# Measurement of long-term ambient noise and tidal turbine levels in the Bay of Fundy

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## ABSTRACT

The Fundy Ocean Research Center for Energy (FORCE) is a leading research centre for in-stream tidal energy technology. Located at Minas Passage in the Bay of Fundy, the currents can exceed 6 m/s (Oceans Ltd., 2009), making it ideal for testing in-stream technology in harsh environments. The effect of turbine noise on marine life is recognised as a potential environmental impact of in-stream turbines that must be understood (Polagye et al., 2011). It is expected that the rotating mechanical equipment in tidal turbines will emit continuous tones into the water, potentially at levels that may harm or harass marine life (Polagye et al. 2011; Stein, 2011). The differences between the soundscapes with and without the turbine in place must be measured to assess impact. Ideally recordings should be made in all seasons, weather and tidal states and flow noise in the data must be minimised. FORCE made drift measurements of the sound levels at Minas Passage in 2008 and 2009 before and after the installation of an Open Hydro turbine, however, the results were deemed not reliable due to vessel and surface noise issues and the short term nature of drifting measurements (Schillinger, 2010). In 2011 JASCO began a project to demonstrate long-term measurements of ambient and turbine noise at FORCE using a special purpose high-flow mooring (HFM) previously developed for measurements in Bristol Channel. The extreme conditions at Minas Passage make deployments and retrievals challenging. The initial deployment was called off when shock loading severed the anchor block on the acoustic releases. Both moorings in the second deployment were lost. Detailed hydrodynamic modelling and discussions with mooring experts were conducted before the third deployment in March 2012. The HFM and a more traditional stream-lined buoy design were deployed and recovered. The data show that the high-flow mooring provides usable measurements in all tidal states.

## INTRODUCTION

The Fundy Ocean Research Center for Energy (FORCE) is a leading research facility for in-stream tidal energy technology. Located at Minas Passage in the Bay of Fundy, where the currents can exceed 6 m/s (S Melrose 2012, pers. comm., 11-12 January; Oceans Ltd. 2009) the FORCE test site is an ideal location for testing in-stream technology in harsh environments.

Effects of underwater noise from turbines on marine life are recognised as a potential environmental impact of in-stream turbines that must be understood (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). The differences between soundscapes with and without a turbine in place must be measured to assess the acoustic impact. Ideally, recordings would be made in all seasons, weather conditions, and tidal states, and flow noise artefacts in the data would be minimised.

FORCE made drifting measurements of the underwater sound levels at Minas Passage in 2008 and 2009, before and after the installation of an Open-Centre Turbine (OpenHydro, Dublin), respectively; however, the results were unreliable because of vessel and surface noise contamination and the short-term nature of drifting measurements (Schillinger 2010). In 2011, JASCO Applied Sciences (JASCO) began a project to demonstrate long-term measurements of ambient and turbine noise at FORCE using a specialised high-flow mooring (HFM). The extreme conditions at Minas Passage made deployments and retrievals challenging. There was mooring equipment failures during two deployments attempted in the fall of 2011. Detailed hydrodynamic modelling and discussions with mooring experts were conducted before the third deployment in March 2012. The JASCO HFM and a more traditional streamlined buoy design were deployed and recovered. The data show that the JASCO HFM provides usable measurements in all tidal states. This is in contrast to Stein (2011) who argued that only drifting measurements made using an autonomous buoy are reliable in high current areas.

### Acoustic Measurements in High-Flow Conditions

Hydrophones measure changes in pressure. In calm water, acoustic waves are the only source of pressure change. Pressure fluctuations from other sources can also be measured by hydrophones and are called flow-noise or pseudo-noise. Float-on-a-rope moorings are commonly used for acoustic measurements. In high flow conditions, movement of the hydrophone in the water column (Figure 1) causes changes in pressure that the hydrophones measure. The hydrophone can also receive strumming noise from ropes under tension from currents. Movement of water around the hydrophone increases pressure on one side and creates an area of lower pressure on the other. Eddies behind the hydrophone are also pressure fluctuations that the hydrophone measures. Most of these pressure fluctuations are at frequencies below 100 Hz.

