Vessel hull cleaning project
and
Operation of the underwater listening station

Final Executive Summary Report
2019

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1. Project background and objectives

The Whale Shark hull cleaning validation project was initiated in 2015, as a contract between Public Works and Government Services Canada (PWGSC), on behalf of Transport Canada, and Vancouver Fraser Port Authority.

The initial objectives of the project were to validate a new in-water hull cleaning technology, and to investigate if hull cleaning a vessel's hull may result in reductions to fuel consumption and underwater noise. The two key tasks for the port authority-led Enhancing Cetacean Habitat and Observation (ECHO) Program to manage included: 1) to develop the ability to measure underwater ambient noise and vessel source levels in the Strait of Georgia, and 2) to provide third-party validation of the environmental benefits of a new underwater hull cleaning technology (the Whale Shark) developed by All-Sea Enterprises Ltd.

The contract had been amended several times to extend the timeframe for both tasks. The ECHO Program successfully completed the first task through the installation of the underwater listening station (ULS), which was in operation from September 2015 to April 2018 in the Strait of Georgia.

The second task included facilitating the cleaning of three vessels in the Port of Vancouver using the Whale Shark technology, and studying the environmental safety, fuel consumption and underwater noise emissions of these vessels before and after underwater hull cleaning. Two of the three hull cleanings were completed using Whale Shark, and the results were provided in the December 2017, Summary Report[1] to Transport Canada. Due to significant delays in the readiness of the Whale Shark for environmental validation, Transport Canada proposed that a Canadian Coast Guard Vessel, the *CCGS Cygnus*, be used as the third vessel to fulfill the requirements of the contract to assess the potential benefits of hull cleaning to underwater noise and fuel consumption. As such, the coordination of the hull cleaning and data collection on underwater noise and fuel consumption was conducted by the National Research Council of Canada and Transport Canada. These parties provided the necessary data to the ECHO Program and subcontractors to conduct the third and final noise and fuel consumption evaluation.

This report summarizes the hull cleaning validation project, which includes the evaluation of underwater noise and fuel consumption data for the vessels cleaned with the Whale Shark in 2017, as well as the results of the sea trials completed for the *CCGS Cygnus*. The operation of the ULS from 2015 to 2018 is also summarized herein.

2. Whale Shark summary of results

2.1. Whale Shark objectives

All-Sea Enterprises (acquired by Subsea Global Solutions (SGS) LLC in March, 2017) developed the Whale Shark, which was promoted as an environmentally responsible underwater hull cleaning technology, aiming to capture and filter all effluent from the hull cleaning process. The development of the Whale Shark technology for a commercial-grade product has been underway for the last number of years, with several modifications to the system. Transport Canada's interest in the Whale Shark included not only whether the technology was environmentally safe for use in Canada, but also whether there were potential benefits to fuel consumption and vessel underwater noise emissions as a result of hull cleaning.

[1] Whale Shark Vessel Hull Cleaning Validation Project And Year 2 Operation Of The Underwater Listening Station. Summary Report 2017.

In February, 2017, it was believed that the Whale Shark technology was ready for environmental validation. As such, the ECHO Program facilitated the hull cleaning of two vessels; a bulk vessel and a tanker, which call the Port of Vancouver on a regular schedule.

The objectives of the Whale Shark validation project, were to clean a minimum of three vessel hulls and undertake the following:

1. Evaluation of the containment and capture of debris/contaminants released during the underwater hull cleaning. Environmental sampling was conducted by Fisheries and Oceans Canada and Transport Canada, with sub-contractors and logistics managed by Vancouver Fraser Port Authority.
2. Evaluation of the potential noise reduction resulting from a clean hull after the Whale Shark technology has been used. Vessels transited the ULS, both before and after hull cleaning, and JASCO Applied Sciences conducted an evaluation of the potential changes in underwater radiated noise levels.
3. Evaluation of the potential fuel savings resulting from a clean hull after the use of the Whale Shark technology. Vessels provided approximately three months of fuel consumption data before and after hull cleaning for evaluation by Det Norske Veritas (DNV-GL).

Based on these objectives, a summary report was provided to Transport Canada in December 2017, which included details and results of the two hull cleanings and associated environmental sampling, underwater noise measurements and fuel consumption analysis. A summary of these results are provided in Sections 2.2 – 2.5.

2.2. Environmental validation

To ensure that the Whale Shark technology is safe to use in the marine environment, an environmental sampling protocol including methodology and sampling locations was designed by Fisheries and Oceans Canada (DFO) and Transport Canada, in consultation with the ECHO Program. The environmental sampling and analysis was to be completed on three vessels, however, it was conducted for only one vessel during the first hull cleaning.

Representatives from DFO and Transport Canada directed the collection of environmental samples during hull cleaning operations in February, 2017. Observations indicated that the Whale Shark technology was not adequately capturing the fouling as it was being cleaned from the hull surface. A cloudy plume surrounding the cleaning brush cart was observed and recorded, and the analytical results indicated release of contaminants (metals) above guidelines into the aquatic environment. Subsequent environmental testing was therefore not completed.

2.3. Underwater noise analysis summary

The potential noise reduction was evaluated by JASCO Applied Science for the two vessels cleaned using the Whale Shark technology.

The radiated noise levels (RNL) of the vessels were measured as they transited over the Strait of Georgia ULS on route to the Port of Vancouver. Passes were made by each vessel both before and after hull cleaning, and the results of these passes were analyzed for potential changes in RNL.

The analysis concluded that hull cleaning using the Whale Shark technology did not appear to significantly reduce the overall RNL for either vessel. It was recognized that the Whale Shark technology does not clean the entire hull, leaving the curved bulk head and stern end surfaces fouled, therefore the potential benefits to underwater noise recognized by IMO[2] may not be fully accomplished using this technology.

2.4. Fuel consumption analysis summary

An evaluation of fuel consumption before and after hull cleaning with the Whale Shark technology was conducted for the two vessels.

Fuel consumption data were evaluated by Det Norske Veritas (DNV-GL) for three months before and three months after hull cleaning for the two vessels. The voyage data and fuel consumption data were assessed from noon reports and voyage reports prepared by each vessel's Chief Engineer and Captain.

Given the limitations of the data available before and after hull cleaning, the effect of hull cleaning using the Whale Shark technology on fuel consumption and power demand could not be clearly identified. DNV-GL reported that the cleaning limitations of the Whale Shark for curved surface areas (bulk head and stern end) may have limited the potential beneficial effects. The DNV-GL report recommended that if future evaluations are conducted, collecting data over a longer time period to reduce the uncertainty in the data, and/or the use of additional on-board instrumentation for delivering more accurate fuel consumption information may provide more reliable results.

2.5. Whale Shark current status

Vancouver Fraser Port Authority's Environmental Programs department is currently assessing the status of future permit applications from Subsea Global Solutions to use the Whale Shark technology in the Port of Vancouver.

DFO and Transport Canada have concluded that they will not be conducting any further environmental validation of the Whale Shark.

3. CCGS Cygnus

A Canadian Coast Guard Ship (CCGS), the *Cygnus*, was the third and final vessel evaluated to fulfill the objective of assessing the potential benefits of hull cleaning to underwater noise and fuel consumption.

The coordination of the hull cleaning and data collection on underwater noise and fuel consumption was conducted by the National Research Council of Canada (NRC) and Transport Canada. Additional information on the hull cleaning and fouling were provided in NRC's draft report and attached to this report as Appendix A.

The *CCGS Cygnus* is an offshore patrol ship that operates out of St. John's, Newfoundland. In order to evaluate the effects of hull cleaning on underwater noise and fuel consumption, sea trials were conducted at varying speeds over dedicated hydrophone installations in Conception Bay, Newfoundland. Table 1 provides the dates of the cleaning events and the three dedicated sea trials completed in 2018.

[2] IMO. 2014. Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life.

Table 1: *CCGS Cygnus* cleaning and sea trial dates

Date	Activity
May 23, 2018	Baseline sea trial
June 5, 2018	Hull cleaning
June 18, 2018	Post hull cleaning sea trial
July 18, 2018	Propeller cleaning
August 1, 2018	Post propeller cleaning sea trial

3.1. CCGS Cygnus underwater noise analysis

The underwater noise evaluation for the *CCGS Cygnus* was conducted by JASCO Applied Sciences using an Autonomous Multichannel Acoustic Recorder (AMAR-G3) and dedicated sea trials in Conception Bay, Newfoundland.

Both radiated noise level (RNL) and monopole source level (MSL) measurements were evaluated for a total of 38 passes over the AMAR G-3. For each trial, multiple passes at low, medium, and high speeds were performed and bridge crews logged vessel operating parameters, which included the vessel's speed through water (STW), shaft power, shaft RPM, and propeller pitch.

Analysis of the data provided statistically significant evidence that increasing vessel speed was associated with higher overall noise emissions. The completed analysis of the estimated broadband and 1/3-octave-band levels for the three sea trials (baseline, post hull cleaning and post propeller cleaning), suggested that the cleaning activities did not significantly affect vessel noise emissions. However, the uncertainties in both the operating conditions during the sea trials, and the statistical assumptions may have contributed to the inconclusive results.

JASCO recommended that future trials limit the variability of controllable parameters such as propeller pitch, shaft speed, shaft power, closest point of approach (CPA), and increase the number of passes (i.e., sample size).

Detailed results are provided in the JASCO final report in Appendix B.

3.2. CCGS Cygnus fuel consumption analysis

An evaluation of fuel consumption for the three sea trials was completed by both NRC and DNV-GL for the *CCGS Cygnus*. The *CCGS Cygnus* is equipped with vessel performance monitoring system which measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. This information was collected by NRC and provided to DNV-GL for an independent assessment.

DNV-GL analyzed fuel consumption from the baseline, post hull cleaning and post propeller cleaning sea trials using the data provided by NRC. Environmental conditions were corrected for, according to ISO 15016:2015 standards. DNV-GL also used a specialized program, ECO Insight, to analyze opportunistic data collected before, between, and after the sea trials to assess the *CCGS Cygnus* voyage performance and fuel consumption.

The results of the speed and power analysis and fuel consumption analysis were found to be inconclusive as both positive and negative effects were observed post hull and propeller cleaning when compared to the baseline trial results. DNV-GL reported that inconsistencies in the environmental conditions, draft and trim during the different sea trials, as well as the possibility of re-fouling of the hull between trials, were likely to have an effect on the vessel's performance.

Similar results were also identified in the NRC report[3]. How best to limit uncertainties were discussed for future consideration, to improve the reliability of the results.

Given the uncertainties potentially affecting the sea trial data, DNV-GL reported that it was not possible to conclude whether the propeller and hull cleaning of the *CCGS Cygnus* had benefits to fuel consumption and power.

The results of the power and fuel consumption analysis of the *CCGS Cygnus* are detailed in DNV-GL's full report, which is provided as Appendix C.

4. Strait of Georgia ULS summary of results

The installation of the Strait of Georgia ULS initially started as a means of evaluating potential underwater noise reductions as part of the Whale Shark validation project, however, the ULS evolved to become a world-leading project independent of Whale Shark. The ULS was first installed in September, 2015 and continued operation until April 18, 2018, when a technical failure of the station occurred. As the Strait of Georgia ULS was envisioned as a short-term feasibility project to assess whether real-time, high-quality measurements of vessel source levels could be conducted, the project concluded after the station failure.

This section summarizes the results of the two and a half years of ULS operation. The project report[4] prepared by Ocean Networks Canada provides additional details and is available on the ECHO Program website.

4.1. Ambient noise conditions

As expected for a busy, confined coastal waterway, the monthly mean ambient underwater noise levels at the ULS have been consistently high throughout all measurement years, relative to open-ocean and high shipping traffic reference levels. Sound pressure levels indicate that a significant portion of the acoustic energy is produced by short duration, high intensity sound sources. This is consistent with a heavily trafficked waterway and vessels with daily scheduled transits of the Strait of Georgia (e.g., BC Ferries) are evident in the data plots.

4.2. Marine mammal detections

The ULS automatically detected marine mammal vocalizations for humpback whales, killer whales and Pacific white-sided dolphins. Humpback whale vocalizations were detected in the months of October, November and December, in all years, with additional detections recorded in January for 2018. Killer whale vocalizations were primarily recorded in the late summer and early fall each year. Pacific white-sided dolphin vocalizations were not detected during the entire duration of the ULS operation. A gray whale vocalization was manually detected on May 31st, 2017. A monthly summary of the detections of humpback whale and killer whales (all ecotypes) are reported in Table 2.

[3] Kennedy, A., Pallard, R., Murrant, K. National Research Council Canada. October 2018. CCGS Cygnus – Hull and Propeller Cleaning Draft Report. St. John's, Newfoundland.

[4] Ocean Networks Canada. 2018. Annual Project Report on the Vancouver Fraser Port Authority Strait of Georgia Underwater Listening Station, October 2017-September 2018.

Table 2: Marine mammal detection summary

Date	Humpback Whale		Killer Whale	
	Number of Detections	Days with Detections	Number of Detections	Days with Detections
Sep-15	0	0/10	3091	5/10
Oct-15	79	1/31	2526	9/31
Nov-15	12	1/30	0	0/30
Dec-15	3670	8/31	111	4/31
Jan-16	0	0/31	0	0/31
Feb-16	0	0/29	17	1/29
Mar-16	0	0/31	0	0/31
Apr-16	0	0/30	148	5/30
May-16	0	0/31	338	7/31
Jun-16	0	0/30	1053	8/30
Jul-16	0	0/31	464	9/31
Aug-16	0	0/31	3333	16/31
Sep-16	0	0/30	2027	10/30
Oct-16	6	1/31	142	4/31
Nov-16	985	13/30	167	2/30
Dec-16	895	10/31	8	1/31
Jan-17	0	0/31	53	1/31
Feb-17	0	0/28	553	4/28
Mar-17	0	0/31	58	3/31
Apr-17	0	0/30	140	5/30
May-17	0	0/31	314	4/31
Jun-17	0	0/30	1041	7/30
Jul-17	0	0/31	283	8/31
Aug-17	0	0/31	236	7/31
Sep-17	0	0/30	4936	17/30
Oct-17	194	6/31	126	2/31
Nov-17	918	4/30	373	1/30
Dec-17	101	2/31	7	1/31
Jan-18	27	1/31	983	2/31
Feb-18	0	0/28	0	0/28
Mar-18	0	0/31	267	6/31
Apr-18	0	0/17	8	1/17

4.3. Vessel source level measurements

The total number of valid vessel source level measurements collected by the Strait of Georgia ULS was 5134, which is the largest known non-military inventory of vessel source levels in the world. The loudest average vessel class measured was container ships greater than 200m in length, whereas the quietest recorded vessel was a naval vessel. The quietest average vessel class (with more than one reading) was fishing vessels.

The goal of obtaining 100 valid vessel measurements per class to allow for ranking, was achieved for five vessel classes. These classes include: tugs less than 50 m, bulkers less than 200 m, bulkers greater than 200 m, tankers, and container ships greater than 200 m.

Table 3 provides a summary of the total number of vessel source level measurements by vessel class, as well as the minimum, maximum and average radiated noise levels (RNL).

Table 3: Summary of vessel source level measurements by vessel class

Vessel Class	Max RNL (dB)	Average RNL (dB)	Min RNL (dB)	Number of Transits
Bulkers <200 m	198.7	185.9	169.1	567
Bulkers >200 m	204.2	186.6	172.5	494
Container Ship <200 m	190.8	181.2	172.1	22
Container Ship >200 m	201.2	189.7	169.3	361
Ferry >50 m	197.4	186.5	165.7	2787
Fishing Vessel	192.3	177.1	165.7	67
Government/Research	188.8	174.9	168.0	24
Naval Vessel	199.4	173.7	160.9	17
Other	187.6	180.4	171.8	30
Passenger <100 m	180.8	177.0	174.2	15
Passenger >100 m	192.5	181.9	169.8	45
Recreational Vessel	180.4	174.3	168.3	3
Tanker	200.4	185.9	173.4	188
Tug <50 m	191.3	179.7	163.0	409
Tug >50 m	189.5	183.1	172.8	33
Vehicle Carrier	193.1	181.8	173.0	72
Total Number of Accepted Transits				**5134**

5. Conclusions

The Strait of Georgia underwater listening station was successful in providing high-quality data on vessel source levels, marine mammal detections and ambient noise levels from September, 2015 to April, 2018. This internationally-recognized project has provided the largest known non-military database of vessel source levels with over 5,000 accurate transit reports.

The hull cleaning validation project was completed using two commercial cargo vessels cleaned by the Whale Shark in-water hull cleaning technology in the Port of Vancouver, and one Canadian Coast Guard patrol vessel, cleaned independently in Conception Bay, Newfoundland. Based on the analyses completed for these studies, hull cleaning did not appear to reduce the overall radiated noise levels, nor provide measurable benefits to power or fuel consumption for the three vessels involved. Data limitations, variations in environmental conditions during measurements, and changes in the operational profiles of the vessels render the results of this study somewhat inconclusive. Recommendations have been provided by both JASCO and DNV-GL to help improve and reduce the uncertainties in future studies.

Appendix A

NRC Report – CCGS Cygnus – Hull and Propeller Cleaning

TECHNICAL REPORT
OCRE-TR-2018-036

NRC·CNRC Ocean, Coastal and River Engineering

CCGS Cygnus – Hull and Propeller Cleaning

Unclassified
OCRE-TR-2018-036

Allison Kennedy
Kevin Murrant
Rob Pallard

St. John's

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Allison Kennedy, Kevin Murrant, Rob Pallard

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Fraser Winsor
Program Lead

Signature

Martin Richard
Director of R & D

Signature

NRC – OCRE Addresses

Ottawa
1200 Montreal Road, M-32
Ottawa, ON, K1A 0R6

St. John's
P.O. Box 12093, 1 Arctic Avenue
St. John's, NL, A1B 3T5

Executive Summary

The Canadian Coast Guard Ship (CCGS) Cygnus is an offshore patrol ship that operates out of St. John's, NL. It is the first CCG vessel to be instrumented with a vessel performance monitoring system, developed by OpDAQ. The system measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. The National Research Council (NRC) of Canada has a separate Data Acquisition System (DAS) onboard the CCGS Cygnus since Fall 2015. The NRC DAS stores data from a number of vessel systems such as the navigation system and propulsion system. The NRC has also been obtaining OpDAQ data from the CCGS Cygnus since 2016. The data from the NRC DAS and OpDAQ system is used for the current project to quantify changes in vessel performance as a result of hull and propeller cleaning.

This report summarizes the propulsion efficiency analysis of the CCGS Cygnus operational data prior to and subsequent to cleaning the hull and propeller. This data is used to quantify any changes in vessel performance, specifically the power versus speed relationship. In addition, the vessel fuel consumption at a given power level will be quantified prior to and post cleaning events.

Three dedicated sea trials were conducted to support this project. Each set of trials is a dedicated Speed and Power trial and was planned and conducted in accordance with International Towing Tank Conference (ITTC) guidelines. The first set of trials is a baseline trial to quantify the performance before the hull or propeller are cleaned. The second set of trials is a post hull cleaning trial to quantify the performance subsequent to cleaning the vessel hull only. The third trial is conducted post propeller cleaning and is used to quantify any changes in speed and power performance as a result of cleaning the propeller.

The results of the study demonstrate an improvement in efficiency of 5% on average at the cruising speed range of 13.5-16 knots when analyzed using the prescribed method in the referenced guidelines. An improvement of similar magnitude was observed across a wider band of ship speeds when simply taking the mean of the data during the double runs. However, some variability was observed in the results due to the changing conditions between each set of trials. For example, the results were not corrected for variation in displacement across trials or the re-occurrence of slight fouling during the post cleaning trials, which was unknown at the time. The results compare reasonably to estimations of power increase for a mid-sized Naval frigate for similar baseline and fouled conditions.

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1 Introduction

The Canadian Coast Guard Ship (CCGS) Cygnus is an offshore patrol ship that operates out of St. John's, NL. It is the first CCG vessel to be instrumented with a vessel performance monitoring system, developed by OpDAQ. The system measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. The National Research Council (NRC) of Canada has a separate Data Acquisition System (DAS) onboard the CCGS Cygnus since Fall 2015. The NRC DAS stores data from a number of vessel systems such as the navigation system and propulsion system. The NRC has also been obtaining OpDAQ data from the CCGS Cygnus since 2016. The data from the NRC DAS and OpDAQ system is used for the current project to quantify changes in vessel performance as a result of hull and propeller cleaning.

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The result of this project suggests how the power and speed relationship for the CCGS Cygnus changes after cleaning events within the scope of the trials. It also quantifies how the power and fuel consumption relationship changes as per the observed data. These changes are quantified using measured data from dedicated sea trials. This information could be used to support planning and optimization of vessel cleaning schedules.

2 CCGS Cygnus – Vessel Details

The CCGS Cygnus is an offshore fisheries patrol vessel that operates out of St. John's, NL. It operates on a two week rotational schedule. This generally involves the vessel departing St. John's, transiting to the Grand Banks area which it patrols and then returning to St. John's for crew change. The day after crew change the vessel departs again for Grand Banks to continue patrolling. The vessel has two main medium speed, diesel engines. The general particulars of the CCGS Cygnus are outlined in Table 1.

Table 1. CCGS Cygnus Main Particulars

Particular	Value
Length (m)	62.4
Breadth (m)	12.2
Draft (m)	4.0
Freeboard (m)	0.9
Cruising Speed (kts)	13.0
Maximum Speed (kts)	16.0
Number of engines	2
100% MCR (kW)	~3000
Number of propellers	1

3 Hull and Propeller Fouled Condition

Prior to cleaning the hull and propeller, a subsea survey was conducted to characterize the level of fouling present. A guideline from the Royal Navy (2011) was followed for this procedure. The hull fouling was characterized as a specific type and rated from 0 to 100 to indicate the level of severity. A description of the hull fouling types and rating values is provided in Appendix A. The hull cleaning was completed by divers when the vessel was docked in Conception Bay, NL. The diving company prepared a report to document the level of fouling on the hull. This report is provided as part of Appendix A for ease of reference. When assessing the level of fouling on the hull, the divers divided the vessel into 27 regions. At each of these regions photos were taken to document the fouling condition. The location of each region is shown in Figure 1, as taken from the divers report. Note that this image is not to scale, nor is it a representation of the CCGS Cygnus. It is used only to indicate general location and quantity of underwater areas that were surveyed.

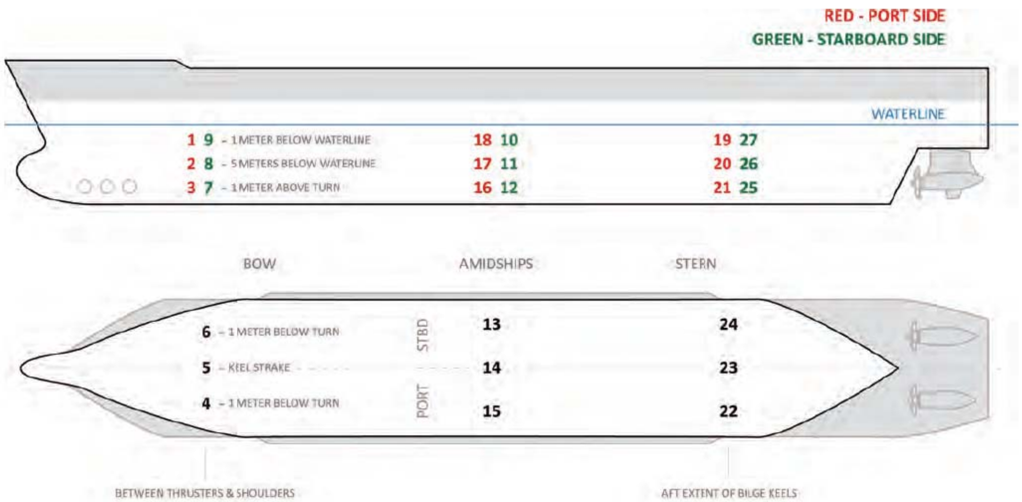

Figure 1. Hull fouling characterization locations (From diver's report)

An underwater video was also taken to support characterization of hull fouling. By evaluating the vessel in situ, through photographs and using the underwater videos, the divers characterized the level of fouling at each of the 27 locations across the hull. The diver's used the Royal Navy (2011) and US Naval Ships Technical Manual (2006) to define fouling type and rating values so that results would be consistent with Navy practices. A summary of the hull fouling characterization is provided in Table 2. All fouling on the CCGS Cygnus hull was noted to be soft. The dominant organisms in the soft fouling type are slime and grass. The fouling rating included FR 20 and FR 30. This type of fouling involves advanced slime and grass filaments up to 76 mm long. The percentage of fouling coverage in each area ranged from 40-100%. It was noted that fouling was located from waterline down to turn of the bilge with heavier growth present near the waterline.

Table 2. Hull fouling characterization – type, rating and percent coverage

Location	Fouling Type	Fouling Rating	Percentage Coverage (%)
1	Soft	30	80
2	Soft	20	50
3	Soft	20	75
4	Soft	20	100
5	Soft	20	80
6	Soft	20	90

7	Soft	20	100
8	Soft	20	50
9	Soft	30	50
9	Soft	20	50
10	Soft	30	70
11	Soft	20	50
12	Soft	20	40
13	Soft	20	80
14	Soft	20	80
15	Soft	20	90
16	Soft	20	90
17	Soft	30	65
18	Soft	30	80
19	Soft	20	90
20	Soft	20	60
21	Soft	20	90
22	Soft	20	100
23	Soft	20	90
24	Soft	20	100
25	Soft	20	95
26	Soft	20	50
27	Soft	20	80

The hull and propeller of the CCGS Cygnus had not been cleaned in two years prior to this project. The level of fouling present was a result of 2 years of operation. The CCGS Cygnus operates year round on a two week rotation with a two day layover. Vessels with an off-season or with long layover periods would likely have more fouling in similar operational and environmental conditions.

The propeller was also assessed by divers to quantify the level of fouling present. All propeller blade faces were covered in a light to moderate slime which was heavier at the root and tapered towards the tips. Under the slime the propeller blades were covered with a heavy calcium buildup. The level of propeller fouling was measured using a ship propeller roughness gage which characterizes the propeller roughness per the Rubert Comparator scale. The propeller fouling was rated as Rubert scale E. Once polished, the propeller was rated at a Rubert scale A/B. Post polishing trials were conducted at this polished state. Figure 2 illustrates the pre cleaning and post cleaning condition of a typical propeller pressure face of the CCGS Cygnus propeller. The diver’s report on propeller polishing is also included in Appendix A for ease of reference. This report includes a number of images of pre and post cleaned propeller surfaces.

Figure 2. Typical propeller pressure face pre (left) and post (right) cleaning

4 Sea Trials

Three separate sets of sea trials were completed. The first was conducted prior to cleaning the hull or propeller and provides data to use as a baseline. The second set of sea trials were completed after the hull was cleaned and the third set of sea trials were completed after the propeller was cleaned.

All trials followed the same procedure and occurred at the same location. The trials followed ITTC 2014 guidelines for the completion of speed and power trials. These guidelines outline boundary conditions as a cutoff point for the completion of such trials. These boundary conditions relate to location, water depth and environmental conditions and vary based on the vessel size. The specific trials boundary conditions for the CCGS Cygnus, are summarized in Table 3.

Table 3. Sea Trials Boundary Conditions

Parameter Description	**Parameter Detail or Value**
Location	Selected location should have minimal vessel traffic and should be sheltered to avoid wind / wave where possible.
Water Depth	Minimum water depth of 52.2 m. Data corrections required for water depths less than 71.8 m.
Wind	Wind shall not be higher than Beaufort 5. Beaufort 5 relates to mean wind velocity between 17-21 knots.
Sea State	The maximum wave height when derived from visual observation should be 1.2 m.
Current	Areas with known large current variations in time or space should be avoided. Small currents will be corrected for by completing tests in two directions, one upwind and the other downwind.

Prevalent weather conditions and vessel traffic intensity were considered when selecting a trials location. The location was selected to be within Conception Bay to reduce the likelihood of heavy sea states when compared to a location along the normal Cygnus operational route. The location was set to north of Bell Island since there was relatively little vessel traffic at this location than other areas of the Bay.

During each trial three or four different power settings were tested. The power settings tested included 50%, 65%, 80%, and 100% of the main engines Maximum Continuous Rating (MCR). All tests were completed in two directions: upwind and downwind. A double run at 65% MCR was conducted once during each set of trials. The double runs completed at 50%, 80% and 100% MCR were conducted twice, as per the ITTC 2014 guideline. The baseline trials included only three power settings (65%, 80%, and 100%) as the original plan did not specify runs at 50% power setting. After analysis of the baseline trial data, it was decided to include runs at 50% power in the subsequent trials to provide additional context for the higher power data points. It was attempted to perform all trials at a consistent displacement and as such there were no significant changes in cargo or machinery between trials.

The location of each set of sea trials is shown in Figure 3. The direction of all trials was along the yellow line, between the points NRC 1 and NRC 2. This track has a total length of approximately 10 km to provide space for the high speed runs. Each test required 10 minutes of constant rpm, pitch, and speed settings. As such, some tests were shorter in distance than others. All tests were centered near the subsea acoustic probe (Autonomous Multichannel Acoustic Recorder – AMAR) point in Figure 3. The AMAR point is located at 47^{o}41.757’ latitude and -52^{o}56.509’ longitude. The direction of the yellow line relates to in and out of the Bay, which corresponds with the prevailing wind direction. Once a test was completed in one direction (e.g. upwind) the vessel would turn around and complete the same test in the opposite direction.

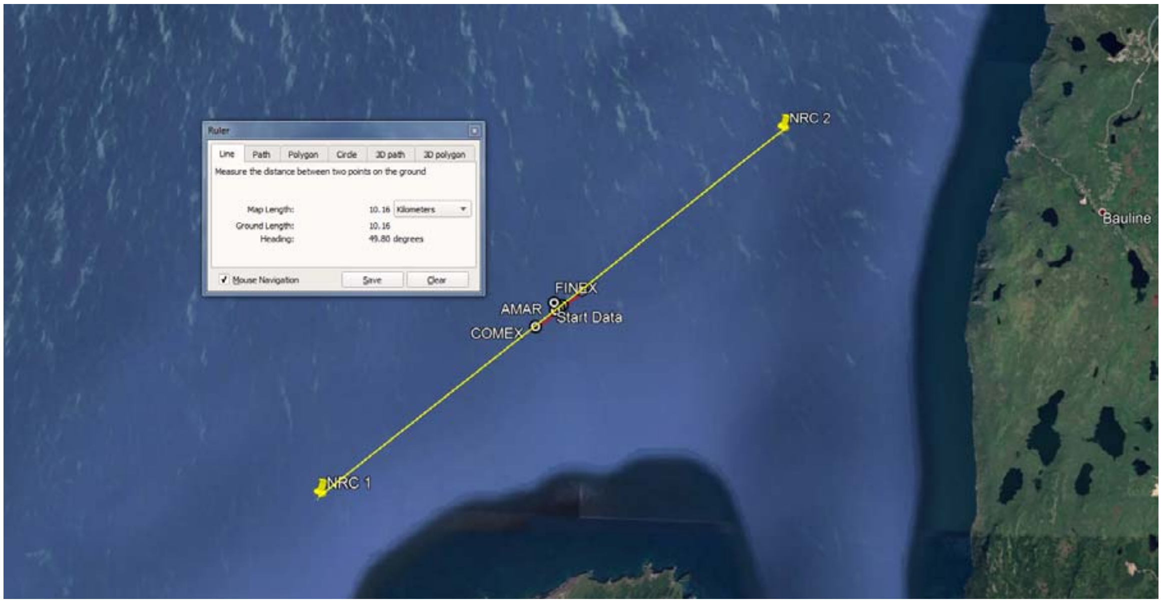

Figure 3. Trials location and direction

Each trial run involved a period to get up to speed and attain constant settings, a 10 minute constant setting period, and then a Williamson turn to return vessel to opposite direction for subsequent testing. The trial trajectory was similar to that shown in Figure 4.

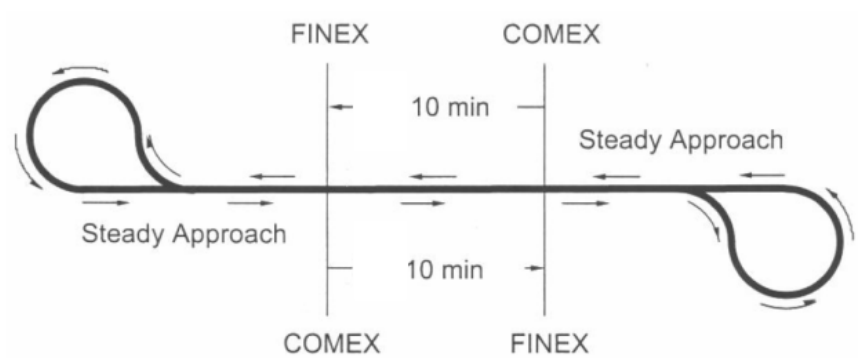

Figure 4. Trial trajectory

4.1 Baseline Trials

Baseline (pre-cleaning) trials were completed on May 23, 2018. The wind and sea conditions during the morning were higher than the boundary conditions for these tests and as such all tests were completed in the afternoon when conditions calmed. The conditions during baseline trials are summarized in Table 4. The trials log, in Appendix A, indicates the conditions during each specific test. There were 11 runs completed in total. Two of these were runs at a MCR setting of 65% (upwind and downwind), four at MCR of 80% (two upwind and two downwind) and four at a 100% MCR (two upwind and two downwind). There was a repeat test of the first run which was 65%

MCR in the upwind direction. The repeat was conducted because the wave and wind conditions were higher during the first test of the day than they were during the remainder of the tests.

Table 4. Baseline Trial Conditions

Condition	Value
Testing timeframe	13:30 – 16:15
Vessel forward draft (m)	3.35
Vessel aft draft (m)	4.83
Range in true wind speed (kts)	16 - 22
Range in wave heights (m)	0.5 – 1.0
Range in swell height (m)	0 – 0.5
Water temperature (^oC)	4.0

During the baseline trials the wave and swell heights were estimated by the vessel Captain. These values were not measured during baseline trials as the wave buoy was not deployed due to morning weather conditions. The water temperature was also estimated for the baseline trial, using historic water temperature values from the area. In addition, the estimated water temperature was compared to water temperature measurements taken from a wave buoy that was located in Holyrood Harbor, which is not too far from the trials site.

4.2 Post Hull Cleaning Trials

The post hull cleaning trials were completed on July 18, 2018. The weather conditions during post hull cleaning trials are summarized in Table 5. The trials log, in Appendix A, indicates the conditions during each specific test. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at a 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at a throttle setting of 100% MCR (two upwind and two downwind).

Table 5. Post Hull Cleaning Trial Conditions

Condition	Value
Testing timeframe	10:30 – 14:00
Vessel forward draft (m)	3.05
Vessel aft draft (m)	4.66
Range in true wind speed (kts)	14 - 25
Range in wave heights (m)	0.2 – 0.4
Range in swell height (m)	0 – 0.25
Water temperature (^oC)	10.2

During the post hull cleaning trials the wave and swell heights were estimated by the vessel Captain. These values were also measured by a wave buoy during these trials. Estimated values were compared with those measured. Values estimated were consistently higher than those measured, by approximately 50%. Measured values are summarized in the trials log as well as in Table 5.

4.3 Post Propeller Cleaning Trials

The post propeller cleaning trials were completed on August 1, 2018. The weather conditions during post propeller cleaning trials are summarized in Table 6. The trials log, in Appendix A, indicates the conditions during each specific test. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at 100% MCR (two upwind and two downwind).

Table 6. Post Propeller Cleaning Trial Conditions

Condition	Value
Testing timeframe	11:45 – 15:05
Vessel forward draft (m)	3.02
Vessel aft draft (m)	4.72
Range in true wind speed (kts)	4.5 – 10.2
Range in wave heights (m)	0.3 – 0.6
Range in swell height (m)	0
Water temperature (^oC)	14.9

During the post propeller cleaning trials the wave and swell heights were measured by a wave buoy. These values were not estimated by Captain during this particular trial.

5 Measured Speed and Power Data

The measured shaft power versus speed through water for each test during each trial were plotted on the same plot for ease of comparison (see Figure 5). All data points align to the same general curve relatively well. There appears to be less variability in the post propeller trials data when compared to the other trials results for a given engine setting. This was expected since the wind and sea conditions during the post propeller polishing trials were lower than those for the other two trials.

Figure 5. Uncorrected power versus speed

The measured data was analyzed first using the mean of means method to provide further insight towards data trends between trials. The mean of means method involves taking the mean of consecutive double runs at a given engine setting and then taking the mean of those means to represent the speed and power values at that engine setting. The intent of this method is to eliminate the unidirectional effects of wind and current under the assumption that these effects will average to zero. The mean of means for all trials completed at a given engine setting, within each sea trial, were calculated. The results of shaft power and vessel speed through water for each sea trial were plotted (Figure 6). Trend lines were fitted through the data for each sea trial.

