Test Plan

Acoustic Characterization of ORPC Device Sound Signatures

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Executive Summary

The objective of this project was to characterize the radiated noise from several river current turbines developed by Ocean Renewable Power Company (ORPC), Inc. A team of researchers from the University of Washington (UW) conducted surveys around a pair of prototype Modular RivGen turbines in Millinocket, ME in August 2023 and a pair of RivGen turbines in Igiugig, AK in June 2024. Measurements utilized the shallow version of the Drifting Acoustic Instrumentation SYstem (DAISY), which is purpose-built to collect high-fidelity acoustic data in energetic currents. During the surveys, ORPC coordinated with the UW team to vary turbine operations to assess the influence of power output and rotation rate on radiated noise and shut down the turbines mid-drift to create operating-ambient snapshots.

In Millinocket, the prototype Modular RivGens had different powertrains: one with a gearbox and the other with a direct drive generator. Because of the relatively low levels of ambient noise at this location, we were able to unambiguously identify the contributions from each turbine. Radiated noise from the geared turbine consisted of a set of tones associated with rotating elements of the powertrain and a prominent tone at 8 kHz from generator winding excitation by the variable-frequency drive (VFD) used to regulate rotation rate. At a range of 20 m, radiated noise exceeded ambient levels by > 10 dB in the over frequencies from 0.2 – 10.5 kHz. In contrast, the direct drive turbine produced relatively faint noise consisting of a single tone associated with rotation, a moderate tone from the VFD, and a once-per-revolution broadband impulse. Unlike the geared turbine, noise from the direct drive turbine only intermittently exceeded ambient levels from 0.2 – 10.5 kHz. Because the radiated noise from the geared turbine was so much higher intensity, when both turbines were in operation, the direct drive turbine noise was entirely masked by the geared turbine noise. Spatial asymmetry was observed in the radiated noise patterns for each turbine, with higher received levels in the downstream direction for the geared turbine and upstream direction for the direct drive turbine. This may suggest directional asymmetry in the acoustic source. In the turbine band (0.2 – 10.5 kHz), radiated noise from both turbines was not correlated with power output and only weakly correlated with rotation rate.

In Igiugig, while the original plan was to survey a pair of identical turbines to assess array-level contributions, only one unit could be operated in a power generating mode due to a technical issue. As result, a more intense effort was directed at evaluating spatial patterns around the fully operating turbine, with a secondary objective of characterizing the combination of acoustic pressure from the pair of turbines in freewheel. At a range of 20 m, radiated noise from the turbine exceeded ambient noise from 0.06 – 2 kHz due to radiated noise from rotating elements in the powertrain and from 4-5 kHz due to radiated noise from VFD excitation of the generator windings. Radiated noise levels had a moderately positive correlation with rotation rate and negative correlation with power output. In assessing spatial trends, we observed that RivGen affects the soundscape through two mechanisms: direct radiated noise in the turbine band (0.06 – 5 kHz) and indirect alteration of noise from sediment transport at higher frequencies due to the turbine's hydrodynamic influence. When both turbines were operated in freewheel, received levels at an equidistant location increased by no more than 6 dB, consistent with expectations for combinations of multiple sources. We also employed acoustic localization to attribute specific events (e.g., a "clank") to a specific turbine, but this was challenging due to unfavorable receiver geometry and relatively low signal-to-noise ratios.

Across the two sites, the consistent theme was that the construction and operation of the powertrain had a significant influence on radiated noise. If it is desirable to reduce the acoustic footprint – noting that eliminating it would remove an important cue for marine animals – then taking steps to acoustically isolate noise from the powertrain components or tune VFDs to reduce their noise could be considered. All turbines surveyed produced noise primarily in the range of 100 Hz to 10 kHz, consistent with other observations in the public domain and radiated noise levels had a moderately positive correlation with rotation rate. The largest of the turbines surveyed – the RivGen turbine in Igiugig – produced radiated noise of similar amplitude to a recreational fishing boat.

At each site, we also employed the IEC 62600-40 methodology, which involves observations of different turbine power states at 100 m from the turbines. For turbines of this scale, we found that measurements at closer range provided more useful information about radiated noise characteristics, as received levels were substantially reduced by transmission loss at 100 m and often indistinguishable from ambient noise. Similarly, given that we observed no positive correlation between power output and received levels, the requirement to stratify measurements by power output may not be informative. A better strategy may be to make observations across a range of inflow conditions with the turbine operating in its standard mode.

1 Introduction to the Project

ORPC is developing a portfolio of hydrokinetic devices that range from riverine to tidal applications. ORPC's power systems have the same core component: the proprietary Turbine Generator Unit (TGU). A TGU consists of multiple Advanced Design Cross Flow turbines on a single drive shaft, connected to an underwater permanent magnet generator; with all of these components mounted on a chassis. The TGU and the chassis comprise the power system device. ORPC's portfolio of power systems include the RivGen® Power System and Modular RivGen® Power System. A single RivGen device has been deployed in Igiugig, Alaska (AK) since 2019. Igiugig Village Council (IVC) and ORPC deployed a second RivGen device in approximately August 2023. A single Modular RivGen device was deployed for testing in Millinocket, Maine (ME) in early 2023 and ORPC deployed a second Modular RivGen device in May 2023.

Any current turbine will introduce additional noise into aquatic environments, which may be a potential concern because marine or aquatic animals use sound for a variety of purposes (e.g., communication, foraging, navigation). In some cases, the radiated noise from a turbine may be negligible in comparison to other ambient noise, but this can be difficult to predict, with certainty, in advance of a deployment. This uncertainty is a barrier to the commercial adoption of current turbines in some sensitive environments.

The deployment of multiple ORPC turbines at two locations presented an opportunity to significantly reduce these uncertainties. By collecting information consistent with IEC 62600-40 (IEC 2019), measurements can add to the body of knowledge about radiated noise from current turbines and compare/contrast radiated noise between the turbines and sites. The primary reported metric from these measurements is the sound pressure spectral density (intensity of sound as a function of frequency) at defined distances from the turbines, with secondary metrics obtained by integrating spectral density over multiple frequency bands (i.e., band levels). In addition, by shutting down one or both turbines during a subset of the measurements in Millinocket, ME and Igiugig, AK, we were able to isolate the acoustic signatures of individual turbines in the arrays. Finally, a sufficient number of time-synchronized acoustic receivers may be able to localize specific sounds from the turbines and identify opportunities for reductions in radiated noise. Overall, this information is intended to reduce regulatory uncertainty about radiated noise from current turbines and thereby reduce barriers to commercial deployment.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

ORPC provided University of Washington (UW) researchers with site access and adjusted turbine operating modes upon request. Post-survey, ORPC provided UW researchers with co-temporal information about turbine operation (rotation rate and electrical power generation) and engineering insight into the potential sources of sound attributable to the turbines (e.g., bearings, generators, power electronics). ORPC reviewed the post-access report.

2.2 Network Facility Responsibilities and Tasks Performed

The University of Washington (UW) was responsible for collection and analysis of acoustic data around the ORPC turbines in Millinocket, ME and Igiugig, AK. UW drafted the post-access report.

3 Project Objectives

The objective of this project was to characterize the radiated noise from two Modular RivGen riverine energy devices in Millinocket, ME (Millinocket Stream) and two RivGen riverine energy devices in Igiugig, AK (Kvichak River). This provided information about the radiated noise from cross-flow current turbines with similar designs, but operating in different environments. Because two turbines were operating in both locations, these measurements were intended to also provide insight about radiated noise within turbine arrays. As discussed in Section 7, this objective could not be practically met at either site due to the significant imbalance in radiated noise for the Modular RivGen turbines in Millinocket and the inability to operate one of the RivGen turbines in Igiugig in a power generation mode. However, the data that was collected is consistent with physical expectations for source combination.

In addition to increasing knowledge about radiated noise from current turbines, the measurements benefited the continued evolution of IEC 62600-40. At present, this is a Technical Specification – the precursor to an International Standard – and is in a maintenance period for updates. The information developed through this study:

- Assessed the accuracy of guidance on acoustic measurements around arrays;
- Tested several approaches to objectively differentiating turbine sound from ambient noise (at present, IEC 62600-40 assumes that the turbine dominates the soundscape); and
- Provided insight into drivers of radiated noise characteristics.

Overall, this information should reduce regulatory uncertainty about radiated noise from current turbines, thereby reducing barriers to their commercial deployment, as well as refine industry standards.

4 Test Facility, Equipment, Software, and Technical Expertise

Underwater noise was measured by Drifting Acoustic Instrumentation SYstems (DAISYs, Polagye et al. 2025), which are purpose-built for measurements in energetic currents. For drifting measurements, IEC 62600-40 requires that the hydrophone be deployed at least 5 m below the water surface, but not deeper than rotor hub height. However, it also contains a provision for shallower depths if the standard depth would put the measurement system at risk. This provision was necessary for both Millinocket, ME, and Igiugig, AK due to limited water depth and the potential for a deeper hydrophone to become entangled with the turbine rotors.

This study employed a “shallow” variant of the DAISY (Figure 1). The standard DAISY is a two-piece unit with the surface expression connected to the hydrophone recording package by a flexible tether. Here, the surface expression and hydrophone are rigidly connected. The surface expression is instrumented with a GPS, meteorological station (wind speed, air temperature), inertial measurement unit (IMU), and data logger. The hydrophone recording package consists of a hydrophone (HTI-99-UHF), pressure sensor, IMU, GPS for clock synchronization while on the surface, and data logger. The hydrophone is protected from physical contact by a guard formed from PVC. While this configuration cannot be equipped with a flow shield, previous testing of shielded versus unshielded DAISYs indicates that, when the distance between the surface expression and hydrophone package is less than 5 m, unshielded DAISYs are relatively unaffected by flow noise (Strasberg 1979, Polagye et al. 2025). This is likely a consequence of low differential water motion between the surface expression and hydrophone as overall system length decreases. The shallow DAISY is still sensitive to flow noise at frequencies below 50 Hz when it “bobs” vertically through standing waves, which can occur around shallow turbines and other underwater features.

While the reduced hydrophone depth is necessary for these sites, proximity to the surface increases the likelihood of multipath interference in received sound, which can complicate localization. On the other hand, the relatively shallow depth does not increase received levels for near-surface phenomena such as wind or rain. Because these are distributed sound sources with received levels effectively integrated over large areas, a hydrophone at any possible depth for these sites (< 5 m) would likely receive similar levels of wind and rain noise as the shallow DAISYs.

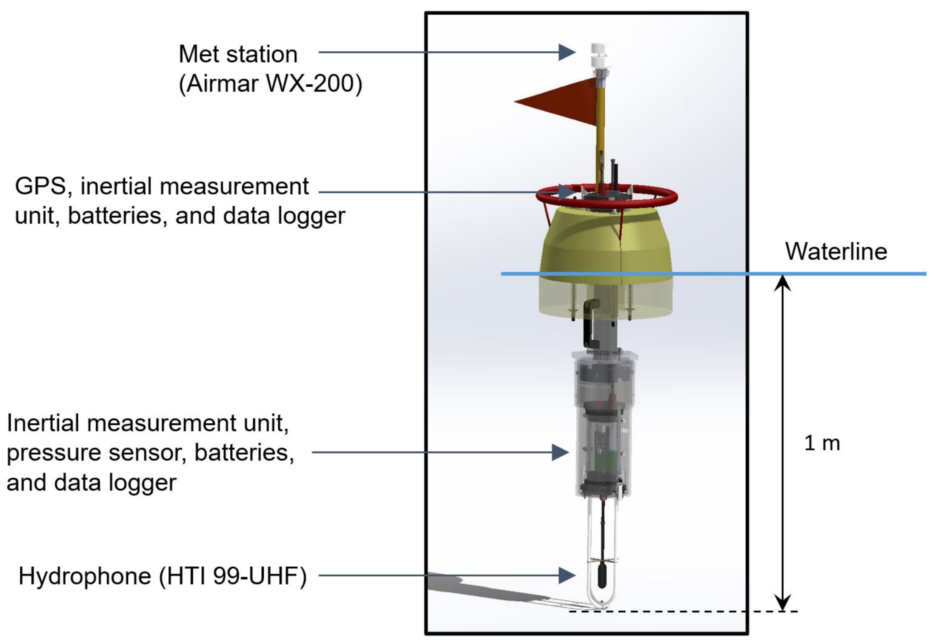

Figure 1: Annotated rendering of the “shallow” DAISY for deployment in currents.

UW personnel have deployed DAISYs in multiple current environments, including prior work in Igiugig, AK around a RivGen prototype in 2014 (Polagye and Murphy 2015). The DAISYs have a mature suite of post-processing tools in MATLAB that allow collected data to be rapidly analyzed and compared.

5 TEST OR ANALYSIS ARTICLE DESCRIPTION

The parameters of the two cross-flow turbines to be characterized are summarized in Table 1. The power take-off (PTO) varies between the turbines. One Modular RivGen has a direct drive generator and the other has a geared generator (i.e., generator with integrated gearbox). Both of the RivGen turbines have direct drive generators, though each is from a different manufacturer. Acoustic measurements of a RivGen prototype (Polagye and Murphy 2015) indicated that the primary source of radiated noise was the direct-drive generator (primary tonal signature matched the product of turbine rotation rate and number of poles). Based on this, we hypothesized that the acoustic signatures from the two Modular RivGen units would be distinct, but that the two RivGen units would be similar.

Table 1: Summary of ORPC Turbines

Turbine	Deployment Site	Cross-stream Length [m]	Stream-wise Diameter [m]	Rated Power [kW]	Clearance [m]
Modular RivGen 	Millinocket Stream, Millinocket, ME	~7.8 m	~2.7 m	18 kW at 2.5 m/s	0.6 m
RivGen 	Kvichak River, Igiugig, AK	~14.3 m	~15.7 m	35 kW at 2.25 m/s	1.2 m

5.1.1 Modular RivGen: Millinocket, ME

ORPC's Modular RivGen Power System is a new product designed for deployments in rivers and canal systems in more urban settings. The Modular RivGen is a horizontally-oriented cross-flow turbine housed in a steel rectangular fairing structure raised on a tubular base sled. The turbine has a box-like design such that multiple devices can be stacked or connected horizontally to one another using a bridge clamp system. A single Modular RivGen device measures approximately 2.7 m long (stream-wise) by 7.8 m wide (cross-stream) by 2.6 m high. When brought to a desired site, the device is connected to an anchor and mooring system, and then submerged to settle on the river bottom. The Modular RivGen has a single TGU and a rated capacity 18 kW at a flow speed of 2.5 meters per second (m/s). The Modular RivGen has a normal operational speed of 40-50 revolutions per minute (rpm). If unloaded and allowed to freewheel, the maximum rotational speed is 75 rpm; however, this is not an intended mode of normal operation. During the survey, two horizontally-connected Modular RivGen turbines were operating in Millinocket, ME (Figure 2, Figure 3).

Figure 2: Modular RivGen power system (two horizontally connected devices), Millinocket, ME.

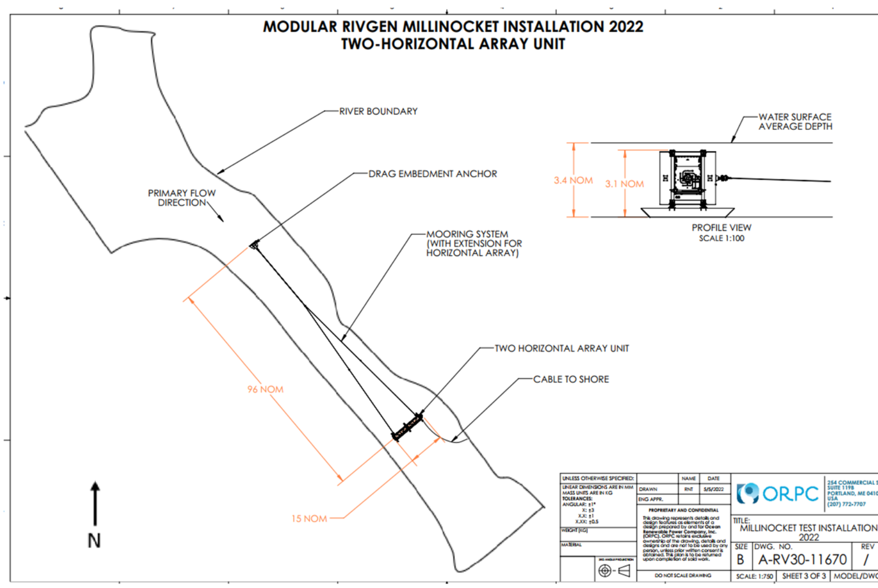

Figure 3: Two Modular RivGen device layout, Millinocket, ME.

5.1.2 RivGen: Igiugig, AK

The RivGen Power System is ORPC's first commercial scale product (Figure 4). ORPC's RivGen system has been deployed in Igiugig, AK for almost six years. A RivGen device measures approximately 15.7 m long (stream-wise) by 14.3 m wide (cross-stream) by 3.5 m high. The RivGen's TGU rests on a buoyant pontoon support structure frame. When brought to a desired deployment site, the device is connected to an anchor and mooring system and then the pontoon support frame is ballasted to submerge the device to the river bottom. The RivGen has a rated capacity of 35 kW at a flow speed of 2.25 meters per second (m/s). The RivGen has a normal operational speed of 60 revolutions per minute (rpm). If unloaded and allowed to freewheel, the maximum rotational speed is 90-100 rpm, but this is not a normal operating mode.

A single RivGen device has been deployed in Igiugig, AK since 2019 (Figure 4). Igiugig Village Council (IVC) and ORPC deployed a second RivGen device in approximately August 2023. The separation distance between the upstream and downstream turbines is approximately 91 m (Figure 5). However, issues with shore-side electronics prevented normal operation of the second unit during the survey in June 2024.

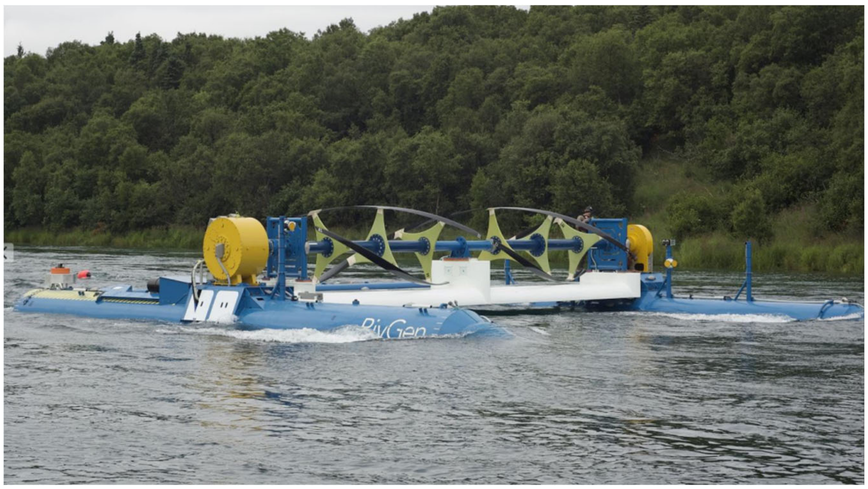

Figure 4: ORPC's RivGen power system at the water's surface in Igiugig, AK.

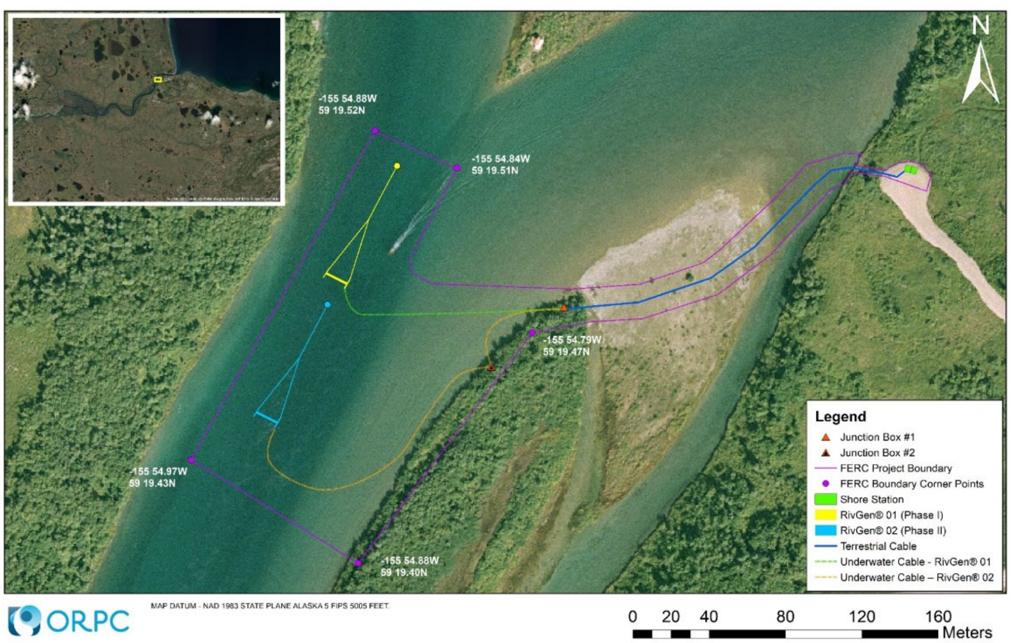

Figure 5: Two RivGen device layout, Igiugig, AK.

6 Work Plan

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

6.1.1 Shallow DAISY Specifications

Shallow DAISYs (Figure 1) are equipped with instrumentation described in Table 2. All sensor data streams are digitized and time stamped by microcomputers (Beaglebone "PocketBeagle") and archived on SD cards. Metadata about turbine operational state is summarized in Table 3.

In addition, sound speed profiles were collected using a CTD (Sontek Castaway). Similarly, hydrophone functionality was confirmed by a pistonphone calibrator (G.R.A.S. 42AA) periodically throughout the deployments.

Table 2: Standard DAISY instrumentation

Instrument	Data Streams	Sample Rate [Hz]
Surface Expression		
Global Positioning System (GPS)	Location Speed over ground Direction over ground	>1
Weather Station (Airmar WX200)	Backup GPS Wind speed and direction Air temperature Air pressure	1
Inertial Measurement Unit (IMU)	3-axis accelerometer 3-axis magnetometer 3-axis gyroscope	50
Hydrophone Recording Package		
Hydrophone (HTI 99-UHF)	Acoustic pressure (calibrated May 2021 by PNNL and Ocean Networks Canada)	512,000
IMU	Same as surface	50
Pressure	Depth (estimated from pressure)	5
Backup GPS	Location of deployment and recovery	>1

Table 3: ORPC metadata

Instrument	Data Streams	Sample Rate [Hz]
RivGen		
Electrical drive	Electrical power output from turbine Turbine rotation rate	1 Hz
Modular RivGen		
Electrical drive	Electrical power output from turbine Turbine rotation rate	1 Hz

At both sites, DAISYs were deployed and recovered from small workboats (e.g., skiff, zodiac). The rigid configuration of the shallow DAISY allows the units to be deployed at moderate relative velocity (i.e., vessel holding station in currents or “crabbing” cross-current while DAISYs are deployed). This was necessary for both sites due to the limited upstream distance between viable deployment sites and the turbines. Given the current speeds and site layouts, deployment from a free-drifting vessel would result in DAISYs far from optimal position by the end of a deployment cycle and difficulty spacing out DAISYs. Once all DAISYs were deployed, the vessel maneuvered to a moderate stand-off distance, powered down its engines, and drifted with the DAISYs. Once DAISYs cleared the intended survey area (tracked in real time using a handheld unit), the vessel restarted its engines for recovery operations.

6.1.2 Measurement Approaches

Multiple types of passive surveys were conducted at each measurement site in support of the project objective. These included application of the IEC 62600-40 methodology, as well as augmentation to improve the ability to differentiate turbine sound from ambient noise and characterize spatial patterns in radiated noise.

6.1.2.1 IEC Survey

IEC 62600-40 involves acoustic data collection from “zones” surrounding a turbine. The default zones (squares, 25 m on edge) are centered 100 m upstream, downstream, port, or starboard of the turbine. Acoustic measurements were obtained in each zone with the turbine at 0%, 25%, 50%, 75%, and 100% (±10%) of its rated electrical power. Each zone-power state combination was assessed on the basis of 10 or more 1-s “valid” acoustic samples. Valid samples required normal hydrophone operation (e.g., voltage within saturation limits), an absence of significant, intermittent anthropogenic or biological noise, absence of self-noise, and normal operation of the GPS on the drifting unit. While 10 samples meet the IEC specifications, experience to date suggests that intercomparisons between zones and power states are improved with a higher sample count (e.g., > 40 samples) (Haxel et al. 2022).

In analyzing data, the low-frequency propagation limit is specified by IEC 62600-40 as

$$f_{\text{low}} = \frac{c}{4D\left(1 - {c^2}/{c_s^2}\right)^{1/2}}$$

where c is the speed of sound at mid-water in m/s, c_s is the sound speed of the sediment in m/s, and D is the water depth in m.

At both measurement sites, flow rates were relatively consistent over the survey period. As such, the turbine power state would not normally modulate outside of a single IEC power state. However, a measurement at the 0% power state can be obtained by shutting down the turbine and intermediate power states can be obtained by intentionally varying the torque applied by the generator. Because none of the turbines reached their 100% rated power state during these tests, this quantity was defined in a deviation from the IEC methodology as the maximum time-averaged power observed during the survey period. Freewheel conditions, which also correspond to near-zero power, but relatively high rotation rates, were excluded from analysis.

IEC 62600-40 requires a measurement of current speed. The Millinocket, ME site was equipped with a Teledyne Channel Master horizontal acoustic Doppler current profiler and the Igiugig, AK site was equipped with a Nortek Signature 1000 acoustic Doppler current profiler. While not compliant with IEC6200-40, the shallow DAISY speed over ground is also a reasonable estimate for current speed in these relatively shallow environments.

6.1.2.2 Augmented Survey Methodologies

The primary limitation with IEC 62600-40 is the presumption that turbine noise dominates the soundscape, such that, when intermittent sources of ambient noise (e.g., vessel traffic, biological sounds) are controlled for, the statistical difference between the 0% power state and other power states is entirely attributable to the turbine. In measurements around a similarly-sized cross-flow turbine (15 kW instantaneous power output) in a busy port setting, Haxel et al. (2022) were unable to attribute any underwater noise to the turbine. While this turbine has a similar power level to the ORPC turbines, its generator is located above the water surface and the deployment site (Portsmouth, NH) has higher levels of ambient noise than either of these locations. As the authors of the 2022 study note, the "null result" means that the turbine's contribution to the soundscape was negligible and that its radiated noise was not an environmental concern. At the same time, this does not provide useful feedback to scientists and regulators to inform deployments at other locations.

Because of this, we conducted two additional types of measurements and analysis that go beyond the IEC 62600-40 methodology and allow a more granular investigation of sound attributable to the ORPC turbines.

First, measurements were taken during shutdown and/or startup transients for one turbine while the other was braked. Because turbine shutdown and startup are rapid actions (i.e., transients of a few seconds), when they are enacted during a drift, the ambient soundscape can be assumed to be unchanged to either side of the shutdown/startup event. Differences are, therefore, directly attributable to the turbine. These events also allowed us to synchronize data acquisition clocks for the DAISYs and turbines because they have distinct acoustic and operational transients.

Second, if the same sound is received by three or more DAISYs, it can be "localized" in horizontal space based on time-delay-of-arrival differences between the receivers (Whalberg et al. 2001). The accuracy of localization depends on how well the arrival time differences can be determined and the magnitude of the difference in arrival times. The difference in arrival times depends on the receiver arrangement relative to the source. Errors are minimized by receiver geometries that bracket the source at relatively close range (e.g., a group of DAISYs surrounding a turbine). Three receivers are the minimum required for horizontal localization and as the number of receivers increases, the solution becomes over-determined, allowing a more robust least-squares minimization of source location. At the same time, a significant challenge for both sites is that the DAISYs tended to be clustered by river streamlines into a line array. In addition, the water depth resulted in multipath distortion of acoustic signals, complicating determination of arrival time.

6.1.3 Millinocket, ME

Figure 6 shows the layout of the Modular RivGen deployment site in Millinocket Stream, Millinocket, ME. The turbines were deployed roughly 100 m downstream of the tailrace of the Millinocket hydroelectric power plant. This is a run-of-the-river facility with 37.4 MW of generation capacity. Upstream of the tailrace, Millinocket Stream is shallow (< 1 m depth) and low velocity. Downstream of the tailrace, where the Modular RivGen turbines are operating, the water is deeper and faster (~ 2 m/s velocity) due the relatively narrow width (33 m). Velocity decreases as the channel widens and, further downstream, Millinocket Stream merges with the west branch of the Penobscot River at Shad Pond.

The site poses some unique challenges for the IEC survey methodology, but also has several advantages. Millinocket Stream is only marginally wider than the IEC survey zone, such that DAISYs in the channel are likely to pass through a survey zone. Unfortunately, there are no public domain measurements of the soundscape around the hydropower tailrace, so ambient noise levels at the site are unknown. However, the shallow water upstream of the tailrace means that motorized vessel traffic is limited. Finally, the foot bridge upstream of the turbine could be used for DAISY deployment at relatively close range to the turbine.

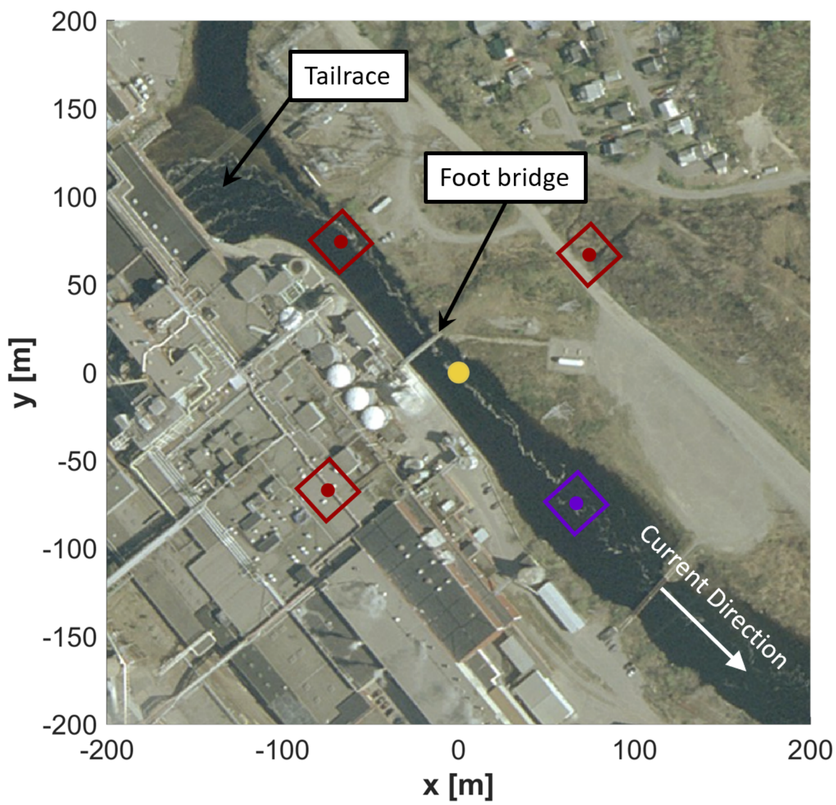

Figure 6: Millinocket, ME site. Location of Modular RivGen turbines indicated by yellow circle. Default IEC survey zones are denoted by the red squares and modified IEC survey zones by purple square.

We initially expected to only be able to survey the downstream zone because of concerns about overhead clearance around the Modular RivGen turbines (i.e., DAISYs would need to be deployed downstream of the turbine). However, in practice, there was sufficient overhead clearance and we were able to survey both upstream and downstream zones by releasing DAISYs near the hydropower tailrace. The port and starboard zones were be surveyed because of the stream width (the zones would overlap and fall within the turbine's acoustic near field which, as discussed in Section 7.1.1.3, is not representative of received levels at greater range).

While IEC 62600-40 calls for the deployment vessel to move to a standoff distance of 100 m, the time required to do this would significantly compromise survey logistics. Specifically, moving 100 m downstream of the furthest downstream DAISY after all DAISYs have been deployed would likely result in the lead DAISY clearing the survey zones before the deployment vessel powered down. As a result, the vessel powered down immediately following DAISY deployment and drifted as quietly as possible.

