OERA Final Report

Real-Time Particle Acceleration/Particle Velocity (PA/PV) Measurement System Evaluation in a Tidal Environment

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Contents

Figures

Tables

Executive Summary

The purpose of this project was to evaluate a real-time Particle Acceleration/ Particle Velocity (PA/PV) (vector) sensor based drifting acoustic measurement system in a tidal environment. An experiment was proposed in the Minas Passage to evaluate the performance of the PA/PV sensor in a flowing environment. It was hoped that the PA/PV sensor would provide more sensitive and more accurate acoustic measurements than traditional hydrophone-based system. It was intended that the system would also demonstrate the delivery of acoustic measurement data via the internet in near real-time.

The Observer Buoy system we intended to use to support this trial was lost at sea in May 2017 during another project. That system was an in-kind contribution to this project and thus needed to be replaced, which introduced delays in the project schedule. Due to that expensive loss experience, we chose to perform the initial measurements with the directional sensor offshore of Halifax, which is a less energetic tidal environment than Minas Passage. The acoustic measurements recorded on 5 Dec 2017 and were highly successful. The combination of a catenary mooring and the M20 PV/PA sensor provided clean acoustic data, and accurately estimated the bearing (i.e. direction) of the trial vessel and an acoustic projector source suspended from the trial vessel.

The loss of the original Observer Buoy also affected our system development activities when the in-kind hardware became unavailable. The re-built Observer-Buoy system telemetered Automatic Identification System (AIS) and Global Positioning System (GPS) reports to shore in real time but did not send onboard acoustic event detections. This did not diminish our ability to achieve our primary goal of evaluating the sensor performance because full-bandwidth data was recorded for post-analysis and the transmitted data demonstrated the ability of the platform to act as a real-time information delivery system. It was the calculation of real-time acoustic measurements aboard Observer that was deferred into future research and development initiatives.

Since assembling the re-built hardware platform, JASCO has continued to develop the Observer Buoy software and communications protocols as part of our internal research and development program. The drifter is now ready for a full demonstration in Minas Passage. We recommend conducting additional drifting measurements during the spring/summer of 2019.

1. Introduction and Objectives

Short-term acoustic recordings are often used for measuring sounds produced near their source. For example, Fundy Ocean Research Center for Energy (FORCE) and Offshore Energy Research Association of Nova Scotia (OERA) have made many recordings using drifting systems that move with the currents in Minas Passage and Grand Passage to quantify the typical background noise levels and measure the source level of tidal turbines. Surface drifters have been used at these sites because they are easy to deploy and recover, and they suffer less performance degradation due to flow noise.

Acoustic recordings are made with hydrophones that are sensitive to small changes in pressure caused by sound waves travelling in the water. Large pressure changes can occur when currents move water around the hydrophone, a problem for stationary hydrophones that is overcome by using drifters. However, drifters move up and down in the water due to waves, which also causes large pressure changes. These pressure changes from hydrophone movement and currents are called flow noise. It is a measurement artefact that must be minimized when collecting data and accounted for when analyzing data. Minimizing vertical movement noise in acoustic drifters requires a method of suspending the hydrophone so that it does not move up and down when the surface buoy is affected by waves. Previous measurements performed by FORCE compared an elastic-and-bristle suspension (icListen drifter) with an ‘S’ shaped catenary suspension (AMAR Drifter) and found evidence of better performance from the catenary suspension (Martin et al. 2018). One of the objectives of this project was to obtain further data to understand when catenary suspensions are effective.

An important element of the Environmental Effects Monitoring Plans for tidal turbine installations is evaluating technologies for measuring the interaction of marine life with the turbines. Standard hydrophones are omni-directional, which means they are equally sensitive to sounds arriving from all directions. They are useful for detecting the presence of vocalizing marine life, but not the direction or location of the vocalization. PV/PA sensors offer the potential to provide the relative bearing from the sensor to the sounds they measure. This additional capability means that they have the potential to separate sounds arriving from different directions, including measuring the spatial relationship between vocalizing marine life and tidal turbines. Internally, directional hydrophones are assembled from very sensitive accelerometers that are capable of measuring accelerations where the physical displacement is on the order of 10 nm. Therefore, to make effective measurements of sound directions using an acoustic drifter, good isolation of the PV/PA sensors from surface movement is essential.

The objectives of this project were to:

- Evaluate a PV/PA sensor measurement system in a tidal environment.
- Test and trial a near real-time, drifting, acoustic-measurement system including a directional hydrophone.
- Demonstrate the delivery of acoustic measurement data via the internet in near real-time.
- Evaluate the accuracy of the direction (bearing) of acoustic noise sources produced by the PV/PA sensors.

2. Methodology and Results/Deliverables

2.1. Acoustic Data Acquisition

Two drifting acoustic recording systems were employed for this project. One drifter had an Autonomous Multichannel Acoustic Recorder (AMAR G3 Drifter; Figure 1) equipped with a standard M36 omnidirectional hydrophone (Table 1). For the M36 drifter, the recorder and hydrophone were both at the end of a catenary suspension (Figure 2), and the M36 hydrophone was surrounded by a fabric cover to further minimize flow noise. The second drifter included the M20 PV/PA sensor was suspended at the surface in the Observer pressure housing (Figure 3). The reason two drifters were deployed was to try and understand the background environmental noise separate from the mooring & wave induced noise. The M36 drifter had been previously used and its performance was well understood. This sensor was used to characterize the background noise.

Acoustic data were stored on a 512 GB internal solid-state flash memory for the M36 and a 200 GB microSD for the M20. All devices had a gain of 6 dB. See Appendix A for further details about the M20 PV/PA sensor.

The M36 hydrophone on the AMAR was calibrated before deployment and again in the JASCO facility after retrieval with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S). The pistonphone calibrator produces a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space with known volume. The recorded level of the reference tone on the AMAR yields the system gain for the AMAR and the hydrophone. To determine absolute sound pressure levels, this gain is applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure. The manufacturer’s calibration was used for the M20 PV/PA sensor.

Figure 1. The Autonomous Multichannel Acoustic Recorder (AMAR; JASCO) used to measure underwater sound on one of the drifters.

Table 1. The duration, system spectral noise floor, sampling rate (continuous recordings stored in 30 min .wav files), frequency range, and sensitivity for acoustic devices (GeoSpectrum Technologies Inc.).

Station	Hydrophone/ sensor device	Channel(s)	Sensitivity (dBV)	Sampling rate (ksps)	Acoustic frequency range (Hz)	Spectral noise floor (dB re 1 µPa²/Hz)
AMAR Buoy	M36-V35-100	1 omnidirectional	−165	64	10–32,000	21
Observer Buoy	M20-601	x, y, z directional	−165	8	10–4,000	32
		1 omnidirectional	−165	8	10–4,000	32

Each mooring (Figures 2 and 3) was ~50 m long and weighed ~90 kg. Each mooring consisted of:

- A surface float with iridium and flashing beacons, as well as AIS and hi-flyers for tracking.
- An adjustable line to trim weight (zeroed to allow minimum depth).
- A catenary system with either an AMAR or M20-601 PV/PA sensor ≤50 m deep, depending on current.

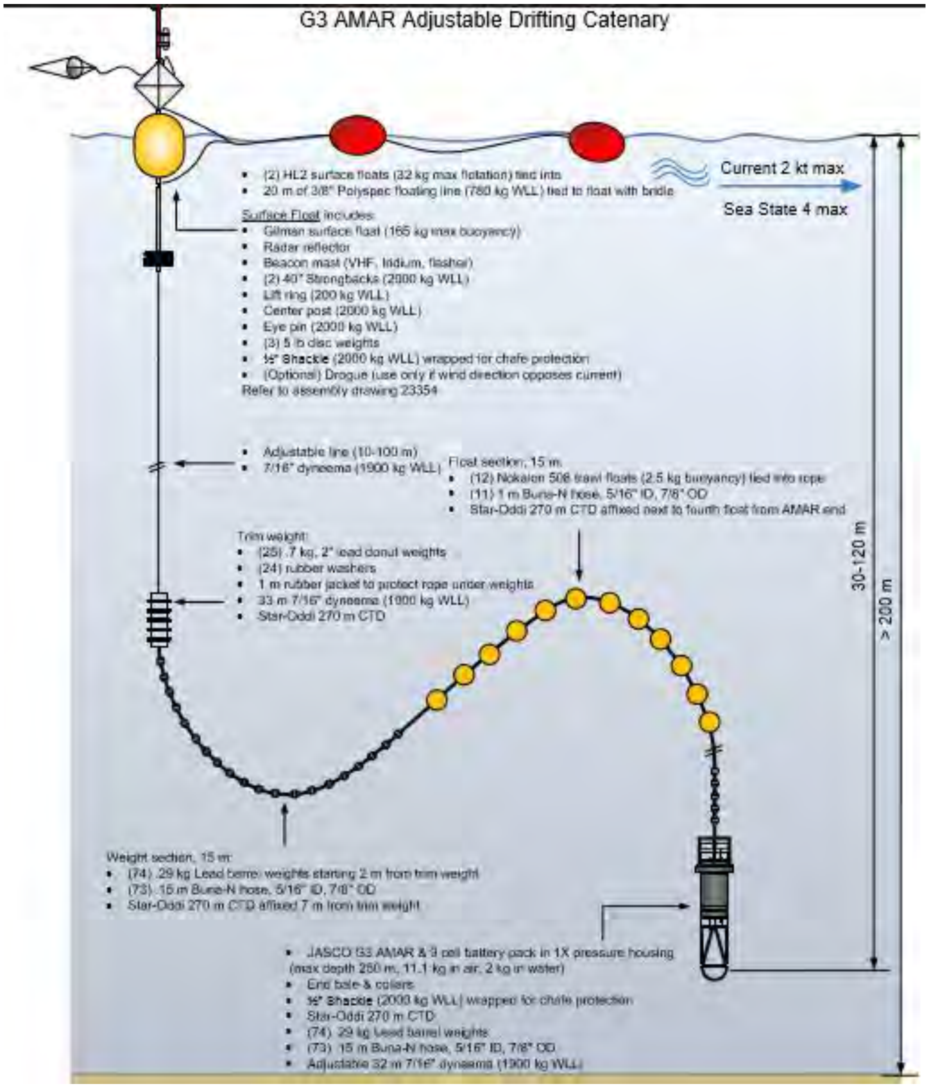

Figure 2. Mooring 167 used for deployment of AMAR G3 Drifter

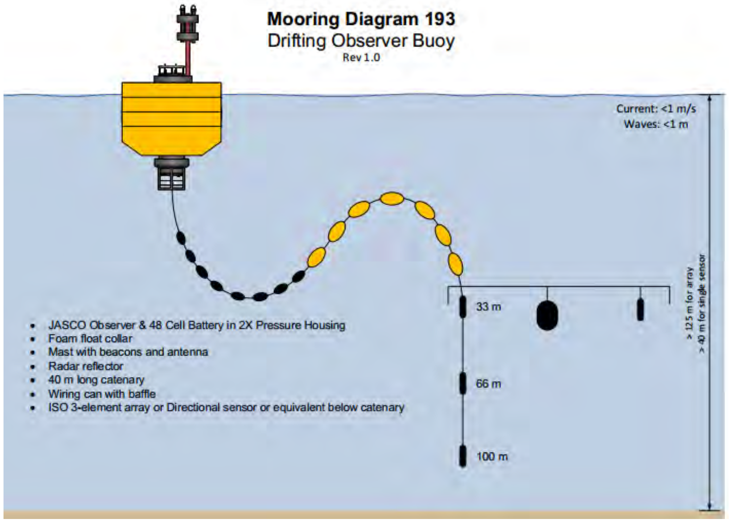

Figure 3. Mooring 193, directional sensor for deployment east of Yankee Bank.

