further information on when this began has been requested from the ship's engineers; however, we have not yet heard back from them.

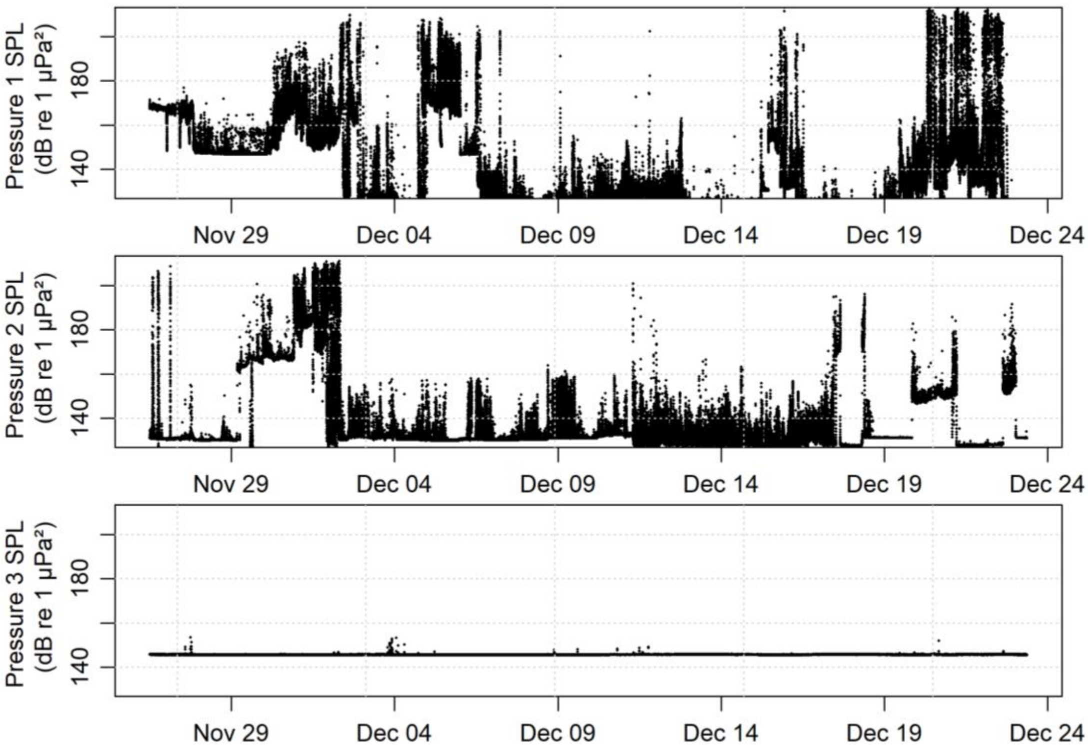

Figure 7. Time series of the three pressure sensors during the Field Trial. Pressure sensor 3 was also non-functional during the Baseline Trial.

The first step in the CDA determines if the pressure sensors are underwater using a pressure level threshold of 140 dB re 1μPa^2. Thus, for most data collected, the CDA reported levels were too low to predict any cavitation states (using a value of '3'). An important improvement to the algorithm would not only determine if the sensors are underwater, but also determine if they are working properly.

The three components of the acceleration (Figure 8) exhibit a very similar pattern with the X and Y axes showing similar values, a maximum of around 110 dB re 1 μm/s^2, and a minimum of 90 dB re 1 μm/s^2. The Z axis has a better dynamic range with values from 90 dB re 1 μm/s^2 up to 130 dB re 1 μm/s^2. These levels correspond to what was also measured during the Baseline Trial.