6.1.4 Igiugig, AK

The Kvichak River, in Igiugig, is located in southwestern AK, connecting Lake Iliamna to Bristol Bay. The deployment site is located just downstream of Lake Iliamna's outlet. At the deployment site (Figure 7), the river has steady currents of ~2 m/s and variable cross-channel depth (~5 m thalweg).

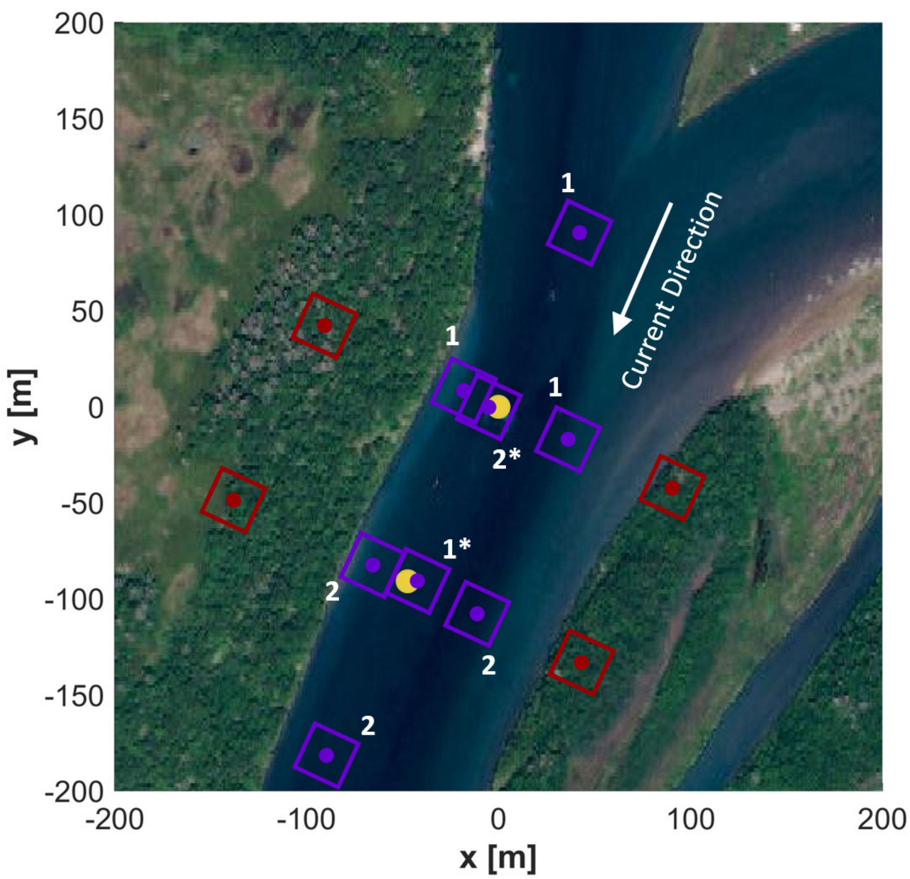

Figure 7: Igiugig, AK site. Location of RivGen turbines indicated by yellow circles. Default IEC survey zones are denoted by the red squares and modified IEC survey zones by purple squares. Numbers denote the turbine associated with the zone. Zones marked with an asterisk are only evaluated when the other turbine is braked.

DAISYs were deployed upstream of the turbines, allowed to drift through the site, and then recovered in the low velocity region near the next downstream river braid. Following deployment, the vessel moved swiftly towards one edge of the river before shutting down to increase separation distances between the DAISYs and vessel. Because of the channel width and water depth, the port and starboard zones were shifted towards the turbines. Because the turbine separation distance (91 m) is similar to the IEC zone separation (100 m), the downstream and upstream zones for turbines 1 and 2, respectively, are nearly coincident with the other turbine. However, because only one turbine was operating in a power generating state, the zonal overlap was immaterial.

Traffic from other fishing and recreational vessels is common on the Kvichak River near Igiugig. When present, this traffic elevates the ambient noise floor and can mask radiated noise from the turbine. In 2014, we found that vessel traffic declined during the afternoon, but in 2024, we were able to effectively survey mid-morning.

6.2 Test Matrix and Schedule

6.2.1 Millinocket, ME

The surveys conducted each day are summarized in **Error! Reference source not found.**. The original survey matrix with additional detail is included in the Appendix, as is a list of all tracks containing usable information. Over the three days, we collected nearly 100 DAISY tracks with 79 deployments from a small boat and 20 deployments on tethers from the upstream footbridge. While communication issues with the geared turbine controller presented some challenges during the second day, we were able to complete all primary objectives on the third day.

Table 4: DAISY deployment summary for Millinocket, ME

Survey Day	Planned	Actual
Day 1	Obtain preliminary information about differences in radiated noise at full power and freewheel conditions, as well as ambient noise and transient events.	Direct drive turbine could not be operated due to insufficient flow rates (hydropower dam maintenance and lateral shear). Objectives met for geared turbine.
Day 2	Collect distributed spatial information at multiple power states with both turbines operating.	Communication issues with geared turbine resulted in abnormal operating state. These tracks were not usable. Data collected for direct drive turbine with geared turbine braked.
Day 3	Collected distributed spatial information at multiple power states with only one turbine operating.	Collected distributed spatial information with individual turbines operating and both turbines operating.

6.2.2 Igiugig, AK

The surveys conducted each day are summarized in Table 5. The original survey matrix with additional details is included in the Appendix, as is a list of all tracks containing usable information. The pre-deployment initial survey plan assumed that two RivGen turbines would be generating power, but during the survey only one turbine was operational. The other turbine could be either braked or in a freewheel state. Over the five days of operation, over 200 DAISY tracks were collected during more than 50 deployment and recovery cycles.

Table 5: DAISY deployment summary for Igiugig, AK

Survey Day	Planned	Actual
Day 1	Obtain preliminary information about differences in radiated noise at each power state, transients associated with shutdown and restart, and spatial extent of noise from freewheel condition. Deploy three DAISYs.	Measurements of radiated noise at each power state (25% state not realized), transients associated with shutdown and restart, and freewheel comparison for both turbines. Only able to deploy two DAISYs due to hardware accidentally left in Seattle.
Day 2	Collect distributed spatial information at maximum power operating state and with both turbines braked to characterize the Kvichak River soundscape	Collected distributed spatial information with turbine at maximum power and variable operating states (2 DAISYs)
Day 3	Attempt localization with 5 DAISYs deployed from two vessels Characterize freewheel conditions	Collected distributed spatial information with turbine at variable operating states and both turbines braked (5 DAISYs) Characterized freewheel conditions (3 DAISYs)
Day 4	Outcomes guided by surveys on prior days	Collected distributed spatial information with turbine at maximum power, variable operating states and both turbines braked (5 DAISYs)
Day 5	No surveys planned	Collected distributed spatial information with turbine at maximum power (3 DAISYs)

6.3 Safety

UW personnel who worked aboard the small boats received a full safety briefing on emergency vessel procedures (e.g., shore safety, person overboard, fire, medical emergency). While aboard, all personnel wore wear personal floatation devices (PFDs). UW personnel who operated small boats during both surveys received hands-on training from a UW vessel captain.

The primary personnel risk during shallow DAISY deployment and recovery was falling overboard due to loss of balance. This risk was mitigated by:

(1) Vessel choice: low freeboard reduced the need to lean over the side to deploy or recover DAISYs; high maneuverability facilitates recovery;

(2) Shallow DAISY design: large "grab rings" and handles facilitated deployment and recovery of the surface expression using boat hook or by hand; lack of tether allowed DAISYs to be rapidly deployed and recovered without entanglement risk.

During operations, including operations aboard a vessel, any member of the team could call an "all stop" if they observed an imminent safety risk.

6.4 Contingency Plans

The major risks to project execution were equipment malfunction – either of the DAISYs or RivGen turbines. These were mitigated through redundancy.

To mitigate the risk of DAISY malfunction, all units went through a pre-deployment benchtop checkout at UW and underwent a field calibration prior to and proceeding each deployment. While five DAISYs were shipped to each site, survey objectives could be met with as few as three functional units.

Similarly, if one of the RivGen turbines was to be rendered inoperative during a survey, array noise could not be characterized, but individual turbine noise could be. Because the second RivGen turbine had not yet been deployed in Igiugig, AK, at the start of the project, there was a risk of schedule slip. While the UW team held two blocks of dates for the survey (one near the end of August and a second near the end of September 2023), it was ultimately necessary to delay the survey until June 2024 due to the number of activities required in advance of river ice up.

Finally, Igiugig is a remote site with limited capacity for equipment repair in the event of an accident. The team was prepared to operate self-sufficiently, the PI had prior experience working on site, and the entire team participated in the Millinocket survey to increase familiarity with these types of operations.

6.5 Data Management, Processing, and Analysis

6.5.1 Data Management

Raw data is stored on each instrument, copied to portable hard drives for transport, and backed up on a redundant Network Attached Storage (NAS) system at UW. Raw data files are processed in MATLAB (Section 6.5.2) and saved in MATLAB binary format (.mat). The data structure is documented in a "readme" file included with the MHK-DR upload.

ORPC provided the UW team with time series of electrical power output and rotation rate for each turbine for the testing periods, as well as current speed measured by the acoustic Doppler current profiler (ADCP) deployed at each site. These metadata streams were merged with acoustic data on the basis of their time stamps. As discussed in Section 7, DAISY and ORPC clocks were synchronized to within 1 s in Millinocket, but ORPC clock drift needed to be corrected for in Igiugig due to intermittent time-server synchronization for the ORPC data acquisition system.

MHK-DR data uploads, which may be restricted for up to 5 years, are summarized in Table 6. Data may be released earlier with commercially sensitive parameters (turbine power output and rotation rate) averaged or otherwise filtered.

Table 6: MHK DR data uploads

Data Product	Content
Merged acoustic data for each drift (1 file per drift, .mat format) associated with surveys in Millinocket, AK and Igiugig, AK	Pressure spectral density time series Time synchronized metadata: • Location • Speed and direction over ground • Hydrophone depth • DAISY motion • Wind speed and direction • Air temperature and pressure • Electrical power output and rotation rate for Turbine 1 and Turbine 2 • Current speed measured by the ADCP Hardware configuration

6.5.2 Data Processing

Acoustic data are processed according to IEC 62600-40. The voltage produced by the hydrophone is converted to a voltage spectral density [dB re 1 V^2/Hz] using a Discrete Fourier Transform with 1-second windows and 50% overlap. Frequency-dependent receive voltage sensitivity are applied to convert this to pressure spectral density [dB re 1μPa^2/Hz] over a frequency range of 0.001 – 200 kHz. To reduce file size, the 1 Hz spectral density are averaged across millidecade bands (Martin et al., 2021) for frequencies greater than 434 Hz (the point at which millidecade frequency bands are > 1 Hz). This results in a mild loss of fidelity at higher frequencies but reduces file sizes by an order of magnitude. Uncertainty in acoustic spectra associated with temporal variability are quantified by the interquartile range as a function of frequency.

Co-temporal data from other sensors (e.g., pressure) are embedded with the acoustic data, providing georeferenced location and environmental covariates (e.g., wind speed, DAISY speed over ground). Raw data QA involves:

1. A review of metadata time series to identify metadata sensor malfunctions or hydrophone impairment (e.g., irregular depth, significant tilt angle);
2. A review of the bivariate pressure spectral density (i.e., probability of a given spectral density as a function of frequency) to identify changes in the instrument noise floor and variations in pressure spectral density within a single drift; and
3. Review of each drift using acoustic playback synchronized with a spectrogram (pressure spectral density as a function of time) to identify masking ambient noise (anthropogenic or natural) and DAISY self-noise. The review tool allows periods with high levels of ambient noise to be flagged and excluded from further analysis.

6.5.3 Data Analysis

Data are analyzed according to the IEC survey methodology, localization of discrete events, evaluation of spatial patterns in turbine noise.

6.5.3.1 Turbine Sound Extent

The most fundamental question this project addressed is the extent to which the radiated noise from the turbines, or an individual turbine, is distinct from ambient noise. This was evaluated statistically through the IEC methodology, but, because the survey zones are located relatively far from the turbine, this comparison could not identify the entire extent of turbine sound and, further, the IEC methodology assumes that the turbine is the dominant sound source between the low-frequency limit given by water depth and the high-frequency limit (default to 100 kHz). Three approaches were employed to evaluate the extent of turbine sound with additional fidelity: shutdown during drifts, comparisons between operating states in a zone closer to the turbine than the IEC zones, and spatial comparison between operating states. First, when the turbine is shut down during a drift with a DAISY is at close range (i.e., within 10 m of the turbine centroid), differences between ambient and operating conditions are particularly apparent because the ambient soundscape is roughly stationary to either side of the shutdown event. Second, zones closer to the turbines increase the signal-to-noise ratio and can allow for straightforward identification of frequencies containing turbine noise based on differences between median pressure spectral densities during operating conditions. However, if a zone is set too close to the turbine, differences in transmission loss within the zone, compounded by GPS uncertainty, can be misleading. Third, if a sufficient number of drifts are conducted at different operating states, a spatial comparison between operating and ambient conditions can be made at relatively high resolution can provide additional insight into the spatial extent of turbine sound in various frequency ranges.

6.5.3.2 IEC Zone Evaluation

Valid data points were binned by survey zone and co-temporal turbine power state (averaged over the time spent in the survey zone). A Mann-Whitney U-test (Tougaard 2015) was used to assess the statistical independence of the median spectral density for each zone-power level combination, relative to the 0% power state. Statistical significance was assessed at the 0.1% significance level. Because of the differences in radiated noise between the turbines in Millinocket and only a single power generating turbine in Igiugig, data are presented for individual turbines in operation with the other braked.

6.5.3.3 Localization

The goal of localization is to estimate the origin of a signal to aid in source attribution by comparing the estimated origin to the known location of the turbines. Localization requires knowledge of the location of each receiver in an array, as well as the ability to temporally resolve signals of interest. Localization is performed using a time-difference-of-arrival (TDOA) technique on signals of interest identified in manual review. Using the locations of the receivers, the differences in the arrival time of the signal can be used to estimate the source location.

The first step is to identify the arrival time and frequency ranges corresponding to signals of interest in each of the co-temporal DAISY tracks. For each event, we detrended the hydrophone voltage and applied a bandpass filter around the frequencies of interest. The voltage wave forms were then Hilbert-transformed to reduce the influence of local maxima prior to cross-correlation. The cross-correlation lag between a reference DAISY and other DAISYs is then the difference in the time of arrival. A window of 0.0375 s (roughly corresponding to 50 m separation between DAISYs) was used to search for events.

Once this information is available, there are two approaches to estimating source position. Fundamentally, the difference in the distances between the source and the i^{th} DAISY and the source and the j^{th} DAISY is give as

$$r_i - r_j = (t_i - t_j)c,$$

where *r* is the distance from the source to the subscripted DAISY, *t* is the reference time for the event, and *c* is the speed of sound in water. One approach is to solve a set of hyperbolic, algebraic equations (Wahlberg et al. 2001) which can provide an exact solution for sound source (three receivers) or over-determined solution (more than three receivers). A second approach is to perform a brute force search. This approach is not effective in bioacoustics with large search areas, but, in this case, given that the location of the turbines was known *a priori*, the search domain is relatively limited. Because of this, we could calculate the arrival time at each DAISY for a source located anywhere on a relatively fine grid (2 m resolution) and find the location that minimized the difference between the actual time of arrival differences and the guess for a given source position. This approach also allows uncertainty to be visualized using the contours of these distances. In practice, we employed both methods, but only accepted solutions as valid that were within 10 m of each other for both methods. This proved most effective when five receivers were used, as the three receiver solutions were sensitive to the time of arrival identified by cross-correlation.

6.5.3.4 Soundscape Variability

While surveys were of insufficient duration to capture significant temporal variability in ambient noise, it was possible to capture spatial variability. This was assessed through surveys with both turbines braked. This information contextualizes the radiated noise from the turbines relative to their deployment locations. One lesson learned is that the ambient soundscape could change if the river current changed. This was the case for the Millinocket survey, but this consideration was not obvious until data were post-processed. As such, the comparisons between operating and ambient conditions in Millinocket have greater uncertainty than for Igiugig, where the current speeds were relatively consistent and ambient surveys were conducted across multiple days.

6.5.3.5 Inter-turbine and Inter-site Comparisons

Of particular interest for these surveys is the comparison between the turbines at each site and between sites. As previously discussed (Section 5), the two Modular RivGen turbines (Millinocket, ME) employ different electrical generators, which may lead to differences in radiated noise, while the two RivGen turbines (Igiugig, AK) were functionally identical and expected to have similar radiated noise. This was evaluated by a comparison of sound pressure levels at equivalent power state and range for all turbines.

7 Project Outcomes

7.1 Results

7.1.1 Millinocket, ME (Modular RivGen Turbines)

7.1.1.1 Overview

The survey was conducted from August 22-24, 2023 with a day for mobilization and demobilization on either side. Operations were conducted by a small boat deploying DAISYs upstream of the turbines near the exclusion floats for the hydropower plant outlet, with supplemental tethered deployments from an upstream footbridge (Figure 8). While we were initially concerned that there would be insufficient clearance for DAISYs to pass over the turbines, this was possible, which substantially simplified operations. Acoustic data were reviewed for general consistency and the portion of tracks falling within the IEC and closer range survey zones reviewed in more detail to exclude acoustic sequences contaminated by self-noise (e.g., bottom contact). Tracks were grouped into the categories described in Table 7 and shown visually in Figure 6. Turbine location was determined by georeferencing the time of overflight observed by GoPro cameras on the base of the DAISYs.

Five issues of operational significance were encountered in collecting data:

1. Water velocity varied substantially over the course of the survey due to the operation of the hydropower plant and a survey was not conducted with only the direct drive turbine operating at maximum power.
2. During the survey, ORPC experienced some issues configuring the geared turbine's variable-frequency drive (VFD), which reduced the number of drifts that could be conducted with the geared turbine in a power generating state.
3. Radio-frequency interference between GPS antennas and the footbridge are apparent in some tracks, such as Case 5 where the DAISYs deployed from the footbridge appear to be traveling upstream. The footbridge also resulted in electromagnetic noise from the tracking collars that intermittently appeared in acoustic data. Because of this, tracking collars were removed on the third day of the survey.
4. Because of this, on the third day of operation the primary GPS failure on one DAISY rendered all data unusable (i.e., acoustic data could not be geo-referenced).
5. On the third day, the hydrophone recording package on the DAISY deployed on a tether from the bridge stopped recording halfway through the survey, further reducing data intensity for that day.

Table 7: Summary of surveys in Millinocket, ME

Category	Geared Turbine	Direct-drive Turbine	Description	# Tracks
1	Braked	Braked	Ambient noise	2
2	Max	Braked	Geared at > 90% max power	4
3	Variable	Braked	Geared at various operating states	13
4	Freewheel	Braked	Geared in freewheel	8
5	Freewheel + VFD	Braked	Geared in freewheel with VFD engaged	6
6	Transient	Braked	Geared shutdown during track	9
7	Control error	Various	Geared VFD control error / direct drive at various operating states	14
8	Braked	Max	Direct drive at > 90% max power	-
9	Braked	Variable	Direct drive at various operating states	18
10	Braked	Freewheel	Direct drive in freewheel	3
11	Braked	Freewheel + VFD	Direct drive in freewheel with VFD engaged	5
12	Braked	Transient	Direct drive shutdown during track	4
13	Operating	Operating	Both turbines operating at various states, including shutdowns	10
14	Freewheel	Freewheel	Both turbines in freewheel	3

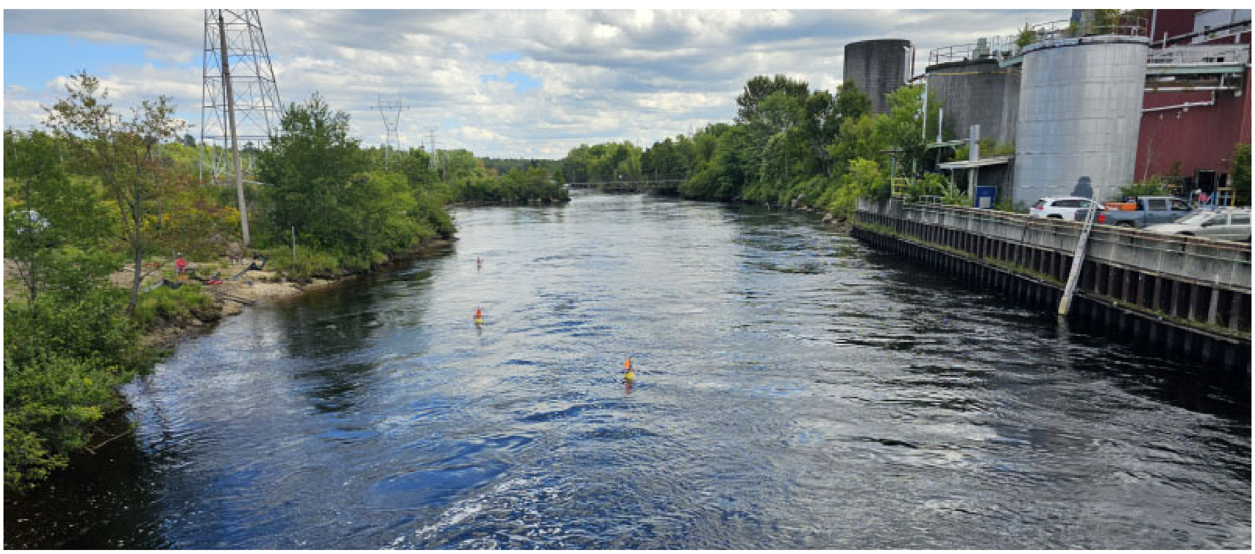

Figure 8: DAISYs drifting over Modular RivGen turbines in Millinocket, ME.

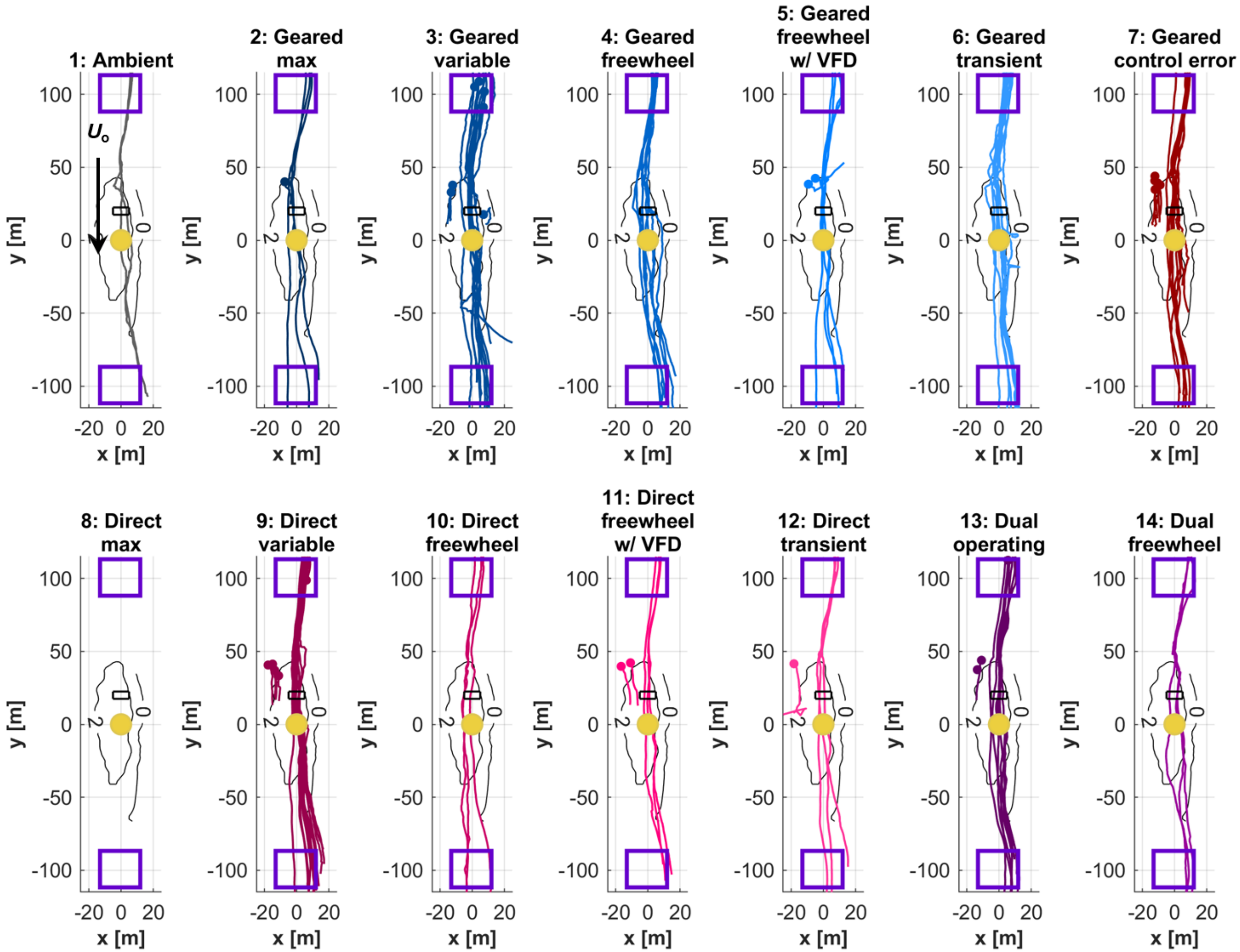

Figure 9: Summary of drift tracks by operating states around Modular RivGen turbines (yellow marker) in Millinocket, ME. Circles denote start of drifts. Purple boxes denote IEC survey zones and the black box denotes a close-range survey zone. Tracks have been rotated and referenced to turbine.

To verify alignment between ORPC operational data and acoustic data, we evaluated the correlation between power, rotation rate, and radiated noise for cases when one or both turbines were shut down during a drift. As shown in Figure 10 for a representative shutdown event for the geared turbine, there is an obvious change in the soundscape during the shutdown event (~128 s from the start of the track). At approximately the same time, the reported rotation rate begins to rapidly decrease. Given the distinctive tonal structure that is proportional to rotation rate (Figure 10b, magenta line), this does not indicate that the turbine takes two seconds to come to a stop. Rather, this is likely an artifact of the way rotation rate is inferred from the voltage wave form. Based on this, we believe that the turbine SCADA and DAISY clocks were synchronized to at least 1 s accuracy. However, in comparing the same shutdown event across multiple DAISYs, we discovered that several of the DAISY clocks likely lagged by exactly 1 s due to a file time stamp issue and corrected this in post-processing.

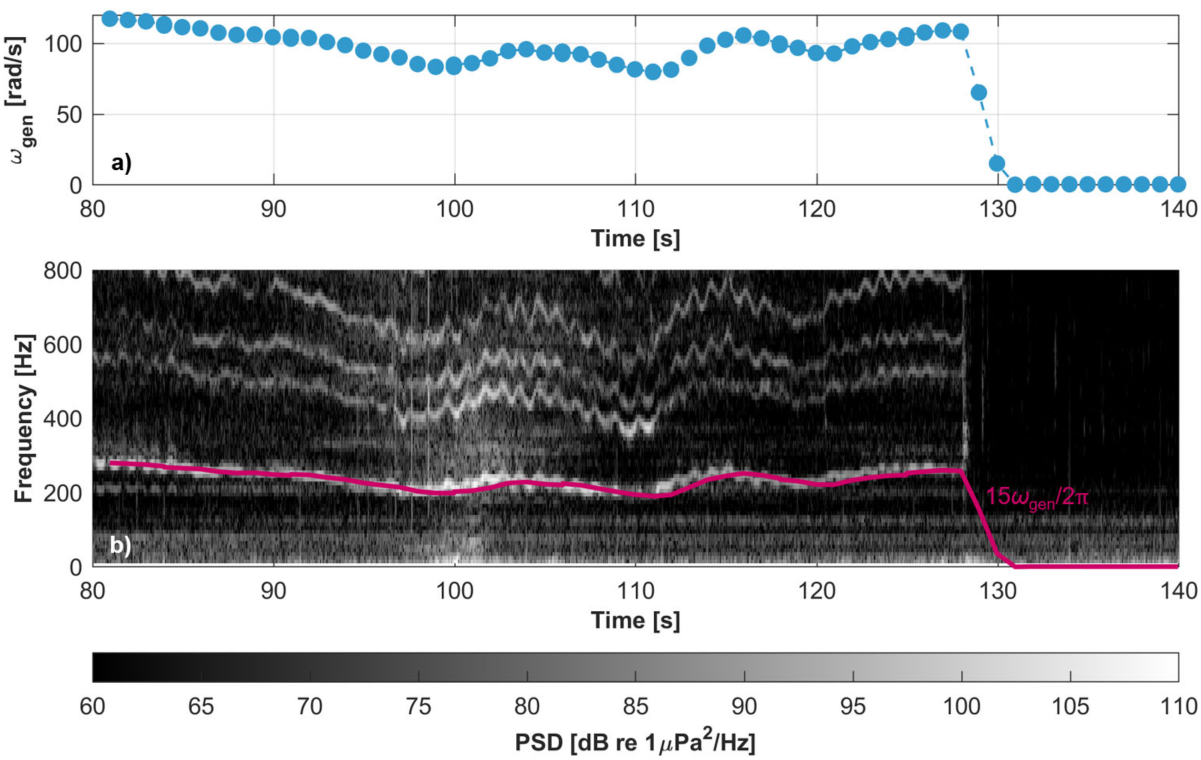

Figure 10: Comparison between radiated noise and rotation rate during a geared turbine shutdown: (a) generator rotation rate and (b) radiated noise superimposed with empirical function describing primary generator tone as a function of generator rotation rate.

For both turbines, we defined the 100% power state as the maximum time-average power within a drift track. For the geared turbine, this occurred during a drift during which only it was operating. However, maximum power for the direct drive turbine occurred during a drift when both turbines operating, such that there were no tracks containing acoustic measurements with only that turbine at the 100% power state. In addition, due to lateral shear in the river, power output and rotor rotation rates were substantially lower for the direct drive turbine than the geared turbine.

7.1.1.2 IEC Survey Results

In Millinocket, CTD casts indicated a sound speed of approximately 1490 m/s and the maximum water depth was approximately 4 m. The bottom composition was unknown but appeared to be solid rock along portions of the river bank, so we assumed a sound speed of 4000 m/s. This suggests a low-frequency limit of approximately 100 Hz (Section 7.1.2.2). As discussed in Section 7.1.1.3, the observed high-frequency limit for turbine sound was approximately 10.5 kHz. As such, the IEC band was defined as 0.1 – 10.5 kHz. As discussed in subsequent sections, the true low-frequency limit was likely higher, particularly for the direct drive turbine.

<u>Geared Turbine</u>

Table 13 lists the number of valid samples from each IEC zone as a function of power state. Recalling that the IEC requirement is a minimum of 10 valid samples per zone-power state combination, we obtained roughly an order of magnitude more samples than required for zones that were surveyed, but, in the downstream zone, did not obtain any valid samples for the 50% power state and an insufficient number of samples at 100% power state.

Table 8: Number of valid samples for each IEC zone as a function of power state (±10 %) for the geared turbine

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	68	-	158	-
25 %	323	-	219	-
50 %	58	-	-	-
75 %	93	-	56	-
100 %	24	-	1	-

Table 14 presents median turbine-band levels for each IEC zone. For the upstream and downstream zones, turbine-band levels are slightly elevated relative to ambient conditions with no clear relation to power state. The difference between the upstream and downstream zones suggests a substantial variation in sound propagation or source directionality.

Table 9: Median turbine-band level [dB] (0.2 – 10.5 kHz) for each IEC zone as a function of power state (±10 %) for the geared turbine. '-' denotes combinations of zone and power state with insufficient valid samples to satisfy IEC 62600-40.

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	96	-	92	-
25 %	97	-	104	-
50 %	99	-	-	-
75 %	99	-	105	-
100 %	99	-	-	-

Figure 11 considers the frequency variations with power state within each zone, considering a slightly wider range of frequencies (10 Hz - 10 kHz) than the IEC band. Here, we see that, while upstream and downstream IEC band levels are relatively invariant with power state, there are frequency characteristics of the operating states are unique to each zone. We can assess these differences more rigorously through a Mann-Whitney statistical analysis for each combination of power state and zone relative to ambient conditions (Figure 12). Expanding to the full set of frequencies available (1 Hz – 200 kHz), this analysis indicates that geared turbine sound is unlikely drawn from the same population as ambient noise above a few hundred Hz and that the high-frequency limit is consistently around 10 kHz. As subsequently discussed, this is roughly consistent with observations at closer range.