2.2. Acoustic Projector

The low-frequency acoustic projector used in this trial was built around GTI’s M21 flexural disk transducer. Flexural disk transducers, or benders, provide an omnidirectional signal and are, therefore, well suited as projectors. GTI designed the M21’s resonant frequency to be 100 Hz. The bender was supplied with a frequency in a .WAV file stored on an MP3 player, that was then input to a power amplifier to drive the transducer. All the electronics for the projector, including 48 D-cell batteries delivering 24VDC, MP3 player, and power amplifier, were stored within a PVC AMAR G3 pressure housing to provide environmental shielding. Figure 4 presents a picture of the full projector assembly.

Figure 4. Complete projector assembly used in the trial

The projector was deployed by lowering the transducer with a line over the side of the vessel until the transducer was submerged and below the vessel Next, the following MP3 sweeps were played for at least 2 minutes until complete:

- 2 second FM sweep, 800–900 Hz
- 4 second FM sweep, 1000–1300 Hz
- 6 second FM sweep, 1300–800 Hz
- 5 second FM sweep, 800–1200 Hz
- 7 DTMF (dual-tone multi-frequency) tones, each tone 0.154 seconds long, entire set is 2.4 seconds long with gaps. Numerical sequence 429-6666

This procedure was completed four times at a distance of 250 m from the drifter buoy in each cardinal direction, while the receipt of the tones was monitored in real-time over Wi-Fi. The vessel’s engine was left running for the duration of the projection.

2.3. Field Trial Plan

The field trial Operations Plan is attached as Appendix B. The two drifters were deployed from the *Captain's Pride* (Figure 5) on 5 Dec 2017 (Table 2 and Figure 6). They were retrieved after ~80 minutes of operation. The deployment area was located east of Yankee Bank, at a 55 m water depth.

Table 2. Observer Drifter deployment and retrieval times and locations on 5 Dec 2018.

Station	Time (UTC)	Latitude	Longitude
Deployment	14:47:00	44° 33.940' N	63° 16.228' W
Retrieval	16:06:23	44° 33.986' N	63° 16.173' W

Figure 5. Captain's Pride vessel.

Figure 6. Proposed mooring track for AMAR Drifter buoys. Minimum water depth ≥50m.

2.4. Field Trial Results

The acoustic data recorded during the trial was extracted and analyzed using JASCO's custom software suite. Figures 7 and 8 show the power spectral density percentile plots for the Observer Buoy M20 and AMAR G3 recorders, respectively. The figures present the average distribution of sound across frequencies for the entire trial timeframe, excluding periods of noise during deployment and retrieval. Figure 9 shows the M20 spectrogram before and after applying the 10 Hz high pass filter, which effectively removes the noise from low-frequency oscillation. The M20 figures, such as Figure 9, use colour to indicate the direction of the sound source, while the intensity of the received sound is shown by the brightness of each colour. The M20 is fitted with an internal compass and compensation system so that the outputs are always a north-south dipole and an east-west dipole.

To test for validity in the recorded sound levels and directionality of the M20 PV/PA sensor on the Observer buoy, the recorded vessel transits were compared to vessel tracks from the *Captain's Pride*. The data were analyzed using a 4-term Blackmann Harris window function and a high pass filter with a cut-off frequency of 10 Hz. The vessel transit recordings, identified by the Lloyd's Mirror (or "bathtub") effect in the spectrograms, were compared in time and directionality to the vessel GPS position data (Figures 10 and 11). It was found that the directional M20 PV/PA sensor accurately reported the time and direction of the vessel passes. Closest point of approach (CPA) distances and sound levels at the Observer buoy are presented in Figure 11. Figure 12 shows the spectrograms of the acoustic data recorded by the M36 on the AMAR buoy over the same deployment period. The different locations of the two sensors causes a different acoustic response in the M20 and M36 (to vessel CPA) due to the difference in relative range & bearing.

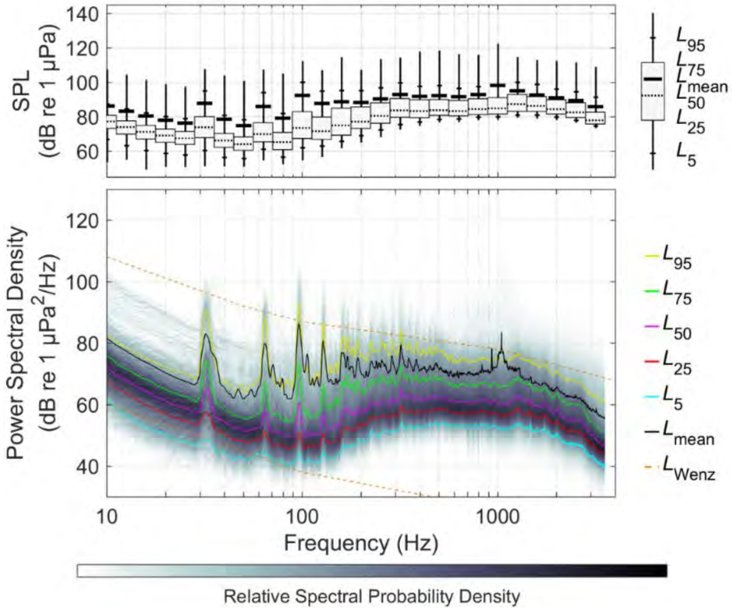

Figure 7. (Bottom) Power spectral density levels and (top) 1/3-octave-band rms SPL at Observer Buoy with M20 PV/PA sensor.

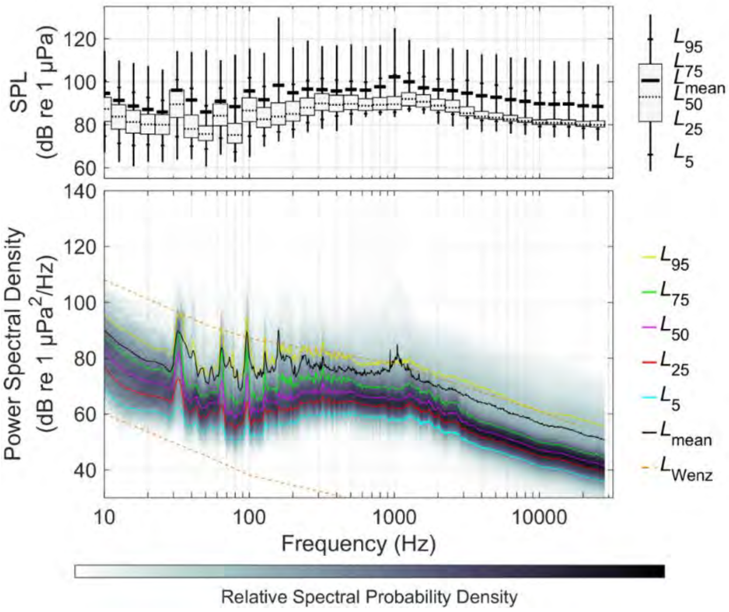

Figure 8. (Bottom) Power spectral density levels and (top) 1/3-octave-band rms SPL at AMAR G3 Drifter with M36 hydrophone.