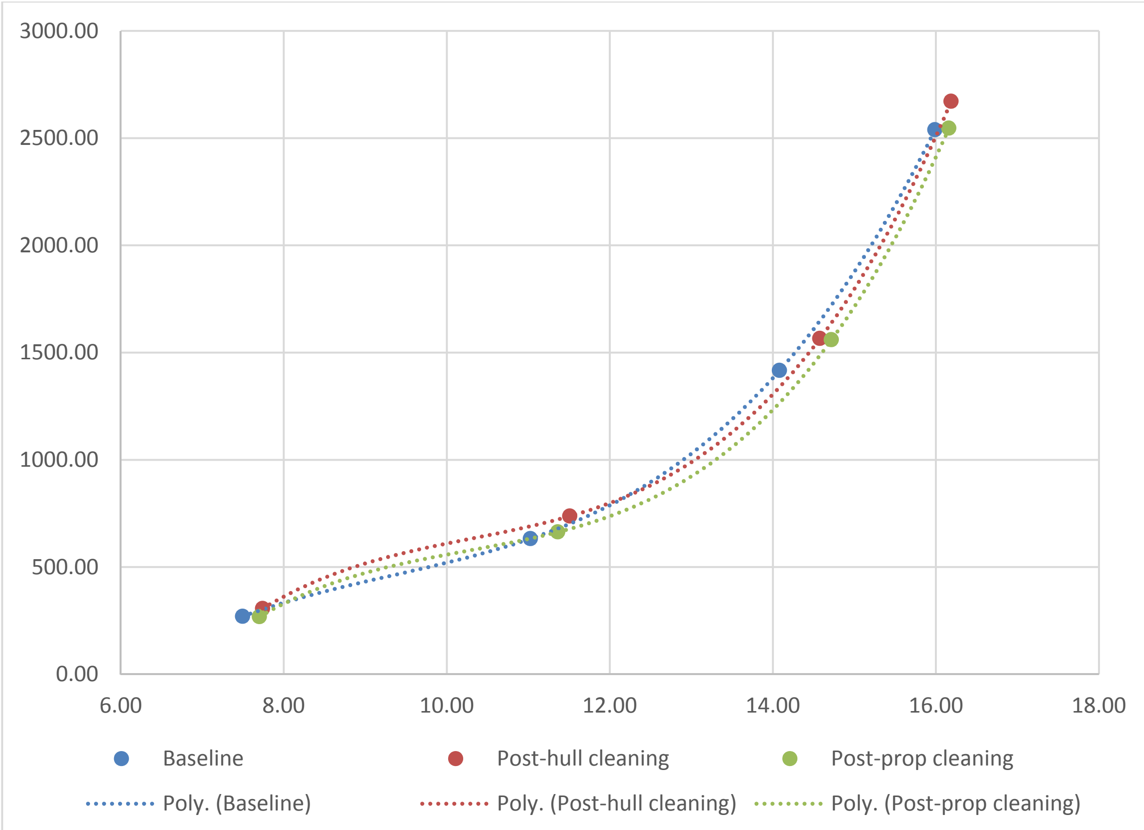

Figure 6. Means of Measured Data - Shaft Power versus Speed through Water

The differences in the relationships between power and speed for the three sea trials is clearer here. The trend line relationships between trials change across the speed range. The post-hull cleaning trials trend line requires on average ***4.1%*** less power to attain speeds between 12.5 and 16 knots. In this same speed range, the post-propeller cleaning trials trend line indicates that on average ***5.0%*** less power is required to attain a given speed when compared to the post hull cleaning trials. These results indicate that a total of approximately ***9%*** less power is required to attain a given speed (in speed range between 12.5-16 knots) as a result of cleaning both the hull and propeller. For speeds less than approximately 12 knots, more power is required to attain a given speed for the post hull cleaning trials when compared to the baseline trials. This result is unexpected and may be influenced by the higher level of uncertainty involved in the lower engine setting trials.

It is also noteworthy to discuss the fact that these results are presented in terms of power versus speed rather than overall resistance versus speed. Overall resistance is more difficult to characterize since it takes into account the propulsion as well as associated efficiencies (hull efficiency, propulsive efficiency, and relative rotative efficiency). The power can be roughly calculated by dividing the resistance multiplied by the vessel speed, by the overall system efficiency. The overall propulsion system efficiency is a combination of multiple complex factors. For example, the propulsive efficiency would increase as a result of cleaning the propeller. Another example is that the hull efficiency, which describes how the water flows around the hull and into the propeller, can affect the propeller efficiency as a result of cleaning the hull. It is therefore possible that the resistance versus speed relationship for each set of trials would not exhibit the same performance gains across the speed range compared to simply comparing power versus speed.

6 Speed and Power Analysis and Results

The speed and power data measured during field trials was analyzed to remove variations due to environmental differences between trials. This was completed following ITTC guidelines for the analysis of full scale speed and power trials (ITTC, 2005). This analysis method was complimented using insight from ISO 15016 when additional guidance was needed. The ITTC guideline requires the conversion of measured power data to vessel resistance in order to apply certain correction factors to account for environmental effects and correct data to a common, calm state. The ITTC guideline describes a method to determine the resistance of each trial run by using the measured torque along with information from associated propeller curves. A major element of uncertainty in this analysis is that the open water propeller curves for the Cygnus propeller are not available to support data analysis. As such, a standard B-Series propeller curve was assumed to be representative of the Cygnus propeller.

The ITTC guideline provides methods to calculate resistance corrections for: wind, waves, deviation in water temperature and density, water current, shallow water, and displacement variation. Resistance corrections were calculated for each trial run within each specific sea trial. For all cases, the resistance correction to account for water current was not calculated since the vessel speed through water was measured directly. Also, the shallow water correction was not calculated for any trials since the trials were conducted in deep water. The resistance correction to account for variations in vessel displacement were provided only for displacements that varied less than 2%. Based on the forward and aft draft measurements taken at the beginning of each trial, the displacement varied by approximately 8%, exceeding the range of the correction method. As such, there were no corrections added to account for displacement variation and the change in displacement is a source of variability within the results. Note that the forward and aft were estimated by the vessel crew based on draft marks prior to each trial and were not measured directly. Therefore, the variation in displacement could differ than the percentage value calculated using the estimated trim values.

The resistance corrections calculated for each trial were subtracted from the trial resistance that was calculated to reduce the resistance to a calm water baseline which could be used for direct comparison between trials. The corrected vessel resistance was used to calculate the corrected power. The ITTC analysis method required estimation of a number of coefficients specific to the vessel used in trials as well as the estimation of a number of environmental parameters that were not directly measured. Estimation of these parameters leads to a level of uncertainty in the results. A summary of the estimated parameters is provided below.

- Wake fraction, thrust deduction fraction and propeller relative rotative efficiency. These coefficients can be found from model test results for a particular vessel. Model test data for the CCGS Cygnus was not available for this data analysis. As such, the commercial software NavCad was used to model each trial and output the associated coefficients. The measured and predicted shaft power values compared well (within 10%) and thus the coefficients output from NavCad were deemed as reasonable.
- Thrust coefficient and advance coefficient. The ITTC analysis guideline states that the propeller open water thrust and advance coefficients, both required to calculate resistance, are to be retrieved from propeller open water curves. The CCGS Cygnus propeller open water curves were not available for this analysis. As such, standard B-Series open water propeller curves were used to represent the Cygnus propeller. The standard B-Series open water propeller curves were updated to match the pitch (as approximated by NavCad) of each trial run. Each unique set of curves was then used to retrieve the required data associated with the corresponding run. Unfortunately, the actual pitch relating to each test

was not known and had to be approximated based on the pitch percentage which was noted from a gage on the bridge of the vessel and using NavCad. This added to the uncertainty involved in using the standard B-Series curve. In addition, the Cygnus propeller is controllable pitch and the standard B-Series propeller is not. The ratio of hub diameter to propeller blade length is larger for a controllable pitch propeller than for a fixed pitch propeller.

- Wetted surface area. The wetted surface area of the CCGS Cygnus was estimated with NavCad using input of the vessel main particulars and selection of representative vessel type.
- Transverse projected area above waterline. The transverse projected area above waterline of the CCGS Cygnus was estimated using measurements from the general arrangement drawing of the vessel and known draft.
- Wind resistance correction. The correction for wind resistance was estimated using recommended equations for the calculation of wind resistance.
- Wave height during baseline trials. The wave height was not measured during baseline trials. It was estimated using the measured wind speed and the fetch limited JONSWAP wave spectrum. The value of fetch used for the trials was 30 km. These estimates were compared to measured wave height data from a nearby (Holyrood) wave buoy and the results matched well (within 10%).
- Water temperature during baseline trials. The water temperature was not measured directly during baseline trials and was estimated based on historic water temperature data during the same time of year. The estimated value was compared to measured data from a nearby (Holyrood) wave buoy and the results were similar.
- Water density for all trials. It was assumed that 3.5% salinity was representative of the water density during trials.
- Kinematic viscosity for all trials. The water kinematic viscosity was not directly measured and was estimated using the water temperature and ITTC Salt Water Property tables.

Preliminary results of the analysis showed that the wind resistance correction the most significant factor in comparison to the other corrections, for all sea trials. In addition, for the baseline trials and the post hull cleaning trials, where wind speeds were towards the upper wind speed limits of the trials, the wind resistance correction was very large in comparison to the bare hull resistance, particularly at the lower speeds.

The measured speed and power data was analyzed three separate times to correct for environmental conditions, each using the ITTC 2005 method or a slight variation to the method. The first analysis approach was conducted strictly to the ITTC guideline. The second and third analysis approaches were conducted using the ITTC 2005 guideline with a different estimation of wind resistance correction. The second attempt involved a wind resistance correction estimation using the Fujiwara method. This method was one of the wind resistance predictors recommended in NavCad, a commercially available vessel performance evaluation software. The third attempt involved a wind resistance correction estimation of half the predicted value using the Fujiwara method. Three separate analysis were completed to illustrate the variation in result that occurs due to different estimations of wind resistance correction.

6.1 Results – Baseline Trials

The results of the three analysis methods for the baseline trials data is summarized in Figure 7. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

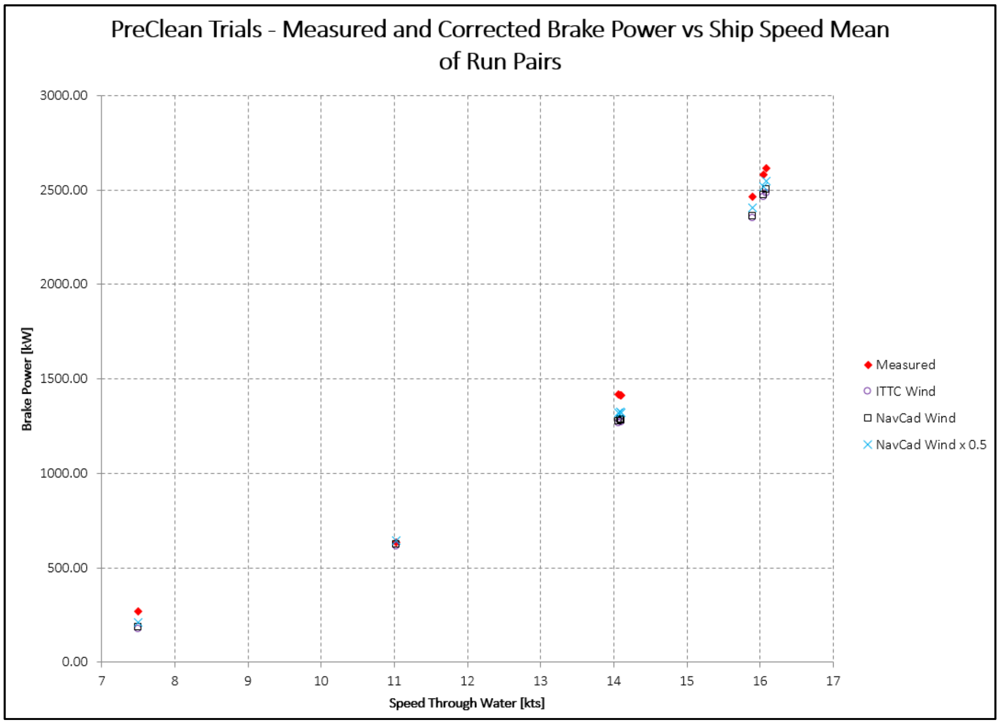

Figure 7. Corrected Speed and Power Results for Baseline Trials

The measured trials data have higher power per speed than the corrected data for all test cases except the 11 knot speed. It is expected that the measured power would be higher since the power is being corrected to a calm condition and less power would be required to attain a given speed in calm seas. The measured data is very close to the corrected values at 11 knots which suggests that the wind and wave conditions during these tests were relatively mild. There is not much difference between the corrected results using the ITTC wind correction and the NavCad (Fujiwara) wind correction, for all tests. The corrected data using half the Fujiwara wind correction, lies in between the measured data and the other corrected data. A summary of the measured power and corrected power values from each analysis method are provided in Table 7 for each test during the baseline trials.

Table 7. Corrected and Measured Power Data for Baseline Trials

Speed Through Water (knots)	Power (kW)			
	Measured (uncorrected)	ITTC Wind	NavCad Wind	0.5 x NavCad Wind
7.1	276	88	98	149
7.9	265	267	274	278
10.8	637	503	524	580
11.2	629	724	722	715
13.9	1446	1077	1111	1220
14.2	1395	1457	1445	1425
13.9	1433	1096	1128	1226
14.3	1393	1447	1435	1416
16.0	2653	2271	2328	2446
16.2	2574	2696	2677	2646

15.9	2592	2234	2272	2391
15.9	2338	2469	2451	2420

6.2 Results – Post Hull Cleaning Trials

The results of the three analysis methods for the post hull cleaning trials data is summarized in Figure 8. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

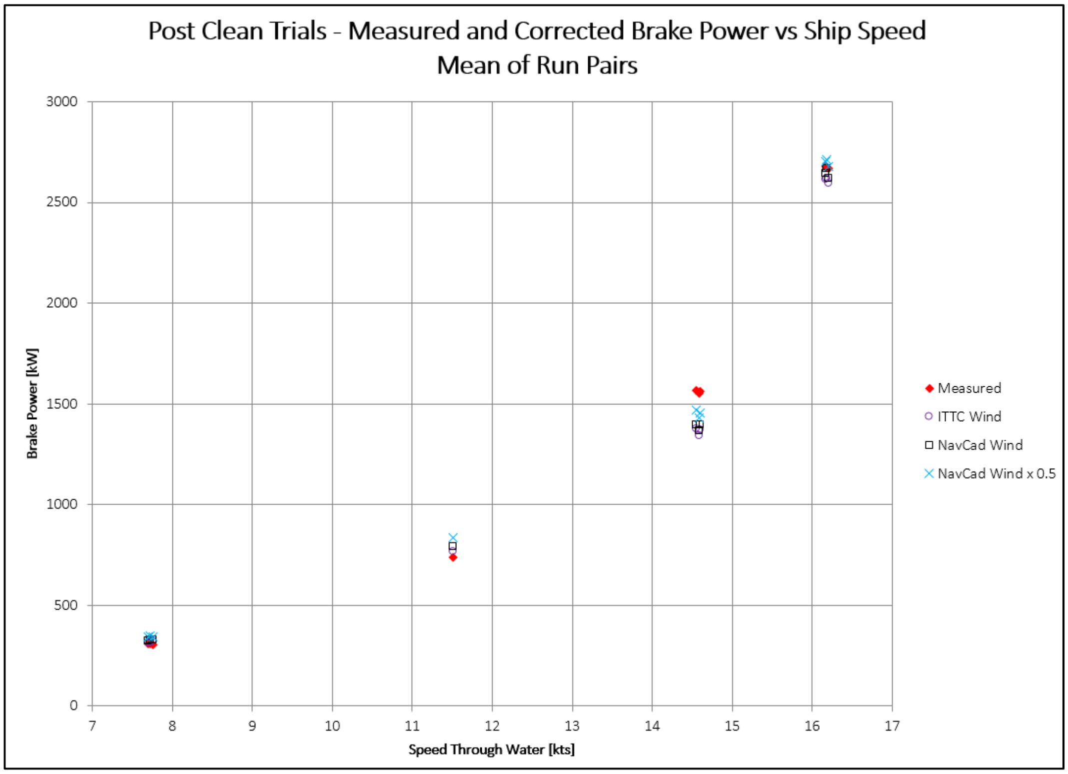

Figure 8. Corrected Speed and Power Results for Post Hull Clean Trials

The data corrected using the ITTC wind correction and the NavCad wind correction are very similar. The spread between the measured and corrected data increases with speed for the post hull cleaning trials. A summary of the measured power and corrected power values from each analysis method are provided in Table 8 for each test during the post hull cleaning trials.

Table 8. Corrected and Measured Power Data for Post Hull Cleaning Trials

Speed Through Water (knots)	Power (kW)			
	Measured (uncorrected)	ITTC Wind	NavCad Wind	0.5 x NavCad Wind
7.6	310	288	298	330
7.9	300	357	359	358
7.5	320	269	286	330
8.0	300	362	371	365
11.2	761	656	692	789

11.8	715	879	896	884
14.2	1601	1189	1231	1396
14.9	1537	1566	1561	1542
14.3	1563	1124	1176	1320
14.9	1563	1619	1616	1588
16.0	2702	2390	2462	2617
16.3	2654	2839	2823	2791
16.1	2694	2397	2518	2630
16.4	2639	2790	2721	2723

6.3 Results – Post Propeller Cleaning Trials

The results of the three analysis methods for the post propeller cleaning trials data is summarized in Figure 9. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

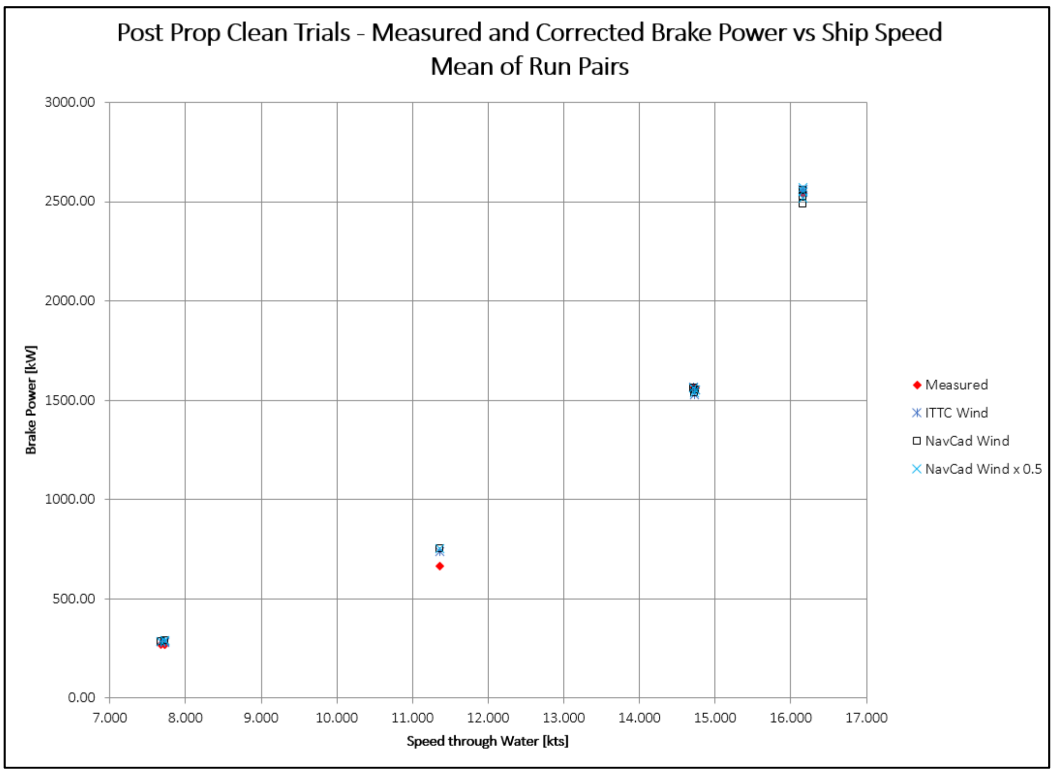

Figure 9. Corrected Speed and Power Results for Post Prop Clean Trials

The measured data is very close to the corrected data for the post propeller cleaning trials due to the mild environmental conditions during the trials. There does appear to be one outlier for the tests at speed between 11 and 12 knots for which the measured power is below the corrected power values. A summary of the measured power and corrected power values from each analysis method are provided in Table 9 for each test during the post propeller cleaning trials.

Table 9. Corrected and Measured Power Data for Post Prop Cleaning Trials

	Power (kW)

Speed Through Water (knots)	Measured (uncorrected)	ITTC Wind	NavCad Wind	0.5 x NavCad Wind
7.9	266	299	298	295
7.5	274	268	269	279
7.9	264	300	307	299
7.5	272	262	272	277
11.5	656	759	769	753
11.2	672	722	739	753
14.8	1549	1585	1576	1566
14.6	1572	1548	1547	1563
14.8	1553	1557	1556	1543
14.6	1566	1502	1516	1533
16.3	2540	2615	2599	2580
16.1	2567	2505	2517	2564
16.3	2527	2617	2536	2542
16.1	2553	2478	2438	2495

6.4 Results – Comparison of Trials

The corrected power results for each sea trial were plotted against speed on the same plot to illustrate differences in performance. This was completed for each of the three wind correction approaches considered. For each analysis method, the results of each trial are relatively similar in terms of the power required at a given speed. Given this, it is difficult to quantify the gain in power associated with cleaning the hull and propeller, from this data. The regression lines for each trial are very similar for all analysis methods used. For each approach, the baseline trial regression line is higher than the post hull and post propeller cleaning regression lines, at speeds higher than approximately 13 knots. This indicates that there is a benefit of cleaning the hull and propeller in these speed ranges in terms of power required to attain a given speed. Below, approximately 13 knots, the regression line for baseline trials falls below the regression line for the other two trials. This change in regression line relationship between trials is consistent to the measured data results and may be due to higher uncertainty levels at the low speed tests.

The power savings above 13 knots were quantified using the regression line equations from the NavCad wind correction approach. Between 13.5 and 16 knots an average of ***5%*** less power is required to attain a given speed after cleaning the hull, when compared to the baseline power requirements. There is no additional power reduction identified within this speed range as a result of cleaning the propeller which was unexpected. In fact, the performance after cleaning the propeller, in terms of power versus speed, is worse in this speed range.

Note that there is variability within the tests conducted at a given throttle setting for a given trial in terms of speed through water and corrected power. The corrected power for a throttle setting for one trial often falls within the range of corrected power for the same throttle setting in a different trial. For example, at a throttle setting of 10 the speed through water varies between 15.9-16.2 knots for the baseline trials, 16.0-16.4 knots for the post hull clean trials and 16.1-16.3 knots for the post propeller cleaning trials. For this same throttle setting the corrected power (NavCad wind) ranges from 2272-2677 kW for the baseline trials, 2462-2823 kW for the post hull clean trials and 2438-2599 kW for the post propeller cleaning trials. The speed and power values from one trial, fall within the speed and power range for a different trial for this throttle setting. This is consistent for the other throttle settings considered and is true for the measured data as well as the corrected. This may be due to variability between trials (e.g. displacement variation, fouling present) and leads to less reliability in the power savings quantified using this data.

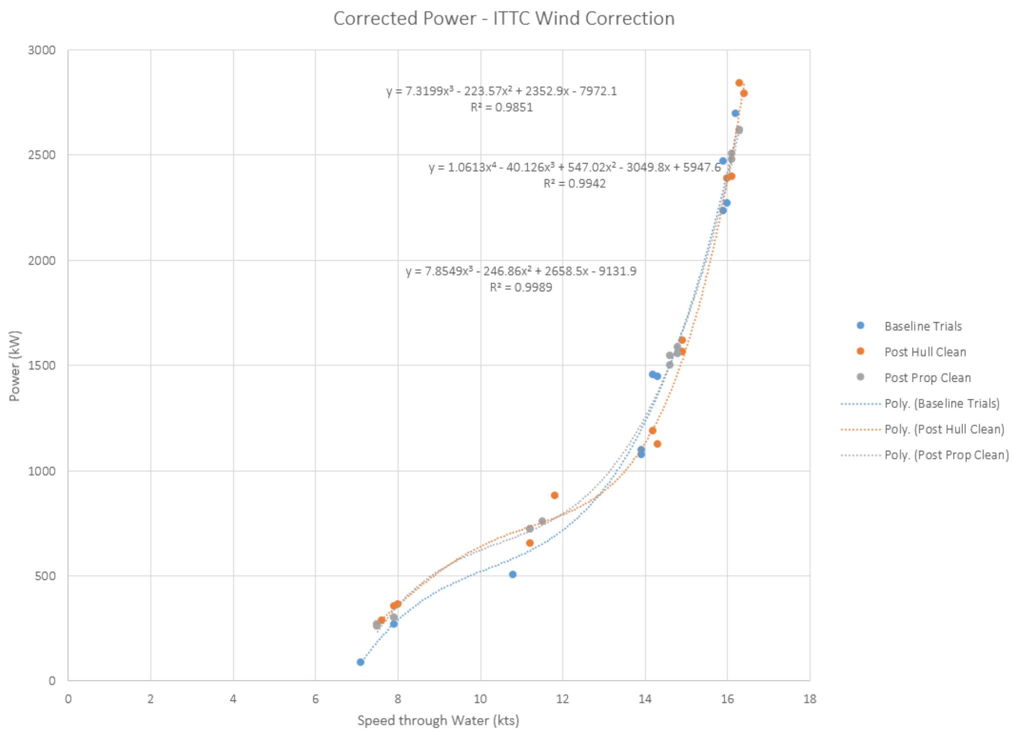

Figure 10. Corrected Power Results for All Trials – ITTC Wind Correction

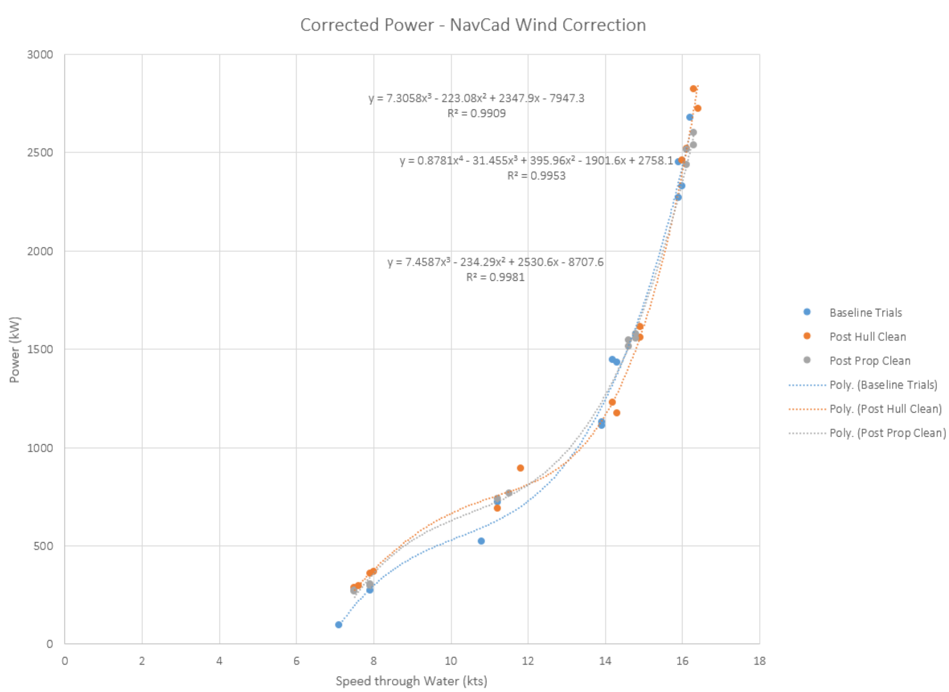

Figure 11. Corrected Power Results for All Trials – NavCad Wind Correction

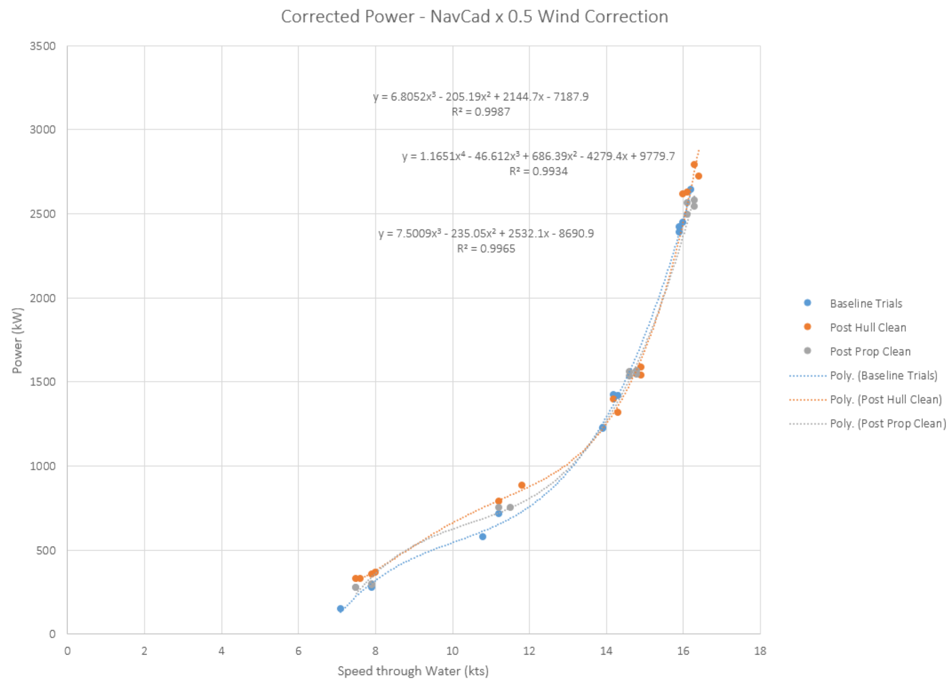

Figure 12. Corrected Power Results for All Trials – NavCad x 0.5 Wind Correction

7 Measured Data, Analysis and Results – Fuel Consumption and Speed

The measured total fuel consumption rate of both main engines was plotted against the speed through water for each test during each trial. The results from all trials were added to a single plot to allow comparison between the data sets. All data aligns relatively well to a single fuel consumption versus speed curve, though there is variability in the data sets. The post propeller cleaning trials have the least variability amongst the data points at a single engine setting, particularly at the higher engine settings tested. This was expected since the wind conditions during the post propeller cleaning trials were milder than the other two trials. The post hull cleaning points are slightly lower in terms of the fuel consumption rate that is required to attain a given speed when compared to the results of the other two trials. However, the post propeller cleaning points appear to be in line with the baseline trials results in terms of fuel consumption requirements for a given speed.

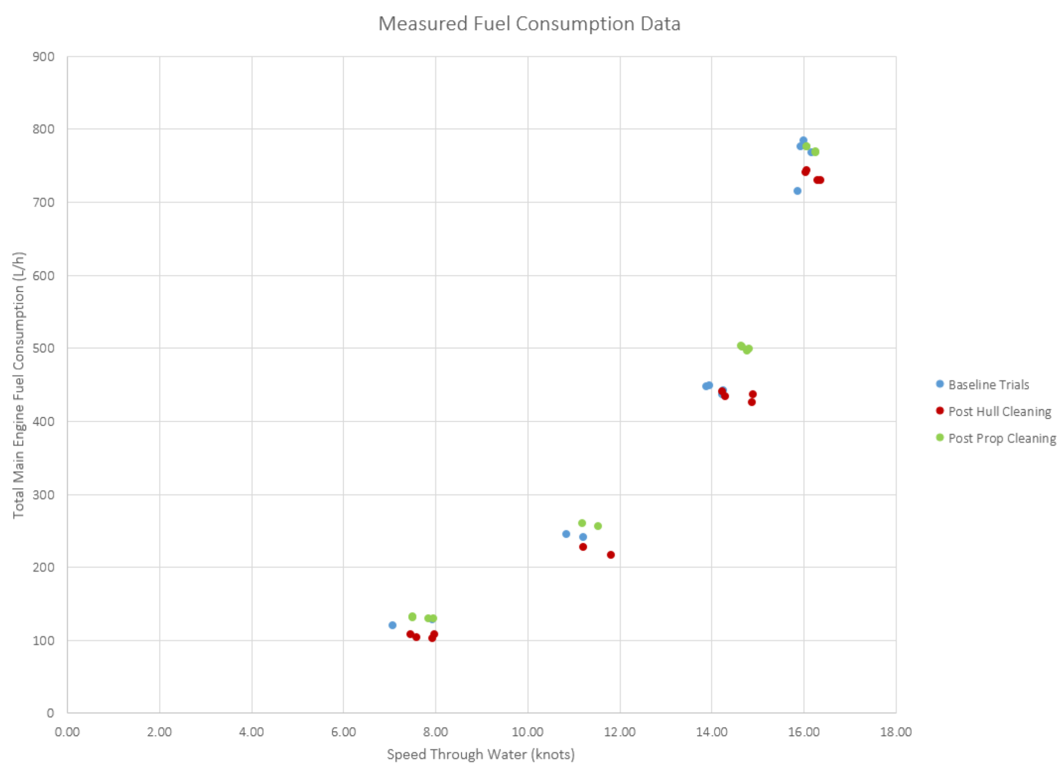

Figure 13. Uncorrected fuel consumption versus speed

The mean speed and fuel consumption rate at each engine setting was computed for each of the three trials. The mean fuel consumption values were plotted against the mean speed values and regression lines were fit through the data representing each trial. The results of this analysis is provided in Figure 14. The differences between the data sets from each trial, in terms of the relationship between fuel consumption and power, are clearer here. The fuel consumption savings as a result of cleaning the hull alone is larger than the fuel consumption savings resulting from cleaning the hull and propeller, which was unexpected.

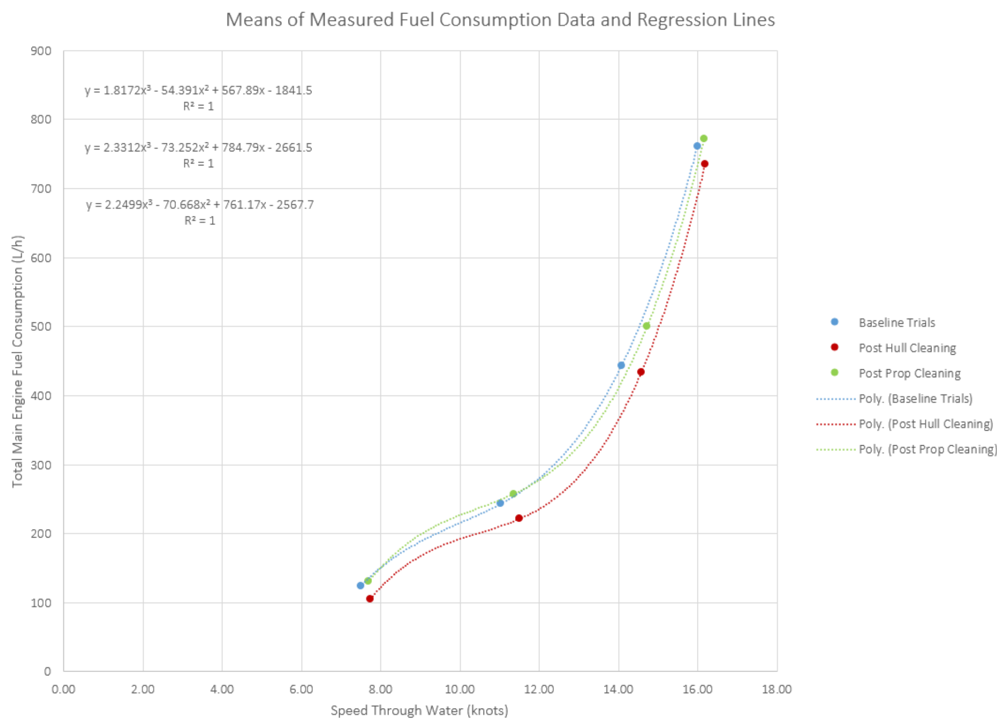

Figure 14. Means of Measured Data – Fuel Consumption versus Speed through Water

To investigate this further the total main engine fuel consumption versus shaft power was plotted for each trial. The fuel consumption versus power curve should be consistent for all trials since both fuel consumption and shaft power are not affected by external parameters such as environmental condition or hull and propeller condition. The speed attained however, does change as a result of variation in these external parameters. The measured total main engine fuel consumption versus power curve for all trials is shown in Figure 15. For each engine setting tested during trials, the baseline trials and post propeller cleaning trials data aligns well. However, there is an offset when it comes to the post hull cleaning trials data. For these trials there is less fuel required for a given power setting, particularly at higher power values. It is expected that there was some mechanical difference in the fuel measurement system that led to the discrepancy in the post hull cleaning fuel versus power data. A possibility is that one (or more) of the fuel flow meters surrounding one of the main engines was bypassed or partially bypassed or blocked during the post hull cleaning trials. However, the OpDAQ system bypass indicator did not highlight a complete bypass during this, or any of the trials.