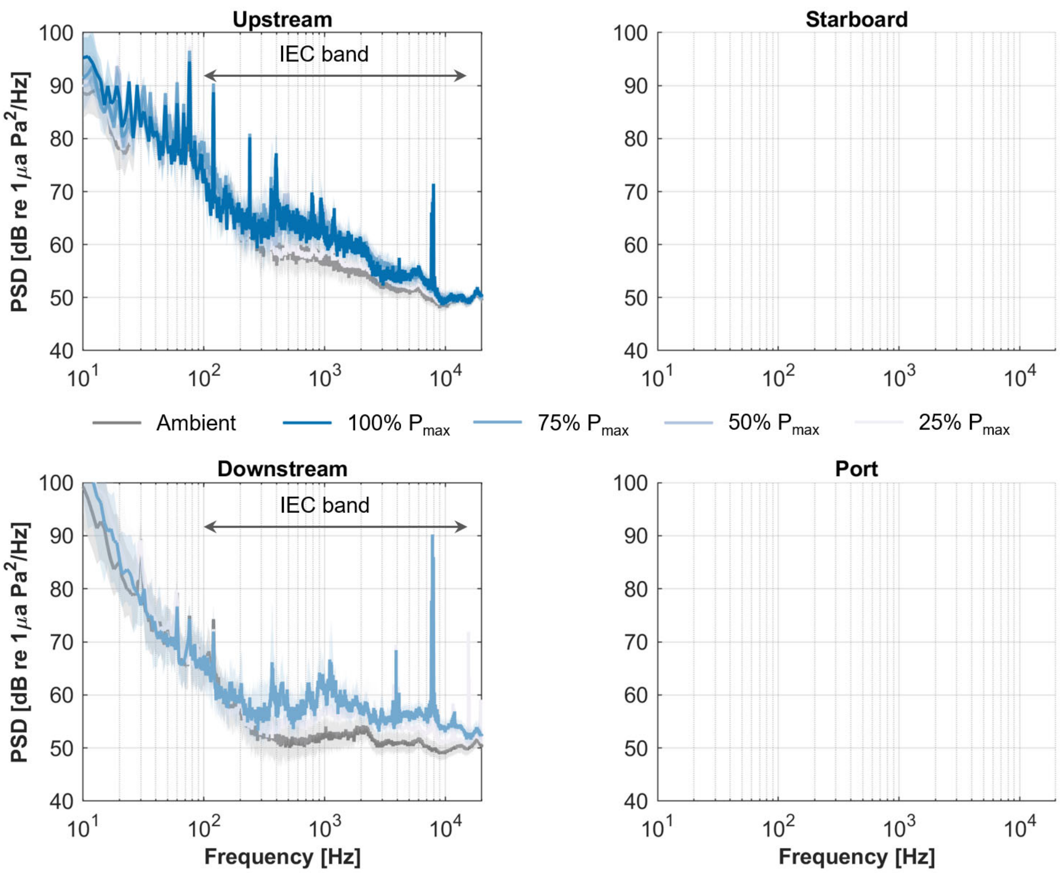

Figure 11: Pressure spectral density as a function of survey zone and power state for the geared turbine. Solid lines denote median values and shaded regions denote interquartile ranges.

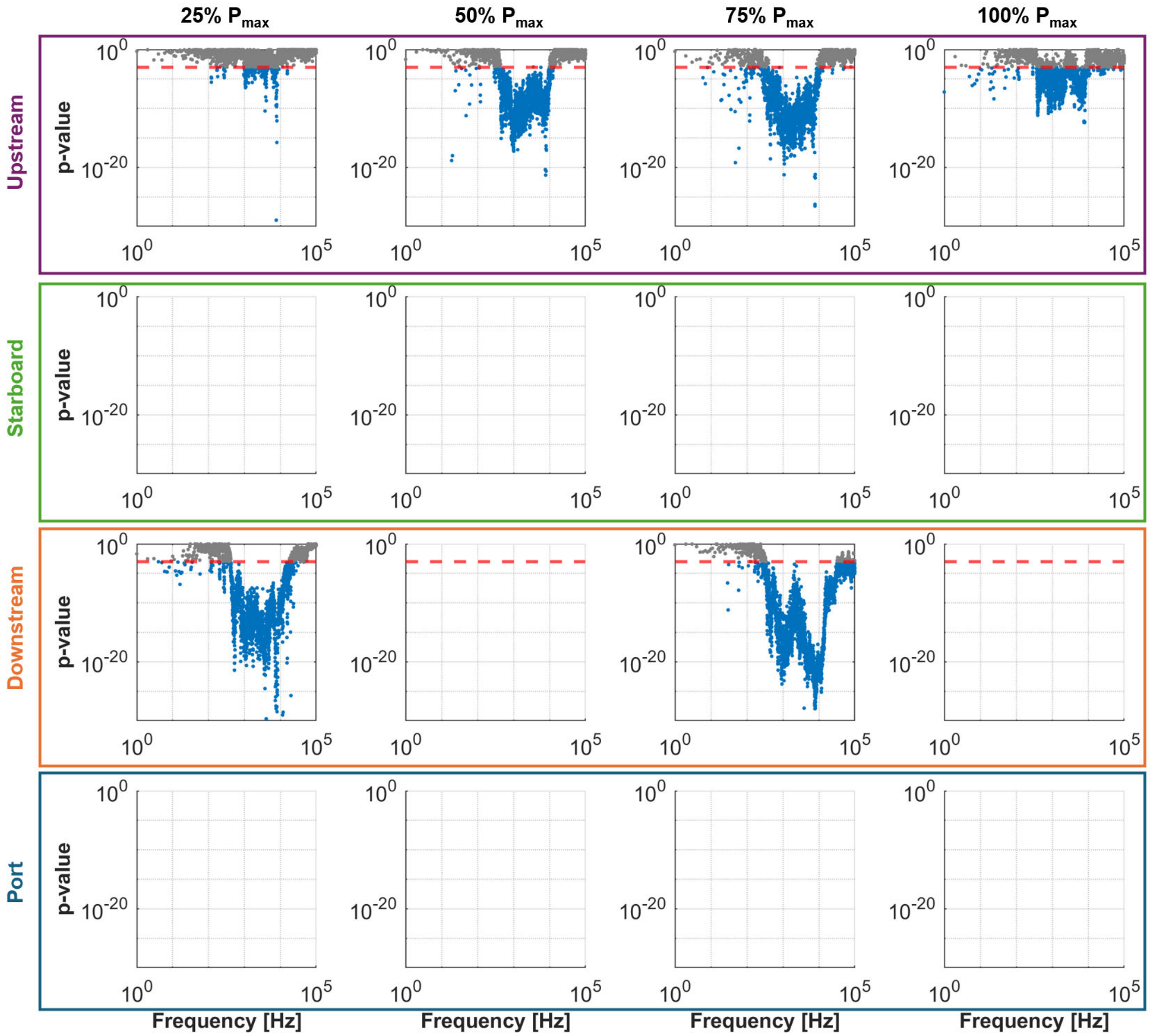

Figure 12: Mann-Whitney statistical analysis for combinations of IEC survey zones and power states for the geared turbine. The dashed red line denotes the threshold for statistical significance. Grey dots denote frequencies for which there is no statistical significance between ambient and operating conditions. Blue dots denote frequencies where ambient and operating acoustic pressure are unlikely to be drawn from the same populations.

Direct Drive Turbine

As shown in Table 8, we were successful in collecting a sufficient number of samples in the upstream and downstream zones for all power states. When the turbine was operating, turbine-band levels were slightly elevated in the upstream zone and unexpectedly reduced in the downstream zone. This reduction occurs at frequencies on the order of a few kHz (Figure 13), but these differences are only marginally significant (Figure 14). Similarly, as discussed in Section 7.1.1.3, the radiated noise from the direct drive turbine was quite limited and the differences between ambient and operating conditions in the upstream zone and are likely caused by unquantified differences in ambient noise over the course of the survey.

Table 10: Number of valid samples for each IEC zone as a function of power state (±10 %) for the direct drive turbine

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	68	-	89	-
25 %	66	-	66	-
50 %	163	-	44	-
75 %	131	-	37	-
100 %	53	-	35	-

Table 11: Median turbine-band level [dB] (2 – 10.5 kHz) for each IEC zone as a function of power state (±10 %) for the direct drive turbine. '-' denotes combinations of zone and power state with insufficient valid samples to satisfy IEC 62600-40.

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	96	-	97	-
25 %	100	-	95	-
50 %	100	-	95	-
75 %	99	-	96	-
100 %	100	-	95	-

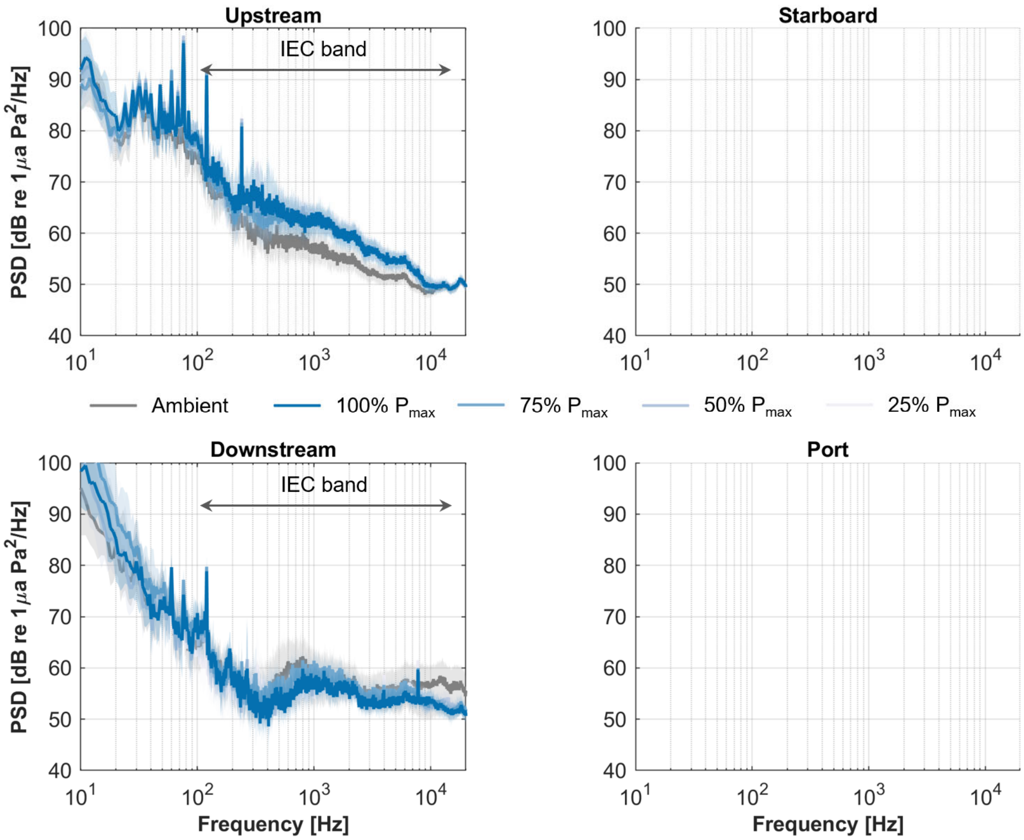

Figure 13: Pressure spectral density as a function of survey zone and power state for the direct drive turbine. Solid lines denote median values and shaded regions denote interquartile ranges.

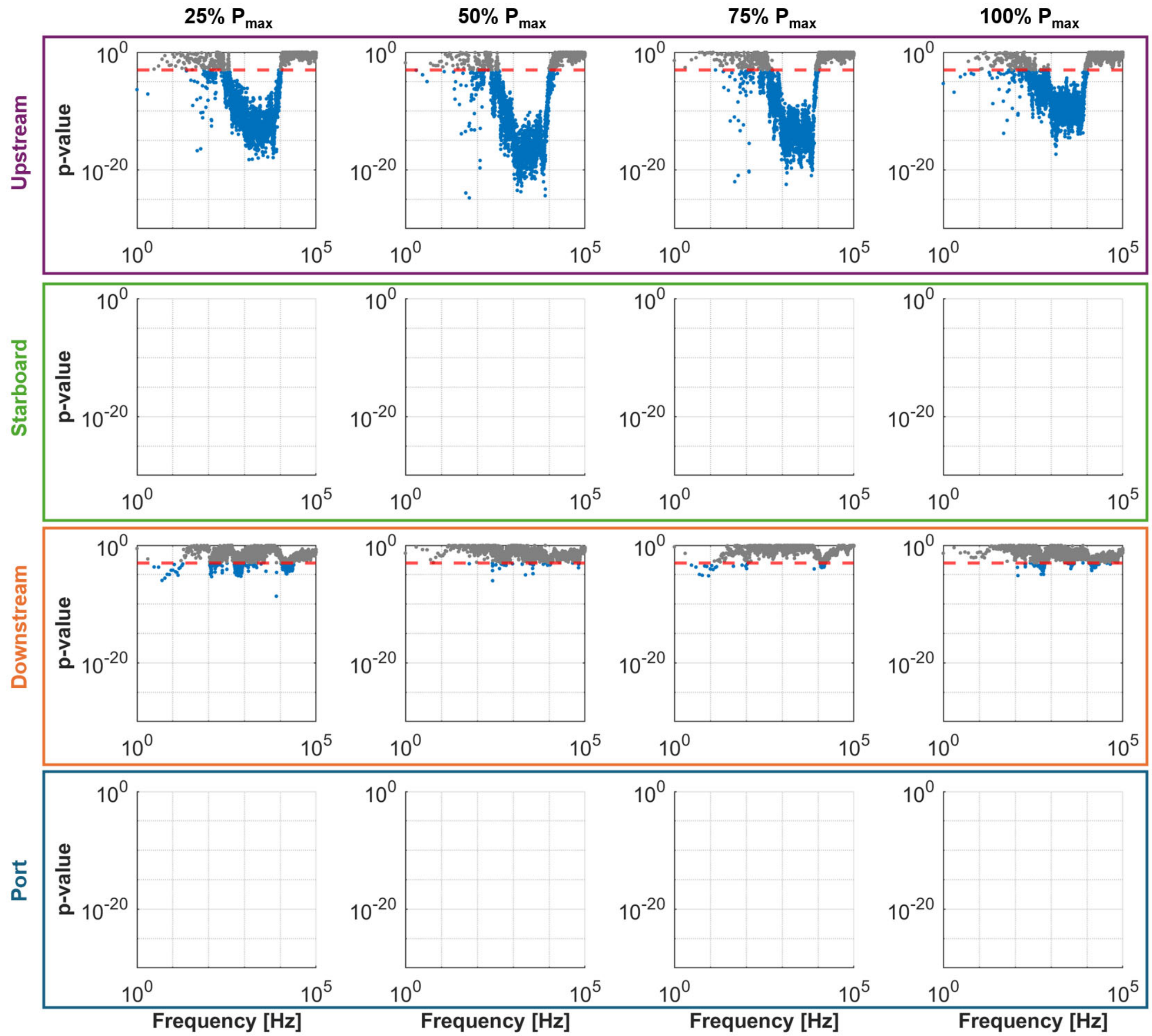

Figure 14: Mann-Whitney statistical analysis for combinations of IEC survey zones and power states for the geared turbine. The dashed red line denotes the threshold for statistical significance. Grey dots denote frequencies for which there is no statistical significance between ambient and operating conditions. Blue dots denote frequencies where ambient and operating acoustic pressure are unlikely to be drawn from the same populations.

7.1.1.3 Turbine Sound Characteristics

Geared Turbine

Figure 15 shows information about a direct pass over the geared turbine with the direct drive turbine braked. Periodograms are presented for a zone directly over the turbine (10 m in the across-channel direction and 5 m in the along-channel direction) and a similarly sized zone centered 20 m upstream of the turbines. The general structure of geared turbine sound consists of a series of oscillating tones below 6 kHz and a more intense tone centered around 8 kHz with higher harmonics. At the closest point of approach, there are higher frequencies (> 20 kHz) that are not observed further from the rotor. These appear near the closest point of approach for only some cases and have no obvious correlation with power state or rotation rate (not shown), suggesting a local source sensitive to the specific path taken by each DAISY near the turbine. Finally, the highest intensity radiated noise occurs slightly (1-2 m) downstream of the turbine position identified through camera footage review. This suggests GPS accuracy is likely on the order of a few meters, consistent with manufacturer specifications.

Overall, this suggests a lower limit to the standoff distance from the turbine for meaningful acoustic evaluation. As range to the turbine decreases, we avoid mode stripping and other bathymetric effects, but if too close, measurements can be inside the acoustic nearfield and transmission loss can vary appreciably within a survey zone large enough to collect a reasonable number of samples.

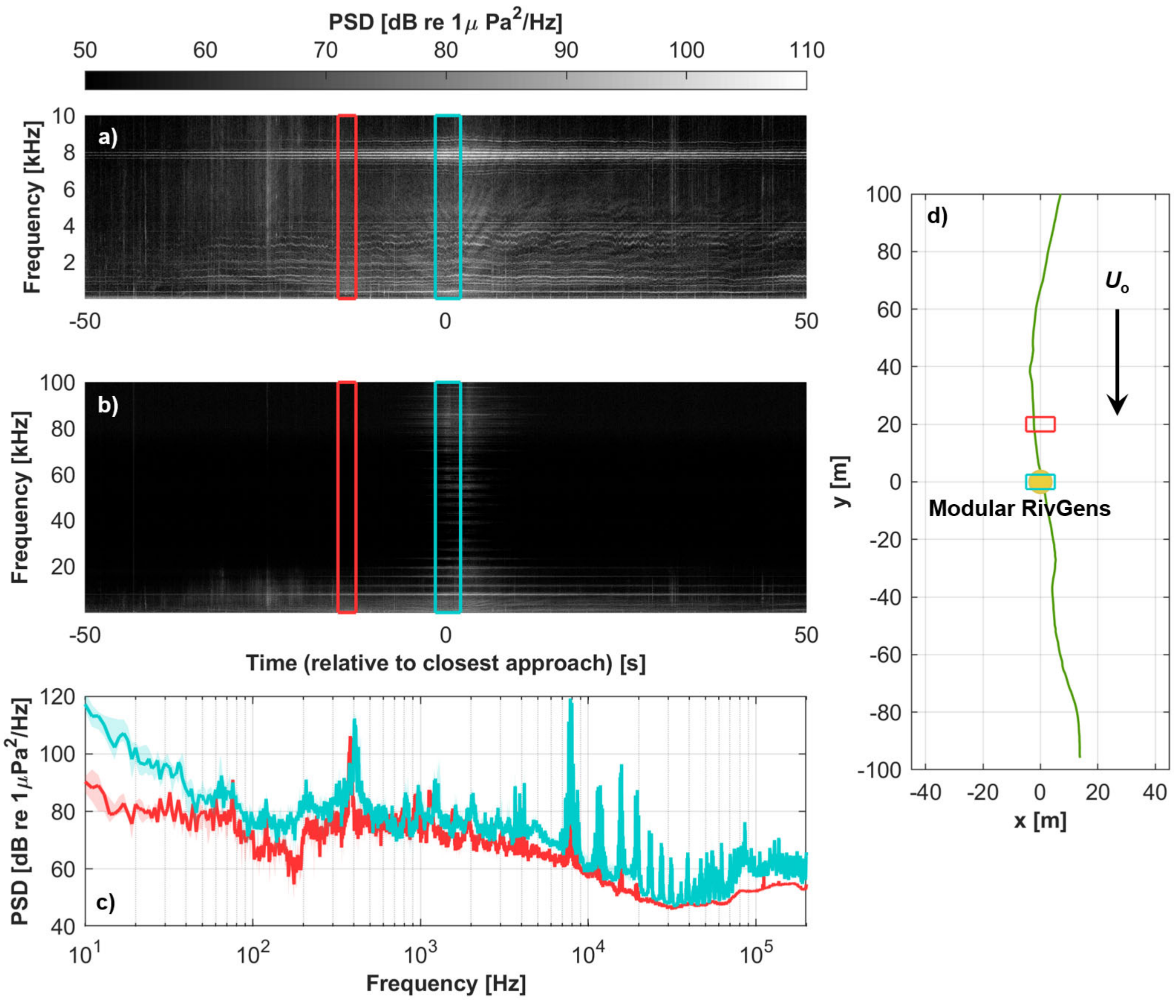

Figure 15: Direct pass in the vicinity of Modular RivGens with geared turbine operating at full power and direct drive turbine braked: spectrograms from a) 0-10 kHz and b) 0 – 100 kHz with comparison zones denoted by color, c) periodograms within the comparison zones with solid lines denoting median pressure spectral densities and shaded regions denoting the interquartile range, and d) track trajectory and zone extent.

Since our primary interest is in sound measurable at reasonable distances from the turbines, further analysis focuses on the zone located 20 m upstream. As shown in Figure 16, geared turbine radiated noise is statistically different from ambient noise over a frequency range of 0.2 – 10.5 kHz (slightly narrower than the low-frequency limit specified by IEC 62600-40). The frequency constant depends somewhat on the rotation rate with a primary harmonic for the powertrain at a frequency given by

$$f_{\text{primary}} = \frac{15}{2\pi}\omega_{\text{gen}}$$

where ω_{gen} is the rotation rate of the generator, with higher harmonics at integer multiples. The empirical factor of 15 does not obviously correspond to available information about the generator or gearbox, which is incomplete, but is consistent across all rotation rates. A prominent tone associated with the variable frequency drive (VFD) is apparent at 8 kHz, along with its higher harmonics. Above 20 kHz, there is limited propagating sound from the turbine and received levels fall below the DAISY's high-frequency noise floor.

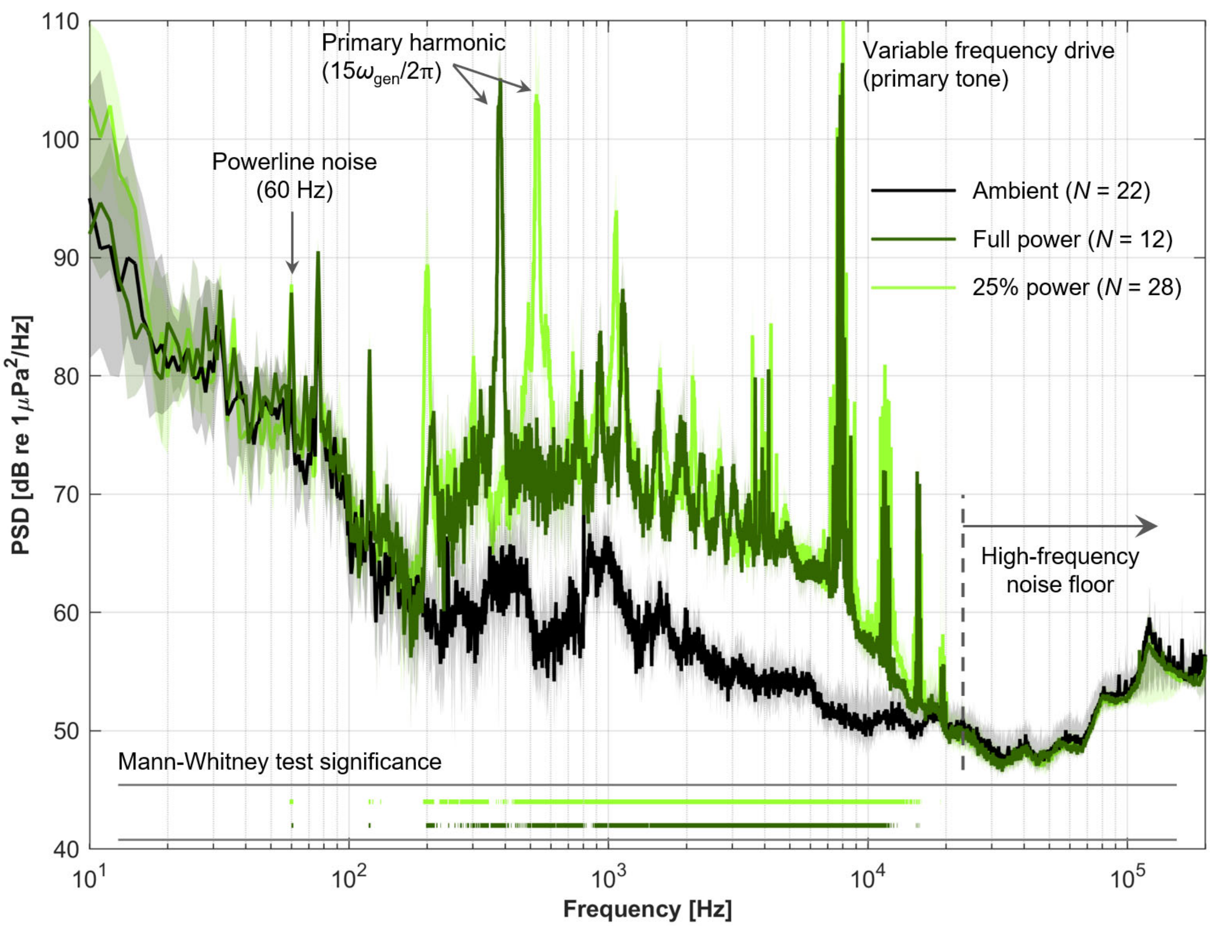

Figure 16: Comparison between ambient, full power, and 25% power operating conditions for the geared turbine in a survey zone 20 m upstream from Modular RivGens with specific frequency components annotated. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of 1×10^{-3} are indicated below the periodogram.

The prominent nature of the VFD tone is also apparent in freewheel when the VFD is engaged – despite the turbine generating little power (Figure 17). Interestingly, the VFD itself is located 100 m away on shore and does not directly produce sound. Rather, the primary tone at twice the switching frequency is produced by excitation of the generator that propagates into the water through the generator housing and turbine frame.

The two freewheel conditions are nearly identical before 7 kHz, with the primary deviation associated with the VFD tone and its harmonics. We note that there are statistically significant differences between the freewheel and ambient conditions at 60 Hz and 120 Hz (as for the power generating states previously considered), but these differences arise not from the turbine, but from the status of the switchgear for the nearby hydropower plant. Specifically, on the first day of survey activity when ambient noise was characterized by braking both turbines, the hydropower plant was in a near-idle state due to maintenance. On subsequent days, 60 Hz powerline noise is apparent in all acoustic data.

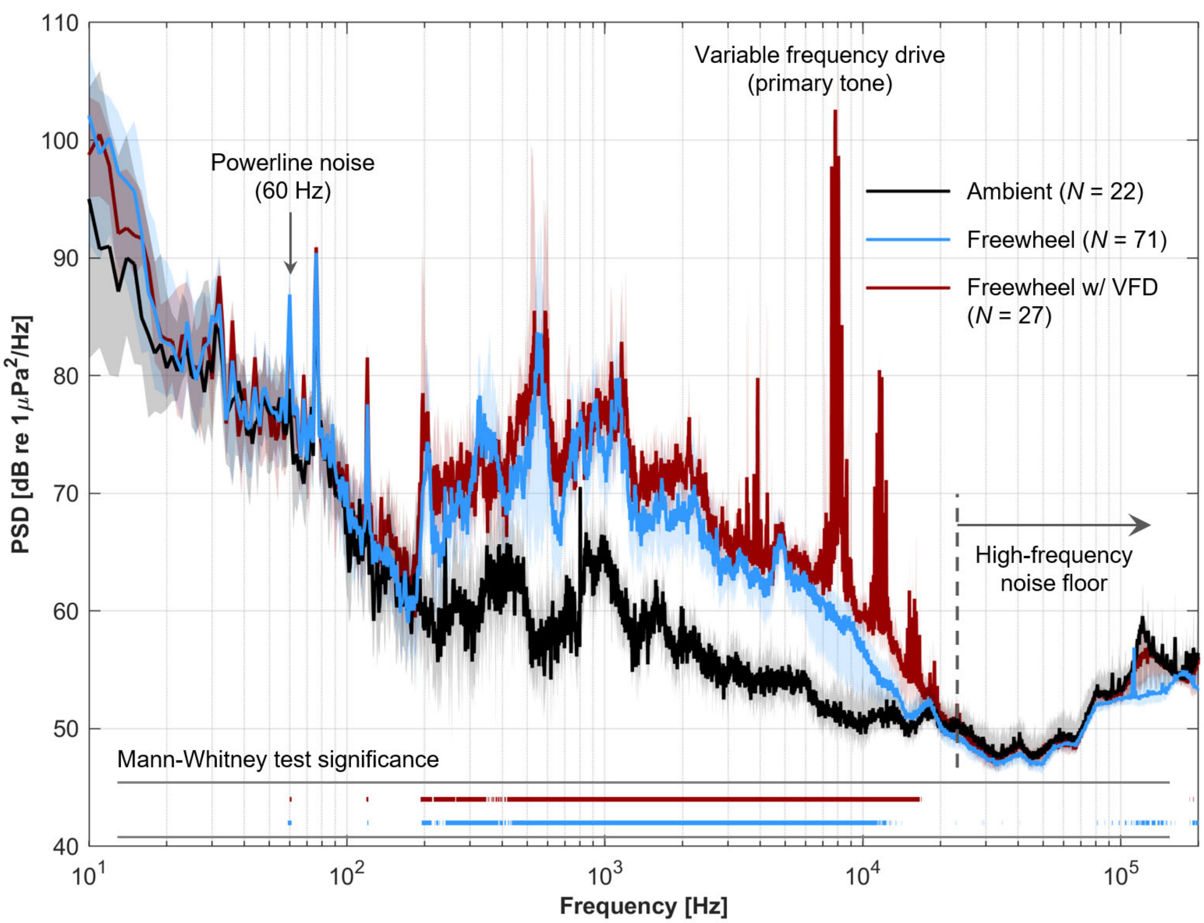

Figure 17: Comparison between ambient, freewheel, and freewheel with the VFD engaged for the geared turbine in a survey zone 20 m upstream from Modular RivGens with specific frequency components annotated. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram.

Figure 18 shows the relation between the turbine-band level (0.2 – 10.5 kHz) and rotation rate or power (normalized units), distinguishing between normal operating conditions, freewheel, and freewheel with the VFD energized. When the VFD is energized, whether in normal operations or freewheel, there is no apparent correlation between power output and the turbine-band level. When the turbine is in true freewheel or in a normal operating mode, there may be a weakly positive correlation between radiated noise and rotation rate. Overall, this suggests that, in normal operation, while the frequency characteristics of turbine noise vary with rotation rate, in an aggregate sense, the noise is consistent.

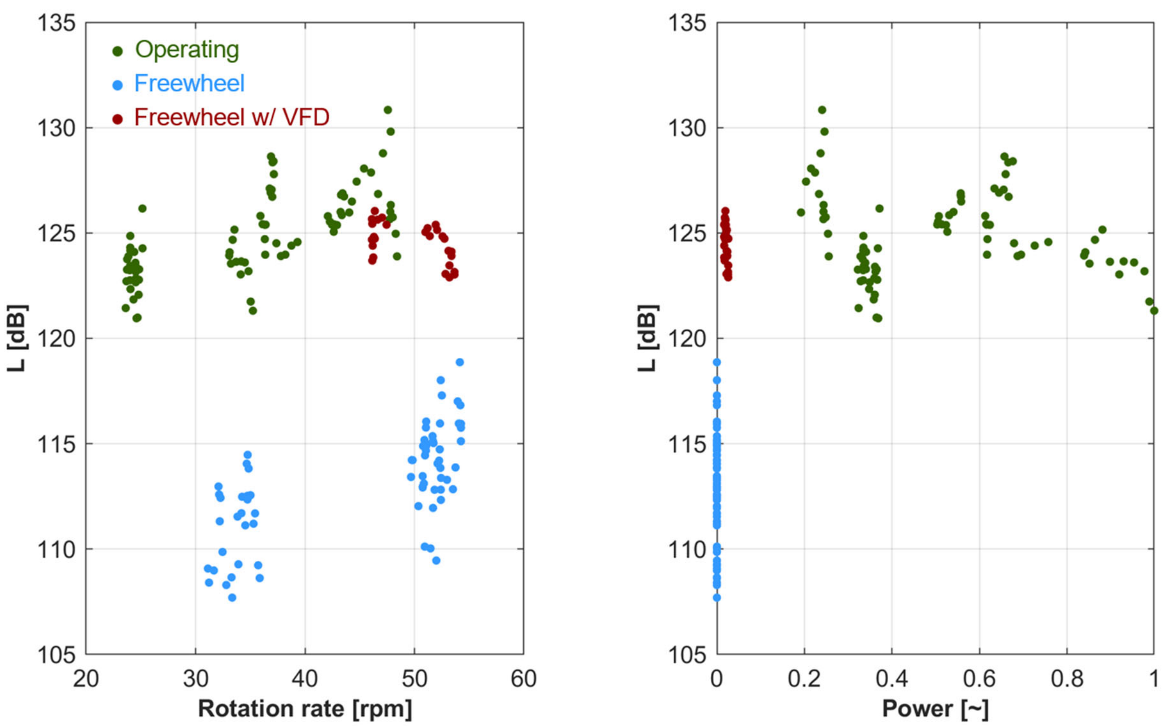

Figure 18: Relation between turbine-band level (0.2-10.5 kHz) and rotation rate (left) or power (right) for geared turbine in survey zone 20 m upstream of Modular RivGens. Blue dots denote instantaneous correlations between 1-s acoustic measurements and turbine operating state.

