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Acoustic Monitoring in the Bay of Fundy

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Executive Summary

The Fundy Ocean Research Centre for Energy (FORCE) is a leading research facility for in-stream tidal energy technology. Located at Minas Passage in the Bay of Fundy, NS, where currents can exceed 6 m/s (Melrose 2009 2012), the FORCE test site is ideal for testing in-stream technology in harsh environments.

Effects on marine life from underwater noise generated by turbines are recognized as a potential environmental impact of in-stream turbines (Polagye et al. 2011). The rotating mechanical equipment in tidal turbines is expected to emit continuous tones into the water, perhaps at levels that could harass or harm marine life (Polagye et al. 2011, Stein 2011). To assess the acoustic impact, differences between soundscapes with and without a turbine present must be measured. Ideally, recordings would be made in all seasons, weather conditions, and tidal states, and flow noise artefacts in the data would be minimized.

In 2008, before an Open-Centre Turbine was installed (OpenHydro, Dublin), FORCE made drifting measurements of the underwater sound levels at Minas Passage. FORCE repeated this process in 2009 after the turbine was installed. However, because of vessel and surface noise contamination and the short-term nature of drifting measurements (Schillinger 2010), the data were unreliable.

The goal of this study was to measure ambient sound levels as a function of tidal state at the FORCE site. Successful measurements demonstrated the ability to subsequently measure turbine sound levels at all tidal states.

Marine life near the FORCE site includes fish, harbour seals, and harbour porpoises. The lowest frequency these animals hear is about 100 Hz. Rotating turbines are expected to generate continuous tones. Existing literature and accepted standards suggest that a root-mean-square (rms) sound pressure level (SPL) above 140 dB re 1 µPa may disturb marine life, especially porpoises. Therefore, to measure sounds above the disturbance threshold 100 m from the turbines, the autonomous monitoring system must have a one-third octave rms SPL noise floor of 100 dB re 1 µPa for 1/3-octaves above 100 Hz.

JASCO Applied Sciences (JASCO) deployed two autonomous acoustic recorders in High-Flow (HF) moorings in October 2011, one near the Berth Holder sites, and one at the FORCE reference site. The harsh conditions in the Bay of Fundy damaged the moorings, which were not recovered. JASCO reviewed the mooring design in the winter of 2011-2012, and deployed a modified HF mooring and a Streamlined Float-based (SFL) mooring on 23 March 2012. Hydrophones were set in different locations on both moorings to investigate the effects of hydrophone positions on measured sound levels. We retrieved the HF mooring on 4 April 2012. The SFL mooring surfaced on its own on 27 March 2012; we secured it on Scot's Bay beach on 28 March 2012. Both moorings provided excellent data.

On retrieval, JASCO downloaded the data and computed the sound levels as a function of time and frequency using our automated data analysis tools. The measured sound levels are presented as band levels versus time, spectrograms, percentile histograms, and 1/3-octave band-and-whisker plots of the spectral density values.

At full flow, the hydrophone internal HF mooring that was sheltered from the flow by the mooring structure had a 25^{th} percentile one-third octave rms SPL noise floor below 100 dB re

1 µPa for one-third octaves from 100 Hz–3 kHz. This sound pressure is low enough that it allows us to accurately measure turbine sound levels in all flow states that may disturb marine life. The shape of the measured noise spectra varied smoothly with frequency, so that we will easily distinguish any tidal turbine sources from the background noise spectra in the future.

Given the success of the HF mooring measurements, we recommend that future noise measurements in the Bay of Fundy use the mooring with a sinking surface float for equipment retrieval. The HF mooring should have two internal hydrophones, one on each side behind acoustically transparent windows. With this configuration one hydrophone will always be protected from the flow and that the system will record near-ambient noise levels throughout the tidal cycle.

1. Introduction

1.1. Background

The Fundy Ocean Research Centre for Energy (FORCE) is a leading research facility for in-stream tidal energy technology. The FORCE test site is located at Minas Passage in the Bay of Fundy, NS (Figure 1), where currents can exceed 6 m/s (Melrose, 2012). The test site is ideal for testing in-stream technology in harsh environments. Typical tidal variation at the test site is 11–13 m; 14 billion tonnes of seawater move through the passage each tidal cycle.

Figure 1. Project Site in the Bay of Fundy, NS. Water depth at the project site is 30–60 m; in the Minas Passage it's approximately 4.5 km wide.

Effects on marine life by underwater noise from turbines are recognized as a potential environmental impact of in-stream turbines (Polagye et al. 2011). The rotating mechanical equipment in tidal turbines is expected to emit continuous tones into the water, perhaps at levels high enough to harass or harm marine life (Polagye et al. 2011, Stein 2011). To assess the acoustic impact, differences between soundscapes with and without a turbine must be compared. Ideally, we would record this information in all seasons, weather conditions, and tidal states, and flow noise artefacts in the data minimized.

In 2008, before an Open-Centre Turbine was installed (OpenHydro, Dublin), FORCE made drifting measurements of the underwater sound levels at Minas Passage. FORCE repeated this process in 2009 after the turbine was installed. However, because of vessel and surface noise contamination and the short-term nature of drifting measurements (Schillinger 2010), the data were unreliable.

The goal of this study was to collect ambient noise data over many tidal cycles. The results demonstrate that it is possible to collect ambient and in-stream turbine noise signature using a fixed autonomous recorder.

1.2. Acoustic Monitoring in High Flow Conditions

There are three basic designs for acoustic monitoring: bottom-mounted hydrophones, hydrophones suspended in the water column, and drifting hydrophones. Stein (2011) argued that only drifting measurements made using an autonomous drifting buoy are reliable in high flow measurements. Schillinger (2010) discussed difficulties making drifting measurements from a vessel in high flow conditions, which supported Stein's conclusions. Drifting measurements only take a snapshot of the ambient noise and turbine noise when the hydrophone drifts past. Determining turbine noise levels as a function of tidal state and machinery state using drifting hydrophones is difficult. Therefore, long term measurements that use either bottom-mounted hydrophones or hydrophones suspended in the water column could provide much better information.

Hydrophones measure pressure changes. In calm water, acoustic waves are the only source of pressure change. Hydrophones can also measure pressure fluctuations from other sources, called flow noise or pseudo-noise. In high flow conditions, the flow knocks down moorings that suspend the hydrophone in the water column (Figure 2); the hydrophones measure this pressure change. The hydrophones also measure strumming noise from ropes under tension in the currents. As Stein argued, and as JASCO's measurements demonstrated, suspended hydrophone moorings cannot measure ambient sound levels in high flow conditions.

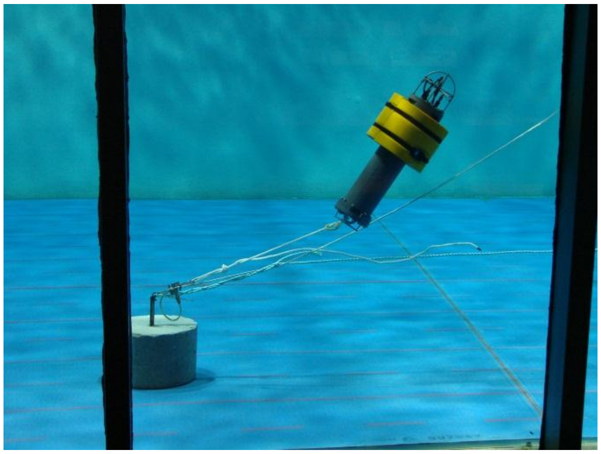

Figure 2. JASCO's Autonomous Multichannel Acoustic Recorder (AMAR) in a 0.8 m/s current in the flume tank at the Centre for Sustainable Aquatic Resources (CSAR) at Memorial University, St. John's, NL.

When water moves around the hydrophone, pressure increases on one side and decreases on the other. Eddies behind the hydrophone also create pressure fluctuations. The hydrophones measure these types of pressure changes, most of which are at frequencies below 100 Hz. Drifting measurements minimize this noise since the hydrophone moves with the water. Bottom-mounted hydrophone mooring designs also reduce flow noise due to water pressure because flow speeds at the bottom of water columns are generally lower than elsewhere in the column (Figure 3). Shielding the hydrophone also minimizes flow-induced noise. JASCO used a streamlined design called the High-Flow (HF) Mooring (Figure 4) to reduce flow noise.