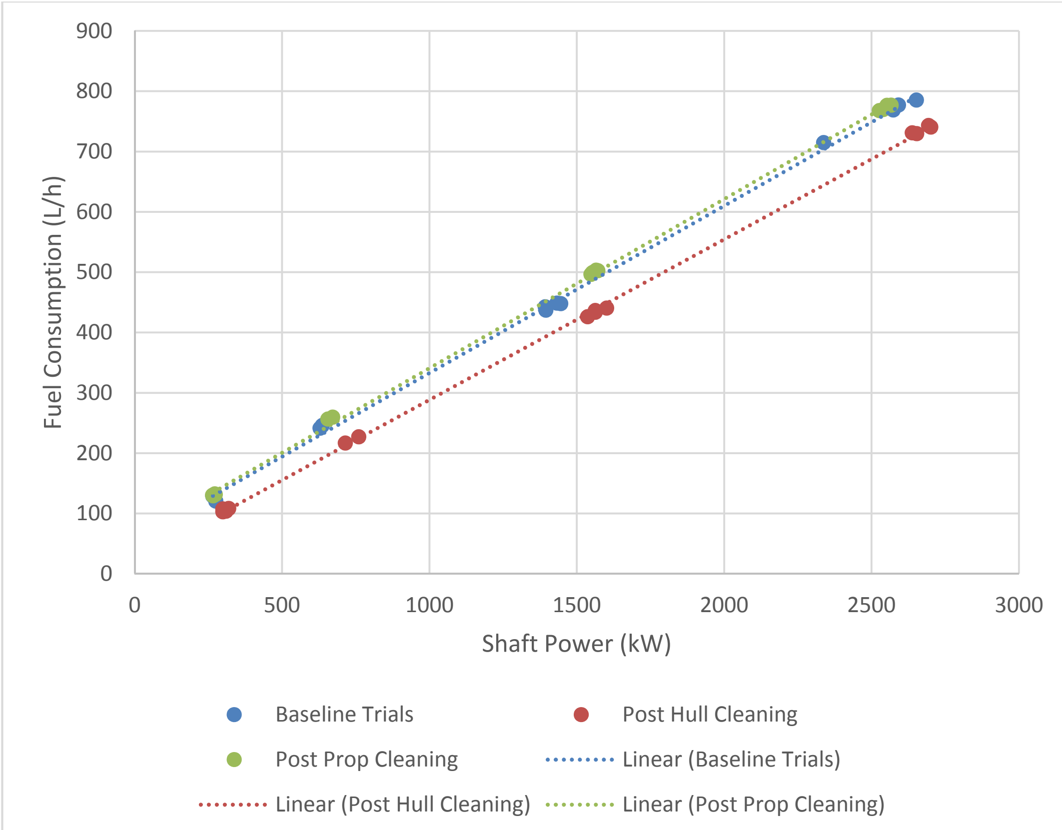

Figure 15. Uncorrected total main engine fuel consumption rate versus shaft power

The baseline and post propeller trials data for fuel consumption versus power was used to define the general fuel versus power curve for the Cygnus main engines. The post hull cleaning trials data was not used for this purpose due to the discrepancy from the other trials data. The general fuel versus power regression equation (regression equation listed in Figure 15) was used to calculate the "corrected" fuel consumption by adding the corrected power values at each engine setting for each trial. The power values corrected using the NavCad wind correction were used in this analysis. Once the "corrected" fuel consumption rate was identified for each test, the corrected fuel consumption versus speed was plotted for each specific trial so that the data could be easily compared (see Figure 16). There is no quantifiable difference between the fuel consumption rate and speed through water for the different sea trials. This is due to the level of variation in data at single test condition within a given trial and how data from different trials fall within this variability range. For example, at a throttle setting of 8.0, the baseline trials speed through water ranges from 13.9-14.3 knots and the corrected fuel consumption ranges from 373-475 L/h. At this same throttle setting, the post hull cleaning trials speed through water ranges from 14.2-14.9 knots and the corrected fuel consumption ranges from 393-526 L/h. There is overlap in the speed and fuel consumption variability ranges between trials for each engine setting.

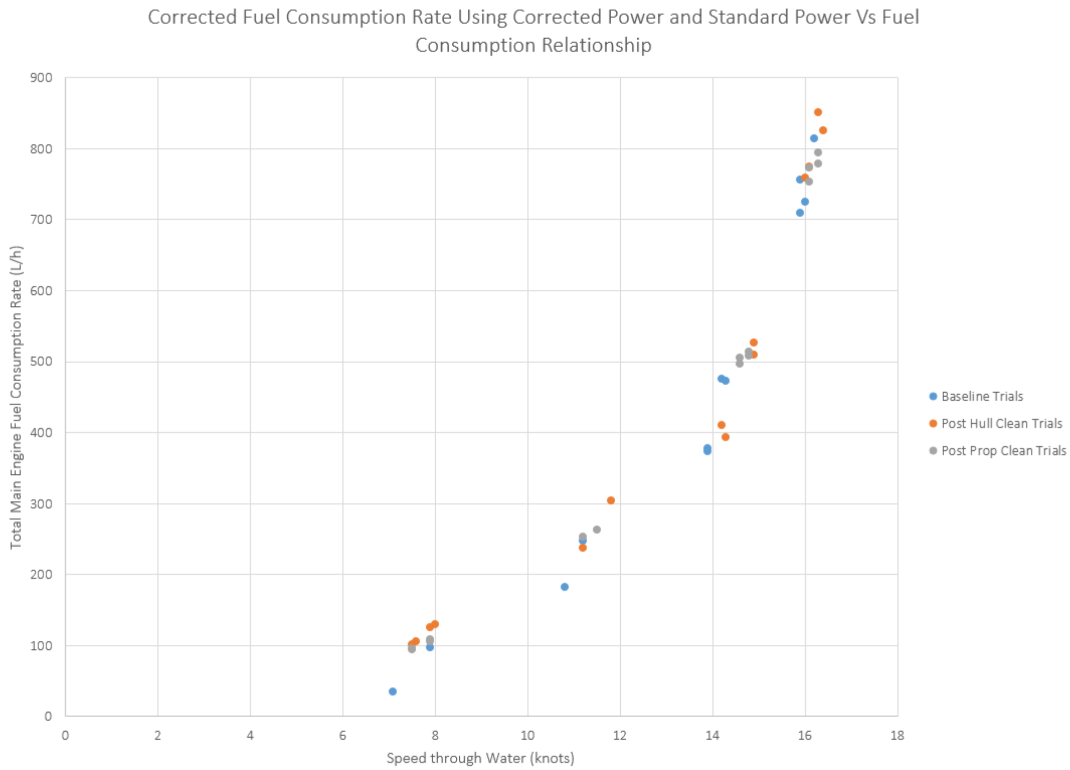

Figure 16. Corrected total main engine fuel consumption rate versus speed

8 Condition of Cygnus Hull in September 2018

The CCGS Cygnus was taken into dry dock on September 11, 2018 to perform vessel maintenance. When in dry dock, the hull was observed to have a relatively high level of fouling on one side in particular (port). The level of fouling present on the port side was similar to the amount that was present during the underwater survey conducted in May, 2018, prior to cleaning the hull. Specifically, there was slime and sea grass covering a large portion of the underwater hull (see Figure 17). These observations were unexpected for two reasons. The first relates to the speed of fouling taking place on the Cygnus hull. Prior to the May hull cleaning, the Cygnus hull had not been cleaned in two years. It was anticipated that the level of fouling present in September, just 3.5 months post hull cleaning, would be much less than that observed during the May survey. Some reasons that could have led to rapid fouling growth during this short period include the relatively warm temperatures during summer 2018 in the region and a depletion in anti-fouling coating.

Figure 17. Images of port side of hull during September, 2018 dry dock

The second oddity relating to the September hull condition is that the level of fouling differed on the port and starboard sides of the vessel with the starboard side having a higher level of fouling. The May survey results indicated that the starboard side of the hull had a slightly worse level of fouling. It was anticipated that if one side was more fouled than the other in September, it would have been the starboard side to be consistent with earlier results. Increased fouling on one side of the vessel could result from frequent docking on one side (fouling occurs more on side subject to sunlight) or lower quality of anti-fouling coating on one side of vessel. Cygnus Captains were consulted and it was confirmed that the docking side varies. The anti-fouling paint was noted to be highly depleted in September, on both sides of the vessel (see Figure 18). This likely played a role in the high fouling accumulation rate during the summer period.

Note that the anti-fouling paint is the black paint that can be observed in Figure 18. This image indicates the level of depletion of the anti-fouling paint after the biofouling was removed using a pressure washer in dry dock. The anti-fouling paint adhesion was investigated by brushing it lightly by hand using a scouring pad. This resulted in the anti-fouling paint flaking off as a result of the brushing. It is possible that the May and September hull cleaning events enhanced this level of depletion. However, if the anti-fouling paint had adhered properly upon initial application, it would not flake away so easily.

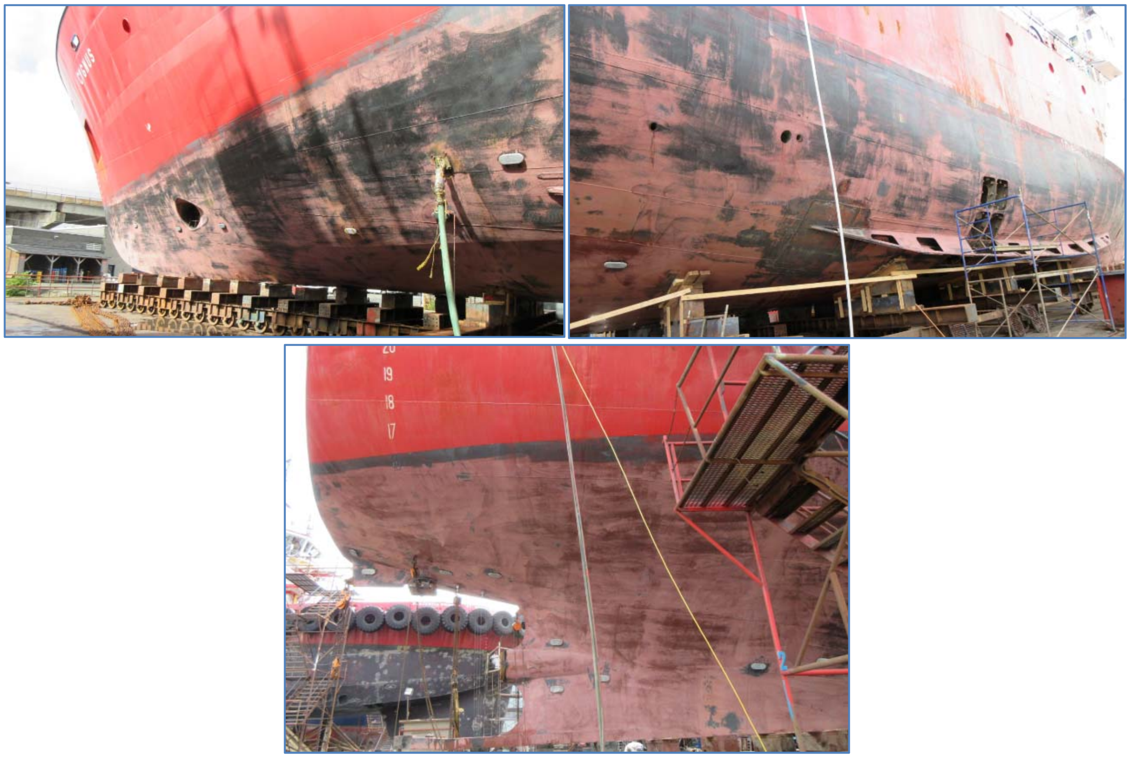

Figure 18. Images of Anti-fouling coating after biofouling was removed

The status of the anti-fouling paint was considered further by consulting with the Canadian Navy. A Canadian Navy biofouling Subject Matter Expert (SME) noted that the level of depletion of anti-fouling coating on the CCGS Cygnus was not typical given that the anti-coating was applied to the vessel only two years prior. The Canadian Navy SME indicated that this level of depletion was not seen on Navy vessels even after 5 years of use. They suggested to check on conditions during application and noted that application during high humidity levels could lead to faster depletion of coating. They also indicated that the type of coating used on the CCGS Cygnus was different than that used on Navy vessels and recommended that the CCG use an alternative coating.

The relatively high level of fouling present in September likely has an impact on the results presented in this report since there may have been a level of fouling present on the hull during post cleaning trials. This is particularly true for the post propeller cleaning trials which were not conducted until August 1, 2018. Unfortunately, there is no way to quantify the amount of fouling present during the post hull cleaning and post propeller cleaning trials. In general, if fouling was present during the post hull cleaning trials the analysis would indicate a lower level of power and fuel savings than the actual values. Also, if more fouling was present during post propeller cleaning trials than during post hull cleaning trials, the discrepancy between the measured savings potential and the actual savings potential would differ between trials and be larger for the post propeller cleaning trials. This could relate to the unexpected result of the post propeller trials found from the ITTC analysis methods.

9 Discussion and Recommendations

The measured results indicated a 4.1% savings in terms of required power to attain a given speed as a result of cleaning the hull and a 5.0% savings as a result of cleaning the propeller, for speeds between 12.5 and 16 knots. However, there were variations in the environmental conditions and condition of the vessel between trials and these differences have an influence on vessel performance. The wind, wave and water temperature variations between trials were corrected based on ITTC guidelines. The wind correction was also made using two variations of the ITTC recommended wind resistance correction method for comparison. The discrepancy between vessel displacement during the different trials was not corrected for since there was no standard guideline available to correct for this when the displacement varied by more than 2%. It was estimated that the displacement between trials varied by approximately 8%. The hull condition also varied between trials in that there was likely some level of fouling present during both the post hull clean and post propeller clean trials. Therefore there is some uncertainty in level of fouling between the post hull and post propeller cleaning trials. Based on the data that was corrected for wind (NavCad correction method), waves and water temperature, there is an average of 5% savings in terms of power required to attain a given speed as a result of cleaning the hull, for speeds between 13.5 and 16 knots. The performance decreases after the propeller polishing in this same speed range based on this analysis. To correct for wind, wave and temperature variation a number of parameters (e.g. wind resistance coefficient, propeller pitch for each trial, hull underwater area) had to be estimated. As a result, there is uncertainty involved in the corrected power values.

In terms of fuel consumption, there appeared to be a measurement error during the post hull cleaning trials which led to lower fuel consumption rates for a given power setting. This could be a result of partially closed fuel valve(s) surrounding one of the main engines. Therefore, it was impossible to quantify fuel savings resulting from cleaning the hull directly from the measured data. The general fuel consumption rate versus shaft power regression equation was used to calculate the corrected fuel consumption rates for each trial using the corrected (NavCad wind, ITTC wave and sea temperature) power values. This resulted in a corrected fuel consumption rate versus speed through water plot for each set of sea trials. The results for each trial were very similar and there were no quantifiable differences in the three curves.

9.1 Sources of Variation and Correction Consequences

As noted, three main sources of variation between the trials includes environmental conditions, vessel displacement and the hull fouling condition. Corrections for wind, wave and sea temperature variation were made and resulted in power versus speed curves that were lower (less power required for a given speed) for both the baseline and post hull cleaning trials. The post propeller cleaning trials were not as affected by this correction due to the relatively small wind and wave conditions during trials. This correction pushed the power versus speed curves for the baseline and post hull trials towards and even lower than that of the post propeller polishing trials as can be seen when comparing Figure 6 and Figure 11. The variation in displacement was not corrected for but it should be noted that the displacement during baseline trials was approximately 8% higher than that of the other two trials. If this discrepancy between trials was corrected for the power versus speed curve for the baseline trials would be lower (less power required to attain a given speed) and the power versus speed curves for the post hull and post propeller cleaning trials would be relatively unaffected. This would reduce the gap between the baseline and post cleaning trials, indicating less performance increase subsequent to cleaning. The variation in hull fouling condition was also not accounted for. This was the variable factor in this study since the goal is to quantify changes to vessel speed and power performance prior to and subsequent to cleaning the hull and propeller. However, it was not anticipated that there would be some level of fouling present on the hull during the post hull cleaning and post propeller cleaning trials. It is probable that some fouling was present at the time of the final two trials given the condition of the hull in early September 2018. If the results were corrected to account for slight fouling present during the post cleaning trials the power versus speed curves for these two trials would be lower, pushing these curves further away from the baseline trials curve and indicating better performance post cleaning.

In terms of both the power and fuel consumption, there is a range in the measured values at a given throttle setting during each of the sea trials. There is also a range in the speed through water values between the different tests at each throttle setting. There is some overlap between these ranges across the baseline, post hull and post propeller cleaning trials which makes it difficult to quantify power and fuel performance changes between trials. However, multiple tests were conducted at each throttle setting and the means of the data from each of these tests was used to define regression equations describing each of the sea trials. These mean based regression equations were used to quantify the variation between trials.

9.2 Recommendations to Reduce Uncertainty and Gain Result Clarity

There were a number of recommendations identified for conducting a similar study in the future which would lead to lower uncertainty in the data and more clarity in the results. These are summarized in point form below.

1. Conduct all tests in very low wind and wave conditions. In this project the baseline trials and post hull cleaning trials were conducted in similar conditions which were high in terms of the environmental condition limit. The post propeller cleaning trials were conducted in relatively mild conditions. The methods to correct for wind and wave conditions lead to uncertainty in the results since certain parameters need to be estimated. In mild conditions these corrections are much smaller and therefore less significant.
2. Conduct all tests at the same displacement. Variations in displacement lead to changes in vessel performance. In this project it was attempted to complete all trials at the same draft levels. However, since the Cygnus is an operational vessel and trials were completed weeks apart this was difficult to manage. As such, there was a variation in the draft (and displacement) and the effect of this on the results was not quantified. Trials at the same displacement would not have this source of variation and would lead to increased confidence in results.
3. Select vessel that has available propeller open water curves, wind tunnel test data and model resistance test data. This would reduce the number of parameters estimated in the data correction analysis and lead to lower uncertainty in the results.
4. Conduct tests closer together in time. The three tests involved in this test were completed between May – August of 2018. During this time there was some level of fouling that developed on the hull between trials and subsequent to the hull cleaning. This leads to a lower level of confidence in the results since there may have been some fouling present during both post hull and post propeller cleaning trials. If the trials had occurred closer together in time (e.g. days apart rather than months) this would limit the potential for fouling to develop on the hull or propeller between trials.
5. Conduct study on a vessel that has an off-season or longer alongside duration. The CCGS Cygnus is continuously in operation throughout the year and has a short, 2 day, layover period between operations. This gives limited time for the accumulation of biofouling and as such it was expected that the amount of fouling present initially on the Cygnus would be relatively low. The performance increase as a result of cleaning the hull and propeller would be larger for a vessel with more fouling in the baseline condition. A good candidate

would be a vessel that does not operate for a portion of the year, during which time fouling would accumulate faster than during operations.

9.3 Comparisons to Similar Publically Available Data

A brief literature search was completed to compare the results of this study to data available in the public domain. There were no directly comparable results identified in the literature in terms of comparable vessel size or initial level of fouling. However there were guidelines identified that provided insight as to what performance increases could be expected from cleaning the hull based on different initial levels of fouling (Schultz, 2007). These guidelines are based on model scale drag measurements and boundary layer similarity law analysis and were made for a mid-sized naval combatant at two speeds, 15 and 30 knots. Different fouling ratings (FR) as per the Naval Ships Technical Manual (2006) were used in this study. Table 10 summarizes the results of this study for a vessel speed of 15 knots in terms of increase in shaft power resulting from different levels of fouling. As discussed in Section 3, the fouled (baseline) condition of the CCGS Cygnus was mostly FR 20 with some areas having FR 30 (~15% of vessel). The corrected (for wind, wave and temperature) results indicate that the baseline trials required approximately 5 % more power than trials during which the hull was clean, for speeds greater than 13.5 knots. This is smaller than the 11% estimated increase in power for FR 10-20 as outlined in Table 10. However, the baseline condition was not a hydraulically smooth surface and was better described as a somewhat deteriorated coating. Therefore, it is reasonable to expect a lower power savings when comparing the two conditions.

Table 10. Expected performance changes as a result of hull fouling (From Shultz, 2007)

NSTM Rating	Description	Increase in SHP
0	Hydraulically smooth surface	0%
0	Typical as applied antifouling coating	2%
10-20	Deteriorated coating or light slime	11%
30	Heavy slime	21%
40-60	Small calcareous fouling or weed	35%
70-80	Medium calcareous fouling	54%
90-100	Heavy calcareous fouling	86%

Giorgiutti et al. (2014) conducted a study to investigate the impact of fouling on a crude oil tanker. This study investigated the effects of fouling on the hull and propeller separately and involved several sea trials. The data from sea trials was analyzed using ITTC analysis guidelines and complimented with other recommended methods. The analysis involved corrections for wind, wave, sea temperature and displacement variation. Details on the displacement during each trial or how this was corrected for were not provided. In this study the level of fouling at baseline condition was much higher on both the hull and propeller than that which was present on the Cygnus. The fouling was not rated as per Naval Guidelines however it was indicated that there was severe hard, calcareous fouling that was difficult to remove covering the majority of the propeller and underwater hull surface. The savings resulting from cleaning the hull and propeller were approximately 45 % in terms of reduced power at cruising speed. This study included both propeller cleaning and polishing.

A Computational Fluid Dynamics (CFD) based study was presented by Demirel et al. (2016) in the Journal of Applied Ocean Research. This investigation predicted the effect of biofouling on resistance and power requirements of a container ship based on full scale simulations. These predictions indicated an increase in power by 18.1% for the ship fouled with light slime and an increase by 38% for the ship fouled with heavy slime. There were no full scale sea trials used to compare or validate the CFD results. However, model test data was compared to the non-fouled predictions and they compared well.

In general, there is limited comparison data available in the public domain for this type of study, particularly data resulting from sea trials. The data that does exist can be compared generally but not directly since the hull forms and initial level of fouling vary. In addition, there are gaps in the methodologies applied for data analysis and trial corrections for the comparative data that is available in the literature.

9.4 Concluding Remarks

The primary goal of this study was to quantify the effects of cleaning the hull and propeller on the vessel performance in terms of speed and power, for the CCGS Cygnus. The corrected sea trials data indicated a reduction in power required to attain a given speed by an average of 5% between the speed ranges of 13.5-16 knots. However, these results were not corrected for variation in displacement across trials or the presence of slight fouling during the post cleaning trials. The results compare reasonably to estimations of power increase for a mid-sized Naval frigate for similar baseline and fouled conditions.

This study provided insight towards steps that could be taken to increase the value of future tests of a similar nature. These recommendations should be considered when planning future work to increase the level of confidence in results.

10 Acknowledgement

The authors would like to thank the Canadian Coast Guard for their support in coordinating sea trials, providing necessary vessel data and prompt response to questions during this work. Thanks go out to the Captain and crew of the CCGS Cygnus who executed the sea trials and were cooperative and supportive towards this research initiative.

11 References

Giorgiutti, Y, Rezende, F, Van, S., Monterio, C. and Preterote, G. (2014). “Impact of Fouling on Vessel’s Energy Efficiency,” Proceedings of the 25th National Congress of Waterway Transportation, Shipbuilding and Offshore, Rio de Janeiro, 10-12 November, 2014.

ITTC (2014). “Speed and Power Trials, Part 1: Preparation and Conduct,” International Towing Tank Conference, 7.5-04-01-01.1, Revision 1.1.

ITTC (2005). “Full Scale Measurements Speed and Power Trials Analysis of Speed/Power Trial Data,” International Towing Tank Conference, 7.5-04-01-01.2, Revision 00.

ISO (2016). “Ships and Marine Technology – Measurement of Changes in Hull and Propeller Performance – Part 1: General Principles,” International Standard, ISO 19030-1, First Edition 2016-11-15.

ISO (2015). “Ships and Marine Technology – Guidelines for the Assessment of Speed and Power Performance by Analysis of Speed Trial Data,” International Standard, ISO 15016, Second Edition 2015-04-01.

Royal Navy (2011). “Surface Ship Hull Fouling Management,” Maritime Acquisition Publication No 01-026, Issue 02, June 2011.

Naval Ship’s Technical Manual (2006). “Waterborne Underwater Hull Cleaning of Navy Ships,” Chapter 081, S9086-CQ-STM-010, Revision 5, Published by Direction of Commander, Naval Sea Systems Command.

Appendix A – Trials Test Logs

Baseline trial:

Measured or observed data														
1	Main engine output setting		50%		65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12
3	Heading	(deg)	229.41	48.71	227.16	48.79	228.08	47.99	226.88	46.72	227.71	48.04	227.58	47.23
4	Mid time of each run	(hour)	12:57:00	13:15:00	16:11:00	13:47:00	14:04:00	14:19:00	14:34:00	14:50:00	15:08:00	15:24:00	15:39:00	15:55:00
5	Ship speed over ground	(knots)	6.91	8.02	10.77	11.23	13.73	14.45	13.84	14.38	16.10	16.41	16.01	16.06
6	Ship speed through water	(knots)	7.06	7.93	10.84	11.22	13.89	14.23	13.95	14.26	16.00	16.17	15.93	15.86
7	Current velocity	(knots)	-0.15	0.09	-0.07	0.01	-0.16	0.21	-0.11	0.13	0.10	0.24	0.09	0.20
8	Propeller shaft speed	(rpm)	172.21	174.04	198.03	199.33	223.18	223.33	223.31	223.08	249.82	249.81	249.84	248.99
9	Propeller shaft torque	(kN-m)	15.29	14.56	30.70	30.15	61.87	59.65	61.27	59.64	101.39	98.39	99.07	89.66
10	Propeller shaft power	(kW)	275.73	265.30	636.67	629.25	1446.04	1395.13	1432.80	1393.31	2652.58	2573.89	2592.02	2337.86
11	Fuel Consumption	(l/hr)	120.28	128.85	245.58	241.22	447.69	436.83	448.54	442.33	785.00	768.62	776.80	714.65
12	Relative wind velocity	(knots)	31.97	12.59	29.05	6.10	35.43	2.65	33.90	0.55	35.40	0.12	34.53	-0.45
13	Relative wind direction	(deg)	-11.45	158.18	-4.25	147.81	-6.21	115.15	-6.00	108.35	-1.93	75.15	5.47	80.16
14	True wind velocity	(knots)	25.24	20.26	18.33	16.71	21.83	15.76	20.19	14.57	19.32	16.38	18.66	16.14
15	True wind direction	(deg)	214.84	215.35	220.42	217.58	217.97	219.24	216.77	224.66	224.18	227.64	237.74	228.79
16	Wind resistance coefficient		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17	Mean wave period	(s)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
18	Significant wave height	(m)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
19	Mean wave direction	(deg)	214.84	215.35	220.42	217.58	217.97	219.24	216.77	224.66	224.18	227.64	237.74	228.79
20	Incident angle of waves	(deg)	14.57	-166.64	6.74	-168.79	10.11	-171.25	10.11	-177.94	3.53	-179.60	-10.16	-181.56

Post hull cleaning trial:

Measured or observed data																
1	Main engine output setting		50%				65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Heading	(deg)	228.71	46.68	229.59	48.48	232.50	52.85	229.54	48.41	229.48	48.27	227.50	47.41	228.35	46.03
4	Mid time of each run	(hour)	10:30:00	10:45:00	11:00:00	11:16:00	11:32:00	11:46:00	12:04:00	12:20:00	12:36:00	12:52:00	13:08:00	13:25:00	13:41:00	13:58:00
5	Ship speed over ground	(knots)	7.81	7.88	7.63	7.86	11.30	11.69	14.53	14.78	14.45	14.86	16.36	16.40	16.39	16.39
6	Ship speed through water	(knots)	7.58	7.94	7.46	7.99	11.20	11.81	14.24	14.88	14.29	14.90	16.03	16.31	16.06	16.35
7	Current velocity	(knots)	0.23	-0.06	0.17	-0.12	0.10	-0.12	0.30	-0.09	0.15	-0.04	0.32	0.10	0.34	0.03
8	Propeller shaft speed	(rpm)	173.66	173.73	173.85	173.70	201.71	201.72	227.31	227.50	226.36	228.28	249.94	249.97	249.94	249.92
9	Propeller shaft torque	(kN-m)	17.07	16.46	17.56	16.47	36.02	33.86	67.28	64.52	65.96	65.39	103.22	101.39	102.92	100.83
10	Propeller shaft power	(kW)	310.36	299.51	319.63	299.60	760.72	715.20	1601.45	1537.08	1563.32	1563.15	2701.52	2653.77	2693.55	2638.58
11	Fuel Consumption	(l/hr)	103.52	102.41	108.23	107.42	226.94	216.41	440.20	425.90	433.36	436.39	740.38	729.48	742.93	730.64
12	Relative wind velocity	(knots)	23.61	7.91	27.76	6.72	35.91	10.41	41.59	7.22	39.99	0.12	38.47	3.08	37.05	5.66
13	Relative wind direction	(deg)	-8.15	153.49	-13.78	160.60	-9.62	140.10	-8.29	142.46	-7.90	130.43	-2.00	98.48	-8.90	108.27
14	True wind velocity	(knots)	15.92	15.37	20.43	14.37	24.83	20.78	27.29	20.98	25.76	14.94	22.13	17.13	21.01	18.94
15	True wind direction	(deg)	216.57	213.41	210.70	219.54	218.52	214.12	216.85	216.29	217.15	227.91	224.02	217.19	212.52	209.55
16	Wind resistance coefficient		0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9
17	Mean wave period	(s)	2.50	2.25	2.00	2.10	2.20	2.30	2.40	2.45	2.50	2.85	3.20	3.20	3.20	2.90
18	Significant wave height	(m)	0.18	0.20	0.21	0.24	0.27	0.32	0.36	0.36	0.36	0.38	0.40	0.39	0.38	0.36
19	Mean wave direction	(deg)	242.00	241.00	240.00	238.50	237.00	239.00	241.00	244.00	247.00	246.00	245.00	245.00	245.00	243.00
20	Incident angle of waves	(deg)	-13.29	-194.32	-10.41	-190.02	-4.50	-186.15	-11.46	-195.59	-17.52	-197.73	-17.50	-197.59	-16.65	-196.97

Post propeller cleaning trial:

Measured or observed data																
1	Main engine output setting		50%				65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Heading	(deg)	49.52	229.46	50.05	230.90	49.60	232.30	51.21	232.13	50.59	232.04	52.51	232.94	52.96	233.72
4	Mid time of each run	(hour)	11:50:00	12:05:00	12:24:00	12:39:00	12:56:00	13:10:00	13:25:00	13:38:00	13:51:00	14:04:00	14:19:00	14:33:00	14:47:00	15:00:00
5	Ship speed over ground	(knots)	7.68	7.66	7.70	7.73	11.11	11.47	14.40	15.02	14.50	14.95	16.09	16.49	16.10	16.46
6	Ship speed through water	(knots)	7.85	7.50	7.95	7.50	11.54	11.18	14.77	14.65	14.82	14.63	16.26	16.07	16.25	16.05
7	Current velocity	(knots)	-0.17	0.16	-0.25	0.23	-0.43	0.29	-0.37	0.37	-0.32	0.32	-0.17	0.42	-0.15	0.40
8	Propeller shaft speed	(rpm)	172.80	172.88	172.71	172.68	200.07	200.14	228.96	229.02	229.02	228.99	249.82	249.80	249.83	249.83
9	Propeller shaft torque	(kN-m)	14.72	15.12	14.62	15.05	31.30	32.06	64.59	65.54	64.76	65.30	97.10	98.13	96.58	97.58
10	Propeller shaft power	(kW)	266.38	273.68	264.39	272.21	655.70	671.88	1548.65	1571.79	1553.17	1565.75	2540.21	2566.80	2526.67	2552.92
11	Fuel Consumption	(l/hr)	129.18	131.08	130.03	132.11	256.19	259.37	496.24	502.18	498.96	503.07	769.33	776.50	767.61	776.35
12	Relative wind velocity	(knots)	2.64	14.10	1.78	14.25	3.88	18.96	10.01	18.86	10.44	20.16	9.14	24.69	6.13	24.91
13	Relative wind direction	(deg)	80.64	-13.04	86.27	-7.61	56.94	-9.50	37.94	-9.09	32.57	-6.13	25.35	6.42	13.93	11.89
14	True wind velocity	(knots)	7.71	6.86	7.78	6.67	9.56	7.88	8.95	4.68	8.01	5.53	8.76	8.50	10.26	9.43
15	True wind direction	(deg)	209.78	201.82	216.90	214.45	209.70	208.89	187.80	192.53	186.01	209.13	205.98	251.89	224.68	266.66
16	Wind resistance coefficient		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17	Mean wave period	(s)	12.70	12.70	6.70	6.70	6.90	6.90	6.40	6.40	7.80	7.80	7.40	7.40	7.00	7.00
18	Significant wave height	(m)	0.35	0.35	0.53	0.53	0.46	0.46	0.47	0.47	0.57	0.57	0.54	0.54	0.59	0.59
19	Mean wave direction	(deg)	242.00	241.00	240.00	238.50	237.00	239.00	241.00	244.00	247.00	246.00	245.00	245.00	245.00	243.00
20	Incident angle of waves	(deg)	-192.48	-11.54	-189.95	-7.60	-187.40	-6.70	-189.79	-11.87	-196.41	-13.96	-192.49	-12.06	-192.04	-9.28

Appendix B

JASCO Report – M / V Cygnus Underwater Radiated Noise Level Measurements in Conception Bay, NL

M/V Cygnus Underwater Radiated Noise Level Measurements in Conception Bay, NL

Coast Guard Patrol Vessel Noise Analysis before and after hull cleaning and propeller cleaning to investigate potential noise savings

Submitted to:

Rangyn Lim
Vancouver Fraser Port Authority

Authors:

Jorge Quijano
Zizheng Li
Christopher Whitt

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JASCO Applied Sciences (Canada) Ltd
Suite 2305, 4464 Markham St.
Victoria, BC V8Z 7X8 Canada
Tel: +1-250-483-3300
Fax: +1-250-483-3301
www.jasco.com

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Contents

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Summary

In this work, underwater radiated noise level (RNL) and monopole source level (MSL) of the Coast Guard patrol vessel *Cygnus* were investigated using underwater noise measurements in the frequency range 10 Hz to 63 kHz, made in 2018 in Conception Bay, NL, using an Autonomous Multichannel Acoustic Recorder (AMAR-G3; JASCO Applied Sciences). The measurements were conducted to investigate possible noise reductions due to cleaning of the hull and propeller. To this end, three measurement sessions were performed in this period: on 23 May before cleaning, on 18 Jul after hull cleaning, and on 1 Aug after propeller cleaning.

During each session, the vessel was sailed at several prescribed speeds along a measurement track that passed ~150 m to the side of the recorder. For each pass, bridge crews also logged vessel operating parameters, including vessel speed through water (STW), shaft power, shaft RPM, and propeller pitch. The analysis was performed using ShipSound, a component of JASCO's automated vessel noise measurement system PortListen®. RNL and MSL were estimated as broadband levels and in 1/3-octave frequency bands. RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone. MSL is equal to the measured sound pressure level scaled according to a frequency-dependent acoustic transmission loss model that accounts for the effect of the local environment on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and seabed losses).

Broadband noise emissions for the *Cygnus* ranged between 177–194 dB re 1 µPa m for RNL and between 178–200 dB re 1 µPa m for MSL. Such a wide range of variability in the measurements was mainly driven by the STW, which ranged between 6.9–16.5 kn. Regression analysis provided statistically significant evidence that increasing speed was associated with higher overall noise emissions.

To reduce the measurement variability caused by STW, broadband and per-octave band RNL and MSL were adjusted to a reference speed of 11 kn using heuristic (measurement-based) speed compensation factors. This adjustment resulted in broadband noise emissions that ranged between 180–185 dB re 1 µPa m and 180–189 dB re 1 µPa m for RNL and MSL, respectively. A significant reduction in measurement variability was also observed when comparing per-octave band levels before and after speed compensation.

Spectral analysis (1 Hz bands) was performed at frequencies below 2000 Hz to identify lower-frequency tonal noises, typically associated with propeller and machinery rotational vibrations. It was observed that passes at speeds 13–16 kn exhibited a prominent spectral peak around 16-17 Hz, corresponding to the propeller's blade rate. Passes at speeds <13 kn showed less distinctive spectral features within 0–100 Hz. Some of the measurements also showed a noticeable noise component at the 50 kHz band, associated to sounds from an onboard echosounder.