On the second day of the survey, ORPC encountered difficulties communicating with the VFD for the geared turbine. During this abnormal operating state, radiated noise from that turbine was substantially elevated. As shown in Figure 19, this operating state resulted in the turbine radiating considerably higher intensity noise from the rotating components of the power take-off (roughly matching the intensity of the primary tone from the variable frequency drive). While radiated noise was sufficiently loud that the turbine was audible to personnel on shore, Figure 19 also shows that the peak pressure spectral densities did not exceed those generated during normal operations. This points to the potential role of passive acoustics to detect abnormal operation. During this time, the direct drive turbine was also operating but, as discussed in the next section, its acoustic footprint was entirely masked by the geared turbine.

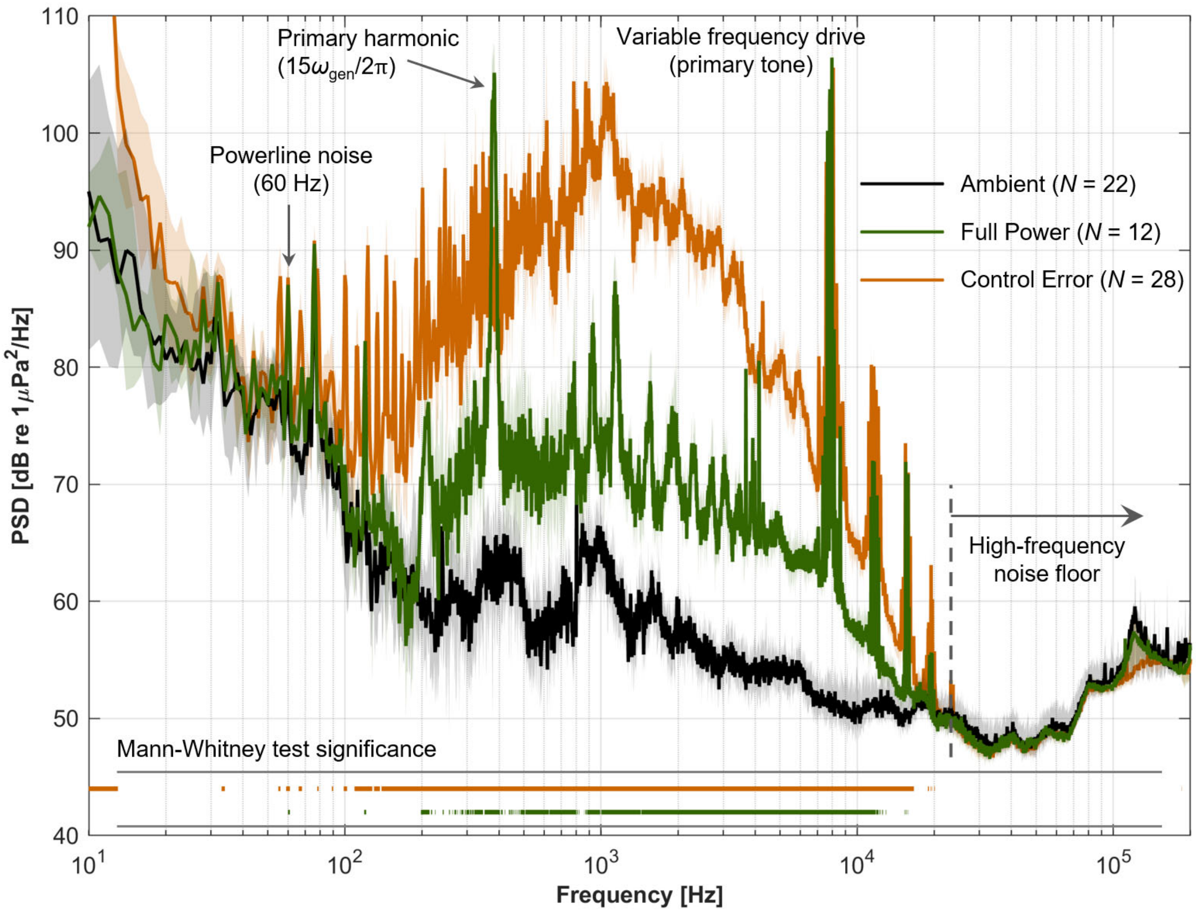

Figure 19: Comparison between ambient, full power, and abnormal operating state (50% power) for the geared turbine in a survey zone 20 m upstream from Modular RivGens with specific frequency components annotated. The direct drive turbine is also operating. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram.

To evaluate spatial variations in radiated noise, we considered acoustic measurements with the geared turbine operating at least at 90% of maximum power and the direct drive turbine braked. Measurements were pooled on a grid with 3 m resolution and median band levels (0.2 – 10.5 kHz) were calculated in pressure-squared space for grid elements containing at least 5 samples. A similar operation was performed for ambient noise measurements with both turbines braked. As shown in Figure 20, the acoustic footprint for the geared turbine extends to a range of approximately 100 m in the upstream direction and substantially more than 100 m in the downstream direction. This asymmetry could either be an indication of source directionality or differences in acoustic propagation along the river, though, as discussed in the next section, evidence suggests that this is a consequence of source directionality. Unfortunately, because of the limited number of tracks and the relatively consistent path taken by the DAISYs, we are only able to evaluate along-channel variations in received levels, not those in the across-channel direction.

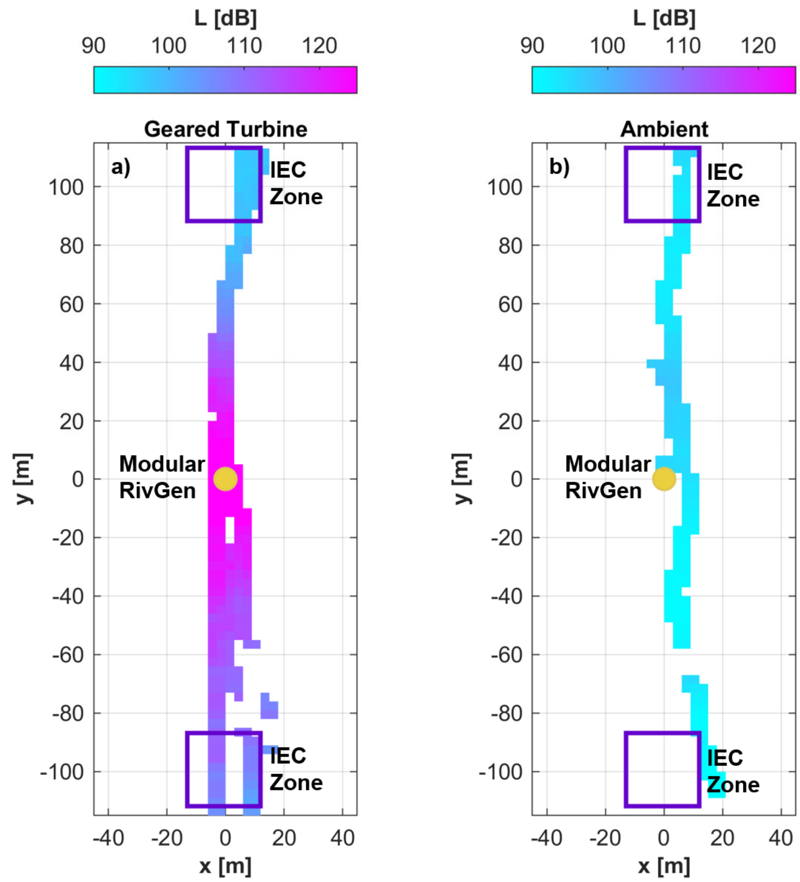

Figure 20: Spatial variation in turbine-band levels (0.2-10.5 kHz) around geared turbine for (a) operating conditions at > 90% of max power and (b) ambient conditions with both turbines braked.

<u>Direct-Drive Turbine</u>

A direct pass over the direct drive turbine with the geared turbine braked is shown in Figure 21. As previously mentioned, the direct drive turbine power output was substantially lower than the geared turbine due to lateral shear in the currents, but even accounting for this, the acoustic footprint is substantially lower, consisting of three relatively low-intensity components: a tone from the VFD excitation at 4 and 8 kHz, a tone several hundred time the rotation rate likely associated with a mechanical component in the driveline, and a relatively a faint, broadband impulse approximately once per revolution. The limited acoustic footprint is particularly clear in Figure 22, which considers radiated noise to either side of a shutdown event, such that the ambient soundscape is stationary. In a statistical sense, Figure 23 shows that the noise from the direct drive turbine in a zone 20 m upstream of the Modular RivGens only intermittently exceeds ambient levels between 0.2 and 2 kHz. This trend extends to the freewheel condition where, when the VFD is not energized, the rotating components of the driveline are only appreciably different from ambient noise at about 3 kHz. We note that, given the limited deviation between ambient noise and turbine sound during the shutdown event (Figure 22), the differences shown in these figures may be magnified by the timing of the dedicated ambient noise measurements, which took place on a day with relatively lower flow rates in Millinocket Stream. As shown in Figure 25, there is no obvious correlation between power output and turbine-band levels, but a slight positive correlation between rotation rate and radiated noise. As for the geared turbine, there are spatial patterns in the turbine-band level (Figure 26), but these are only apparent when the color scheme is saturated 15 dB lower than for the geared turbine. Interestingly, the spatial patterns are also asymmetric, but have the opposite pattern, with higher received levels upstream than downstream. Given that the range of frequencies under consideration is the same for both turbines, this suggests that there is likely some source asymmetry (i.e., there should be no appreciable difference in transmission losses between the two turbines).

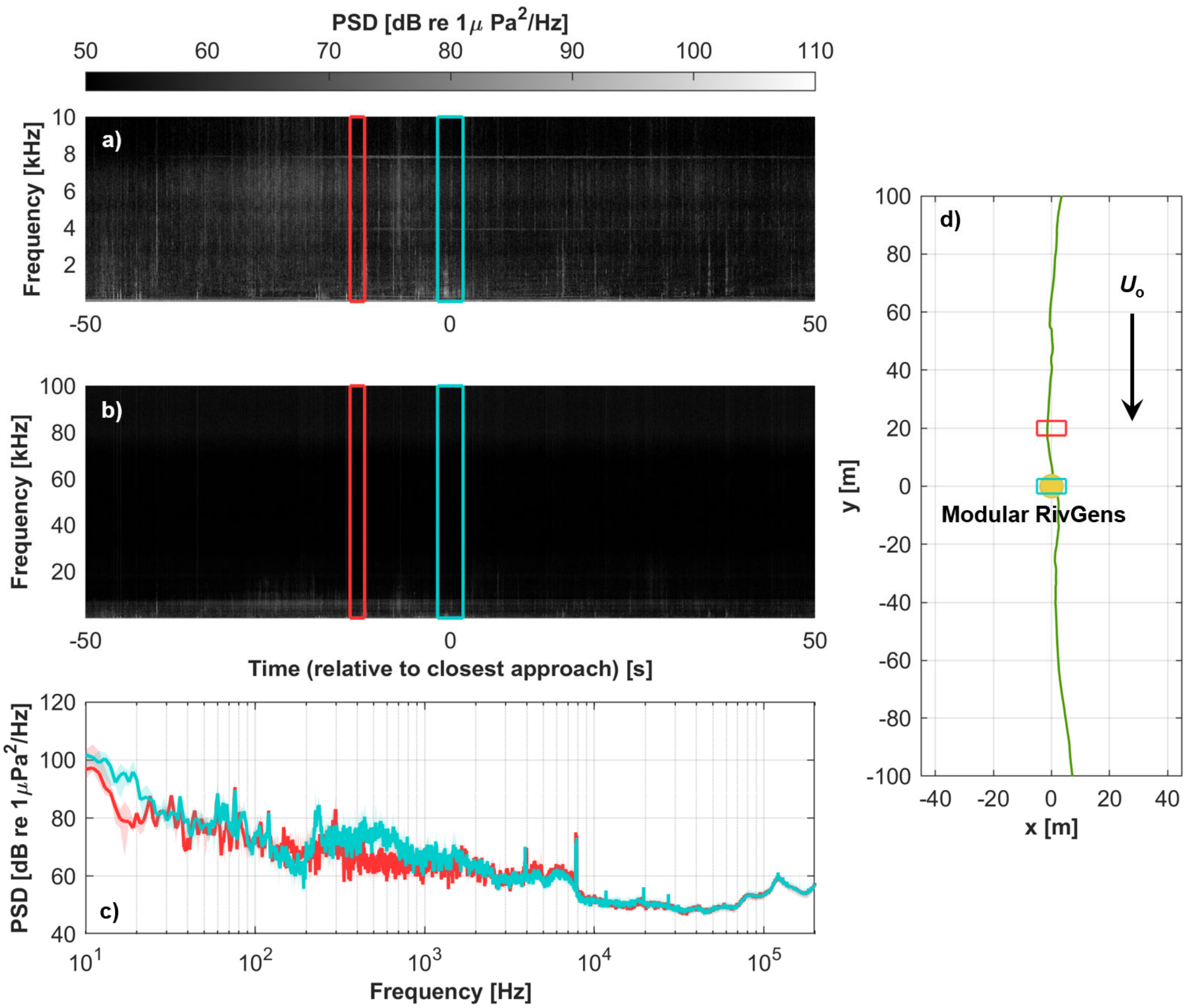

Figure 21: Direct pass in the vicinity of Modular RivGens with direct drive turbine operating at ~90% power and direct drive turbine braked: spectrograms from a) 0-10 kHz and b) 0 – 100 kHz with comparison zones denoted by color, c) periodograms within the comparison zones with solid lines denoting median pressure spectral densities and shaded regions denoting the interquartile range, and d) track trajectory and zone extent.

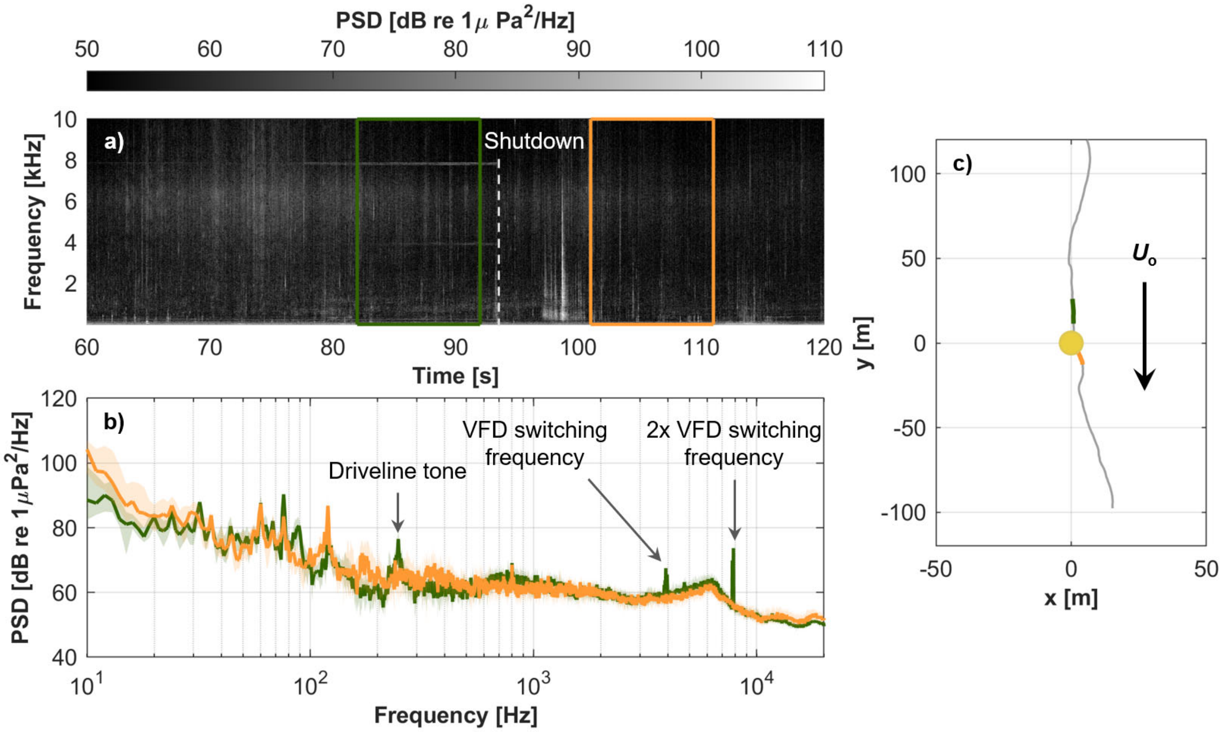

Figure 22: Direct drive turbine shutdown event: (a) spectrogram, (b) periodogram for annotated events before and after shutdown, and (c) DAISY position during shutdown.

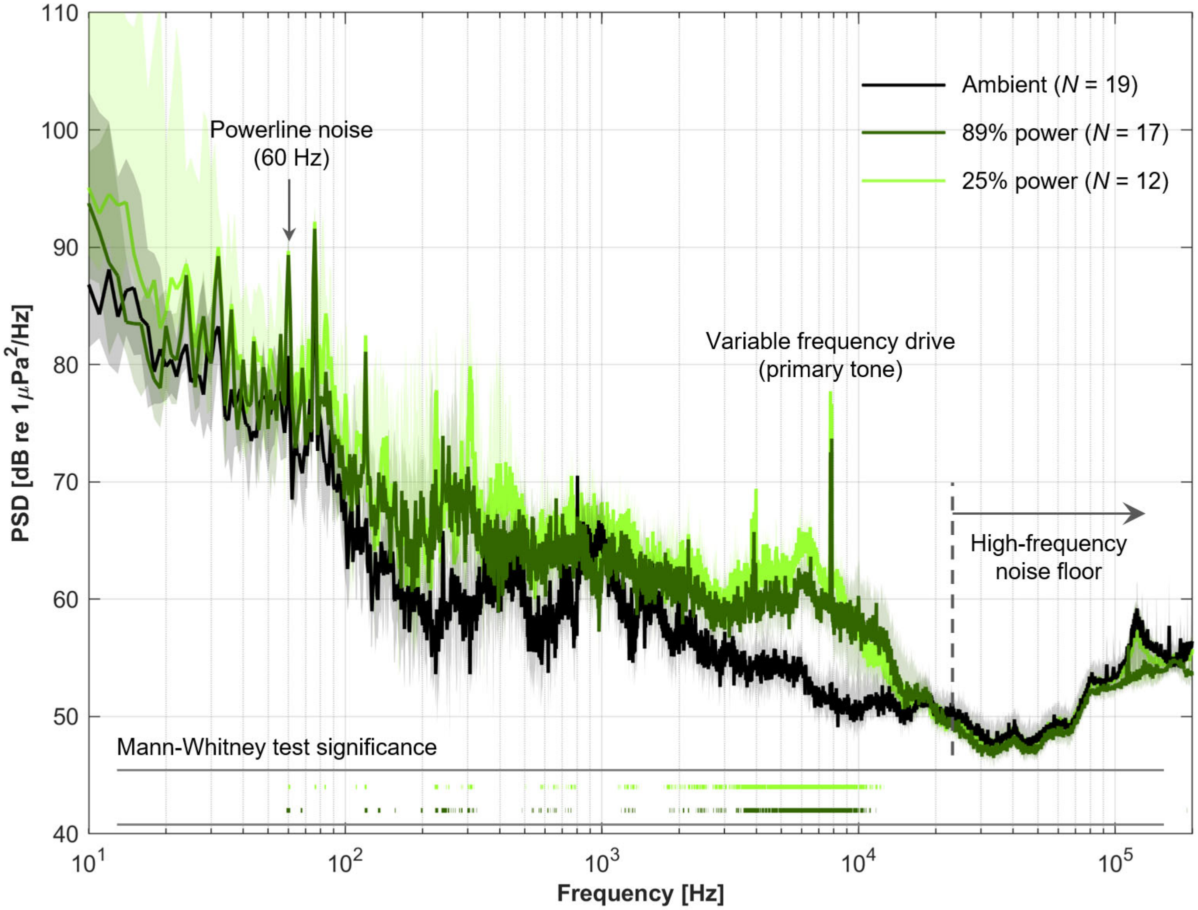

Figure 23: Comparison between ambient, 89%, and 25% power operating conditions for the direct drive turbine in a survey zone 20 m upstream from Modular RivGens with specific frequency components annotated. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram.

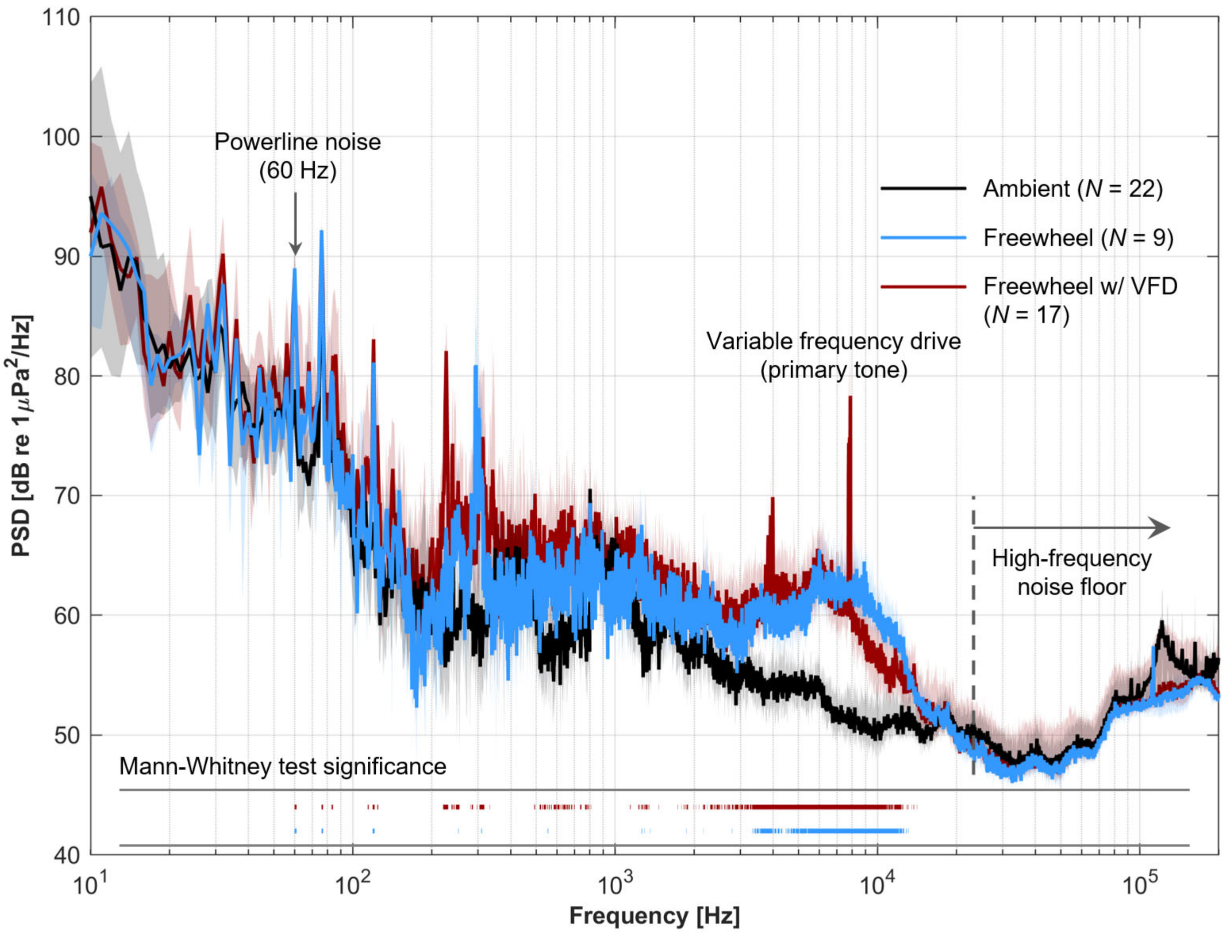

Figure 24: Comparison between ambient, freewheel, and freewheel with the VFD engaged for the direct drive turbine in a survey zone 20 m upstream from Modular RivGens with specific frequency components annotated. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram.

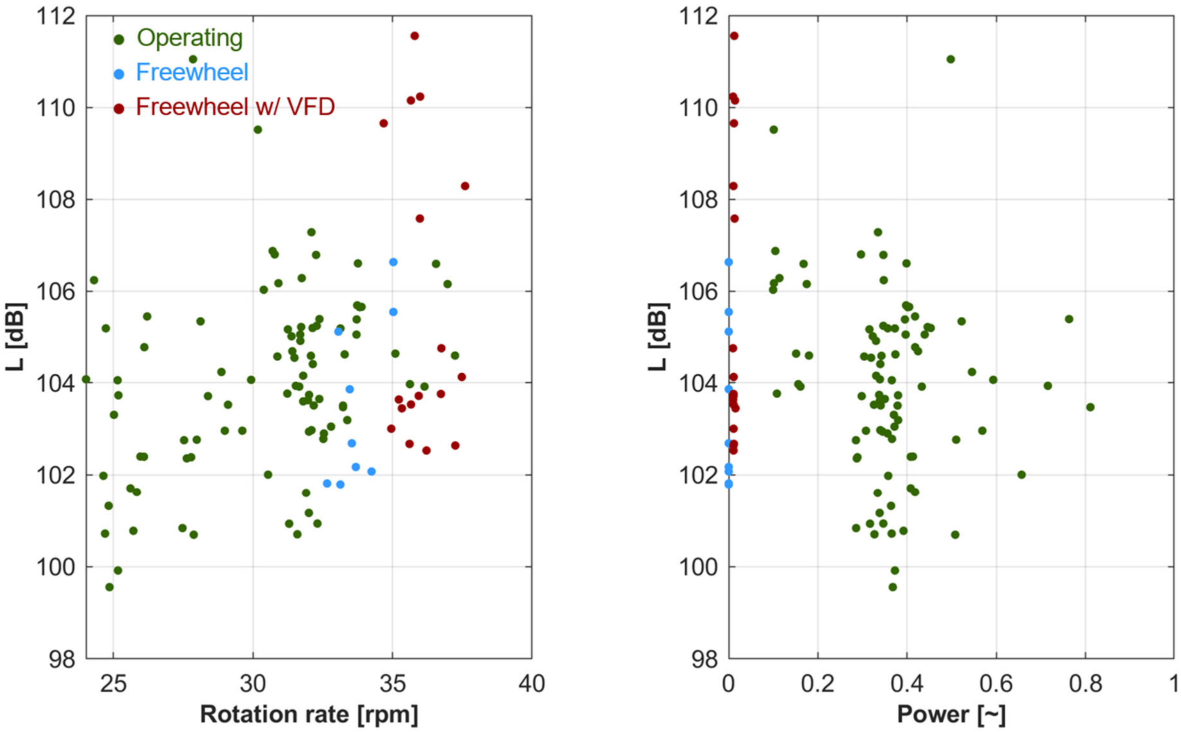

Figure 25: Relation between turbine-band level (0.2-10.5 kHz) and rotation rate (left) or power (right) for direct drive turbine in survey zone 20 m upstream of Modular RivGens. Blue dots denote instantaneous correlations between 1-s acoustic measurements and turbine operating state.

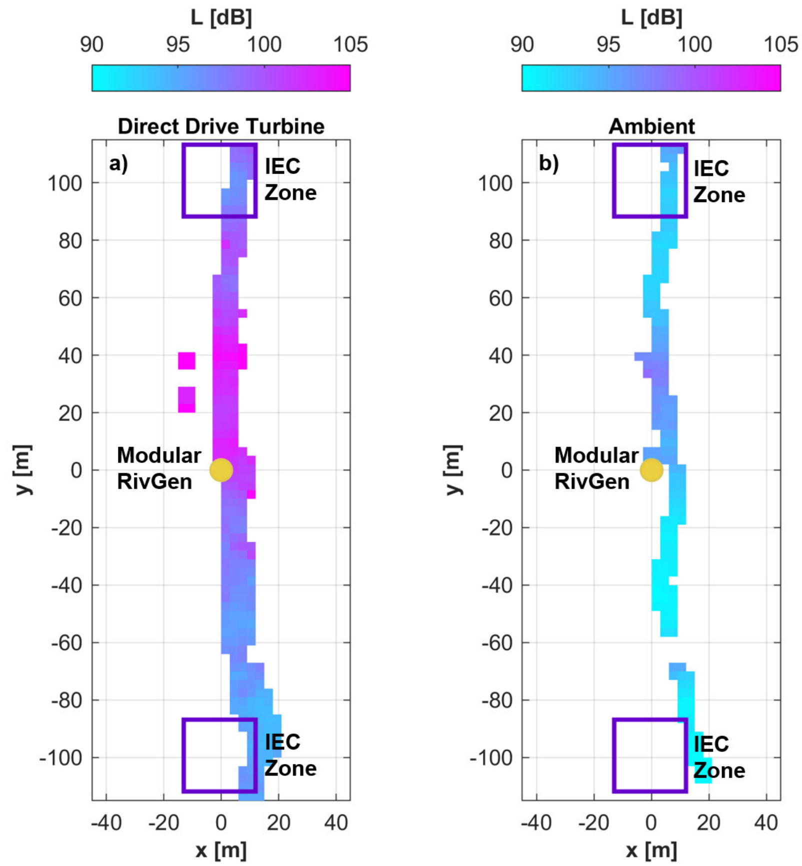

Figure 26: Spatial variation in turbine-band levels (0.2-10.5 kHz) around direct drive turbine for (a) operating conditions at > 80% of max power and (b) ambient conditions with both turbines braked.

Dual Turbine

While an initial survey objective was to compare differences in radiated noise when individual turbines were operating versus both operating simultaneously, the considerable difference in radiated noise between the two turbines meant that the noise from the geared turbine noise almost entirely masked the noise from direct drive turbine when both were in operation. As shown in Figure 27, the only significant difference between the two cases was at the lowest frequencies, which is likely attributable to variations in flow noise. In contrast, the direct drive turbine radiated noise was significantly different from the geared turbine noise between approximately 0.3 and 5 kHz (lower amplitude).

