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Task 4: Environmental Impact Monitoring at WETS

Surface Wave Instrumentation Float with Tracking (SWIFT) Drifter Survey Reports

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SWIFT Survey Report #1
Acoustic Characterization of Pre-Installation Conditions
REV 1.0 September 7, 2015

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1 Introduction

This report describes acoustic measurements of the at the Wave Energy Test Site (WETS) in Kaneohe Bay, Oahu, Hawai'I prior to installation of wave energy converters (WECs). Drifting hydrophones are used to characterize ambient noise over a three-day period with varying metocean conditions. This survey also tested two drifter variants to assess relative performance.

2 Methodology

2.1 SWIFT Drifters

Ambient noise was measured by Surface Wave Instrumentation Float with Tracking (SWIFT) drifters equipped with recording hydrophones and supporting instrumentation, as summarized in Table 1. "Type A" SWIFTs were equipped with Loggerhead DSG hydrophones. These hydrophones are designed for extended deployments and include a relatively large battery housing that was fitted into the SWIFT hull. "Type B" SWIFTs were equipped with icListen HF hydrophones. These are smaller units designed for short-term or cabled operation. In both cases, hydrophones were positioned approximately 1 m below waterline and protected by perforated PVC shields. This reduced the risk of hydrophone damage during deployment and recovery, at the cost of increased directional sensitivity. The Loggerhead DSG hydrophones recorded continuously at a sample rate of 100 kHz, allowing ambient noise to be resolved down to 50 kHz. The icListen HF hydrophones recorded continuously at a sample rate of 256 kHz, allowing ambient noise to be resolved down to 128 kHz.

SWIFT position was tracked by a QStarz GPS logger, recording position and horizontal velocity at 10 Hz. An Airmar weather station mounted to each SWIFT monitored wind speed, wind direction, and temperature. The Airmar stations also recorded buoy position (a backup to the primary GPS logger) and buoy orientation (heading, pitch, and roll). All quantities were recorded at a rate of 1-2 Hz. Finally, each SWIFT was equipped with a GoPro Hero 3 camera at the top of the mast, which provided visual metadata about meteorological and wave conditions (breaking vs. non-breaking), as well as nearby activities that may be producing noise (e.g., vessel operations).

To reduce self-noise, SWIFTs were equipped with an anti-splash dome on the top of the hull to more quietly shed waves that broke across the surface. As discussed in this report, the "Type B" SWIFTs (icListen) were better able to maintain attitude in the waves and most results presented here are for this variant.

Table 1 – SWIFT Instrumentation

Instrument	Model	Measurement
Hydrophone (Type A)	Loggerhead DSG	Underwater sound
Hydrophone (Type B)	OceanSonics icListen HF	Underwater sound
GPS	QStarz BT-Q1000eX	Spar position and speed (high res)
Weather Station	Airmar PB200	Wind velocity, air temperature, air pressure Spar position, orientation, and speed (low res)
Camera	GoPro Hero 3	Visual metadata from surface

SWIFT drifts were conducted at WETS on March 24-March 26, 2015 at the 30 m and 80 m WEC deployment sites. Drift conditions are summarized in Table 2 and track densities are shown in Figure 1

(30 m site) and Figure 2 (80 m site). On March 24, conditions were nearly flat calm, with increasing sea states on March 25 and 26.

A drift sequence consisted of the following steps:

- Deploy SWIFT drifters from survey vessel
- Slowly motor off survey vessel into the waves for a period of 20-30 minutes
- Come about and slowly approach SWIFT for recovery over a similar time frame

This approach was preferred to maintain maneuverability of the deployment vessel and measurements suggest limited vessel noise contamination from this strategy. This being said, in cases where it is possible for the deployment vessel to motor off and drift dead ship, such a strategy would be preferred.

Table 2 – Drift Summary with wind conditions measured by SWIFT drifters and wave conditions reported by CDIP station Kaneohe Bay (in close proximity to 80 m site).

Date	No. of Drifts	Total Drift Time	Avg. H_s (m)	Avg. T_e (s)	Avg. Wind Speed (m/s)
3/24/2015	6	2 h 45 m	-	-	< 3
3/25/2015	6	5 h 30 m	1.4	4	6
3/26/2015	6	5 h 50 m	2.3	10	5

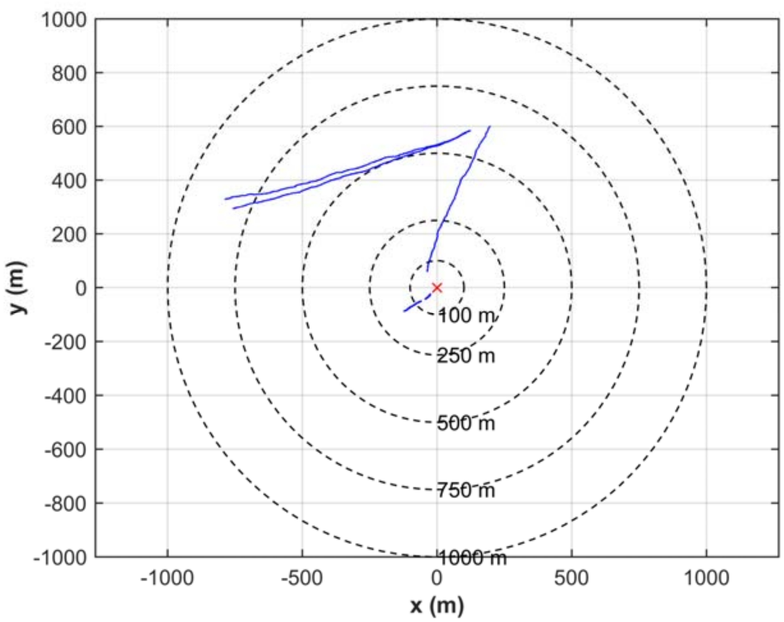


Figure 1 – Drifter track density around 30 m site ("Type B" icListen SWIFTs only). Individual drifts shown in blue. Coordinate system relative to the WEC deployed site.

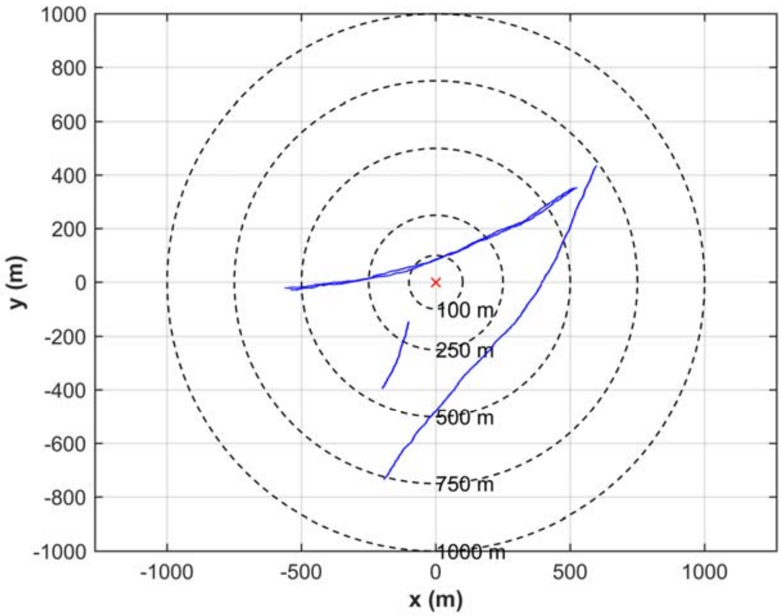


Figure 2 – Drifter track density around 80 m site ("Type B" icListen SWIFTs only). Individual drifts shown in blue. Coordinate system relative to the CDIP Waverider buoy.

2.2 Acoustic Measurements

2.2.1 Hydrophone Calibration

The PVC shields used to protect the hydrophone elements have been shown to introduce directional attenuation of up to 10 dB above frequencies of 5 kHz. This effect is somewhat diminished by a consideration of spectral averages, but suggests a need for a new hydrophone guard with less significant directional attenuation. For the purposes of this analysis, the manufacturer specification for hydrophone sensitivity was utilized. A subsequent revision will incorporate adjustments for frequency-dependent sensitivity determined by calibration.

2.2.2 Data Processing

Acoustic data sampled continuously at 256 kHz was buffered into samples consisting of 2^{18} points (1.02 second duration) with 50% overlap between samples to improve time resolution of lower frequency events. Each sample was processed by further buffering to windows with 2^{15} points and 50% overlap. Each window was linearly detrended, a hamming filter applied, and processed with an FFT. Resulting spectra were merged to yield a frequency bandwidth of 8 Hz and narrow confidence intervals. These processing parameters strike a balance between ability to resolve low frequencies and ability to distinguish time-varying features in spectrograms.

2.2.3 Data Quality Assurance

Acoustic data were manually reviewed in two ways to identify periods of questionable data. First, spectrograms of all drifts were reviewed. Vessel noise at the beginning or ending of drifts was readily identifiable and excluded. Broadband, high-intensity events were similarly identified and audio sequences containing these manually reviewed. In most cases, these were associated with breaking waves in close proximity to a SWIFT or chain rattle at close range to a mooring. Second, manual acoustic review of data was performed on a subset of time series to relate spectral signatures to underlying sound sources.

2.3 Metocean Conditions

Metocean conditions were variable during the study period. On March 24, conditions were flat calm with limited wind. On the 25th and 26th, the sea state intensified with significant wave heights exceeding 2 m on the 26th and the peak period increasing from 4 s on the 25th to 10 s on the 26th. There was no significant precipitation during surveys.