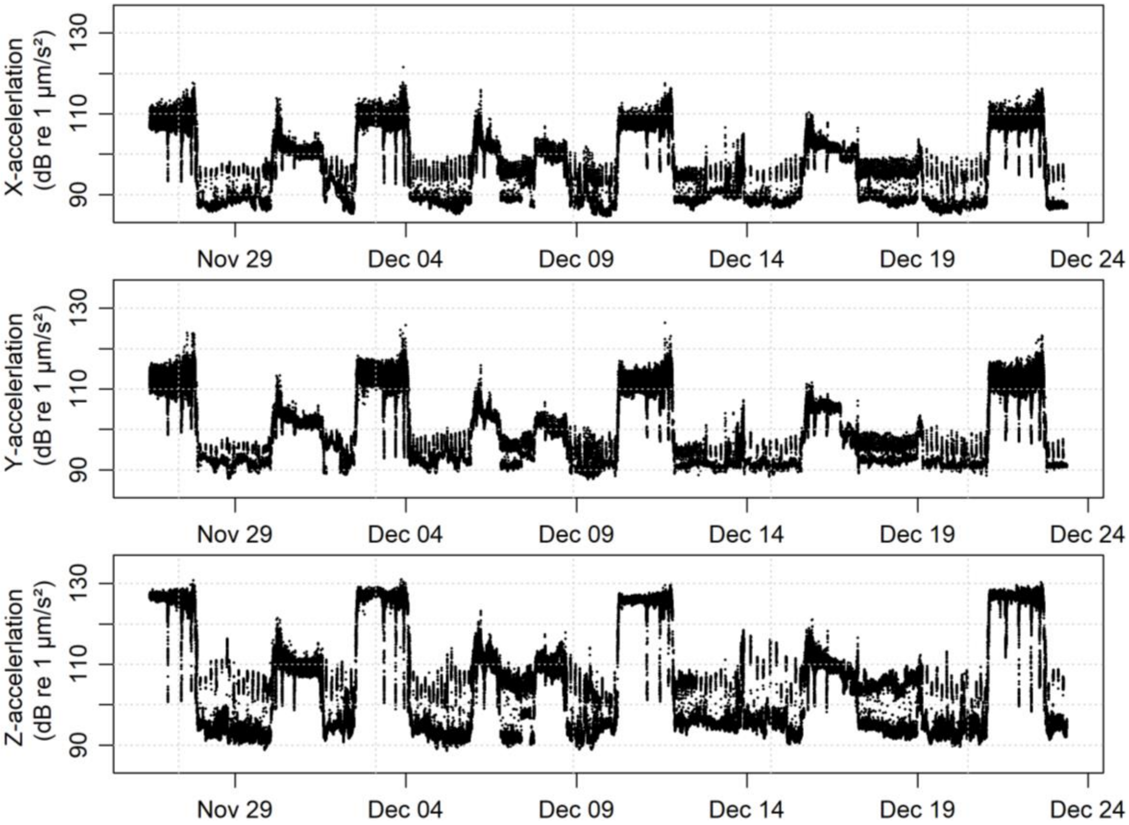

Figure 8. Time series of the acceleration sensors during the Field Trial. These sensors show the same patterns as was observed during the Baseline Trial.

Figure 9 provides more information about the behaviour of the acceleration levels, in particular the Z component, by presenting them as a function of shaft RPM and location during one complete transit cycle (in this case Mon 29 Nov to Sun 5 Dec 2021). A key element when designing the CDA was determining whether the sensors were underwater. The acceleration levels as a function of shaft RPM clearly indicate both scenarios as clusters of data points in which the same RPM value results in two distinct acceleration values. This phenomenon is amplified when viewing the levels as a function of geographic position of the vessel where two curves appear corresponding to the direction of travel. Finally, when looking at the levels with respect to a day of the week, it is possible to identify periods when the vessel was in port (90 dB re 1 µm/s^2), and periods when the vessel was travelling loaded (130 dB re 1 µm/s^2) or in -ballast (110 dB re 1 µm/s^2). Dips in the acceleration curve can be noted on Tuesdays, Fridays, and Saturdays, which corresponded to the vessel decelerating to pick up pilots.