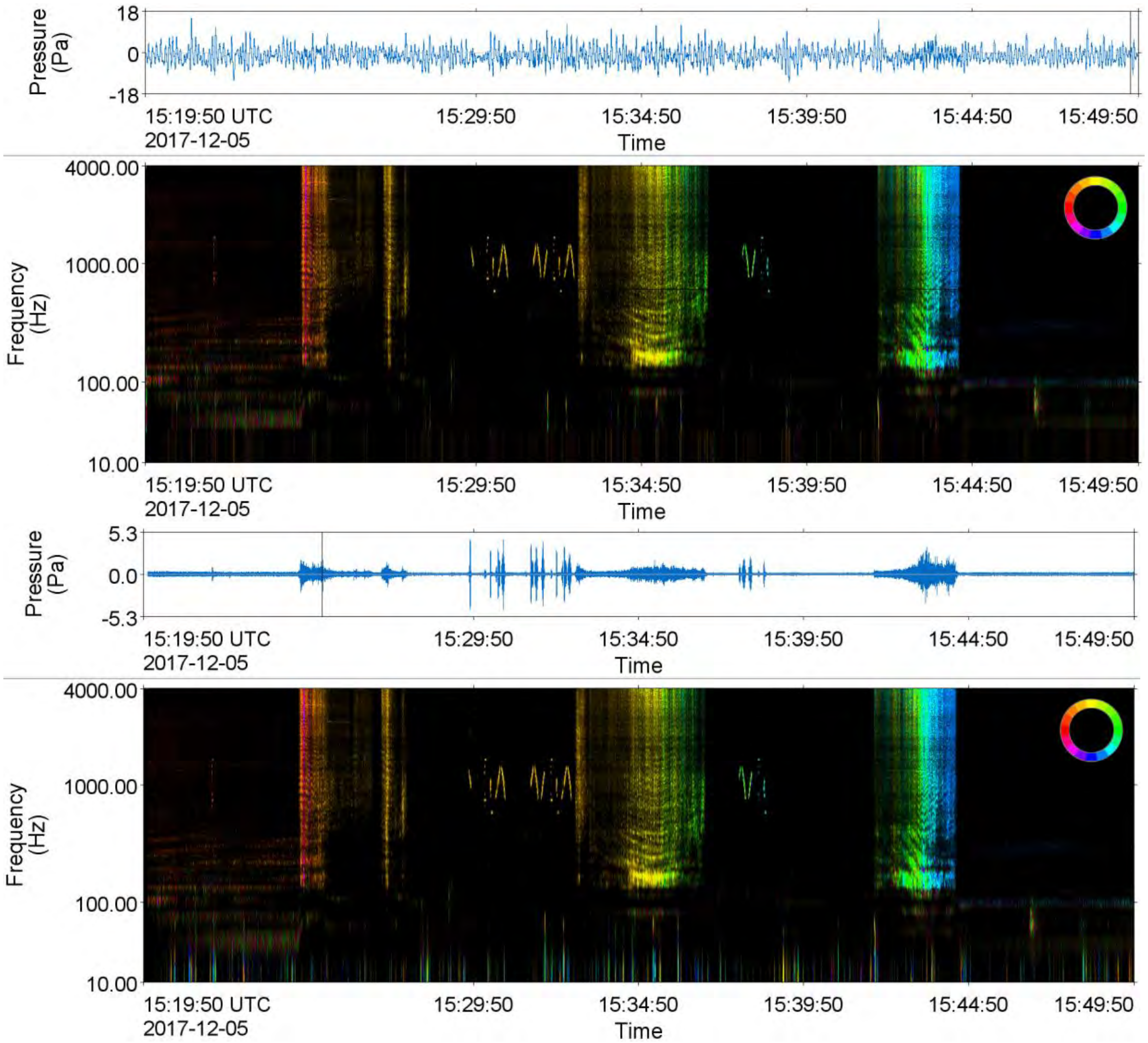

Figure 9. M20 spectrograms and time-series data before (top) and after (bottom) applying a 10 Hz high pass filter.

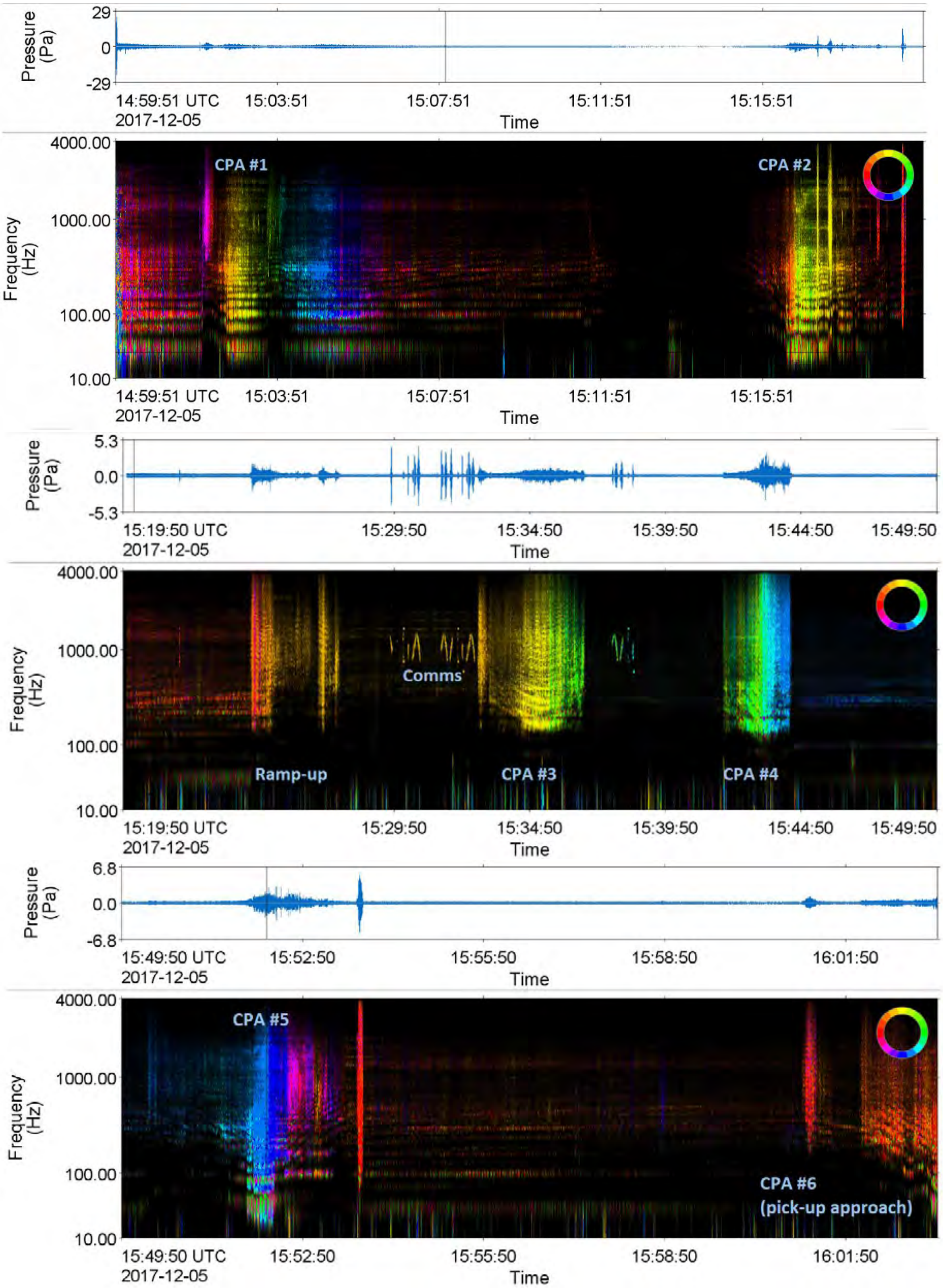

Figure 10. Spectrogram of M20 acoustic recordings. Directionality is indicated by colour based on the legend wheel in the upper-right corner. Vessel tracks showing directionality for *Captain's Pride* CPA #1 to #6 are shown in Figure 11.

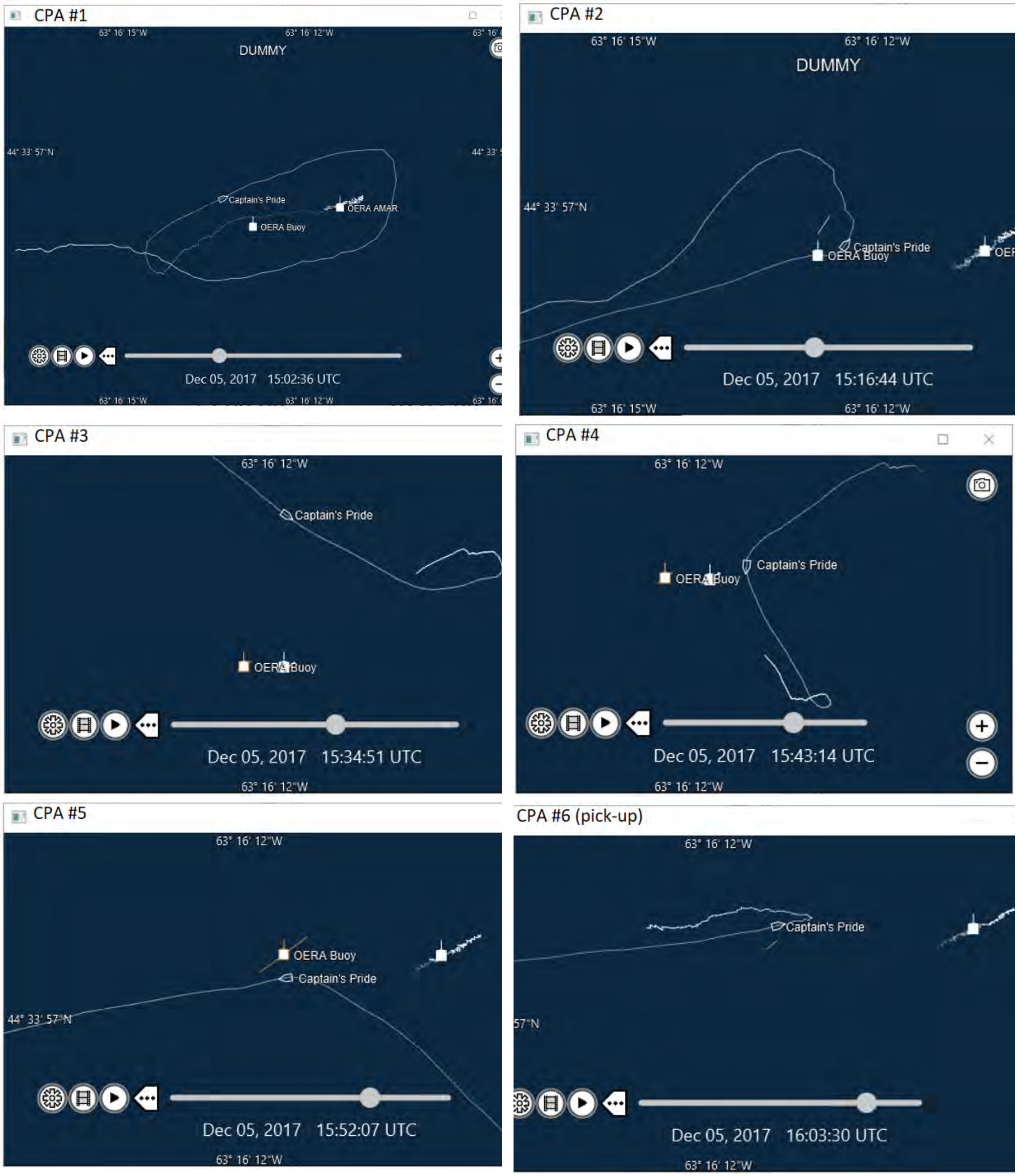

Figure 11. Vessel tracks for *Captain's Pride* CPA #1 at 15:02, CPA #2 at 15:16, CPA #3 at 15:35, CPA #4 at 15:43, CPA #5 at 15:52, and CPA #6 upon retrieval at 16:03. Observer buoy tracks are in orange.