3 Results and Discussion

3.1 SWIFT Performance

The “Type A” hulls (Loggerhead DSG) were noticeable less stable than the “Type B” hull (icListen), with a high amplitude pitch and roll response to the incident wave field. This leads to significantly higher flow-noise contamination for the “Type A” hulls. The predominant reason for this was the volume of air in the DSG pressure housing on the “Type A” hulls. Since the DSG hydrophones are intended for long-term deployment, the pressure housing is oversized for short-term drifts and the instrument does not require a full load batteries. Consequently, this moves the center of buoyancy closer to the center of mass and reduces the righting moment of the hull. While this could be addressed by filling the housing with a full load of batteries, this would make the drifter heavier and, consequently, more difficult to deploy and recover in rough seas.

The Airmar met stations performed erratically during the survey, with partial outages during several drifts. The root causes for this were loose wiring on the data logger (corrected after recovery) and a “feature” of the Airmar that causes it to go into a low power consumption mode if set down in a horizontal position. For future deployments, more careful pre-deployment checks of wiring will address the first issue and racking the SWIFTs at an angle of at least 30 degrees off horizontal between drifts will address the second.

3.2 Description of Ambient Noise

Despite the relatively close proximity of the 30 m and 80 m sites, the contributors to ambient noise varied between the two, as noted in the annotated periodograms in Figure 3 and Figure 4. At both sites, wind and wave noise dominates the acoustic spectra. Similarly, significant periodic noise is generated in both locations by motion of anchor chain, with primary sounds at 2 kHz and high frequency harmonics. However, snapping shrimp, which dominate the spectra between 5-20 kHz at the 30 m site are absent in the spectra at the 80 m site. Similarly, humpback whale vocalizations are prevalent in all drifts at the 80 m site, but absent at the 30 m site.

There is also some short-term temporal variability and smaller-scale spatial variability.

- At the 30 m site on March 24, anomalously high vessel traffic elevated broadband sound pressure levels and introduced high-amplitude sound at 50 kHz associated with depth sounders.
- At both sites, increasing sea state intensified sound from anchor chains on March 25th and 26th.
- At the 30 m site, snapping shrimp noise was more pronounced on the 24th than on the 25th or 26th, even for drifts on the 25th that came within 100 m of the location surveyed on the 24th. Data from stationary hydrophones should be used to assess temporal trends in snapping shrimp noise.

The SWIFTs also generated self-noise during these surveys that should be addressed in future surveys. Most surveys on the 25th and 26th contain noise from flapping of the marker flag, elevating spectra around 100 Hz. This can be addressed in future drifts by furling the marker flags, albeit at the cost of reducing the range for visual detection of drifters during recovery. Several of the drifts contain relatively broadband "thumps" at frequencies below 1 kHz which are likely associated with a loose fitting between the upper spar and lower hull. The connection loosened after initial assembly and is now inspected prior to each drift deployment. Finally, one drift contained several impulsive events that are likely associated with contact between a SWIFT drifter and surface mooring[1].

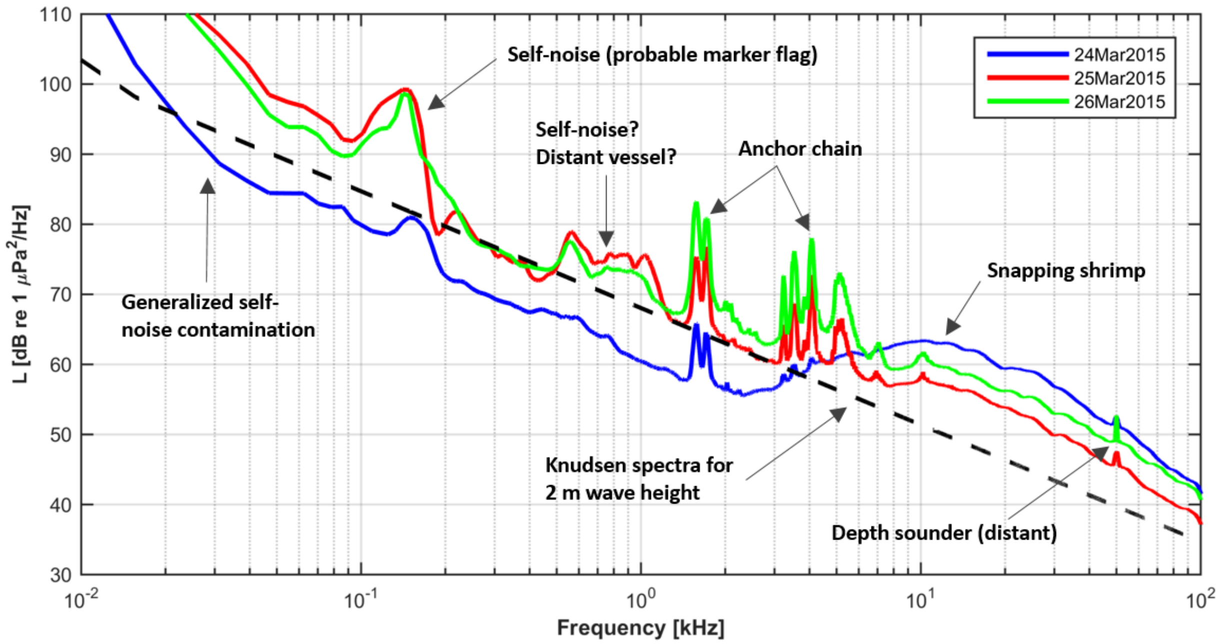


Figure 3 – Periodogram for drifts at 30 m site. Features of spectra as noted.

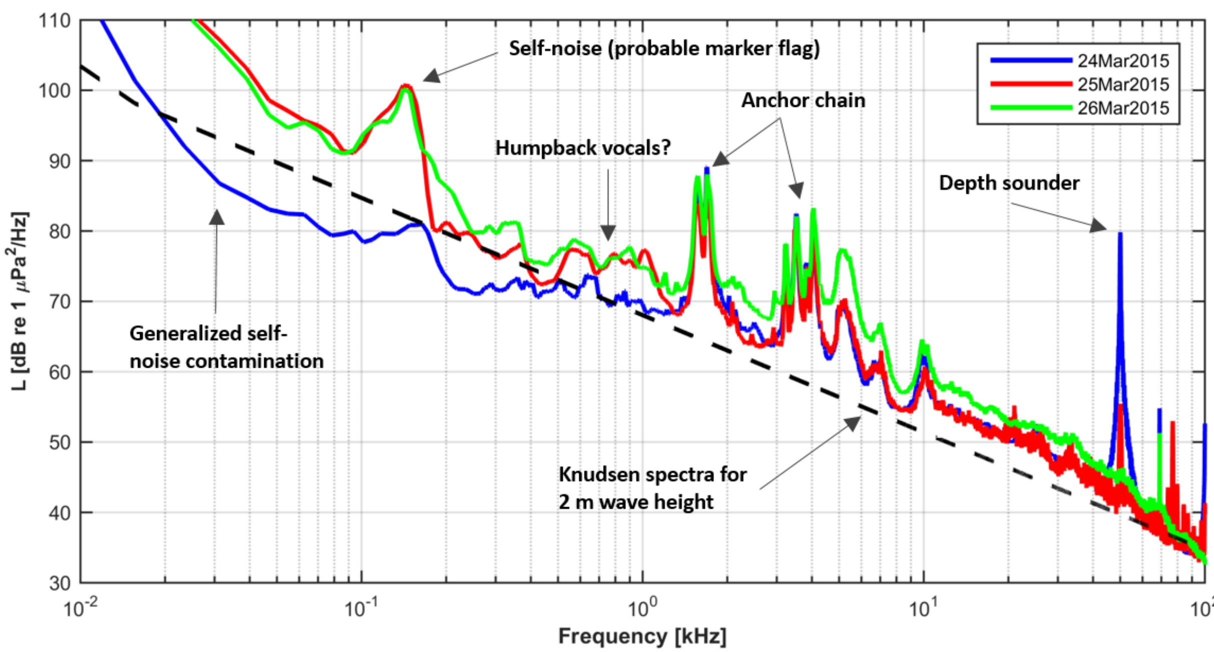


Figure 4 – Periodogram for drifts at 80 m site. Features of spectra as noted.

[1] Contact events quarantined and excluded from analysis.

4 Conclusions

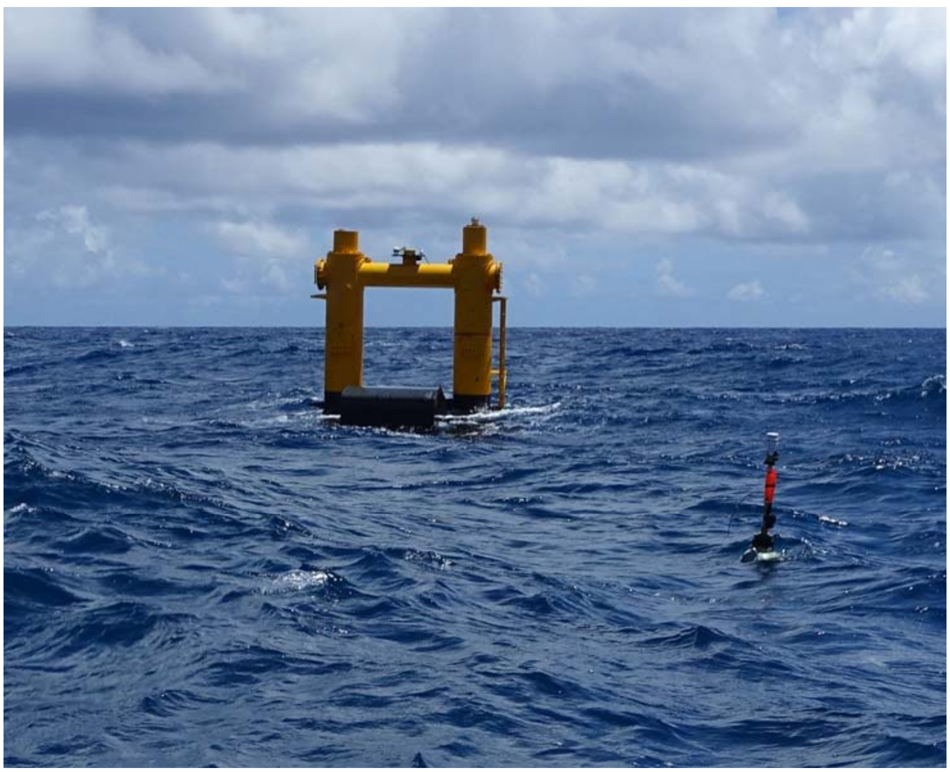
Drifts over a three day period in March indicate significant variations in ambient noise between the 30 m and 80 m sites at WETS. Temporal variations are likely to be best addressed by stationary hydrophone measurements.