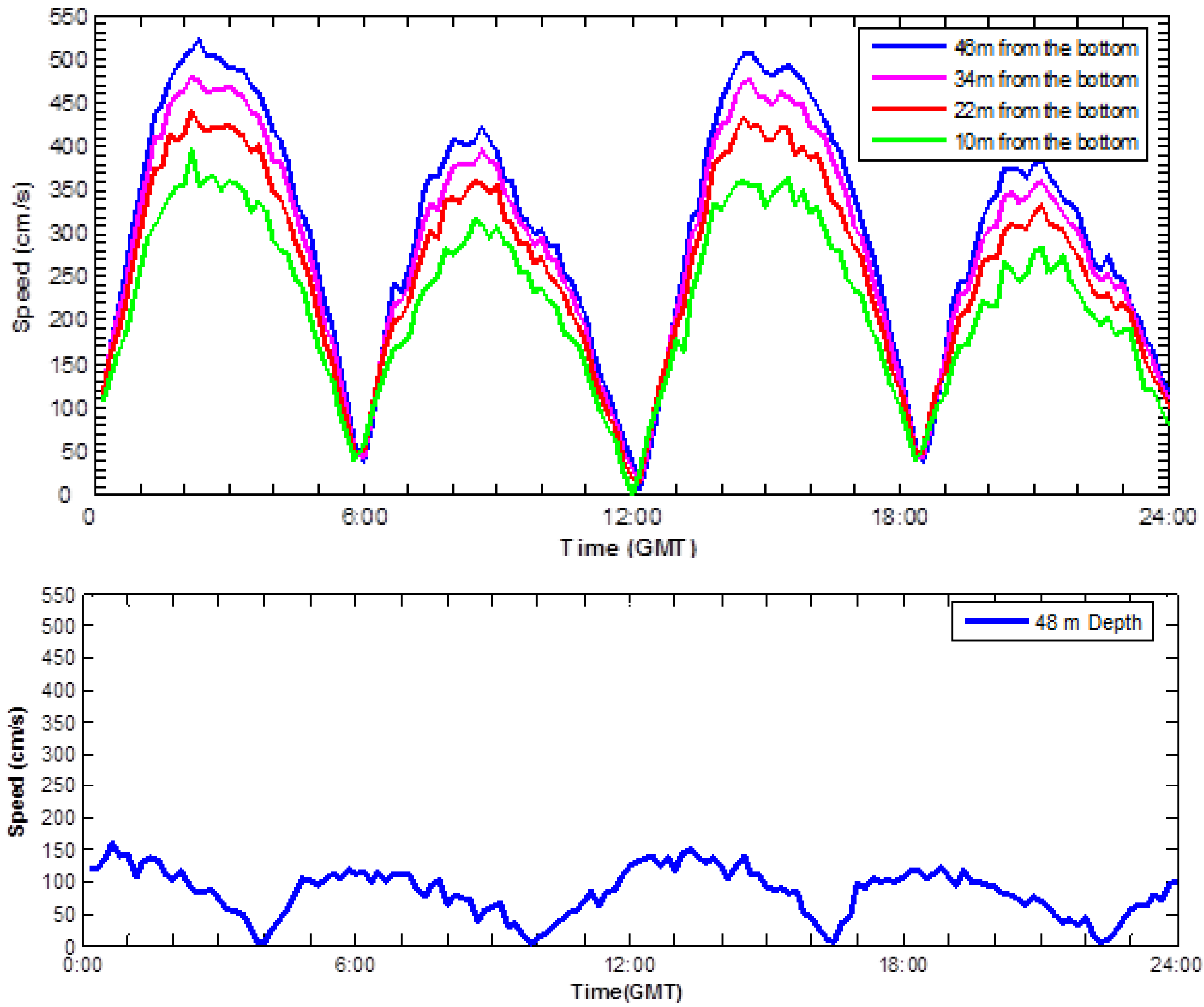

Figure 3. Current profiles from FORCE site. Top: Acoustic Doppler Current Profiler measurements of spring tides 7 May 2008. Bottom: InterOcean S4 measurements of spring tides 0.5 m above the bottom. Data courtsey of Oceans Ltd. and Minas Pulp and Paper (Ocean's 2009). The flood tides are shorter and stronger than the ebb tides at the FORCE site.

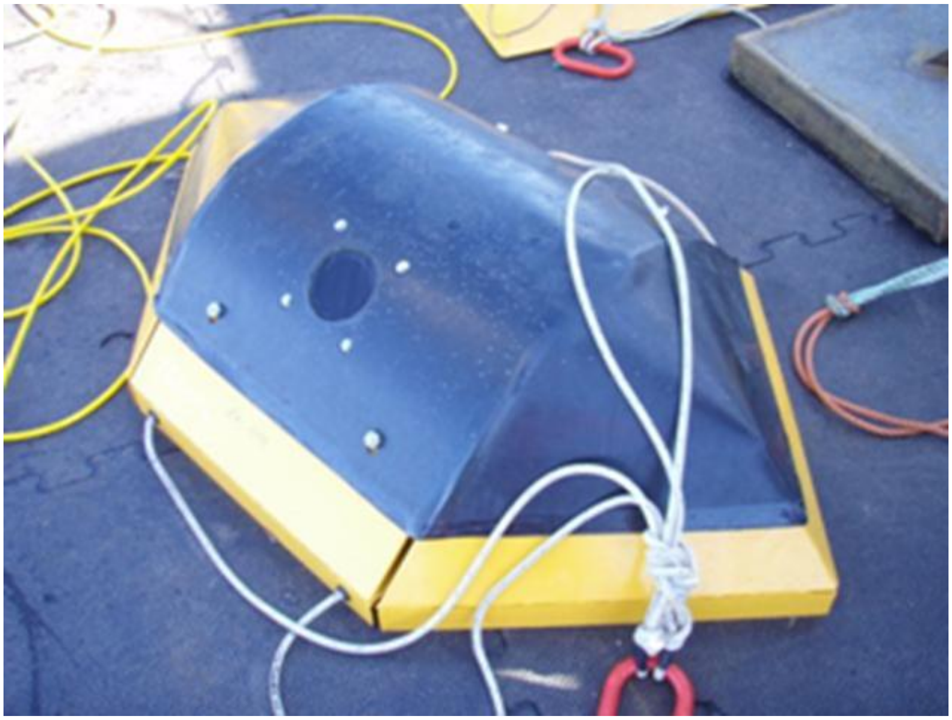

Figure 4. JASCO's High-Flow mooring (HFM).

1.3. Acoustic Thresholds for Impacts of Tidal Turbines on Marine Life

We expect the tidal turbines will generate continuous frequencies from the shaft rate, blade rates, and gearing ratios (if present) at frequencies from 1-1000 Hz. The sound levels emitted by tidal turbines should increase in frequency and amplitude as the tidal flow increases from slack tide to full flow. The root-mean-square (rms) sound pressure levels (SPLs) threshold for disturbance of marine mammals from continuous noise sources is ranges from 100–140 dB re 1 µPa (Southall et al. 2007). There are no commonly accepted thresholds for exposure to continuous sounds of fish and sea turtles.

Southall et al. (2007) recommend applying a frequency-dependent M-weighting to the sound spectrum before determining the sound pressure level. The M-weighting bands are outlined in Table 1.

Table 1. Marine Mammal Hearing groups (Southall et al. 2007).

Hearing Group	Auditory Band	Example Species
Low frequency cetaceans	7 Hz–22 kHz	Blue, fin, humpback, gray, right and bowhead whales
Mid frequency cetaceans	150 Hz–160 kHz	Dolphins, toothed whales, killer whales
High frequency cetaceans	200 Hz–180 kHz	Porpoises
Pinnipeds in water	75 Hz–75 kHz	Seals

We expect to encounter high frequency cetaceans (harbour porpoises) and pinnipeds (harbour seals) at the FORCE test site. Porpoises have shown profound and sustained avoidance behaviours to continuous sounds at 140 dB rms SPL re 1 µPa (Southall et al. 2007). Pinnipeds show limited reactions to sound levels from 90–140 dB rms SPL re 1 µPa; however, at higher SPLs data are unavailable (Southall et al. 2007).

In the absence of accepted disturbance criteria for fish and sea turtles, we examined known audiograms for these species (Figure 5, Figure 6). The audiograms indicate fish and turtles typically have an auditory range from 70 Hz–1 kHz.

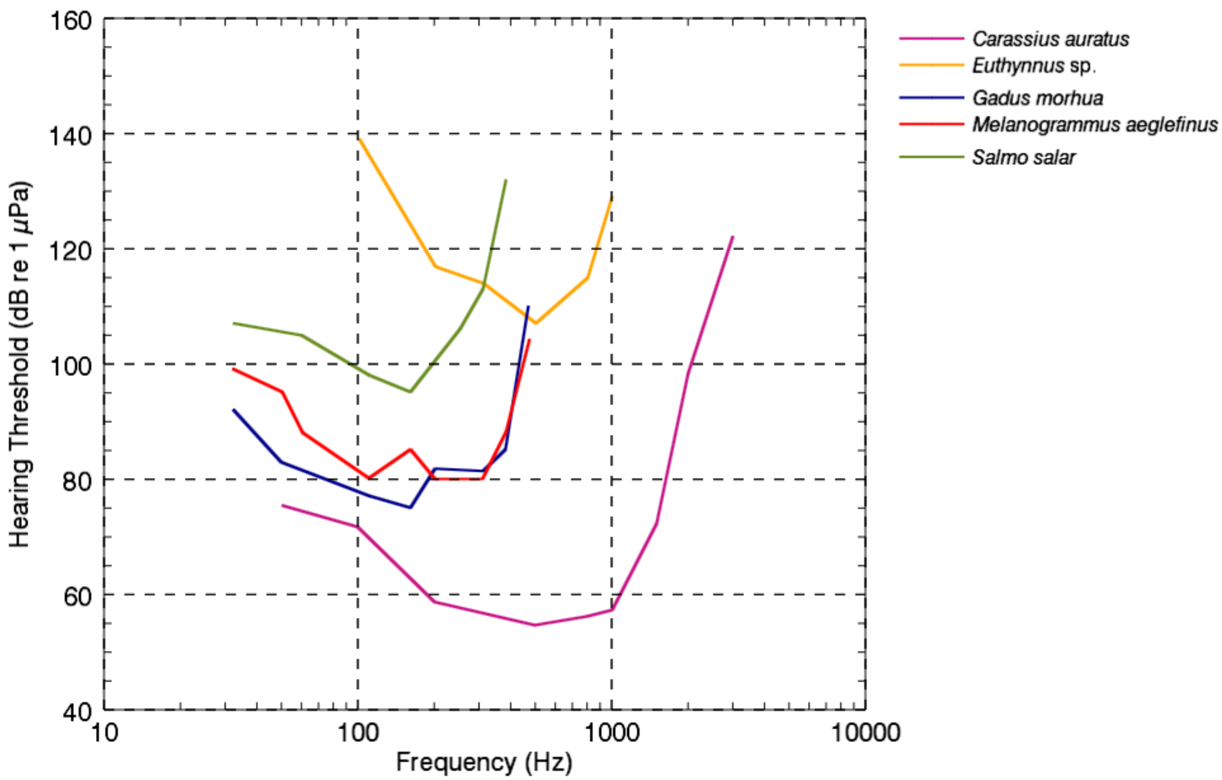

Figure 5. Audiograms for common fish species. The hearing range for fish is approximately 70 Hz-1 kHz. These hearing thresholds are directly comparable to1/3-octave band noise levels (Popper and Hastings 2009, Fay 1988).