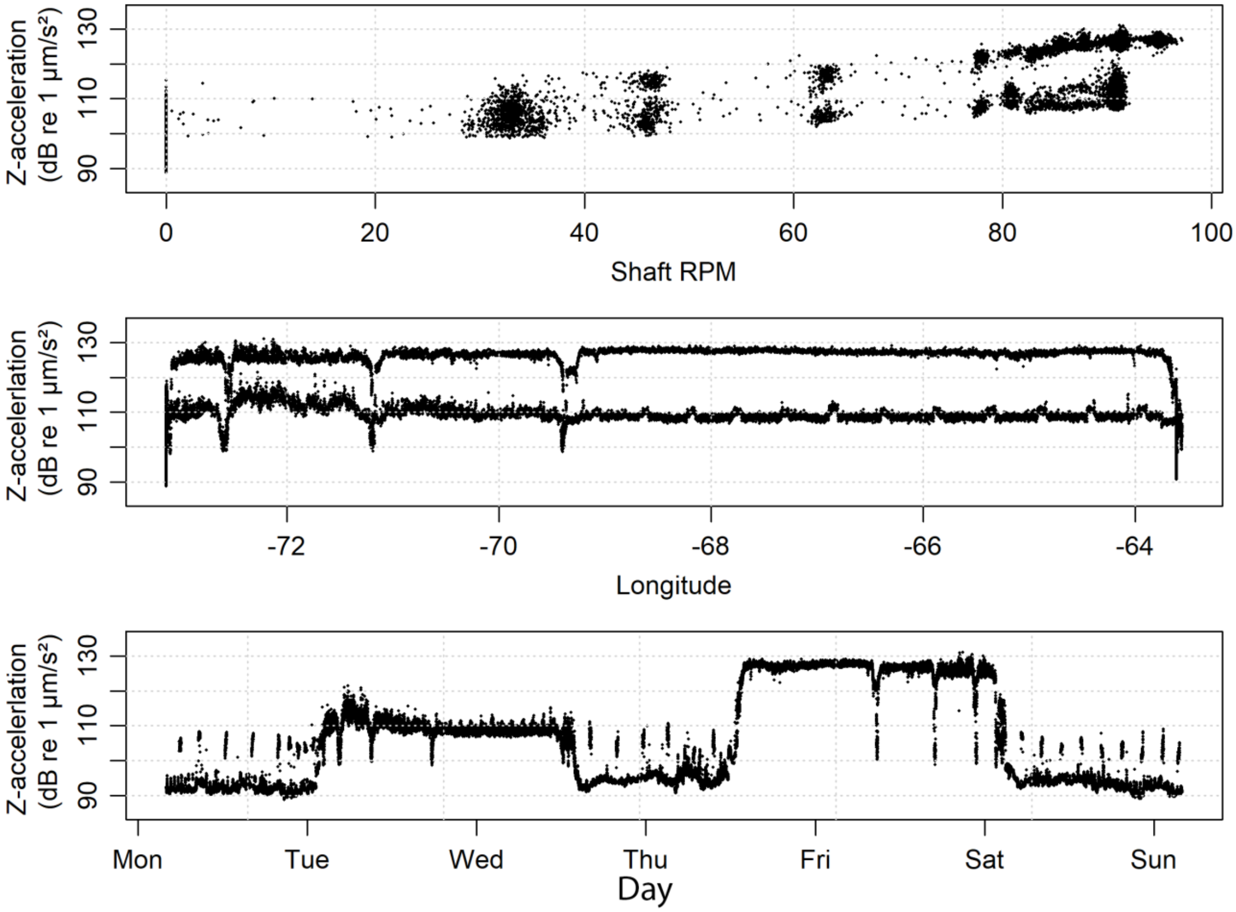

Figure 9. Summary of the Z-acceleration levels against key trial co-variates: (A) Shaft RPM, (B) longitude (-73 near Sorel, -63.5 near Havre-Saint-Pierre); and (C) day of the voyages (Mon 29 Nov to Sun 5 Dec).

While the CDA, and hence the CMS, were unable to be tested properly due to the malfunction of the pressure sensors, the accelerometer sensor performed well and aligned with what was recorded during the Baseline Trial. Accelerometer data confirmed that the state of the vessel, i.e., loaded or in ballast, is key not only for the CMS but also for assessing the overall noise effect on marine life in the region. The accelerometer results show at least a 10 dB re 1 µm/s^2 difference between loaded or in ballast for 60 RPM and above.

3.2. Notes from the HMI Tip Interface

The HMI Tip interface performed as expected. Vessel operators could choose either the ‘useful’ or ‘not useful’ option when cavitation level is indicated, providing data on the usefulness of displayed information. However, the *Ferbec* captain and crew did not use the CMS-O2 system to guide operations due to commercial requirements. No notes were entered by the bridge crew in the comments sections.

3.3. Captain’s Observations

JASCO representatives had the pleasure of interviewing the captain of the *Ferbec* in coordination with staff from CSL’s project management, environmental, and engineering teams. This allowed an evaluation of perspective from vessel operator on the usefulness of knowing their vessel’s cavitation state. In general, commercial vessel operators are not concerned about the underwater sound signature of their vessel, rather the timing of their voyage. The following information was obtained from the interview with the captain.