In future surveys, comparison between WEC sound and ambient noise using SWIFT drifters may be best obtained by comparison between recordings in close proximity to the WEC and at greater distance, with judicious selection to maintain equivalent ambient sound levels from anchor chain and snapping shrimp. These surveys should also use "Type B" hulls with icListen HF hydrophones to avoid excessive pitch and roll associated with "Type A" hulls.

5 Acknowledgement

Financial support for this work is provided by the University of Hawai'i. Many thanks for the field operations support from Tor Harris and Patrick Anderson of Sea Engineering, Keith Bethune of the University of Hawai'i, and Alex deKlerk from the University of Washington.

SWIFT Survey Report #2
Acoustic Characterization of Azura Wave Energy Converter
REV 1.1 September 7, 2015



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1 Introduction

This report describes acoustic measurements of the Azura wave energy converter (WEC) which is undergoing field testing at the Wave Energy Test Site (WETS) in Kaneohe Bay, Oahu, Hawai'i. Drifting hydrophones are used to characterize the sound produced by the Azura WEC over a three-day period with relatively moderate metocean conditions (i.e., significant wave heights less than 2 m).

2 Methodology

2.1 SWIFT Drifters

WEC sound was measured by Surface Wave Instrumentation Float with Tracking (SWIFT) drifters equipped with recording hydrophones and supporting instrumentation, as summarized in Table 1. An icListen HF hydrophone was fitted at the base of the hull, approximately 1 m below waterline and protected by a PVC ring with stainless steel stand-offs. This reduced the risk of hydrophone damage during deployment and recovery, at the cost of increased directional sensitivity. The hydrophones recorded continuously at a sample rate of 256 kHz, allowing WEC sound to be resolved down to 128 kHz.

SWIFT position was tracked by a QStarz GPS logger, recording position and horizontal velocity at 10 Hz. An Airmar weather station mounted to each SWIFT monitored wind speed, wind direction, and temperature. The Airmar stations also recorded buoy position (a backup to the primary GPS logger) and buoy orientation (heading, pitch, and roll). All quantities were recorded at a rate of 1-2 Hz. To more accurately track SWIFT motion and develop estimates for wave properties from this motion, each SWIFT was also equipped with a Lowell Instruments MAT-1 Data Logger, a 6-axis IMU recording at 64 Hz. Finally, each SWIFT was equipped with a GoPro Hero 3 camera at the top of the mast, which provided visual metadata about meteorological and wave conditions (breaking vs. non-breaking), as well as nearby activities that may be producing noise (e.g., vessel operations).

To reduce self-noise, SWIFTs were equipped with an anti-splash dome on the top of the hull to more quietly shed waves that broke across the surface. Similarly, the marker flags on the SWIFTs were furled tightly to prevent flapping noise in moderate winds.

Table 1 – SWIFT Instrumentation

Instrument	**Model**	**Measurement**
Hydrophone	OceanSonics icListen HF	Underwater sound
GPS	QStarz BT-Q1000eX	Spar position and speed (high res)
Weather Station	Airmar PB200	Wind velocity, air temperature, air pressure Spar position, orientation, and speed (low res)
Inertial Motion Unit (IMU)	Lowell Instrument MAT-1	Spar acceleration and orientation (high res)
Camera	GoPro Hero 3	Visual metadata from surface

SWIFT drifts were conducted in the vicinity of the Azura WEC on July 7-July 9, 2015, with an emphasis on collecting data at relatively close range. Drift conditions are summarized in Table 2 and track density is shown in Figure 1. The Azura was actively generating power during all drifts.

A drift sequence consisted of the following steps:

- Deploy SWIFT drifters from survey vessel

- Motor off survey vessel until several hundred meters from SWIFTs
- Disengage engine and drift dead ship
- Drift until vessel approaching shore exclusion area for MCBH
- Restart engines and recover SWIFTs

Drifts were conducted successfully, with complete data return from all instruments.

Table 2 – Drift Summary with wave and wind conditions measured by SWIFT drifters.

Date	No. of Drifts	Total Drift Time	Avg. H_s (m)	Avg. T_e (s)	Avg. Wind Speed (m/s)
7/7/2015	12	6 h 15 m	1.5	8.5	4.4
7/8/2015	8	3 h 15 m	1.6	8.8	5.3
7/9/2015	10	4 h 50 m	1.7	8.8	5.3

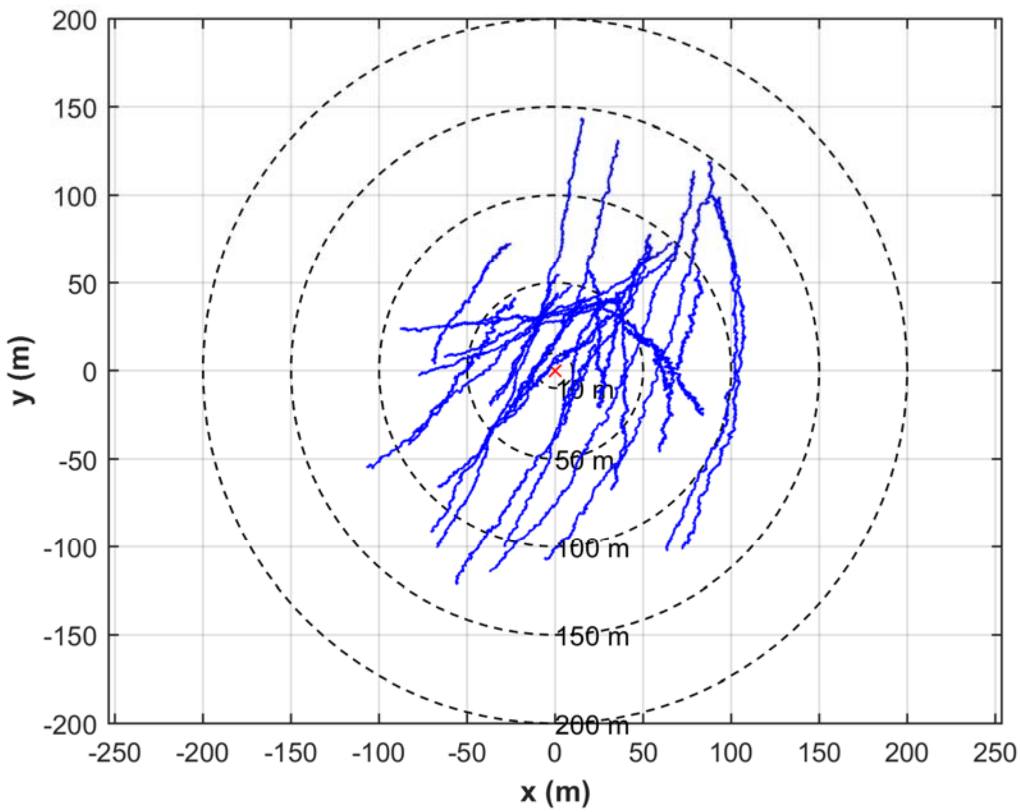

Figure 1 – Drifter track density around Azura WEC. Individual drifts shown in blue. Coordinate system relative to the location of the Azura WEC. Note: Not shown are two drifts at range > 200 m.

2.2 Acoustic Measurements

2.2.1 Hydrophone Calibration

Hydrophones were field calibrated using a GeoSpectrum M351 calibrator. This calibration is not yet reflected in the results and constant, manufacturer supplied sensitivities are used for analysis in this report. A subsequent revision will incorporate adjustments for frequency-dependent sensitivity determined by calibration.

In addition, at UW, one lower spar assembly was further tested to quantify directional attenuation associated with the lead-weighted heave plate located directly above the hydrophone element. At frequencies up to 10 kHz, attenuation is less than 5 dB for ray angles up to 120^o relative to the hydrophone element (i.e., up to 30^o past horizontal). Ray angles directly in line with the heave plate are attenuated by approximately 10 dB. Given that the majority of sound-radiating structure on the Azura WEC is located substantially below waterline, directional attenuation by the SWIFT hull is unlikely to substantially increase uncertainty in interpreting these results.

2.2.2 Data Processing

Acoustic data sampled continuously at 256 kHz was buffered into samples consisting of 2^{18} points (1.02 second duration) with 50% overlap between samples to improve time resolution of lower frequency events. Each sample was processed by further buffering to windows with 2^{15} points and 50% overlap. Each window was linearly detrended, a hamming filter applied, and processed with an FFT. Resulting spectra were merged to yield a frequency bandwidth of 8 Hz and narrow confidence intervals. These processing parameters strike a balance between ability to resolve low frequencies and ability to distinguish time-varying features in spectrograms.

2.2.3 Data Quality Assurance

Acoustic data were manually reviewed in two ways to identify periods of questionable data. First, spectrograms of all drifts were reviewed. Vessel noise at the beginning or ending of drifts was readily identifiable and excluded. Broadband, high-intensity events were similarly identified and audio sequences containing these manually reviewed. In most cases, these were associated with breaking waves in close proximity to a SWIFT or wave slap against the Azura's float with a SWIFT at close range. However, one event was identified as the SWIFTs bumping into each other and this period was excluded from further analysis. Second, manual acoustic review of data was performed on a subset of time series to relate spectral signatures to underlying sound sources.