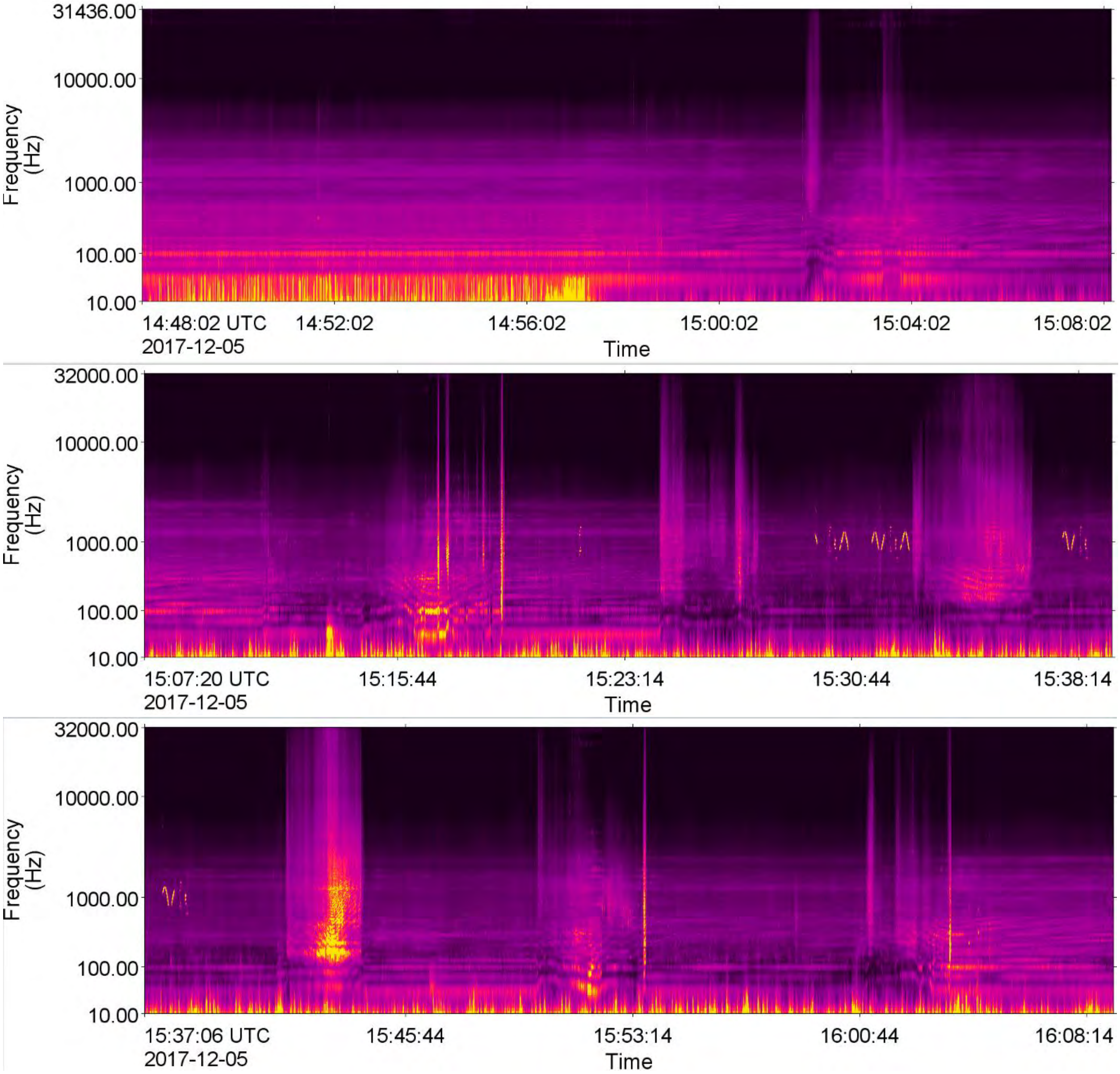

Figure 12. Spectrograms of omnidirectional M36 acoustic data for the deployment period.

Table 3. *Captain's Pride* CPAs recorded on the Observer drifter M20 PV/PA sensor on 5 Dec 2018.

CPA	Time	Duration (sec)	Horizontal range (m)	Slant range (m)	SPL (dB re 1 µPa)	SEL (dB re 1 µPa²·s)	1/3-octave frequency band (Hz)	Peak frequency (Hz)
1	15:04	60	16	57	126.32	144.1	89.1–112	99
2	15:15	60	2	55	126.64	144.42	89.1–112	96
3	15:36	60	245	251	106.88	124.66	70.8–89.1	79
4	15:42	60	135	146	117.95	135.73	178–224	180
5	15:52	60	11	56	113.79	131.57	70.8–89.1	73

The slant range assumes the M20 depth was 55 m. The SEL computations based on 60 seconds duration.

SEL provides the measure of the total energy of a signal. Assuming the M20 and the M36 are collocated, the SEL measured by the two systems should be the same. Given the two drifting systems were located in close proximity, the SEL only provides subjective evidence of similar and correct response. For Table 3 the SPL and SEL were computed from the M20's omni hydrophone and hence the directionality is not an issue.

Table 4. *Captain's Pride* CPAs recorded on the AMAR drifter M36 hydrophone on 5 Dec 2018.

CPA	Time	Duration (sec)	Horizontal range (m)	Slant range (m)	SPL (dB re 1 µPa)	SEL (dB re 1 µPa²·s)	1/3-octave frequency band (Hz)	Peak frequency (Hz)
1	15:03	60	19	58	120	137.78	89.1–112	99
2	15:16	60	42	69	129.49	147.27	89.1–112	96
3	15:35	60	216	223	109.22	127.00	70.8–89.1	79
4	15:43	60	63	84	128.76	146.54	178–224	180
5	15:51	60	40	68	121.06	138.84	70.8–89.1	73

The SPL frequency band was based on frequency peak at 1/3-octave-bands.

3. Conclusions & Recommendations

This project successfully tested and trialed a real-time drifting acoustic measurement system using a directional hydrophone sensor. The performance of the PV/PA compared favourably with a traditional hydrophone drifter but added the capability to discriminate the arrival direction of the received sounds.

The Observer Buoy system we intended to use to support this trial was lost at sea in May 2017 during another project. The lost system was an in-kind contribution to this project and thus needed to be replaced, which introduced delays in the project schedule. Due to that loss, we chose to perform the initial measurements with the directional sensor offshore of Halifax, which is a less energetic environment than Minas Passage because of risk of loss of the PV/PA sensor. This loss negatively affected the project schedule and budget. The addition project cost was absorbed solely by JASCO. This loss also affected JASCO's ability to implement the intended telemetry of measurements Observer-Buoy functionality as effort had to be re-directed. JASCO did, however, successfully demonstrate the telemetry of AIS and GPS data from Observer-Buoy, which proves the potential real-time reporting capability of this system.

The project team suggests the following conclusions:

- The PV/PA sensor did function correctly in the selected tidal environment.
- The measured frequency and received signal strength aligned with that measured by a calibrated M36 hydrophone.
- The PV/PA was able to correctly measure the relative bearings of the narrowband and broadband sound sources.
- The Observer-Buoy and catenary functioned as intended, providing isolation and damping from surface buoy motion and tidal turbulence induced noise.
- The loss of the planned Observer-Buoy contribution negatively impacted the initially planned project schedule and budget; the project schedule shifted right and the cost to JASCO was significantly more than planned.

The project team makes the following recommendations:

- More tidal drift experiments are required to more fully characterize the performance of the PV/PA system in various tidal environments.
- Additional measurements should be conducted in a more energetic tidal environment.
- The real-time, in-situ measurement, and measurement telemetry software should be completed and implemented for the Observer-Buoy

6. Literature Cited

Martin, B., L. Horwich, and C.J. Whitt. 2018. *Acoustic Data Analysis of the OpenHydro Open-Center Turbine at FORCE: Final Report*. Document Number 01588. Version 2. Technical report by JASCO Applied Sciences for Cape Sharp Tidal and FORCE.

Nedelec, S.L., J. Campbell, A.N. Radford, S.D. Simpson, and N.D. Merchant. 2016. Particle motion: the missing link in underwater acoustic ecology. *Methods in Ecology and Evolution* 7: 1-7. http://dx.doi.org/10.1111/2041-210X.12544.

Yeatman, P. and B.A. Amstrong. 2011. Particle Velocity Measurements. *Proceedings of the Institute of Acoustics* 33(5): 1-5.

Appendix A. Particle Motion

A.1. Relationship between Particle Velocity and Acoustic Pressure

In acoustics, the particle velocity, *u*, and the acoustic pressure, *p*, are related by the linearized Euler's equation:

$$\rho_0 \left(\frac{\partial u}{\partial t}\right) = -\nabla p \, .$$

Here, ρ is the density of the medium, and ∇ is the spatial gradient function.

In the case of an idealized point source at a single frequency ω, the acoustic pressure as a function of distance from source, *r*, may be written as:

$$p(r,t) = \frac{P_0}{r} \exp\big(j(kr - \omega t)\big) \, ,$$

where P_0 is the amplitude of the acoustic pressure at the source.

Applying the linearized Euler's equation to this provides the relation:

$$u(r,t) = \frac{P_0}{r\rho_0 c}\left(1 - \frac{1}{jkr}\right) \exp\big(j(kr - \omega t)\big) \, .$$

It can be instructive to split the result as follows:

$$u(r,t) = u(r,t)_{\text{in-phase}} + u(r,t)_{\text{out-phase}}$$

where

$$u(r,t)_{\text{in-phase}} = \frac{P_0}{r\rho_0 c} \exp\big(j(kr - \omega t)\big)$$

and

$$u(r,t)_{\text{out-phase}} = j\frac{P_0}{r\rho_0 c}\left(\frac{1}{kr}\right) \exp\big(j(kr - \omega t)\big) \, .$$

The subscripts denote the fraction of the particle velocity that is in phase or out of phase with the acoustic pressure at the same point. Due to the 1/kr term in the out of phase portion, this fraction reduces with distance from the source. '*k*' is 2·π·f/c, where *f* is the frequency of the wave and *c* is the speed of sound. Thus, the out-of-phase effect diminishes rapidly as the frequency and the range increase. At distances far from the source (and at high frequency), the relationship between particle velocity and acoustic pressure becomes:

$$p(r,t) = \rho c u(r,t) \, .$$

This is also the solution if considering a plane wave rather than taking spherical spreading into account. The phenomenon associated with a point source is encompassed in the out of phase term that only exists in the near field. Figure A-1 shows the relationship between range, frequency, and the ratio of the in-phase and out-of-phase terms.