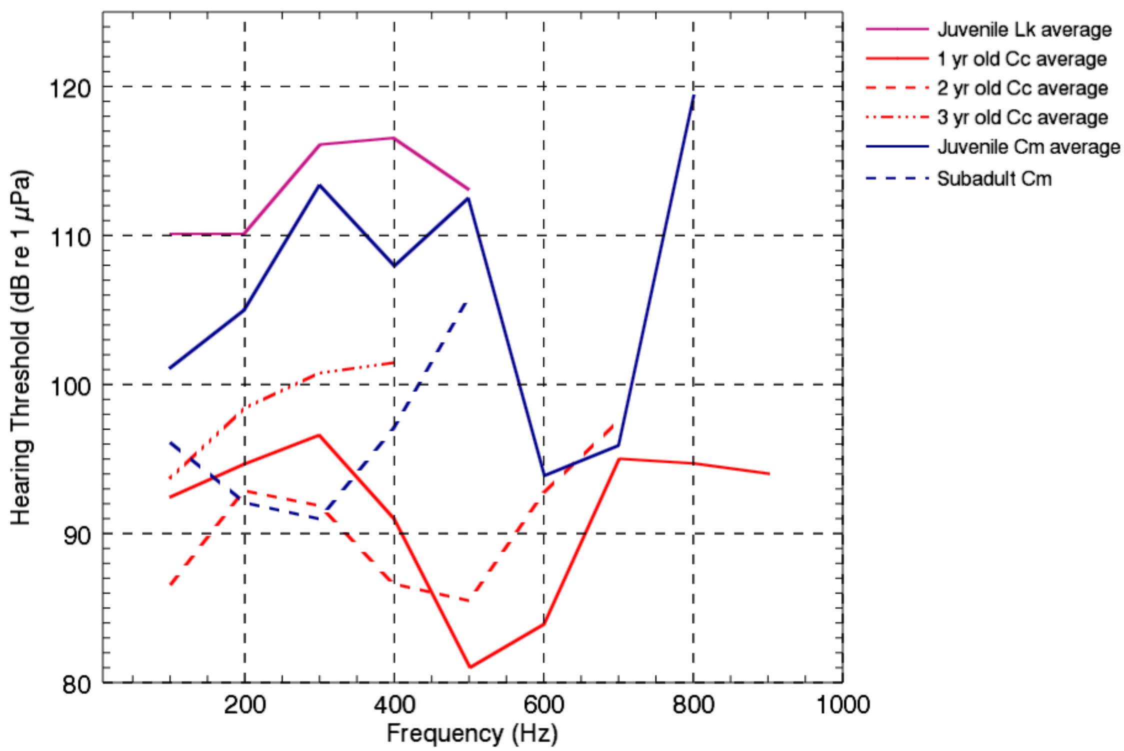

Figure 6. Audiograms for sea turtle species. The hearing range for sea turtles is approximately 100 Hz-1 kHz. These hearing thresholds directly compare to 1/3-octave band noise levels (Ketten and Bartol 2006).

Based on fish and sea turtle audiograms and harbour seal and harbour porpoise criteria, this study proposes that to measure potential impacts of a turbine on marine mammals at the FORCE site, the recorder system must be capable of measuring a source level from the turbine of 140 dB re 1 µPa at frequencies above 100 Hz. 140 dB re 1 µPa is the lowest accepted threshold level known to cause impact on the species that may be present (from porpoise). 100 Hz is lower than the bottom frequency of porpoise hearing, however, it is represents the approximate start of hearing for most fish, turtles and pinnipeds. If the recorder is 100 m from the turbine, the largest propagation loss from the turbine to the recorder would be 40 dB. Thus, the noise threshold is 100 dB re 1 µPa in any 1/3-octave band above 100 Hz.

2. Methods

2.1. Acoustic Data Acquisition

Underwater sound was recorded with Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences; Figure 7). The AMAR electronic board is the basis of the AMAR family of sound measurement instruments: single channel autonomous recorders, multichannel and directional sensor recorders, vertical arrays, towed arrays, over-the-side real-time analysis systems, and cabled observatories. The AMAR board features eight channels of 24-bit analog-to-digital conversion at simultaneous sample rates up to 128 kHz; it also supports one channel of 16-bit digital sampling at rates up to 800 kHz. The AMAR board can host up to seven solid-state memory modules, each with a 256GB capacity, giving 1792GB of on-board solid-state memory.

Figure 7. Autonomous Multichannel Acoustic Recorder (AMAR; JASCO Applied Sciences).

The AMARs deployed at the FORCE site recorded continuously at 64 ksps. The recording channel had a 24-bit dynamic range with a spectral noise floor of 20 dB re 1 µPa^2/Hz and a ceiling of 171 dB re 1 µPa. Each recorder was fitted with an M8 omnidirectional hydrophone (−164 ±3 dB re 1 V/µPa sensitivity; GeoSpectrum Technologies Inc.). Data were stored on 1TB of internal solid-state flash memory.

2.2. Deployments

JASCO made three deployments, two in October 2011 and one in March 2012. We aborted the first deployment when the anchor blocks failed on the acoustic releases. Some equipment from the second deployment was damaged; some was lost. We successfully recovered the moorings and recorders from the third deployment.

2.2.1. Initial Deployments

The initial FORCE deployments occurred in October 2011. Two High-Flow (HF) moorings were deployed, one on the volcanic plateau at the FORCE site, and one at the FORCE reference site (Figure 8, Table 2). A HF mooring was connected by 125 m of poly-spec ground-line to a low-drag elliptical float with an ORE Port-LF acoustic release (Figure 9), which kept the relatively noisy chains below the acoustic release far from the acoustic recorder. The AMAR and the HF mooring have a net negative buoyancy of 94 kg; initial calculations indicated this was a 2.5:1 safety margin to prevent movement, assuming a 2 m/s current, the strongest known current at the time (Figure 3). The Port-LF has a working load of 350 kg and a shock load limit of 1000 kg. A 274 kg steel weight created from a 6 mm steel plate anchored the acoustic release.

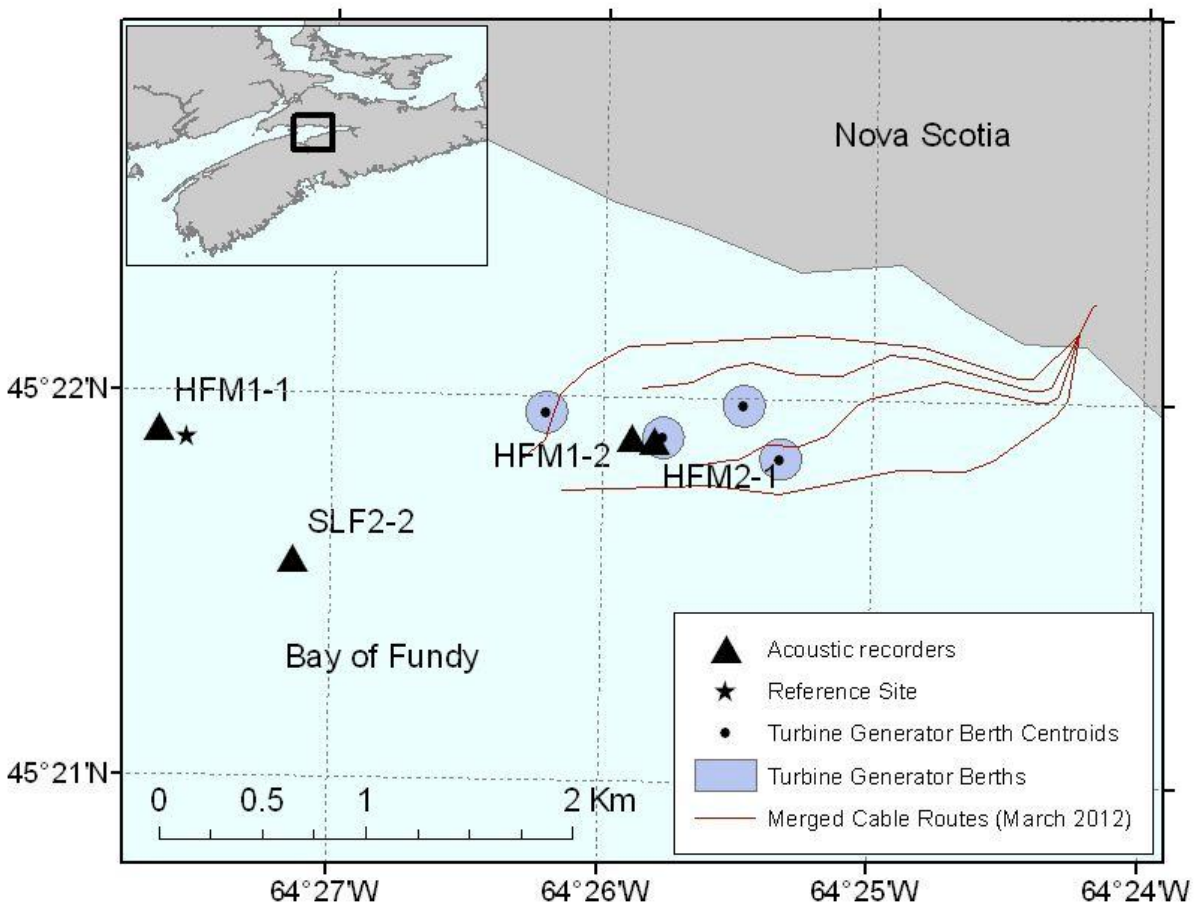

Figure 8. Mooring sites for two October 2011 FORCE deployments.

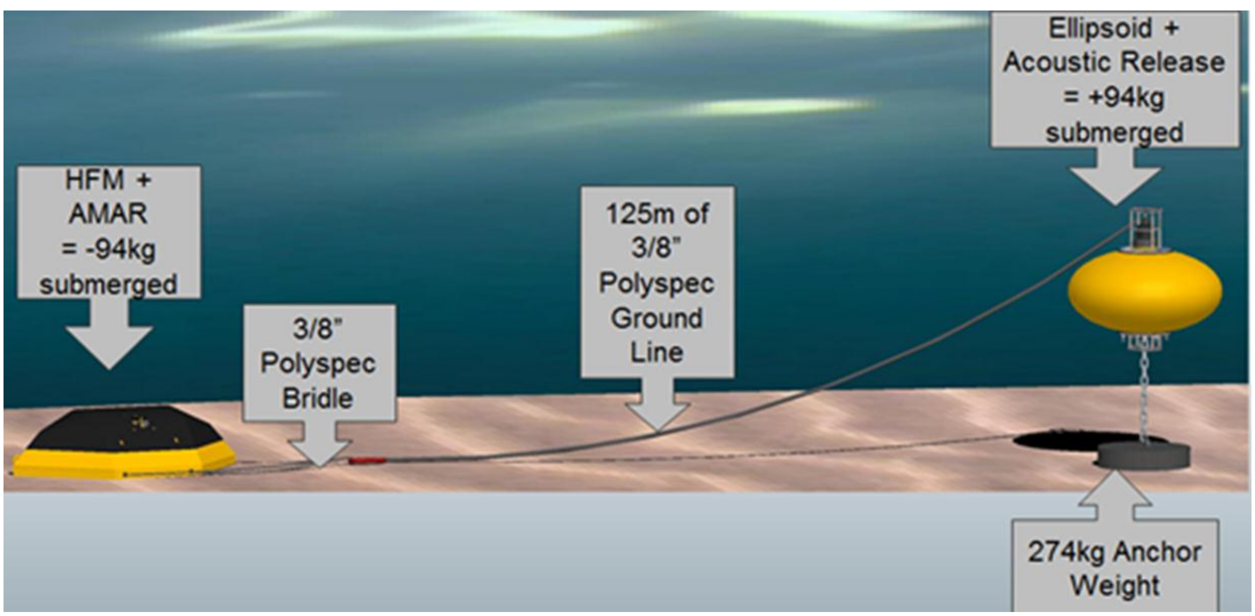

Figure 9. Mooring diagram for October 2011 FORCE deployments.