The key finding of the analysis of estimated broadband and 1/3-octave-band levels for Trial 1 (pre-cleaning), Trial 2 (hull cleaned), and Trial 3 (propeller cleaned) is the suggestion that these activities did not affect vessel noise generation. However, more conclusive evidence could have been obtained by limiting the variability of controllable parameters (propeller pitch, shaft speed, shaft power, closest point of approach (CPA), trim, draft) and by increasing the number of passes for combinations of these experimental settings. Confidence intervals obtained for the sample mean for RNL and MSL suggest, however, that any savings in noise before and after cleaning are likely to be at most ~3–3.5 dB for RNL and ~4–6 dB for MSL.

As an additional output from this analysis, this work also provides ANSI/ISO standard Grade C source levels at various speeds for the *Cygnus*.

Sommaire

Dans cette étude, les niveaux de bruit sous-marin tant rayonné que de source monopole du patrouilleur *Cygnus* de la garde côtière ont été étudiés en analysant des mesures de bruit sous-marin, dans la gamme de fréquence entre 10 Hz et 63 kHz, effectuées en 2018 en Baie de la Conception, à Terre-Neuve, par un enregistreur acoustique multicanaux autonome (AMAR-G3; JASCO Applied Sciences). Les mesures ont été effectuées pour étudier les possibles réductions du bruit suite au nettoyage de la coque et de l'hélice. À cette fin, trois sessions de mesures furent mises en place: le 23 mai avant le nettoyage, le 18 juillet après le nettoyage de la coque, et le 1 août après le nettoyage de l'hélice.

Durant chaque session, le navire suivit à plusieurs vitesses spécifiées un parcours de mesure passant à ~150 m sur le côté de l'enregistreur. À chaque passage l'équipage de passerelle notait également les paramètres opératifs du navire, incluant la vitesse-surface, la puissance et la vitesse de rotation de l'essieu, et le pas de l'hélice. L'analyse a été exécutée en utilisant le logiciel ShipSound, un des composants de PortListen®, le système automatisé de JASCO pour la mesure du bruit produit par les navires. Le niveau de bruit rayonné et le niveau de source monopole ont été évalués tant à large bande qu'en tiers d'octave. Le niveau de bruit rayonné est équivalent au niveau mesuré de pression acoustique rétro-propagé selon la distance entre la source et l'hydrophone. Le niveau de source monopole est équivalent au niveau mesuré de pression acoustique ajusté selon un modèle d'affaiblissement de transmission acoustique dépendant de la fréquence, prenant en compte tout effet de l'environnement local sur la propagation du son (c.-à-d. la réflexion à la surface de la mer, la réfraction et l'absorption dans la colonne d'eau, et les pertes dans le fond marin).

Les émissions de bruit à large bande du *Cygnus* s'échelonnèrent entre 177 et 194 dB re 1 µPa m pour le niveau de bruit rayonné et entre 178 et 200 dB re 1 µPa m pour le niveau de source monopole. Cette variation si prononcée dans les mesures était causée principalement par la vitesse-surface du navire, qui oscillait entre 6.9 et 16.5 nœuds. L'analyse de régression démontra de manière statistiquement significative que l'accroissement de la vitesse était associé avec de plus fortes émissions de bruit.

Pour réduire la variabilité des mesures causée par la vitesse-surface, le niveau de bruit rayonné et le niveau de source monopole, tant à large bande qu'en tiers d'octave, ont été normalisés à une vitesse référence de 11 nœuds par des facteurs heuristiques (basés sur les mesures) de compensation de vitesse. Cet ajustement a résulté dans des émissions sonores à large bande s'échelonnant entre 180 et 185 dB re 1 µPa m et entre 180 et 189 dB re 1 µPa m pour le niveau de bruit rayonné et le niveau de source monopole respectivement. Une réduction significative dans la variabilité des mesures a été également observée en comparant les niveaux en tiers d'octave avant et après l'ajustement pour la vitesse.

Une analyse spectrale (en bandes de 1 Hz) a été exécutée pour les fréquences au-dessous de 2000 Hz pour identifier des bruits tonaux à basse fréquence, typiquement associés avec les vibrations de rotation de l'hélice et de la machinerie. On a observé que les passages à des vitesses entre 13 et 16 nœuds révélaient un pic spectral proéminent autour de 16-17 Hz, correspondant à la fréquence de répétition des pales d'hélice. Les passages à des vitesses inférieures à 13 nœuds montraient des caractéristiques spectrales moins distinctives entre 0 et 100 Hz. Certaines mesures présentaient également un composant notable du bruit dans la bande à 50 kHz, associé aux sons d'un échosondeur.

La conclusion principale de l'analyse des niveaux à large bande et en tiers d'octave pour l'essai 1 (avant le nettoyage), l'essai 2 (après le nettoyage de la coque), et l'essai 3 (après le nettoyage de l'hélice) est la perception que ces activités n'ont aucun effet sur l'émission de bruit du navire. Cependant, des preuves plus concluantes pourraient avoir été obtenues en limitant la variabilité de paramètres contrôlables (le pas de l'hélice, la vitesse de rotation et la puissance de l'essieu, le moindre point d'approche, la compensation, le tirant d'eau) et en augmentant le nombre de passages pour différentes combinaisons de ces réglages expérimentaux. Les intervalles de confiance de la moyenne de l'échantillon obtenus pour les niveaux de bruit rayonné et les niveaux de source monopole suggèrent, en tout cas, que la réduction en bruit avant et après le nettoyage n'excèderait probablement ~3–3.5 dB pour le niveau de bruit rayonné et ~4–6 dB pour le niveau de source monopole.

Comme résultat supplémentaire de l'analyse, cette étude fournit aussi les niveaux sonores de source selon le standard ANSI/ISO de grade C pour différentes vitesses du *Cygnus.*

1. Overview

This report presents underwater radiated noise level (RNL) and monopole source level (MSL) measurements of the Coast Guard patrol vessel *Cygnus* (Figure 1, Table 1). The measurements were made to investigate possible noise reductions due to cleaning of the hull and propeller. Visual underwater inspection of the Cygnus revealed slime, grass, and/or calcium build up on rudders, propeller, thrusters, stern tubes, vessel bottom, and vertical sides (Subsea Global Solutions 2017a). Hull cleaning of the entire submerged hull was carried out, followed by polishing of the vessel's main propeller (Subsea Global Solutions 2017b).

High-resolution acoustic recordings were made in Conception Bay, NL, between 23 May and 1 Aug 2018. Three measurement sessions were performed in this period (Table 2): on 23 May before cleaning, on 18 Jul after hull cleaning, and on 1 Aug after propeller cleaning. During each session, the vessel was sailed at several prescribed speeds along a measurement track that passed ~150 m to the side of the recorder. This approach produced consistent high-resolution measurements that met and exceeded the Grade-C requirements of the vessel radiated noise measurement standard ANSI 12.64-2009 (R2014). Data and measurement quality were excellent and provided near-optimal results for the goals of the project.

Figure 1. Coast Guard patrol vessel *Cygnus.* Photo: MarineTraffic.com

Table 1. Technical specifications of the vessel *Cygnus*.

Specification	Data for *Cygnus*
Year built	1982
IMO number	7927831
MMSI	316017000
Length (m)	62.5
Nominal draft (m)	4.8
Breadth (m)	12.2
Nominal cruising speed (kn)	13
Maximum speed (kn)	16
Propulsion	Main engine: 2 × Polar Nohab F212V, 12-cylinder diesel engines
Propeller Diameter (mm)	2800
Number of propeller blades	4
Power (kW)	3455
Generators	2 x Caterpillar–353
Speed log system	Sperry Naviknot
Onboard sonar equipment	Skipper GDS 101 Echosounder, operated at 38 kHz and 200 kHz. Sperry Marine ES 5100 Echosounder, operated at 50 kHz and 200 kHz.

Table 2. Details of the trials. All recorded passes underwent a quality control review. Three passes were rejected because the vessel was not within the measurement funnel for the entire pass.

Trial	Measurement date (UTC)	Details	Number of accepted pass	Number of rejected pass
1	23 May 2018	Pre-cleaning	13	0
2	18 Jul 2018	Hull cleaned	11	3
3	01 Aug 2018	Propeller cleaned	14	0

The Canadian Coast Guard and Transport Canada initiated these measurements to better understand possible underwater noise reductions from hull and propeller cleaning. The measurements will also potentially be helpful for identifying noise features of the vessel and whether these features can be correlated to certain specific machinery. This would then possibly allow for reducing the vessel's noise levels through servicing its machinery and isolating vibrations. This report examines the radiated noise level (RNL) correlation with speed, and cleaning state, but it did not assess other parameters. Monopole Source Levels (MSL) were also calculated, as different quiet certification systems use both of these noise emission metrics.

RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone (Appendix C). MSL is equal to the measured sound pressure level scaled according to a numerical acoustic transmission loss (TL) model that accounts for the effect of the local environment (Appendix F) on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and bottom loss). MSL back-propagation is performed using predictions of the Parabolic Equation model RAM, modified to treat shear wave reflection losses, in 1/3-octave-bands to 5 kHz, and an image reflectivity model at higher frequencies.

Noise measurements were performed as the *Cygnus* transited a defined track passing through a measurement zone as shown on the map of Figure 2. Bridge crews also logged vessel operating parameters, including vessel speed, shaft power, shaft RPM, and propeller pitch (Appendix A) for each measurement pass. Acoustic measurements were made with an Autonomous Multichannel Acoustic Recorder (AMAR-G3; JASCO Applied Sciences). Data were acquired at 128 ksps sample rate with 24-bit resolution. The AMAR was calibrated in the lab before and after the measurements. The sound recordings were analyzed to estimate RNL and MSL of the vessel passes. The analysis was performed using ShipSound, a component of JASCO's automated vessel noise measurement system PortListen® (Appendix B). The measurement geometry, acoustic system calibrations, and data processing methods conformed with ANSI S12.64 (2009) (Appendix C). PortListen uses vessel's GPS data to track its position and speed over ground. Positional information is refined using acoustic tracking methods. Environmental conditions (wind speed and current speed) were also recorded for each pass. RNL and MSL were tabulated as broadband levels and in 1/3-octave frequency bands. Regression analysis was performed to identify variations of RNL and MSL with speed.

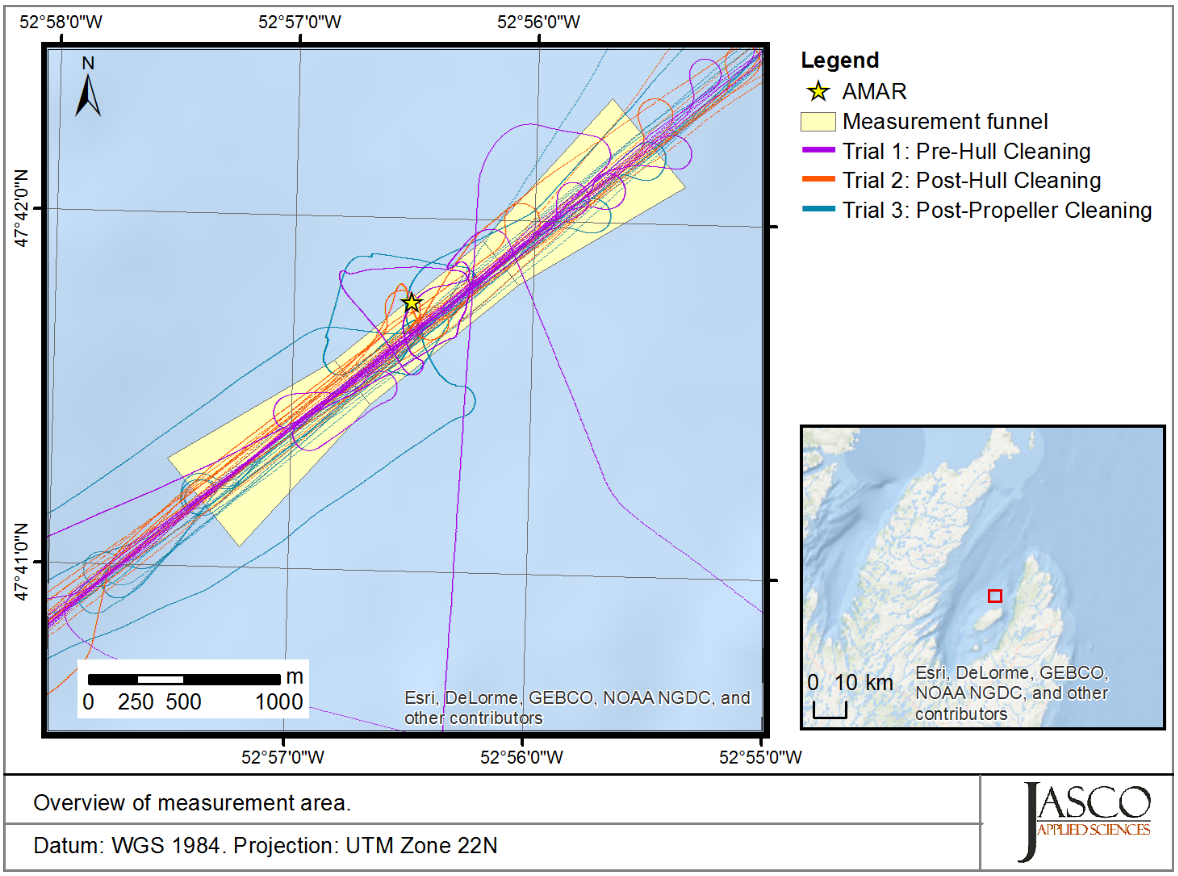


Figure 2. Map of the study area at Conception Bay, NL, and sailing tracks for the *Cygnus*. The hydrophone was located at 47° 41' 45.6959" N, 52° 56' 30.4362" W, 5.4 m above seafloor. The water depth is 120 m.

2. Results

This section presents measured levels and a statistical analysis of the *Cygnus* underwater noise for Trials 1–3. Measured data are also presented as spectral densities and in 1/3-octave-bands for the frequency range 10 Hz to 63 kHz.

2.1. Vessel noise emissions

The source RNL and MSL of all passes are summarized in box-and-whisker plots, showing the corresponding range of variability of all accepted measurements (Figure 3). These levels include all accepted measurements, independent of vessel speed (ranging from 6.9–16.5 kn) and of environmental conditions at the times of the measurements. A 5-number statistic summary of these measurements (Table 3) shows only small variations on median and maximum broadband RNL between trials. Larger variability was observed for Trials 1 and 3 (pre-cleaning and propeller cleaned, respectively), compared to Trial 2 (hull cleaned). For broadband MSL, the maximum, upper quartile, and median levels exhibit a mild decay from Trial 1 through to Trial 3. Similar to broadband RNL, the MSL for Trial 2 exhibit lower variability compared to MSL Trials 1 and 3.

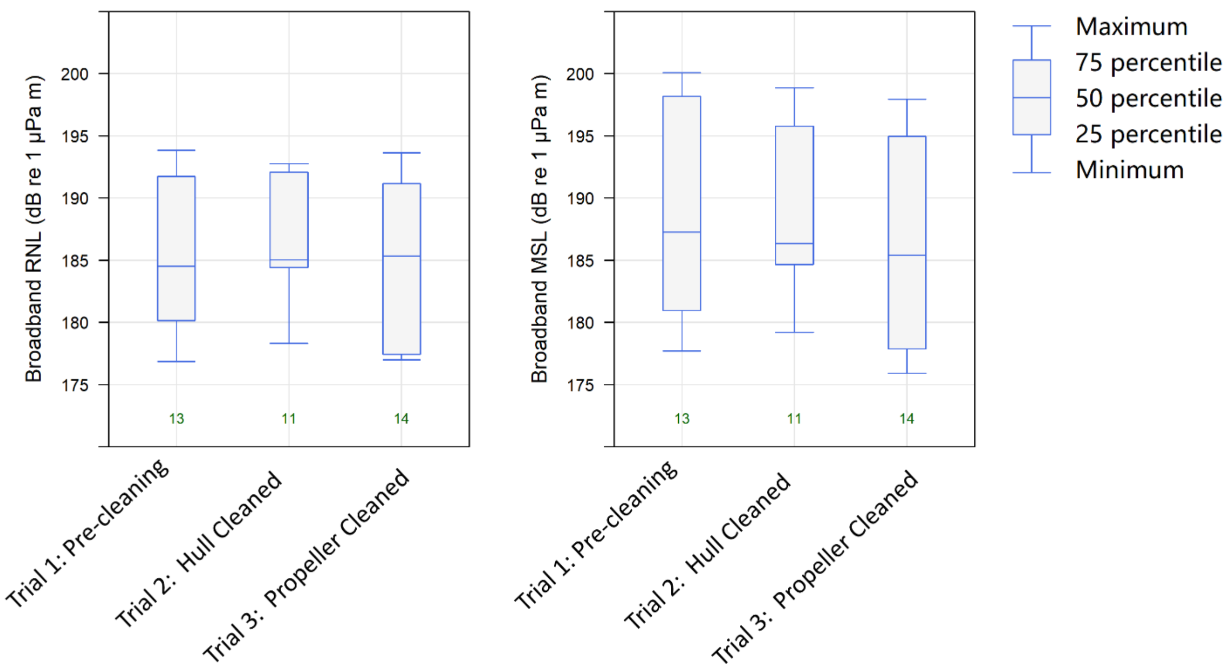


Figure 3. Summary of broadband RNL (left) and broadband MSL (right) percentile levels corresponding with Trial 1–Pre-cleaning, Trial 2–Hull cleaned, and Trial 3–Propeller cleaned, for all accepted measurements. The total number of accepted measurements is indicated below each box. Note that no speed corrections have been applied for these measurements, and the vessel speeds are ranging from 6.9–16.5 kn.

Table 3. Statistic summary (minimum, lower quartile, median, upper quartile, maximum) of accepted source level measurements (RNL and MSL, dB re 1 µPa m). These levels are independent of vessel speed (ranging from 6.9–16.5 kn) and of environmental conditions at the times of the measurements.

Statistic	Broadband RNL (dB re 1 µPa m)			Broadband MSL (dB re 1 µPa m)		
	Trial 1 Pre-cleaning	Trial 2 Hull cleaned	Trial 3 Propeller cleaned	Trial 1 Pre-cleaning	Trial 2 Hull cleaned	Trial 3 Propeller cleaned
Maximum	193.8	192.8	193.6	200.1	198.9	197.9
Upper quartile	191.7	192.1	191.2	198.2	195.8	195.0
Median	184.5	185.0	185.3	187.3	186.3	185.4
Lower quartile	180.2	184.4	177.4	181.0	184.6	177.9
Minimum	176.9	178.3	177.0	177.7	179.2	175.9

2.2. Vessel speed analysis

Vessel noise was measured at several transit speeds (Figure 4), calculated from GPS-reported speed over ground, and corrected according to the direction and speed of water currents to obtain speed through water (STW). Throughout all measurements, current speed was lower than 0.003 kn, making the speed over ground essentially the same as STW. Based on clustering of the measured RNL and MSL, three speed ranges (6.9–12 kn, 13–15 kn, and 15–16.5 kn) can be identified for the *Cygnus*. To quantify trends of Source Level SL (RNL or MSL) with STW, a power-law model (Ross 1976) of the following form was fit to the data:

$$\mathrm{SL} = C_v \times 10\log_{10}\left(\frac{v}{v_{\mathrm{ref}}}\right) + \mathrm{SL}_{\mathrm{ref}}\,, \tag{1}$$

where C_v is the slope of variation in SL relative to the STW, v, measured in knots. $\mathrm{SL}_{\mathrm{ref}}$ (dB re 1 µPa m) is defined here as the reference source level, representing the SL at the reference STW, v_{ref}. Figure 4 shows the values of C_v, obtained by fitting broadband MSL and RSL to Equation 1. The analysis shows statistically significant increasing trends of RNL and MSL with speed (Table 4). A reference v_{ref} = 11 kn (i.e., in the mid range of STW for all the passes) was used in Equation 1.

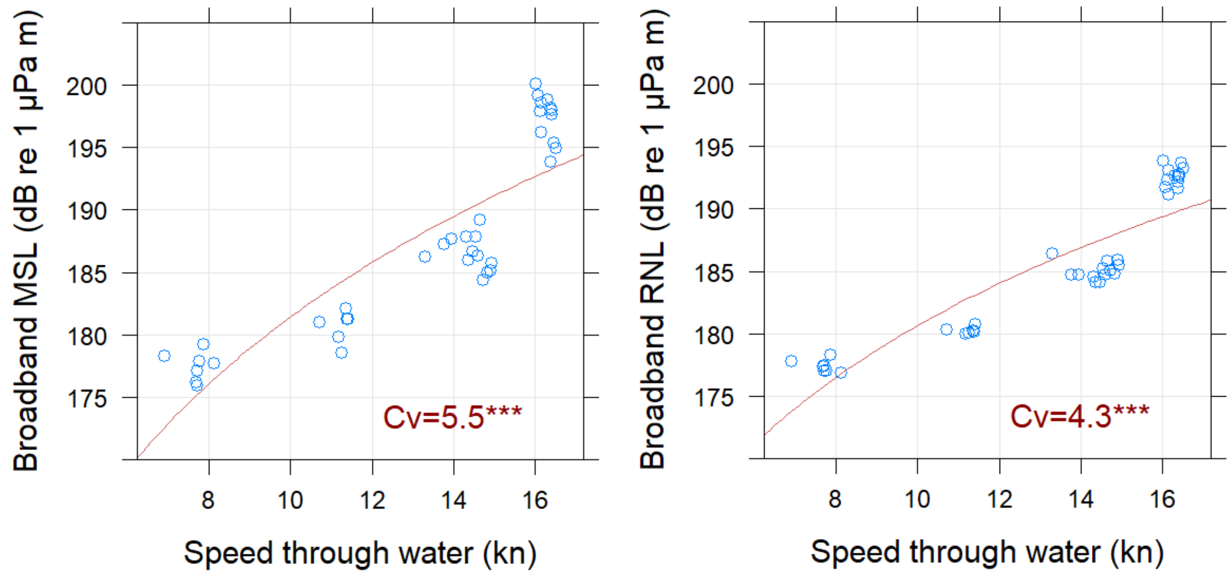


Figure 4. Scatter plots of MSL (left) and RNL (right) versus speed through water (STW). Solid lines show best-fit trend lines. Asterisks indicate that the C_v parameter was found to be statistically significant. See Table 4 for the best-fit trend line parameters.

Table 4. Best-fit trend line parameters of broadband RNL and MSL versus speed through water (STW), as determined by linear regression analysis. C_v is the best-fit slope of the trend line, and SL_{ref} is the best-fit source level (RNL or MSL) at the reference speed (v_{ref}). The coefficient of determination (r^2) is a number in the range 0–1 that indicates the strength of correlation between RNL and speed through water (0 = no correlation, 1 = total correlation). Asterisks indicate the p-values (*** corresponds to p-values with $p < 0.001$). The level of significance is α=0.05.

Fit parameter	RNL	MSL
C_v	4.3***	5.5***
SL_{ref} (dB re 1 µPa m)	182.4***	183.7***
v_{ref} (knots)	11	11
Coefficient of determination (r^2)	0.79	0.73
Significant	Yes	Yes

The parameters in Table 4 provide a summary of the relation between broadband noise and vessel speed. However, vessel noise is strongly driven by frequency, as it is related to distinct vibrations from various mechanisms and structures (engines, pumps, generators, propeller cavitation, hull vibration and its acoustic coupling into the water) involved in its generation. For this reason, it is convenient to perform a frequency-dependent analysis in which Equation 1 is fit to the vessel noise at each frequency band. This results in the band-dependent C_v factors shown in Figure 5 (RNL) and Figure 6 (MSL). With the exceptions of the 10 Hz MSL and RNL bands and the 400 Hz MSL band, all C_v were found to be statistically significant.

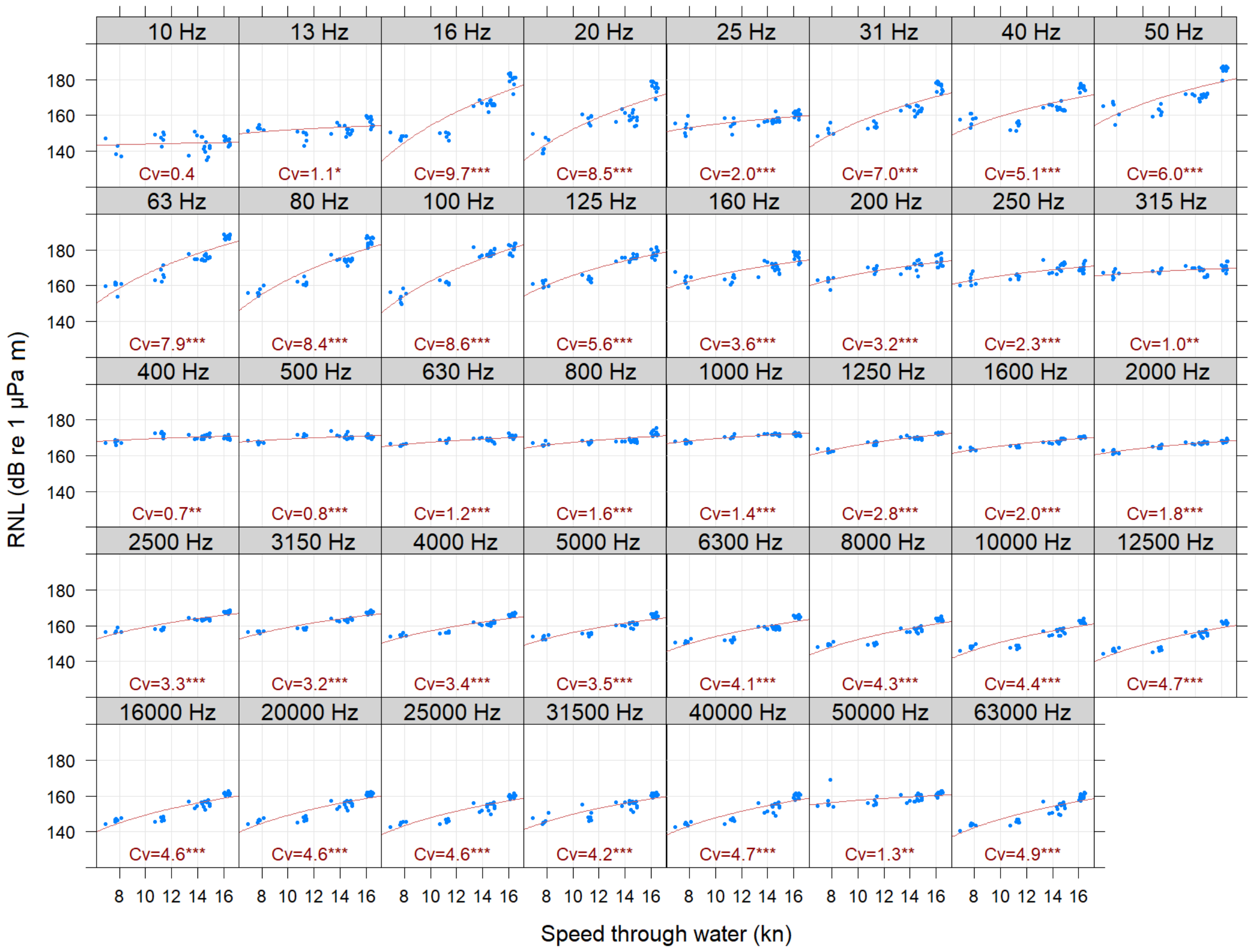


Figure 5. Scatter plots of 1/3-octave-band RNL versus speed through water. In each frequency band, every point corresponds to a single vessel pass from all trials. Asterisks indicate that the C_v parameter was found to be statistically significant (p-values: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

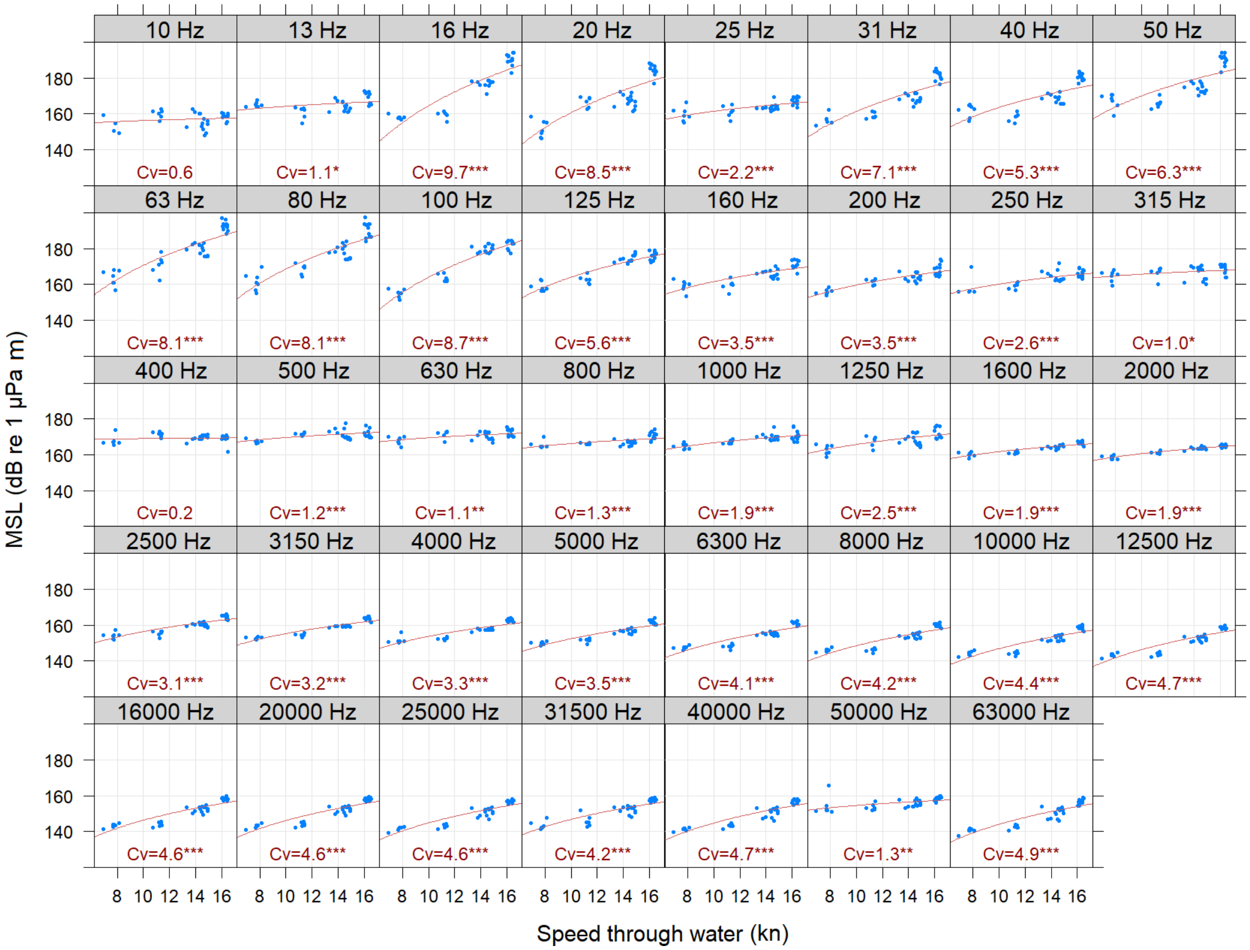


Figure 6. Scatter plots of 1/3-octave-band MSL versus speed through water. In each frequency band, every point corresponds to a single vessel pass from all trials. Asterisks indicate that the C_v parameter was found to be statistically significant (p-values: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

The estimated broadband and per-band C_v can be used to remove (or at least minimize) the effect that vessel speed has on the RNL and MSL range of variability (Figure 3). To this end, a speed-dependent factor

$$\mathrm{F} = C_v \times 10\log_{10}\left(\frac{v_{\mathrm{ref}}}{v}\right), \tag{2}$$

is added to the estimated levels at each band. Equation 2 was applied with v_{ref} = 11 kn to 1/3-octave-band RNL and MSL, and broadband levels for each trial were computed from the adjusted band levels. The resulting speed-adjusted broadband levels (Figure 7) and the corresponding 5-number statistic summary (Table 5) shows very small variation in the statistics between trials, suggesting that the effect of hull/propeller cleaning on broadband vessel generated noise is minimal.

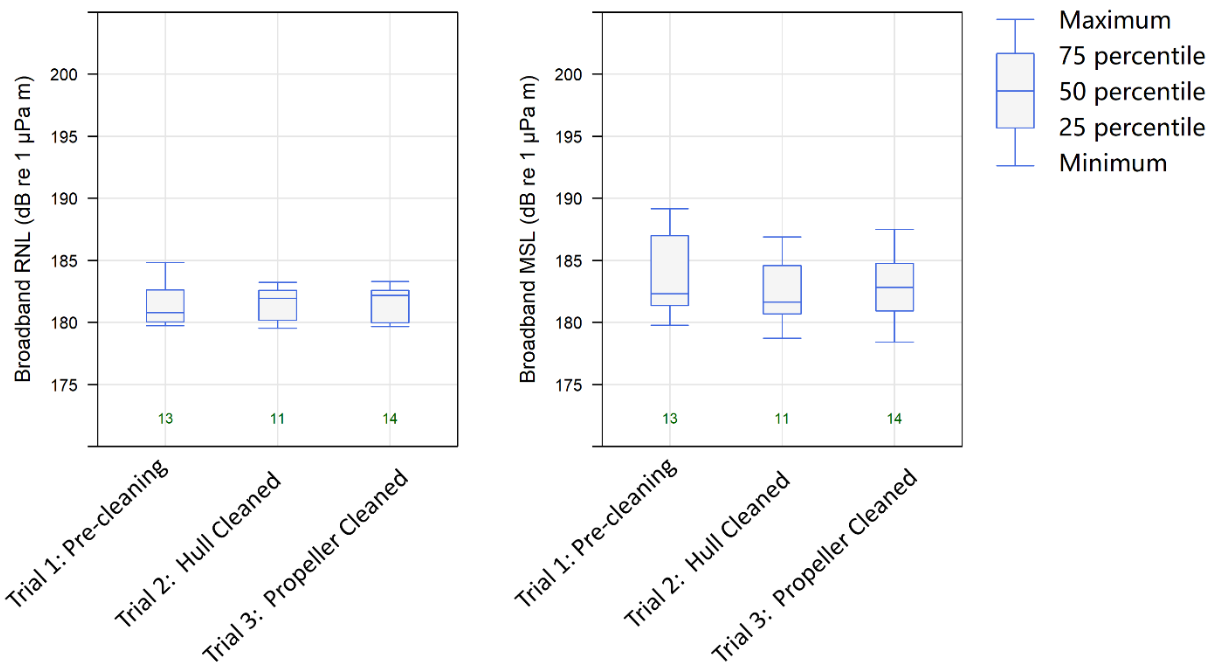


Figure 7. Summary of broadband RNL (left) and broadband MSL (right) percentile levels corresponding with Trial 1–Pre-cleaning, Trial 2–Hull cleaned, and Trial 3–Propeller cleaned, for all accepted measurements, adjusted to a reference speed v_{ref} = 11 kn using Equation 2. The total number of accepted measurements is indicated below each box.

Table 5. Five-number summary (minimum, lower quartile, median, upper quartile, maximum) of accepted source level measurements (RNL and MSL, dB re 1 µPa m), adjusted by applying Equation 2 to normalize to a reference speed of 11 kn.

Statistic	**Broadband RNL (dB re 1 µPa m)**			**Broadband MSL (dB re 1 µPa m)**		
	Trial 1 Pre-cleaning	Trial 2 Hull cleaned	Trial 3 Propeller cleaned	Trial 1 Pre-cleaning	Trial 2 Hull cleaned	Trial 3 Propeller cleaned
Maximum	184.8	183.2	183.3	189.2	186.9	187.5
Upper quartile	182.6	182.6	182.6	187.0	184.6	184.8
Median	180.8	181.9	182.2	182.3	181.7	182.8
Lower quartile	180.0	180.2	180.0	181.4	180.7	180.9
Minimum	179.7	179.5	179.7	179.8	178.7	178.4

The sample RNL and MSL means (i.e., the means obtained from the limited number of measurements available per trial) also exhibited very small variation between trials (Table 6). For this statistic, 95% confidence intervals were also obtained to quantify the level of uncertainty in the estimated mean.

Table 6. 95% confidence intervals of the sample mean for accepted source level measurements (RNL and MSL, dB re 1 µPa m), adjusted by applying Equation 2 to normalize to a reference speed of 11 kn.