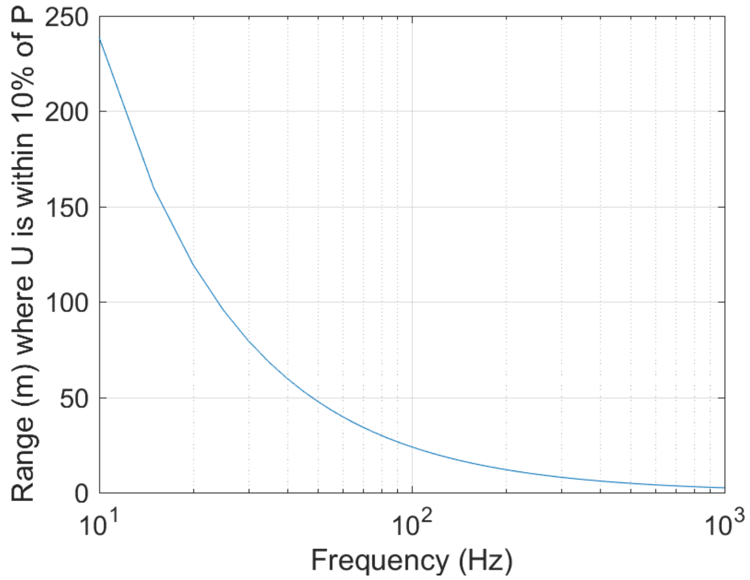

Figure A-1. Plot of the frequency-range curve where the magnitude of the out-of-phase term of particle velocity (U) is 10% of the in-phase term (P).

The acoustic intensity is a measure of the flow of acoustic energy per unit area and is related to the acoustic pressure and particle velocity by the relationship:

$$I = |pu| = \frac{P_0^2}{r^2\rho_0 c}\sqrt{1+\left(\frac{c}{2\pi f r}\right)^2}\,.$$

The intensity field comprises two components: these are the active and the reactive intensity. As is clear from the intensity expression, for low frequencies and low ranges, there is a near-field boost in the sound intensity. Where the acoustic pressure and the particle velocity are in phase the two cooperate to propagate sound to generate the far-field of the source–this is the active field. The result of the acoustic pressure and the particle velocity being in quadrature (out-of-phase) is that this generates a localised form of energy transportation in which the local elements' energy oscillates between kinetic and potential with no net transport of energy–this is the reactive field. The ranges at which this boost is significant is shown in Figure A-2 for 25 Hz and 100 Hz.

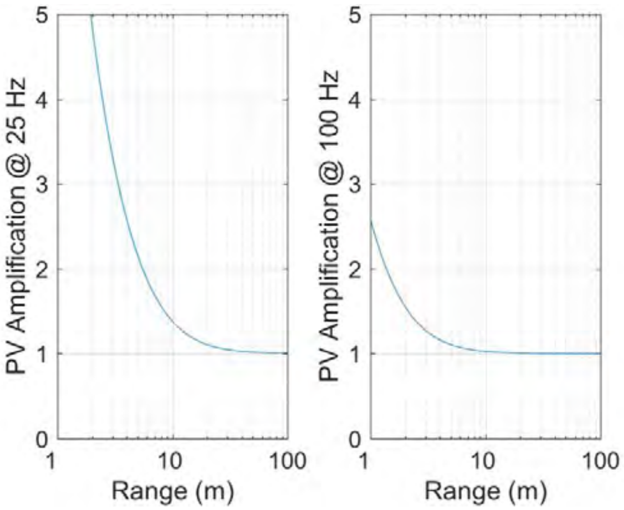

Figure A-2. Intensity amplification magnitudes in the near-field of a point source where PV is the ratio of pressure to particle velocity multiplied by the characteristic impedance of the medium (i.e., p/ρcU).

As well as near-field effects, the acoustic pressure and the particle velocity are also constrained by boundary conditions. For an acoustic wave hitting a rigid (infinite impedance) boundary perpendicularly to the surface, the particles at the surface are unable to move and as such, the particle velocity is zero. This requires that the pressure be completely reflected, hence the reflection coefficient is one and there is a doubling of the pressure near the surface. Conversely, for a pressure-release boundary, a condensation of particles cannot exist and consequently the acoustic pressure is constrained to zero. In this case, the pressure must go to zero, the reflection coefficient is −1, and there is a zone near the surface with no pressure signal. In ocean acoustics, a near pressure-release boundary exists at the water-air interface. Near-rigid boundaries are less common due to the prevalence of sediments on the ocean floor; however, the increased impedance at the ocean floor appreciably reduces the particle velocity and correspondingly increases pressure to balance the energy.

When the seabed is not a perfectly rigid surface, sound energy propagates in both the seabed and water column. The normal modes of a shallow water waveguide illustrate this effect (Figure A-3). In Figure A-3 left, the sediment is a near-perfect reflector, so there is very little penetration of the modes into the sediment and only two modes propagate. In Figure A-3 right, a 200 m thick silt sediment was modelled over the same near-perfect basement. Six modes propagate and there is a complex relationship between the pressure and particle motion near the seabed. Similar to the in-phase out-of-phase relationship (Figures 1 and 2), there is a frequency range for a shallow water waveguide where the particle motion is not directly related to the pressure. In this case the difference in density between the water column and the seabed determines the relationship and can be parameterized by the cut-off frequency:

$$f_c = \frac{c_w}{H}\left(\pi - \frac{\rho_{sed}}{\rho_w}\right)/(2\pi\sin(\arccos\left(\frac{c_w}{c_{sed}}\right))),$$

where c_w is the speed of sound in the water, H is the water depth, ρ_{sed} is the sediment density, ρ_w is the water density, and c_{sed} is the sediment density (Ainslie 2010, Nedelec et al. 2016). Nedelec et al. (2016) provide a visualization of this relationship (copied as Figure A-4) and recommend making direct particle motion measurements when the experimental domain is on the left-side of the curve (in the blue).

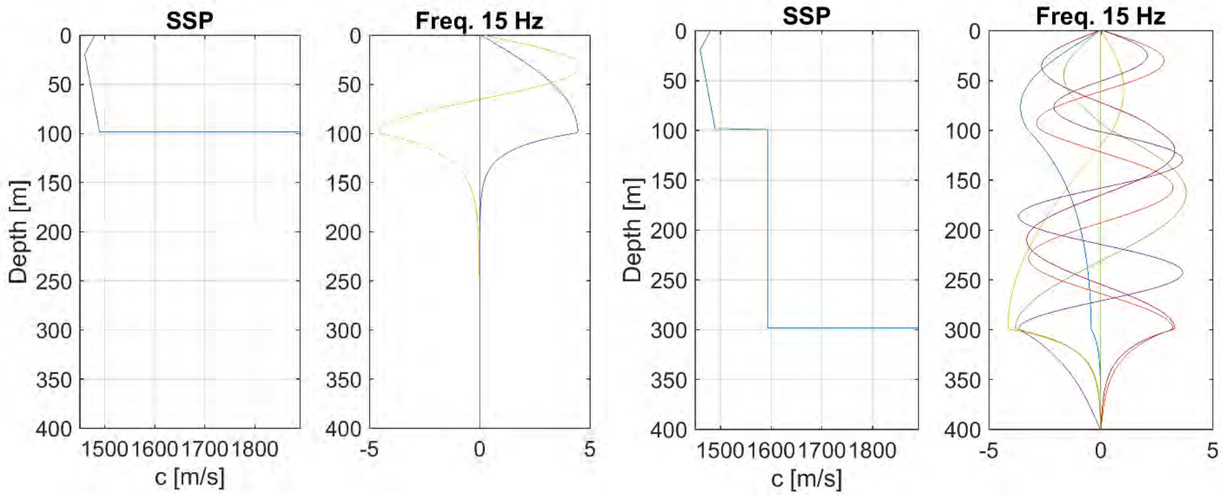

Figure A-3. Propagating modes for a 100 m deep water waveguide. In each subfigure, the left plot is the sound-speed profile vs depth, and the right shows the propagating mode shapes for a 15 Hz sound.

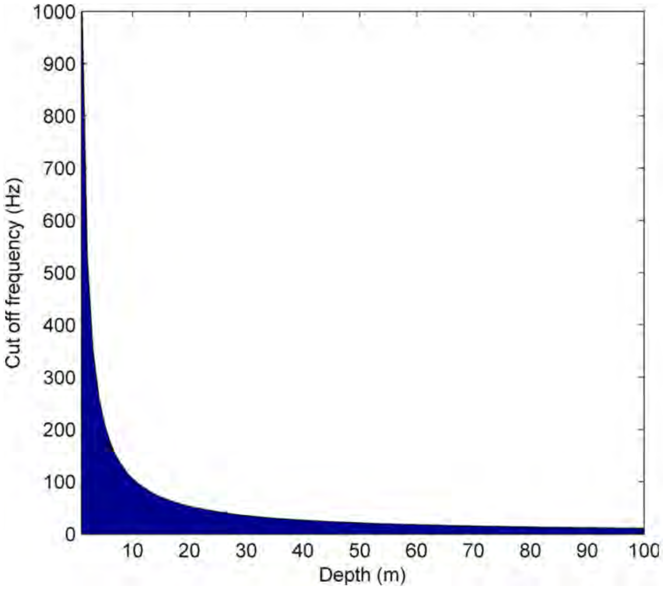

Figure A-4. Cut-off frequency vs depth relationship for silt sediment with 1593 m/s sound speed and 1693 kg/m^3 density (Figure 1, Nedelec et al. 2016). Figure A-3 uses the same sediment parameters.

A.2. Particle Motion Measurements

An M20 PV/PA sensor from GeoSpectrum Technologies Inc. was used to measure particle motion. This section provides information on measuring particle acceleration and operating these sensors.

The particle acceleration is proportional to the spatial gradient of the pressure field, which is expressed as the linearized Euler's equation in Appendix A.1. The gradient is a function of frequency, as it depends on the phase difference measured over some distance (i.e., a 1500 Hz source, for a sound speed of 1500 m/s, changes phase by 6.28 radians (2π) in 1 m, whereas a 150 Hz source changes phase by 0.63 radians, and 15 Hz by 0.063 radians–a decrease of 20 dB per decade or 6 dB per octave). This has three implications:

1. The acceleration may be measured by subtracting the signal from two hydrophones placed some distance 'X' apart.
2. The maximum unambiguous response is obtained when the hydrophones are a distance equivalent to π/2 radians, or λ/4 metres or apart. Thus, to measure acceleration at higher frequencies the sensors should be closer together. Frequencies above this cut-off should be removed from the analysis.
3. As the frequency decreases, the amplitude of accelerations that may be measured approaches the sensor or environment noise floor. We would like the signal to be at least 10 dB above the environmental noise for the hydrophone subtractive method to work. The presence of signals from multiple sources makes this problem more difficult, however, this is an equally difficult problem for standard pressure measurements.