2.3 Sound Attributable to Azura WEC

The frequencies of sound attributable to the Azura WEC were estimated by comparing the mean spectra at ranges between 8 and 12 m from the WEC to spectra at ranges between 550 and 650 m. The distant spectra were used as a quasi-baseline comparison. While drift data from pre-installation conditions at the site of the WEC could also be used as a point of comparison, pre-installation surveys suggest considerable temporal variation in ambient noise. The comparison of WEC sound and ambient noise utilized 12 minutes of acoustic data at close range to the WEC and 31 minutes of data at far range.

2.4 Metocean Conditions

Metocean conditions were generally uniform over the study period. Winds were light, at 5 m/s, predominantly out of the southwest. Little precipitation fell, save for a light rain at the start of one drift on July 8. The significant wave height averaged 1.6 m (range of 1.2-1.7m) and the energy period averaged 9 s (range of 8-10 s).

The sound velocity profile was measured on July 8 with a Valeport mini-SVP (acoustic time of flight measurement). As shown in Figure 2, sound velocity is relatively consistent over the upper four meters of the water column, decreases by 1.5 m/s at an interface layer, then continues to slowly decrease.

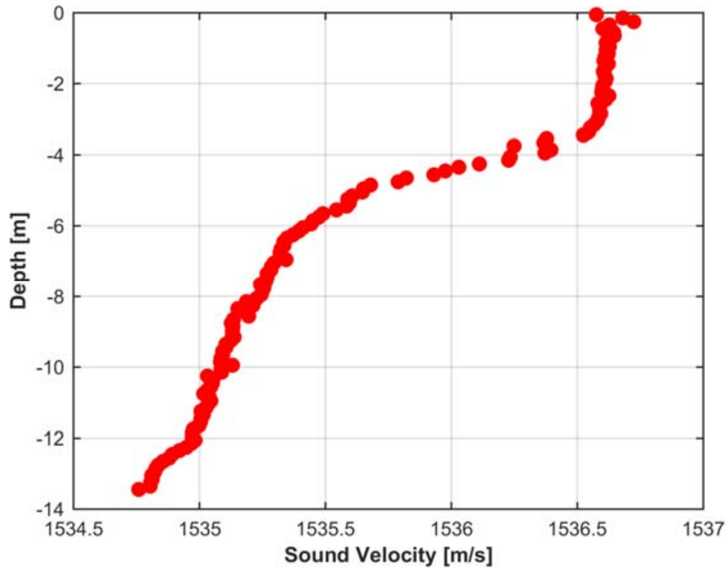

Figure 2 – Sound velocity profile at 30 m site (8 July, 2015)

3 Results

3.1 SWIFT Performance

Representative time series from SWIFT sensors are given in Figure 3. Overall, this iteration of SWIFT performed well and did not experience excessive pitch and roll in response to the incident wave field.

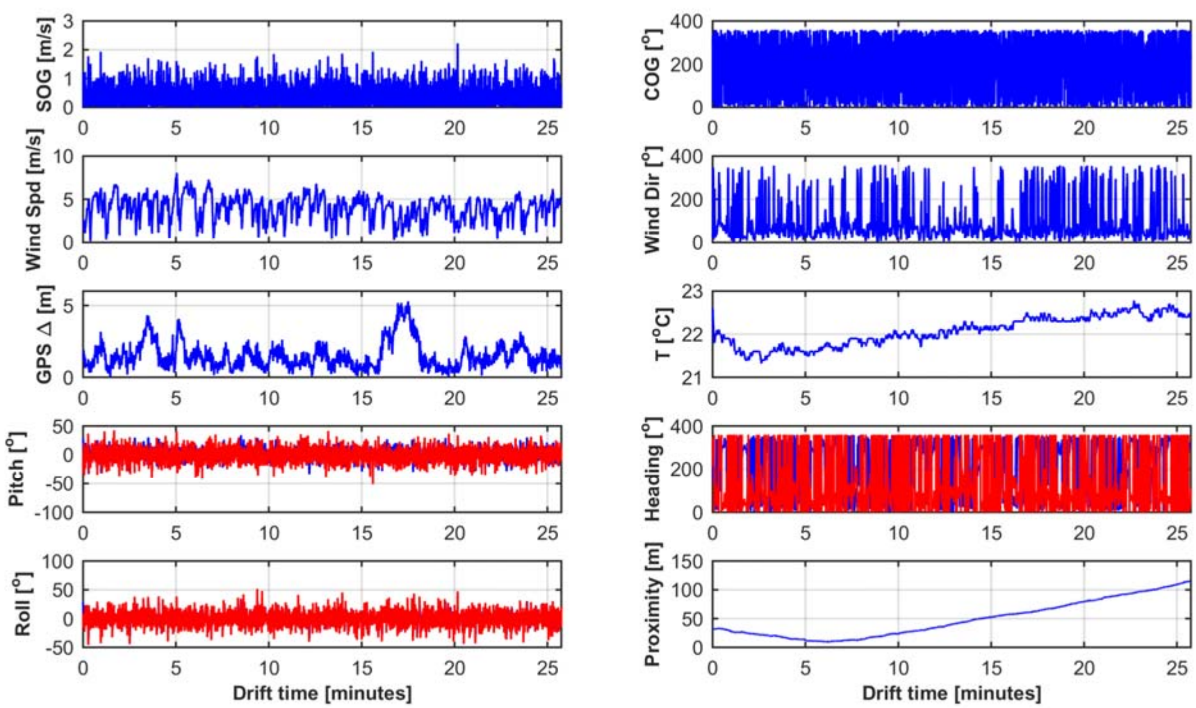

Figure 3 – Representative time series from SWIFT instruments. Lower right panel shows proximity to the WEC. Heading, pitch, and roll measured by both MAT-1 IMU and Airmar weather station.

3.2 Description of Ambient Noise and WEC Sound

This section describes sounds present in the background, sounds originating from the Azura, and sounds generated by the SWIFT (i.e., self-noise). A representative spectrogram for a drift in close proximity to the Azura is shown in Figure 4.

The dominant background noise is broadband in nature and produced by winds and waves, with the highest amplitude noise associated with waves breaking close to a SWIFT. Snapping shrimp are present in all recordings at frequencies from 5-20 kHz. Anchor chains rattle periodically with primary sounds at 2 kHz and higher frequency harmonics. In a few recordings, light rain is apparent, elevating sound above 1 kHz, consistent with expectations for light rain in light wind. Finally, a number of recordings contain sea turtle vocalizations, consisting of “squeaks” and “croaks”.

Close to the Azura WEC, a periodic “moan/whine” from the generator with time varying frequency is audible. Multiple tones are present from 200 Hz up to 3 kHz. There are also occasional higher frequency squeaks and lower frequency muffled bangs/clanks from wave slap against the float.

SWIFT self-noise is primarily associated splashing against the hull and an infrequent rattle, neither of which is associated with a particular rate of change in pitch or roll nor spectrally distinctive from other sources of propagating sound. For the first two drifts conducted at significant range (i.e., > 500 m) from the Azura WEC there is significant self-noise around 100 Hz. The marker flags were unfurled during these, and only these, drifts making them the most probable explanatory variable for this sound.

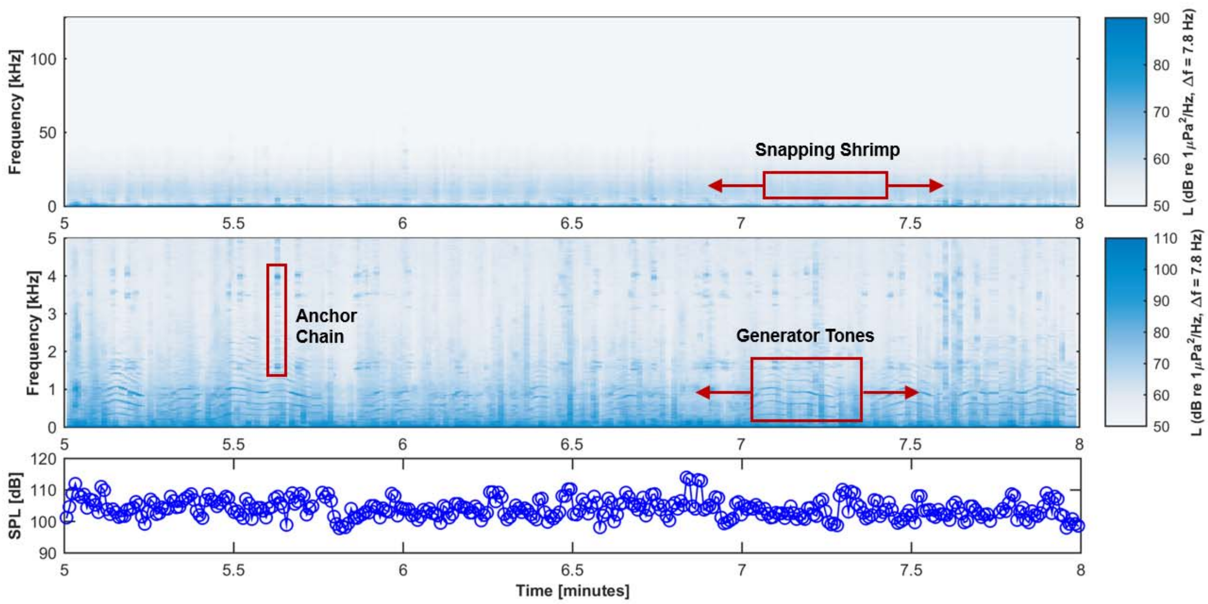

Figure 4 – Representative drift in close proximity to Azura WEC. *Top panel*: spectrogram for frequencies up to 128 kHz. Snapping shrimp noise apparent as elevated sound in the 5-20 kHz bands. *Middle panel*: spectrogram for frequencies up to 5 kHz. Periodic anchor chain noise signature throughout (one noted) and continual generator tones. *Bottom panel*: Broadband (50 Hz – 20,000 Hz) sound pressure level.