Source level	Trial 1: Pre-cleaning (13 measurements)		Trial 2: Hull cleaned (11 measurements)		Trial 3: Propeller cleaned (14 measurements)	
	Sample mean	95% confidence interval	Sample mean	95% confidence interval	Sample mean	95% confidence interval
Broadband RNL	182.4	180.6–184.1	182.3	180.4–184.1	182.6	181.1–184.0
Broadband MSL	184.6	181.9–187.3	183.1	180.1–186.2	183.3	181.3–185.4

2.3. Spectrum analysis

Spectral analysis (1 Hz bands) was performed at frequencies below 2000 Hz to identify lower-frequency tonal noises, typically associated with propeller and machinery rotational vibrations (Appendix D). As an example, Figure 8 shows a zoomed-in view of the spectra (0–100 Hz) for Trials 1–3. Passes at speeds >16 kn exhibited a prominent peak around 16-17 Hz (i.e., 960–1020 rpm). The frequency of this peak is likely related to the blade rate, which can be estimated by multiplying the shaft rate (reported as 250 rpm, Table A-1) by four, the number of blades per propeller. At this high-speed setting, a second harmonic at 32 Hz was also identified in all passes.

Harmonic peaks at 16 and 32 Hz were observed in passes at speeds within the range 13–16 kn. Most passes at this speed range were also performed at a shaft rate of 250 RPM. However, the spectral peaks in this speed range exhibited lower amplitude compared to the ones at high-speed settings. Passes at speeds <13 kn showed less distinctive spectral features within 0–100 Hz.

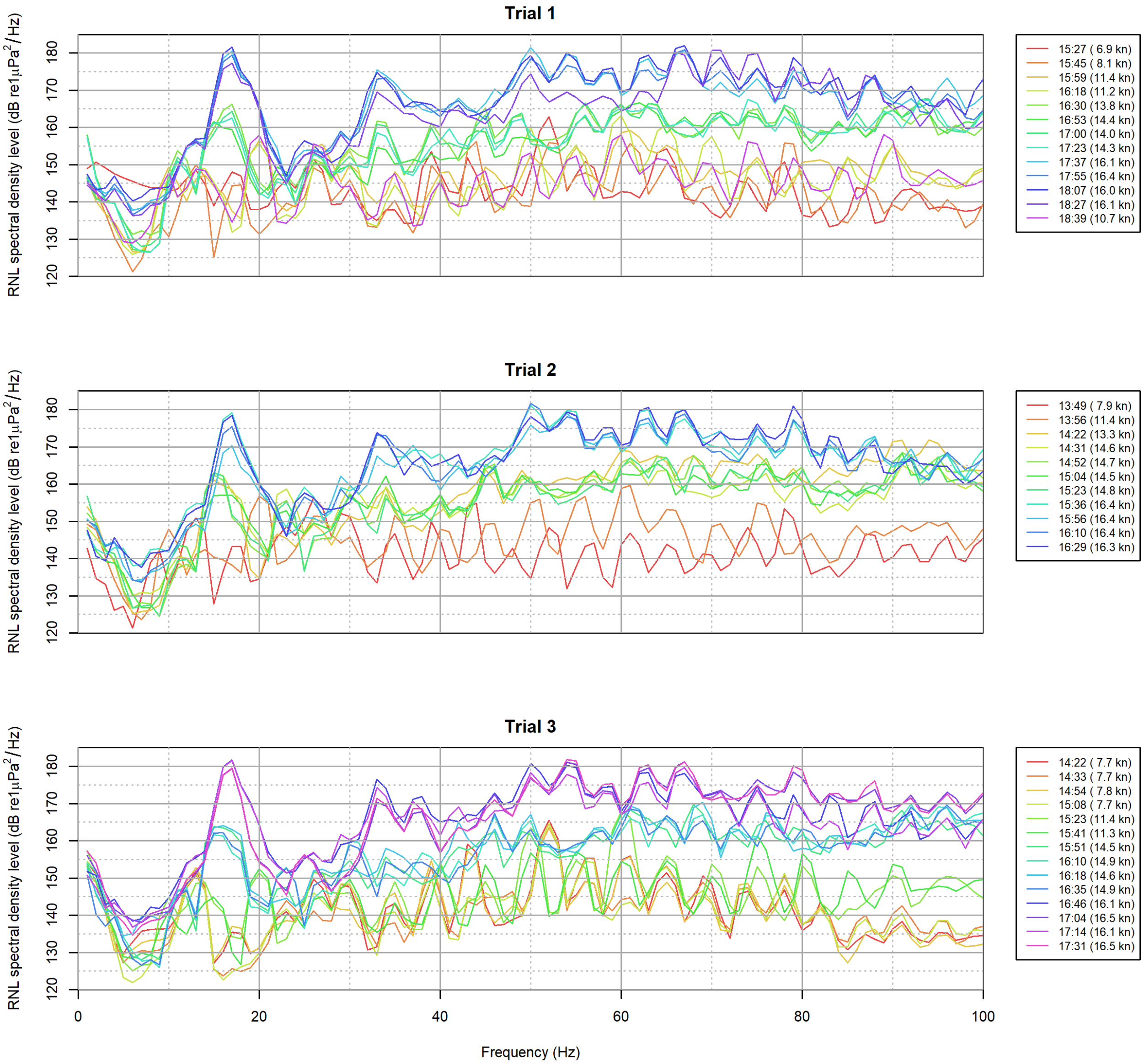


Figure 8. Spectra (0–100 Hz) corresponding to passes during Trial 1 (May 2018), Trial 2 (July 2018), and Trial 3 (August 2018), showing propeller blade rate modulation. The legend indicates the time and speed of each pass, in the same order of the Vessel Operating Logs entries (Appendix A). Appendix D shows the spectra with a broader frequency range (0–2000 Hz).

Figures 9 and 10 show RNL and MSL, respectively, in 1/3-octave-bands (see the Glossary) for all measurements prior to adjusting for speed. Based on this analysis, the *Cygnus* had the highest noise emissions below 100 Hz, with the loudest contributions around 50–80 Hz. Some of the measurements show a noticeable noise component at the 50 kHz band, which is attributed to sounds from an onboard Sperry Marine ES 5100 echosounder.

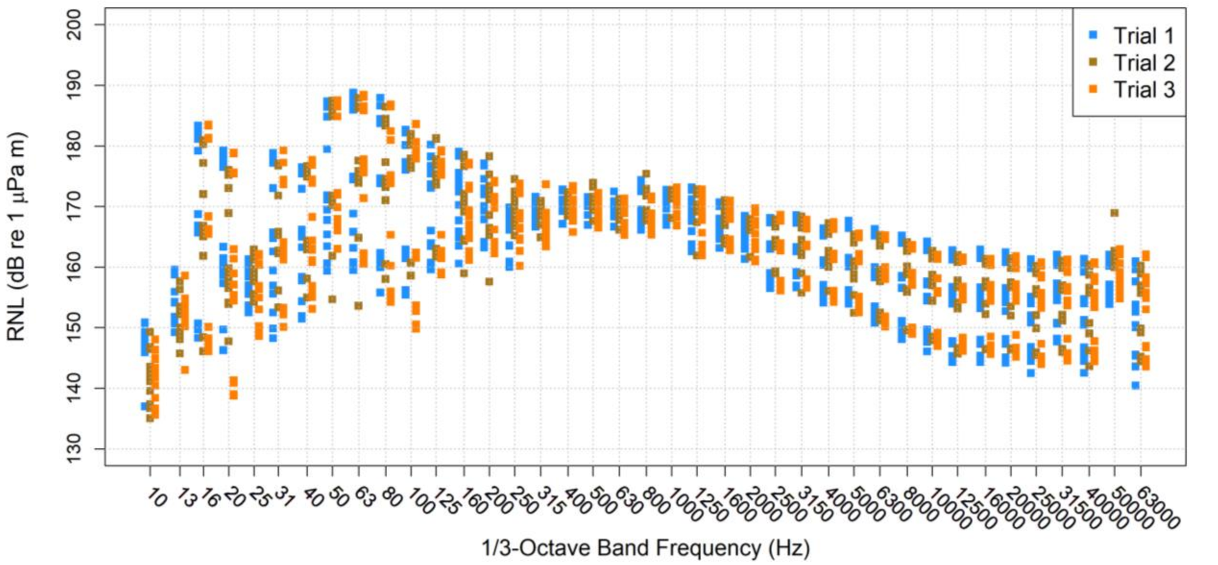


Figure 9. Scatter plot of 1/3-octave-band RNL versus frequency for Trials 1–3. Every point corresponds to a single vessel pass. No speed correction was applied to generate this figure. A small horizontal offset was applied to the points for each trial, for display purposes only, to avoid overlap.

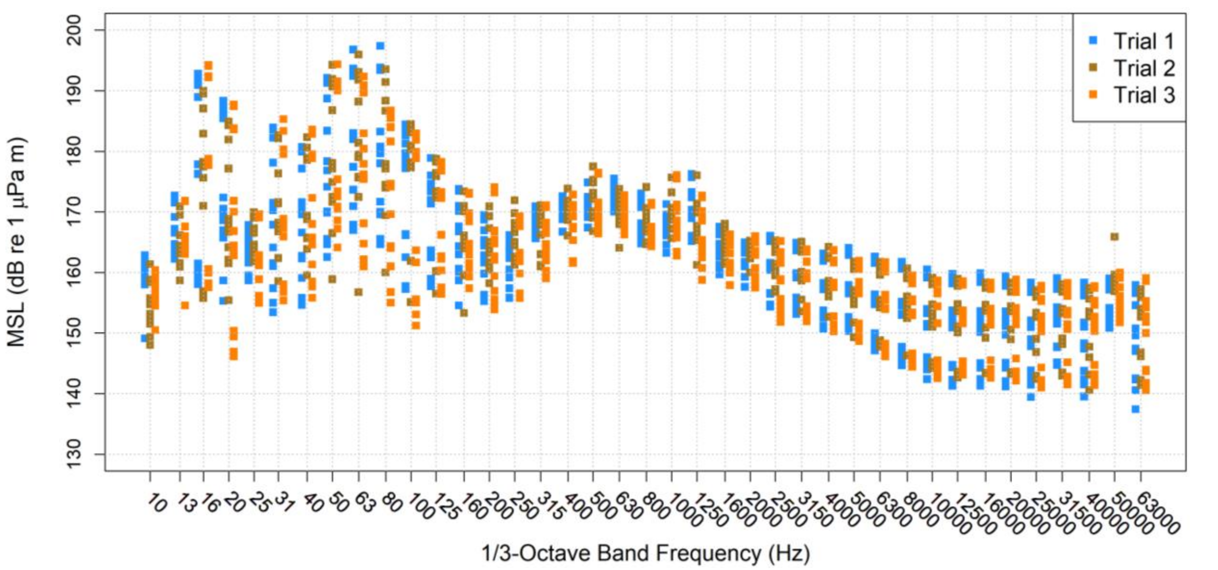


Figure 10. Scatter plot of 1/3-octave-band MSL versus frequency for Trials 1–3. Every point corresponds to a single vessel pass. Note that no speed correction was applied to generate this figure. A small horizontal offset was applied to the points for each trial, for display purposes only, to avoid overlap.

The vertical spread of the RNL and MSL in Figures 9 and 10 is mostly due to the variability introduced by transit speed. By applying Equation 2 using the per-band C_v introduced in Section 2.2, the mean and standard deviation per band was computed for each trial for RNL (Figure 11) and MSL (Figure 12). Despite small differences between the mean RNL and MSL for Trial 1 compared to mean levels for Trials 2 and 3, the range of variability (shown as ±1 standard deviation in Figures 11 and 12) was very similar among the three trials at most frequency bands. The most noticeable feature distinguishing between pre- and post-cleaning levels is the suppression of the pre-cleaning MSL peak around 63-80 Hz (Figure 12). This MSL peak for the pre-cleaning trials is likely caused by a peak in the modelled transmission loss for measurement distances 100 –160 m, as in all passes in Trial 1 (Table A-1). The accuracy of this peak mostly depends on how well the geoacoustic profile in Table F-1 represents the seabed at the measurement location. Therefore, interpretation of this feature as noise reduction from pre- to post-cleaning is a hypothesis that would require further investigation, including on-site geoacoustic inversion work.

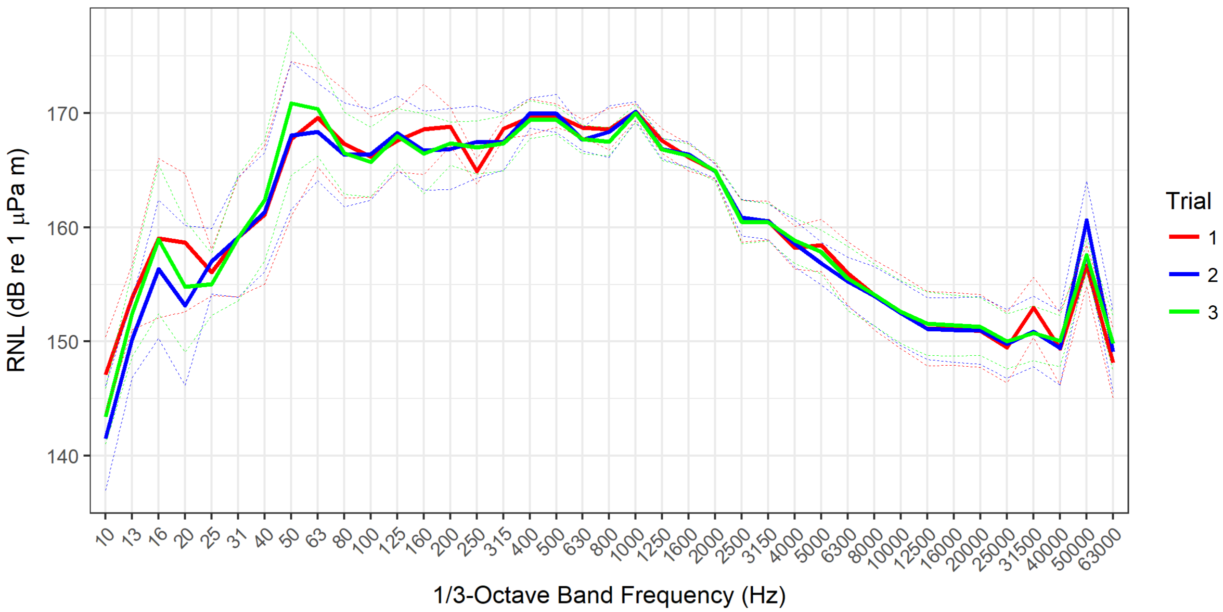


Figure 11. Mean (solid) ±1 standard deviation (dotted) for the RNL, obtained after normalizing all measurements to a reference speed v_{ref} = 11 kn by applying Equation 2 at each 1/3-octave-band.

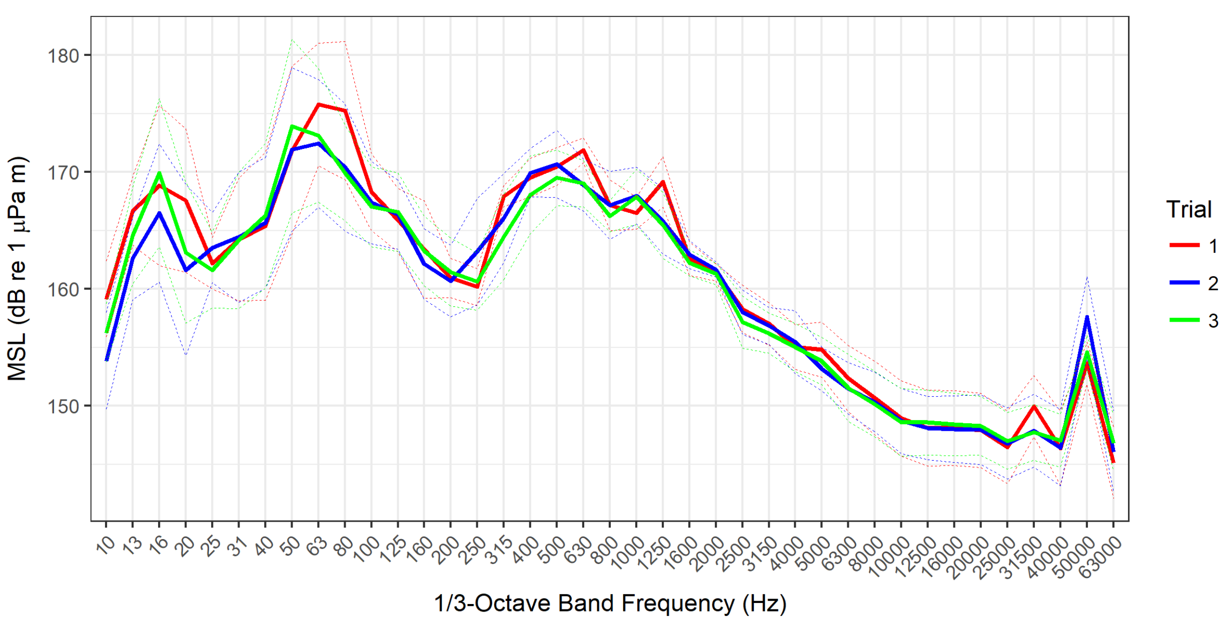


Figure 12. Mean (solid) ±1 standard deviation (dotted) for the MSL, obtained after normalizing all measurements to a reference speed v_{ref} = 11 kn by applying Equation 2 at each 1/3-octave-band.

2.4. Grade C source levels

Because measured RNL or MSL varies between repeat passes of the same vessel, the ANSI/ISO standard specifies that Grade C source levels must be derived from the average of four or more passes of a vessel, when those passes have similar speeds and operating parameters. To satisfy this requirement, average source levels for the *Cygnus* were calculated from multiple passes and for each trial (Figures 13 and 14, Table 7). Tabulated 1/3-octave-band Grade C (i.e., n ≥4) source levels are presented in Appendix E.

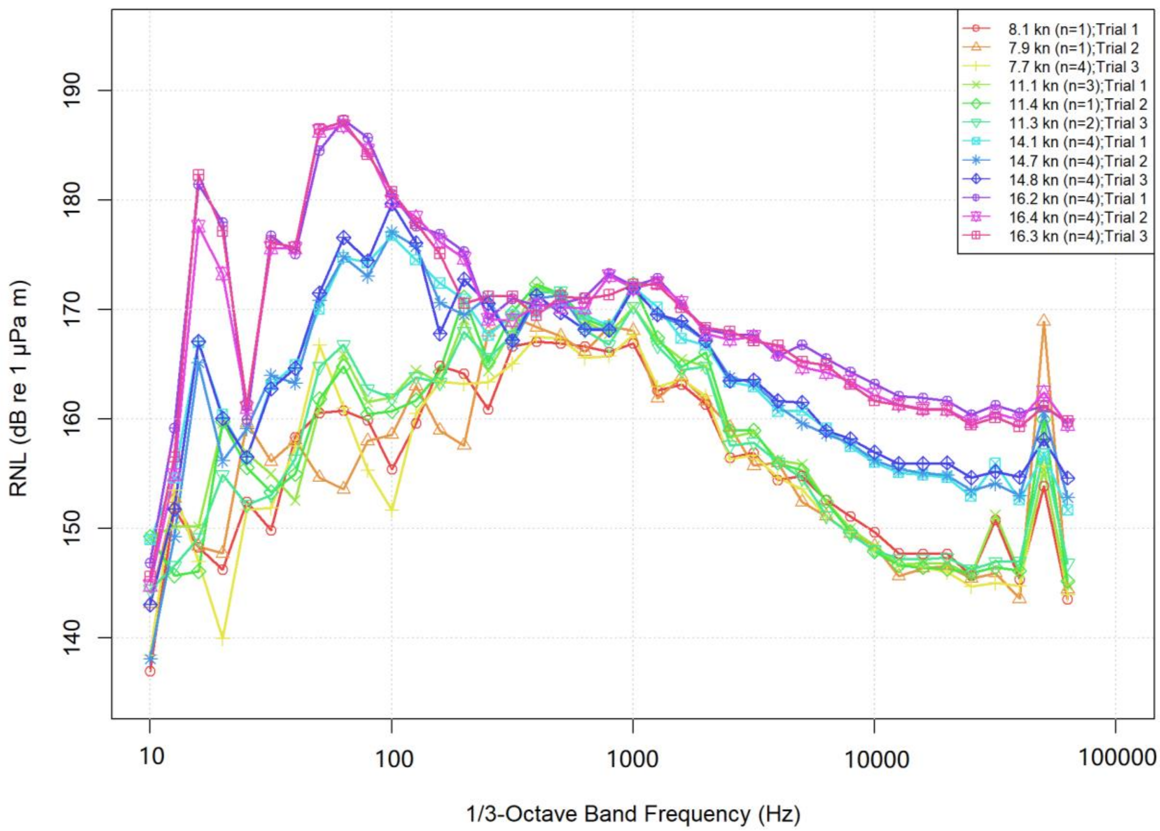


Figure 13. Multi-pass average RNL in1/3-octave-bands. Grade C source levels correspond to measurements with number of passes, *n*, greater than or equal to 4.

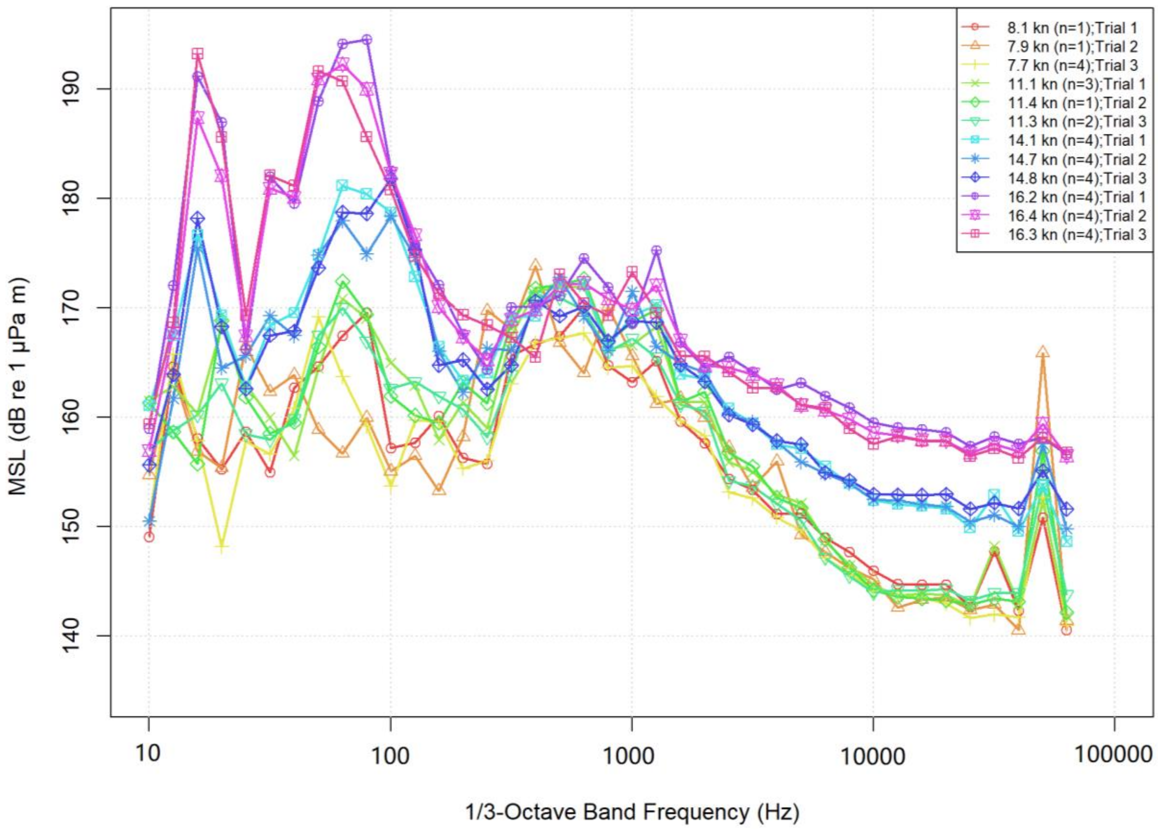


Figure 14. Multi-pass average MSL in1/3-octave-bands. Grade C source levels correspond to measurements with number of passes, *n*, greater than or equal to 4.

Table 7. Average RNL and MSL. ANSI Grade C source levels are based on the average of four or more measurements.

Trial	Mean speed through water (knots)	RNL (dB re 1 µPa m)	MSL (dB re 1 µPa m)	Passes	ANSI measurement grade
1	8.1	176.9	177.7	1	Non-conformant
	11.1	180.2	180.7	3	Non-conformant
	14.1	184.5	187.2	4	C
	16.2	192.7	199.0	4	C
2	7.9	178.3	179.2	1	Non-conformant
	11.4	180.7	181.2	1	Non-conformant
	14.7	184.7	185.6	4	C
	16.4	192.4	197.1	4	C
3	7.7	177.2	176.8	4	C
	11.3	180.1	180.3	2	Non-conformant
	14.8	185.6	187.0	4	C
	16.3	192.6	196.1	4	C

3. Discussion and Conclusions

RNL and MSL were measured for 38 passes of the Coast Guard patrol vessel *Cygnus*. The key findings are listed as follows,

- The analysis showed that STW had statistically significant influence on RNL and MSL for *Cygnus.* Increasing speed was associated with higher overall noise emissions.
    - For each trial, multiple passes at low, medium, and high speed were performed. The broadband RNL and MSL were increased with increased STW. As shown in Table 7, the broadband RNL increased from 176.9 to 192.7 dB re 1µPa m, and the broadband MSL increased from 176.8 to 199.0 dB re 1µPa m, with the STW changed from 7.7 to 16.4 kn.
    - The Grade C spectrum measurements showed that RNL and MSL at frequencies <125 Hz were strongly dependent on speed settings, with high amplitude peaks in the 16 Hz band and around 50–80 Hz for speeds >14 kn. At all speeds, Grade C RNL and MSL at frequencies 125 Hz–1250 Hz tended to plateau and cluster together, while at frequencies >1250 Hz, RNL and MSL decayed at approximate rates of 10 dB/decade, 15 dB/decade, and 20 dB/decade for speed ranges of 16.2–16.4 kn, 14.1–14.8 kn, and 7.7–11.4 kn, respectively.
- Analysis of the estimated broadband and 1/3-octave-band levels for Trial 1 (pre-cleaning), Trial 2 (hull cleaned), and Trial 3 (propeller cleaned) suggests that these activities did not affect vessel noise generation. Such assertion, however, remains inconclusive in this study since the following points regarding statistical inference must be considered:
    - Ideally, statistical analysis to determine whether the clean up procedures had an impact on noise generation would require significantly more measurements, all of them obtained under constant experimental conditions (i.e., constant SOG, propeller pitch, shaft speed and power). In practice, only a limited number of measurements are available, and the vessel parameters during these passes exhibit variability. The speed adjustment presented in Section 2.2 removed some of the measurement variability caused by the vessel noise dependence on STW.
    - The statistics used for comparing noise levels between trails have an inherent uncertainty due to the limited number of samples used to derive them. This uncertainty can be quantified using confidence intervals (Table 6). For example, the *sample* mean RNLs were 182.4, 182.3, and 182.6 dB re 1 µPa m for Trials 1, 2, and 3, respectively. Their corresponding 95% confidence intervals indicate that the *true* mean RNL would likely be anywhere between 180.6–184.1, 180.4–184.1, and 181.1–184.0 dB re 1 µPa m, respectively. Therefore, pre- and post-cleaning mean RNLs could potentially show differences, but such differences are undetectable from the limited number of measurements available for this study. Following this example, the true mean RNL from Trial 1 (pre-cleaning) could have a value of 184.1 dB re 1 µPa m (i.e., upper confidence interval bound), while Trial 2 (hull cleaned) could have a true mean RNL of 180.4 dB re 1 µPa m (i.e., lower confidence interval bound).
    - Variations on the vessel trim and draft between passes might also have contributed to measurement variability, since these parameters relate to the depth at which the vessel noise is generated in the water. Statistical analysis to determine correlation of trim and draft to noise generation was not carried out as it would require more vessel passes. It most be noted, however, that even if more passes were available for this study, the conclusion would likely remain that noise savings due to hull and propeller cleaning are bounded by the confidence intervals indicated above.

- Trials corresponding to grade C RNL and MSL showed similar broadband and 1/3-octave-band RNL and MSL for a given range of STW. Table 8 summarizes grade C broadband RNLs and MSLs, classified in four STW groups (0.2–0.7 kn variation within each group).
    - For each STW group, the RNL varied 0.3–1.4 dB, and the MSL varied 0.9–2.9 dB.
    - As shown in Figures 13 and 14, for medium and high STW (Table 8 group 2–4), 1/3-octave-band RNL and MSL exhibit low variability and similar spectral features between trials.
    - For the low STW (group 1 in Table 8), the 1/3-octave-band RNL and MSL exhibit more variability between trials (compared to groups 2–4) at frequencies below 1 kHz. At frequencies above 1 kHz, the 1/3-octave-band RNL and MSL exhibit more repeatability between trials.
- Power spectral density analysis for each trial showed that the Cygnus had repeatable noise emission spectral characteristics for a given speed range (Appendix D). In particular:
    - The four pre-cleaning passes (Trial 1, time 17:37–18:27, with 250 RPM shaft speed, 2335–2650 kW shaft power, and 16.4–16.0 kn STW, Figure D-1) all exhibit similar spectral peaks below 150 Hz, which are also undistinguishable from passes running at the same settings after propeller cleaning (Trial 3, time 16:47–17:32, Figure D-3).
    - Similar spectral peaks (with slightly lower amplitude) can be observed for passes after hull cleaning (Trial 2, time 15:37–16:29, Figure D-2).
    - Consistency in the spectra between all trials can also be seen for passes in the STW range of 13.3–14.6 kn.
    - Spectral levels for passes with speed <8.1 kn exhibited the largest variability, probably due to more variations on the shaft speed, shaft power, and STW settings.
- Despite the analysis presented in this study suggests that cleaning activities did not affect vessel noise generation, more conclusive evidence could be obtained by limiting the variability of controllable parameters (propeller pitch, shaft speed, shaft power, CPA) and by increasing the number of passes for predefined combinations of these experimental settings. In this work, a heuristic (measurement-based) speed compensation factor was used to increase the number of passes per trial available for statistical analysis, but this approach shall be considered as an approximation to measuring multiple passes at a single speed.

Table 8. Summary of ANSI Grade C average RNL and MSL and the mean speed through water (STW) group.

STW Group No.	Mean STW (knots)	RNL (dB re 1 µPa m)	MSL (dB re 1 µPa m)
1	7.7–8.1	176.9–178.3	176.8–179.2
2	11.1–11.4	180.1–180.7	180.3–181.2
3	14.1–14.8	184.5–185.6	185.6–187.2
4	16.2–16.4	192.4–192.7	196.1–199.0

As a final point, the presence of a prominent peak at 50 kHz likely from the onboard echosounder unit requires consideration regarding potential impact to marine mammals in the area. Lurton and DeRuiter (2011) reviewed the potential risks to auditory systems of marine mammals by echo sounders. In the absence of actual hearing threshold data for mysticetes, a few anatomical studies and computer models have been used to predict their hearing capabilities (Ketten 1997, Houser et al. 2001, Parks et al. 2007, Ketten and Mountain 2011, Cranford and Krysl 2015). The range of best hearing is supposed to span from tens of Hz to about 20 kHz, which means they may be less susceptible to effects of echosounders. Pinnipeds, including seals, have a hearing frequency range (Erbe et al. 2016) which overlaps with frequencies used by echosounders. The maximum effect is expected for odontocetes, since their frequencies of best hearing (10–100 kHz; Erbe et al. 2016) overlap with low-and medium-frequency echosounder signals. Lurton and DeRuiter (2011) concluded that while echo sounders transmit high sound pressure levels, their narrow beam (commonly between 5° and 15°) limits the potential for direct auditory damage to marine mammals.

Marine mammals potentially present in the Conception Bay area during the *Cygnus trials* may include:

- Mysticetes: fin whale (*Balaneoptera physalus*, possible), blue whale (*Balaenoptera musculus*, possible), minke whale (*Balaenoptera acutorostrata*, probable) and humpback whale (*Megaptera novaeangliae*, probable).
- Odontocetes: Killer whale (*Orcinus orca*, possible), Sperm whale (*Physeter macrocephalus*, possible), long-finned pilot whale (*Globicephala melaena*, probable), white-beaked dolphin (*Lagenorhynchus albirostris*, probable), white-sided dolphin (*Lagenorhynchus acutus*, probable), harbour porpoise (*Phocoena phocoena*, probable).
- Pinnipeds: harbor seal (*Phoca vitulina*, probable) and grey seal (*Halichoerus grypus*, probable).

4. Recommendations

- The statistical analysis carried out in this work only considered correlations of vessel STW to noise generation. For future analysis of vessel noise characterization, incorporating other parameters, such as shaft power, shaft RPM, and fuel consumption, in a multivariate analysis could reveal new relations about the effect of these parameters on vessel noise.
- The uncertainty in the noise level measurements could be reduced by increasing the number of passes per speed setting. For the measurements presented in this work, a variety of settings were used (Table A-1), which allowed us to investigate the relationship between noise levels and STW. However, in cases in which the goal of the measurements is to verify compliance to certain vessel noise certification systems, speed settings must be adjusted according to the certification requirements. As an example, the Det Norske Veritas (DNV 2010) requires that measurements are obtained using a 85% maximum continuous rating (MCR) shaft power setting.

Acknowledgements

The authors would like to thank Kevin Murrant (National Research Council Canada), Marcel Montrose (Department of Fisheries and Oceans Canada), and the crew of the Coast Guard patrol vessel Cygnus for their cooperation during this investigation. The support of the Innovation Centre of Transport Canada and the Vancouver Fraser Port Authority is gratefully acknowledged.

Glossary

1/3-octave-band
Non-overlapping frequency passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands comprise one octave-band. 1/3-octave-bands become wider with increasing frequency. Also see octave.

box-and-whisker plot
A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The ends of the box are the upper and lower quartiles (25th and 75th percentiles). The horizontal line inside the box is the median (50th percentile). The whiskers and points extend outside the box to the highest and lowest observations, where the points correspond to outlier observations (i.e., observations that fall more than 1.5 × IQR beyond the upper and lower quartiles, where IQR is the interquartile range).

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cavitation
The rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates noise.

closest point of approach (CPA)

The point at which the distance between two objects, of which at least one is in motion, reaches its minimum value. For a fixed underwater system measuring noise produced by a transiting vessel, the CPA occurs when the vessel is at the shortest distance from the measurement system.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.

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

harmonic
A sinusoidal sound component that has a frequency that is an integer multiple of the frequency of a sound to which it is related. For example, the second harmonic of a sound has a frequency that is double the fundamental frequency of the sound.

hertz (Hz)
A unit of frequency defined as one cycle per second.

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

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

null hypothesis
In statistics, when estimating the relationship between two or more variables, at least two hypotheses can be formulated: the (default) null hypothesis, which claims that there is no relation between the variables, and the alternative hypothesis, which claims that there is a relation. Disproving the null hypothesis (and thereby concluding that there might be grounds to believe the alternative hypothesis) is an important task in statistics for which various techniques (such as p-values) are available.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

p-value
A number between 0 and 1 used in null hypothesis testing to decide if there is sufficient statistical evidence to reject the null hypothesis. For example, for a level of significance α of 5%, a p-value significantly smaller than 0.05 is considered strong evidence to reject the null hypothesis, while a p-value larger than 0.05 indicates weak evidence against the null hypothesis.

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

received level
The sound level measured at a receiver.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2 / p_0^2\right) = 20\log_{10}\left(p / p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level. See also 90% sound pressure level and fast-average sound pressure level.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 μPa m.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution compared with frequency.

speed through water (STW)
The speed of a ship with respect to the water, which therefore accounts for the effect of currents.

Literature Cited

[DNV] Det Norske Veritas. 2010. *Rules for Classification of Ships Newbuildings, Special Equipment and Systems*. *Silent Class Notation*. Part 6 Chapter 24, Høvik, Norway. https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2010-01/ts624.pdf.

ANSI 12.64-2009. R2014. *Grade C – Survey Method - Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*. Acoustical Society of America.

Brocher, T.M. 2005. *Compressional and shear wave velocity versus depth in the San Francisco Bay Area, California: Rules for USGS Bay Area Velocity Model 05.0. 0*. Report Number Open-File Report 05–1317.

Buckingham, M.J. 2005. Compressional and shear wave properties of marine sediments: Comparisons between theory and data. *Journal of the Acoustical Society of America* 117: 137-152. https://doi.org/10.1121/1.1810231.

Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. Document Number NRL Memorandum Report 7330-09-9165. U.S. Naval Research Laboratory, Stennis Space Center, MS. 21 pp.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93(4): 1736-1742. https://doi.org/10.1121/1.406739.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862-863. https://doi.org/10.1121/1.382038.

Cranford, T.W. and P. Krysl. 2015. Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing. *PLoS ONE* 10(1): e0116222. https://doi.org/10.1371/journal.pone.0116222.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R. Dooling. 2016. Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin* 103(1): 15-38. https://doi.org/10.1016/j.marpolbul.2015.12.007.