On 7 Oct 2011, we attempted the first deployments from the *M/V Tide Nova*. The elliptic float and anchor were held over the side of the ship by a crane, while the HF moorings were lowered to the bottom from an A-frame. When the ground line was taught, the float and weight were released. However, when the float struck the water, the shock load on the acoustic release anchor block exceeded ratings and the float remained on the surface. The mooring was recovered and the team returned to shore to investigate the problem (Figure 10, left).

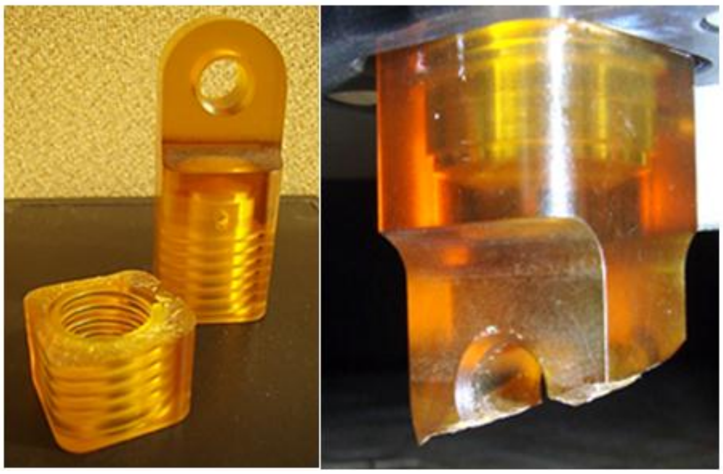

Figure 10. Release blocks from ORE PORT-LF acoustic releases used during initial two FORCE deployments. Left: Release block failure due to shock loading during first deployment. Right: Fractured release block from second deployment.

Successful deployments occurred on 23 Oct 2011. The anchor weight and float were lowered into the water and secured with a quick release. The HF moorings were lowered to the bottom with an A-frame, and then the anchor and float were released as the ground line tightened. Ranging with the acoustic releases showed that all equipment was in place and operating correctly.

On 24 Nov 2012, we attempted to retrieve the moorings. The acoustic releases did not respond to release commands and the HF moorings were not recovered. Several days later, local fishers found one of the elliptical floats and its acoustic release. The anchor block had failed again, this time likely due to torqueing from the movement of the float in the current (Figure 10, right). At this point, the field program was suspended so we could thoroughly review the moorings. In January 2012, we discovered that eddies, even at the bottom of the Minas Passage, can reach 6 m/s (Melrose 2012).

Table 2. Location and recording periods of the Autonomous Multichannel Acoustic Recorders (AMARs) deployed in the Bay of Fundy.

Station	Latitude	Longitude	Deployment, Record start (dd/mm/yyyy)	Retrieval, Record end (dd/mm/yyyy)
HFM1-1	45°21.907′ N	64°27.640′ W	23/10/2011	*
HFM1-2	45°21.897′ N	64°25.893′ W	23/10/2011	*
HFM2-1	45°21.891′ N	64°25.808′ W	23/03/2012	05/04/2012
SLF2-2	45°21.571′ N	64°27.142′ W	23/03/2011	28/03/2012

2.2.2. Mooring Review

Over the winter of 2011-2012, JASCO reviewed the mooring designs, including computational fluid dynamics (CFD) modelling of the high flow mooring by the University of New Brunswick (UNB) and extensive discussions with other teams that deployed oceanographic moorings in the Bay of Fundy.

An Engage grant between JASCO and UNB funded the CFD modelling. The CFD modelling results showed that the mooring produced significant lift and needed to be at least 300 kg negative to remain in place. The CFD predicted that the noise levels from flow over the HF moorings would decrease 40 dB between 10 Hz and 1 kHz, and that the pseudo-noise levels at a hydrophone inside the HF mooring would be much lower than the levels for a hydrophone on the outside of the HF mooring.

Through extensive discussions on retrieving equipment from the Bay of Fundy and reviewing mooring designs with local experts (especially Murray Scotney, ROMOR Ocean Solutions), we changed the mooring designs. Most moorings in the Bay of Fundy use streamlined floats to hold equipment such as ADCPs and acoustic releases. The floats stabilize the equipment in the currents and are robust for long periods. We developed a HF mooring (Figure 11) and a streamlined float-based (SFL) mooring (Figure 12) were developed. Both moorings included heavy ORE 8242 acoustic releases and tethered floats as a redundant recovery mechanisms. The tethered floats were partially inflated so they would only surface for approximately one-half hour around slack tide. Local lobster fishers use this technique. The lower red floats on both moorings kept the 1.6 cm polytron line (4500 kg break strength) away from the bottom to minimize chaffing. Both moorings had XEOS Iridium beacons which notified JASCO where the equipment was every 15 min in the event the moorings surfaced early.

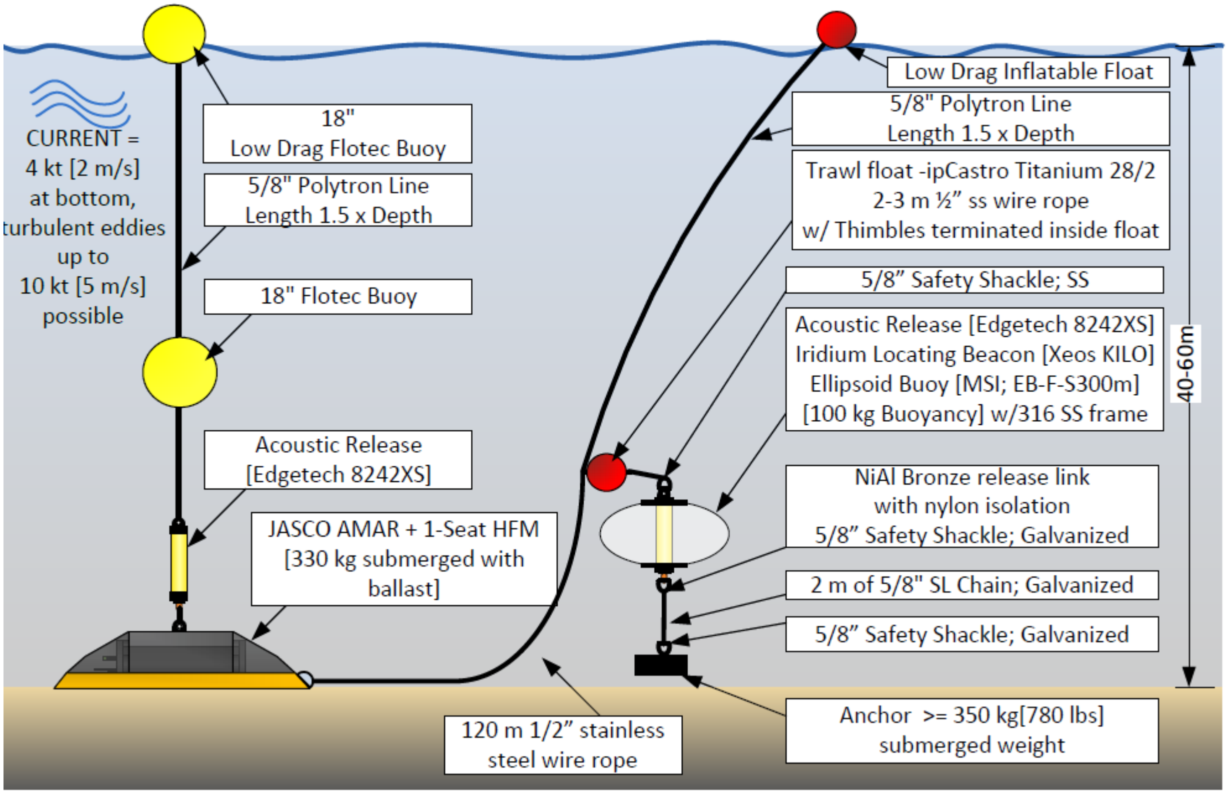

Figure 11. Modified High-Flow (HF) mooring. Floats and acoustic release attached to the HF mooring ensuring proper orientation on deployment and allowing the recorder to be dropped instead of lowered.