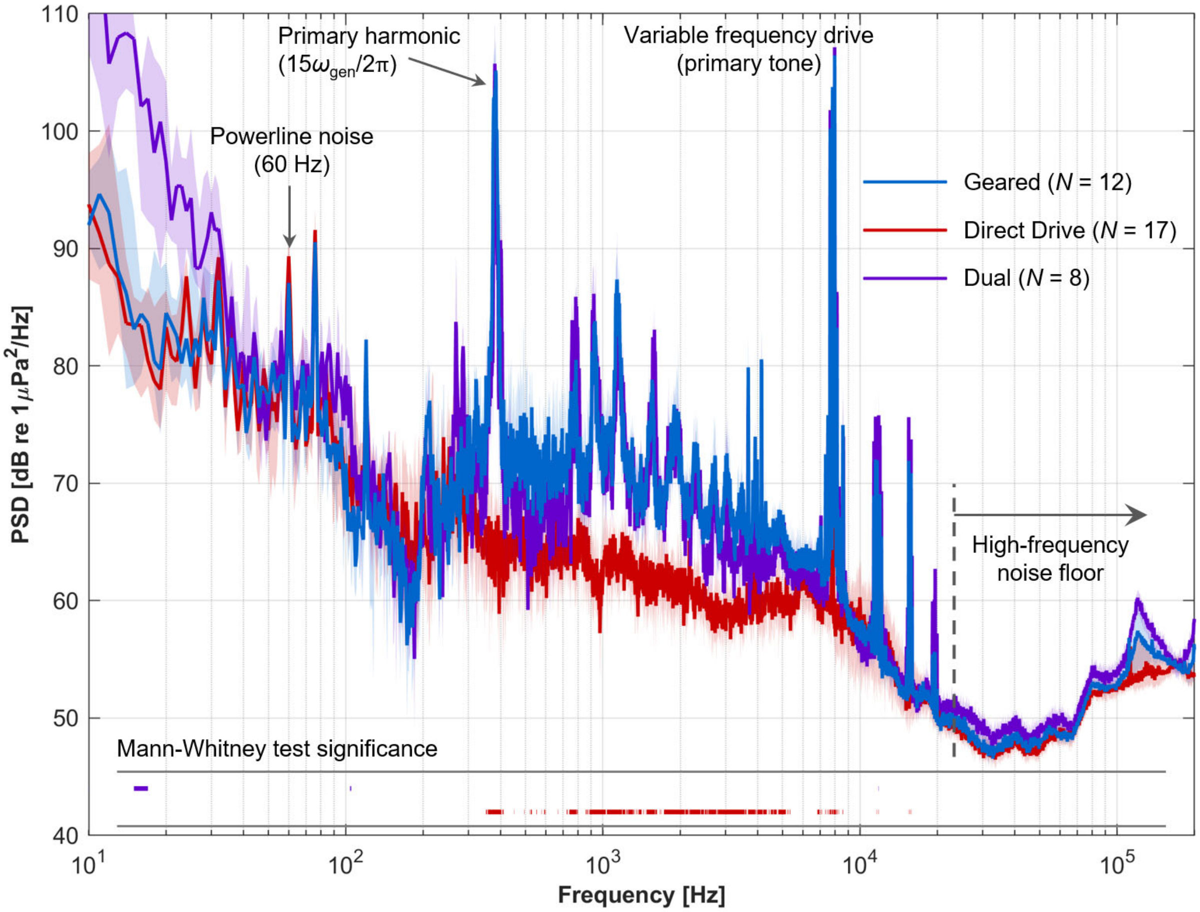

Figure 27: Comparison between individual Modular RivGens and both operating at > 90% of maximum power for a survey zone 20 m upstream. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as the individual geared turbine) is rejected at a signifiance level of $1x10^{-3}$ are indicated below the periodogram.

7.1.1.4 Localization

While there were intermittent acoustic events at close range that were reasonable candidates for localization (e.g., clanks with relatively high signal-to-noise ratio and finite duration), localization was not attempted from the data collected in Millinocket because of unfavorable array geometry. Specifically, once deployed from the survey vessel, DAISYs tended to travel in a line array, which (as discussed in Section 7.1.2.4) leads to inaccurate localization. While the array aperture was expanded by the pair of DAISYs deployed from the footbridge, the GPS coordinates for these units were intermittently malformed by electromagnetic interference from the bridge structure (Figure 9). This occurred for most of the deployments with the geared turbine operating normally (the case with the highest SNR), such that five receivers were only available for measurements of the direct drive turbine (low SNR) or the geared turbine operating in an abnormal mode. Despite this, the low levels of ambient noise at the site allowed for straightforward attribution of georeferenced radiated noise for a single hydrophone to either a turbine or a natural source.

7.1.2 Igiugig, AK (RivGen Turbines)

7.1.2.1 Overview

First, we wish to emphasize the outstanding level of support provided to the team by everyone we worked with in the village – whether operating a boat or strategizing how to get replacement parts into Igiugig. This project would not have been successful without their contributions.

The survey in Igiugig was originally planned for late summer 2023, but because of delays in commissioning the second RivGen turbine, were instead conducted June 10-14, 2024. Unfortunately, during this time, the second RivGen turbine (RivGen 21) could not be operated in a power generating mode due to an issue with its shore-side power electronics. Consequently, survey effort focused on RivGen 20, with a limited number of surveys around RivGen 21 in a freewheel state.

Operations were conducted from either one or two vessels (a vessel provided by the village and a UW vessel equipped with an engine provided by the village). By operating from a pair of vessels, we were able to deploy up to five DAISYs at a time and achieve a relatively high track density (Figure 28). Each track was manually reviewed using a semi-automated pipeline to identify and mask appreciable anomalies (e.g., bottom contact, fishing vessels in area), as well as instrumentation errors (e.g., non-sensical GPS tracks).

Tracks were grouped into the categories described in Table 12 and shown visually in Figure 29. The majority of effort focused on the comparisons between full power and ambient conditions, but appreciable effort was devoted to other cases (e.g., transients during shut down or startup, freewheel). The vast majority of tracks contained usable data, with nearby fishing boat traffic being the most common reason to entirely discard data.

Because of the nature of the grid interconnection, when RivGen 20 was set to full power, this was only realized if the battery storage system was in service or there was sufficient demand on the grid. The "full power" state for RivGen 20 was established based on average operating conditions on June 14 while the battery storage system was in service. For other days, "full power" corresponds to power output within 1 kW and 2 rpm of those values.

Table 12: Summary of surveys in Igiugig, AK

Category	RivGen 20	RivGen 21	Description	# Tracks	% Usable
1	Braked	Braked	Ambient noise	48	96%
2	Full power	Braked	RG20 full power	82	85%
3	Variable	Braked	RG20 variable power	57	88%
4	Transient	Braked	RG20 transient	7	100%
5	Freewheel	Braked	RG20 freewheel	5	100%
6	Braked	Freewheel	RG21 freewheel	3	83%
7	Freewheel	Freewheel	Dual freewheel	2	100%
8	Full power	Braked	Intentional boat operations	10	100%

Figure 28: DAISY deployment around RivGen in Igiugig, AK.

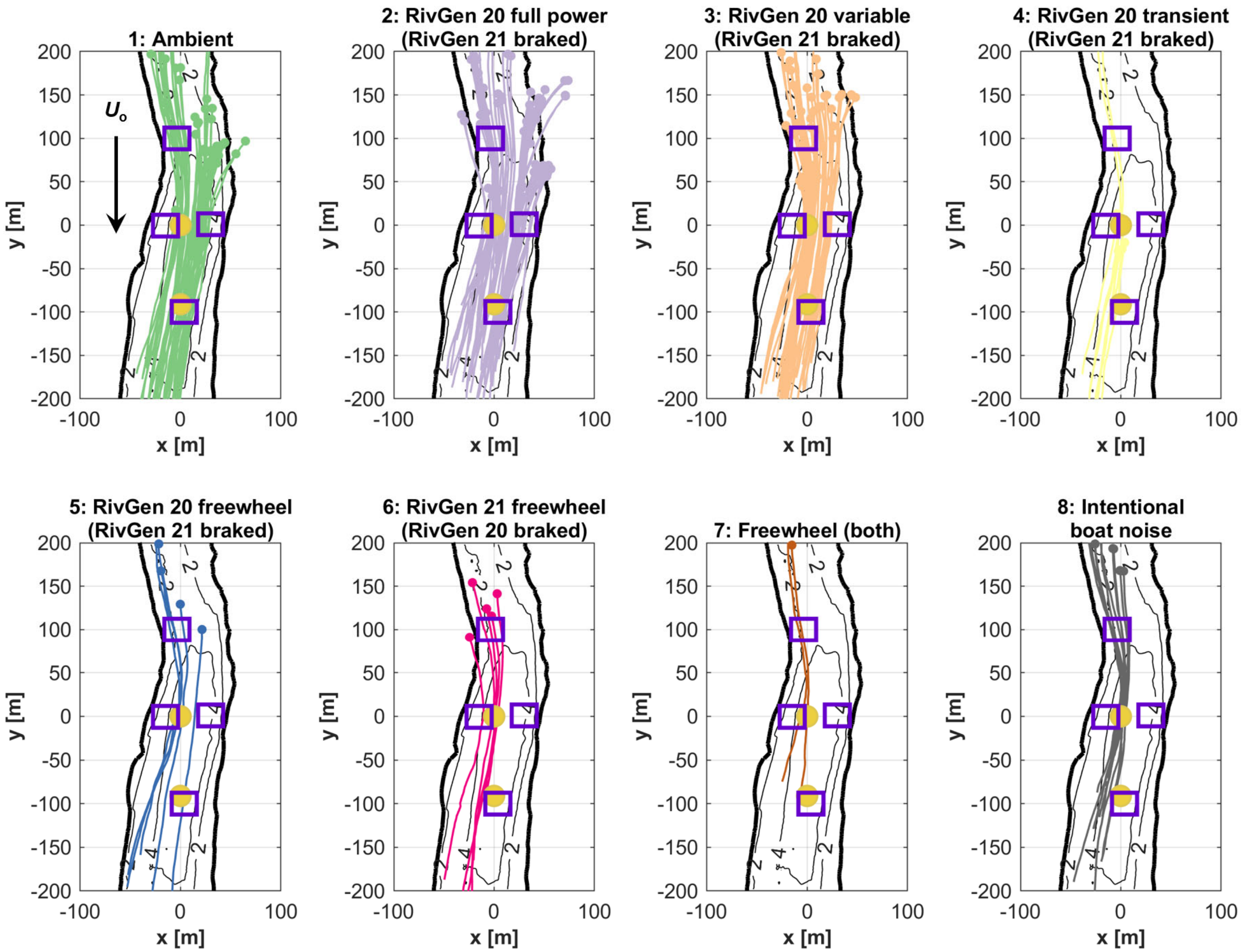

Figure 29: Summary of drift tracks by operating states during surveys around RivGen 20 (upstream yellow marker) and RivGen 21 (downstream yellow marker) in Igiugig, AK. Circles denote start of drifts. Boxes denote IEC survey zones. Tracks have been rotated and referenced to RivGen 20 position.

While ORPC had approximate deployment coordinates for the RivGen turbines, a more robust estimate was obtained from review of GoPro camera footage on the DAISYs, extracting the absolute time of overflight events (GoPro cameras were time-synchronized with a cell phone clock prior to deployment), and correlating that time with DAISY position measured by the on-board GPS (Figure 30). Overflight locations (e.g., river right edge, center) were also noted when available. For RivGen 20, an average of six points for DAISY tracks directly over the center support was used as the best estimate of position. For RivGen 21, no tracks passed directly over the center support and position is based on an unweighted average of all overflight points. This unit's position is, therefore, somewhat less accurate, this does not materially affect results given the survey focus on RivGen 20. The orientation of the turbines was estimated from a best fit to all the overflight points (15.9° for RivGen 20, 23.9° for RivGen 21). This rotation angle were translated to the IEC survey zones for RivGen 20 (Figure 30).

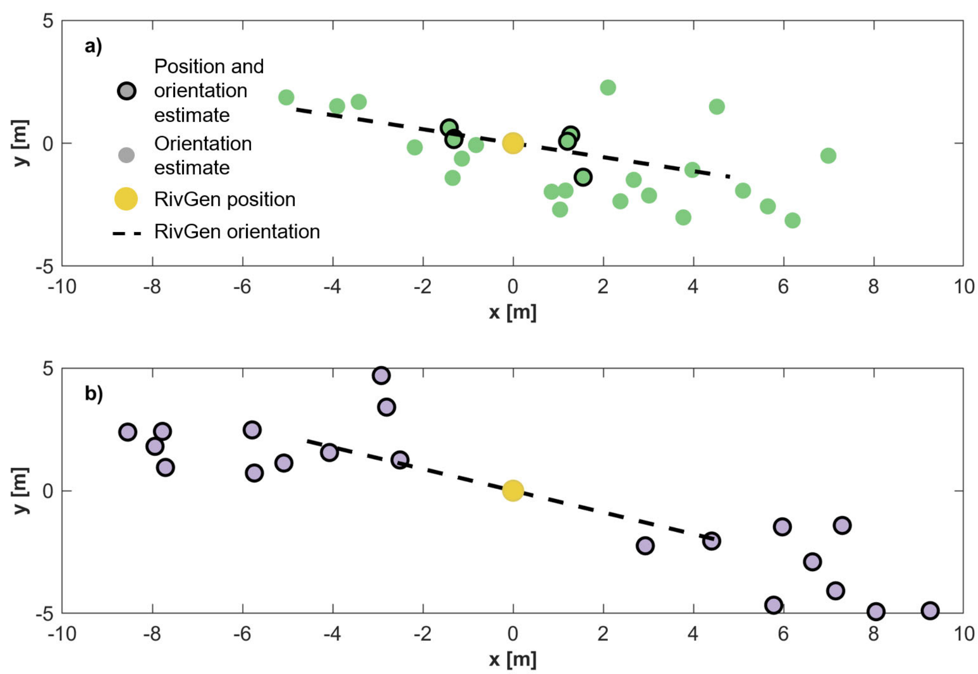

Figure 30: Estimates of RivGen turbine positions based on downward-looking video review: (a) RivGen 20 and (b) RivGen 21. The dashed orientation line is the physical extent of the turbine rotor, which suggests that GPS uncertainty could be up to 4 m.

7.1.2.2 IEC Survey Results

In Iguigig, CTD casts indicated a sound speed of approximately 1440 m/s and the maximum water depth was approximately 5 m. Because the sediment composition was unknown and could not be determined due to the cobble pavement, the sound speed was conservatively assumed to be approximately 1800 m/s, consistent with sand. This suggests a low-frequency limit of approximately 120 Hz (Section 7.1.2.2). As a higher sediment sound speed would reduce the low-frequency limit and we observe appreciable differences between operating and ambient conditions down to 50 Hz (Section 7.1.2.3), we set this as the lower limit. Similarly, turbine sound exceeds ambient noise to approximately 5 kHz, beyond which the soundscape is dominated by sediment-generated noise. As such, 5 kHz is taken as the high-frequency limit.

Table 13 lists the number of valid samples from each IEC zone as a function of power state. Given that the IEC requirement is a minimum of 10 valid samples per zone-power state combination, we obtained an order of magnitude more samples than required for several combinations, but did not obtain any valid samples for the 25% power state and did not obtain samples from the downstream or port zones at the 50% power state. The former was a consequence of not operating the turbine at this power level (i.e., 25% of maximum control torque produced more than 25% maximum power) and the latter a consequence of a limited number of surveys at the 50% power state. The relatively high number of samples obtained from each zone means that statistics for these zones are robust to artifacts (e.g., self-noise) that were not flagged in manual review.

Table 13: Number of valid samples for each IEC zone as a function of power state (±10 %)

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	275	323	503	125
25 %	-	-	-	-
50 %	107	48	-	-
75 %	105	118	189	18
100 %	312	662	845	94

Table 14 presents median turbine-band levels for each IEC zone. For starboard and port zones, turbine-band levels in operation are elevated relative to ambient, while the upstream and downstream zones are not. However, recall that the starboard and, particularly, port zones were shifted closer to the turbine, such that the signal-to-noise ratio would be expected to be higher in these zones. We observe minor (< 4 dB) increases in the turbine-band level as power generation decreases and rotation rate increases. Finally, while the equidistant upstream and downstream zones do not indicate an operating state dependence, they suggest a substantial difference in ambient noise in the streamwise direction.

Table 14: Median turbine-band level [dB] (50 – 5000 Hz) for each IEC zone as a function of power state (±10 %). '-' denotes combinations of zone and power state with insufficient valid samples to satisfy IEC 62600-40.

Power State / Zone	Upstream	Starboard	Downstream	Port
0 % (ambient)	122	119	117	122
25 %	-	-	-	-
50 %	122	125	-	-
75 %	122	124	118	129
100 %	122	122	118	125

Figure 31 considers the frequency variations with power state within each zone, considering a slightly wider range of frequencies (10 Hz - 10 kHz) than the IEC band. Here, we see that, while upstream and downstream IEC band levels are relatively invariant with power state, there are apparent differences in the frequency characteristics between operating and ambient conditions that are unique to each zone. For the starboard and port zones closer to the turbine, these differences are more pronounced.

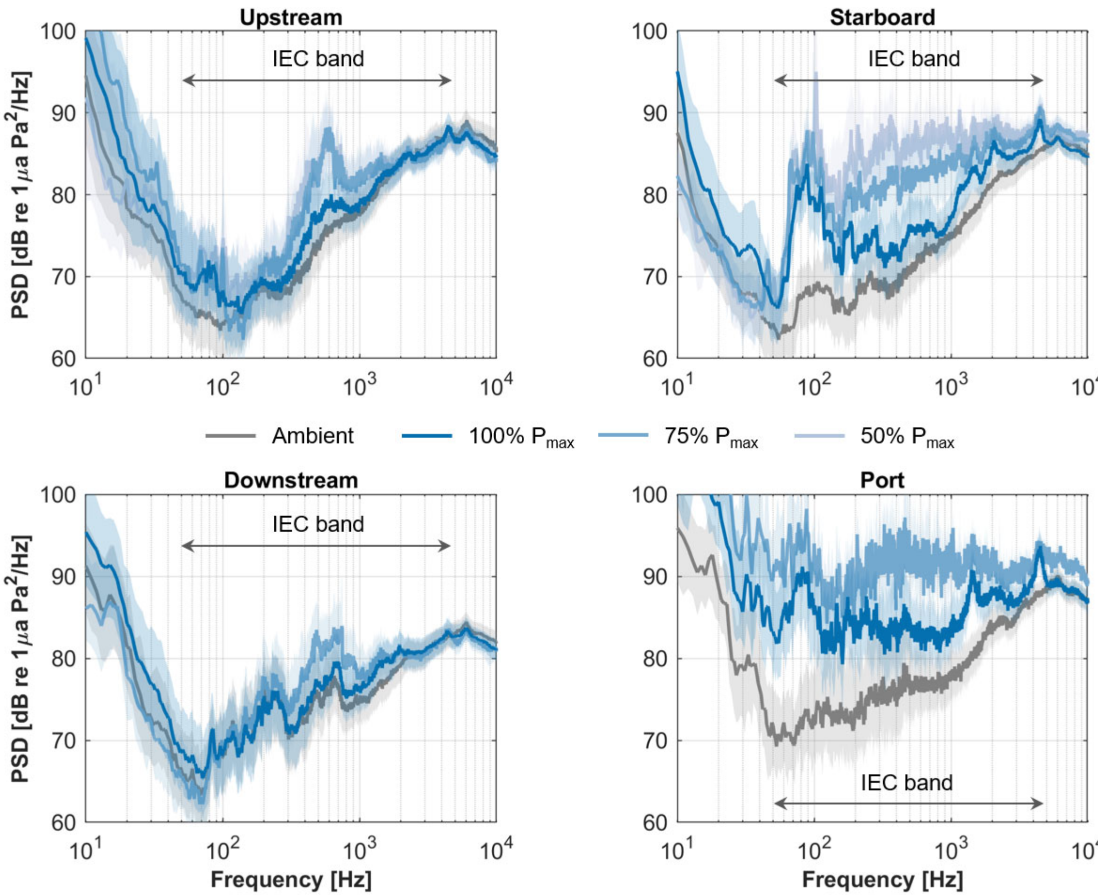

Figure 31: Pressure spectral density as a function of survey zone and power state. Solid lines denote median values and shaded regions denote interquartile ranges.

As for Millinocket, we assess these differences more rigorously through a Mann-Whitney statistical analysis for each combination of power state and zone relative to ambient conditions (Figure 32). Expanding to the full set of frequencies available (1 Hz – 200 kHz), this analysis indicates a relatively broad range of frequencies for which it is unlikely that measurements during ambient and operational conditions are drawn from the same statistical distribution (up to 200 kHz for some zones). This analysis similarly suggests that for the upstream and downstream zones (100 m from the turbine), radiated noise around 200 Hz is invariant between operating and ambient conditions (consistent with the convergence of the median spectra in Figure 31). However, as subsequently discussed, this is a consequence of acoustic propagation in the river, not an absence of turbine-generated noise. As discussed in the next section, this frequency is significantly elevated from ambient at closer range. Similarly, as subsequently discussed, the influence of turbine operating conditions on relatively high frequencies (> 5 kHz) is indirect, which leads to elevated levels in the starboard and port zones and reduced levels in the upstream and downstream zones. These examples highlight two weaknesses in a purely statistical approach: (1) it indicates that there may be a difference between operating and ambient conditions at some frequencies, but not why, and (2) unless measurements are obtained at a suitable distance from the turbine, the outcomes can be misleading.

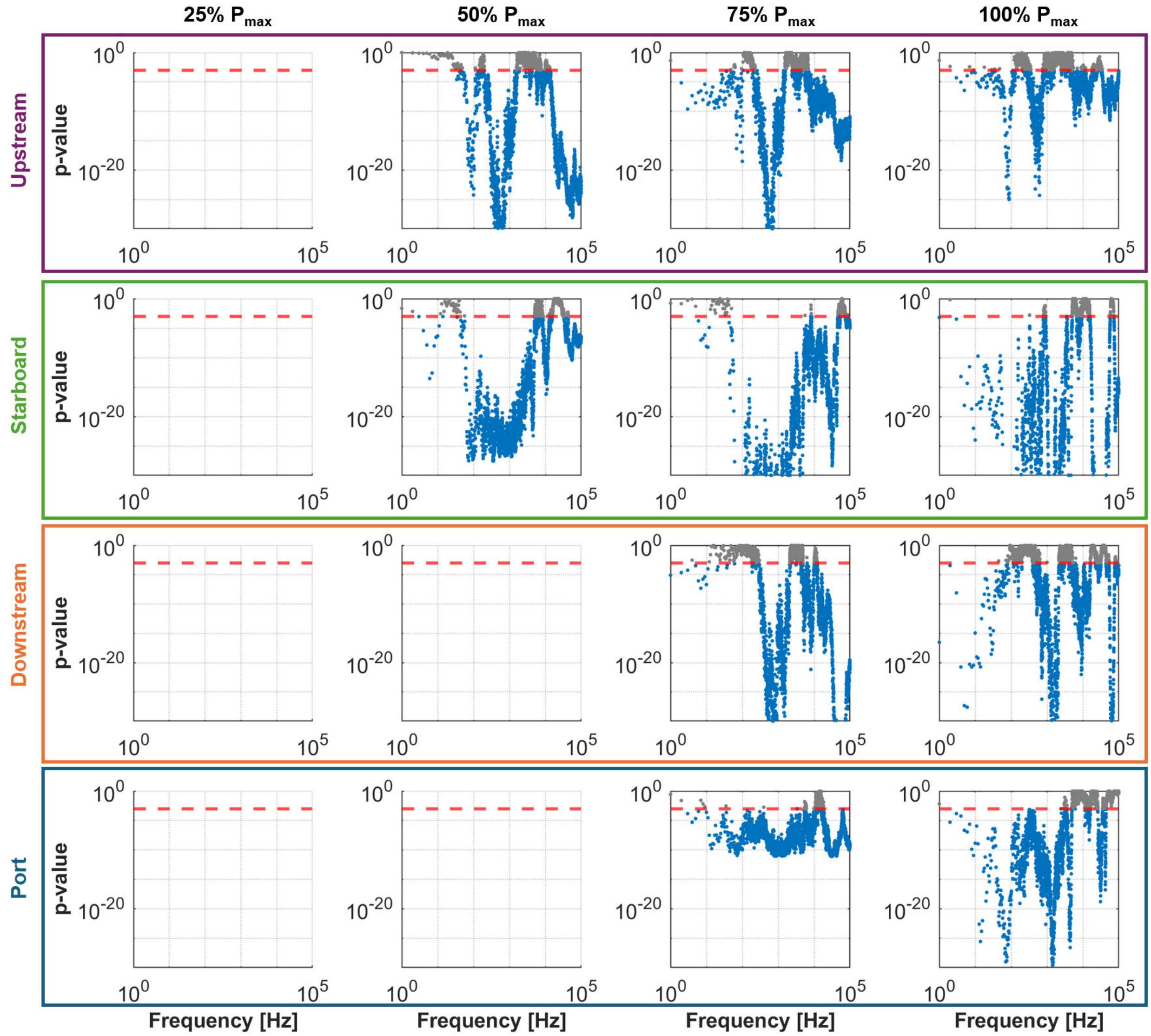

Figure 32: Mann-Whitney statistical analysis for combinations of IEC survey zones and power states. The dashed red line denotes the threshold for statistical significance. Grey dots denote frequencies for which there is no statistical significance between ambient and operating conditions. Blue dots denote frequencies where ambient and operating acoustic pressure are unlikely to be drawn from the same populations.

7.1.2.3 Turbine Sound Characteristics

We first consider a track that passes in close proximity to RivGen 20 while it is operating at full power (Figure 33), which shows a Lloyd's mirror pattern typical of a sound source in relatively shallow water. Overall, radiated noise is elevated in closer proximity, though there is thought there is some high-frequency (20-60 kHz) sound observed a near the turbine that is not observed at modest distances upstream and downstream at higher frequencies (20-60 kHz, Figure 33b).

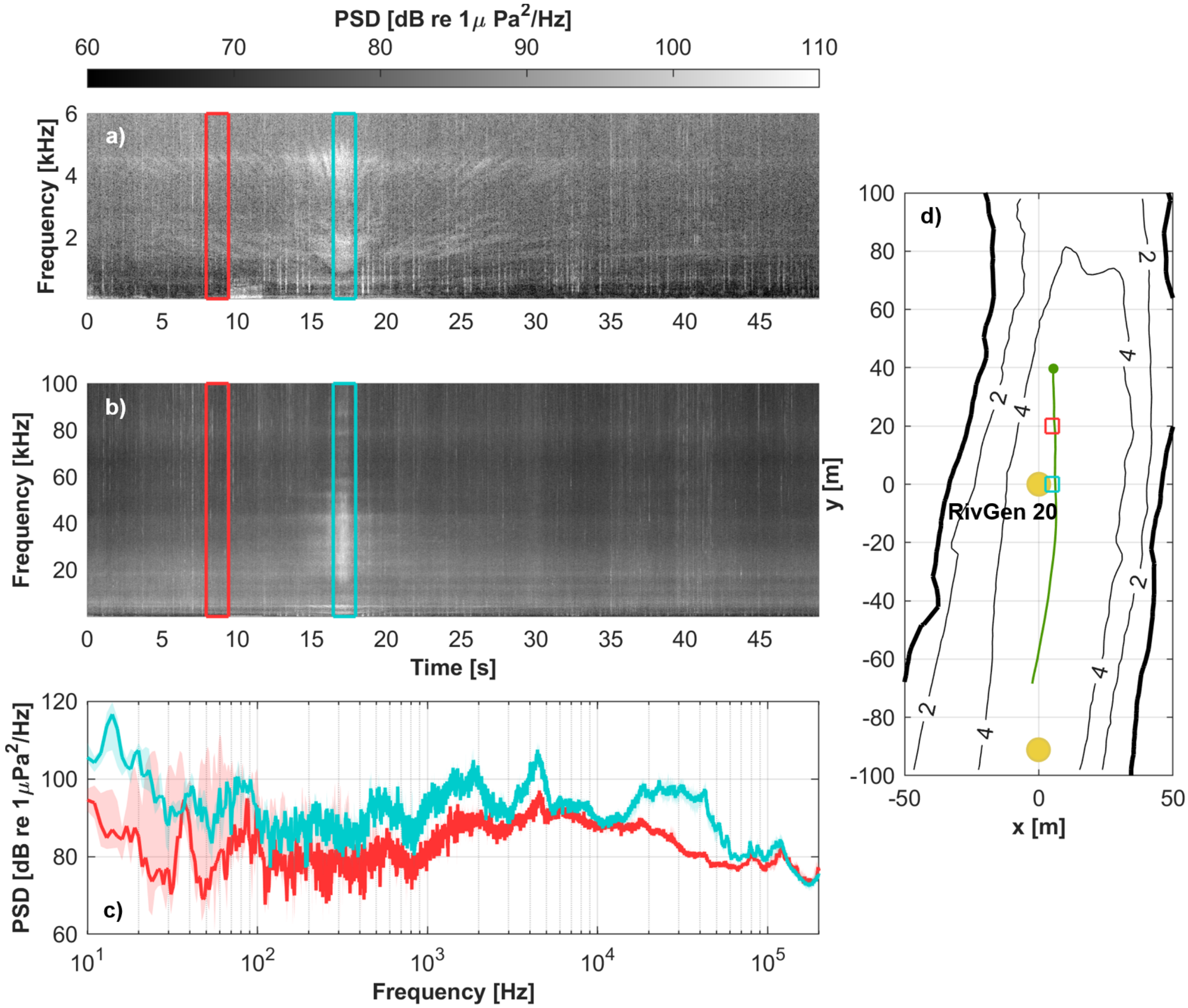

Figure 33: Direct pass in the vicinity of RivGen 20 while operating at full power: spectrograms from a) 0-6 kHz and b) 0 – 100 kHz with comparison zones denoted by color, c) periodograms within the comparison zones with solid lines denoting median pressure spectral densities and shaded regions denoting the interquartile range, and d) track trajectory and zone extent.

As for Millinocket, we focus on a zone 20 m upstream from RivGen 20 (5 m in the along-channel direction and 10 m in the across-channel direction). As shown in Figure 34, at full power, noise is radiated primarily at frequencies from 60 Hz – 2 kHz (attributable to rotating elements in the powertrain) and from 4-5 kHz (attributable to excitation of the generator windings by the VFD used to regulate rotation rate). During freewheel, a wider range of frequencies are radiated and there is a prominent tone around 100 Hz. At frequencies above 5 kHz, both operating conditions result in lower radiated noise than ambient, but not generally at a level considered statistically significant. At frequencies < 60 Hz, radiated noise is, in general, not statistically different between ambient and operating conditions, but flow noise is likely masking propagating sound, so it is possible that the turbine is producing some sound at lower frequencies.

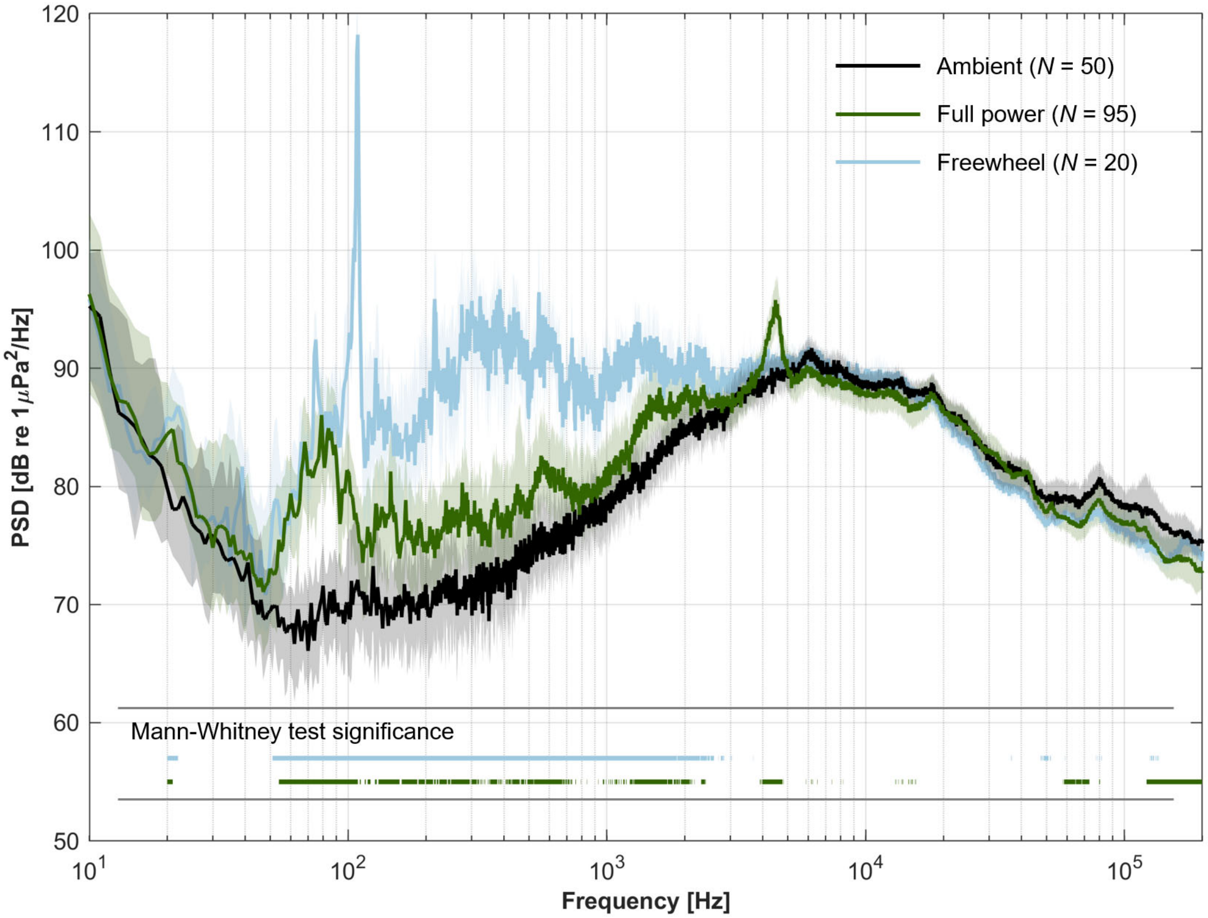

Figure 34: Comparison between ambient, full power, and freewheel conditions for a survey zone 20 m upstream from RivGen 20. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as ambient conditions) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram.