3.3 WEC-Attributable Sound

A periodogram comparing drifts conducted at significant distance from the Azura WEC (550 – 650 m) and those at close range (8 – 12 m) is presented in Figure 5. Several features are notable. At frequencies above 7 kHz, spectra are dominated by noise from snapping shrimp. Below this frequency there are several spectral peaks coincident between distant and close range spectra are associated with noise from anchor chains. At 1 kHz, in the distant spectra there is a broadly distributed peak that may be associated with SWIFT self-noise. Between 200 Hz and 1000 Hz, the tones from the Azura's generator are apparent. Around 100 Hz there is a broadly distributed peak in the distant spectra associated with SWIFT self-noise induced by the use of unfurled marker flags on these drifts[1]. Below this frequency, the near and distant spectra merge and their departure from the Knudsen spectra suggests this to be generalized self-noise contamination, likely from flow-noise associated with relative motion between the hydrophones and wave orbital velocities that cannot be completely surpressed.

The broadband (50 Hz – 128,000 Hz) sound pressure level is 114 dB for the drifts far from the Azura and 115 dB for the spectra at close range to the Azura, in both cases dominated by sound at lower frequencies. If practical spreading is assumed (i.e., 15log transmission loss), then this suggests a broadband source level no greater than 130 dB for the Azura when operating in this sea state.

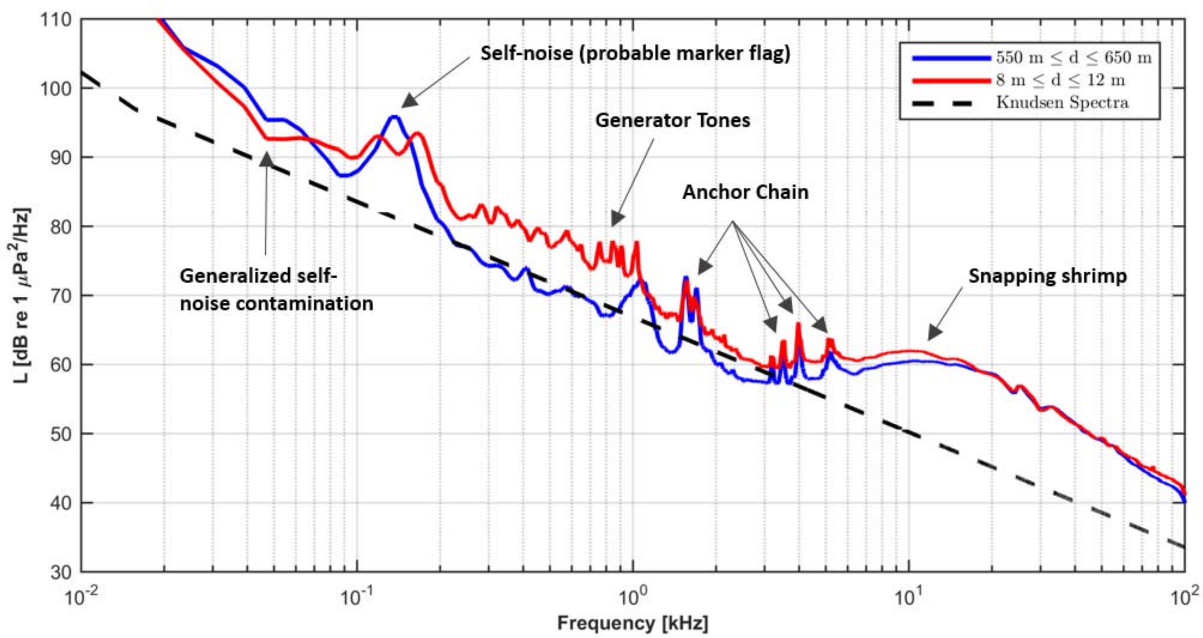

Figure 5 – Periodogram of Azura WEC spectra compared to quasi-baseline. Features of spectra as noted. Reference Knudsen spectra shown for *H* = 1.6 m.

3.4 Spatial Variation

Figure 6 shows mean broadband (50 Hz – 128,000 Hz) sound pressure levels gridded to 20 m resolution from drifts around the Azura. No clear pattern is apparent, which is, perhaps, unsurprising, given the relatively small difference in broadband levels between sound at close range to the Azura and sound at much greater ranges. A comparison restricted to the specific band of generator tones may be more illuminating.

[1] Confirmed by review of spectra from drifts conducted at the 80 m site, for which marker flags were furled and no peak is present around 100 Hz.

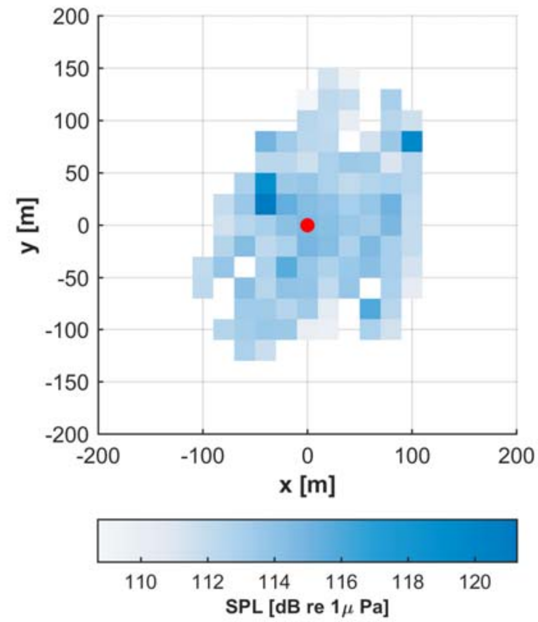

Figure 6 – Variations in broadband (50 Hz – 128,000 Hz) sound pressure levels in the vicinity of the Azura WEC (red dot).

4 Conclusions

While sound attributable to the Azura WEC is measurable, it is only distinct from background noise below 20 kHz and the Azura appears to produce limited sound above a frequency of 1 kHz. At the 30 m site, the amplitude of ambient noise generated by snapping shrimp will likely make it difficult to identify WEC sound above 5 kHz. This suggests that future surveys should be able to capture relevant information at lower sample rates (e.g., 50 kHz) and focus, instead, on reducing self-noise at lower frequencies.

5 Acknowledgement

Financial support for this work is provided by the University of Hawai'i. Many thanks for the field operations support from Tor Harris and Patrick Anderson of Sea Engineering, Keith Bethune of the University of Hawai'i, and Alex deKlerk and James Joslin from the University of Washington.

SWIFT Field Survey #3
Spatial Characterization of the Azura Wave Energy Converter
REV 1 January 8, 2017
(Deliverable No. 7)

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1 Introduction

This report describes drifting acoustic measurements using Acoustic Surface Wave Instrumentation Floats with Tracking (A-SWIFTs) at the US Navy Wave Energy Test Site (WETS) in Kaneohe Bay, HI conducted from March 18 – 21, 2016. Surveys emphasized observations of spatial variations in sound around the NWEI Azura WEC. At times during these surveys, sea states were relatively extreme, exceeding 3 m.

2 Methodology

2.1 A-SWIFT Drifters

WEC sound was measured by A-SWIFTs equipped with recording hydrophones and supporting instrumentation, as summarized in Table 1. An icListen HF hydrophone was fitted at the base of the hull, approximately 1 m below waterline and protected by a PVC ring with stainless steel stand-offs. For all surveys, the hydrophones recorded continuously at a sample rate of 256 kHz, allowing WEC sound to be resolved down to 128 kHz.

A-SWIFT position was tracked by a QStarz GPS logger, recording position and horizontal velocity at 10 Hz. An Airmar weather station mounted to each A-SWIFT monitored wind speed, wind direction, and temperature. The Airmar stations also recorded buoy position (a backup to the primary GPS logger) and buoy orientation (heading, pitch, and roll). All quantities were recorded at a rate of 1-2 Hz. Each A-SWIFT was also equipped with a Lowell Instruments MAT-1 Data Logger, a 6-axis IMU recording at 64 Hz. Finally, GoPro Hero 3 cameras were attached to the top of the mast or lower spar on some A-SWIFTs to provide visual metadata for surface and sub-surface conditions.

Table 1 – A-SWIFT Instrumentation

Instrument	Model	Measurement
Hydrophone	OceanSonics icListen HF	Underwater sound
GPS	QStarz BT-Q1000eX	Spar position and speed (high res)
Weather Station	Airmar PB200	Wind velocity, air temperature, air pressure Spar position, orientation, and speed (low res)
Inertial Motion Unit (IMU)	Lowell Instrument MAT-1	Spar acceleration and orientation (high res)
Camera	GoPro Hero 3	Visual metadata from surface

Drifts are summarized in Table 2. Track density around the Azura is shown in Figure 1.

A drift sequence consisted of the following steps:

- Deploy A-SWIFT drifters from survey vessel
- Motor off survey vessel until at least 100 m from A-SWIFTs
- Disengage engine and drift dead ship
- Drift until A-SWIFTs reached end of desired survey track
- Restart engines and recover SWIFTs

All drifts were conducted successfully, with nearly complete data return from all instruments. On a limited number of drifts, the weather station malfunctioned and did not report data for short periods of time.