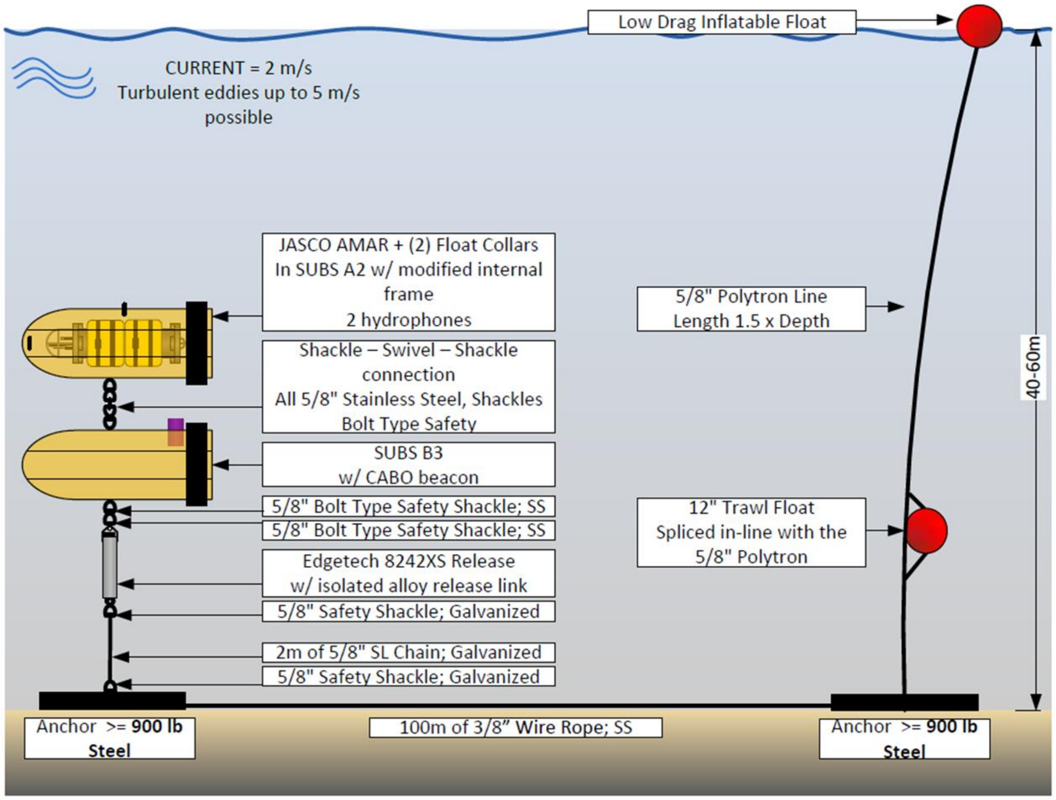

Figure 12. SLF mooring from the March 2012 FORCE deployment.

2.2.3. Third Deployment

The HF mooring had two hydrophones: an M8E inside the cover behind the acoustic window and another M8E in a cage and flow shield in the current (Figure 13). The SFL mooring had three hydrophones: an M8E inside the float with the AMAR, an M8E on the top of the float, and an M56 multi-element hydrophone also on top of the float (Figure 14).

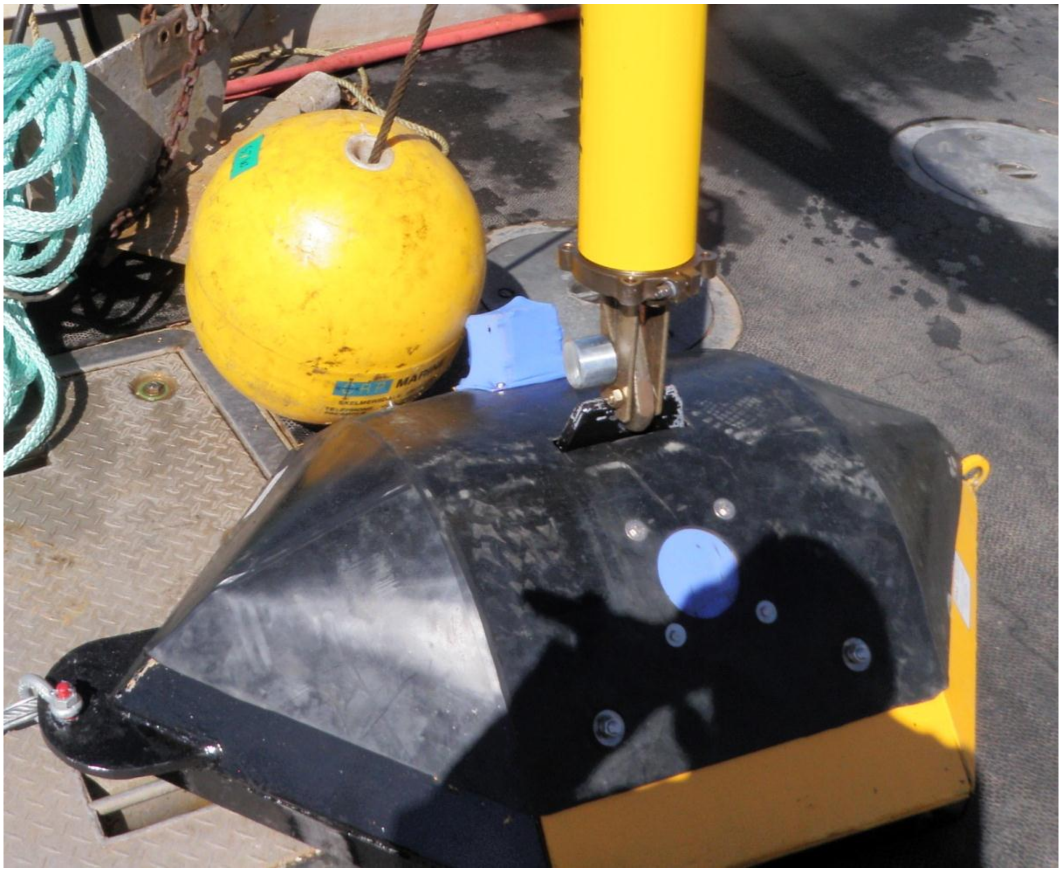

Figure 13. High Flow Mooring ready for deployment. Two hydrophones were deployed, one behind the blue fabric window in the foreground of the HF mooring, and another inside a cage and blue fabric flow shield on the back-side of the HF mooring.

Figure 14. Streamlined float showing two of three hydrophones. Foreground: M8E hydrophone (small black cylinder underneath a gray clamp at the top left of the streamlined float). Background: M56 hydrophone (blue and black torpedo-shaped hydrophone). The M56 hydrophone has six hydrophone elements spaced throughout the volume. Similar to towed arrays, the intent of the M56 was to reduce flow noise by summing the elements to amplify external sound waves and cancel uncorrelated local flow noise.

We successfully deployed the moorings from the *M/V Tide Nova* on 23 Mar 2012. At 00:00 28 Mar 2012 (UTC) the SLF mooring began to send sporadic Iridium messages. The mooring landed on the Scot's Bay, NS beach 12 h later. It was discovered that the internal HDPE float frame had failed in two locations (Figure 15, black material). The forward (right) side mechanically failed first, and then the aft (left) side suffered a plastic failure sometime later.

Figure 15. Streamlined floats at Scot's Bay, NS, 28 Mar 2012. The black HDPE frame of the streamlined float in the foreground had failed.

Retrieval of the HF mooring occurred on 5 Apr 2012. On arrival at the site, the field team discovered the elliptical float was on the surface. Analysis showed that the 1.2 cm stainless steel bolt and nylock nut securing the acoustic release into the elliptical float had failed, sending the float to the surface and leaving the acoustic release on the bottom.

2.3. Data Analysis

Automated processing of the entire dataset was performed with JASCO’s Acoustic Analysis software suite to calculate ambient sound levels and to detect vessel noise. Ambient sound levels from each station were examined to document baseline underwater sound conditions in the Bay of Fundy area. The spectral density is calculated using the fast Fourier transform (FFT) and is the sound power in 1 Hz wide frequency bands (Oppenheim and Shafer 1999).

Ambient noise levels at each recording station are presented using percentile plots of the spectral density levels: histograms of each frequency bin per 1-min of data. The 5th, 25th, 50th, 75th, and 95th percentiles are plotted. The 5th percentile curve is the frequency dependent sound power level that was exceeded 5% of the time during the deployment. Equivalently, 95% of the time, the spectral levels were below the 5th percentile curve.

The 50th percentile (i.e., median) of the 1-min spectral density levels can be compared to the Wenz ambient noise curves (Figure 16). The Wenz curves show ranges of variability of ambient spectral density levels as a function of frequency for measurements off the US Pacific coast over a range of weather, vessel traffic, and geologic conditions. The Wenz curve levels are generalized and are provided for approximate comparison only.

Time domain ambient analysis was performed for all stations to find the root-mean-square (rms) sound pressure levels (SPLs) of the time series for each minute of data.