François, R.E. and G.R. Garrison. 1982a. Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America* 72(6): 1879-1890. https://doi.org/10.1121/1.388673.

François, R.E. and G.R. Garrison. 1982b. Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. *Journal of the Acoustical Society of America* 72(3): 896-907. https://doi.org/10.1121/1.388170.

Hamilton, E.L. 1980. Geoacoustic modeling of the sea floor. *Journal of the Acoustical Society of America* 68(5): 1313-1340. https://doi.org/10.1121/1.385100.

Houser, D.S., D.A. Helweg, and P.W.B. Moore. 2001. A bandpass filter-bank model of auditory sensitivity in the humpback whale. *Aquatic Mammals* 27(2): 82-91. http://aquaticmammalsjournal.org/share/AquaticMammalsIssueArchives/2001/AquaticMammals_27-02/27-02_Houser.PDF.

Kearey, P., M. Brooks, and I. Hill. 2002. *An Introduction to Geophysical Exploration*. 3rd edition. Wiley-Blackwell.

Ketten, D.R. 1997. Structure and function in whale ears. *Bioacoustics* 8(1-2): 103-136. https://doi.org/10.1080/09524622.1997.9753356.

Ketten, D.R. and D. Mountain. 2011. *Modeling minke whale hearing*. Report by Woods Hole Oceanographic Institution, Harvard Medical School, and Boston University for the Joint Industry Programme on E&P Sound and Marine Life. 30 pp.

Lurton, X. and S. DeRuiter. 2011. Sound radiation of seafloor-mapping echosounders in the water column, in relation to the risks posed to marine mammals. *The International Hydrographic Review* (6). https://journals.lib.unb.ca/index.php/ihr/article/view/20886/24046.

Parks, S.E., D.R. Ketten, J.T. O'Malley, and J. Arruda. 2007. Anatomical predictions of hearing in the North Atlantic right whale. *The Anatomical Record* 290(6): 734-744. https://doi.org/10.1002/ar.20527.

Ross, D. 1976. *Mechanics of Underwater Noise*. Pergamon Press, New York.

Slatt, R.M. 1974. Geochemistry of Bottom Sediments, Conception Bay, Southeastern Newfoundland. *Canadian Journal of Earth Sciences* 11(6): 768-784. https://doi.org/10.1139/e74-077.

Stolze, L., A. Kennedy, M. Hukobyan, and P. Hülse. 2008. *Cruise Report: Field Oceanography Team 5, Leg 3*. Memorial University, Department of Physics and Physical Oceanography. https://www.physics.mun.ca/~bdeyoung/P6314/data/Reports/CruiseReportTeam5.pdf.

Subsea Global Solutions. 2017a. *CCGS Cygnus. IMO: 7927831. Hull Cleaning June 5, 2018. Long Pond NFLD*. Report for the Canadian Coast Guard. 23 pp.

Subsea Global Solutions. 2017b. *CCGS Cygnus. IMO: 7927831. Propeller Polish July 19, 2018 St Johns, NFLD*. Report for the Canadian Coast Guard. 6 pp.

Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167-7183. https://doi.org/10.1029/JC095iC05p07167.

Appendix A. Vessel Operating Logs

All source level measurements were manually reviewed for quality. Invalid measurements were not analyzed. Invalid measurements were those that were rejected due to the vessel not transiting along the measurement funnel. There were 38 valid measurements (out of 41 measurements) corresponding to operating logs for *Cygnus*. Table A-1 details the logs.

Table A-1. Detailed logs for valid *Cygnus* passes (CPA–closest point of approach; SOG–speed over ground; RPM–revolutions per minute; STW–speed through water; UKC–under keel clearance). Throttle setting is from 1 to 10.

Measurement time (UTC)	From PortListen					From logs							Current		STW (kn)
	CPA (m)	SOG (kn)	Wind speed (kn)	MSL (dB re 1 µPa m)	RNL (dB re 1 µPa m)	Throttle	True heading (°)	Propeller pitch (%)	Shaft speed (rpm)	Shaft power (kw)	Fuel consumption (L/h)	UKC (m)	Speed (kn)	Direction (°)	
23 May 2018 15:28	130.4	6.9	23.8	178.3	177.8	5.0	229.4	N/A	172.2	275.7	120.3	112	0.003	194.9	6.9
23 May 2018 15:45	132.3	8.1	18.4	177.7	176.9	5.0	48.7	N/A	174.0	265.3	128.8	112	0.003	194.9	8.1
23 May 2018 16:00	124.4	11.4	18.4	181.3	180.2	6.5	227.2	55	198.0	636.7	245.6	110	0.003	194.9	11.4
23 May 2018 16:19	155.2	11.2	18.4	179.8	180.0	6.5	48.8	70	199.3	629.2	241.2	107	0.003	194.9	11.2
23 May 2018 16:30	109.8	13.8	13.5	187.3	184.7	8.0	228.1	80	223.2	1446.0	447.7	113	0.003	191.5	13.8
23 May 2018 16:53	152.4	14.4	13.5	186.0	184.1	8.0	48.0	90	223.3	1395.1	436.8	95	0.003	192.9	14.4
23 May 2018 17:01	119.6	14.0	13.5	187.7	184.7	8.0	226.9	90	223.3	1432.8	448.5	115	0.003	192.6	14.0
23 May 2018 17:24	129.1	14.3	13.5	187.8	184.5	8.0	46.7	90	223.1	1393.3	442.3	93	0.002	190.2	14.3
23 May 2018 17:37	136.1	16.1	14.6	198.6	193.1	10.0	227.7	100	249.8	2652.6	785.0	93	0.002	190.3	16.1
23 May 2018 17:56	134.5	16.4	14.6	198.2	192.1	10.0	48.0	100	249.8	2573.9	768.6	93	0.002	187.2	16.4
23 May 2018 18:08	122.0	16.0	14.6	200.1	193.8	10.0	227.6	100	249.8	2592.0	776.8	103	0.001	186.7	16.0
23 May 2018 18:27	134.5	16.1	14.6	199.1	191.7	10.0	47.2	90	249.0	2337.9	714.6	92	0.001	180.0	16.1
23 May 2018 18:39	141.4	10.7	10.3	181.0	180.3	6.5	227.2	55	198.0	636.7	245.6	110	0.001	160.6	10.7
18 Jul 2018 13:50	46.2	7.9	18.4	179.2	178.3	5.0	48.5	50	173.7	299.6	107.4	104	0.003	194.9	7.9
18 Jul 2018 13:56	129.4	11.4	18.4	181.2	180.7	6.5	232.5	75	201.7	760.7	226.9	110	0.003	194.9	11.4
18 Jul 2018 14:22	228.4	13.3	18.4	186.2	186.4	6.5	52.9	75	201.7	715.2	216.4	94	0.003	191.9	13.3
18 Jul 2018 14:32	91.1	14.6	18.9	186.3	184.7	8.0	229.5	90	227.3	1601.5	440.2	107	0.003	192.1	14.6
18 Jul 2018 14:53	175.2	14.7	18.9	184.4	185.0	8.0	48.4	90	227.5	1537.1	425.9	99	0.002	192.5	14.7
18 Jul 2018 15:05	110.4	14.5	18.9	186.6	184.1	8.0	229.5	90	226.4	1563.3	433.4	95	0.002	189.9	14.5
18 Jul 2018 15:24	166.6	14.8	18.9	184.9	184.8	8.0	48.3	90	228.3	1563.1	436.4	96	0.002	189.6	14.8
18 Jul 2018 15:37	102.3	16.4	19.4	198.0	192.8	10.0	227.5	100	249.9	2701.5	740.4	95	0.002	186.8	16.4
18 Jul 2018 15:57	157.9	16.4	19.4	193.8	191.6	10.0	47.4	100	250.0	2653.8	729.5	97	0.001	182.9	16.4
18 Jul 2018 16:10	138.6	16.4	19.4	197.7	192.6	10.0	228.3	100	249.9	2693.6	742.9	98	0.001	180.0	16.4

Measurement time (UTC)	From PortListen					From logs							Current		STW (kn)
	CPA (m)	SOG (kn)	Wind speed (kn)	MSL (dB re 1 µPa m)	RNL (dB re 1 µPa m)	Throttle	True heading (°)	Propeller pitch (%)	Shaft speed (rpm)	Shaft power (kw)	Fuel consumption (L/h)	UKC (m)	Speed (kn)	Direction (°)	
18 Jul 2018 16:29	117.4	16.3	19.4	198.9	192.7	10.0	46.0	100	249.9	2638.6	730.6	93	0.000	155.7	16.3
01 Aug 2018 14:23	149.8	7.7	8.1	177.1	177.0	5.0	49.5	50	172.8	266.4	129.2	107	0.002	10.2	7.7
01 Aug 2018 14:34	181.2	7.7	11.9	175.9	177.4	5.0	229.5	50	172.9	273.7	131.1	111	0.002	10.2	7.7
01 Aug 2018 14:54	129.1	7.8	11.9	177.9	177.0	5.0	50.1	50	172.7	264.4	130.0	112	0.002	6.4	7.8
01 Aug 2018 15:09	166.1	7.7	11.9	176.2	177.3	5.0	230.9	50	172.7	272.2	132.1	106	0.002	7.4	7.7
01 Aug 2018 15:23	133.3	11.4	11.9	182.1	180.2	6.5	49.6	75	200.1	655.7	256.2	112	0.001	1.4	11.4
01 Aug 2018 15:42	185.2	11.3	8.6	178.6	180.1	6.5	232.3	75	200.1	671.9	259.4	94.5	0.001	0.0	11.3
01 Aug 2018 15:52	147.3	14.5	8.6	187.8	185.2	8.0	51.2	90	229.0	1548.7	496.2	112	0.001	346.7	14.5
01 Aug 2018 16:11	183.5	14.9	8.6	185.1	185.9	8.0	232.1	90	229.0	1571.8	502.2	106	0.000	284.0	14.9
01 Aug 2018 16:19	140.6	14.6	8.6	189.2	185.8	8.0	50.6	90	229.0	1553.2	499.0	112	0.000	237.8	14.6
01 Aug 2018 16:36	169.0	14.9	13.0	185.7	185.4	8.0	232.0	90	229.0	1565.7	503.1	104	0.001	215.3	14.9
01 Aug 2018 16:47	96.6	16.1	13.0	197.9	192.4	10.0	52.5	100	249.8	2540.2	769.3	113	0.001	205.7	16.1
01 Aug 2018 17:04	237.8	16.5	13.0	195.0	193.3	10.0	232.9	100	249.8	2566.8	776.5	98	0.001	204.9	16.5
01 Aug 2018 17:15	92.1	16.1	13.0	196.2	191.2	10.0	53.0	100	249.8	2526.7	767.6	110	0.002	202.0	16.1
01 Aug 2018 17:32	238.1	16.5	11.3	195.3	193.6	10.0	233.7	100	249.8	2552.9	776.3	105	0.002	199.0	16.5

Appendix B. PortListen

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

Figure B-1. JASCO's PortListen: Underwater noise management solution for the marine transport industry and environmental regulators

The acoustic data were analyzed in 1/3-octave frequency bands from 10 Hz to 63 kHz. Each sound recording was processed using 1-s sliding Fast Fourier Transforms (FFTs) applied with a power-normalized Hanning window, with 50% overlap, to obtain power spectral density (PSD) levels versus time. Vessel track information was obtained from Automatic Identification System (AIS) data. Since the AIS transmitter/receiver was not necessarily coincident with the *Cygnus'* acoustic source, the acoustic closest point of approach (CPA) was determined by tracking the range and speed of the source using an automated tracking algorithm based on the cepstrogram method. The background noise levels were computed by averaging noise levels over two one-minute intervals—1 min just before the vessel entered the entrance funnel and 1 min after it left the exit zone. Measured received levels were compared with the background noise levels in 1/3-octave-band frequencies and were adjusted as needed based on the method prescribed in ANSI 12.64-2009.

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

MONM computes sound propagation in range-varying acoustic environments through a wide-angle parabolic equation (PE) solution to the acoustic wave equation (Collins 1993). MONM accounts for the environmental parameters including water depth, seabed geoacoustic parameters, and water sound speed profile (SSP). For both RNL and MSL, the attenuation of acoustic energy by molecular absorption in seawater was also considered and computed using the formulae of François and Garrison (1982a), 1982b).

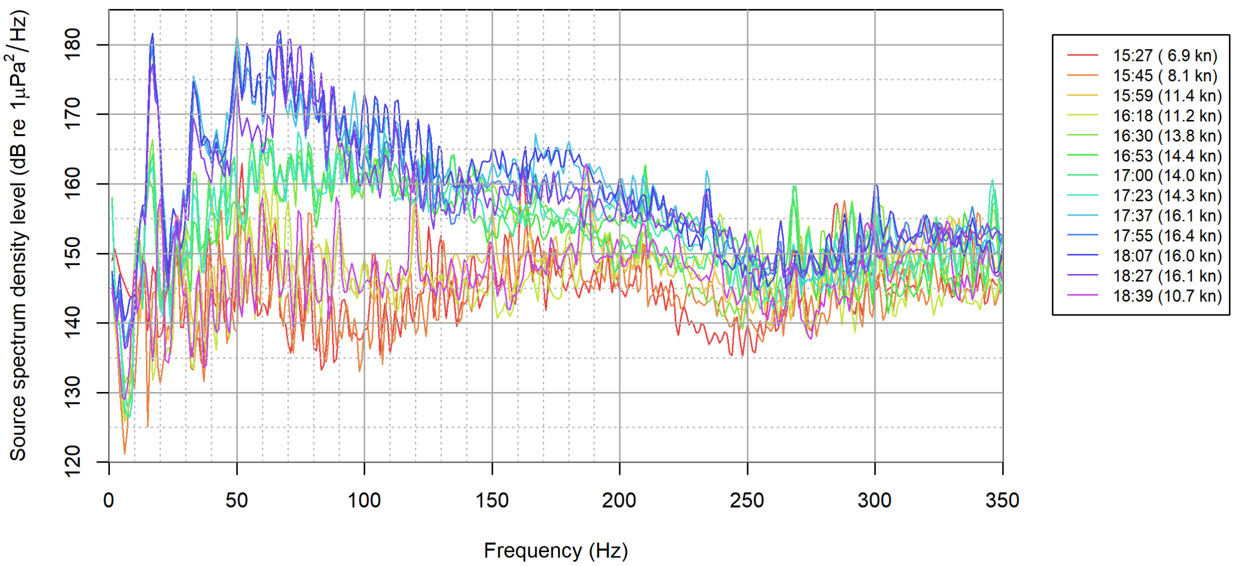
The RNLs and MSLs (broadband and 1/3-octave-band) were computed in decibels as a linear average from the RNLs and MSLs from all 1-s sample locations along the vessel track within the ±30° data window as defined in ANSI S12.64-2009.

Appendix C. Conformance with ANSI Standard

The reported vessel source measurements were acquired using procedures that approximately conform to 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 exceptions to conforming to this standard was that this vessel noise measurement system permitted vessel CPA measurements from any distance from 45 m to 240 m, whereas the standard requires vessel CPA be the larger of 100 m or one vessel length. Further, we applied the higher-resolution data window method specified by the Standard for Grades A and B. The *Cygnus* dimension and operation information were provided by the client from the vessel masters or pilots, and from registry information provided by MarineTraffic.com.

Appendix D. Spectrum Analysis

The plots below show the RNL source spectrum levels of *Cygnus*, in 1 Hz frequency bands, as measured at the AMAR. Each spectrum was calculated from the mean power spectral density level during a single vessel pass, averaged between ±30° surrounding the vessel CPA. Two different frequency ranges are shown for each vessel: 0–350 Hz and 0–2000 Hz. The time and speed of each pass is shown on the legend to the right of the plots. The spectrum plots are intended to show individual tones generated per trial and speed. These tones are generally associated with either propeller blade rate cavitation or vibrations from engines or other machinery.



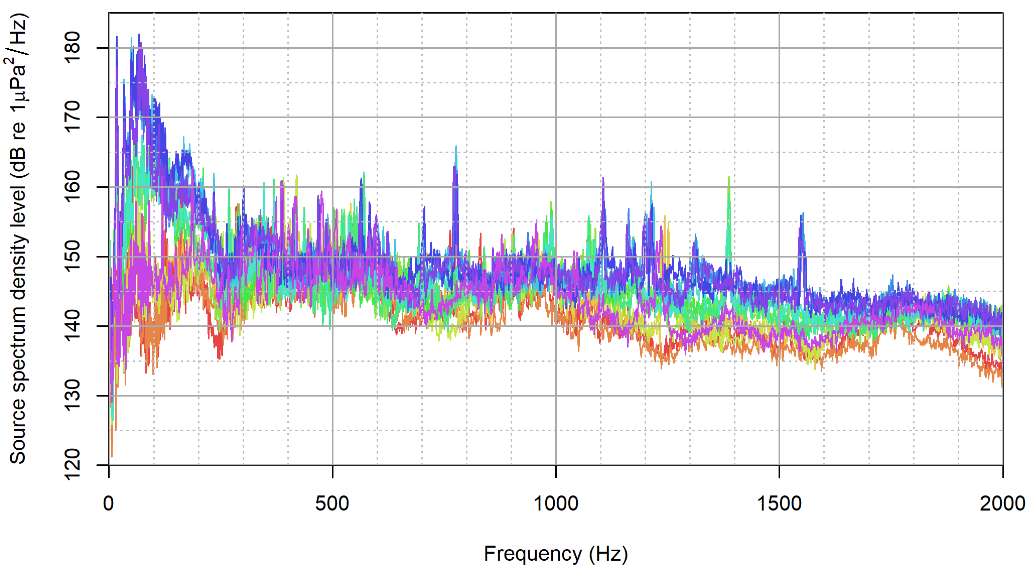
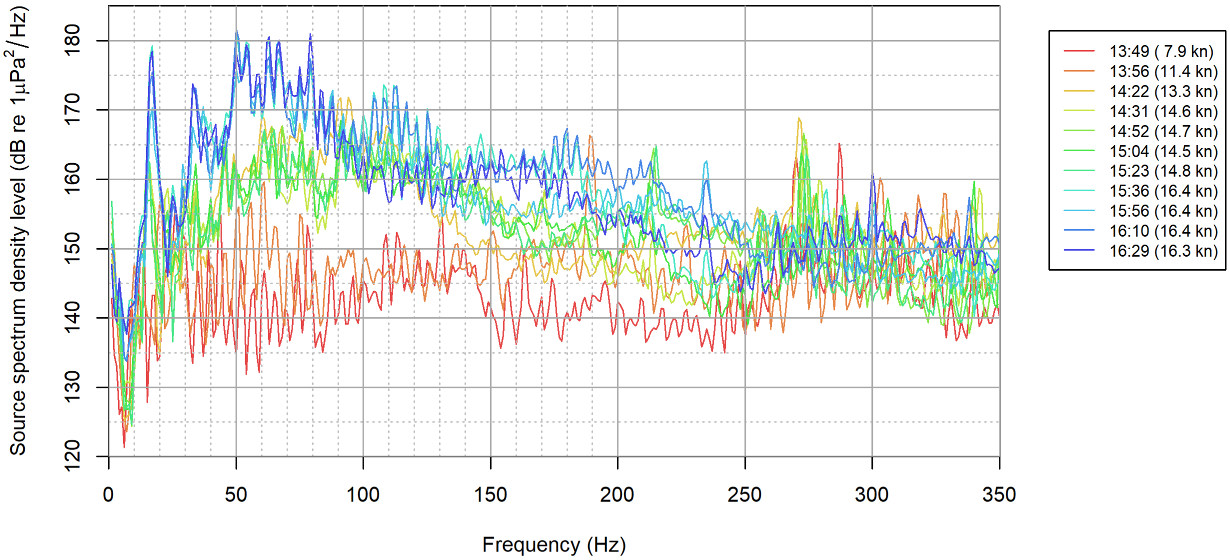


Figure D-1. Spectra corresponding to passes during Trial 1 on May 2018: 0–350 Hz (top) and 0–2000 Hz (bottom). The time and speed of each pass are indicated in the legend.



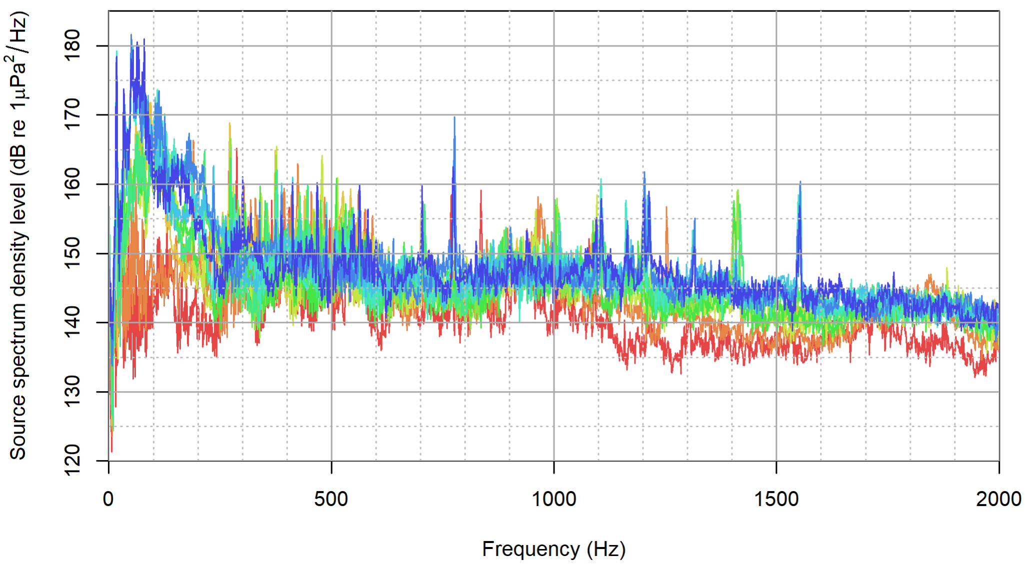


Figure D-2. Spectra corresponding to passes during Trial 2 on July 2018: 0–350 Hz (top) and 0–2000 Hz (bottom). The time and speed of each pass are indicated in the legend.

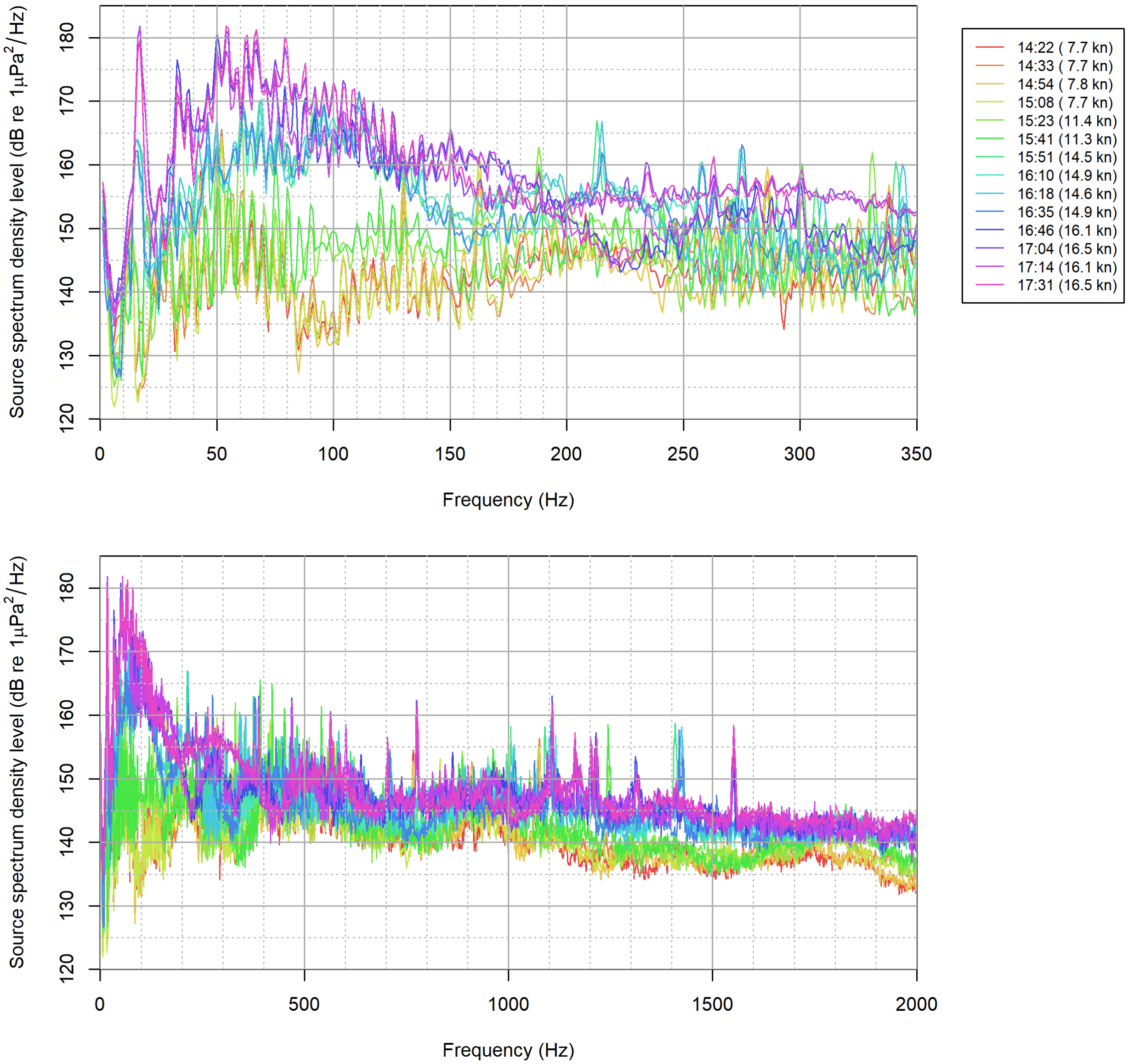


Figure D-3. Spectra corresponding to passes during Trial 3 on August 2018: 0–350 Hz (top) and 0–2000 Hz (bottom). The time and speed of each pass are indicated in the legend.

Appendix E. Tabulated Grade C Source Levels

Tables E-1 to E-3 provide tabulated 1/3-octave-band Grade C source levels (RNL and MSL in dB re 1 µPa m) calculated from averages of four or more passes, as per the ANSI standard. The speed configuration is indicated in the column headings.

Table E-1. One-third-octave-band Grade C source levels (RNL and MSL in dB re 1 µPa m) obtained from measurements before cleaning (Trial 1).

1/3-octave-band frequency (Hz)	RNL (dB re 1 µPa m)		MSL (dB re 1 µPa m)	
	14.1 kn	16.2 kn	14.1 kn	16.2 kn
10	149.0	146.9	161.1	159.0
13	154.6	159.2	167.5	172.0
16	167.0	181.5	176.7	191.2
20	160.4	178.0	169.3	187.0
25	156.4	160.0	162.8	166.2
31	163.1	176.8	168.4	182.0
40	165.0	175.1	169.6	179.6
50	170.0	184.5	174.8	188.9
63	174.8	187.3	181.2	194.1
80	174.3	185.7	180.4	194.5
100	176.8	180.6	178.7	182.6
125	174.5	177.6	172.9	175.7
160	172.4	176.9	166.5	172.1
200	170.9	175.3	163.3	167.6
250	167.6	169.2	164.1	164.4
315	169.5	171.0	169.1	170.1
400	169.8	170.4	169.3	170.1
500	170.6	170.6	172.2	171.1
630	169.5	171.1	172.1	174.5
800	168.5	173.3	166.5	171.9
1000	172.0	172.2	169.3	168.6
1250	170.2	172.9	170.3	175.2
1600	167.4	170.4	163.9	166.9
2000	166.8	168.2	163.5	164.5
2500	163.4	167.7	160.8	165.5
3150	163.0	167.7	159.5	164.1
4000	160.7	165.8	157.5	162.5
5000	160.8	166.8	157.2	163.2
6300	159.2	165.6	155.5	162.0
8000	157.5	164.3	153.9	160.9
10000	156.1	163.2	152.4	159.5
12500	155.1	162.1	152.1	159.1
16000	154.9	161.9	151.9	158.9
20000	154.7	161.7	151.7	158.7
25000	153.0	160.4	149.9	157.4
31500	156.0	161.3	152.9	158.3
40000	152.6	160.6	149.6	157.6
50000	156.8	161.2	153.8	158.2
63000	151.7	159.6	148.7	156.6
Broadband	**184.5**	**192.7**	**187.2**	**199.0**

Table E-2. One-third-octave-band Grade C source levels (RNL and MSL in dB re 1 µPa m) obtained from measurements after hull cleaning (Trial 2).

1/3-octave-band frequency (Hz)	RNL (dB re 1 µPa m)		MSL (dB re 1 µPa m)	
	14.7 kn	16.4 kn	14.7 kn	16.4 kn
10	138.1	144.8	150.5	157.0
13	149.2	154.9	161.7	167.7
16	165.2	177.6	175.5	187.4
20	156.2	173.3	164.5	182.1
25	159.1	161.0	165.7	167.5
31	164.0	175.6	169.3	180.9
40	163.3	175.6	167.5	180.1
50	170.8	186.3	174.8	190.9
63	174.8	186.8	178.0	192.3
80	173.0	184.5	174.9	190.0
100	177.1	179.9	178.4	182.3
125	175.8	178.4	174.6	176.6
160	170.6	176.2	166.0	170.1
200	169.5	174.7	162.3	167.4
250	171.1	169.1	166.3	165.3
315	166.9	169.0	166.1	168.9
400	171.0	170.4	170.1	169.8
500	171.3	170.2	172.8	172.0
630	168.2	170.1	169.2	172.3
800	168.3	173.1	166.1	170.8
1000	172.1	171.9	171.5	169.8
1250	169.5	172.5	166.5	172.1
1600	168.6	170.6	164.9	167.0
2000	167.1	167.8	164.1	164.8
2500	163.8	167.3	160.4	164.6
3150	163.3	167.5	159.6	163.9
4000	161.2	166.1	157.7	162.9
5000	159.6	164.8	155.9	161.1
6300	158.6	164.3	154.9	160.7
8000	157.8	163.4	154.0	159.8
10000	156.3	162.2	152.5	158.6
12500	155.4	161.4	152.4	158.3
16000	155.1	161.0	152.1	157.9
20000	154.9	160.9	151.9	157.9
25000	153.5	159.8	150.5	156.7
31500	154.1	160.6	151.1	157.6
40000	153.0	159.9	150.0	156.9
50000	160.6	162.5	157.6	159.4
63000	152.8	159.5	149.8	156.5
Broadband	**184.7**	**192.4**	**185.6**	**197.1**

Table E-3. One-third-octave-band Grade C source levels (RNL and MSL in dB re 1 µPa m) obtained from measurements after propeller cleaning (Trial 3).

1/3-octave-band frequency (Hz)	RNL (dB re 1 µPa m)			MSL (dB re 1 µPa m)		
	7.7 kn	14.8 kn	16.3 kn	7.7 kn	14.8 kn	16.3 kn
10	138.4	143.1	145.6	150.5	155.7	159.4
13	153.5	151.8	156.5	165.7	163.9	168.7
16	147.0	167.1	182.3	157.9	178.2	193.2
20	140.0	160.1	177.2	148.2	168.3	185.6
25	151.7	156.5	161.2	157.8	162.6	169.3
31	151.9	162.8	176.1	156.6	167.5	182.1
40	157.5	164.6	175.7	160.9	167.9	181.2
50	166.7	171.5	186.5	169.2	173.6	191.6
63	161.0	176.6	187.2	163.7	178.7	190.7
80	155.3	174.5	184.2	159.2	178.6	185.6
100	151.7	179.6	180.8	153.7	181.8	180.8
125	160.5	176.1	177.9	159.7	175.3	174.7
160	163.5	167.8	175.1	159.6	164.8	171.3
200	163.2	172.8	170.6	155.3	165.3	169.4
250	163.4	170.6	171.2	156.0	162.6	168.4
315	165.0	167.2	171.2	163.0	164.8	167.3
400	167.5	171.3	169.5	166.8	170.7	165.5
500	167.4	169.7	171.2	167.3	169.3	173.1
630	165.6	168.2	171.0	167.7	170.1	170.5
800	165.8	168.1	171.3	164.6	167.0	169.3
1000	167.7	171.9	172.3	164.7	168.8	173.3
1250	162.9	169.6	172.3	161.9	168.7	169.5
1600	163.7	168.9	170.2	159.7	164.8	165.6
2000	162.1	167.1	168.4	158.3	163.2	165.6
2500	156.4	163.5	168.0	153.2	160.3	164.2
3150	156.7	163.6	167.1	152.6	159.3	162.7
4000	154.7	161.7	166.7	150.9	157.9	162.7
5000	153.6	161.5	165.3	149.7	157.5	161.2
6300	151.1	158.9	164.9	147.1	155.0	160.9
8000	149.7	158.2	163.2	145.8	154.3	159.0
10000	148.1	157.0	161.7	144.1	153.0	157.6
12500	146.8	155.9	161.3	143.8	152.9	158.3
16000	146.5	155.9	160.9	143.5	152.9	157.8
20000	146.0	156.0	160.8	143.0	153.0	157.8
25000	144.7	154.7	159.5	141.7	151.6	156.5
31500	145.0	155.2	160.2	142.0	152.2	157.1
40000	144.8	154.7	159.3	141.8	151.7	156.3
50000	155.7	158.2	161.2	152.7	155.1	158.2
63000	144.0	154.6	159.8	140.9	151.6	156.8
Broadband	**177.2**	**185.6**	**192.6**	**176.8**	**187.0**	**196.1**

Appendix F. Environmental Parameters

Transmission loss for RNL and MSL estimation were obtained for a flat bathymetry (120 m water depth), a receiver depth of 114.6 m measured during AMAR deployment, and assuming a source depth of 2.4 m, which is half of the 4.8 m draft of the Cygnus. The sound speed profile and seabed geoacoustic model used for modelling are described next.

F.1. Sound speed profile

The sound speed profile for acoustic modelling was derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The temperature and salinity profiles were converted to sound speed profiles according to the equations of Coppens (1981).

Sound speed profiles for May, June, and July were calculated at the AMAR location. Transmission loss modelling was conducted using an average profile from these months (Figure F-1).

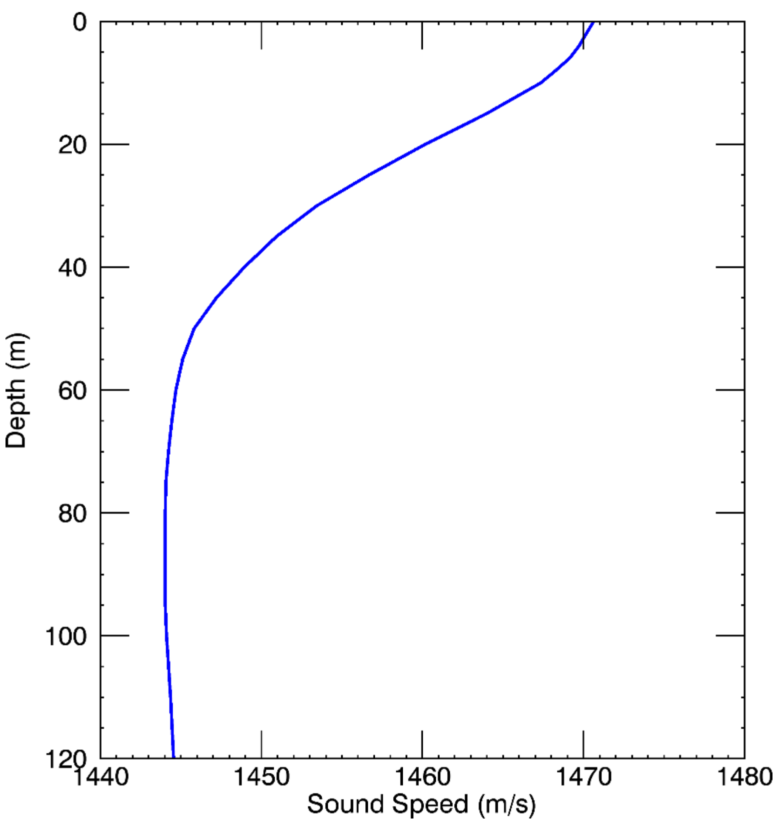


Figure F-1. Sound speed profile used for the modelling, obtained as an average for May, June, and July.The profile was calculated from temperature and salinity profiles from GDEM V 3.0 (Teague et al. 1990, Carnes 2009).

F.2. Seabed geoacoustics

The seabed sediments in this area have been described as muddy sand gravel (Slatt 1974). Sub-bottom profiling (Stolze et al. 2008) in the proximity of the AMAR deployment indicates sediment thickness of up to 10 m. Sound speeds and attenuations for the muddy sand gravel top layer (Table F-1) were estimated from the sediment model of Buckingham (2005). The geoacoustic model was extended by including a sandstone basement below 10 m deep, with density and compressional sound speed obtained from the literature (Hamilton 1980, Kearey et al. 2002, Brocher 2005).