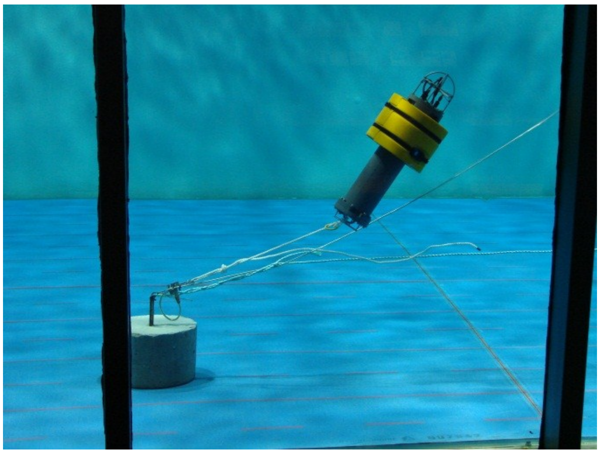

**Figure 1**. JASCO’s Autonomous Multichannel Acoustic Recorder (AMAR) in a 0.8 m/s current in the flume tank at the Centre for Sustainable Aquatic Resources (CSAR) at Memorial University, St. John’s, NL.

We can reduce pressure differences from strumming and hydrophone movement by securely mounting the hydrophone near the water column bottom. Pressure fluctuations caused by water moving around the hydrophone are lower near the bottom since the currents are generally lower there (see Figure 5). Surrounding the hydrophone with a ‘flow shield’ helps to eliminate flow noise. The choice of flow shield material is important. It must allow acoustic pressure waves to reach the hydrophone but keep the flow noises away from the hydrophone (Figure 2). Another technique often used in towed arrays is summing a number of hydrophone elements to increase coherent signals and decrease the uncorrelated flow noise. As part of this project, JASCO evaluated a 15 cm long M56 hydrophone (Geospectrum Technologies, Inc., Dartmouth, NS) that sums six M15B hydrophone elements (sensitivity −160 dBV/µPa), which should produce a 7.8 dB improvement (10·log6) in signal compared to flow noise.

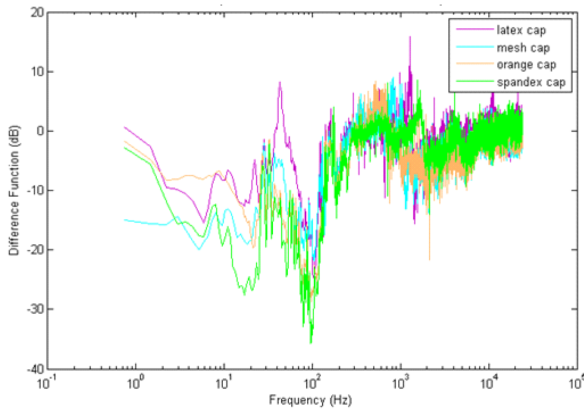


**Figure 2**. Measured sound spectra with various flow shield materials at 0.8 m/s flow.

In high flow (> 2 m/s) conditions, bottom mounting and flow shields are not sufficient to minimise noise. JASCO is iterating the design of a high flow mooring for these conditions. The mooring’s shape (Figure 3) passes the current smoothly over the cover, reducing pressure fluctuations and noise. The cover includes an acoustically transparent window immediately over the hydrophone to permit accurate measurements of real sound. A soft neoprene cover reduces sound caused by impacts from pebbles moved along the bottom by the current.

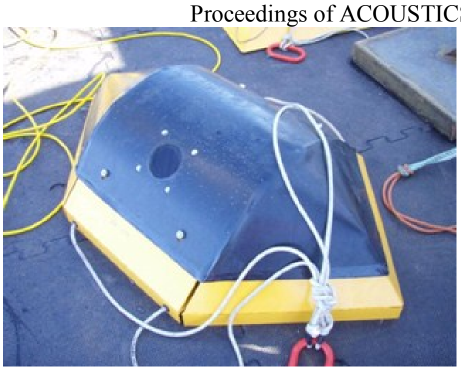

**Figure 3**. JASCO’s high-flow mooring (HFM). The circular window in the cover is acoustically transparent.

## TEST SITE—MINAS PASSAGE

The FORCE test site is located in Minas Passage, between Cape Spear and Cape Split in Nova Scotia (Figure 4). The passage separates the Minas Basin from the rest of the Bay of Fundy and is 40–60 m deep at the FORCE site. It narrows to less than 5 km wide at Cape Spear. At mid-tide, the current in Minas Passage is about 4 $km^3/h$, equal to the estimated combined flow of all the rivers and streams on Earth. With the incoming tide, approximately 14 billion tonnes of seawater flow through Minas Passage (FORCE 2012). The vertical tidal range is typically 11–13 m, with storm surges reaching 16 m.