Observations 2 and 3 work in opposite directions and set limits on the frequency range over which we can measure particle acceleration.

A.2.1. M20 Accelerometer

The fundamental component of the M20 accelerometer is a mass connected to a pair of ceramic disks. When the mass vibrates, the disks experience tension or compression which generates a change in electric charge through the piezoelectric effect (Figure A-5). A charge amplifier converts the capacitance to a voltage that is measured by a standard analog-to-digital converter. In the M20 two ceramic disks are used to provide mechanical support for the mass as well as to double the output response of the sensor. These disks must be carefully matched in amplitude and phase for maximum performance of the sensor. At low frequencies, the acceleration response of the sensor does not change with as the frequency of the acceleration changes. As the acceleration frequency approaches the mechanical resonance of the mass-spring system, the sensitivity increases, then decreases by 12 dB per octave above resonance. Oil is added inside the sensor to dampen the mass' movement and smooth out the resonant peak (Figure A-6). The measured roll-off of the M20-601 used at the Control Site had a roll-off of ~ −14 dB per octave (Figure A-7). The phase of the accelerometer output leads the input forces by 90 degrees at low frequencies, is in phase at resonance, and lags by 90 degrees after resonance (Figure A-8). As noted above, the spatial gradient of pressure (i.e., phase difference between the ends of the can) increases with frequency at 6 dB per octave, and thus the pressure sensitivity of the accelerometer increases as 6 dB per octave below resonance and decreases at 6 dB per octave above resonance (Figure A-9). The sensitivity becomes much more complicated at frequencies above 4 kHz for the M20 when the body resonances of the sensor impact the response. Note that the pressure vessel that contains the oil, ceramic disks and mass is rigid so that the ceramics do not experience any compression or tension directly from a passing acoustic wave.

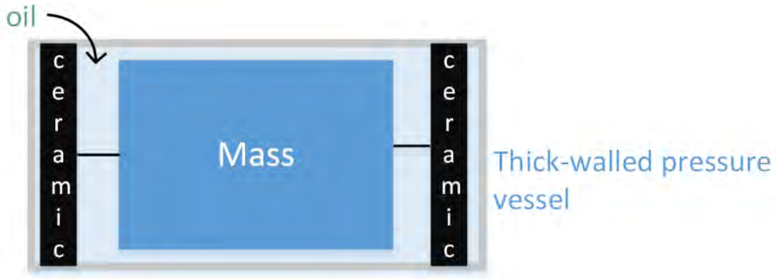

Figure A-5. Fundamental structure of an M20 accelerometer sensing unit.

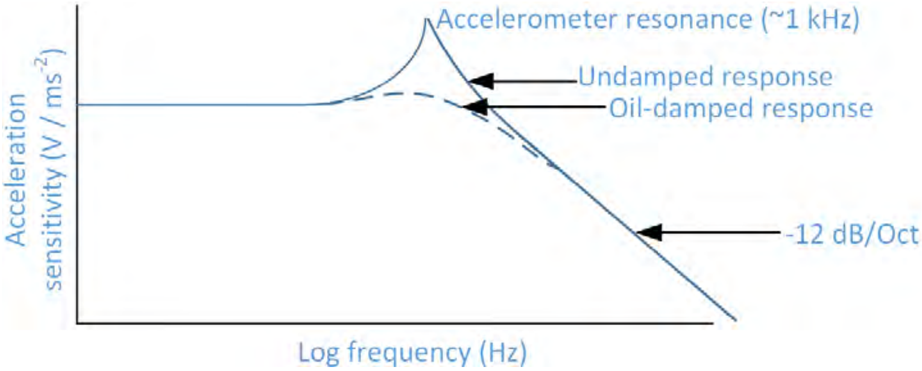

Figure A-6. Theoretical acceleration sensitivity of an M20 accelerometer as a function of frequency.

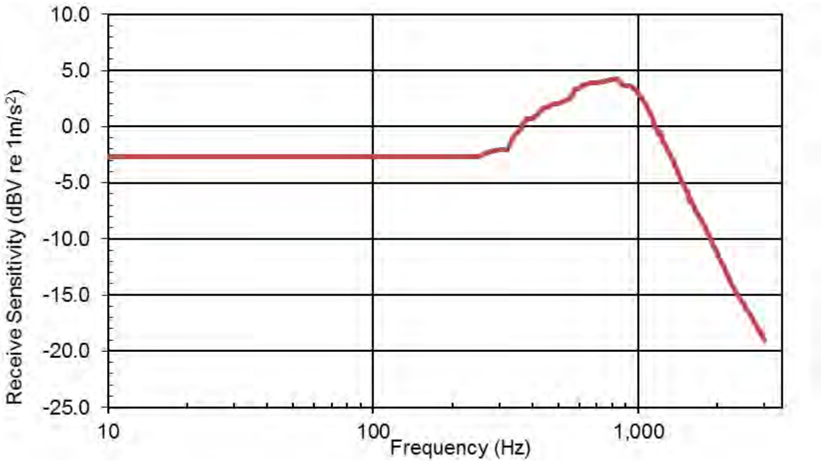

Figure A-7. Measured particle acceleration sensitivity of an M20-601, which has a high-frequency roll-off of ~−14 dB/octave.

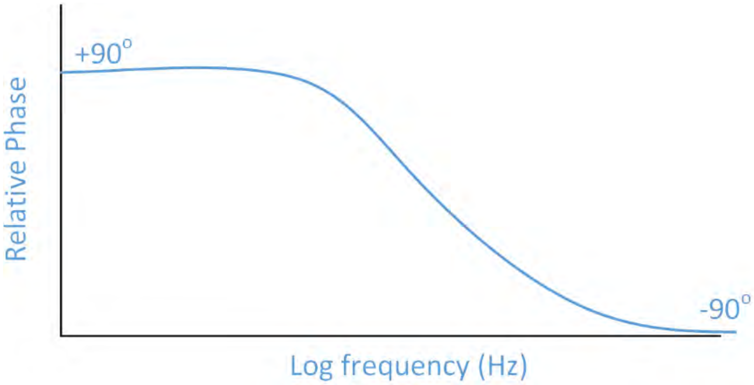

Figure A-8. Phase response of the accelerometer output relative to the inputs.

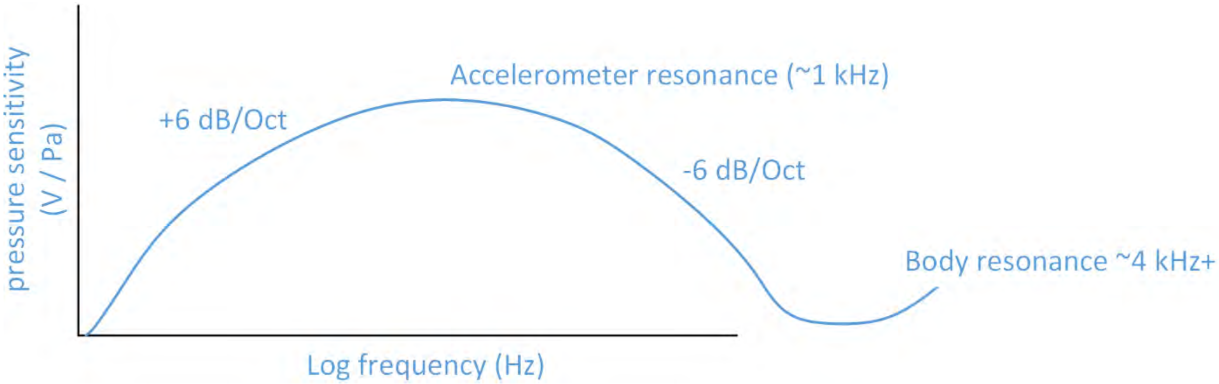

Figure A-9. Pressure sensitivity of the M20 accelerometer.

The M20 is built from five of the fundamental accelerometers: two each for the X and Y axes and one for the Z-axis. The X & Y axes are mounted on a wobbler plate that is only attached to the outer shell of the sensor at it's centre of mass (Figure A-10). This design provides the sensor with some immunity to physical movement noise since physical rocking of the sensor will cancel for the X1 and X2 sensors as well as Y1 and Y2, but outputs from acoustic accelerations will add constructively up to a fraction of the body resonances of the sensor. For best performance of a suspended acceleration sensor the body must be isolated from forces at the electro-mechanical connection point. By putting the wobbler connection point at the centre of the total body mass, forces at the connection point will cause the body to rotate around the centre of mass (the wobbler) rather generating a displacement which would be measured as an acceleration (Figure A-11). This technique also relies on the body being negatively buoyant. A negatively buoyant sensor has less sensitivity than a neutrally buoyant sensor according to the equation:

$$20log_{10}\left(\frac{3\rho_w}{\rho_w+2\rho_s}\right)\ (\mathrm{dB}),$$

where ρw is the density of the water and ρs is the density of the sensor (Yeatman and Amstrong 2011). For the M20, this value is ~−4 dB, a much smaller penalty than the added mechanical noise from a neutrally buoyant sensor in realistic water conditions.

The M20 is a precision sensor whose effectiveness depends on expert design, careful machining, hand matching of components, and skilled assembly. To calibrate an M20, either use a precision shaker table, or compare the accelerometer response to a co-located calibrated hydrophone during a deep-water test in a far-field environment.