Table F-1. Geoacoustic profile used in the acoustic propagation model.

<table>
<tr><th rowspan="2">Depth below seafloor (m)</th><th rowspan="2">Material</th><th rowspan="2">Density (g/cm^3)</th><th colspan="2">Compressional wave</th><th colspan="2">Shear wave</th></tr>
<tr><th>Speed (m/s)</th><th>Attenuation (dB/λ)</th><th>Speed (m/s)</th><th>Attenuation (dB/λ)</th></tr>
<tr><td>0–10</td><td>Muddy sandy gravel</td><td>2.08</td><td>1710–2020</td><td>0.60–1.46</td><td rowspan="2">290</td><td rowspan="2">3.65</td></tr>
<tr><td>10–1000</td><td>Sandstone</td><td>2.3</td><td>2500–3500</td><td>0.3</td></tr>
</table>

Appendix C

DNV-GL Report – Fuel Consumption Analysis of CCG Cygnus for ECHO Program

FUEL CONSUMPTION ANALYSIS OF CCG CYGNUS FOR ECHO PROGRAM

CCGS Cygnus

Vancouver Fraser Port Authority

Report No.: 2018-1336, Rev. 0
Document No.: 16S2JCZ-3
Date: 2019-02-20

Project name:	Fuel Consumption Analysis of CCG Cygnus for ECHO Program	DNV GL USA, Inc. Maritime
Report title:	CCGS Cygnus	Advisory Americas
Customer:	Vancouver Fraser Port Authority,	1600 Sawgrass Corporate Parkway
Customer contact:	Rangyn Lim Krista Trounce	Suite 110 33323 Sunrise
Date of issue:	2019-02-20	FL USA
Project No.:	10117942	Tel:
Organization unit:	Advisory Americas	
Report No.:	2018-1336, Rev. 0	
Document No.:	16S2JCZ-3	

Objective:

The objective of this project is to assess whether the hull and propeller cleaning performed had an effect and to what extent (if any) on fuel consumption for the vessel based on the provided speed trial data.

Prepared by:	Verified by:	Approved by:
Jaeouk Sun Princial Engineer	Daniel Nordas Senior Engineer	Olav Rognebakke Head of Section
Jan Hagen Andersen Business Development Manager		

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0	2018-01-28	First issue	J. Sun J. Andersen	D. Nordås	O. Rognebakke
1	2018-02-07	Second issue	J. Sun J. Andersen	D. Nordås	O. Rognebakke
2	2018-02-20	Third issue	J. Sun J. Andersen	D. Nordås	O. Rognebakke

Table of contents

1 EXECUTIVE SUMMARY

At the request of Vancouver Fraser Port Authority (VFPA) Enhancing Cetacean Habitat and Observation (ECHO) program, the vessel fuel consumption and engine power versus speed before and after hull cleaning was analyzed. The objective of this project was to assess whether the hull and propeller cleaning performed had an effect and to what extent (if any) on fuel consumption for the vessel.

The ECHO Program is a Vancouver Fraser Port Authority led initiative aimed at better understanding and mitigating the impact of shipping on at-risk whales throughout the southern coast of British Columbia. One area of work for the ECHO Program is assisting the shipping industry in reducing its underwater noise footprint.

In 2017, DNV GL delivered a report (DNV GL Report No. 2017-9479) on an analysis of the effect of fuel consumption after in water hull cleaning for two ocean-going vessels, based on daily voyage reporting. The current analysis in this report is for a third vessel, CCGS Cygnus, a Canadian Coast Guard (CCG) vessel, which also had underwater noises measurements conducted during sea trials before and after hull and propeller cleaning. During the sea trials, onboard measurements of vessel speed, shaft power, fuel consumptions, and environmental parameter are collected and recorded. National Research Council Canada (NRC) conducted the trials and collected the data. As the data are also valuable for the VFPA ECHO program, VFPA has requested DNV GL perform an analysis based on the data received from CCGS Cygnus.

Below is the timeline for the hull and propeller cleaning and speed power trials:

Date	Activity
May 23rd, 2018	1st speed power trial (Baseline trial)
June 5th, 2018	Hull cleaning
June 18th, 2018	2nd speed power trial (Post hull cleaning)
July 18th, 2018	Propeller cleaning
Aug 1st, 2018	3rd speed power trial (Post propeller cleaning)

2 MAJOR FINDING

The results of the speed trials on CCGS Cygnus are affected by uncertainties as explained in Section 9, which DNV GL believes could have a significant impact on the results. Based on the given input data available to DNV GL, it is not possible to conclude whether the propeller and hull cleaning of CCGS Cygnus is beneficial or not for fuel consumption. It should be emphasized that this does not mean that DNV GL concludes that there is no benefit on reducing fuel consumption from hull and propeller cleaning in general. Recommendations for future consideration have been provided in Section 10.

The ECO Insight fleet performance solution was used to aggregate the data collected by NRC with filtering to achieve a best possible event-based report to could be evaluated in the standard ECO Insight dashboard. However, no conclusion on the effectiveness of the hull and propeller cleaning can be made because of the limited number of event data points between the cleaning events.

3 BASIS FOR WORK

The evaluation is based on the following data provided by NRC and CCG:

Table 3-1 Main received data

Data
CCGS Cygnus Bilge keel arrangement
CCGS Cygnus Stability booklet
CCGS Cygnus Lines plan
CCGS Cygnus Propeller geometry
CCGS Cygnus Engine test report
CCGS Cygnus Arrangement of shafting
Propeller polish report
Hull cleaning report
NRC Report: CCGS Cygnus – Hull and Propeller Cleaning
CCGS Cygnus Baseline trial, Post hull cleaning trial, Post propeller cleaning trial data, including: Main engine output setting Run number Heading Mid time of each run Ship speed over ground Ship speed through water Current velocity Propeller shaft speed, torque, power Fuel consumption Relative wind velocity and direction at anemometer height True wind velocity and direction at anemometer height
CCGS Cygnus Baseline trial, Post hull cleaning trial, Post propeller cleaning trial sea trial logs, including: Forward and aft draft Air temperature (not available for baseline trial) Trial location in GPS coordinates Throttle setting for each run Up or down wind for each run Start and stop time for each run Vessel heading for each run Speed over ground for each run Under keel clearance for each run Propeller pitch and RPM for each run Shaft power for each run Relative wind speed and direction for each run Wave height and direction for each run Fuel consumption for each run
CCGS Cygnus low frequency between-trials data (May 5 2018-Aug 1 2018), including: Time and duration Portside main engine hours Starboard main engine hours Speed over ground Speed through water Propeller shaft power Propeller shaft speed Portside main engine fuel consumption Starboard main engine fuel consumption Relative wind speed and direction

4 SHIP MAIN PARTICULARS

Based on the information received from NRC, CCGS Cygnus is an offshore fisheries patrol vessel that operates out of St. John’s, NL. It operates on a two week rotational schedule. The vessel has two main medium speed, diesel engines. The general particulars of the CCGS Cygnus are outlined in Table 4-1.

Table 4-1 CCGS Cygnus Main Particulars

Particular	**Value**
Length (m)	62.4
Breadth (m)	12.2
Draft (m)	4.0
Freeboard (m)	0.9
Cruising Speed (knot)	13.0
Maximum Speed (knot)	16.0
Number of engines	2
100% MCR (kW)	~3000
Number of propellers	1

5 HULL AND PROPELLER FOULED CONDITION

DNV GL has not attended the cleaning events. The below hull and propeller fouled condition is quoted from NRC report /2/:

“The hull and propeller of the CCGS Cygnus had not been cleaned in two years prior to this project. The level of fouling present was a result of 2 years of operation. The CCGS Cygnus operates year round on a two week rotation with a two day layover. Vessels with an off-season or with long layover periods would likely have more fouling in similar operational and environmental conditions.

The propeller was also assessed by divers to quantify the level of fouling present. All propeller blade faces were covered in a light to moderate slime which was heavier at the root and tapered towards the tips. Under the slime the propeller blades were covered with a heavy calcium buildup. The level of propeller fouling was measured using a ship propeller roughness gage which characterizes the propeller roughness per the Rubert Comparator scale. The propeller fouling was rated as Rubert scale E. Once polished, the propeller was rated at a Rubert scale A/B. Post polishing trials were conducted at this polished state.”

6 SPEED TRIAL EVALUATION

6.1 Methodology

Based on the speed trial data recorded by NRC, DNV GL has calculated the vessel speed and corrected for environmental effects to an ideal trial condition according to ISO 15016:2015 standard. Ideal trial condition implies infinitely deep water, no waves, no wind and no current.

The calculation is performed using a fully compliant ISO 15016:2015 tool (STAIMO). The analysis of speed power trials consist of:

— evaluation of the acquired data;

— correction to power for resistance increase due to wind and waves;

— correction to power for water temperature and water density;

— correction to speed for current effect;

— correction to speed for the effect of shallow water;

— correction to power for displacement;

— presentation of the trial results.

The flow chart of analysis is shown below. Detailed calculation results are found in Appendix A.

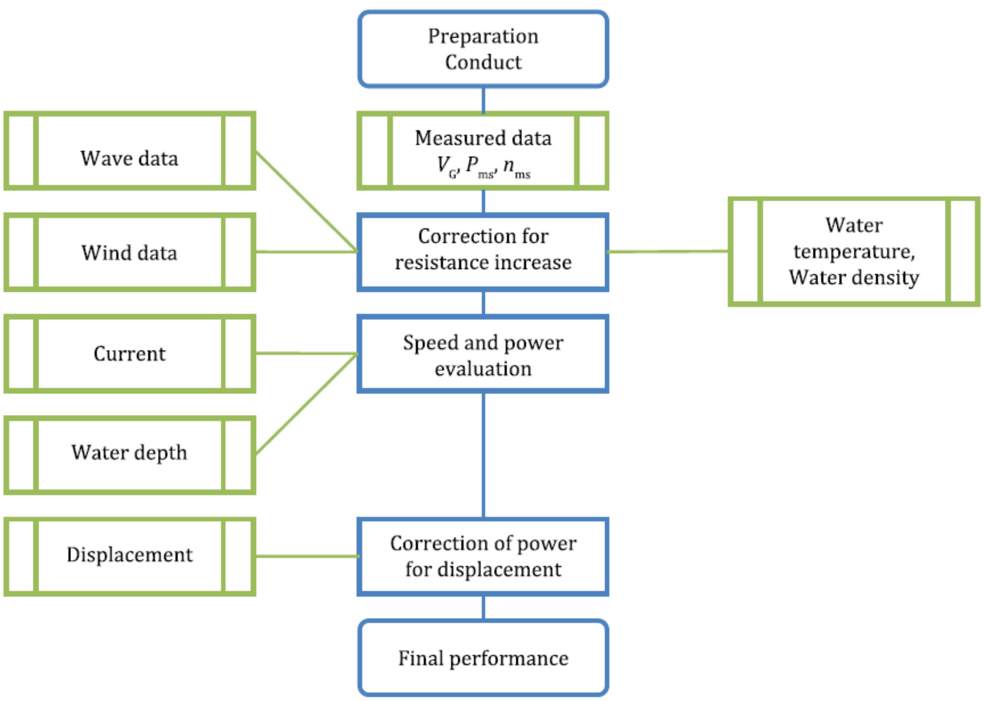


Figure 6-1 Flow chart of analysis based on ISO 15016:2015

There are two wave correction methods in ISO15016:2015 as detailed below.

STAWAVE 1 is a simplified method to estimate the added resistance in waves when speed trial was conducted in low to mild sea states with restricted wave height. The effect of wave induced motions is neglected and the added resistance is dominated by the wave reflection of the hull.

STAWAVE 2 is an empirical method to approximate the added resistance in waves when speed trial was conducted in long period of waves and rough sea states. This method is applicable to the mean resistance increase in long crested irregular waves, which may force ship motions.

In this analysis, only STAWAVE 1 is applicable due to the speed restriction of STAWAVE 2 method (0.10 < Froude number < 0.30).

It should be noted that model tank test results are essential in order to execute speed trial analysis. The model tank test is often performed during the design stage for the prediction of the speed power relation at the design draft. The model test results are the major input to determine the speed power curve. However, as the results are not available, DNV GL has estimated the speed power performance including hydrodynamic coefficients such as propulsion efficiency as inputs in STAIMO.

6.2 Baseline trial

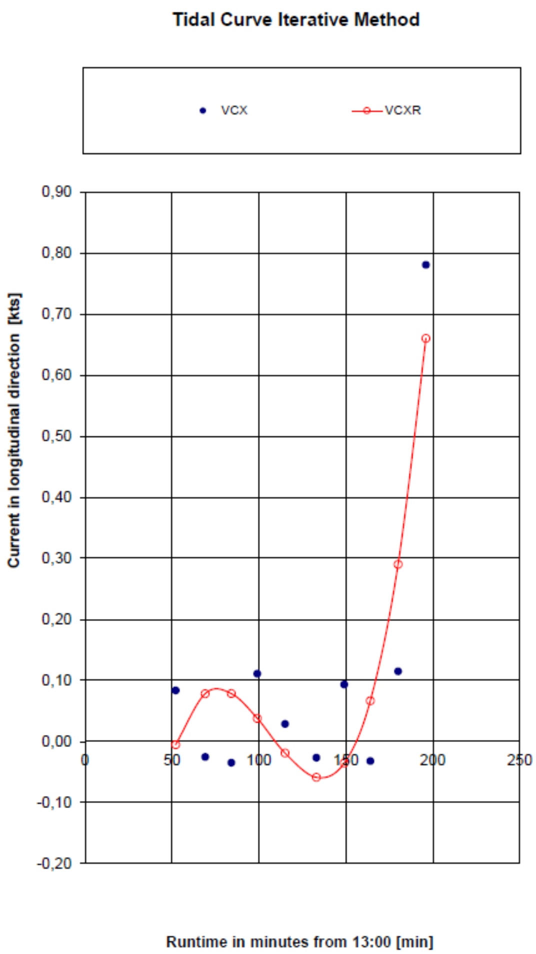
Inputs for the speed trial correction were from the measured average run data.

Significant wave height and direction were based on the received speed trial log data ("Baseline trial may 23 2018.docx"). It was informed that wave buoy was not used. The wave and swell are estimated by visual observation. Detailed inputs can be found in each analysis report in Appendix A.

For the information that was not available during the analysis, the following assumptions have been made:

- Air temperature and pressure were assumed to 17°C which is 1°C lower than the trial after propeller cleaning and 1013 mbar.
- Water temperature was assumed at 10°C. (A different water temperature has been observed in NRC report after DNV GL has completed the analysis. However, this difference is not expected to impact the conclusion on comparison of performance between the trials.)
- Water depth was assumed 100m
- Propulsion efficiency was estimated and assumed to be 0.63 for all engine loads

The trial was executed in current speed from 0.2 knots to 1.0 knots. The current speed is shown in Figure 6-2 below based on the received information.



VCX: Current velocity as difference between run speed and iterative current curve
VCXR: Current velocity in ship direction from iterative current curve
Figure 6-2 Current speeds for baseline trial

Based on the received information, during the baseline speed power measurement the true wind speed is estimated at 9 m/s and direction is approximately 270 degrees. The received wind speeds and directions during the speed power measurement are shown in figure below.

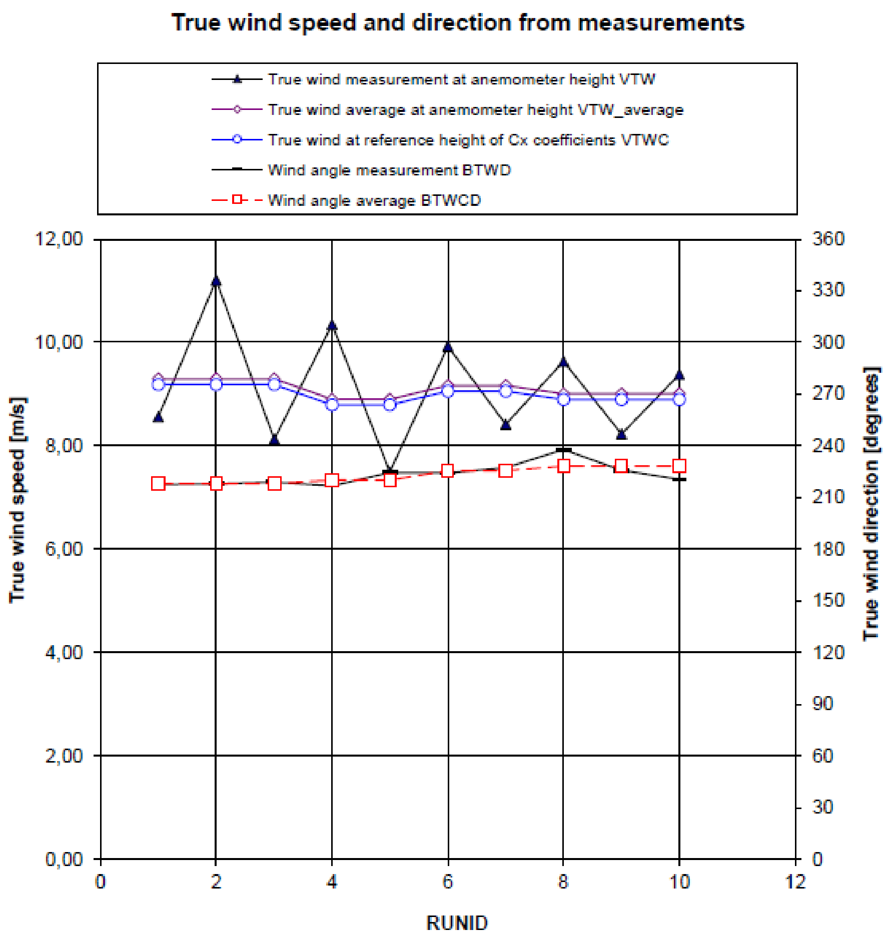


Figure 6-3 Wind speeds and directions for baseline trial

The current and wind speed were accounted for in the correction. Detailed information can be found in Appendix A. The weather corrected speed power curve for baseline trial is shown in Figure 6-4.

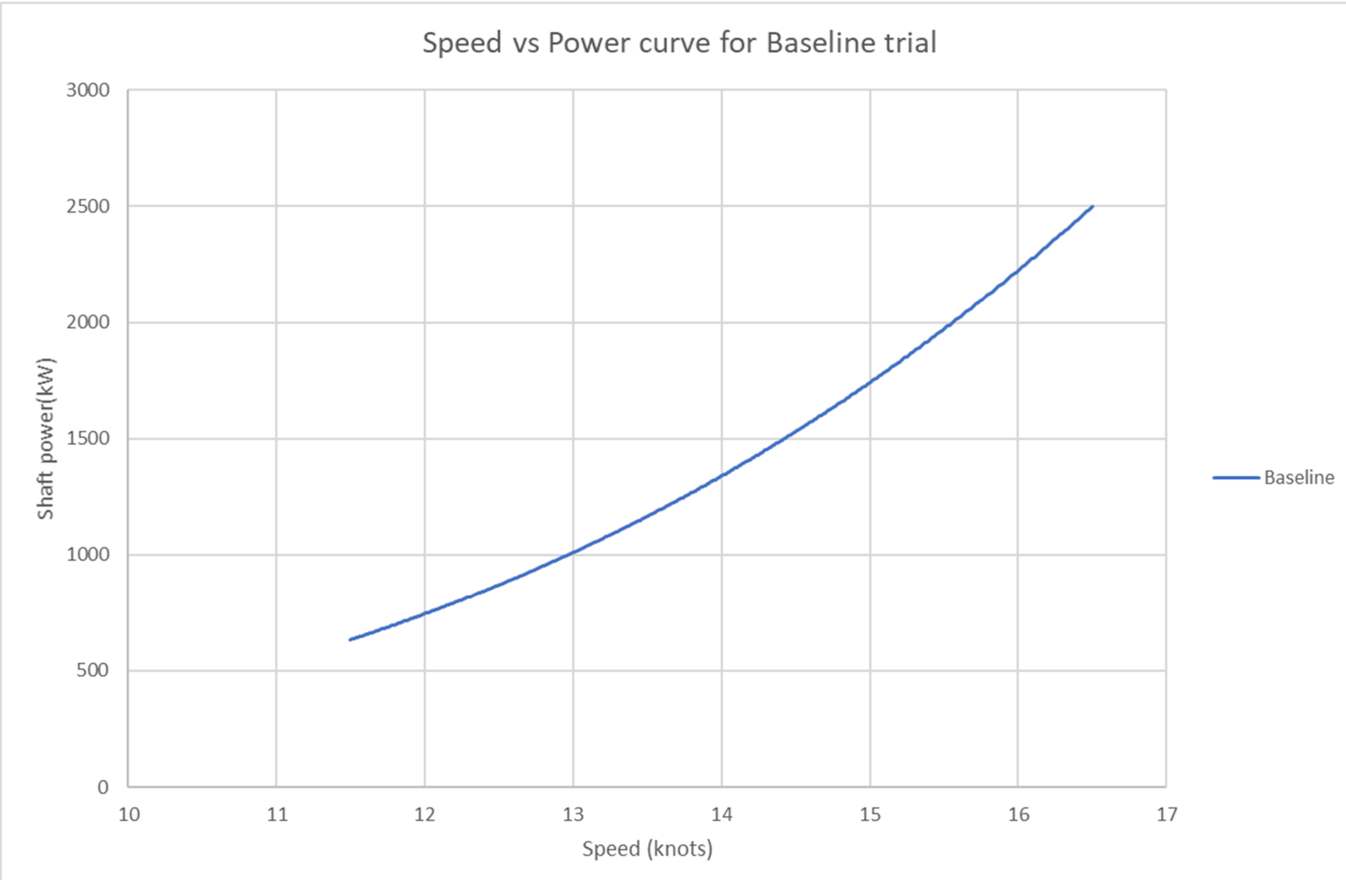


Figure 6-4 Weather corrected speed power curves for baseline trial

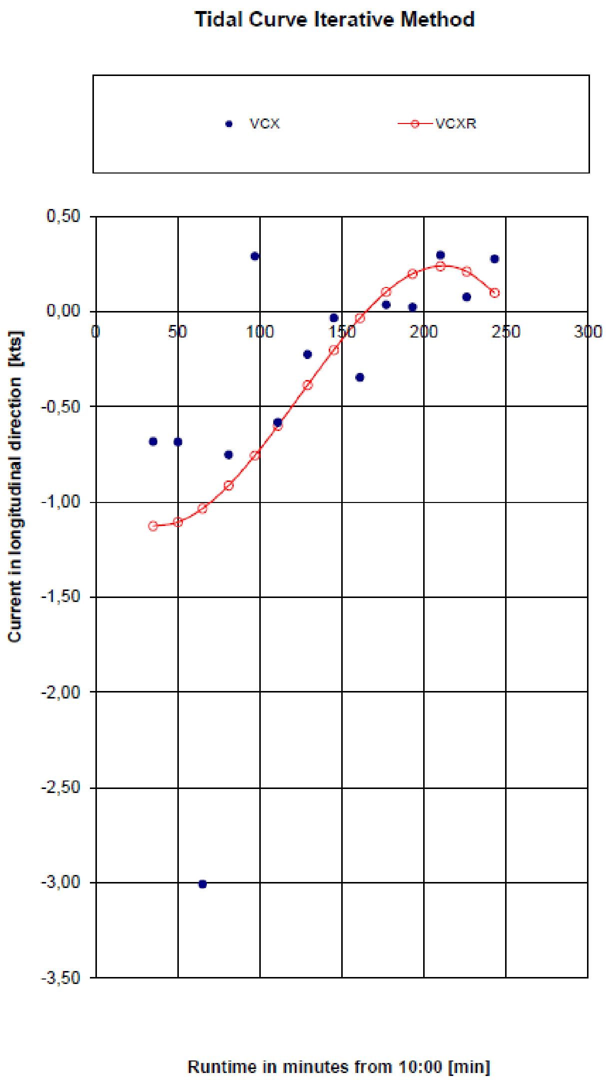
6.3 Post hull cleaning trial

The inputs for the speed trial correction were extracted from the measured average run data. Differently with baseline trial, the significant wave height and direction were measured by wave buoy according to NRC.

The following assumptions have been made for the data which was not available during analysis:

- Ambient pressure was assumed to 1013mbar.
- Water temperature was assumed to 10°C. (A different water temperature has been observed in NRC report after DNV GL has completed the analysis. However, this difference is not expected to impact the conclusion on comparison of performance between the trials.)
- Propulsion efficiency was estimated and assumed to be 0.63 for all engine loads

The current speed for post hull cleaning trial is shown below. The trial was executed in current speed from - 0.7 knots to +0.3 knots.



VCX: Current velocity as difference between run speed and iterative current curve
VCXR: Current velocity in ship direction from iterative current curve
Figure 6-5 Current speeds for post hull cleaning trial

The wind speed and direction during the trial is shown below. The wind speed increased from 8m/s to 12m/s during 65% and 80% engine loads then wind speed was decreased from 12m/s to 5m/s.

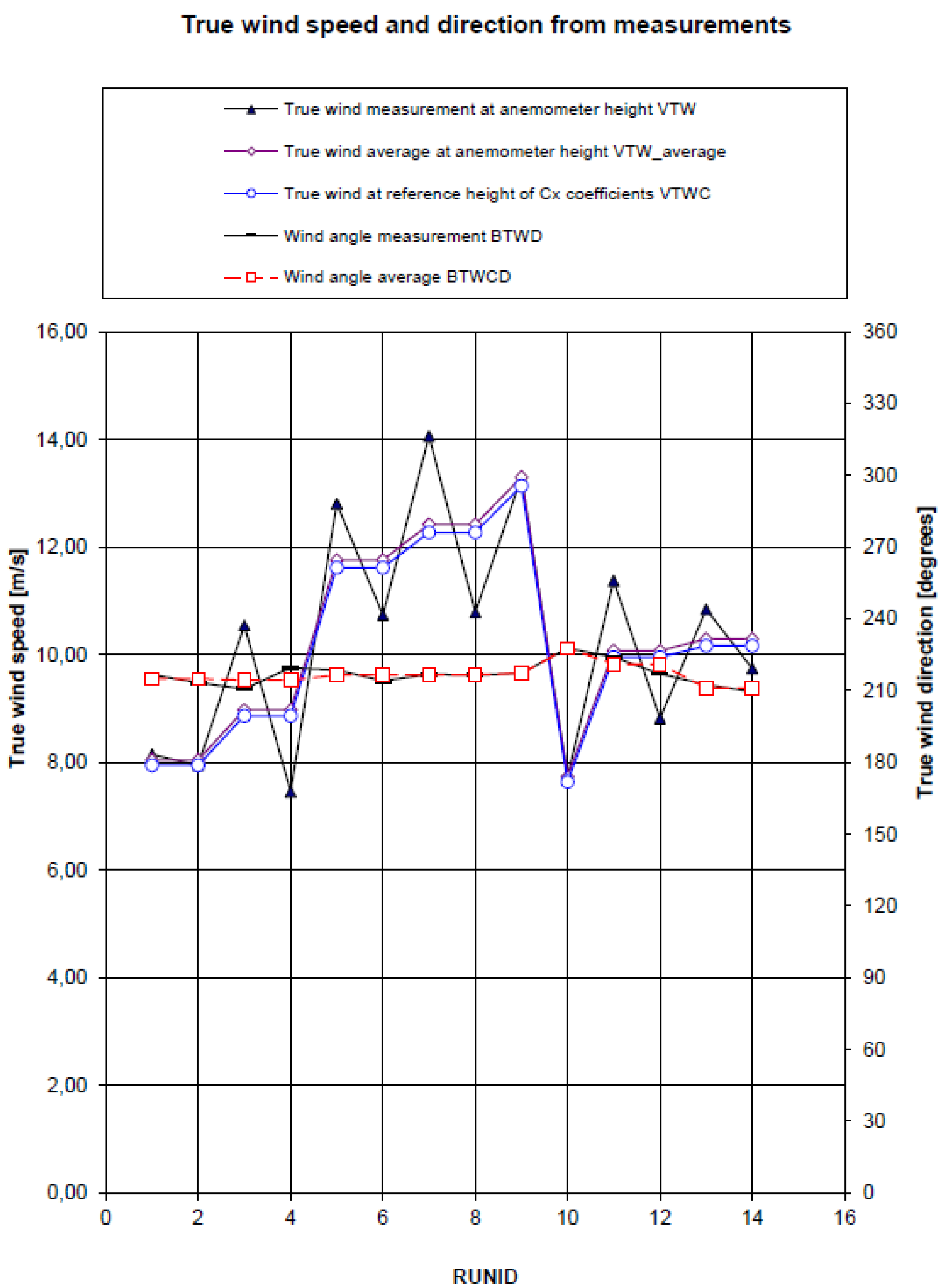


Figure 6-6 Wind speeds and directions for post hull cleaning trial

The wind and current speed were accounted in the correction. More detailed information can be found in Appendix A.

The weather corrected speed power curve for post hull cleaning trial is shown in Figure 6-7.

Figure 6-7 Weather corrected speed power curves for post hull cleaning

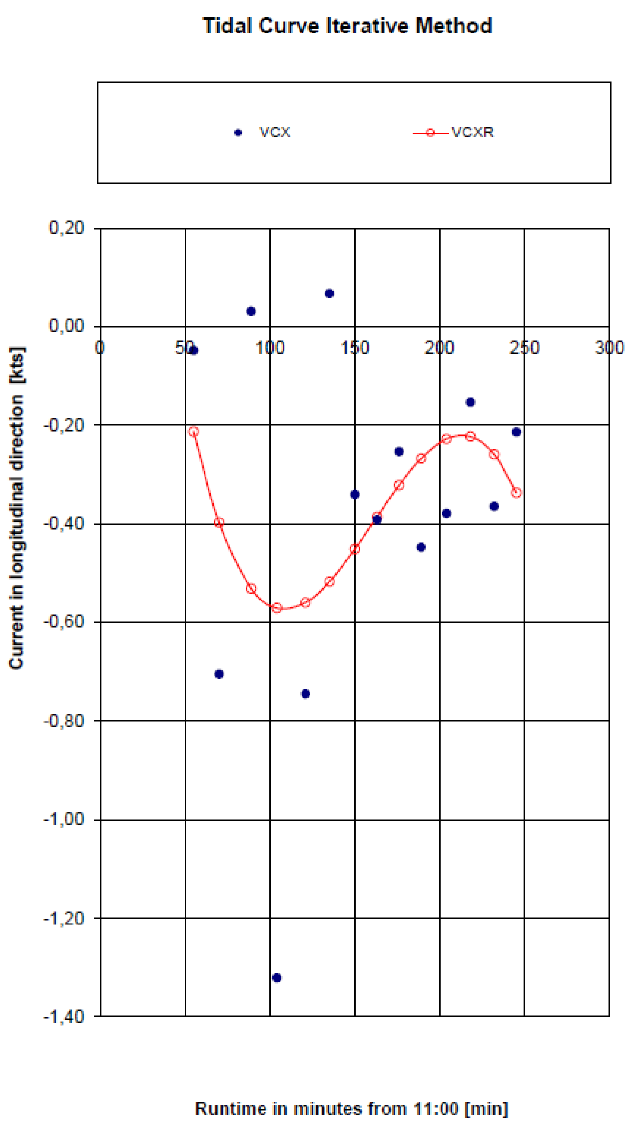
6.4 Post propeller cleaning trial

The speed trial correction was performed based on the measured average run data. During the post propeller cleaning trial, the wave buoy was used. The significant wave height, direction and period were received.

The following assumptions have been made for the data which was not available during analysis:

- Ambient pressure was assumed to 1013mbar.
- Water temperature was assumed to 10°C. (A different water temperature has been observed in NRC report after DNV GL has completed the analysis. However, this difference is not expected to impact the conclusion on comparison of performance between the trials.)
- Propulsion efficiency was estimated and assumed to be 0.63 for all engine loads

Based on the received data, the current speed varied significantly during the post propeller cleaning trial. The maximum difference of current speed is about 1.5 knots between runs and analyzed current speeds are scattered. The analyzed current speed does not fulfill The ISO 15016:2015 requirement with regard to the variation of the current speed. The current speed variation is expected to impact the comparability on the measured speed power performance between trials.



VCX: Current velocity as difference between run speed and iterative current curve
VCXR: Current velocity in ship direction from iterative current curve
Figure 6-8 Current speeds for post propeller cleaning trial

The received wind speeds during trial is shown below. As it can be seen, the wind speed changed slightly from 80% engine load. The average true wind speed is about 3.8m/s and directions are between 190 to 270 degrees.

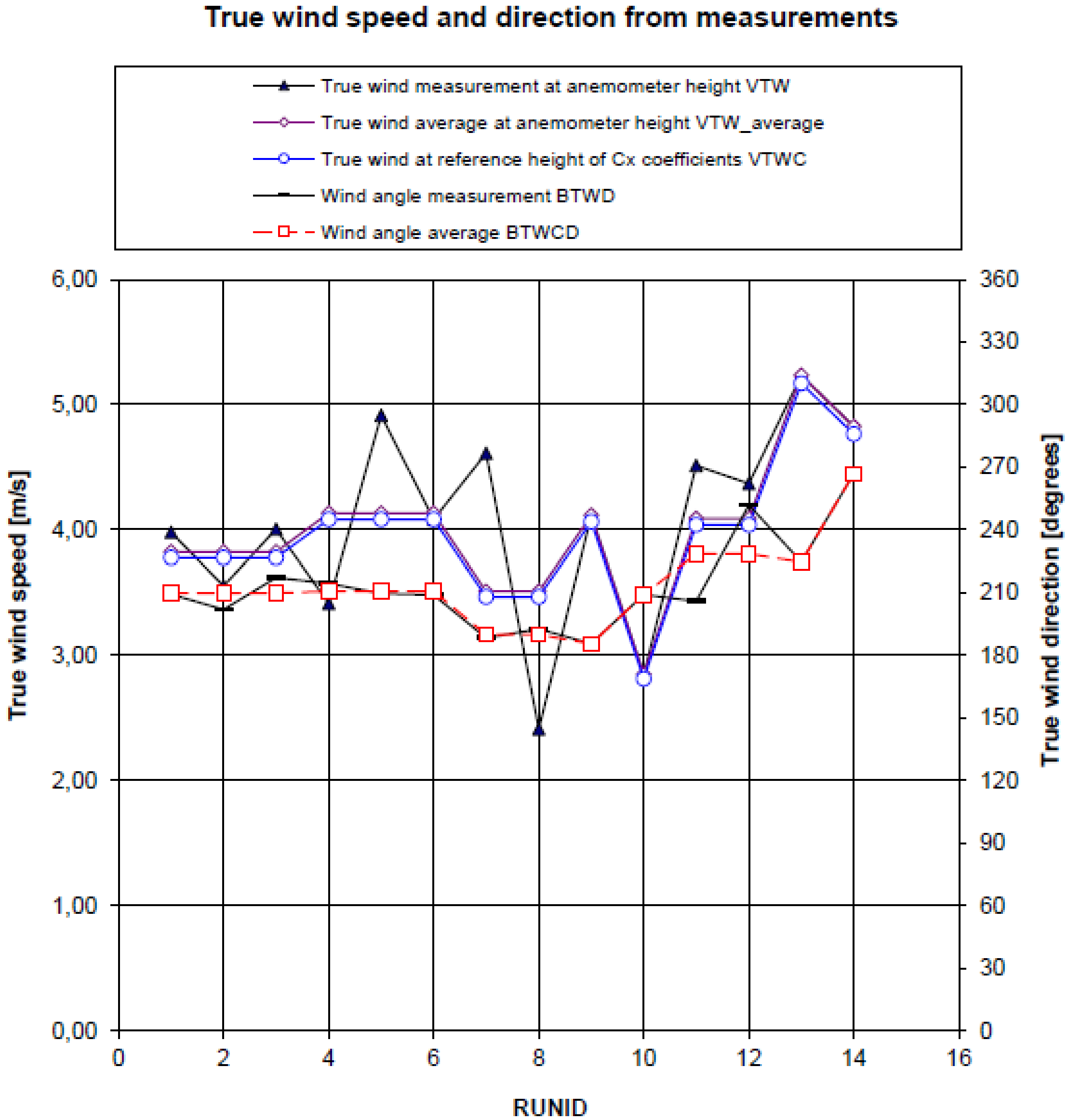


Figure 6-9 Wind speeds and directions for post propeller cleaning trial (Current speed)

More detailed inputs can be found in Appendix A

The weather corrected speed power curve for post propeller cleaning trial is shown in Figure 6-10.