Captain Beaulne has been the Master of many vessel types on routes through Canadian and international waters. During his long career, he has never considered underwater noise emissions while determining how to operate his vessels, although he is aware that it is increasingly of concern and is interested in how to mitigate URN. In almost all cases, determining how fast to sail a vessel is driven by minimizing the transit times while respecting the requirements of local regulations and conditions. For the *Ferbec*, regulations included respecting the 10 kn speeds limits in the Gulf of St. Lawrence and around the mouth of the Saguenay River. He also had to time his arrival at Les Escoumis while laden according to tide cycles to avoid running aground during low tide. While running other vessels, he had to adjust his speed to arrive in time for a scheduled berthing slot. Captains must always adapt to changes in weather and local traffic and consider the comfort and safety of their crew, all while arriving at their destination on time.

The captain spoke of his observations that the density of whales can be high in areas close to the coastline where there is a higher chance of greater densities of vessel traffic. Known marine mammal areas are typically governed by traffic lanes; however, vessels often seek permission to leave the traffic lanes. Areas such as the north shore in Quebec typically have vessels gaining permission to transit outside the traffic lanes to save time transiting along the shore or to avoid weather. Using the *Ferbec* as an example, the captain suggested that there can be very high noise levels around ports during berthing and departure. The noise is due to engine movements to bring the vessels alongside, whether using the ships own power or from tugs.

Captain Beaulne pointed out that the type of propulsion system on a vessel likely affects the noise it generates. Vessels like the *Ferbec* have a single engine directly coupled to a fixed pitch propeller. These vessels change speed by adjusting the engine speed and hence the shaft revolutions per minute. For pilots to communicate precisely with ships crews, all ships have standard engine settings of dead slow, slow, half ahead, and full ahead as their controls. Once at full ahead, the captain does have finer control over the RPM to adjust the speed slightly to account for currents, wind, local traffic, etc. For the *Ferbec*, the captain noted between slow and half ahead, the vessel reaches a critical resonant RPM where the vessel shudders violently but becomes comfortable again above this resonant RPM. Based on the results of the Baseline Trial, we believe that the cavitation inception speed for the *Ferbec* is around 6–7 kn, a speed too low for safely navigating in some areas of the St. Lawrence River.

During earlier discussions, the CSL headquarters staff noted that the captain has almost complete jurisdiction over a ship's schedule and safety during voyages.

4. DISCUSSION AND CONCLUSION

The cavitation indicator was inaccurate during the Field Trial because the pressure sensors malfunctioned, possibly caused by the Aft Peak being used for sewage storage during the Trial. Conversely, the accelerometer sensors performed as expected, the levels agree with the levels calculated during the Baseline Trial, and effectively describe the various stages during the trip of the vessel. Since the first step in the CDA, determine if the sensors were underwater, was based on the pressure sensors, the CMS did not operate and could not be tested.

The results from the accelerometer confirm the hypothesis presented in the Baseline Trial report: because pressure and acceleration are linearly dependent, it could be possible to rely solely on the accelerometer for the CMS. A more rigorous investigation will be presented in the Final Report of this project. It was, however, possible to use data collected during the Baseline Trial analysis to retrain the Logistic regression model, this time using only the acceleration levels. The predicted cavitation states using this modified algorithm are presented in the bottom panel of Figure 10, together with shaft RPM and the Z-acceleration levels for comparison. It is clear that higher levels of the acceleration/RPM match with a cavitation flag of 1, which corresponds to a fully cavitating state.

The *Ferbec*, like most commercial vessels, is on a precisely planned schedule to maximize the revenue from its operations. Like many ports where vessel arrival or departure is timed around the tides, the *Ferbec's* arrival at Les Escoumis is timed to occur near high tide. For the *Ferbec*, commercial requirements for the transit(s) to be successful are dependent on timing of the ship. The vessel has two windows per day for arriving at Les Escoumis, one before and one after low tide to target the loading port. This timing window is known before reaching the loading port, and therefore it is also known if the return trip will be on time to meet the window of opportunity. Thus, the engine may be forced to increase RPM on transit to complete the return trip on time. If the vessel is behind schedule, it is forced to anchor outside the port and wait for high tide before entering. This type of delay increases the cost of the voyage.