**Figure 4**. Tidal rip seen from Cape Split, Nova Scotia looking across the FORCE Test Site toward Cape Spear.

Ice forms in the upper Bay of Fundy in many winters, allowing researchers to investigate its effects on in-stream technology. Ice cover can also interfere with maintenance activities. Ice that forms along the edges of the bay becomes laden with dirt and debris making the ice negatively buoyant, which makes it a physical risk to the turbines (AECOM 2009). Recent mild winters have made this risk difficult to quantify.

Tidal currents in the passage typically reach 5–6 m/s when averaged over 15 m ensembles (Figure 5). Local eddies, even at the passage bottom, range in speed from 2 to 6 m/s (S Melrose 2012, pers. comm., 11-12 January).

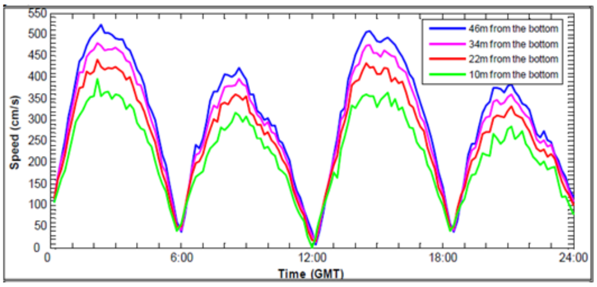


**Figure 5**. Current profile at Minas Passage, 7 May 2008 (Oceans Ltd. 2009).

## INITIAL DEPLOYMENTS

The initial FORCE deployments occurred in October 2011. Two HFMs were deployed, one on the volcanic plateau at the FORCE site, and one at the reference site to the west (Figure 6). Each HFM contained an Autonomous Multichannel Acoustic Recorder (AMAR; JASCO). The AMAR specification has a 24-bit ADC, 2.5V maximum signal amplitude, 104 dB broadband dynamic range and used a 64 ksps sampling rate. A Geospectrum M8E hydrophone (sensitivity of −164 dBV/µPa) was connected to the AMAR. The AMAR and the HFM have a net negative buoyancy of 94 kg, which initial calculations indicated was a 2.5:1 safety margin to prevent movement. This assumed a worst case current of 2 m/s, which was the strongest known current at the time. The HFM was attached by 125 m of abrasion resistant polyspec ground line (diameter 1 cm) to an ORE PortLF acoustic release in a syntactic elliptical float (Figure 7). It is important to keep the relatively noisy mooring chains of the acoustic release far from the acoustic recorder. The PortLF has a working load of 350 kg and a shock load limit of 1000 kg. A 274 kg steel weight created from 6 mm steel plate served as the anchor for the acoustic release.

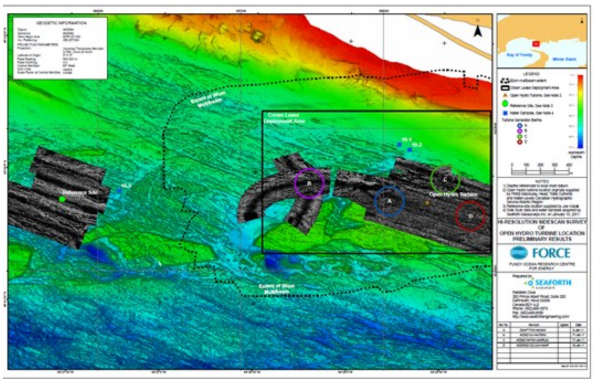


**Figure 6**. Bathymetry of FORCE Project and reference site.

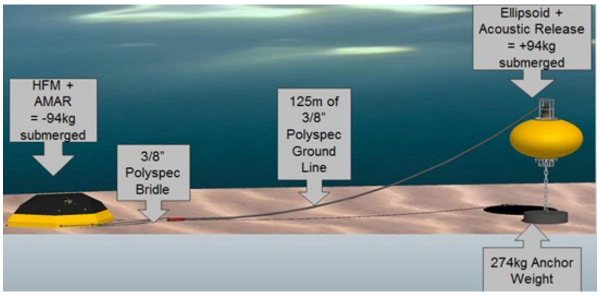


**Figure 7**. Mooring diagram for September and October 2011 deployments.

On 7 Oct 2011, we attempted the initial deployments from the *M/V Tide Nova*. The elliptic float and anchor were held over the side of the ship from a deck crane, while the HFM was lowered to the bottom from an A-frame. As the ground line became taught, the float and weight were released from the crane. 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. We recovered the mooring and the team returned to shore to investigate the problem (Figure 8, left).