To evaluate the correlation between radiated noise and operating states, we re-define the "turbine band" as 60 – 200 Hz, which encompasses the highest signal-to-ambient-noise ratio for the full power state. We then regress this band level against turbine operating condition (rotation rate and power output).

There are two implicit uncertainties that complicate this analysis. First, individual acoustic spectra have higher variability than averages in a zone due to spatial and temporal variation in radiated noise (Figure 33). Second, the ORPC SCADA clock was not synchronized on a regular basis during the acoustic surveys. To align the acoustic measurements with operating state, we compared time-resolved variations in the operating characteristics to acoustic measurements during a shutdown and start-up event on different days. This analysis suggested a clock drift on the order of a few seconds and we adjusted the time stamps for turbine data assuming a linear drift between these two references points. To reduce uncertainty and assess trends, acoustic data were pooled by rotation rate (2 rpm bin width) and power (normalized units), then median levels calculated in pressure-squared space for pools with at least 10 data points. As shown in Figure 35, while the 1-s data are relatively scattered, the pooled data have distinct trends. The turbine-band level is roughly linear with power output, though negatively correlated, such that the acoustic footprint decreases with power output. This is likely because power is negatively correlated with rotation rate in a torque-regulated control scheme (i.e., increasing rotation rate decreases power in a non-linear manner) and increased rotation rates would be expected to cause more noise to be radiated from power take-off components. This suggests that IEC 62600-40 should consider a comparison between radiated noise and rotation rate, as well as power output.

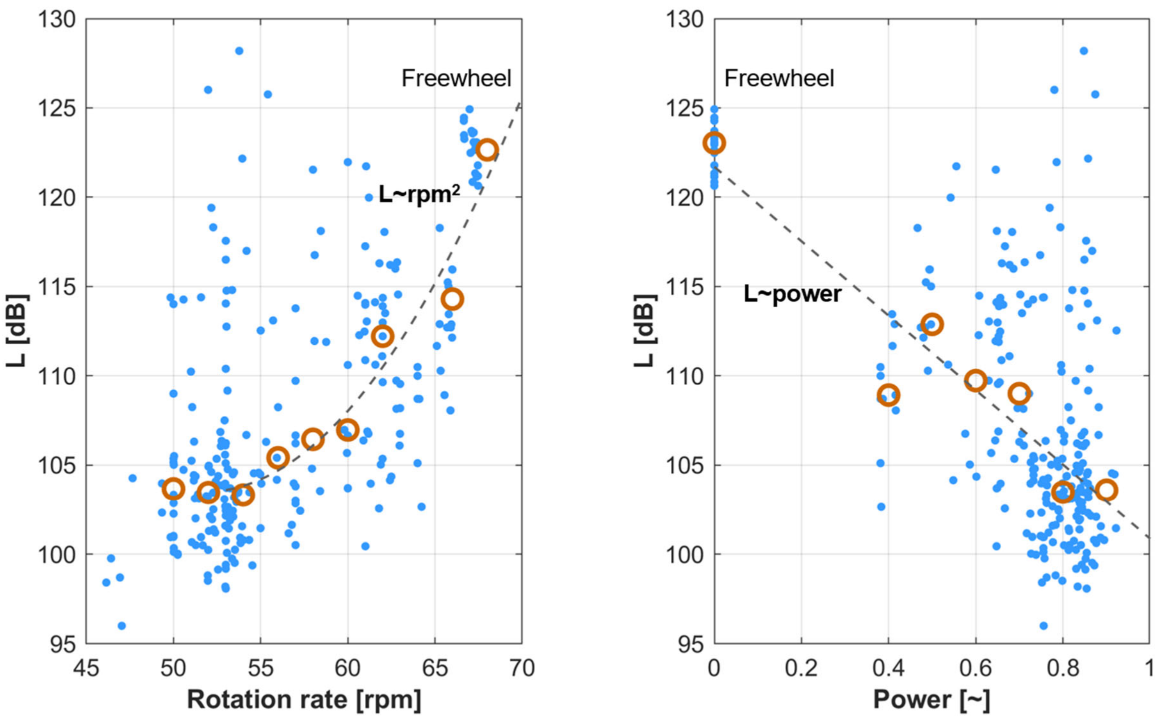

Figure 35: Regression of turbine-band level against rotation rate and power. Blue dots denote instantaneous correlations between 1-s acoustic measurements and turbine operating state. Orange circles denote averages for rotation rate bin widths of 2 rpm and power bin widths (normalized units) that contain at least 10 sample points. Best fit regressions to binned turbine-band levels are indicated by the grey dashed lines.

As alluded to in the preceding discussion, the transients associated with turbine shutdown and startup are distinct. Shutdown (Figure 36a,c) is a two-stage event, with the initial braking producing broadband noise and a tone around 100 Hz, with substantially less noise radiated as the turbine is brought to a complete stop. The acoustic characteristics of startup (Figure 36b,c) are similar to the second stage of shutdown, with the exception of a higher intensity tone around 100 Hz. Because the DAISYs were not equidistant from RivGen20 during shutdown and startup (Figure 36d), direct comparisons should not be made of the amplitudes between the two events.

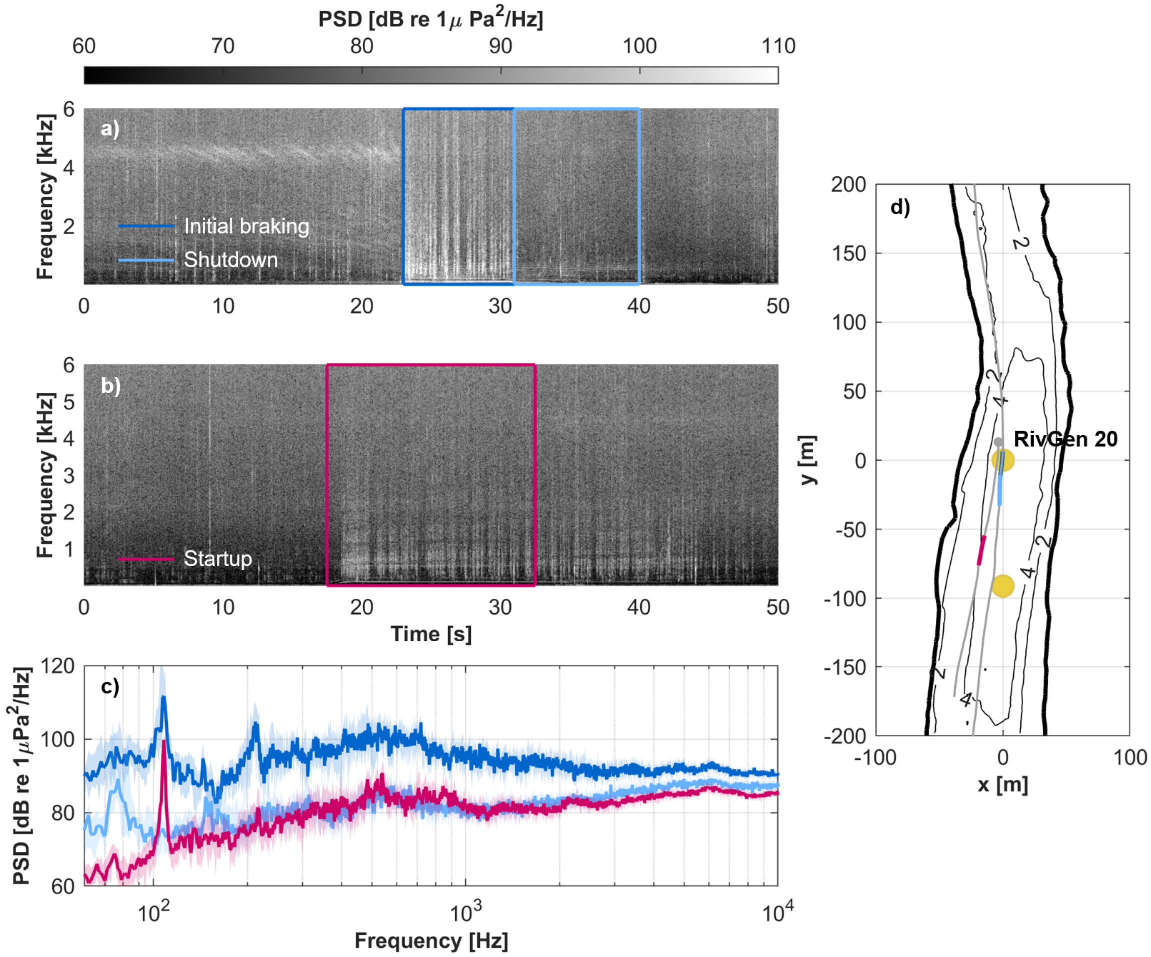

Figure 36: Transient events: (a) spectrogram of turbine shutdown, broken into the initial braking event and remainer of the shutdown sequence, (b) spectrogram of turbine start-up, (c) periodograms corresponding to spectrograms, and (d) location of DAISYs during transient events.

While RivGen 21 could not be operated in a power generating mode during the acoustic survey, it was possible to consider the influence of dual-turbine operation from freewheel conditions. Figure 37 shows a comparison between single-turbine freewheel (RivGen 20 or RivGen 21 with the other turbine braked), dual-turbine freewheel, and ambient noise (both turbines braked) from a survey zone approximate mid-way between the two turbines. Freewheel conditions elevate received levels in this zone relative to ambient noise, with the acoustic signature for RivGen 20 generally higher amplitude than for RivGen 21. RivGen 20 freewheel produces a tonal peak at 108 Hz and harmonic at 216 Hz, as well as generally elevated levels from 500-600 Hz. These differences are attributable to how freewheel operation is implemented for the two turbines. Specifically, when RivGen 20 is in "freewheel" the variable frequency drive remains engaged to limit the turbine's rotation rate, while RivGen 21 is a true freewheel with power electronics completely disengaged. Because of this, we expect that the tonal peak in RivGen 20 freewheel is likely attributable to generator excitation by the variable frequency drive. Turning to the dual-turbine case, at frequencies where the noise amplitude from RivGen 20 is substantially higher than RivGen 21, there is almost no difference between received levels for single-turbine and dual-turbine operation. At the few frequencies where noise is of similar amplitude for the two turbines (e.g., around

150 and 250 Hz), during dual-turbine operation received levels increase by < 6 dB, which is consistent with the physical limit for addition of coherent sound. In other words, we are seeing what would be anticipated from combinations of acoustic pressure. We note that it would be surprising if the sound from two turbines was entirely coherent and that incoherent pressure addition should result in a 3 dB increase. However, there are a limited number of samples for the single-turbine condition for RivGen 20 and the dual-turbine conditions, such that this discrepancy likely falls within uncertainty.

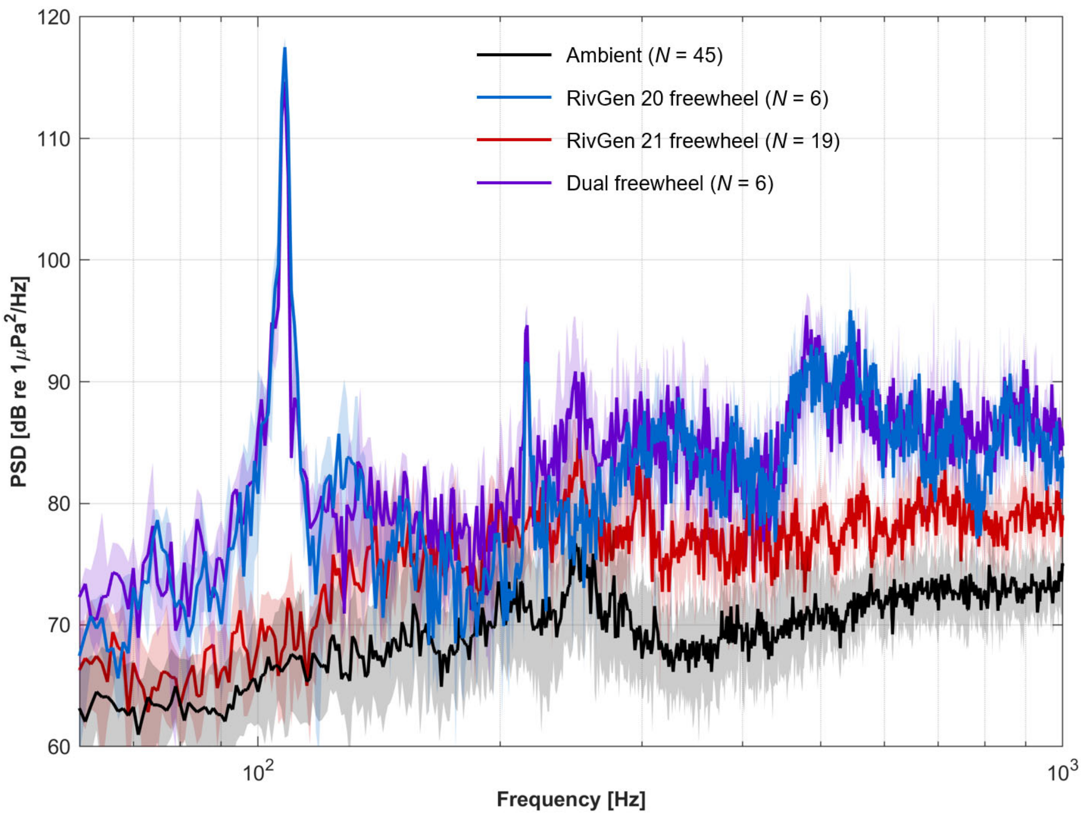

Figure 37: Comparison between single-turbine freewheel conditions, dual-turbine freewheel condition, and ambient noise in a survey zone approximately midway between RivGen 20 and RivGen 21. Solid lines denote median conditions and shaded regions denote the interquartile range. Note that there are only a limited number of samples for RivGen 20 and dual-turbine freewheel conditions.

A general challenge to zone-based analysis in a shallow, reverberant environment is that the complexity of acoustic propagation can lead to appreciable differences in received levels with location. For example, if we compare received levels for RivGen 20 at full power in zones 20 m upstream, downstream, and lateral (river left) (Figure 38), we observe appreciable differences in the acoustic spectra, particularly at frequencies below 1 kHz. There are even greater differences between the upstream and downstream IEC zones, both at 100 m distance. As for Millinocket, the asymmetry between the upstream and downstream zones may be either a consequence of source directionality or differences in propagation between the source and the measurement zones, but we can not differentiate between the two.

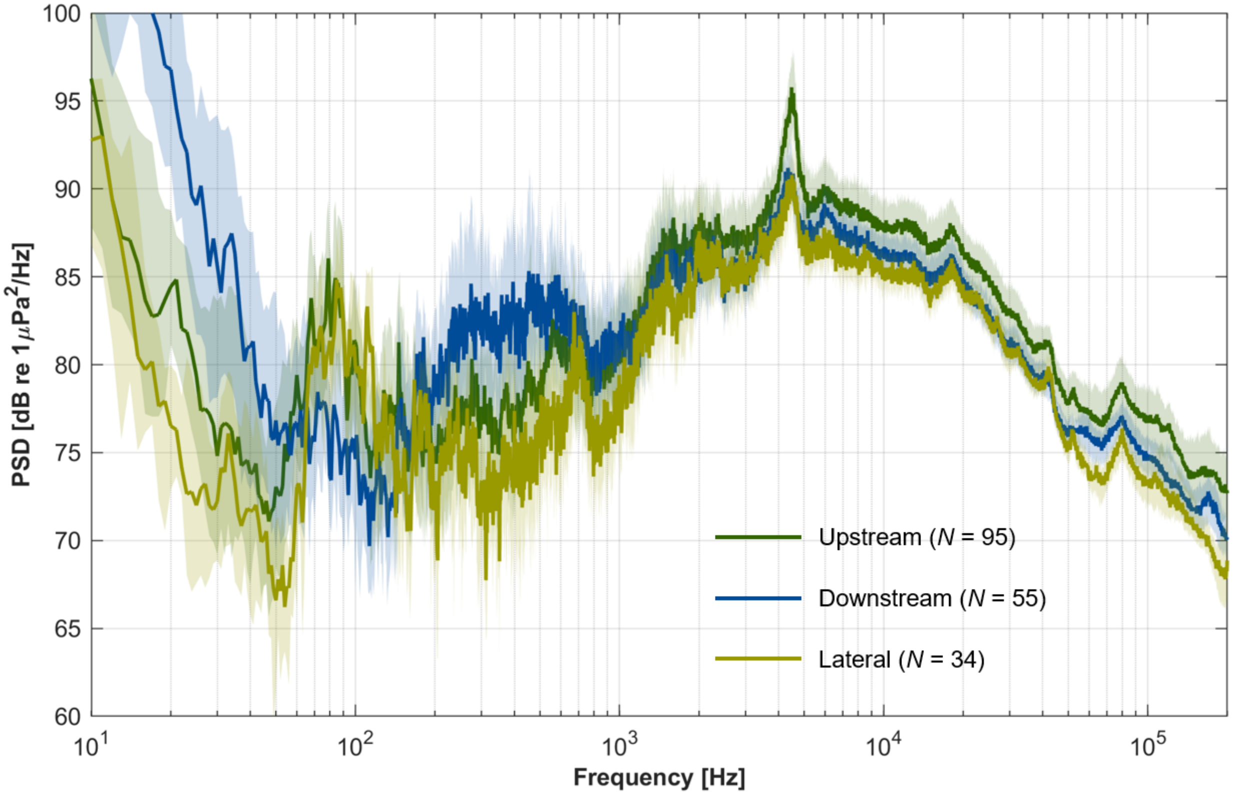

Figure 38: Spatial variability in the acoustic spectra for RivGen 20 at full power for three zones located 20 m from the turbine centroid.

Given this variability, it is instructive to consider overall spatial variations in radiated noise for three frequency bands: (1) 0.06 – 2 kHz corresponding to frequencies that are generally elevated in operation relative to ambient in the Mann-Whitney analysis for the upstream zone (Figure 34), 4-5 kHz which encompasses a prominent tone from the VFD, and frequencies above 5 kHz, which have moderate spatial variability. This is done by pooling acoustic measurements for RivGen 20 at full power on a grid with 3 m resolution and calculating median band levels in pressure-squared space for all grid elements containing at least 5 samples. For the frequency band most likely associated with the turbine (Figure 39a), there is a clear elevation in received levels within approximately 50 m of RivGen 20. Beyond this distance, spatial variations are discontinuous. A similar local elevation is observed for the 4-5 kHz band (Figure 39b), though there are other areas of the river more distant from the turbine with similarly elevated levels. At the highest frequencies (Figure 39c), there are clear spatial patterns, but there is not an apparent range dependence relative to the turbine, suggesting that the turbine is not the source of this noise.

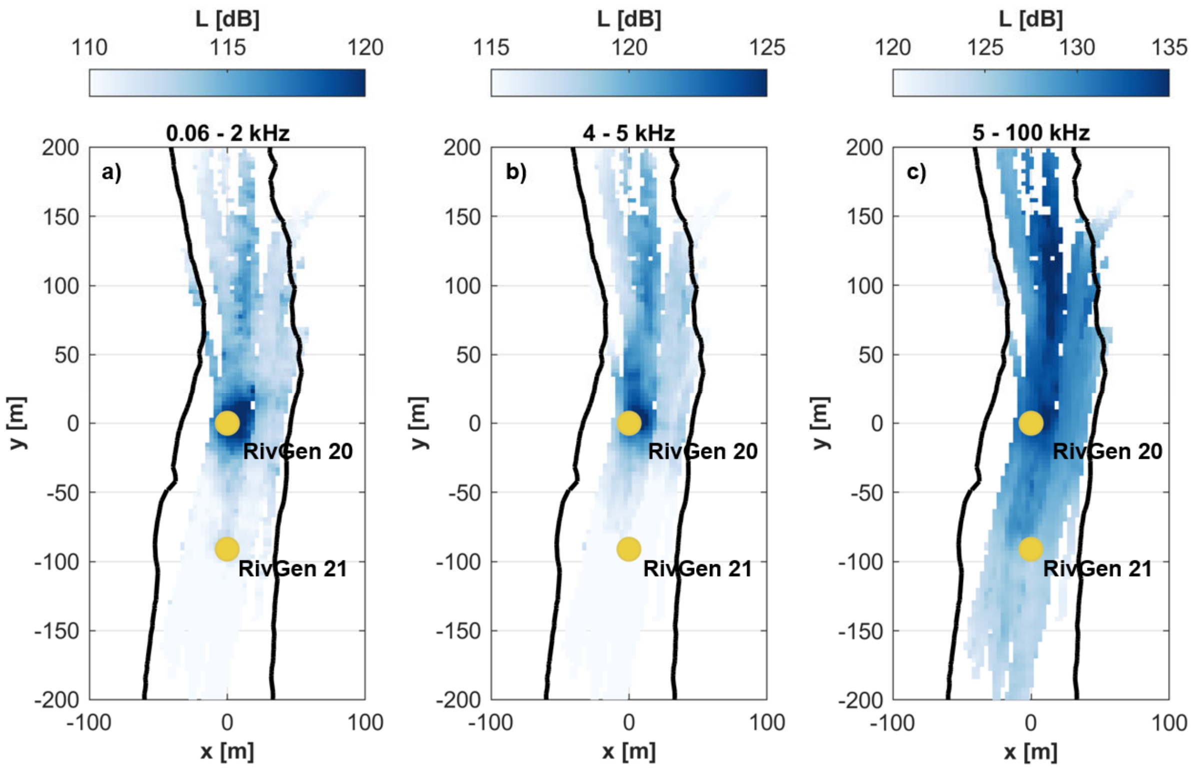

Figure 39: Spatial variation in select band levels with RivGen 20 at full power and RivGen 21 braked. Color bar scale changes for each frequency band and is saturated to emphasize trends.

To gain additional insight, we can compare spatial variations between full power and ambient conditions. Because this requires acoustic samples during both conditions, these maps have less coverage than those for full power operation. For the turbine band, levels are elevated from baseline conditions approximately 100 m upstream and downstream (Figure 40a), with the most appreciable acoustic footprint within 50 m. In the 4-5 kHz range (Figure 40b), there is an increase attributable to the turbine within 50 m, but a curious *decrease* correlated with operation at locations further downstream. This extends to the higher frequencies (Figure 40c), where there are clear regions of elevated noise and decreased noise when the turbine is in operation. We hypothesize that this is attributable to changes in natural processes from the turbine's hydrodynamic disturbance. In operation, the turbine acts as a momentum sink, with reduced velocity in the wake and elevated velocity for the flow "bypassing" the rotor. Above a few kHz, the dominant natural sound source is "sediment generated noise" caused by the collision of sediments (i.e., sand, gravel, and cobbles) that are mobilized by near-bed shear. Downstream of RivGen 20, the turbine wake reduces sediment mobilization, while the bypass flow enhances this. Effectively, the turbine's acoustic footprint consists of direct noise radiation from the rotating components and indirect changes from river hydrodynamics. We note that this alteration in the high-frequency soundscape is not of biological significance, as these frequencies substantially exceed the upper end of fish auditory capabilities for most fishes (around 1 kHz).

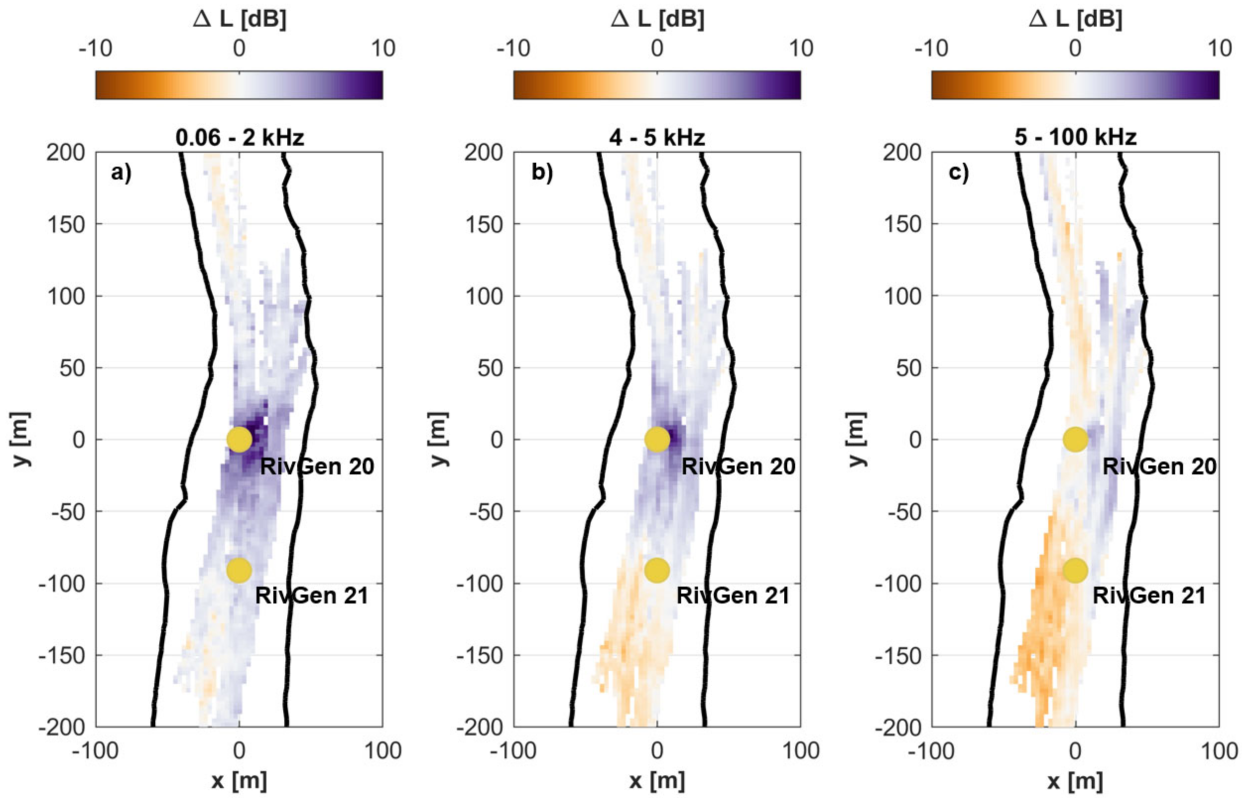

Figure 40: Spatial variations in select band levels with RivGen 20 at full power and RivGen 21 braked versus ambient conditions (both turbines braked). Color bar scale is saturated to emphasize trends.

To contextualize these measurements, we can compare the radiated noise from the turbine to the other main anthropogenic source on the river: vessel traffic. Figure 41 compares radiated noise from RivGen 20 while operating at full power and a pair of fishing boats (dual Lloyd's mirror, Figure 41b) coming up river. The distance between the fishing boats and the DAISY at their closest point of approach is unknown, but likely on the order of 10's of meters. Below 120 Hz, RivGen 20 produces higher intensity noise than the fishing boats (albeit with the DAISY at closer range to the turbine than boat) and similar amplitudes from 120-600 Hz. Above 600 Hz, the fishing boat produces higher intensity noise. Finally, in recent years, jet boats have become more common and produce appreciably higher intensity sound in air than traditional outboard engines. For comparison to the radiated noise from RivGen 20, we intentionally operated a jet boat near the turbine (idle and full throttle). As shown in Figure 42, unlike traditional outboards (Figure 41), the acoustic signature from the jet boat is indistinguishable from RivGen 20 (i.e., no consistent frequencies in the turbine band with statistical differences for either of the jet boat operating states). This counter-intuitive finding may be a consequence of the higher void fraction in the jet boat wash, which would attenuate propagating sound.

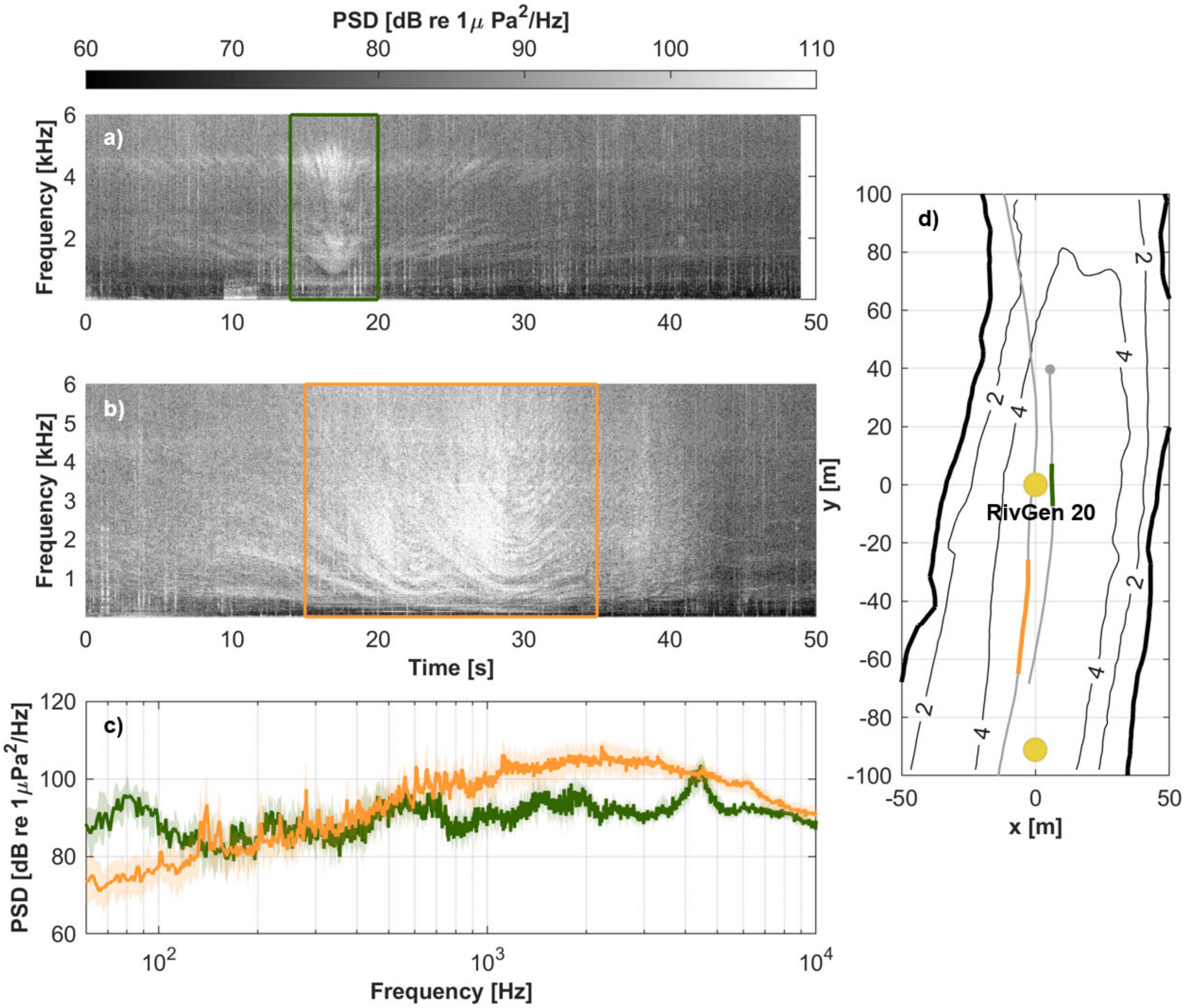

Figure 41: Comparison between closest point of approach to RivGen 20 while operating at full power and closest point of approach between a DAISY and pair of fishing vessels.