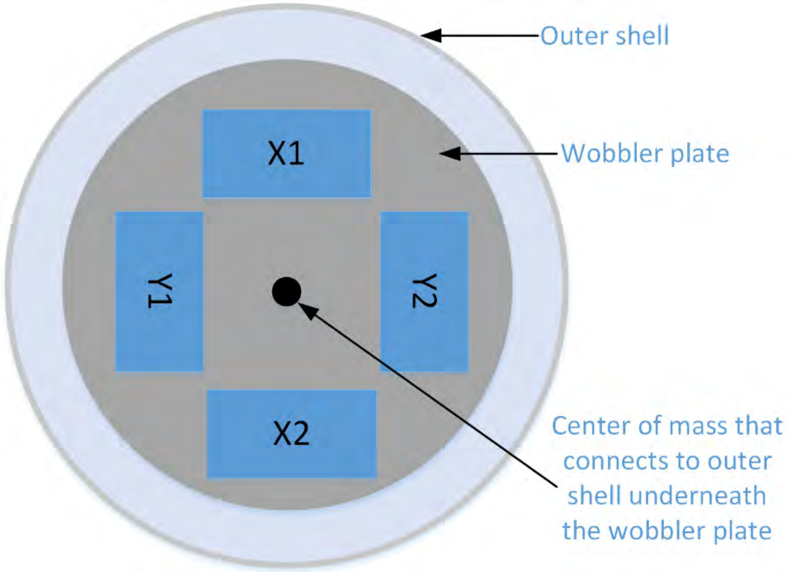

Figure A-10. Sketch of the wobbler plate design that holds two *X* and two *Y* fundamental accelerometers within the M20 body.

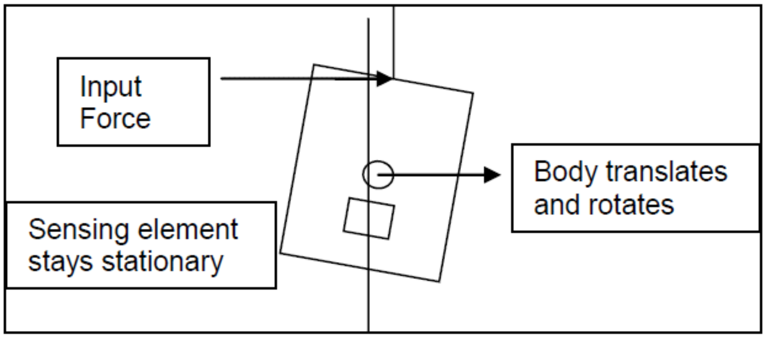

Figure A-11. Acceleration balancing for particle acceleration sensors (Figure 1, Yeatman and Amstrong 2011).

Appendix B. Operations Plan

This operation plan covers the "(PA/PV) Measurement System Evaluation in a Tidal Environment" study planned by JASCO Applied Sciences for the Offshore Energy Research Association of Nova Scotia (OERA). This plan summarizes JASCO's operational requirements, the equipment that will be employed, and the deployment and retrieval methods for that equipment. This document also identifies the person in charge of marine operations. Information on communication, contacts and duties of project personnel, emergency response and incident reporting, insurance and liability, risks, hazards and mitigation, and regulatory compliance are found in JASCO's Health, Safety, and Environment Project Plan (HSEPP).

The goal of the study is to test and trial a real-time, drifting acoustic measurement system using a particle velocity/particle acceleration (PV/PA) sensor. JASCO intends to evaluate the performance of this sensor in a flowing environment. It is hoped that the PV/PA sensor will be more sensitive than traditional pressure-based hydrophones, and will provide more accurate acoustic measurements. The PV/PA sensor to be used is also a directional vector sensor, potentially providing an indication of the bearings to sounds. JASCO also intends to demonstrate the drifting platform as a real-time data delivery system, sending information to shore via satellite communications links.

B.1. Schedule of JASCO Operations

This schedule may be adjusted based on weather and operational constraints. The date of deployment will be contingent on the turbine deployment date and the time of day will reflect tide schedules.

Day	Time	Location	Activity
1	AM	Dartmouth–Eastern Passage	JASCO loads equipment in rental truck Field team drives to Eastern Passage Meet with crew, load-out, MOB
1	PM	East of Yankee's Bank	Deployment of both drifters as per Table B-1. Conduct drifter trial. De-mob in Eastern Passage Gov't wharf.

B.1.1. Operational Control

Primary: Albert Conrad, Captain of the *Captain's Pride*, has full authority over all vessel and safety-related activities while at sea.

Secondary: Eric Lumsden (JASCO) has overall responsibility and authority regarding decisions related to the equipment deployment and retrieval that do not conflict with the captain's decisions.

B.2. Requirements

B.2.1. Resource Requirements

The following resources are required from the vessel to complete the deployment:

- Boom with double block
- 1–2 deckhands/crew
- Current CSI
- Marine ticket for 1x skipper
- VHF comms, sat comms
- Station keep in 1–2 kt current/drift with engines off

B.2.2. Data Requirements

JASCO requires time-stamped GPS navigation data throughout the deployments to interpret the acoustic data. JASCO will maintain tracking via satellite beacons and on radar via hi-flyer.

B.3. Equipment

B.3.1. Acoustic Recording Configuration

Acoustic measurements will be performed with two systems, 1 x AMAR M36 and 1 x Observer buoy M20-601 hydrophone, configurations as follows:

Duration (sec)	Acoustic frequency range	Dynamic range (peak SPL)	Comments
AMAR Buoy			
1800	32 kHz	165 dBV	M36-V35-100
Projector	N/A	M21	MP3 files to play
Observer Buoy			
Continuous	4 kHz	165 dBV	M20-601
	GPS and AIS		Over Iridium
iBCN Beacon			
120	GPS		
120	SBD		

- AMAR memory 512 GB
- Drifter Buoy memory 200 GB microSD

B.3.2. Mooring Design

Each mooring is ~50 m long and weighs ~90 kg. The moorings are shown Figure B-1 and Figure B-2. Each mooring consists of:

- Surface float with iridium and flashing beacons as well as AIS and hi-flyers for tracking
- Adjustable line to trim weight (zeroed to allow minimum depth)
- Catenary system with either an AMAR or M20-601 hydrophone ≤ 50 m deep, depending on current

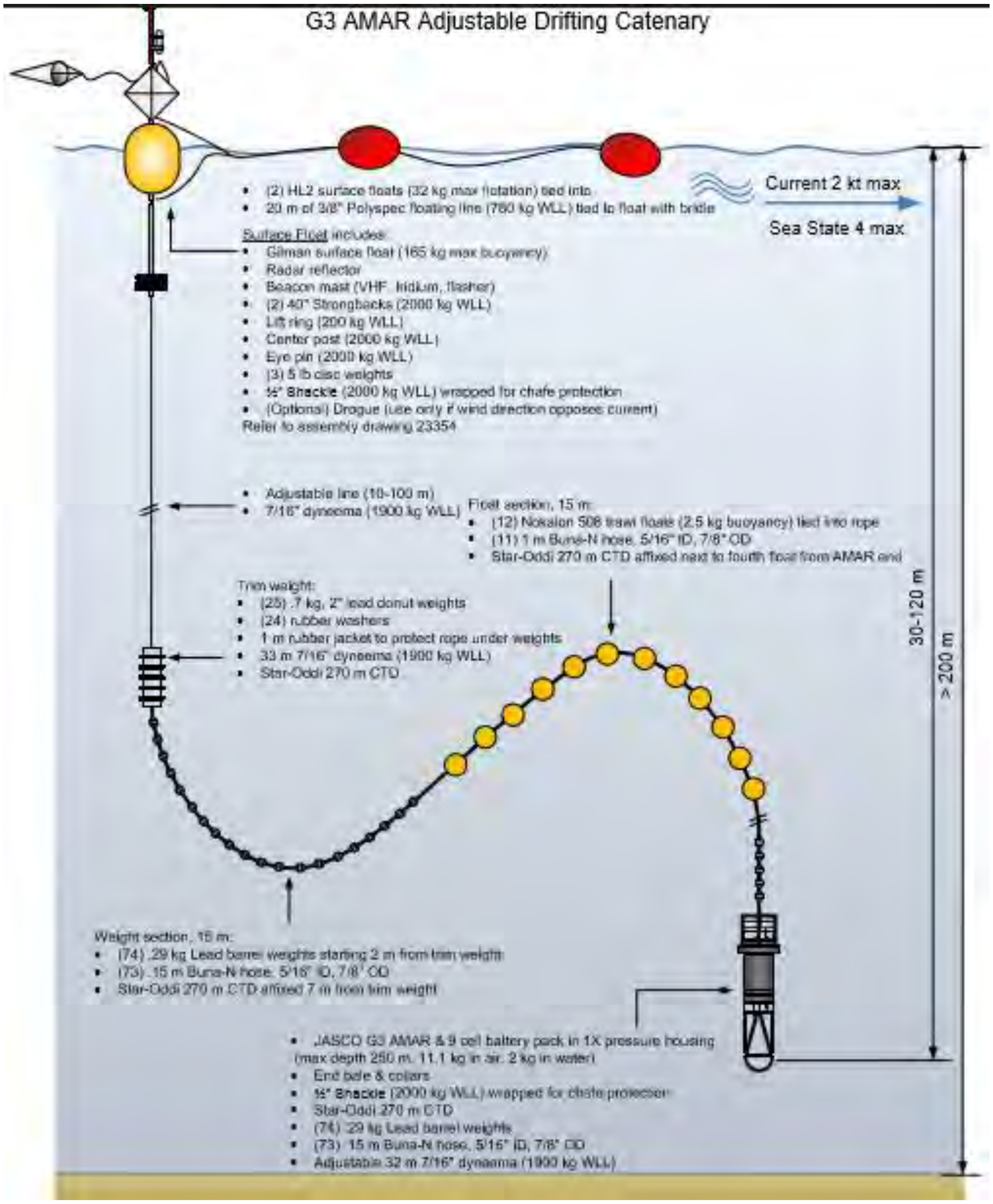

Figure B-1. Mooring 167 for deployment east of Yankee Bank.