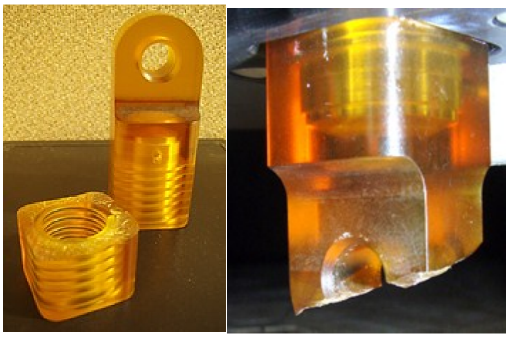

**Figure 8**. Left: Release block failure from shock loading during first deployment. Right: Fractured release block from second deployment.

Successful deployments occurred on 23 Oct 2011. We changed the deployment technique to lowering the anchor weight and float into the water and securing it with a quick release. The HFMs were lowered to the bottom with an A-frame, and then the anchor and float were released as the ground line became taught. Ranging with the acoustic releases showed that all equipment was in place and operating correctly. Retrievals were attempted on 24 Nov 2011. The acoustic releases did not respond to release commands and the HFMs were not recovered. Several days later our vessel was in the area and recovered one of the elliptical floats with 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 8, right). At this point the field program was suspended to perform a thorough review of the moorings. In January 2012, it was reported that eddies even at the bottom of the passage can reach 6 m/s (S Melrose 2012, pers. comm., 11-12 January).

## COMPUTATION HYDRODYNAMIC MODELLING

In December 2011, initial results from Computational Fluid Dynamic (CFD) models of the HFM by the University of New Brunswick (UNB; NSERC Engage Grant EGP 419875-11) were available. The CFD models of the HFM estimated the time-varying pressure at any point on its surface as well as its hydrodynamic lift and drag. UNB created a mesh representation of the HFM with and without a hydrophone protruding above the HFM surface. The models predict the turbulent flow along with any unsteady flow behaviour associated with flow separation around bluff and/or semi-streamlined bodies. Turbulent flow behaviour includes a wide range of spatial and time scales and generally requires a choice, by those using CFD, on what scales to consider relevant to the problem at hand. The CFD model was setup to resolve these scales, leading to a new methodology for resolving the relevant device related fluid flow phenomena to predict noise generation mechanisms. Two turbulence models were investigated: a Reynolds Stress Model (RSM), using the Reynolds Averaged Navier-Stokes Equations (RANS), and a combination of a Detached Eddy Simulation (DES) and the solution to the Navier-Stokes Equations (NSE). Both techniques used supercomputing resources available at UNB. Accurate prediction of unsteady flow phenomena for the known configuration of unsteady flow over a cylinder was the validation baseline.

The models indicate that the shape of the HFM produces lift in the tidal flow, requiring significantly more than 94 kg to anchor the mooring. Further analysis recommended 400 kg of anchor mass. The time varying DES simulation results (Figure 9) predict that the smooth surface of HFM has minimal pressure fluctuations, while having a protrusion for a hydrophone causes significant fluctuations and noise. A Fourier transform (Oppenheim and Shafer 1999) of the DES simulated time series (Figure 10) confirms that most of the flow induced noise is below 100 Hz.

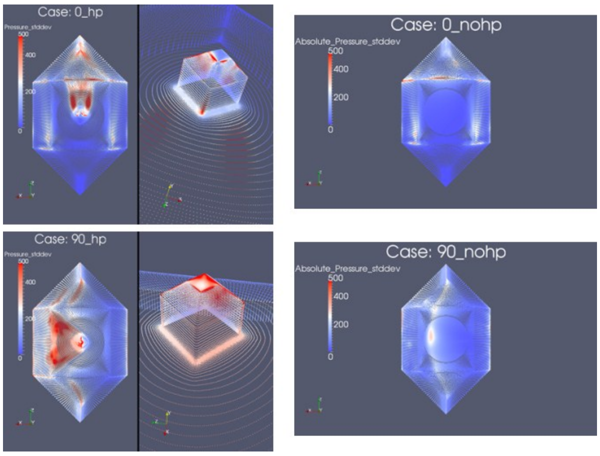


**Figure 9**. Computation Fluid Dynamics (DES) results of the high flow mooring. Left: Results with a hydrophone above the mooring exposed to the current. Right: results for a smooth surface. Top: Current flowing along the vertical axis of the mooring. Bottom: Current flowing perpendicular to the mooring. Colour represents the standard deviation of the pressure, which is directly proportional to sound levels.