Table 2 – Daily drift summary

Date	No. of Drifts	Total Drift Time	Avg. H_s (m)	Avg. T_e (s)
3/18/2016	17	4 h 52 m	3.2	11.9
3/19/2016	28	6 h 55 m	2.3	9.8
3/20/2016	20	8 h 15 m	2.8	10.7
3/21/2016	39	7 h 47 m	2.2	10.4

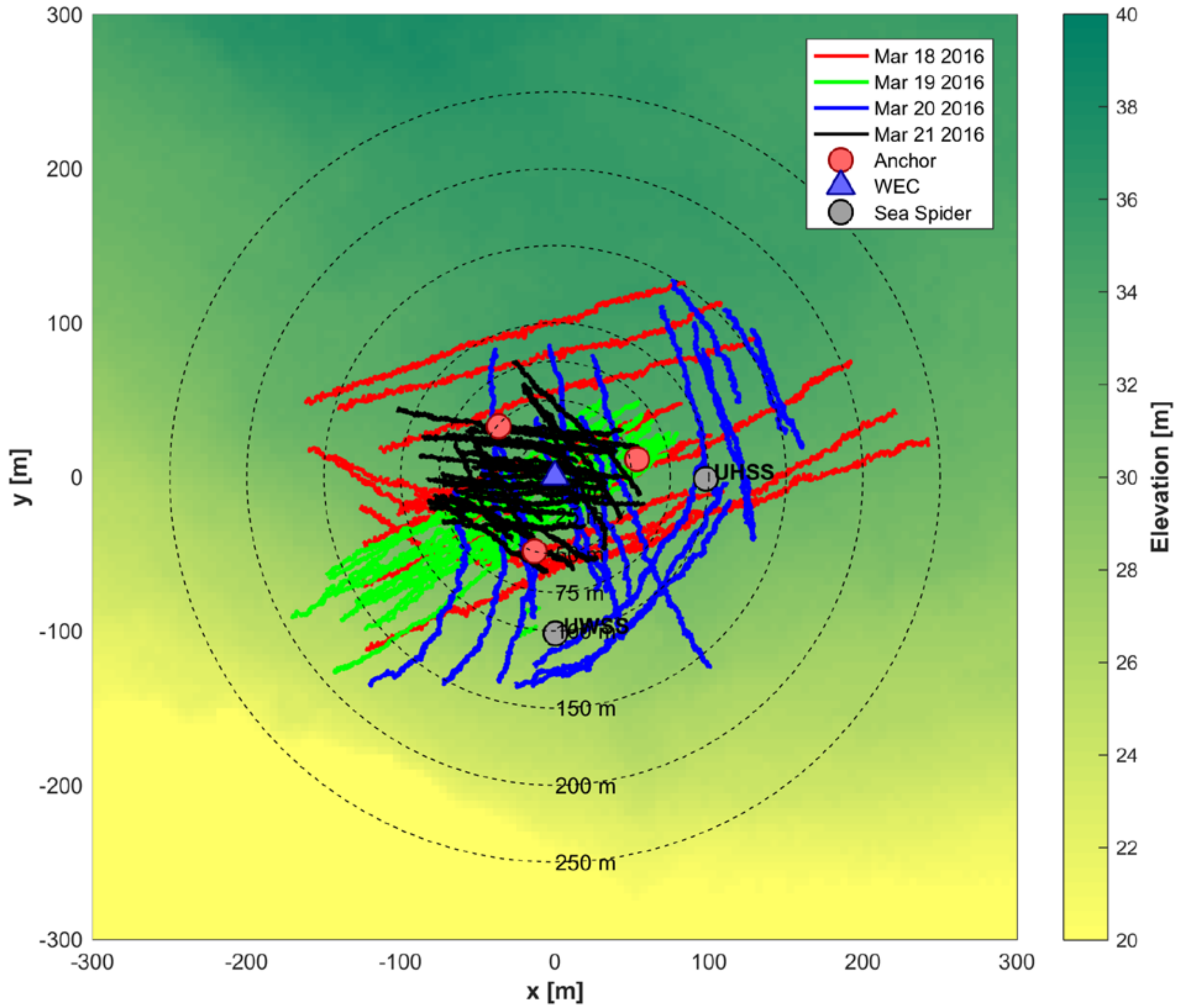


Figure 1 – Drifter track density around Azura WEC. Coordinate system relative to the location of the Azura WEC.

2.2 Acoustic Measurements

2.2.1 Hydrophone Calibration

Hydrophones were field calibrated using a GeoSpectrum M351 calibrator. Average results for pre- and post-drift calibrations were used to construct a low-frequency (< 250 Hz) receive voltage sensitivity (RVS) curve for each hydrophone, while the manufacturer-supplied calibration was used for higher frequencies. Low-frequency sensitivity was consistent drift-to-drift and with previous surveys (±2 dB). Frequency-dependent calibration curves are applied to all acoustic data presented in this report.

2.2.2 Data Processing

Acoustic data sampled continuously at 256 kHz was buffered into samples consisting of 2^{15} points with 50% overlap between samples to improve time resolution of lower frequency events. Each window was linearly detrended, a hamming filter applied, and processed with a fast Fourier transform (FFT). Resulting spectra have a frequency bandwidth of 8 Hz and are further merged, either in frequency or time, to produce spectra with acceptable confidence intervals.

2.2.3 Data Quality Assurance

Acoustic data were visually reviewed by stepping through 30 s spectrograms and "quarantining" periods contaminated by obvious vessel traffic or precipitation. In addition, automatic algorithms specific to the Azura WEC were used to identify and quarantine periods of flow-noise and self-noise. Finally, manual review of subsets of data were also performed to relate spectral signatures to underlying sound sources.

2.3 Spatial Variations in Azura WEC Sound

The emphasis of this survey was on resolving spatial patterns observed in close-range drifts during a prior A-SWIFT survey. The variation in sea states during the survey allowed temporal variations in the spatial pattern to also be explored.

2.4 Comparison between Drifting and Stationary Hydrophones

Several drifts were also conducted in close proximity to the Sea Spiders to enable comparisons between drifting and stationary hydrophone data. Due to the loss of one Sea Spider and clock drift on the Loggerhead DSG-ST hydrophone aboard the intact Sea Spider, this comparison was only possible for a single drift.

2.5 Metocean Conditions

Metocean conditions varied somewhat during the study period with wind direction changing each day, resulting in different drift patterns. The significant wave height varied from 2.1 – 3.3 m and energy period varied from 9.5 – 12.2 s.

The sound velocity profile was measured several times with a Valeport mini-SVP (acoustic time of flight measurement). As shown in Figure 2, sound velocity is relatively consistent over the upper water column.

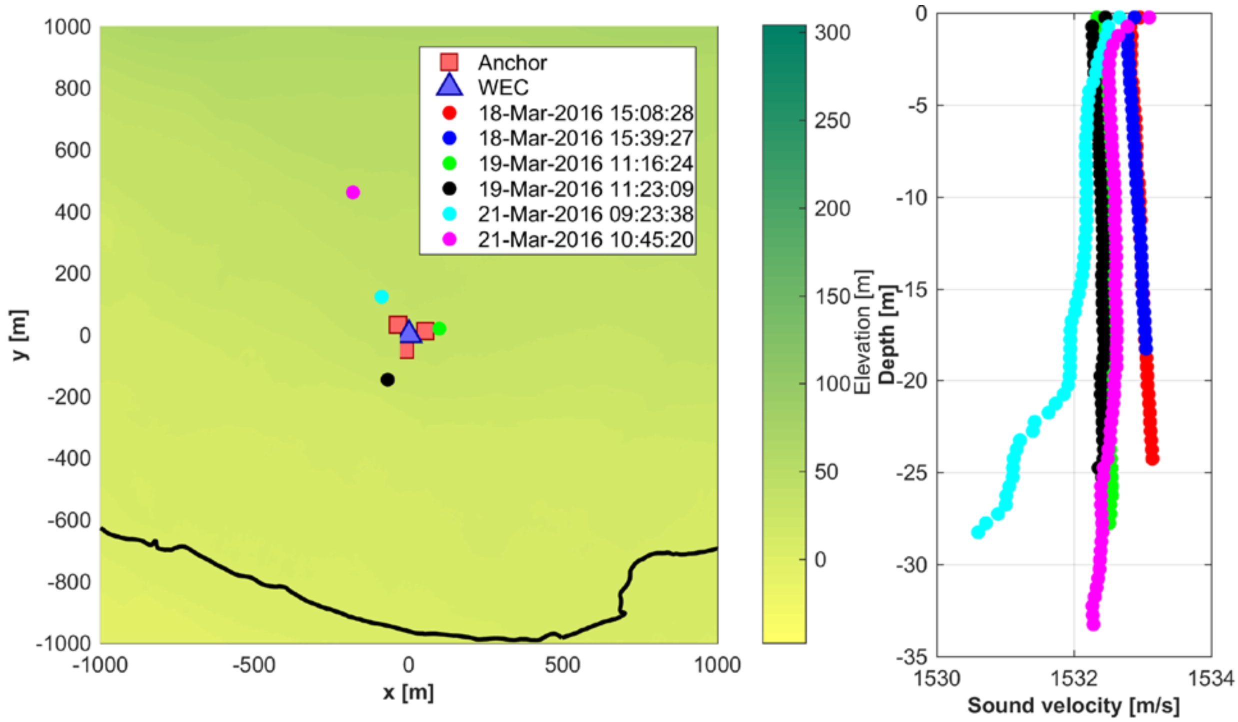


Figure 2 – Sound velocity profiles, with position referenced to the Azura WEC.