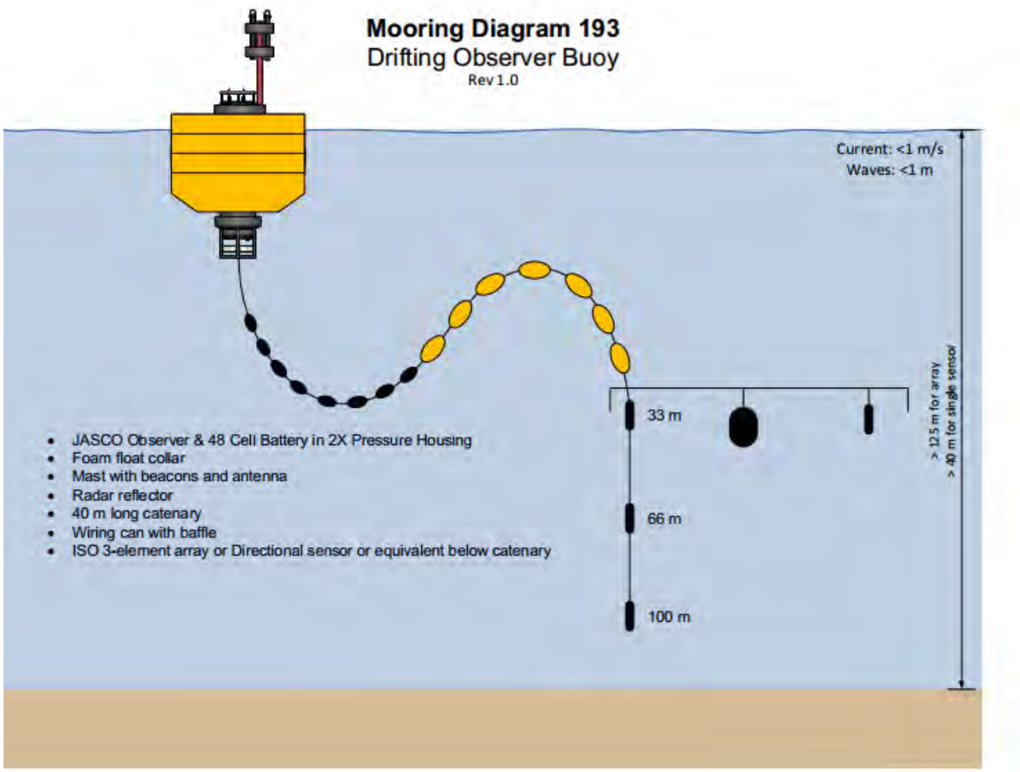

Figure B-2. Mooring 193, directional sensor. Deployment east of Yankee Bank.

Figure B-3. Proposed mooring track for AMAR Drifter buoys. Minimum water depth ≥ 50m.

B.4. Measurement Plan

The AMAR Drifters will be deployed in the deployment area (shown in Figure B-3) in a configuration designed to capture sound levels as a function of range and direction. Two Drifters will be deployed simultaneously on a 10-nm drift track. Sound levels will be recorded continuously through the track.

Table B-1. Proposed deployment and retrieval locations for each drifter.

Location proposed	Deployment latitude	Deployment longitude	Depth (m)	Retrieval latitude	Retrieval longitude	Depth (m)
Drifter 1 & 2	44° 538229 N	063° 081551 W	~ 55	44° 502643 N	063°187360 W	~65
Drift track	TBD					

B.5. Deployment Procedure

The following steps outline the procedure for deploying the AMAR mooring from the Captain’s Pride (Figure B-4). Vessel regulatory compliance is provided in JASCO’s HSEPP. The drifter buoys and catenaries will be deployed by centre-line boom by the vessel crew with JASCO assisting. This procedure is subject to change based on weather conditions and consultation with the vessel master.

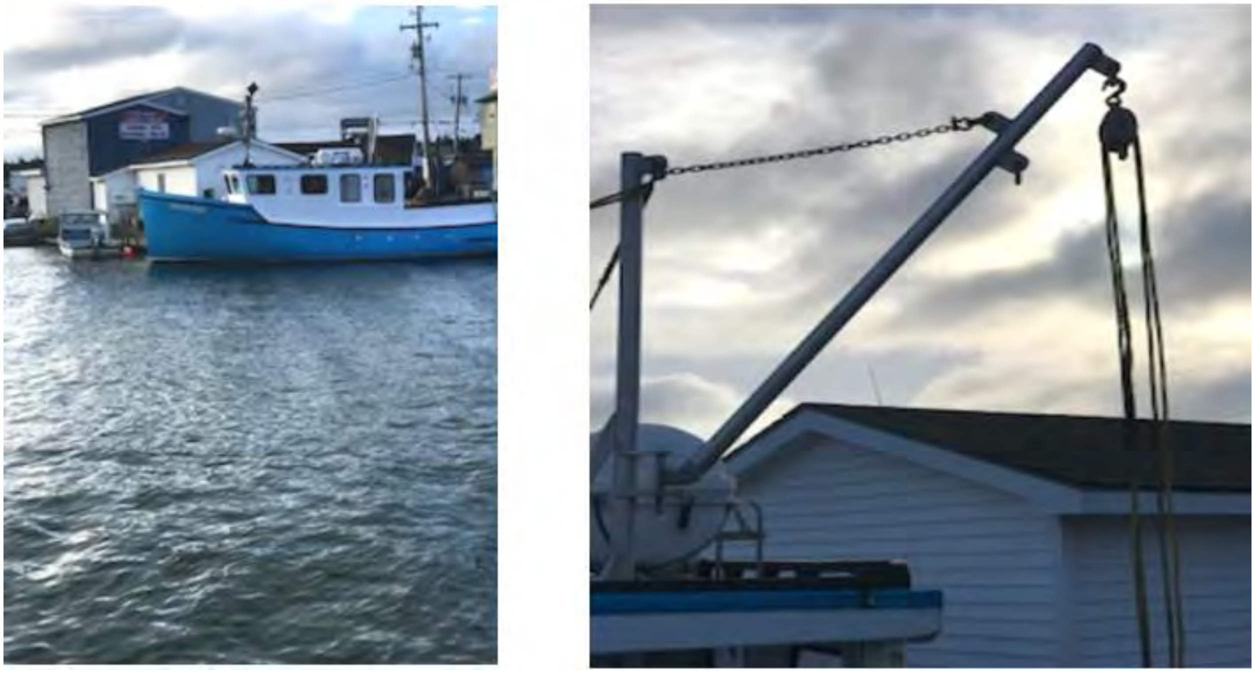

Figure B-4. The JASCO field team and vessel crew will deploy drifters and projector from the *Captain’s Pride.*

Both drifters will be deployed as follows:

1. Job Safety Analysis (JSA) meeting with JASCO crew, ship's crew, and vessel master.
2. **Prepare the equipment for deployment:**
    a. When loading equipment onto the vessel, lift the palletized catenary systems via jetty boom and lower to the vessel's deck.
    b. Flake out both catenaries on the port and stbd side of aft deck.
    c. Utilize the jetty boom to lift the top floats and attach tag lines to prevent from swinging.
    d. Lower the top floats on deck forward of their accompanying catenaries.
3. **Deploy the drifters at low or high slack tide.**
    a. Position the AMAR Drifter Buoy (mooring 167) under the boom and secure winch hook to lifting ring. Lift top float assembly off deck and over false transom until just at the waterline.
    b. Deploy the catenary system by hand over the port side of the vessel. JASCO team to provide assistance.
    c. Once all of the catenary system is deployed and minimal strain is noticeable, lower the top float to the waterline and detach boom hook. Hold mooring alongside vessel via polyspec tagline until second mooring is ready to deploy.
    d. Once mooring 193 is at the ready deploy position, release pass-through tagline on mooring 167 and deploy mooring 193, allow both to drift freely. Take first CTD cast.
    e. Vessel will manoeuvre to cardinal points N/E/S/W @ 250m and conduct projector transmissions for at least two minutes at each point. JASCO personnel monitor acoustic data in real time via WiFi to ensure that projector transmissions are being received.
    f. Vessel to drift downstream with drifters until track complete or under vessel Master's discretion.
    g. JASCO crew member marks the GPS locations of deployments, transmissions of projector and maintain GPS vessel tracking.
    h. Take second CTD cast to bottom, midway through drift cycle.
4. Debriefing meeting to capture lessons learned.

B.6. Retrieval Procedure for Surface Floats, Both Moorings

The following steps outline the procedure for retrieving the drifting moorings from the *Captain's Pride*. This procedure is subject to change based on weather conditions and consultation with the vessel Master and crew.

1. Job Safety Analysis meeting with JASCO crew, ship's crew, and vessel master.
2. **Position the vessel:**
    a. Heading into the current, the vessel approaches the location before low/high slack tide.
3. **Retrieve the mooring:**
    a. The vessel proceeds slowly and positions the float on the vessel's starboard side into the current.
    b. The ship's crew use a Kong boat hook to bring the float alongside and secure to vessel cleat. Vessel takes position up stream. The top float via Kong hook is snapped on to hoisting ring. Vessel crew attaches boom hook on to the lifting ring.
    c. Order is given to retrieve the top float via boom and block.
    d. Once the top float is clear from gunnels or obstructions, it will be slowly lowered to the deck.

   e. Once on board and secured, the catenary(s) will be retrieved by hand and stowed. JASCO crew members secure the mooring and turn off AMAR recorders and beacons.
   f. Take final retrieval GPS position and third CTD cast.

4. Debriefing meeting to capture lessons learned.

B.7. Reporting

Once the recorders are retrieved and back in the Dartmouth facility, the data will be downloaded and backed up.

A comprehensive report of the measurement results will be provided to the science team.

B.8. Health, Safety, and Environment

For the safety of the JASCO team, JASCO requests the vessel crew address the items in this list:

- The JASCO team and crew will conduct a daily safety (toolbox) meeting before any work proceeds including initial equipment loading/unloading periods, which could happen before or after measurement days.
- The vessel must demonstrate maintenance records and valid permits or certificates such that before it leaves dock, the JASCO team is satisfied that the vessel is well maintained and will meet the needs of the project work.
- Submit a JASCO boat safety checklist to the vessel captain for review in advance of the work.
- A complete vessel safety orientation will be provided to the JASCO team before the vessel leaves the dock.
- The JASCO team must be satisfied that the vessel crew is competent. For example, a trained crane operator must be present when one is requested as JASCO teams are not trained or qualified to operate lifting devices.
- Any new, young, or untrained staff, including those that form vessel crews, should be clearly identified to everyone so these individuals can receive additional support as needed.
- First Aid in the form required by local regulations must be present on the vessel. All JASCO team members have Standard First Aid, Adult CPR, and an introduction to AED.
- Where the law requires immersion suits, the suits will be in good condition and properly sized for the JASCO crew.
- Adhere to all environmental and safety laws that apply to the vessel.
- Vessel crew will have and use proper PPE for each part of the work. These are typical PPE: PFD work suit, auto-inflate, hard hat, gloves, safety glasses and steel-toed boots.
- All involved crew members will participate in the JASCO Job Safety Analysis and toolbox meetings.
- Safety calls and communication plans will be communicated to the JASCO team in advance of the work in order to confirm that such is occurring and to allow for planning time with JASCO’s HSE team.
- To ensure JASCO staff comply with vessel safety requirements, these will be communicated to team members before work begins.

Any issues or concerns with this list need to be raised in before staff travel. Vessel crew reviewers should notify JASCO in advance of any items that cannot be complied with and indicate why.