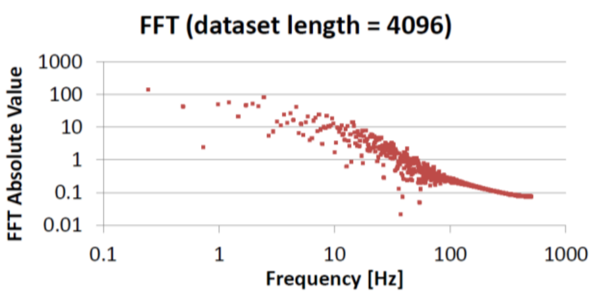


**Figure 10**. FFT of pressure time series for a point on a hydrophone in the current. Data simulated at 2048 samples per second, 4096 point FFT. This DES simulation predicts a 40 dB decrease in induced noise from 10 Hz to 100 Hz.

## THIRD DEPLOYMENT

The knowledge gained from the CFD modelling and extensive discussions with local experts on retrieving equipment from the Bay of Fundy (especially co-author Scotney) changed the mooring designs for the third deployment. Most moorings in the Bay of Fundy use streamlined floats to hold equipment such as ADCPs and acoustic releases. The floats are known to stabilise the equipment in the currents and are robust for long periods. An HFM and a streamlined float-based mooring were developed (Figure 11). Both moorings included heavy ORE 8242 acoustic releases and tethered floats as a redundant recovery mechanism. The tethered floats were partially inflated so that they would only surface for approximately one-half hour around slack tide. This is a technique used by local lobster fishers. The lower red floats on both moorings keep the 1.6 cm polytron line (4500 kg break strength) away from the bottom to minimise chaffing. Both moorings had XEOS Iridium beacons to notify the field team of the equipment position every 15 min if the moorings surfaced early.

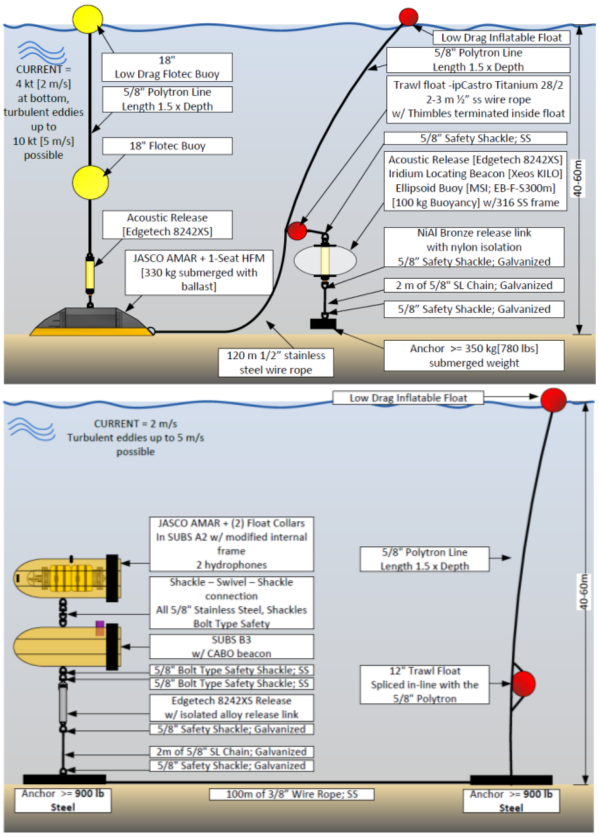


**Figure 11**. Modified high flow mooring (top) and streamlined float mooring (bottom) designs.

The HFM mooring had two hydrophones: an M8E inside the cover behind the acoustic window (see Figure 3) and another M8E in a cage and flow shield in the current (see Figure 9). The streamlined float 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.

The moorings were successfully deployed by the *M/V Tide Nova* on 23 Mar 2012. At 00:00 28 Mar 2012 (UTC) the streamlined mooring began to send sporadic Iridium messages, coming to rest on the beach at Scot's Bay, NS 12 h later. It was discovered that the stream-lined float's internal HDPE float frame had failed in two locations (Figure 12, black material). The forward (right) side mechanically failed first, then the aft (left) side suffered a plastic failure sometime later. The failure left the anchor plate and acoustic release on the ocean bottom.

**Figure 12**. Failed streamline float.

Retrieval of the HFM occurred on 5 Apr 2012. On arrival at the site, the field team discovered the elliptical float 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.