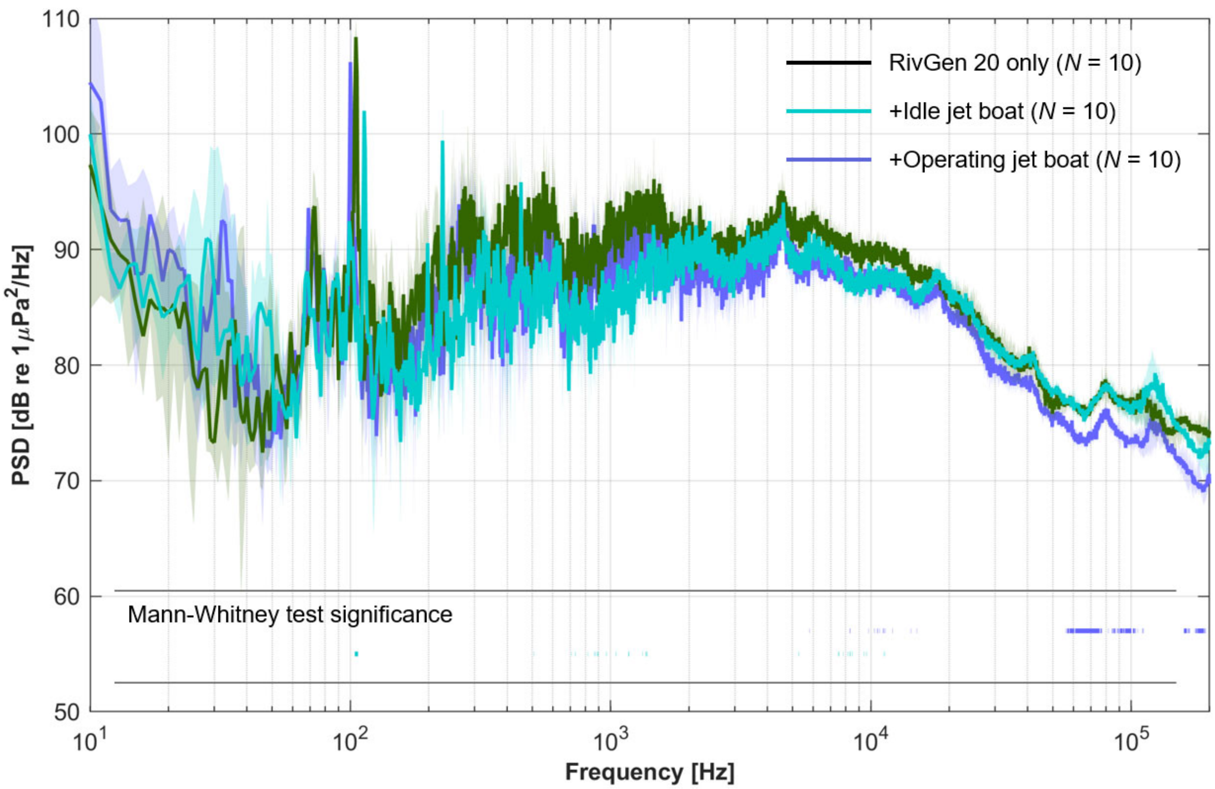

Figure 42: Comparison between RivGen operating with and without a jet boat (idle and operating at full throttle) for a survey zone 20 m upstream from RivGen 20. Solid lines denote median values and shaded bands denote the interquartile range. Frequencies for which the null hypothesis (samples are drawn from the same population as RivGen 20 only) is rejected at a significance level of $1x10^{-3}$ are indicated below the periodogram. RivGen 20 is operating below full power output during these surveys.

7.1.2.4 Localization

Separate from the statistical descriptions of turbine sound presented in the preceding sections, localization can be used to identify the source of individual acoustic events. Manual review identified several recurring events with well-defined start and end times: a “clank”, “mild grinding”, and a “thunk”. A general challenge for localization is that accuracy improves when the source is bracketed by an array of receivers, all of which have relatively high signal-to-noise ratio. However, the river streamline tended to cluster the DAISYs into a line array, regardless of their initial deployment geometry, and the drift speed meant that even the line would only bracket a source for a limited time. To minimize spurious solutions, source location from the hyperbolic equations was compared to the minimum error location from a brute force grid search (Section 6.5.3.3). If estimated source locations from the two methods were displaced by more than 10 m, localization for this event was excluded as spurious.

As shown in Figure 43, the ”clank” and “mild grinding” generally localized to RivGen 20. The “clank” could either be loose recovery hardware or cobble impacts on the turbine support structure. As the “mild grinding” all localized to river left of the turbine centroid and recurred roughly once per second, this suggests a rotating component of the power train as the source. The ”thunk” localized to RivGen 21, perhaps indicating loose recovery hardware.

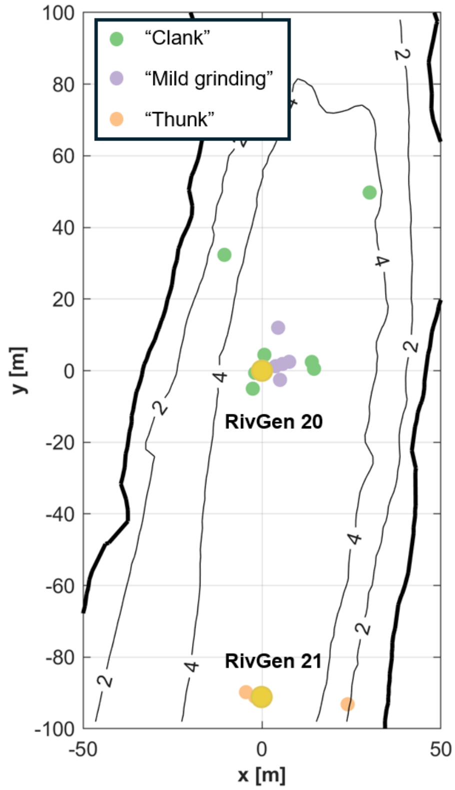

Figure 43: Source estimates from grid search for acoustic events. Only events with less than 10 m displacement between grid search and hyperbolic equation solutions are shown.

7.1.3 Overall Comparisons

Figure 44 presents an overall comparison of the radiated noise from the three turbines surveyed. We emphasize that while all three are cross-flow turbines, they are of substantially different size and utilize different powertrain components. Radiated noise from RivGen 20 (direct drive) has the highest intensity, albeit convolved with sediment generated noise at frequencies above a few kHz. However, the tonal peaks are highest for the geared Modular RivGen and the direct drive Modular RivGen barely exceeds ambient conditions. These results suggest that, while the scale of the turbine is an important factor in radiated noise levels, the powertrain components also play a critical role. Indeed, the abnormal VFD operation for the geared Modular RivGen substantially elevated radiated noise, which suggests that VFD tuning could, potentially, also serve to reduce radiated noise.

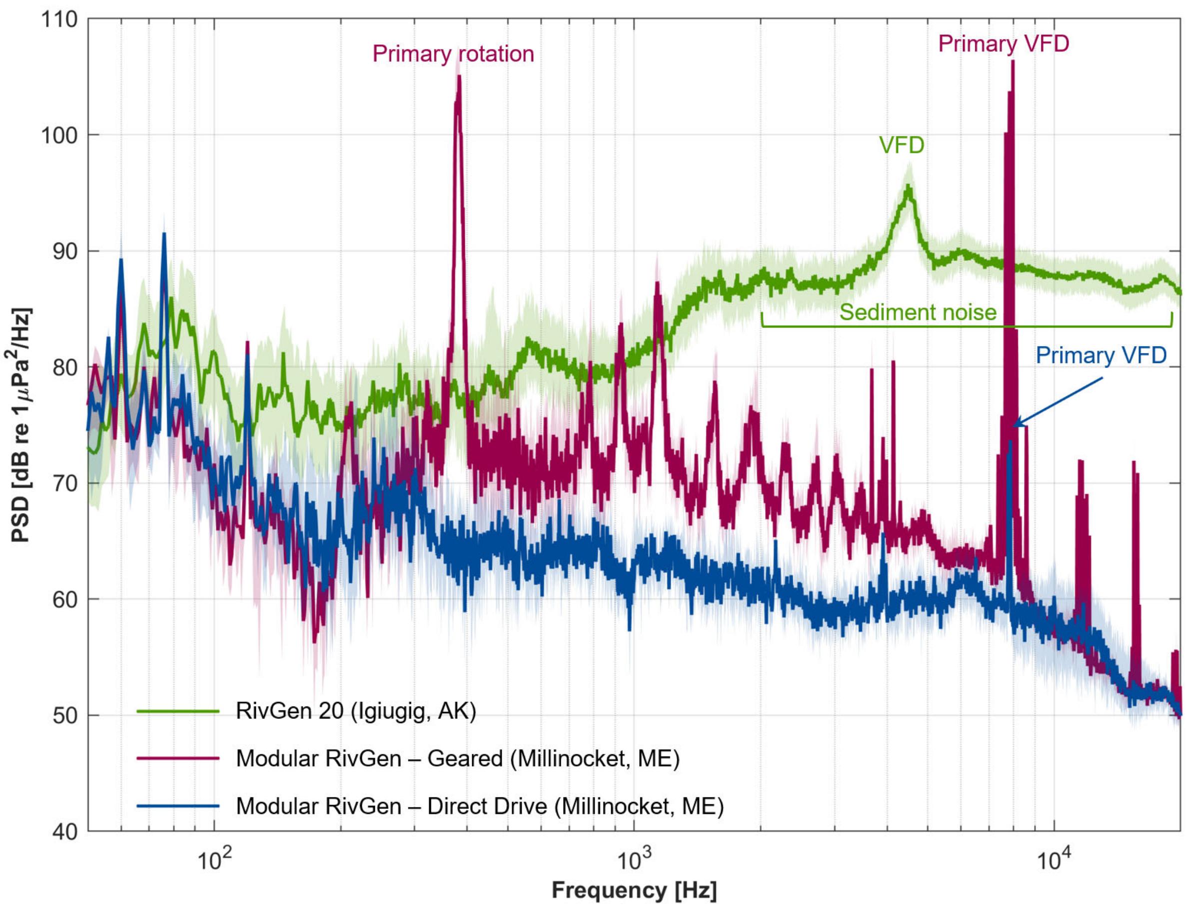

Figure 44: Comparison between RivGen 20 in Igiugig, AK and two variations of Modular RivGens in Millinocket, ME for a survey zone located 20 m upstream of each turbine.

7.2 Lesson Learned and Test Plan Deviation

7.2.1 Overall Lessons Learned

These surveys afforded the opportunity to compare the information obtained from application of IEC 62600-40 to river current turbines with additional information available from more extensive analysis. For both sites, received levels in zones 100 m away from the turbines provided incomplete descriptions of radiated noise due to transmission loss in shallow water and relatively low signal-to-noise ratios. This suggests that collecting information at closer range would be beneficial for standardized comparisons of turbine noise. At the same time, if there is a limited acoustic signature at a range of 100 m, this information may be sufficient for regulators. Regressions of radiated noise with turbine power and rotation rate indicated a stronger dependency on the latter quantity, though this correlation was still relatively weak. This suggests that standardized measurement protocols for current turbines should either emphasize stratification by rotation rate or collect data at a range of inflow velocities (i.e., capturing radiated noise as a function of normal operating states in response to velocity variation).

The delay between surveys in Millinocket, ME and Igiugig, AK allowed us to identify several hardware and methodological issues and correct them. First, in analyzing the Millinocket data, we discovered a 1 s offset in the time stamps for some DAISYs. This was determined to be an issue with how file names were being generated in the DAISY firmware and largely corrected prior to the Igiugig survey. Second, in Millinocket, we only collected ambient noise data on the first day of the survey, when current velocity was substantially lower and the hydropower plant was at a minimal operating state. In hindsight, we should have collected additional ambient data on other days, which motivated us to collect a broader range of ambient noise data in Igiugig. Finally, in Millinocket, the water depth decreased significantly downstream of the Modular RivGens, which resulted in the DAISY hydrophone guards dragging on the riverbed. This caused the guards to break after a few days of survey activity and was a limiting factor in the number of tracks that could be collected. Prior to the Igiugig survey, we modified the guard construction to increase durability and brought multiple spares with us to allow the guards to be used in a semi-expendable manner.

7.2.2 General Deviations

We made three general deviations from the original test plan:

1. The approach to localization was altered and expanded to reflect a better understanding of the technique and its limitations by the project team. The original approach did not involve applying a Hillbert transform to the voltage signal to improve cross-correlation accuracy, nor did it consider a brute force approach to localization, given a set of time delays.
2. We performed pistonphone calibration at the start and end of each survey, rather than each day. Instead of a pair of daily pistonphone calibrations, we performed daily comparisons of radiated noise measurements at similar operating conditions to verify hydrophone functionality. While not an issue at either location, this approach would have allowed us to detect issues over a broad range of frequency bands, not just at the single pistonphone calibration frequency.
3. To establish context for the turbine sound, we had intended to conduct longer duration drifts with single DAISYs with the turbines operating and shut down. These were intended to help to identify spatial variations in the soundscape and the range at which turbine sound exceeds ambient noise. However, given that the acoustic footprint for the turbines did not substantially extend beyond the survey area, such additional surveys (e.g., a drift from the headwaters of Kvichak River past the turbines in Igiugig) were not necessary.

7.2.3 Millinocket Test Plan Deviations

An unexpected challenge for data collection in Millinocket was arranging for a survey vessel to deploy the DAISYs. Our research group normally hires a vessel and operator for survey work, but because of the isolated nature of Millinocket Stream (limited underside clearance upstream and downstream of the project area), no motorized vessels routinely operate on that stretch of the river. The simplest solution was to transport a rigid inflatable boat and motor from Seattle to Maine (motor freight) and conduct operations ourselves, following training by a University of Washington vessel captain.

Initially, out of concern about overhead clearance for the Modular RivGens, we had planned to drift DAISYs only to either side of the turbines, not over the top. In actuality, overhead clearance was sufficient, which was fortunate because the natural streamlines carried the DAISYs directly over the turbines upon release. Had we been forced to rely on tethered DAISY deployments from the upstream footbridge, data quality and quantity would have been severely reduced.

During the survey, ORPC encountered difficulty with controlling the geared turbine. Such issues are not atypical when working with prototype units. Unfortunately, this meant that about half of the data collected during the second day of the survey was not useful. Designing the survey with contingency time allowed us to recover from this issue and collect sufficient data.

Finally, as previously discussed, we did not attempt localization of turbine sounds at this location.

7.2.4 Igiugig Test Plan Deviations

There were several deviations from the original test plan for Igiugig:

1. Measurements were initially delayed by a year, followed by a decision to proceed with the survey even though only one turbine could generate electrical power and export this to the grid. Because of this, the array-level evaluation of radiated noise was limited to the freewheel condition, which had distinct acoustic signatures for each turbine.
2. We did not collect data with RivGen 20 at the 25% power state and did not realize this until we had returned from Igiugig. That deviation has relatively little impact given that the trends in radiated noise with power output and rotation rate were relatively clear from the measurements at other operating conditions.
3. Because only a single turbine was in operation, we executed a higher intensity of data collection around it, enabling broader evaluations of spatial patterns in radiated noise and insight into the turbine's indirect influence on the river soundscape.

8 Conclusions and Recommendations

During this project, we measured radiated noise around three river current turbines: geared and direct drive Modular RivGens in Millinocket, ME and a direct drive RivGen in Igiugig, AK. All three turbines produced radiated noise with different characteristics. While turbine scale played a role in radiated noise levels, powertrain components and control were equally influential. All three turbines were controlled by variable-frequency drives (VFDs) which resulted in appreciable tonal noise at order 10 kHz – twice the primary switching frequency – from excitation of the generator windings. Rotating elements of the powertrains (bearings, generators, and gearboxes) produced tonal and broadband noise at lower frequencies. In the case of the geared Modular RivGen, the tonal structure was directly proportional to the generator rotation rate. The noise produced by the largest turbine – RivGen in Igiugig, AK – was similar to a recreational fishing boat, though lower amplitude. The radiated noise from the Modular RivGens was substantially lower amplitude.

Because Millinocket Stream is relatively isolated by shallow water and scoured to rock in the fastest moving areas, ambient noise levels were quite low. This allowed the radiated noise signatures from the geared and direct drive turbines to be unambiguously identified. In an environment with higher ambient noise levels (e.g., a port setting as in Haxel et al. 2022), the direct drive Modular RivGen turbine would have been extremely difficult to identify.

In Igiugig, by conducting a relatively large number of drifts, we were able to map out ambient noise and turbine-generated noise for a stretch of river extending over 100 m upstream and downstream from RivGen. This allowed us to identify two ways in which the turbine affected the soundscape: through directly radiated noise and indirectly through changes to river hydrodynamics that altered sediment mobilization and collisions. While not of environmental importance at this site because of the hearing ranges for relevant species, this is an unexpected acoustic effect that is worth keeping in mind at other locations.

For both sites, we employed IEC 62600-40 technical specifications for identifying and characterizing turbine sound. While the information from the specified survey zones at 100 m distance provided some information about the characteristics of turbine noise, for rotors of this scale in such shallow environments, data collected at closer range (i.e., 20 m standoff) was more informative. Similarly, broadening the analysis scope to consider general range dependency provided useful insights. While IEC 62600-40 is predicated on a turbine being the dominant source of sound from the low-frequency propagation cut-off to the highest frequency considered, the use of statistical tests, like the Mann-Whitney test employed here, may be a more effective method for identifying the “turbine band” for aggregate statistics. Finally, while IEC 62600-40 is intended to stratify acoustic measurements by power state, we observed no strong trend between radiated noise levels and power state (even if the frequency content varied) but did observe a weak correlation between radiated noise and rotation rate.

Finally, localization was employed in Igiugig, AK to identify the source of episodic noises (e.g., “clanks”). While the technique was effective at localizing these sounds to the RivGen turbine, accurate localization proved challenging due to unfavorable array geometries and relatively low signal-to-noise ratios. Based on this, we would only recommend that localization be employed for targeted purposes and that range dependency be used as a primary tool for source attribution for current turbines.

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11 Appendix

11.1 Millinocket, ME Survey Logistics

11.1.1 Overall Schedule

Day	Activity	Comment
1	Transit from Seattle to Portland, ME	2 h drive to Portland from Boston Logan
2	Assembly equipment at Brunswick facility, bench test, and transit to Millinocket, ME	3 h drive
3	Field operations	Target 4-6 hours of measurements
4	Field operations	Target 4-6 hours of measurements
5	Field operations	Target 4-6 hours of measurements
6	Transit to Brunswick, ME to demobilize equipment, then on to Portland, ME	3 h drive

7	Transit from Portland, ME to Seattle, WA	2 h drive from Portland to Boston Logan

11.1.2 Original Survey Plan

Table 15: DAISY deployment plan for Millinocket, ME

Survey Day	Deployment	Turbine 1	Turbine 2
Day 1	1x DAISY directly downstream of turbine (assess drift trajectory relative to downstream zone and deployment/recovery feasibility)	Standard operation (100% power)	Braked
	1x tethered DAISY (initially uninstrumented) from foot bridge	Standard operation (100% power)	Braked
A	2-3x DAISY downstream of turbines	Standard operation (100% power)	Braked
	2-3x DAISY downstream of turbines	Shutdown during drift	Braked
B	2-3x DAISY downstream of turbines	Braked	Startup during drift to freewheel
C	2-3x DAISY downstream of turbines	Freewheel	Freewheel
D	2-3x DAISY downstream of turbines	Braked	Braked
	1x DAISY directly downstream of turbine – recover in Shad Pond[1]	Standard operation (100% power)	Braked
	Repeat any surveys with suspected issues		
A	1-2x tethered DAISY from foot bridge	Standard operation (100% power)	Braked
B	12x tethered DAISY from foot bridge	Braked	Freewheel
C	1-2x tethered DAISY from foot bridge	Freewheel	Freewheel
D	1-2x tethered DAISY from foot bridge	Braked	Braked
	1-2x tethered DAISY from tailrace (if possible)	Standard operation (100% power)	Braked
Day 2	(morning) *Data analysis to assess extent of radiated noise*		
	3x DAISY downstream of turbines	Standard operation (100% power)	Standard operation (100% power)
	3x DAISY downstream of turbines	Reduced power state (75% power)	Reduced power state (75% power)
	3x DAISY downstream of turbines	Reduced power state (50% power)	Reduced power state (50% power)

[1] If water depth sufficient for vessel operation over this distance

	3x DAISY downstream of turbines	Reduced power state (25% power)	Reduced power state (25% power)
	Localization attempt: 3x DAISY downstream of turbines 2x tethered DAISY from foot bridge	Standard operation (100% power)	Standard operation (100% power)
Day 3	3x DAISY downstream of turbines	Standard operation (100% power)	Standard operation (100% power)
	3x DAISY downstream of turbines	Standard operation (100% power)	Braked
	3x DAISY downstream of turbines	Reduced power state (75% power)	Braked
	3x DAISY downstream of turbines	Reduced power state (50% power)	Braked
	3x DAISY downstream of turbines	Reduced power state (25% power)	Braked
	3x DAISY downstream of turbines	Braked	Braked
	3x DAISY downstream of turbines	Braked	Standard operation (100% power)
	3x DAISY downstream of turbines	Braked	Reduced power state (75% power)
	3x DAISY downstream of turbines	Braked	Reduced power state (50% power)
	3x DAISY downstream of turbines	Braked	Reduced power state (25% power)
	3x DAISY downstream of turbines	Braked	Braked

11.1.3 Millinocket Track Information

Table 16: List of all drifts with usable data collected in Millinocket, ME. Turbine case corresponds to descriptions in Table 7.

Track ID	DAISY	Date	Start Time (local)	End Time (local)	Deployment Mode	Turbine Case	Description
3	DAISY001	8/22/2023	1:50:43 PM	1:55:00 PM	Boat	3	Geared at various operating states (direct drive braked)
4	DAISY002	8/22/2023	1:50:43 PM	1:55:00 PM	Boat	3	Geared at various operating states (direct drive braked)
5	DAISY004	8/22/2023	1:50:43 PM	1:55:00 PM	Boat	3	Geared at various operating states (direct drive braked)
6	DAISY001	8/22/2023	2:06:20 PM	2:11:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
7	DAISY002	8/22/2023	2:06:20 PM	2:11:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
8	DAISY004	8/22/2023	2:06:20 PM	2:11:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
9	DAISY001	8/22/2023	2:21:30 PM	2:26:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
10	DAISY002	8/22/2023	2:21:30 PM	2:26:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
11	DAISY004	8/22/2023	2:21:30 PM	2:26:00 PM	Boat	6	Geared shutdown during track (direct drive braked)
12	DAISY001	8/22/2023	2:39:00 PM	2:43:50 PM	Boat	4	Geared in freewheel (direct drive braked)
13	DAISY002	8/22/2023	2:39:10 PM	2:44:00 PM	Boat	4	Geared in freewheel (direct drive braked)
14	DAISY004	8/22/2023	2:39:00 PM	2:43:30 PM	Boat	4	Geared in freewheel (direct drive braked)
15	DAISY001	8/22/2023	2:51:39 PM	2:55:59 PM	Boat	6	Geared shutdown during track (direct drive braked)

16	DAISY002	8/22/2023	2:51:39 PM	2:55:59 PM	Boat	6	Geared shutdown during track (direct drive braked)
17	DAISY004	8/22/2023	2:51:39 PM	2:55:59 PM	Boat	6	Geared shutdown during track (direct drive braked)
18	DAISY001	8/22/2023	3:06:40 PM	3:11:27 PM	Boat	1	Ambient noise
20	DAISY004	8/22/2023	3:06:40 PM	3:10:38 PM	Boat	1	Ambient noise
21	DAISY002	8/22/2023	3:27:00 PM	3:30:50 PM	Boat	3	Geared at various operating states (direct drive braked)
22	DAISY001	8/23/2023	10:38:30 AM	10:42:10 AM	Boat	14	Both turbines in freewheel
23	DAISY002	8/23/2023	10:38:30 AM	10:42:10 AM	Boat	14	Both turbines in freewheel
24	DAISY004	8/23/2023	10:38:30 AM	10:42:10 AM	Boat	14	Both turbines in freewheel
25	DAISY001	8/23/2023	10:56:20 AM	10:59:20 AM	Boat	10	Direct drive in freewheel (geared braked)
26	DAISY002	8/23/2023	10:56:20 AM	10:59:20 AM	Boat	10	Direct drive in freewheel (geared braked)
27	DAISY004	8/23/2023	10:56:20 AM	10:59:20 AM	Boat	10	Direct drive in freewheel (geared braked)
28	DAISY001	8/23/2023	11:16:40 AM	11:20:20 AM	Boat	4	Geared in freewheel (direct drive braked)
29	DAISY002	8/23/2023	11:16:40 AM	11:20:20 AM	Boat	4	Geared in freewheel (direct drive braked)
30	DAISY004	8/23/2023	11:16:40 AM	11:20:20 AM	Boat	4	Geared in freewheel (direct drive braked)
31	DAISY001	8/23/2023	11:59:50 AM	12:03:00 PM	Boat	5	Geared in freewheel with VFD engaged (direct drive braked)
32	DAISY002	8/23/2023	11:59:50 AM	12:03:00 PM	Boat	5	Geared in freewheel with VFD engaged (direct drive braked)

33	DAISY003	8/23/2023	12:01:00 PM	12:01:30 PM	Tethered	5	Geared in freewheel with VFD engaged (direct drive braked)
34	DAISY001	8/23/2023	12:09:10 PM	12:12:30 PM	Boat	5	Geared in freewheel with VFD engaged (direct drive braked)
35	DAISY002	8/23/2023	12:09:10 PM	12:12:30 PM	Boat	5	Geared in freewheel with VFD engaged (direct drive braked)
36	DAISY003	8/23/2023	12:10:36 PM	12:10:50 PM	Tethered	5	Geared in freewheel with VFD engaged (direct drive braked)
37	DAISY001	8/23/2023	12:21:20 PM	12:24:27 PM	Boat	2	Geared at > 90% max power (direct drive braked)
38	DAISY002	8/23/2023	12:21:20 PM	12:24:29 PM	Boat	2	Geared at > 90% max power (direct drive braked)
39	DAISY003	8/23/2023	12:22:25 PM	12:22:39 PM	Tethered	2	Geared at > 90% max power (direct drive braked)
40	DAISY001	8/23/2023	2:13:08 PM	2:16:25 PM	Boat	7	Geared VFD control error / direct drive at various operating states
41	DAISY002	8/23/2023	2:13:08 PM	2:16:25 PM	Boat	7	Geared VFD control error / direct drive at various operating states
42	DAISY004	8/23/2023	2:13:08 PM	2:16:25 PM	Tethered	7	Geared VFD control error / direct drive at various operating states
43	DAISY003	8/23/2023	2:14:15 PM	2:14:38 PM	Boat	7	Geared VFD control error / direct drive at various operating states
44	DAISY001	8/23/2023	2:23:31 PM	2:26:35 PM	Boat	9	Direct drive at various operating states (geared braked)
45	DAISY002	8/23/2023	2:23:31 PM	2:26:58 PM	Boat	9	Direct drive at various operating states (geared braked)
46	DAISY004	8/23/2023	2:23:31 PM	2:26:58 PM	Boat	9	Direct drive at various operating states (geared braked)
47	DAISY003	8/23/2023	2:24:37 PM	2:24:57 PM	Tethered	9	Direct drive at various operating states (geared braked)

48	DAISY001	8/23/2023	2:35:00 PM	2:37:59 PM	Boat	9	Direct drive at various operating states (geared braked)
49	DAISY002	8/23/2023	2:34:50 PM	2:37:59 PM	Boat	9	Direct drive at various operating states (geared braked)
50	DAISY004	8/23/2023	2:35:00 PM	2:37:59 PM	Boat	9	Direct drive at various operating states (geared braked)
51	DAISY003	8/23/2023	2:35:58 PM	2:36:20 PM	Tethered	9	Direct drive at various operating states (geared braked)
52	DAISY001	8/23/2023	2:46:20 PM	2:49:35 PM	Boat	12	Direct drive shutdown during track (geared braked)
53	DAISY002	8/23/2023	2:46:20 PM	2:49:35 PM	Boat	12	Direct drive shutdown during track (geared braked)
54	DAISY004	8/23/2023	2:46:20 PM	2:49:35 PM	Boat	12	Direct drive shutdown during track (geared braked)
55	DAISY003	8/23/2023	2:47:40 PM	2:48:20 PM	Tethered	12	Direct drive shutdown during track (geared braked)
56	DAISY001	8/23/2023	3:10:40 PM	3:13:30 PM	Boat	11	Direct drive in freewheel with VFD engage (geared braked)d
57	DAISY002	8/23/2023	3:10:40 PM	3:13:30 PM	Boat	11	Direct drive in freewheel with VFD engage (geared braked)d
58	DAISY004	8/23/2023	3:10:40 PM	3:13:30 PM	Boat	11	Direct drive in freewheel with VFD engage (geared braked)d
59	DAISY005	8/23/2023	3:11:48 PM	3:12:10 PM	Tethered	11	Direct drive in freewheel with VFD engage (geared braked)d
60	DAISY003	8/23/2023	3:12:00 PM	3:12:20 PM	Tethered	11	Direct drive in freewheel with VFD engage (geared braked)d
61	DAISY001	8/23/2023	3:21:35 PM	3:24:25 PM	Boat	7	Geared VFD control error / direct drive at various operating states
62	DAISY002	8/23/2023	3:21:35 PM	3:24:25 PM	Boat	7	Geared VFD control error / direct drive at various operating states

63	DAISY004	8/23/2023	3:21:35 PM	3:24:25 PM	Boat	7	Geared VFD control error / direct drive at various operating states
64	DAISY005	8/23/2023	3:22:50 PM	3:23:10 PM	Tethered	7	Geared VFD control error / direct drive at various operating states
65	DAISY003	8/23/2023	3:22:50 PM	3:23:10 PM	Tethered	7	Geared VFD control error / direct drive at various operating states
66	DAISY001	8/23/2023	3:33:20 PM	3:36:30 PM	Boat	7	Geared VFD control error / direct drive at various operating states
67	DAISY002	8/23/2023	3:33:20 PM	3:36:30 PM	Boat	7	Geared VFD control error / direct drive at various operating states
68	DAISY004	8/23/2023	3:33:20 PM	3:36:30 PM	Boat	7	Geared VFD control error / direct drive at various operating states
69	DAISY005	8/23/2023	3:34:40 PM	3:35:05 PM	Tethered	7	Geared VFD control error / direct drive at various operating states
70	DAISY003	8/23/2023	3:34:40 PM	3:35:05 PM	Tethered	7	Geared VFD control error / direct drive at various operating states
71	DAISY001	8/24/2023	11:35:31 AM	11:38:30 AM	Boat	13	Both turbines operating at various states
72	DAISY001	8/24/2023	11:44:16 AM	11:47:34 AM	Boat	13	Both turbines operating at various states
73	DAISY001	8/24/2023	12:00:21 PM	12:03:26 PM	Boat	13	Both turbines operating at various states
74	DAISY004	8/24/2023	12:00:21 PM	12:03:26 PM	Boat	13	Both turbines operating at various states
75	DAISY001	8/24/2023	12:11:40 PM	12:15:20 PM	Boat	13	Both turbines operating at various states
76	DAISY004	8/24/2023	12:11:40 PM	12:15:20 PM	Boat	13	Both turbines operating at various states
77	DAISY003	8/24/2023	12:12:57 PM	12:13:01 PM	Tethered	13	Both turbines operating at various states

78	DAISY001	8/24/2023	12:22:38 PM	12:26:01 PM	Boat	13	Both turbines operating at various states
79	DAISY004	8/24/2023	12:22:38 PM	12:26:01 PM	Boat	13	Both turbines operating at various states
80	DAISY003	8/24/2023	12:23:49 PM	12:24:08 PM	Tethered	13	Both turbines operating at various states
81	DAISY001	8/24/2023	12:46:10 PM	12:49:07 PM	Boat	9	Direct drive at various operating states (geared braked)
82	DAISY004	8/24/2023	12:46:10 PM	12:49:07 PM	Boat	9	Direct drive at various operating states (geared braked)
83	DAISY003	8/24/2023	12:47:00 PM	12:47:20 PM	Tethered	9	Direct drive at various operating states (geared braked)
84	DAISY001	8/24/2023	12:55:25 PM	12:58:40 PM	Boat	9	Direct drive at various operating states (geared braked)
85	DAISY004	8/24/2023	12:55:25 PM	12:58:40 PM	Boat	9	Direct drive at various operating states (geared braked)
87	DAISY001	8/24/2023	1:04:30 PM	1:07:52 PM	Boat	9	Direct drive at various operating states (geared braked)
88	DAISY004	8/24/2023	1:04:30 PM	1:07:52 PM	Boat	9	Direct drive at various operating states (geared braked)
89	DAISY003	8/24/2023	1:05:45 PM	1:06:02 PM	Tethered	9	Direct drive at various operating states (geared braked)
90	DAISY001	8/24/2023	1:12:57 PM	1:16:22 PM	Boat	9	Direct drive at various operating states (geared braked)
91	DAISY004	8/24/2023	1:12:57 PM	1:16:22 PM	Boat	9	Direct drive at various operating states (geared braked)
93	DAISY001	8/24/2023	2:41:56 PM	2:44:59 PM	Boat	2	Geared at > 90% max power (direct drive braked)
95	DAISY001	8/24/2023	2:55:30 PM	2:58:16 PM	Boat	3	Geared at various operating states (direct drive braked)

96	DAISY003	8/24/2023	2:55:58 PM	2:56:17 PM	Tethered	3	Geared at various operating states (direct drive braked)
97	DAISY001	8/24/2023	3:04:35 PM	3:07:41 PM	Boat	3	Geared at various operating states (direct drive braked)
98	DAISY003	8/24/2023	3:05:47 PM	3:06:11 PM	Tethered	3	Geared at various operating states (direct drive braked)
99	DAISY001	8/24/2023	3:37:48 PM	3:40:48 PM	Boat	3	Geared at various operating states (direct drive braked)
100	DAISY004	8/24/2023	3:37:48 PM	3:40:22 PM	Boat	3	Geared at various operating states (direct drive braked)
101	DAISY003	8/24/2023	3:38:58 PM	3:39:18 PM	Tethered	3	Geared at various operating states (direct drive braked)
102	DAISY001	8/24/2023	3:46:09 PM	3:49:15 PM	Boat	4	Geared in freewheel (direct drive braked)
103	DAISY004	8/24/2023	3:46:09 PM	3:49:15 PM	Boat	4	Geared in freewheel (direct drive braked)
105	DAISY001	8/24/2023	4:05:28 PM	4:08:43 PM	Boat	3	Geared at various operating states (direct drive braked)
106	DAISY004	8/24/2023	4:05:28 PM	4:08:43 PM	Boat	3	Geared at various operating states (direct drive braked)

11.1.4 Packing List

Underlined items are non-standard components emphasized for packing.