Before a CMS could be useful, much more research is required, such as the effect of depth on pressure sensor levels, probability of different ship types having sensors out of water, what regulators would envision using cavitation indications for, and how other factors affect vibration levels. If a CMS became successful, Transport Canada could authorize ships to travel at maximum non-cavitation speed. These issues are discussed further in the Final Report

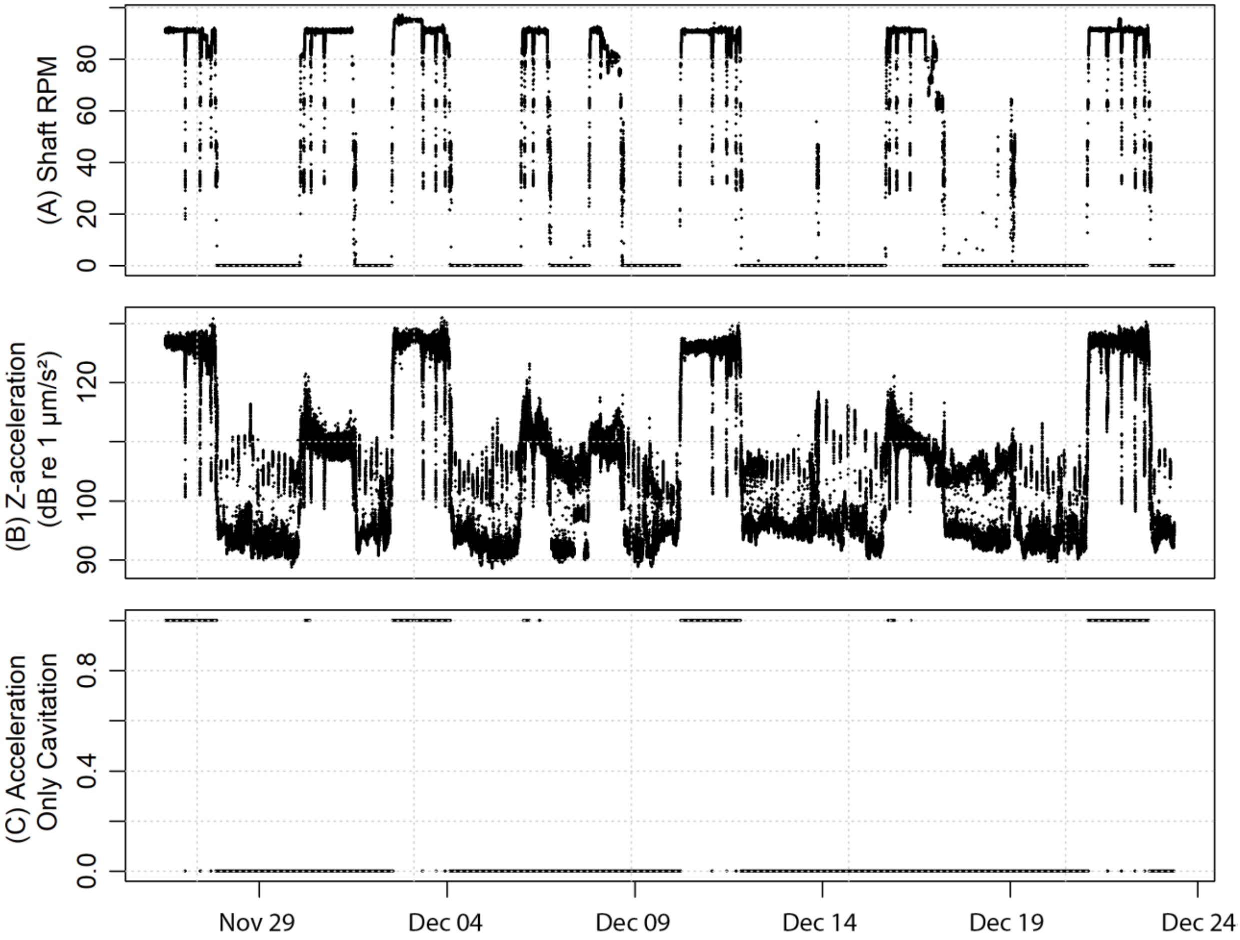

Figure 10. (A) The shaft revolutions per minute (RPM); (B) the z-axis of the accelerometer; and (C) Prediction of the cavitation state using data from the three acceleration channels. The Linear Regression model was retrained only with acceleration data retrieved during the Baseline Trial.

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