## RESULTS

Spectrograms (Figure 13) of the retrieved data show time on the *x*-axis, frequency on the vertical axis and the power spectral density value as colour for each time/frequency bin. The data from the HFM mooring shows significantly increased energy every ~12 h, with lower peaks every 6 h (Figure 13, red peaks top panel). This is clearly pseudo-noise on the mooring induced by the current. The streamlined float data show the same pattern for two tidal cycles. The initial mechanical failure occurred on the third tidal cycle, and total failure followed approximately three days later (Figure 13, bottom panel). The change in noise levels at the right hand edge of the streamlined float spectrogram correlates with the mooring drifting. Aural review of the recordings from both moorings indicated that the high flow mooring is quiet, without any mooring noises from channels or loose components. The streamlined float mooring has significant levels of self-noise from chains and vibrations, despite extensive efforts to control and eliminate them.

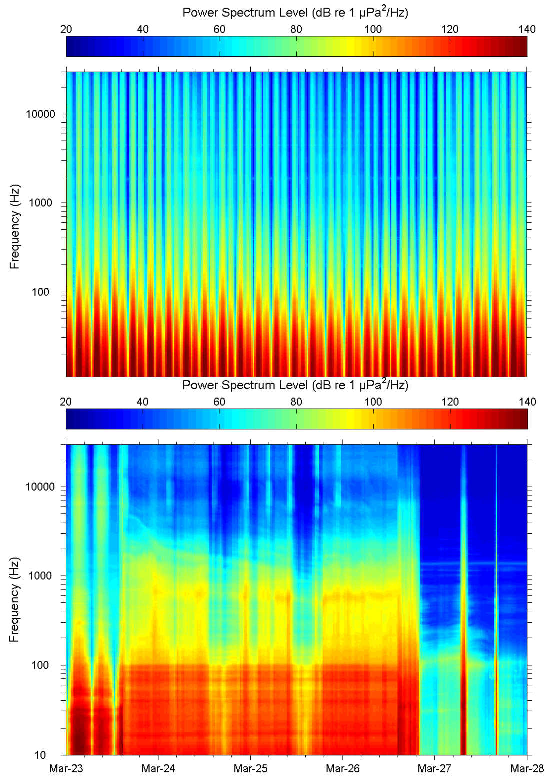


**Figure 13**. Spectrograms of recorded sound levels, Bay of Fundy, March 2012. Top: data from hydrophone internal to the HFM. Bottom: data from M8E hydrophone outside the streamlined float mooring. After 15 h the first mechanical failure of the float-frame occurred, followed by the complete plastic failure of the frame several days later.

To compare the noise levels on all five hydrophones we analysed the period from 23:00 22 Mar to 13:00 23 Mar 2012 when both moorings were operational. The median percentiles of the spectral densities show that the hydrophone inside the HFM clearly has the lowest noise levels below 1 kHz (Figure 14). It has similar sound levels as the hydrophone external to the HFM and the hydrophone external to the streamlined float at higher frequencies. The M56 multi-element hydrophone was approximately 10 dB above the other hydrophones at all frequencies.

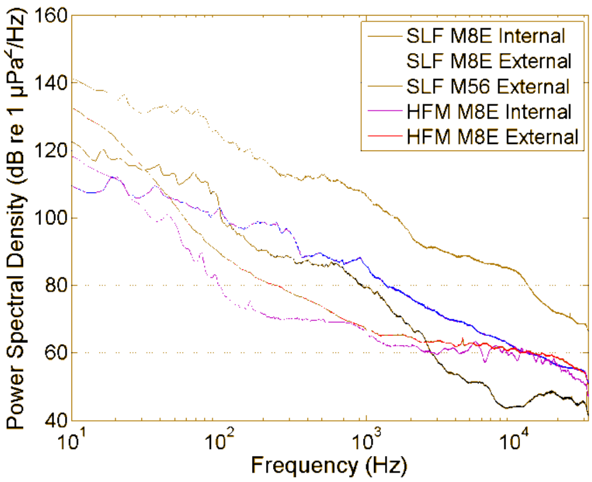


**Figure 14**. Comparison of median sound levels at all five hydrophones, 23:00 22 Mar - 13:00 23 Mar 2012.

The percentile plots show the median sound levels and suppress any repeatable time varying effects. The RMS SPLs for all five hydrophones during the first full tidal cycle suggests there is a significant difference in the received sound level inside the HFM during the ebb flow compared to the flood, and compared to the other hydrophones (Figure 15).