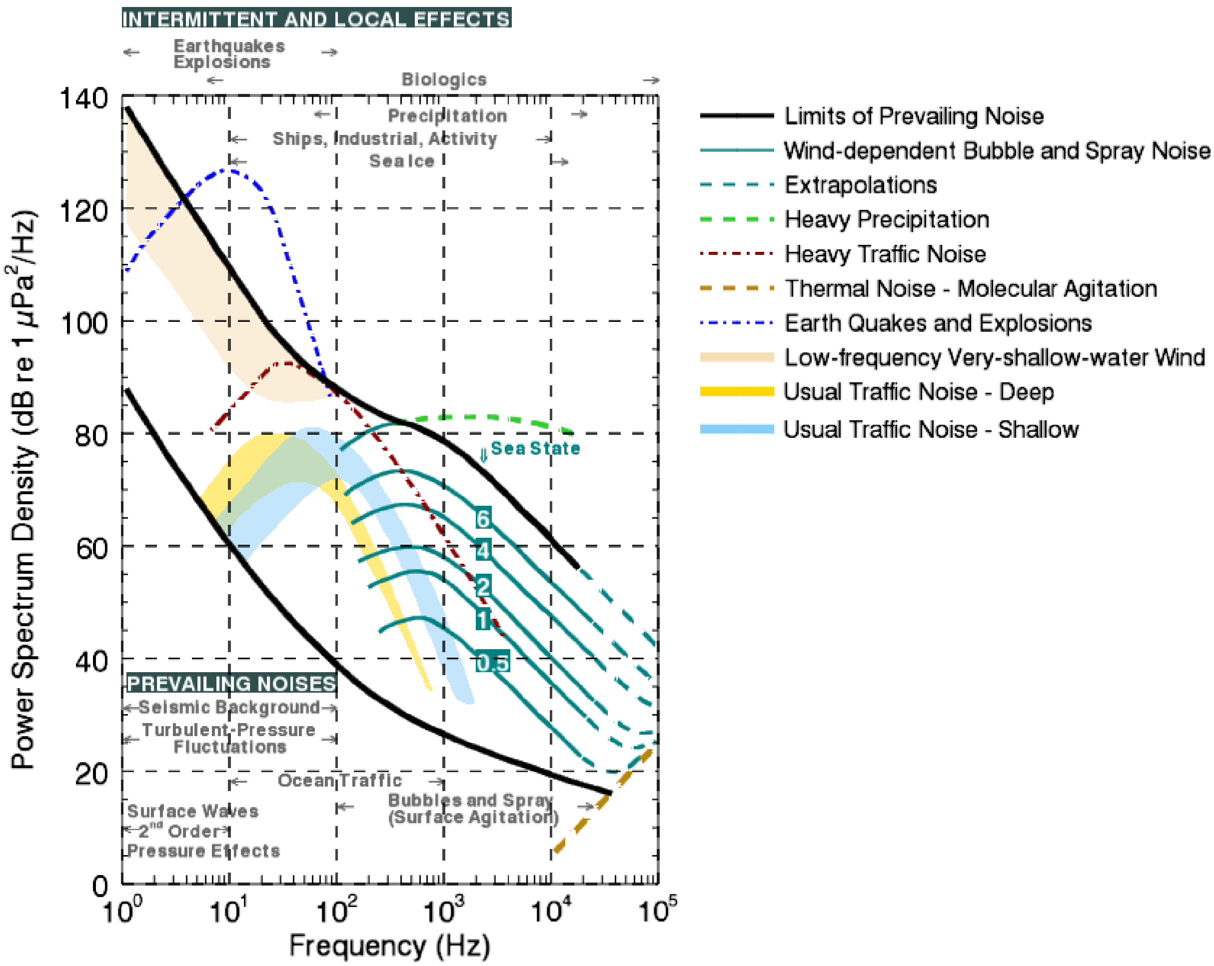

Figure 16. Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping (Adapted from Ocean Studies Board 2003, adapted from Wenz 1962). The thick black lines indicate the limits of prevailing noise.

The SPL percentile statistics for one-half 0.5-h periods of the data were also computed. The sound level statistics quantify the observed distribution of recorded sound, similar to the 1 Hz percentiles. Following standard acoustical practice, the *n*th percentile level (L_n) is the SPL exceeded by *n*% of the data. Sound level statistics were computed at the following standard percentiles:

- L_{max}, the maximum recorded sound level
- L_5, the sound level exceeded 5% of the time
- L_{25}, the sound level exceeded 25% of the time
- L_{50}, the median sound level

- L_{75}, the sound level exceeded 75% of the time
- L_{95}, the sound level exceeded 95% of the time

The mean sound levels (L_{mean}) were computed as the linear arithmetic mean of the sound power, which can be significantly different from the median sound level (L_{50}). The 1/3-octave SPLs are the most appropriate measure of the background sound levels for comparison to the impact thresholds. The one-third octave band frequencies are shown in Table 3.

Table 3. One-third-octave band frequencies.

1/3-octave band	Frequency (Hz)			1/3-octave band	Frequency (Hz)		
	Lower	Nominal centre	Upper		Lower	Nominal centre	Upper
1	8.9	10	11.2	17	362.7	406	455.7
2	11.6	13	14.6	18	456.1	512	574.7
3	14.3	16	17.9	19	574.6	645	723.9
4	17.8	20	22.4	20	724.2	813	912.6
5	22.3	25	28.0	21	912.3	1024	1149
6	28.5	32	35.9	22	1150	1290	1447
7	35.6	40	44.9	23	1448	1625	1824
8	45.0	51	57.2	24	1824	2048	2297
9	57.0	64	71.8	25	2298	2580	2896
10	72.0	81	90.9	26	2896	3251	3649
11	90.9	102	114.4	27	3649	4096	4597
12	114.1	128	143.7	28	4598	5161	5793
13	143.4	161	180.7	29	5793	6502	7298
14	180.8	203	227.9	30	7298	8192	9195
15	228.0	256	287.4	31	9195	10321	11585
16	287.7	323	362.6	32	11585	13004	14597

3. Results and Discussion

The full deployment spectrograms for the hydrophones internal to the High-Flow (HF) mooring and Streamlined Float-based (SFL) moorings (Figure 17, Figure 18) are an overview of the data collected. The spectrograms use colour to indicate power spectral density, which is directly comparable to the Wenz curve levels. Blue tones are quieter and red tones are louder. Clearly low frequencies dominate the measured sound fields at both moorings. As predicted by the CFD modelling, the noise decreases by ~40 dB between 10 Hz and 1 kHz.

The HF mooring spectrogram (Figure 17) has a micro-pattern alternating between very intense sound levels on the flood stage of each tide, and lower sound levels during the ebb stage. This is consistent with acoustic Doppler current profiler measurements that show the flood tide is stronger and shorter than the ebb tide (Figure 3). There is also a macro-pattern of an overall increase in sound levels at the start and end of the deployment, with lower levels in the middle. This is correlated with the lunar cycle.

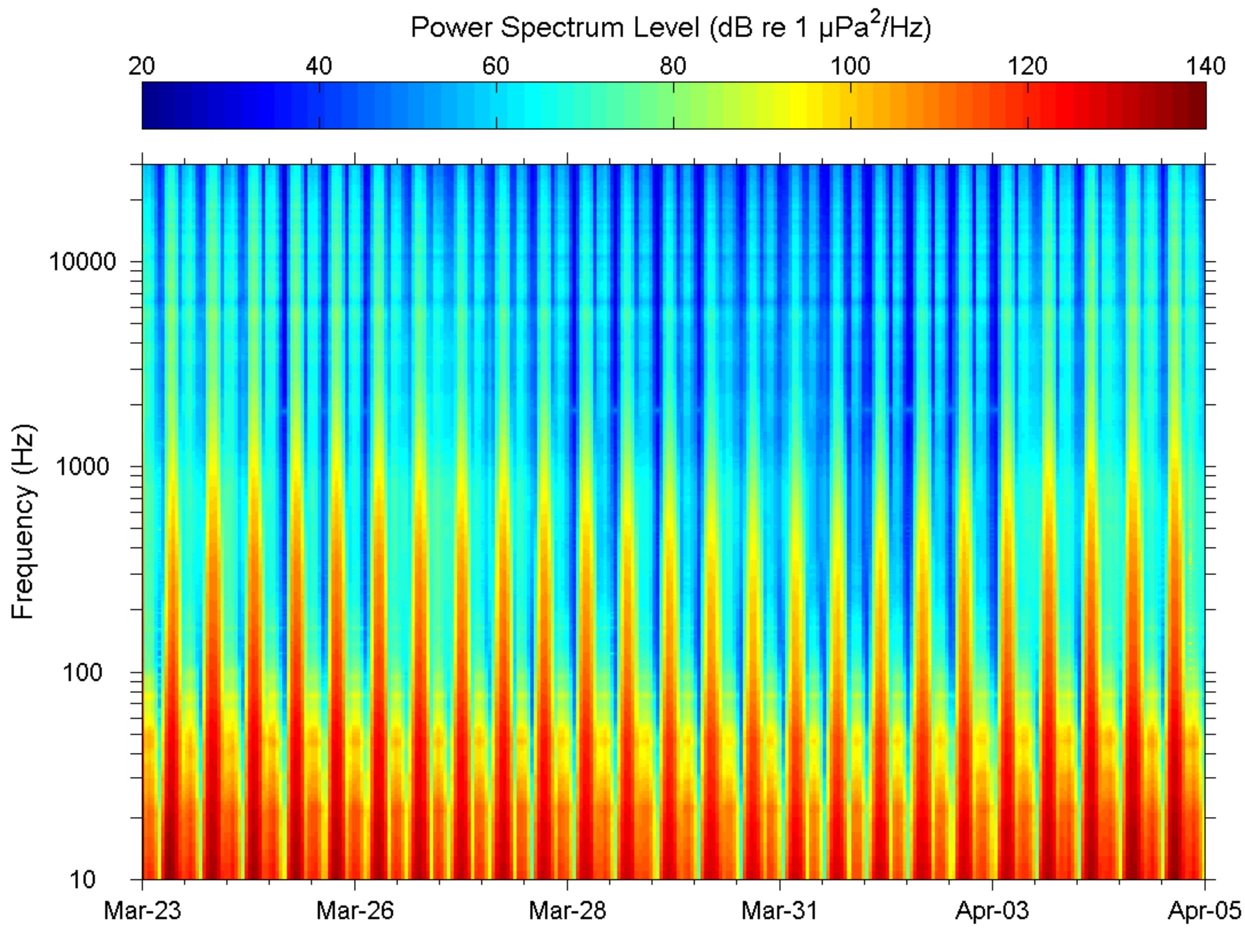

Figure 17. Spectrogram of data from the hydrophone inside the High-Flow (HF) mooring.

The streamlined float spectrogram (Figure 18) helps explain how the mooring failed. There is one full tidal cycle of data after deployment, followed by a sudden change in the measured data near the peak of the third tide. Most likely the forward end of the streamlined float frame suffered a sudden mechanical failure at this point that allowed the entire mooring to move more violently for the next three days. Part way through 27 March, the back end of the frame suffered a plastic failure and the mooring began to drift, resulting in much lower sound levels. The two spikes on 27 and 28 March are associated with the mooring striking the rocks on Scot's Bay beach during high tide. Both the streamlined float and HF mooring were in the water during the first full tidal cycle of the streamlined float deployment; therefore, the remainder of the analysis focused on this period.