Five each Shallow DAISY:

- Rigid hull surface expression
- Anti-roll trim weights
- Hydrophone recording package
- Surface recording package
- Met station
- Extension disks for vertical motion damping
- Garmin tracker
- GoPro, mount, and charging cable

Field equipment:

- Android tracking tablet
- Garmin Astro tracker
- Field tool bag
- Spare hardware kit (x2)
- Boat GPS and charging cable
- G.R.A.S. field calibrator
- Sontek Castaway CTD
- Spare hydrophone guard (PVC)
- Slip line: 500’ (for DAISY deployment/recovery from bridge)
- PFDs (x2)
- Short-range radios (x2)
- Spare AA batteries (x24)
- DAISY wireless base station
- USB hub (GoPro charging)
- High-capacity hard drives (x2)
- Cordless drill and bit set
- Extension cord
- Power strip
- Hot knife for cutting rope to length
- Grigi for bringing in DAISY dropped from bridge

Boat:

- Boat
- Engine oil (1-2 quarters)
- Dollies (2x)
- Boat hook
- Patch kit

11.2 Igiugig, AK Survey Logistics

11.2.1 Overall Schedule

Day	Activity	Comment
1	Transit from Seattle to Anchorage, AK	Overnight stay in Anchorage, AK
2	Transfer air cargo to De'nina and transit to Igiugig, AK	Leave rental vehicle at De'nina
3	Assemble and bench test equipment to verify operation	
4	Field operations	Target 4+ hours of measurements
5	Field operations	Target 4+ hours of measurements
6	Field operations	Target 4+ hours of measurements
7	Field operations	Target 4+ hours of measurements
8	Demobilize equipment	
9	Transit to Anchorage, AK and transfer air cargo to Alaska Airlines, transit to Seattle	

11.2.2 Original Survey Plan

Table 17: DAISY deployment schedule for Igiugig, AK

Survey Day	Deployment	Turbine 1	Turbine 2
Day 1	**Overall Objectives**: Obtain preliminary information about differences in radiated noise at each power state, transients associated with shutdown and restart, and spatial extent of noise from freewheel condition		
	1x DAISY from upstream release point (assess drift trajectory relative to downstream zone and deployment/recovery feasibility)	Standard operation (100% power)	Braked
	3x DAISY upstream of turbines	Standard operation (100% power)	Braked
	3x DAISY upstream of turbines	Shutdown during drift (100% power)	Braked
	3x DAISY upstream of turbines	Braked	Braked
	3x DAISY upstream of turbines	Start up during drift (100% power)	Braked
	3x DAISY upstream of turbines	Reduced power state (75%)	Braked
	3x DAISY upstream of turbines	Reduced power state (50%)	Braked
	3x DAISY upstream of turbines	Reduced power state (25%)	Braked
	3x DAISY upstream of turbines	Freewheel	Braked
	3x DAISY upstream of turbines	Freewheel	Freewheel

	Repeat any prior surveys potentially contaminated by vessel traffic		
Day 2	**Overall Objectives**: • Shore team: Analyze data from Day 1 to assess extent of radiated noise and potential to localize any sounds of interest • Field team: Distributed spatial information at standard operating state, characterize Kvichak River soundscape		
	3x DAISY upstream of turbines	Standard operation (100% power)	Braked
	Repeat to capture spatial variability in radiated noise (4-6x depending on vessel traffic and time)		
	Soundscape drift: 1x DAISY at headwater of Kvichak River to downstream of turbines	Standard operation (100% power)	Braked
	Acoustic comparison: 3x DAISY upstream of turbines, restart engines and motor past turbine at same time as DAISYs	Standard operation (100% power)	Braked
Day 3	**Overall Objectives**: • Shore team: Analysis of spatial data to determine if additional surveys are required, make any necessary repairs to DAISYs • Field teams: If localization appears possible, attempt 5x DAISY deployment from pair of vessels, freewheel acoustic characterization		
	5x DAISY upstream of turbines (John boat + inflatable)	Standard operation (100% power)	Braked
	5x DAISY upstream of turbines	Standard operation (100% power)	Braked
	3x DAISY upstream of turbines	Freewheel	Freewheel
	Repeat to capture spatial variability in radiated noise (4-6x depending on vessel traffic and time)		
Day 4	**Overall Objectives**: • Shore team: Analysis of spatial data to determine if additional surveys are required, analysis of localization results, make any necessary repairs to DAISYs • Field team: surveys guided by outcomes from prior days		
	3x DAISY upstream of turbines	TBD	Braked
	Repeat any prior surveys potentially contaminated by vessel traffic		

11.2.3 Igiugig Track Information

Table 18: List of all drifts with usable data collected in Igiugig, AK. Turbine case corresponds to descriptions in Table 12.

Track ID	DAISY	Date	Start Time (local)	End Time (local)	Deployment Mode	Turbine Case	Description
5	DAISY004	6/10/2024	9:43:30 AM	9:45:36 AM	Boat	2	RG20 full power (RG21 braked)
6	DAISY003	6/10/2024	10:04:56 AM	10:08:34 AM	Boat	1	Ambient noise
7	DAISY004	6/10/2024	10:04:56 AM	10:08:34 AM	Boat	1	Ambient noise
8	DAISY003	6/10/2024	10:17:43 AM	10:21:20 AM	Boat	1	Ambient noise
9	DAISY004	6/10/2024	10:17:43 AM	10:21:20 AM	Boat	1	Ambient noise
10	DAISY003	6/10/2024	10:27:08 AM	10:30:10 AM	Boat	2	RG20 full power (RG21 braked)
11	DAISY004	6/10/2024	10:27:08 AM	10:30:10 AM	Boat	2	RG20 full power (RG21 braked)
12	DAISY003	6/10/2024	10:35:52 AM	10:39:25 AM	Boat	4	RG20 transient (RG21 braked)
13	DAISY004	6/10/2024	10:35:52 AM	10:39:25 AM	Boat	4	RG20 transient (RG21 braked)
14	DAISY003	6/10/2024	10:54:22 AM	10:57:51 AM	Boat	2	RG20 full power (RG21 braked)
15	DAISY004	6/10/2024	10:54:22 AM	10:57:51 AM	Boat	2	RG20 full power (RG21 braked)
16	DAISY003	6/10/2024	11:02:29 AM	11:06:05 AM	Boat	2	RG20 full power (RG21 braked)
17	DAISY004	6/10/2024	11:02:29 AM	11:06:05 AM	Boat	2	RG20 full power (RG21 braked)
18	DAISY003	6/10/2024	11:12:03 AM	11:15:45 AM	Boat	3	RG20 variable power (RG 21 braked)
19	DAISY004	6/10/2024	11:12:03 AM	11:15:45 AM	Boat	3	RG20 variable power (RG 21 braked)

20	DAISY003	6/10/2024	11:20:00 AM	11:23:15 AM	Boat	3	RG20 variable power (RG 21 braked)
21	DAISY004	6/10/2024	11:20:00 AM	11:23:15 AM	Boat	3	RG20 variable power (RG 21 braked)
22	DAISY003	6/10/2024	11:27:35 AM	11:31:40 AM	Boat	5	RG20 freewheel (RG21 braked)
23	DAISY004	6/10/2024	11:27:35 AM	11:31:40 AM	Boat	5	RG20 freewheel (RG21 braked)
24	DAISY003	6/10/2024	11:37:55 AM	11:40:15 AM	Boat	7	Dual freewheel
25	DAISY004	6/10/2024	11:37:55 AM	11:40:15 AM	Boat	7	Dual freewheel
26	DAISY003	6/10/2024	11:48:14 AM	11:50:42 AM	Boat	2	RG20 full power (RG21 braked)
27	DAISY004	6/10/2024	11:48:14 AM	11:50:42 AM	Boat	2	RG20 full power (RG21 braked)
30	DAISY003	6/11/2024	9:37:15 AM	9:39:45 AM	Boat	2	RG20 full power (RG21 braked)
31	DAISY004	6/11/2024	9:37:15 AM	9:39:45 AM	Boat	2	RG20 full power (RG21 braked)
32	DAISY003	6/11/2024	9:43:10 AM	9:45:49 AM	Boat	2	RG20 full power (RG21 braked)
33	DAISY004	6/11/2024	9:43:10 AM	9:45:49 AM	Boat	2	RG20 full power (RG21 braked)
38	DAISY003	6/11/2024	10:01:35 AM	10:04:50 AM	Boat	3	RG20 variable power (RG 21 braked)
39	DAISY004	6/11/2024	10:01:35 AM	10:04:50 AM	Boat	3	RG20 variable power (RG 21 braked)
40	DAISY003	6/11/2024	10:07:27 AM	10:10:40 AM	Boat	3	RG20 variable power (RG 21 braked)
41	DAISY004	6/11/2024	10:07:27 AM	10:10:40 AM	Boat	3	RG20 variable power (RG 21 braked)
42	DAISY003	6/11/2024	10:13:12 AM	10:15:45 AM	Boat	3	RG20 variable power (RG 21 braked)
43	DAISY004	6/11/2024	10:13:12 AM	10:15:45 AM	Boat	3	RG20 variable power (RG 21 braked)
44	DAISY003	6/11/2024	10:18:54 AM	10:21:13 AM	Boat	2	RG20 full power (RG21 braked)

45	DAISY004	6/11/2024	10:18:54 AM	10:21:13 AM	Boat	2	RG20 full power (RG21 braked)
46	DAISY003	6/11/2024	10:24:02 AM	10:27:20 AM	Boat	2	RG20 full power (RG21 braked)
47	DAISY004	6/11/2024	10:24:02 AM	10:27:20 AM	Boat	2	RG20 full power (RG21 braked)
50	DAISY003	6/11/2024	10:35:52 AM	10:38:45 AM	Boat	2	RG20 full power (RG21 braked)
51	DAISY004	6/11/2024	10:35:52 AM	10:38:45 AM	Boat	2	RG20 full power (RG21 braked)
52	DAISY003	6/11/2024	10:42:16 AM	10:45:40 AM	Boat	2	RG20 full power (RG21 braked)
53	DAISY004	6/11/2024	10:42:16 AM	10:45:40 AM	Boat	2	RG20 full power (RG21 braked)
54	DAISY003	6/11/2024	10:48:41 AM	10:52:00 AM	Boat	2	RG20 full power (RG21 braked)
55	DAISY004	6/11/2024	10:48:41 AM	10:52:00 AM	Boat	2	RG20 full power (RG21 braked)
56	DAISY003	6/11/2024	10:54:50 AM	10:58:33 AM	Boat	2	RG20 full power (RG21 braked)
57	DAISY004	6/11/2024	10:54:50 AM	10:58:33 AM	Boat	2	RG20 full power (RG21 braked)
58	DAISY003	6/11/2024	11:01:51 AM	11:04:18 AM	Boat	8	Intentional boat operations
59	DAISY004	6/11/2024	11:01:51 AM	11:04:18 AM	Boat	8	Intentional boat operations
60	DAISY003	6/11/2024	11:09:30 AM	11:13:00 AM	Boat	8	Intentional boat operations
61	DAISY004	6/11/2024	11:09:30 AM	11:13:00 AM	Boat	8	Intentional boat operations
64	DAISY003	6/11/2024	11:21:17 AM	11:25:03 AM	Boat	2	RG20 full power (RG21 braked)
65	DAISY004	6/11/2024	11:21:17 AM	11:25:03 AM	Boat	2	RG20 full power (RG21 braked)
66	DAISY003	6/11/2024	11:29:51 AM	11:36:27 AM	Boat	2	RG20 full power (RG21 braked)

67	DAISY004	6/11/2024	11:29:51 AM	11:36:27 AM	Boat	2	RG20 full power (RG21 braked)
68	DAISY003	6/11/2024	11:40:18 AM	11:44:50 AM	Boat	2	RG20 full power (RG21 braked)
69	DAISY004	6/11/2024	11:40:18 AM	11:44:50 AM	Boat	2	RG20 full power (RG21 braked)
75	DAISY001	6/12/2024	9:56:46 AM	9:58:47 AM	Boat	3	RG20 variable power (RG 21 braked)
76	DAISY002	6/12/2024	9:56:46 AM	9:58:47 AM	Boat	3	RG20 variable power (RG 21 braked)
77	DAISY003	6/12/2024	9:56:46 AM	9:58:47 AM	Boat	3	RG20 variable power (RG 21 braked)
78	DAISY004	6/12/2024	9:56:46 AM	9:58:47 AM	Boat	3	RG20 variable power (RG 21 braked)
79	DAISY005	6/12/2024	9:56:46 AM	9:58:47 AM	Boat	3	RG20 variable power (RG 21 braked)
80	DAISY001	6/12/2024	10:05:56 AM	10:08:25 AM	Boat	3	RG20 variable power (RG 21 braked)
81	DAISY002	6/12/2024	10:05:56 AM	10:08:25 AM	Boat	3	RG20 variable power (RG 21 braked)
82	DAISY003	6/12/2024	10:05:56 AM	10:08:25 AM	Boat	3	RG20 variable power (RG 21 braked)
83	DAISY004	6/12/2024	10:05:56 AM	10:08:25 AM	Boat	3	RG20 variable power (RG 21 braked)
84	DAISY005	6/12/2024	10:05:56 AM	10:08:25 AM	Boat	3	RG20 variable power (RG 21 braked)
85	DAISY001	6/12/2024	10:16:30 AM	10:18:44 AM	Boat	3	RG20 variable power (RG 21 braked)
86	DAISY002	6/12/2024	10:16:30 AM	10:18:44 AM	Boat	3	RG20 variable power (RG 21 braked)
87	DAISY003	6/12/2024	10:16:30 AM	10:18:44 AM	Boat	3	RG20 variable power (RG 21 braked)
88	DAISY004	6/12/2024	10:16:30 AM	10:18:44 AM	Boat	3	RG20 variable power (RG 21 braked)
89	DAISY005	6/12/2024	10:16:30 AM	10:18:44 AM	Boat	3	RG20 variable power (RG 21 braked)
90	DAISY001	6/12/2024	10:29:20 AM	10:32:52 AM	Boat	3	RG20 variable power (RG 21 braked)
91	DAISY002	6/12/2024	10:29:20 AM	10:32:52 AM	Boat	3	RG20 variable power (RG 21 braked)

92	DAISY003	6/12/2024	10:29:20 AM	10:32:52 AM	Boat	3	RG20 variable power (RG 21 braked)
93	DAISY004	6/12/2024	10:29:20 AM	10:32:52 AM	Boat	3	RG20 variable power (RG 21 braked)
94	DAISY005	6/12/2024	10:29:20 AM	10:32:52 AM	Boat	3	RG20 variable power (RG 21 braked)
95	DAISY001	6/12/2024	10:39:27 AM	10:42:50 AM	Boat	1	Ambient noise
96	DAISY002	6/12/2024	10:39:27 AM	10:42:50 AM	Boat	1	Ambient noise
97	DAISY003	6/12/2024	10:39:27 AM	10:42:50 AM	Boat	1	Ambient noise
98	DAISY004	6/12/2024	10:39:27 AM	10:42:50 AM	Boat	1	Ambient noise
99	DAISY005	6/12/2024	10:39:27 AM	10:42:50 AM	Boat	1	Ambient noise
100	DAISY001	6/12/2024	10:52:41 AM	10:56:43 AM	Boat	1	Ambient noise
101	DAISY002	6/12/2024	10:52:41 AM	10:56:43 AM	Boat	1	Ambient noise
102	DAISY003	6/12/2024	10:52:41 AM	10:56:43 AM	Boat	1	Ambient noise
103	DAISY004	6/12/2024	10:52:41 AM	10:56:43 AM	Boat	1	Ambient noise
104	DAISY005	6/12/2024	10:52:41 AM	10:56:43 AM	Boat	1	Ambient noise
105	DAISY002	6/12/2024	11:08:40 AM	11:11:28 AM	Boat	1	Ambient noise
107	DAISY005	6/12/2024	11:08:40 AM	11:11:28 AM	Boat	1	Ambient noise
108	DAISY002	6/12/2024	11:15:56 AM	11:19:24 AM	Boat	1	Ambient noise
109	DAISY004	6/12/2024	11:15:56 AM	11:19:24 AM	Boat	1	Ambient noise
110	DAISY005	6/12/2024	11:15:56 AM	11:19:24 AM	Boat	1	Ambient noise

111	DAISY002	6/12/2024	11:25:40 AM	11:28:40 AM	Boat	1	Ambient noise
112	DAISY004	6/12/2024	11:25:40 AM	11:28:40 AM	Boat	1	Ambient noise
113	DAISY005	6/12/2024	11:25:40 AM	11:28:40 AM	Boat	1	Ambient noise
114	DAISY002	6/12/2024	11:34:05 AM	11:37:20 AM	Boat	5	RG20 freewheel (RG21 braked)
115	DAISY004	6/12/2024	11:34:05 AM	11:37:20 AM	Boat	5	RG20 freewheel (RG21 braked)
116	DAISY005	6/12/2024	11:34:09 AM	11:37:20 AM	Boat	5	RG20 freewheel (RG21 braked)
117	DAISY002	6/12/2024	11:44:30 AM	11:46:58 AM	Boat	6	RG21 freewheel (RG20 braked)
118	DAISY004	6/12/2024	11:44:30 AM	11:46:58 AM	Boat	6	RG21 freewheel (RG20 braked)
120	DAISY002	6/12/2024	11:54:05 AM	11:57:38 AM	Boat	6	RG21 freewheel (RG20 braked)
121	DAISY004	6/12/2024	11:54:05 AM	11:57:38 AM	Boat	6	RG21 freewheel (RG20 braked)
122	DAISY005	6/12/2024	11:54:05 AM	11:57:38 AM	Boat	6	RG21 freewheel (RG20 braked)
128	DAISY001	6/13/2024	10:48:23 AM	10:51:04 AM	Boat	8	Intentional boat operations
129	DAISY002	6/13/2024	10:48:23 AM	10:51:04 AM	Boat	8	Intentional boat operations
130	DAISY001	6/13/2024	10:56:05 AM	10:59:05 AM	Boat	8	Intentional boat operations
131	DAISY002	6/13/2024	10:56:05 AM	10:59:05 AM	Boat	8	Intentional boat operations
132	DAISY001	6/13/2024	11:04:43 AM	11:07:26 AM	Boat	8	Intentional boat operations
133	DAISY002	6/13/2024	11:04:43 AM	11:07:26 AM	Boat	8	Intentional boat operations
134	DAISY001	6/13/2024	11:22:30 AM	11:24:42 AM	Boat	1	Ambient noise

135	DAISY002	6/13/2024	11:22:30 AM	11:24:42 AM	Boat	1	Ambient noise
136	DAISY003	6/13/2024	11:22:30 AM	11:24:42 AM	Boat	1	Ambient noise
137	DAISY004	6/13/2024	11:22:30 AM	11:24:42 AM	Boat	1	Ambient noise
138	DAISY005	6/13/2024	11:22:30 AM	11:24:42 AM	Boat	1	Ambient noise
139	DAISY001	6/13/2024	11:29:28 AM	11:32:52 AM	Boat	1	Ambient noise
140	DAISY002	6/13/2024	11:29:28 AM	11:32:52 AM	Boat	1	Ambient noise
141	DAISY003	6/13/2024	11:29:28 AM	11:32:52 AM	Boat	1	Ambient noise
142	DAISY004	6/13/2024	11:29:28 AM	11:32:52 AM	Boat	1	Ambient noise
143	DAISY005	6/13/2024	11:29:28 AM	11:32:52 AM	Boat	1	Ambient noise
144	DAISY001	6/13/2024	11:50:56 AM	11:51:56 AM	Boat	1	Ambient noise
145	DAISY002	6/13/2024	11:50:56 AM	11:51:56 AM	Boat	1	Ambient noise
146	DAISY003	6/13/2024	11:50:56 AM	11:51:56 AM	Boat	1	Ambient noise
148	DAISY005	6/13/2024	11:50:56 AM	11:51:56 AM	Boat	1	Ambient noise
149	DAISY001	6/13/2024	11:57:23 AM	12:00:20 PM	Boat	1	Ambient noise
150	DAISY002	6/13/2024	11:57:23 AM	12:00:20 PM	Boat	1	Ambient noise
151	DAISY003	6/13/2024	11:57:23 AM	12:00:20 PM	Boat	1	Ambient noise
152	DAISY004	6/13/2024	11:57:23 AM	12:00:20 PM	Boat	1	Ambient noise
153	DAISY005	6/13/2024	11:57:23 AM	12:00:20 PM	Boat	1	Ambient noise

154	DAISY001	6/13/2024	12:04:16 PM	12:07:12 PM	Boat	1	Ambient noise
155	DAISY002	6/13/2024	12:04:16 PM	12:07:12 PM	Boat	1	Ambient noise
156	DAISY003	6/13/2024	12:04:16 PM	12:07:12 PM	Boat	1	Ambient noise
157	DAISY004	6/13/2024	12:04:16 PM	12:07:12 PM	Boat	1	Ambient noise
158	DAISY005	6/13/2024	12:04:16 PM	12:07:12 PM	Boat	1	Ambient noise
159	DAISY001	6/13/2024	12:14:40 PM	12:16:45 PM	Boat	4	RG20 transient (RG21 braked)
160	DAISY002	6/13/2024	12:14:40 PM	12:16:45 PM	Boat	4	RG20 transient (RG21 braked)
161	DAISY003	6/13/2024	12:14:40 PM	12:16:45 PM	Boat	4	RG20 transient (RG21 braked)
162	DAISY004	6/13/2024	12:14:40 PM	12:16:45 PM	Boat	4	RG20 transient (RG21 braked)
163	DAISY005	6/13/2024	12:14:40 PM	12:16:45 PM	Boat	4	RG20 transient (RG21 braked)
164	DAISY001	6/13/2024	12:22:15 PM	12:25:15 PM	Boat	3	RG20 variable power (RG 21 braked)
165	DAISY002	6/13/2024	12:22:15 PM	12:25:15 PM	Boat	3	RG20 variable power (RG 21 braked)
166	DAISY003	6/13/2024	12:22:15 PM	12:25:15 PM	Boat	3	RG20 variable power (RG 21 braked)
167	DAISY004	6/13/2024	12:22:15 PM	12:25:15 PM	Boat	3	RG20 variable power (RG 21 braked)
168	DAISY005	6/13/2024	12:22:17 PM	12:25:15 PM	Boat	3	RG20 variable power (RG 21 braked)
169	DAISY001	6/13/2024	12:29:22 PM	12:32:45 PM	Boat	3	RG20 variable power (RG 21 braked)
170	DAISY002	6/13/2024	12:29:22 PM	12:32:45 PM	Boat	3	RG20 variable power (RG 21 braked)
171	DAISY003	6/13/2024	12:29:22 PM	12:32:45 PM	Boat	3	RG20 variable power (RG 21 braked)

172	DAISY004	6/13/2024	12:29:22 PM	12:32:45 PM	Boat	3	RG20 variable power (RG 21 braked)
173	DAISY005	6/13/2024	12:29:22 PM	12:32:45 PM	Boat	3	RG20 variable power (RG 21 braked)
174	DAISY001	6/13/2024	12:37:35 PM	12:39:43 PM	Boat	3	RG20 variable power (RG 21 braked)
175	DAISY002	6/13/2024	12:37:35 PM	12:39:43 PM	Boat	3	RG20 variable power (RG 21 braked)
176	DAISY003	6/13/2024	12:37:35 PM	12:39:43 PM	Boat	3	RG20 variable power (RG 21 braked)
177	DAISY004	6/13/2024	12:37:35 PM	12:39:43 PM	Boat	3	RG20 variable power (RG 21 braked)
178	DAISY005	6/13/2024	12:37:35 PM	12:39:43 PM	Boat	3	RG20 variable power (RG 21 braked)
179	DAISY001	6/13/2024	12:44:14 PM	12:47:09 PM	Boat	3	RG20 variable power (RG 21 braked)
180	DAISY002	6/13/2024	12:44:14 PM	12:47:09 PM	Boat	3	RG20 variable power (RG 21 braked)
181	DAISY003	6/13/2024	12:44:14 PM	12:47:09 PM	Boat	3	RG20 variable power (RG 21 braked)
182	DAISY004	6/13/2024	12:44:14 PM	12:47:09 PM	Boat	3	RG20 variable power (RG 21 braked)
183	DAISY005	6/13/2024	12:44:14 PM	12:47:09 PM	Boat	3	RG20 variable power (RG 21 braked)
184	DAISY001	6/14/2024	9:43:49 AM	9:46:50 AM	Boat	2	RG20 full power (RG21 braked)
185	DAISY002	6/14/2024	9:43:49 AM	9:46:50 AM	Boat	2	RG20 full power (RG21 braked)
186	DAISY003	6/14/2024	9:43:49 AM	9:46:50 AM	Boat	2	RG20 full power (RG21 braked)
187	DAISY001	6/14/2024	9:50:25 AM	9:53:25 AM	Boat	2	RG20 full power (RG21 braked)
188	DAISY002	6/14/2024	9:50:25 AM	9:53:25 AM	Boat	2	RG20 full power (RG21 braked)
189	DAISY003	6/14/2024	9:50:25 AM	9:53:25 AM	Boat	2	RG20 full power (RG21 braked)
190	DAISY001	6/14/2024	9:56:05 AM	9:59:05 AM	Boat	2	RG20 full power (RG21 braked)
191	DAISY002	6/14/2024	9:56:05 AM	9:59:05 AM	Boat	2	RG20 full power (RG21 braked)
192	DAISY003	6/14/2024	9:56:05 AM	9:59:05 AM	Boat	2	RG20 full power (RG21 braked)

196	DAISY001	6/14/2024	10:06:38 AM	10:07:20 AM	Boat	2	RG20 full power (RG21 braked)
197	DAISY001	6/14/2024	10:08:50 AM	10:09:17 AM	Boat	2	RG20 full power (RG21 braked)
198	DAISY001	6/14/2024	10:12:29 AM	10:14:34 AM	Boat	2	RG20 full power (RG21 braked)
199	DAISY002	6/14/2024	10:12:29 AM	10:14:34 AM	Boat	2	RG20 full power (RG21 braked)
200	DAISY003	6/14/2024	10:12:29 AM	10:14:34 AM	Boat	2	RG20 full power (RG21 braked)
201	DAISY001	6/14/2024	10:17:17 AM	10:19:15 AM	Boat	2	RG20 full power (RG21 braked)
202	DAISY002	6/14/2024	10:17:17 AM	10:19:15 AM	Boat	2	RG20 full power (RG21 braked)
203	DAISY003	6/14/2024	10:17:17 AM	10:19:15 AM	Boat	2	RG20 full power (RG21 braked)
204	DAISY001	6/14/2024	10:24:34 AM	10:28:17 AM	Boat	2	RG20 full power (RG21 braked)
205	DAISY002	6/14/2024	10:24:34 AM	10:28:17 AM	Boat	2	RG20 full power (RG21 braked)
206	DAISY003	6/14/2024	10:24:34 AM	10:28:17 AM	Boat	2	RG20 full power (RG21 braked)
207	DAISY001	6/14/2024	11:00:19 AM	11:01:08 AM	Boat	2	RG20 full power (RG21 braked)
208	DAISY001	6/14/2024	11:02:20 AM	11:03:20 AM	Boat	2	RG20 full power (RG21 braked)
209	DAISY001	6/14/2024	11:06:28 AM	11:09:18 AM	Boat	2	RG20 full power (RG21 braked)
210	DAISY002	6/14/2024	11:06:32 AM	11:09:18 AM	Boat	2	RG20 full power (RG21 braked)
211	DAISY003	6/14/2024	11:06:28 AM	11:09:18 AM	Boat	2	RG20 full power (RG21 braked)
212	DAISY001	6/14/2024	11:12:14 AM	11:15:18 AM	Boat	2	RG20 full power (RG21 braked)
213	DAISY002	6/14/2024	11:12:24 AM	11:15:18 AM	Boat	2	RG20 full power (RG21 braked)

214	DAISY003	6/14/2024	11:12:16 AM	11:15:18 AM	Boat	2	RG20 full power (RG21 braked)
215	DAISY001	6/14/2024	11:20:57 AM	11:22:57 AM	Boat	2	RG20 full power (RG21 braked)
216	DAISY002	6/14/2024	11:20:57 AM	11:22:57 AM	Boat	2	RG20 full power (RG21 braked)
217	DAISY003	6/14/2024	11:20:57 AM	11:22:57 AM	Boat	2	RG20 full power (RG21 braked)
218	DAISY001	6/14/2024	11:34:38 AM	11:37:30 AM	Boat	2	RG20 full power (RG21 braked)
219	DAISY002	6/14/2024	11:34:38 AM	11:37:30 AM	Boat	2	RG20 full power (RG21 braked)
220	DAISY003	6/14/2024	11:34:38 AM	11:37:30 AM	Boat	2	RG20 full power (RG21 braked)
221	DAISY001	6/14/2024	11:45:11 AM	11:48:25 AM	Boat	2	RG20 full power (RG21 braked)
222	DAISY002	6/14/2024	11:45:08 AM	11:48:25 AM	Boat	2	RG20 full power (RG21 braked)
223	DAISY003	6/14/2024	11:45:06 AM	11:48:25 AM	Boat	2	RG20 full power (RG21 braked)
224	DAISY001	6/14/2024	11:51:05 AM	11:54:10 AM	Boat	2	RG20 full power (RG21 braked)
226	DAISY003	6/14/2024	11:51:05 AM	11:54:10 AM	Boat	2	RG20 full power (RG21 braked)

11.2.4 Packing List

Underlined items are non-standard components emphasized for packing.

Five each Shallow DAISY:

- Rigid hull surface expression
- <u>Anti-roll trim weights</u>
- Hydrophone recording package
- Surface recording package
- Met station
- Garmin tracker
- <u>GoPro, mount, and charging cable</u>

Field equipment:

- Android tracking tablet
- Garmin Astro tracker
- Field tool bag
- Spare hardware kit (x2)
- Boat GPS and charging cable
- <u>G.R.A.S. field calibrator</u>
- <u>Spare hydrophone shield</u>
- <u>PFDs (x4)</u>
- <u>Short-range radios</u> (x2)
- <u>Spare AA batteries</u> (x24)
- <u>DAISY wireless base station</u>
- <u>USB hub (GoPro charging)</u>
- <u>High-capacity hard drives (x2)</u>
- <u>Cordless drill and bit set</u>