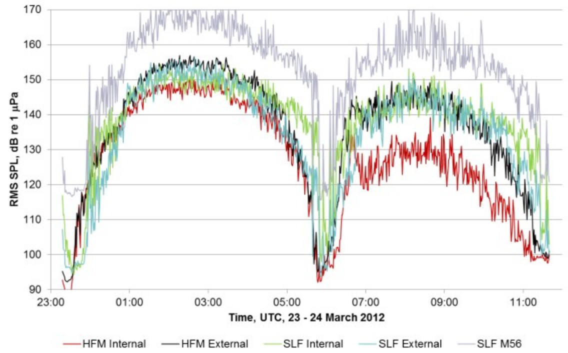


**Figure 15**: Comparison of RMS SPL levels all five hydrophones during the first full tidal cycle. The hydrophone internal to the HFM is significantly different from the other hydrophones during the ebb flow (06:00 – 12:00)

The total RMS levels differ by 20 dB between the ebb and flow; levels in the decade band of 100 – 1000 Hz differ by 25 – 35 dB (Figure 16). We believe that the high flow mooring was positioned so that the internal hydrophone faced into the flow during the flood tide and that it was sheltered from the flow during the ebb tide.

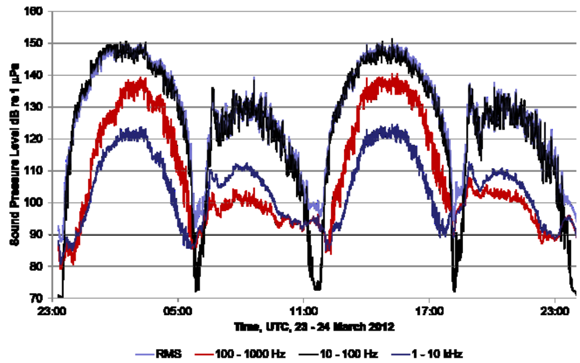


**Figure 16**. RMS and decade sound pressure levels for the hydrophone inside the flow shield of the high flow mooring for the first two tidal cycles. The noise in the band of 100 – 1000 Hz is 25 - 35 dB lower during the ebb flow than the flood.

The spectral densities from the two hydrophones in the high flow mooring during the flood flow shows the contribution to the total noise a function of frequency when the internal hydrophone faced into the flow(Figure 17, first and second row). At less than 50 Hz, the hydrophone inside the mooring had higher levels. Between 100 and 1000 Hz, the hydrophone inside the mooring had lower levels by 9–11 dB. Above 3 kHz, the two hydrophones measured the similar levels. As expected the levels at slack tide are significantly lower (Figure 16, third row).

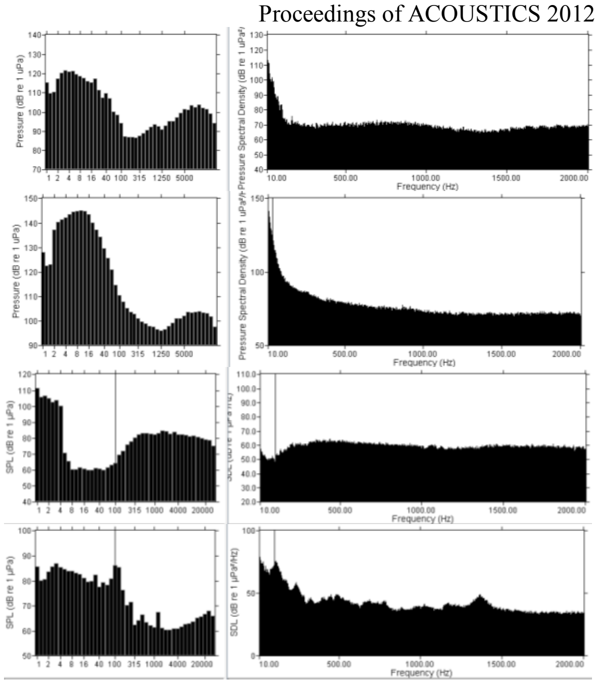


**Figure 17**. One-third-octave band sound pressure levels (left) and 2 Hz power spectral density plots (right) for 10 s of data. Rows from top to bottom: (1) Hydrophone on the high flow mooring inside the cover; 08:50, 24 Mar 2012; (2) hydrophone on the high flow mooring in the flow, 08:50 24 Mar 2012 at peak current flow. The hydrophone inside the housing has 15 dB lower noise levels below 100 Hz, and very similar noise levels above 1000 Hz. (3) The interior hydrophone at slack tide 00:00 25 Mar 2012; (4) The external hydrophone on the streamlined float mooring drifting in full tidal flow 2.5 h after breaking free. (32,768 pt FFT, 16,000 pts advance, 40 averages, Hamming window.