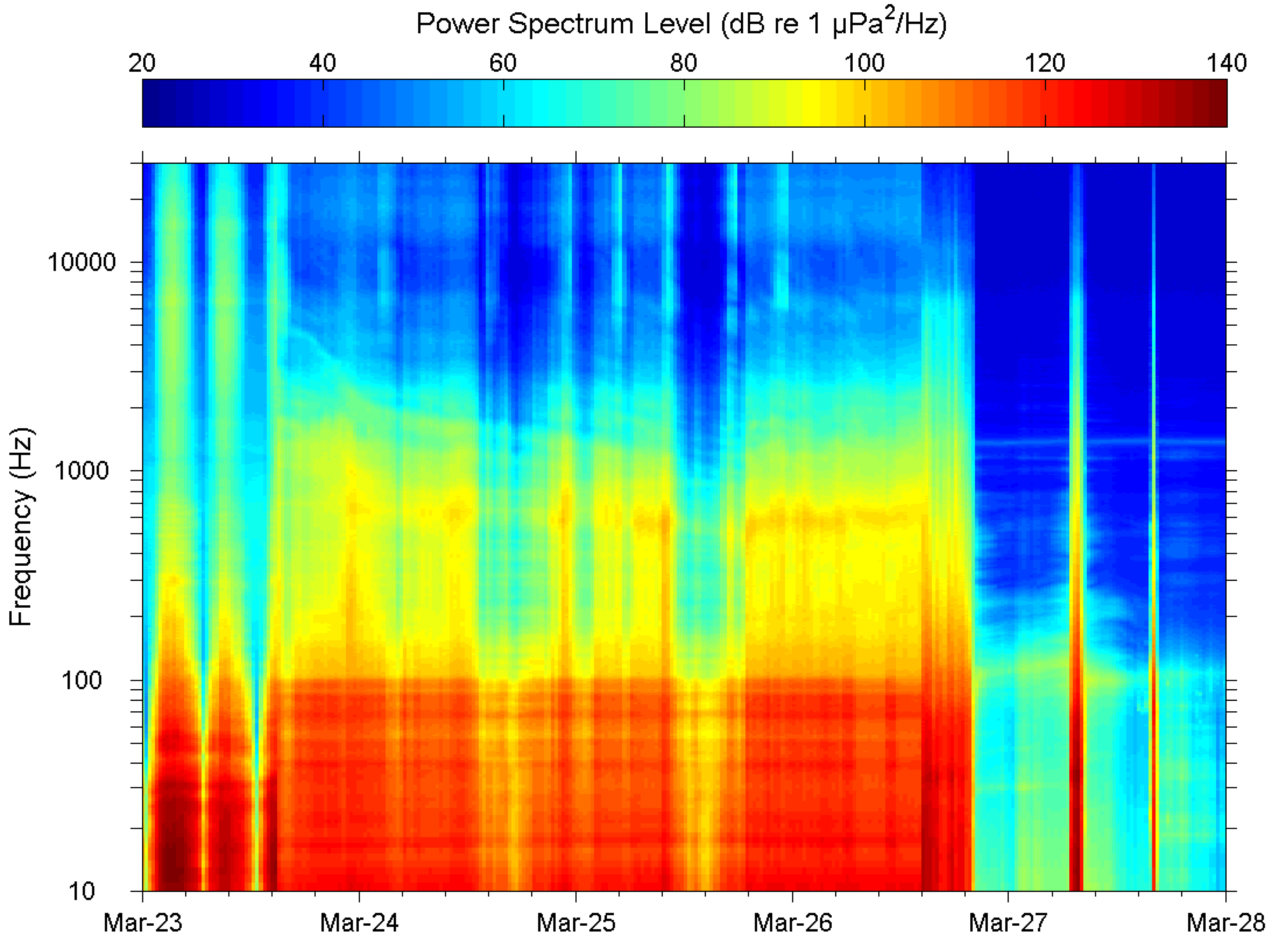

Figure 18. Spectrogram of acoustic data from inside the streamlined float. At the beginning (left-hand side) of the deployment there is one full tidal cycle (ebb and flood) of data from 23:19 23 March–11:40 24 March when the mooring was in tact. At approximately 14:00 24 March the initial failure of the streamlined float frame occurs, resulting in more movement of the mooring and more noise. At approximately 22:00 27 March the SLF mooring completely breaks free and drifts with much lower noise levels. The two loud (red) events on 28 Mar correspond to the highest tides moving the mooring on the beach.

The median power spectral density levels (Figure 19) between the two hydrophones on the HF mooring (Figure 13) and the three hydrophones on the streamlined float (Figure 14) were compared. The hydrophone internal to the HF mooring had the lowest sound levels from 20 Hz–3 kHz. Any pure tones generated by a turbine with a root-mean-square (rms) sound pressure level (SPL) of 140 dB re 1 µPa would be detected above 40 Hz. The extremely low levels on the hydrophone internal to the streamlined float above 3 kHz suggest that the plastic housing of the streamlined float was not acoustically transparent at those frequencies. The levels on the streamlined float's internal hydrophone are higher than those of the external hydrophone below 100 Hz, which indicates that there is significant turbulence on the shell of the streamlined float. The inside of the streamlined float is a poor choice for acoustic measurements. The multi-element M56 hydrophone can be compared to the external hydrophone on the streamlined float. It is predicted that for uncorrelated noise (like flow noise), the M56 will be $20 * \log_{10}(6) = 12$ dB quieter than a single hydrophone in the same noise field. The results show the M56 is 2–8 dB below the external M8E hydrophone in the frequency range of 10–100 Hz, and 8–18 dB below the external M8E in the frequency range of 100 Hz–2.5 kHz. Because the six elements of the M56 are summed, above 2.5 kHz the M56's response becomes highly frequency dependent and is not considered reliable. Further calibration and analysis of the M56 data is required before it can be recommended for future measurements.

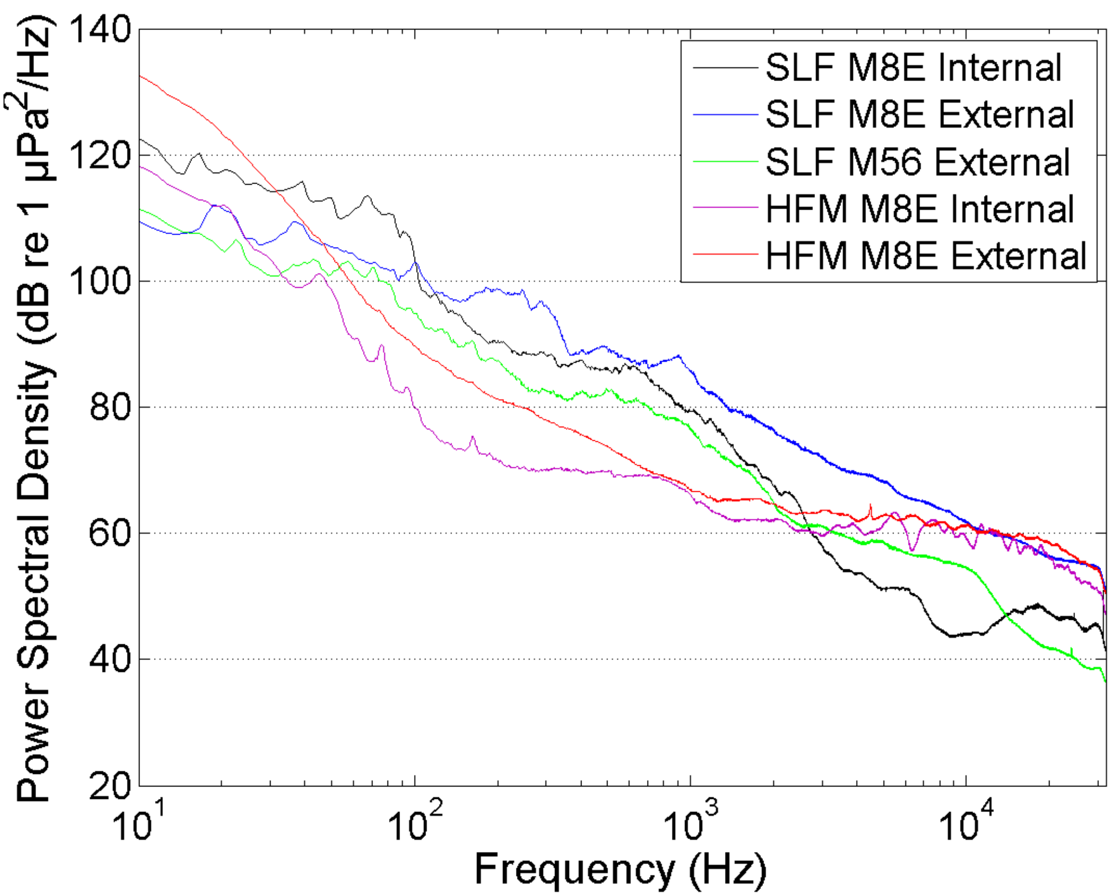

Figure 19. Comparison of median sound levels from all hydrophones during the full tidal cycle of 23:20 23 March 2012–11:40 24 March 2012 (UTC).

The overall sound pressure levels on each hydrophone (Figure 20) are very similar as a function of tidal stage (time), with the exception of the hydrophone internal to the HF mooring. On the ebb tide this hydrophone's total SPL is 15–18 dB below the average of the other single hydrophones. Examining the differences as a function of decade frequency band (Figure 21) the effect is more pronounced. During the ebb tide, the decade band SPL for 100 Hz–1 kHz is 30–35 dB below the SPL for the flood tide. JASCO believes that the acoustic window for the internal hydrophone faced into the flow during the flood tide, and was sheltered behind the crest of the HF mooring during the ebb tide (see Figure 13).

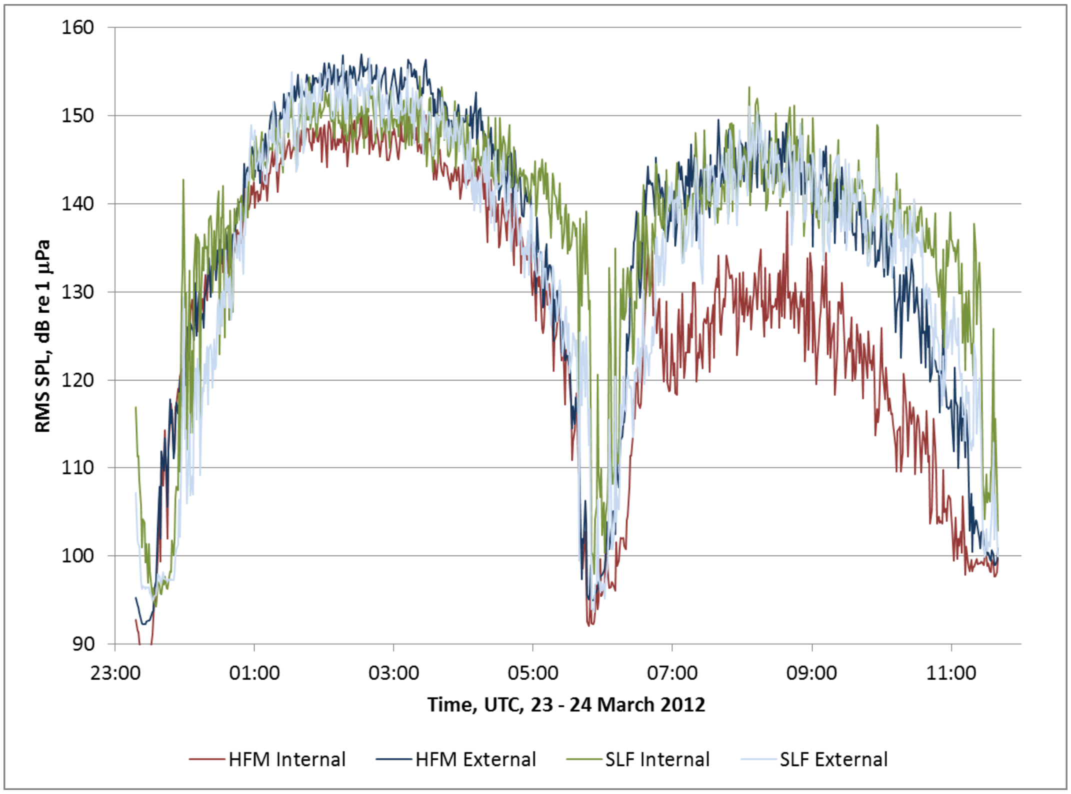

Figure 20. Comparison of root-mean-square (rms) sound pressure levels (SPLs), 23:19 23 March 2012–11:40 24 March 2012 (UTC).