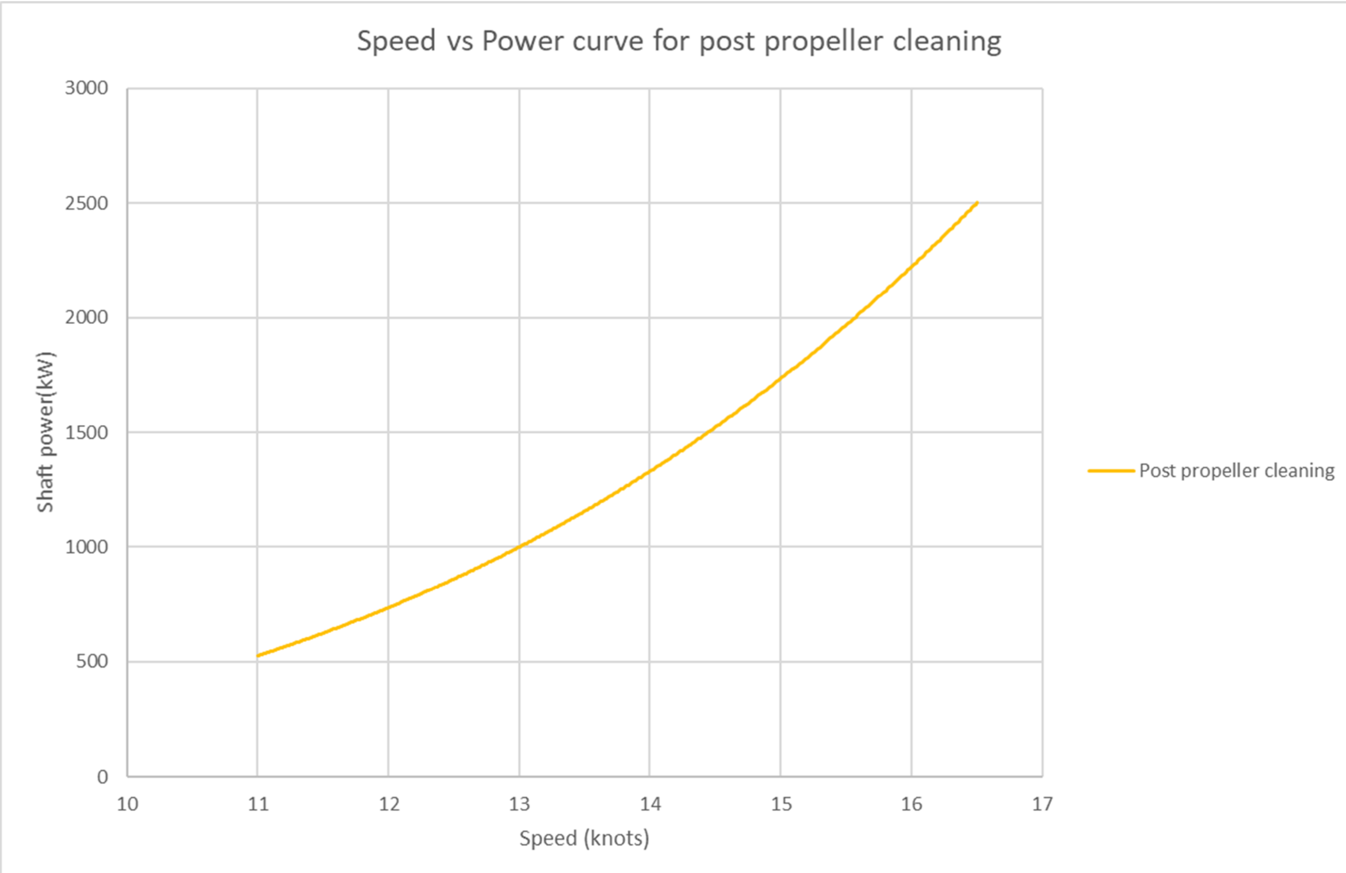


Figure 6-10 Weather corrected speed power curves for Post propeller cleaning

6.5 Comparison between three trials

Based on the inputs, DNV GL performed the correction of the speed power curve for baseline trial, post hull cleaning trial and post propeller cleaning trial. The results are compared in Figure 6-11.

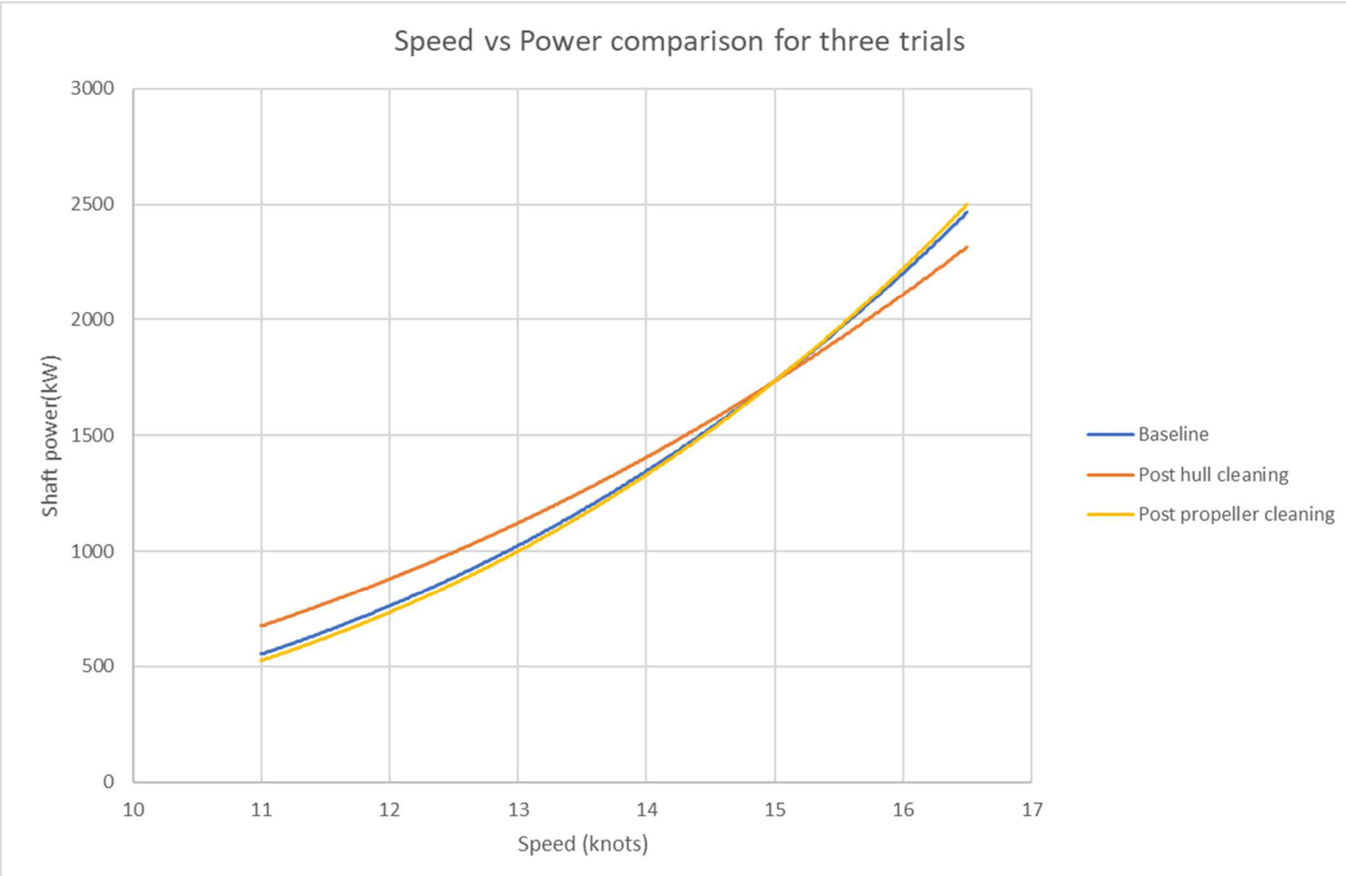


Figure 6-11 Weather corrected speed power curves for three trials (Baseline, Post propeller cleaning and Post hull cleaning)

It shall be noted that the comparison is at the trial draft for each trial without displacement correction. The displacement correction method is generally acceptable within 2% difference of the displacement. However, the three trials were carried out with 5-8% difference in the displacement compared to the baseline trial. In addition, the three trials were carried out with 9-16% difference in trim compared to the baseline trial. Some details on uncertainties about displacement and trim conditions can be found in Section 9.4.

Comparison between baseline trial and post hull cleaning

Based on Figure 6-11, the trend of speed power curve for post hull cleaning trial is considerably different from the other two, i.e. baseline and post propeller cleaning trials. This difference could be induced by two factors: 1) different severity of the weather condition, and 2) the difference on displacement and trim which impact the ship’s hydrodynamic performance.

Comparison between baseline trial and post propeller cleaning

Based on Figure 6-11, it can be seen that the analyzed shaft power for post propeller cleaning is slightly lower than baseline trial when speed is in the lower range. However, when the speed is in the higher range, the analyzed shaft power for post propeller cleaning is slightly higher than the baseline trial.

In general, the hull/propeller cleaning could have a mixture of negative and positive impact on the speed power performance. However, the hydrostatics vary considerably between the two trials. Hence, one cannot decide if it is because of the actual impact from propeller cleaning on speed power performance or the uncertainties from the measurement.

The uncertainties from weather condition, displacement and trim are discussed below.

1) Weather condition

In general, it is challenging to measure waves and swell with visual observation. In the received speed trial data for the baseline trial, it was observed that wave and swell have the same direction. This would make it even more challenging to distinguish between wave and swell without a wave buoy. The post hull cleaning trial has the most severe wind and wave conditions (Section 6.3). According to the analysed current speeds over time, it was noticed that there are large scattered current speeds for the post propeller cleaning. Hence it may introduce uncertainties to the performance analysis.

In the measured wave conditions, it is expected that the vessel actually had pitch and heave motions in the measured weather condition. However, vessel motion has not been corrected due to the speed restriction of STAWAVE 2 method, as discussed in Section 6.1.

The uncertainty from the visual observation of the base line trial and ship motion makes it hard to assess the impact from waves. For the subject vessel which is relatively small scaled, this can have a significant impact on the results.

2) Displacement and trim

The comparison on displacement and trim for the three trials are shown in Table 6-1 and Table 6-2 respectively. The displacement was estimated based on measured draft and received stability booklet. The displacement correction method is generally acceptable within 2% difference of the displacement. However, the three trials were carried out with 5-8% difference in the displacement compared to the baseline trial.

It is deemed that the ship hydrostatics vary substantially between baseline trial and hull cleaning trial. This is also applicable for the comparison of the measurement results for baseline and post propeller cleaning trial. Hence, this disables the possibility to draw a conclusion on the impact from the hull cleaning event on speed power performance.

Table 6-1 Comparison of displacement during three trials

Trial	Displacement (m3)	Difference compared with baseline trial (%)
Baseline trial	1394*	-
Post hull cleaning trial	1327	5%
Post propeller cleaning trial	1280	8%
*This value is different with NRC log. Calculation on displacement has been performed based on stability booklet and the measured draft.		

Table 6-2 Comparison of trim during three trials

Trial	Trim (Aft Perpendicular-Fore Perpendicular, m)	Difference compared with baseline trial (%)
Baseline trial	1.47	-
Post hull cleaning trial	1.60	9%
Post propeller cleaning trial	1.70	15%

6.6 Comparison with NRC's report remarks

NRC's report has been reviewed briefly. In Section 9.4 Concluding Remarks of NRC's report /2/, the following is stated "The corrected sea trials data indicated a reduction in power required to attain a given speed by an average of 5% between the speed ranges of 13.5-16 knots. However, these results were not corrected for variation in displacement across trials or the presence of slight fouling during the post cleaning trials." It is deemed as in line with DNV GL's conclusion, i.e. it is not possible to conclude whether the propeller and hull cleaning of CCGS Cygnus is beneficial or not for fuel consumption based on the received three trials' results.

7 ECO INSIGHT DASHBOARDS

ECO Insight is the DNV GL fleet performance solution and provides a web portal to ship owners, managers, and operators to track and monitor the most important performance categories for their fleet, including voyage, hull and propeller, machinery, and environmental performance.

ECO Insight is generally based on "event" reporting, e.g. noon reports and other voyage reports, that reports fuel consumption, speed, machinery operations, etc. averaged over an interval in time. This is the standard ship-shore reporting done by ocean going cargo vessels that have voyages that last a day or longer with relatively constant speeds and headings. For a vessel like the CCGS Cygnus, a fishery patrol vessel, event reporting is more challenging, since the vessel have short voyage with more maneuvering and load changes. This makes the time averaging of event reporting less accurate.

For these vessels, "snap shot" reporting with higher frequency data collection will be more relevant for fuel consumption analysis, in combination with dedicated performance trials under controlled conditions as was carried out during this project. However, it was agreed that fuel consumption and speed operational data collected onboard the CCGS Cygnus will be aggregated and averaged into a format that could be presented in the applicable standard ECO Insight dashboards. This was performed for the two vessels that were analyzed in the previous fuel consumption study done by DNV GL for VFPA.

7.1 Operational dashboard

The operational data collected between sea trials for the vessel were entered into the ECO Insight data base. The data were collected by the data logging system onboard the vessel and covered the period from May 5, 2018 to August 1, 2018. The hull was cleaned on June 5th, 2018. The propeller cleaning was done on July 18th, 2018. The operational data was filtered to only include days with more than 2 hours of operation and average speeds over 7 knots, to avoid intervals when the vessel was manoeuvring or operated with many load and speed changes.

The charts in Figure 7-1 show the reported Fuel Oil Consumption per day in tons, vessel speed in knots, and wind force in Beaufort scale during the reporting period. Each blue dot on left side chart represents the reported value each day. The green solid line is the average for CCGS Cygnus, and the orange line is the AIS benchmark for the world fleet group of other similar type of vessels with size below 10000 GT.

Because of the short evaluation time and limited data points, no conclusion can be made using ECO Insight on the effect of the hull/propeller cleaning.

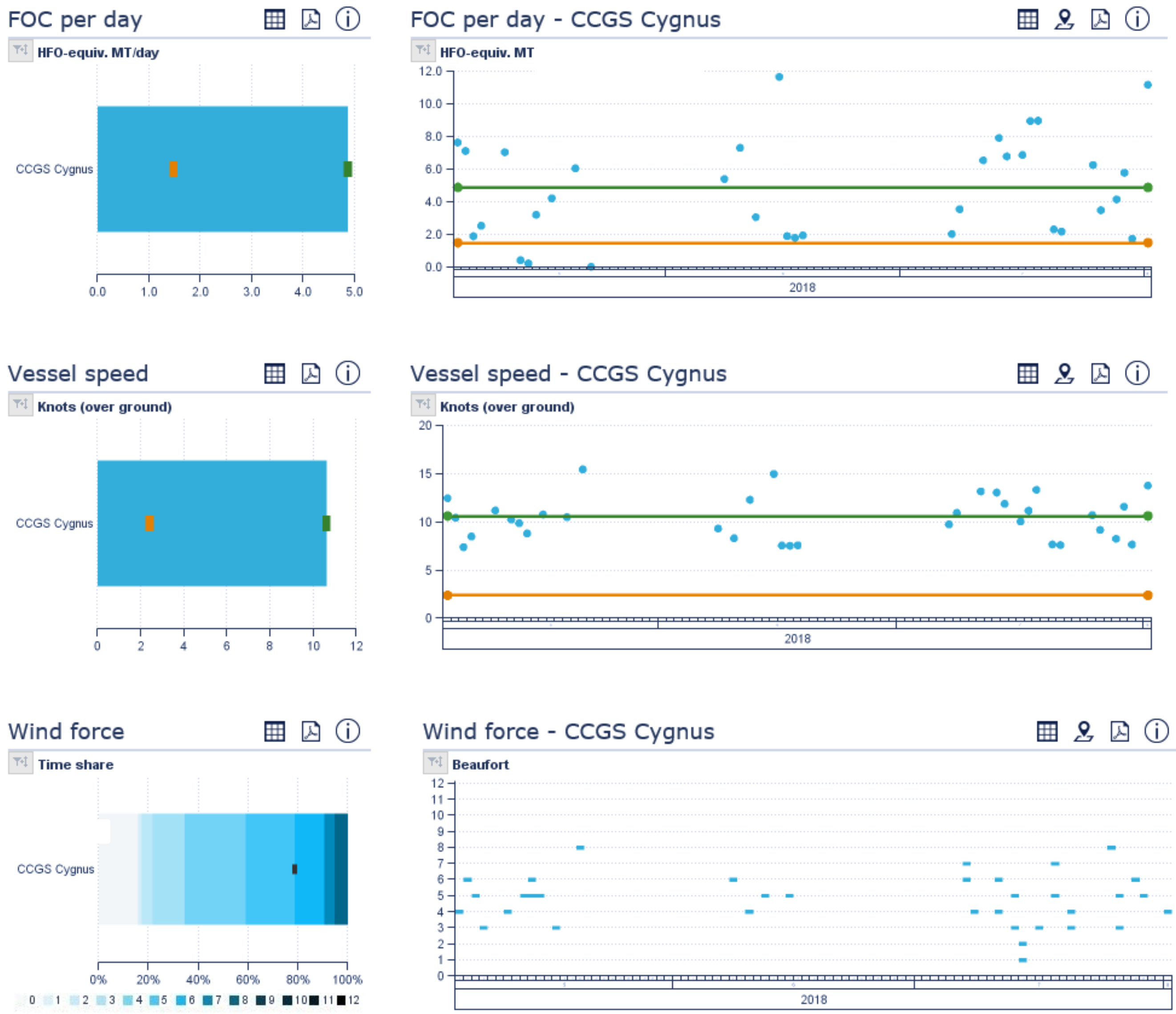
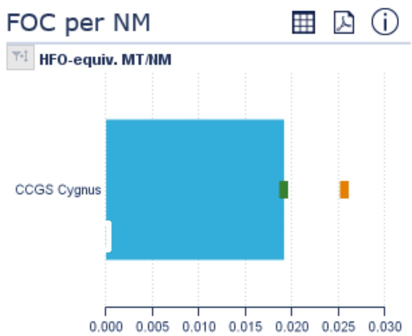


Figure 7-1 Operational dashboards for CCGS Cygnus

The chart in Figure 7-2 shows the reported Fuel Oil Consumption per Nautical mile during the reporting period. Each blue dot on left side chart represents the calculated value each day. The green solid line is the average, and the orange line is the AIS benchmark for the world fleet group of other similar type of vessels with size below 10000 GT. The AIS benchmark for FOC/day is lower while the FOC/NM is higher than was reported for the CCG Cygnus. The reason is that type of vessels that is included in the global benchmark also includes fishing vessels, tug, and other workboats that tend to have a higher fuel consumption at low speed because of e.g. trawling or towing operation.



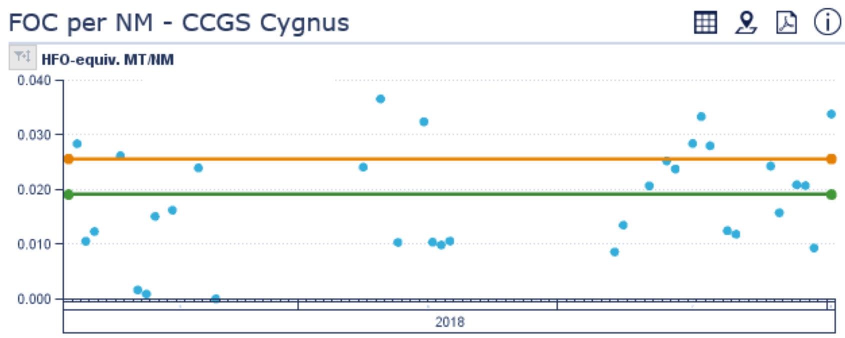
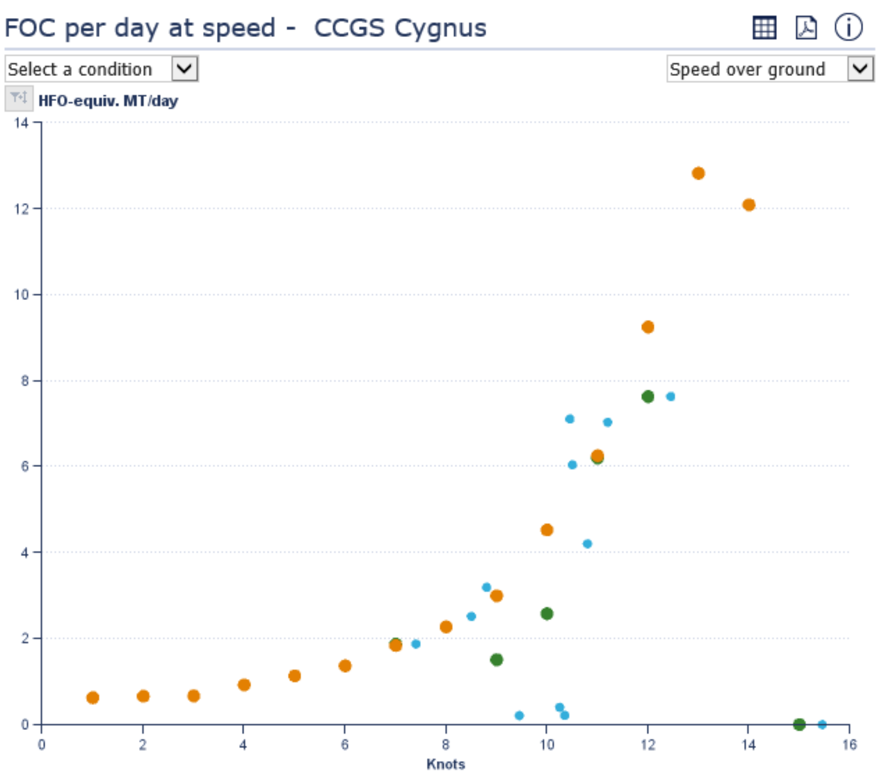


Figure 7-2 Fuel Oil Consumption per NM

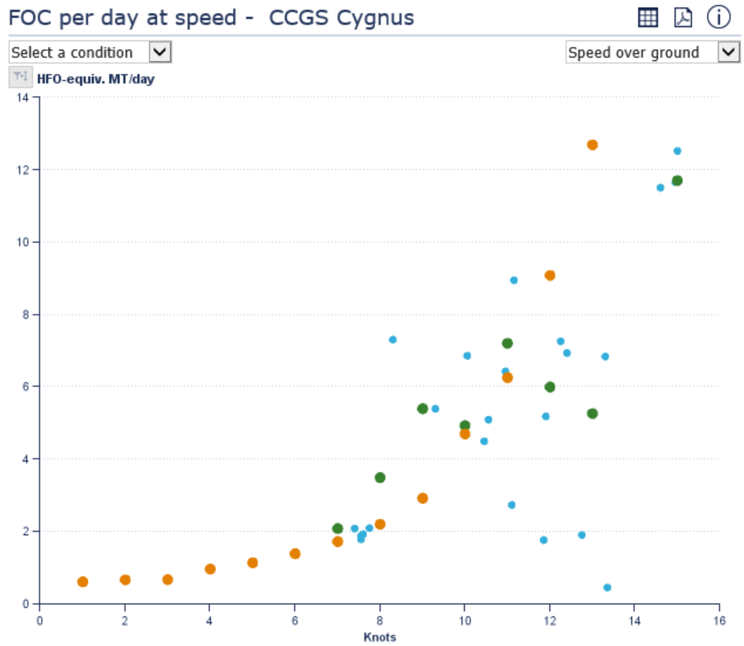
7.2 Speed Consumption Evaluation

The charts below show the fuel oil consumption in tons per day versus the vessel daily average speed. Each blue dot show consumption per day for each single event, the green dots the average at each speed, and the orange dots are the AIS benchmark for the world fleet group of other similar type of vessels with size below 10000 GT.

Before Hull Cleaning:



After Hull Cleaning:



After Propeller Cleaning:

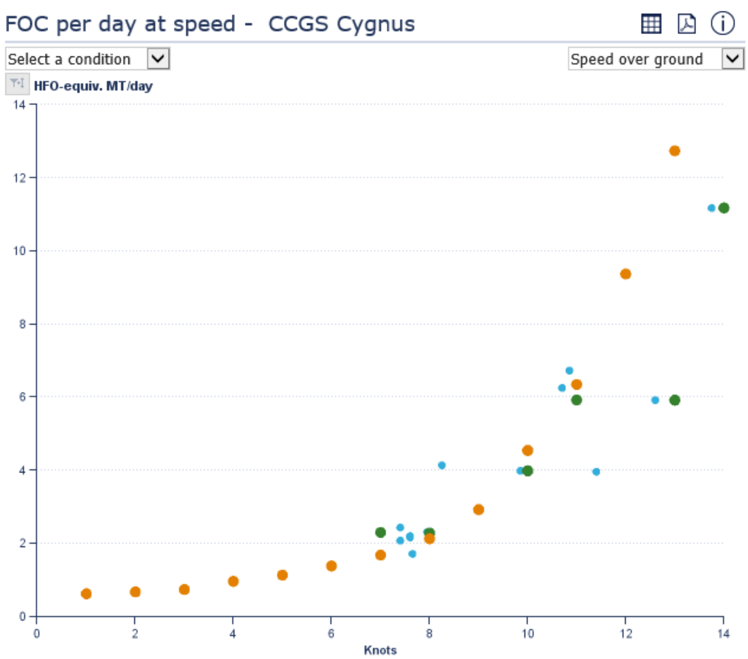


Figure 7-3 Fuel oil consumption in tons per day versus the vessel daily average speed

Due to the limited data points and no environmental corrections, the speed consumption data cannot be used to make any conclusion of the effect of the hull or propeller cleaning on the fuel consumption.

8 FUEL OIL CONSUMPTION CALCULATION

As the main objective of the study is evaluating the impact from hull cleaning events on fuel consumption, the further work on fuel oil consumption has been executed, even though a conclusion can not be drawn on the impact from hull/propeller cleaning to speed power performance.

Specific fuel oil consumption (SFOC) from main engine shop test result was corrected based on the following assumptions:

- Mechanical losses: 5% from engine to shaft
- Application of 5% tolerance between shop test and actual SFOC
- Fuel energy correction from shop test to actual: 42700 KJ/kg for MDO/shop test 41800 kJ/kg for HFO/actual

The corrected SFOC curve is shown below.

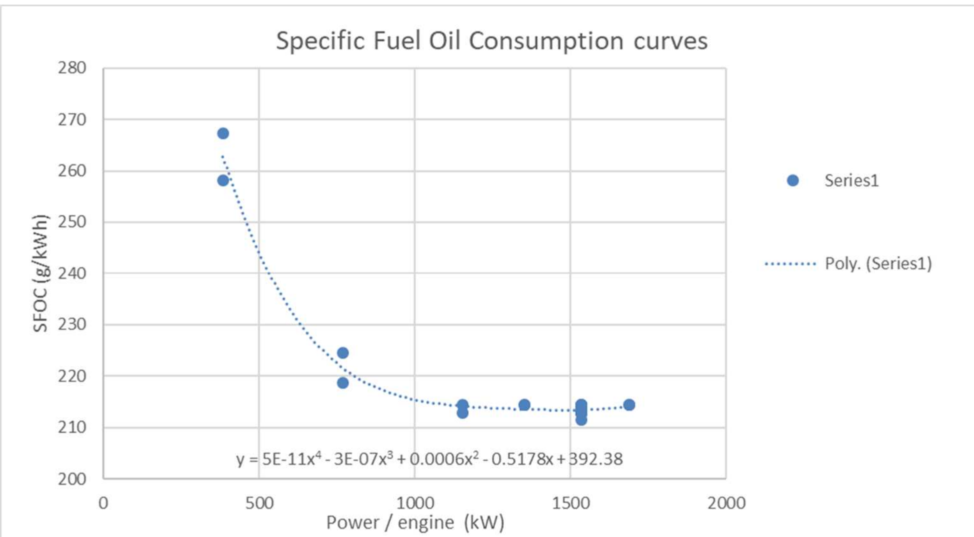


Figure 8-1 Specific fuel oil consumption (SFOC) curve

The daily fuel oil consumption (DFOC) is further calculated based on the corrected SFOC curve and the analyzed speed power performance for three speed power trials. The calculated DFOC curves are shown below.

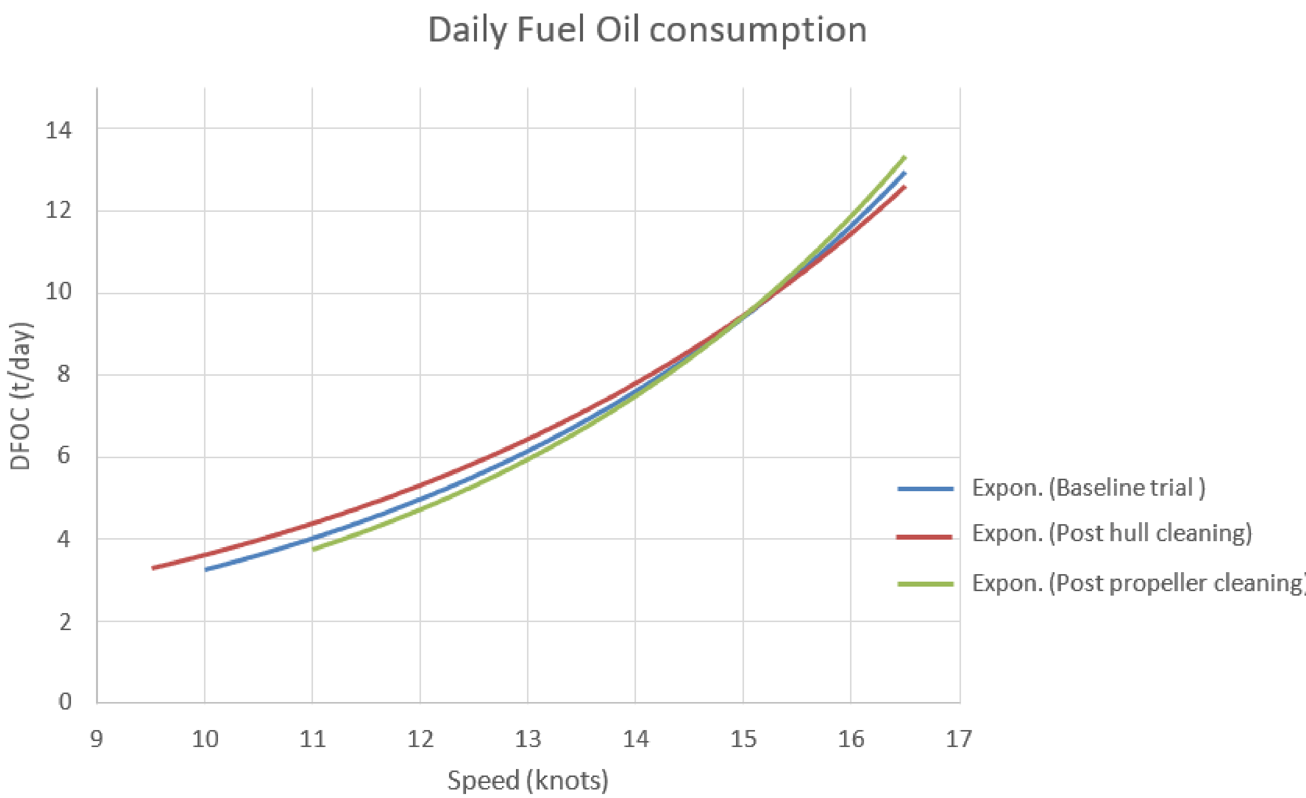


Figure 8-2 Calculated daily fuel oil consumption(DFOC) curve

As there is no clear improvement observed for required power per speed comparing between baseline trial, the post hull cleaning trial and post propeller cleaning trial, the same is applicable for the fuel oil consumption.

9 LIMITATIONS AND UNCERTAINTIES

9.1 Limitations

For this project DNV GL has not performed any on-board measurements or verification of the reported data. Consequently, received information is assumed true and correct. Furthermore, DNV GL has not reviewed the speed trials measurement procedure for this project. This can be done on request prior to any subsequent trials with the objective to enhance the quality of the trials.

9.2 Model test results

Model test results are essential information for the speed trial analysis which is not available. Hence, DNV GL has executed a high-level analysis for resistance for the vessel based on empirical methods. Propulsion efficiency was estimated using Wageningen propeller B series based on propeller's characteristics such as propeller diameter, pitch and RPM. In this analysis, only one propeller pitch is used.

Total propulsion efficiency consists of propeller open water efficiency, hull efficiency and propeller rotational efficiency. Due to the lack of data, the total propulsion efficiency was estimated without separate estimation on the propeller open water efficiency, hull efficiency and propeller rotational efficiency.

It can be noticed that speed trials seem to have been conducted with different propeller pitch at different engine loads, which is a normal operational mode. However, estimation of propulsion efficiency at different propeller pitch is challenging without model test and/or CFD analysis for the propeller. Hence, 0.63 of propulsion efficiency was used for all engine loads and three trials. The propulsion efficiency was estimated based on estimated resistance and propulsion efficiency at one propeller pitch. It should be noted that using one propulsion efficiency introduce uncertainties on analysis which is difficult to evaluate without any information of pitch setting in during the trials.

9.3 Weather condition

In general, it is challenging to measure waves and swell with visual observation. In the received speed trial data for the baseline trial, it was observed that wave and swell have the same direction. This would make it even more challenging to distinguish between wave and swell without a wave buoy.

The post hull cleaning trial has the most severe wind and wave conditions (Section 6.3). According to the analysed current speeds over time, it was noticed that there are large scattered current speeds for the post propeller cleaning. It introduces uncertainties to the speed power performance analysis.

In the given wave conditions, it is expected that the vessel actually had pitch and heave motions in the measured weather condition. However, vessel motion has not been corrected due to the speed restriction of STAWAVE 2 method, as discussed in Section 6.1.

The uncertainty from the visual observation of the base line trial and ship motion makes it hard to assess the impact from waves. For the subject vessel which is relatively small scaled, this can have a significant impact on the results.

9.4 Displacement and trim

In general, moderate draft and trim difference changes the total resistance by decrease or increase wave making/breaking resistance. If the changes are big the wetted surface will also affect the resistance. For conventional merchant vessels such as bulk carries and tankers the displacement correction method such as Admiral formula can be applied unless bulbous bow / stern submergence is changed.

CCGC Cygnus is operating in high Froude number means that the resistance and propulsion efficiency can be sensitive in different draft and trim conditions. It was noticed that post hull and propeller trials were conducted with 5-8% difference in the displacement and 9-16% difference in trim compared to the baseline trial. ISO states that acceptable within 2% difference of the displacement, 0.1m of foredraft difference between trial condition and model test in order to minimize uncertainties from the conditions.

9.5 Fouling regrowth

The post cleaning trial was performed approximately two weeks after the cleaning event. The detailed timeline is referred to Section 1. It is understandable that the possibility of performing speed power measurement is highly relevant with other factors. However the speed power measurement is preferred to be performed immediately after the hull cleaning to avoid fouling regrowth.

10 CONCLUSION AND RECOMMENDATION

The results of the speed trials on CCGS Cygnus were likely affected by the uncertainties explained in Section 9, which DNV GL believes could have a significant impact on the results. Based on the data provided to DNV GL, it is not possible to conclude whether the propeller and hull polishing of CCGS Cygnus is beneficial or not for fuel consumption. It should be emphasized that this does not mean that DNV GL concludes that there is no benefit on reducing fuel consumption from hull and propeller cleaning in general. DNV GL believes the uncertainties listed in this report and the possible impact of fouling between performed cleaning and conducted trial needs to be controlled to be able to produce conclusive results.

The ECO Insight fleet performance solution was used to aggregate the data collected by NRC with filtering to achieve a best possible event-based report to could be evaluated in the standard ECO Insight dashboard. However, no conclusion on the effectiveness of the hull and propeller cleaning can be made because of the limited number of event data points between the cleaning events.

For future evaluation of the benefits of the hull cleaning to fuel oil consumption, the following recommendations may be considered:

1. CCGS Cygnus is a relatively small and unconventional vessel which increase the need for consistency and accuracy of measurement methods between trials. A larger and more conventional merchant vessel will probably be more forgiving with respect to the uncertainties listed in this report.
2. An even more benign weather condition than the stipulation in ISO 15016:2015 is recommended for the speed power trial to limit the impact from weather.
3. If speed power measurement is to be performed, the measurement should strictly follow ISO 15016:2015.

4. The speed power measurement is preferred to be performed immediately after the hull cleaning to avoid fouling regrowth.

11 REFERENCES

/1/ ISO 15016:2015 "Ships and marine technology – Guidelines for the assessment of speed and power performance by analysis of speed trial data", 2015

/2/ National Research Council Canada, "CCGS Cygnus – Hull and Propeller Cleaning. Draft Report. Unclassified OCRE-TR-2018-XXX"

APPENDIX A SPEED TRIAL ANALYSIS PER ISO 15016 – CORRECTED FOR ENVIRONMENTAL EFFECTS

Three trial reports from STAIMO are attached in addition to the report.

APPENDIX B INTERMEDIATE RESULTS

A separate document is attached in addition to the report.

About DNV GL