## DISCUSSION

There is good agreement between the spectral envelope modelled by CFD (see Figure 10) and our results, indicating that flow noise is dominant at low frequencies in these recordings. The envelope of the sound levels for the internal HFM hydrophone (Figure 17, first row) decays by 38 dB from 10 to 100 Hz, and the external HFM hydrophone (Figure 17, second row) decays by 43 dB. This envelope spectra in high flow conditions is very smooth (Figure 17, first and second rows). Therefore, any tonal signals generated by a tidal turbine will be easily detected as a spike in the spectra that is distinct from the smooth envelope of the background.

The difference in flow-induced noise on the internal hydrophone indicates that the preferred solution for future recordings is two hydrophones internal to the HFM, one on each side.

Southall et al (2007) show that marine mammals are disturbed by continuous sound sources with SPLs of 100 – 140 dB re 1 µPa. Southall et al. also proposed a number of M-weighting functions that are generic hearing functions for low, mid, and high frequency vocalizing cetaceans. Only porpoise and some dolphins are present in the areas of high flow of the Bay of Fundy. These animals have a lower threshold of hearing of 70 Hz (20 dB below peak response). This is also the threshold of hearing for many fish species and turtles. The noise level on the internal HFM hydrophone at 70 Hz during full flow was 85 dB re 1 µPa. If we assume an spreading loss of 15logR, and a detection threshold of 10 dB (Clark et al. 2009), then any tones generated by a tidal turbine with a source level of 125 dB re 1 µPa or higher will be detectable at 100 meters by the high flow mooring.

The multi-element hydrophone did not provide the gain against noise expected. The results suggest that the hydrophone was too short and the flow noise was correlated at each of the elements.

## COMPARISON TO DRIFT MEASUREMENT TECHNIQUES

The ideal type of measurement for assessing both the baseline (no anthropogenic source) underwater soundscape and the soundscape with sources such as turbines present is long term measurements. The ability to record across all seasons, weather conditions, tidal states and operational levels allows a complete assessment of acoustic impact to be made. The JASCO's HFM design is the first long term measurement system to be shown to fulfil these requirements in currents greater than 1.5m/s (Copping et al. 2012), the previous highest current situation demonstrated in literature.

Not considering the difference in information gathered between short-term drift and long term measurements, prior to the work discussed in this publication, it had been argued that only drifting measurements made using an autonomous buoy are reliable in high current areas (Stein 2011). This is not always the case, with FORCE's drifting measurements in 2008 and 2009 being unreliable because of vessel and surface noise contamination (Schillinger 2010). JASCO has also conducted drift measurements in high current environments (up to 3 m/s) for clients in other areas of the world and independently found them to be challenging to conduct, despite the data being of reasonable quality due to custom recording configurations.

The short term nature of drift measurements make them highly susceptible to uncontrollable interference during the drift period (including nearby vessels and vessel self noise). Controlling the drift to align with planned distances from the turbine can be almost impossible in vortexing currents, which also increase the risk of fouling/collision with infrastructure around the turbine and the turbine itself. Designing a drift system that minimises the impact of flow noise on recordings is also a complicated process.

Drift systems are also restricted in the results that obtainable through data analysis. It is not possible to determine SPL versus turbine speed from drift measurements; this can only be done if a fixed recording system is used.

While the JASCO HFM system was complex to design and test, the final system results in a substantially larger dataset of higher quality than drift measurement systems for a similar amount of field time. This allows a more detailed understanding of the measured source to be obtained and a more accurate representation reported.

## CONCLUSION

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 to deploy, and acoustically quiet make the development much more difficult. The mooring must be a streamlined shape on the bottom, with an acoustically transparent cover, and have no parts moving in the current generating noise. The data reported here indicate that the HFM design is capable of measuring ambient and turbine sound levels that have the potential to disturb marine life in the most challenging conditions on the planet.

## ACKNOWLEDGEMENTS

JASCO acknowledges FORCE, especially Jennifer Matthews and Joe Kozak, for supporting this project. JASCO's field crews, especially Eric Lumsden, Craig Evans, Christopher Whitt and Jerry Kennedy, were indispensable for reviewing mooring designs and providing feedback to ensure they could be deployed and recovered safely. Thanks to Captain Mark Taylor and the crews of the *M/V Tide Nova*.

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