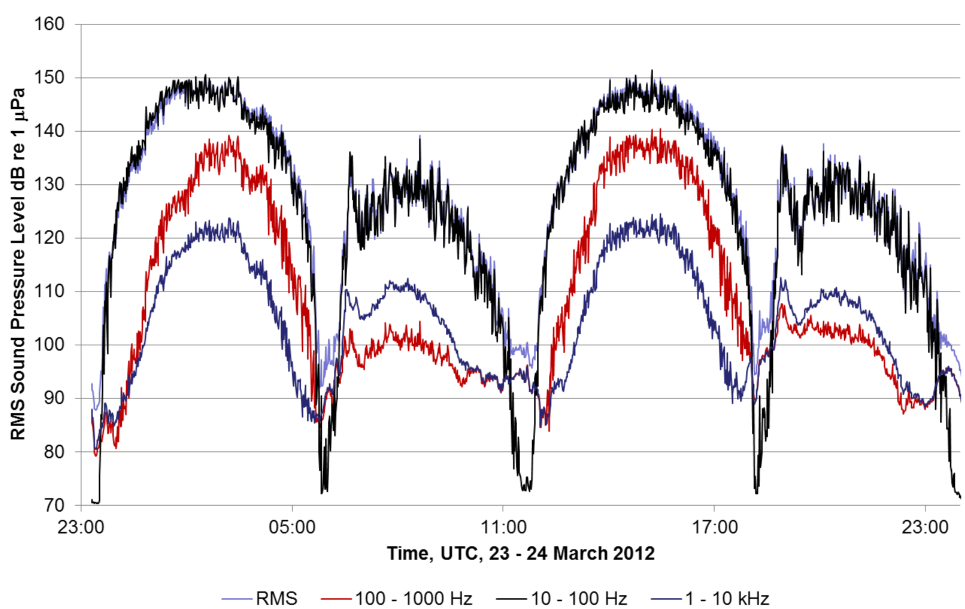

Figure 21. Comparison of root-mean-square (rms) and decade band levels for the hydrophone internal to the HF mooring, 23:19 23 March 2012 through 23:57 24 March 2012 (UTC).

One-third octave percentile statistics for 0.5 h of data near the peak of the flood and ebb tides, as well as slack tide, show the dynamics of the sound at each of these tidal states for the hydrophone internal to the HF mooring (Figure 22, Table 4). The shape of the plots is very smooth for the ebb and flood cases. The smooth shape indicates that flow is the dominant noise source up to 2 kHz in the flood case and 300 Hz in the ebb case. The one-third octave SPLs from 2–20 kHz are very similar in the ebb versus flood case and are due to the sounds of moving gravel and substrate. For comparison, the one-third octave SPL statistics for the first half-hour of drifting by the streamlined float is also given.

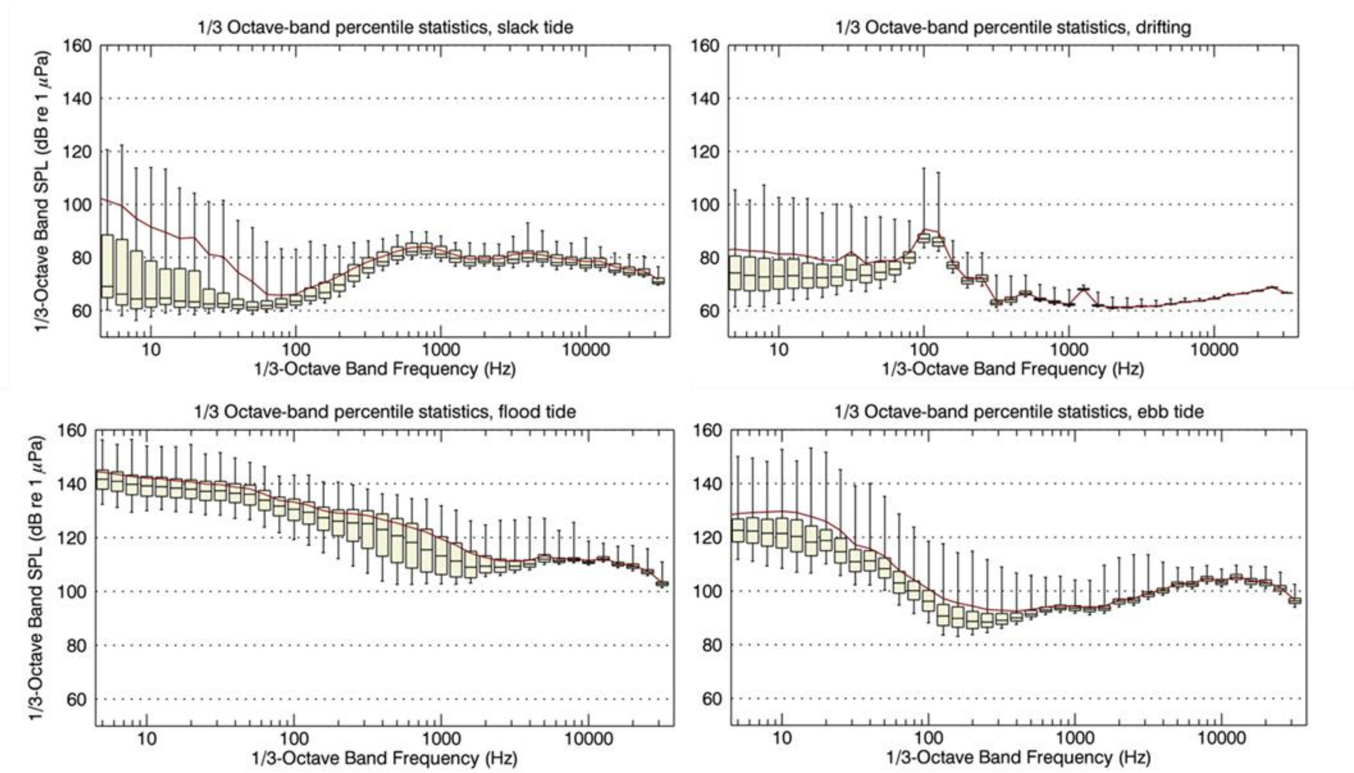

Figure 22. Box-whisker plots of one-third octave sound pressure levels (SPLs). Results are computed from 30 min data using 1 s long FFTs with 50% overlap and Hamming windows. Beige bars indicate the first, second, and third quartiles (L_{25}, L_{50}, and L_{75}). Upper error-bars indicate the maximum levels (L_{max}). Lower error bars indicate the 95% exceedance percentiles (L_{95}). The maroon line indicates the arithmetic mean (L_{mean}). Top Left: hydrophone internal to the HF mooring at slack tide 23:52 24 March. Top Right: hydrophone internal to the streamlined float during its first half-hour of drifting near full tide, 22:04 27 March 2012. This hydrophone was very near the surface, so the high frequency data is not considered accurate. Bottom Left: hydrophone inside the HF mooring during flood tide, 02:22 24 March 2012. Bottom Right: hydrophone inside the HF mooring during ebb tide, 08:22 24 March 2012.

Table 4. Percentile statistics for the third-octave at 100 Hz for each case in Figure 22.

Statistic	Slack tide	Ebb Tide	Flood Tide	Drifting streamlined float
L25	65.8	100.2	134.3	88.8
L50	63.5	96.2	130.5	87.1
L75	62.1	92.5	126.4	85.7

4. Conclusions and Recommendations

Making measurements in high flow conditions is extremely challenging. Designing a mooring that survives deployment and retrieval takes much iteration. Ensuring the mooring is safe and easy for the field team to deploy, as well as acoustically quiet, make the development much more difficult. The mooring must be located on the ocean bottom, have a streamlined shape to encourage laminar flow over the mooring, have an acoustically transparent cover, and have no parts that can move in the current and generate noise.

The data reported here indicate that the High-Flow (HF) mooring design is capable of measuring ambient and turbine sound levels that can potentially disturb marine life. We proposed a threshold for acoustic impact on marine life at the FORCE site of 140 dB re 1 µPa based on the sensitivity of porpoise to continuous sounds and the audiograms of fish, turtles, porpoise and pinnipeds. Noise levels on the hydrophone internal to the HF mooring were lower when the tidal flow did not strike the acoustic window. Even at full flow the noise levels in all 1/3-octave bands from 100 – 3000 Hz were below 100 dB re 1 µPa when the hydrophone was sheltered. With this noise level the system can easily measure tones from tidal turbines at the level 140 dB re 1 µPa at a range of at least 100 meters from the turbine. The shape of the measured noise spectra was very smooth. Therefore we can easily distinguish any tidal turbine sources from the background noise spectra.

We recommend that future noise measurements in the Bay of Fundy use the HF mooring with a sinking surface float for equipment retrieval. The HF mooring should have two internal hydrophones, one on each side, behind acoustically transparent windows. With this configuration one hydrophone will always be protected from the flow and that the system will record near-ambient noise levels throughout the tidal cycle.

5. Acknowledgements

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