3 Results

3.1 Spatial Variations in Azura WEC Sound

Spatial variations around the Azura WEC are shown in Figure 3 and Figure 4. All data are presented as "WEC band" levels for frequencies between 200 and 1450 Hz that have been previously shown to be associated with the Azura WEC. Because of the similarities in sea state on March 19th and 21st, these data are pooled, as are data from March 18th and 20th. Patterns are consistent between sea states, with received levels higher by approximately 5-10 dB on the "upstream" side of the Azura WEC at ranges less than 10 m. Because the primary acoustic emission is associated with the hydraulic generator PTO, this suggests that the sound has some directivity. However, no spatial patterns are discernable at ranges beyond 10 m, which suggests that multiple Sea Spider platforms deployed at ranges of 50 m or greater should observe limited, if any, spatial variation. Further, overall sound levels are similar between the two sets of drifts, suggesting a relatively weak influence of sea state on Azura WEC sound, which is consistent with analysis of stationary hydrophone data.

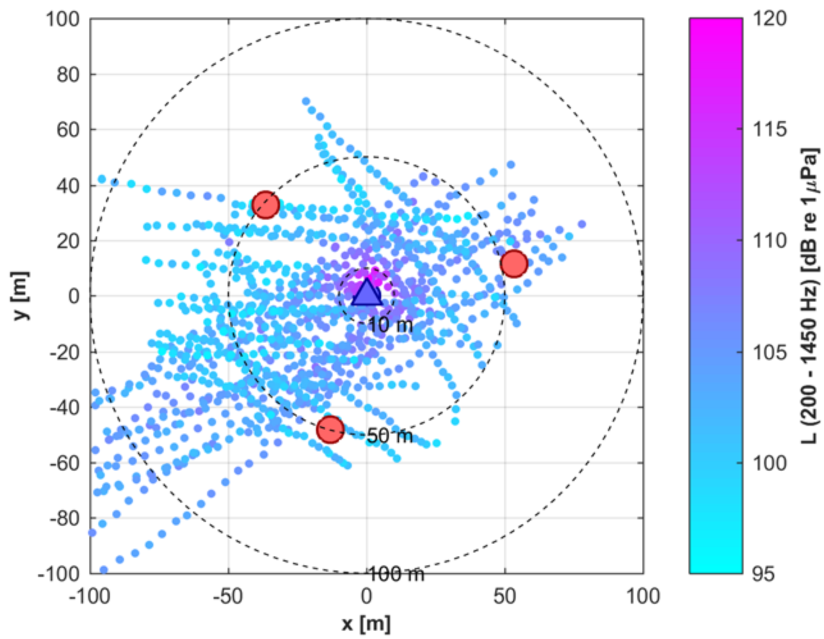


Figure 3 – Spatial patterns in the "WEC band" around the Azura WEC for significant wave heights 2.1 – 2.3 m.

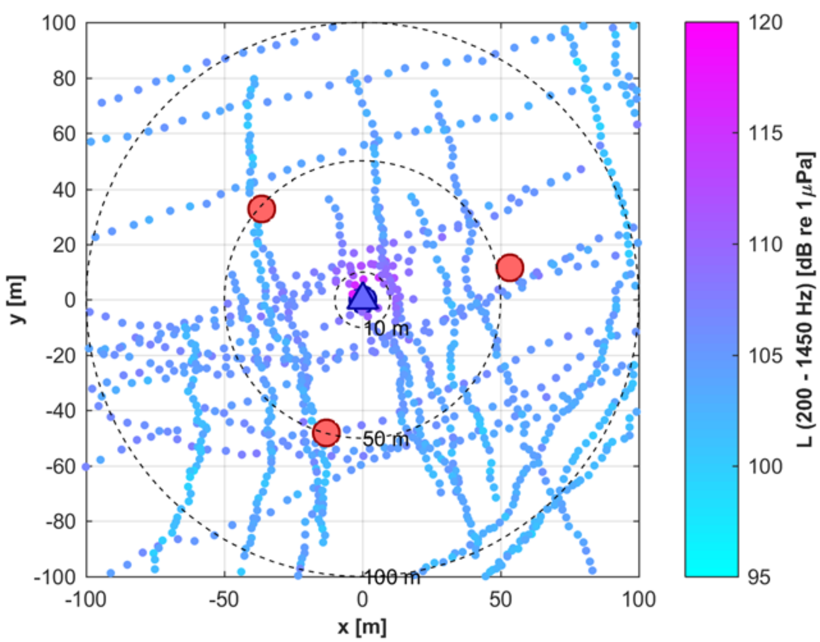


Figure 4 – Spatial patterns in the "WEC band" around the Azura WEC for significant wave heights 2.8 – 3.3 m.

3.2 Comparison between Drifting and Stationary Hydrophones

Figure 5 shows a comparison between co-temporal and co-spatial A-SWIFT and Sea Spider measurements. As expected, A-SWIFT sound is elevated relative to the stationary measurements on the Sea Spider at frequencies less than 100 Hz, where flow-noise affecting the A-SWIFT is largely absent in the stationary measurements. Similarly, the self-noise peak around 150 Hz in A-SWIFT is also observable. In the WEC band (200 Hz – 1450 Hz), the two measurements are often within a few dB of each other and suggest that A-SWIFT measurements of the WEC (depth of 1 m) are providing information about the spatial distribution of WEC sound that are quantitatively representative of the distribution at other depths. In addition to variations in transmission loss for a receiver at the surface and another on the seabed, sound from wind and breaking waves, which are closer to the A-SWIFT, are also present in this range, so differences are to be expected. Similarly, at higher frequencies, where snapping shrimp noise dominates, the Sea Spider, being closer to the source, measures higher received levels until the anti-aliasing filter incorporated into the Loggerhead DSG-ST rapidly attenuates sound above 10 kHz.

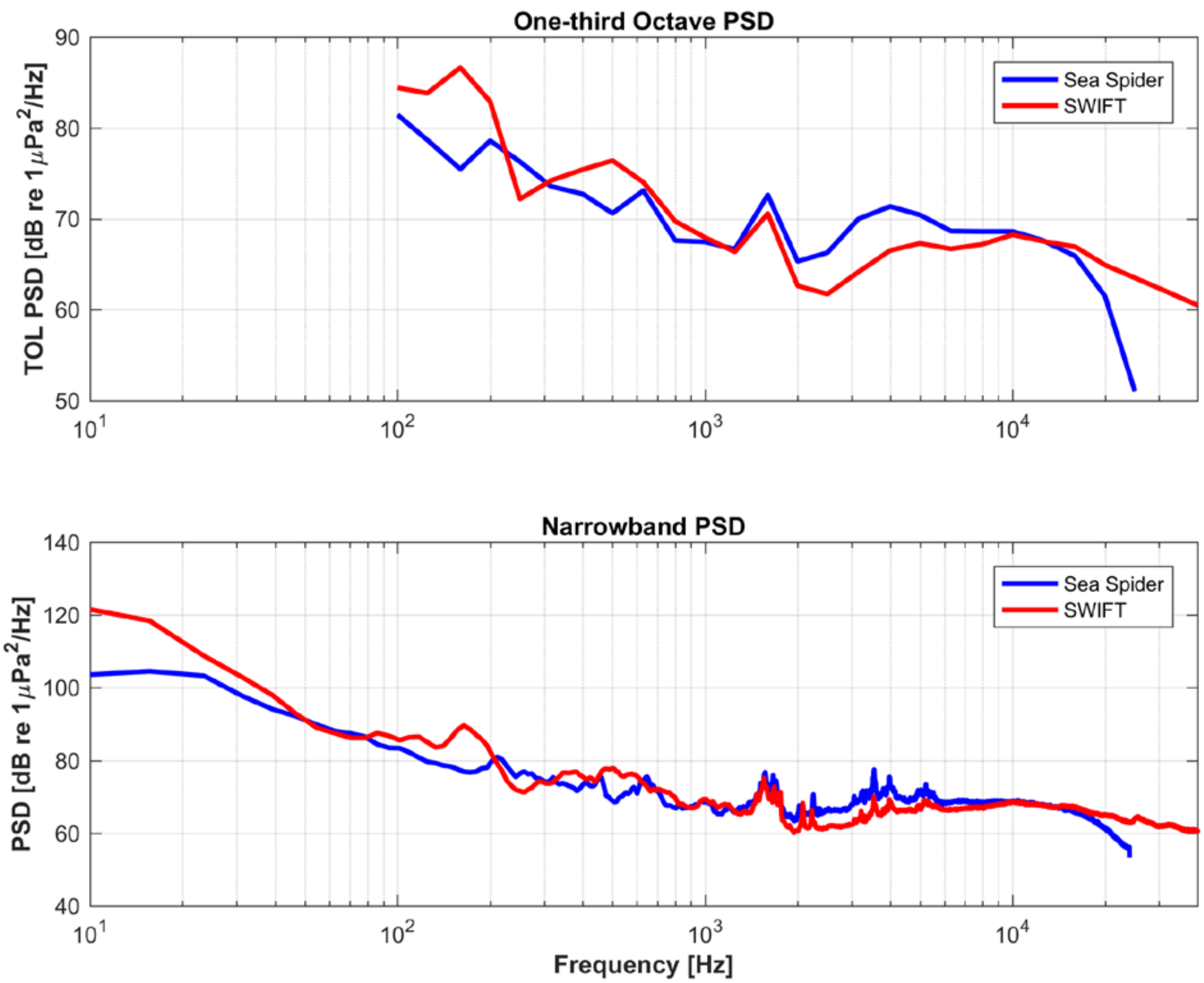


Figure 5 – Comparison between Sea Spider and A-SWIFT platforms in one-third octave pressure spectral density (PSD) and narrowband PSD.

4 Conclusions

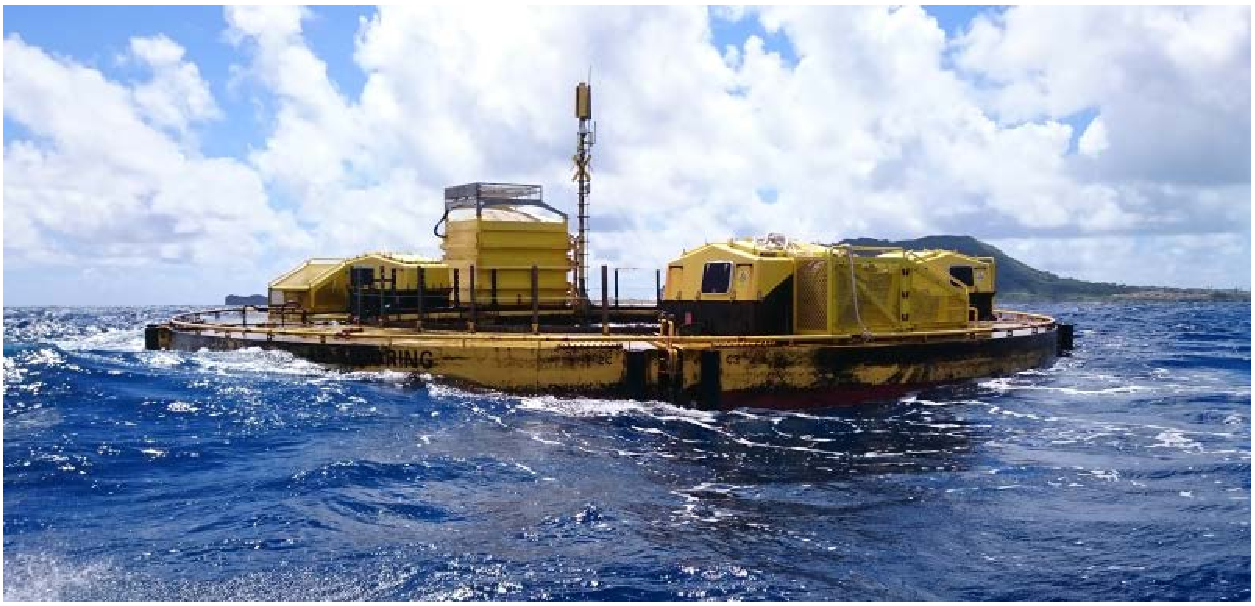
Surveys show that the Azura WEC sound has some spatial variation at close range (i.e., range < 10 m) and that these patterns are relatively persistent across sea states. In addition, co-temporal and co-spatial observations by the Sea Spider and A-SWIFT demonstrate that measurements between the platforms are comparable, though differences of at least 5 dB are to be expected due to variations in source proximity and transmission loss.

5 Acknowledgement

This document was prepared following HINMREC/HNEI specifications and review. The work was funded by the US Department of Energy's Wind and Water Program under Award DE-FG36-08GO18180 to HINMREC/HNEI of the University of Hawai'i

Many thanks for the field operations support from Kydd Pollock of Sea Engineering (who maneuvered us through some fairly "sporting" conditions) and Keith Bethune of the University of Hawai'i.

SWIFT Field Survey #4
Initial Acoustic Characterization of Lifesaver Wave Energy Converter
REV 3 August 30, 2016
(Deliverable No. 8)



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1 Introduction

This report describes drifting acoustic measurements using Acoustic Surface Wave Instrumentation Floats with Tracking (A-SWIFTs) at the US Navy Wave Energy Test Site (WETS) in Kaneohe, HI conducted from August 18 – 21, 2016. Surveys emphasized observations of the Fred Olson Lifesaver wave energy converter (WEC), but also included characterization of the NWEI Azura WEC with its PTO disengaged and testing of flow-shields that could enable measurements of propagating sound at frequencies below 100 Hz. During these surveys, sea states were relatively moderate, ranging from 1.4 – 1.8 m significant wave height, with an energy period of approximately 6 s.

2 Methodology

2.1 SWIFT Drifters

WEC sound was measured by A-SWIFTs equipped with recording hydrophones and supporting instrumentation, as summarized in Table 1. An icListen HF hydrophone was fitted at the base of the hull, approximately 1 m below waterline and protected by a PVC ring with nylon stand-offs. While less durable that stainless steel standoffs, these should reduce directional sensitivity, given their closer impedance match with water. On August 18th and 21st, the hydrophones recorded continuously at a sample rate of 256 kHz, allowing WEC sound to be resolved down to 128 kHz. On August 19, the hydrophones recorded continuously at 512 kHz, allowing WEC sound to be resolved down to 256 kHz. No surveys were conducted on August 20th.

A-SWIFT position was tracked by a QStarz GPS logger, recording position and horizontal velocity at 10 Hz. An Airmar weather station mounted to each A-SWIFT monitored wind speed, wind direction, and temperature. The Airmar stations also recorded buoy position (a backup to the primary GPS logger) and buoy orientation (heading, pitch, and roll). All quantities were recorded at a rate of 1-2 Hz. Each A-SWIFT was also equipped with a Lowell Instruments MAT-1 Data Logger, a 6-axis IMU recording at 64 Hz. Finally, GoPro Hero 3 cameras were attached to the top of the mast or lower spar on some A-SWIFTs to provide visual metadata for surface and sub-surface conditions.

Table 1 – A-SWIFT Instrumentation

Instrument	Model	Measurement
Hydrophone	OceanSonics icListen HF	Underwater sound
GPS	QStarz BT-Q1000eX	Spar position and speed (high res)
Weather Station	Airmar PB200	Wind velocity, air temperature, air pressure Spar position, orientation, and speed (low res)
Inertial Motion Unit (IMU)	Lowell Instrument MAT-1	Spar acceleration and orientation (high res)
Camera	GoPro Hero 3	Visual metadata from surface

Drifts are summarized in Table 2. Track density around the Lifesaver is shown in Figure 1 and for the Azura in Figure 2. The Lifesaver was generating power throughout the drifts. The Azura PTO was disengaged for all drifts on August 18th. This report focuses on the analysis of the sound produced by the Lifesaver. Results of drifts around the Azura will be discussed in a subsequent report.

A drift sequence consisted of the following steps:

- Deploy SWIFT drifters from survey vessel
- Motor off survey vessel until at least 100 m from A-SWIFTs
- Disengage engine and drift dead ship
- Drift until A-SWIFTs reached end of desired survey track
- Restart engines and recover SWIFTs

Drifts were conducted successfully, with nearly complete data return from all instruments. Airmar weather station outages occurs for up to a few minutes during a small number of drifts. This has been affecting a limited number of drifts during each deployment at WETS.

Table 2 – Daily drift summary

Date	No. of Drifts	Total Drift Time	Avg. H_s (m)	Avg. T_e (s)
8/18/2016	27	5 h 51 m	1.4	5.9
8/19/2016	15	6 h 30 m	1.6	6.1
8/21/2016	27	7 h 30 m	1.4	6.4

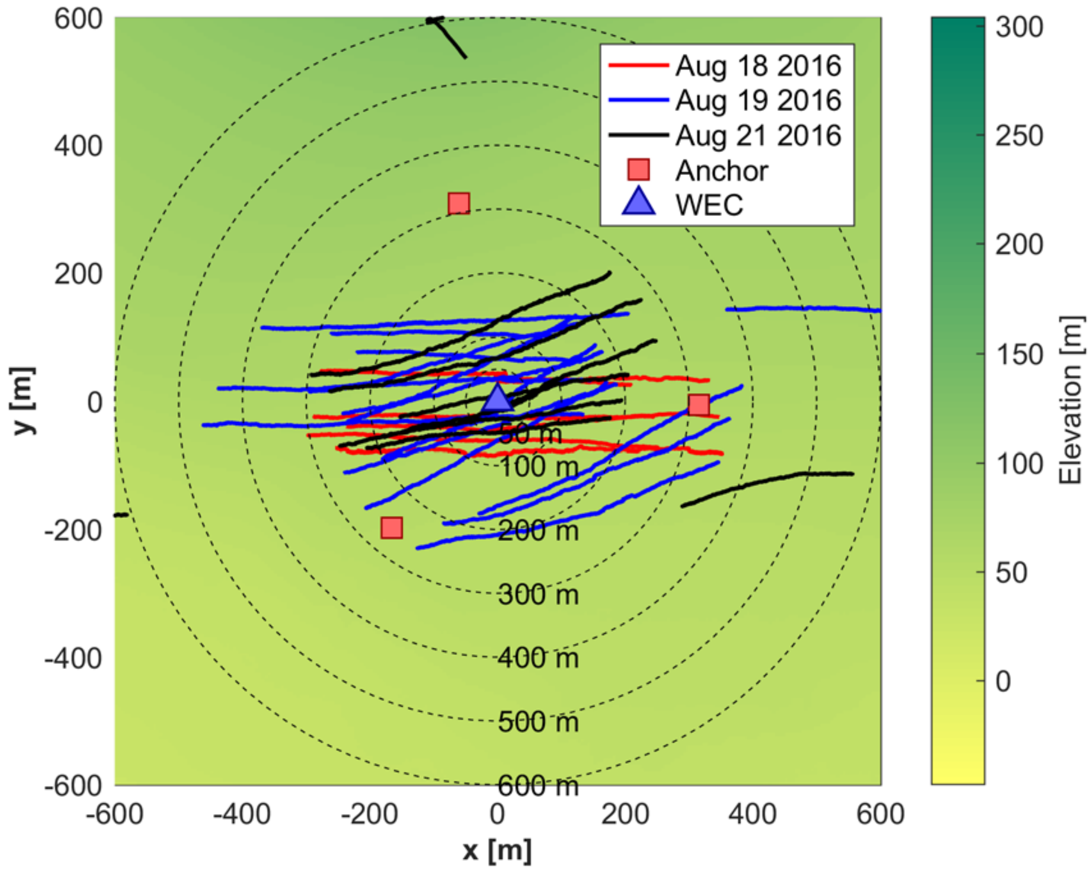

Figure 1 – Drifter track density around Lifesaver WEC. Coordinate system relative to the location of the Lifesaver.

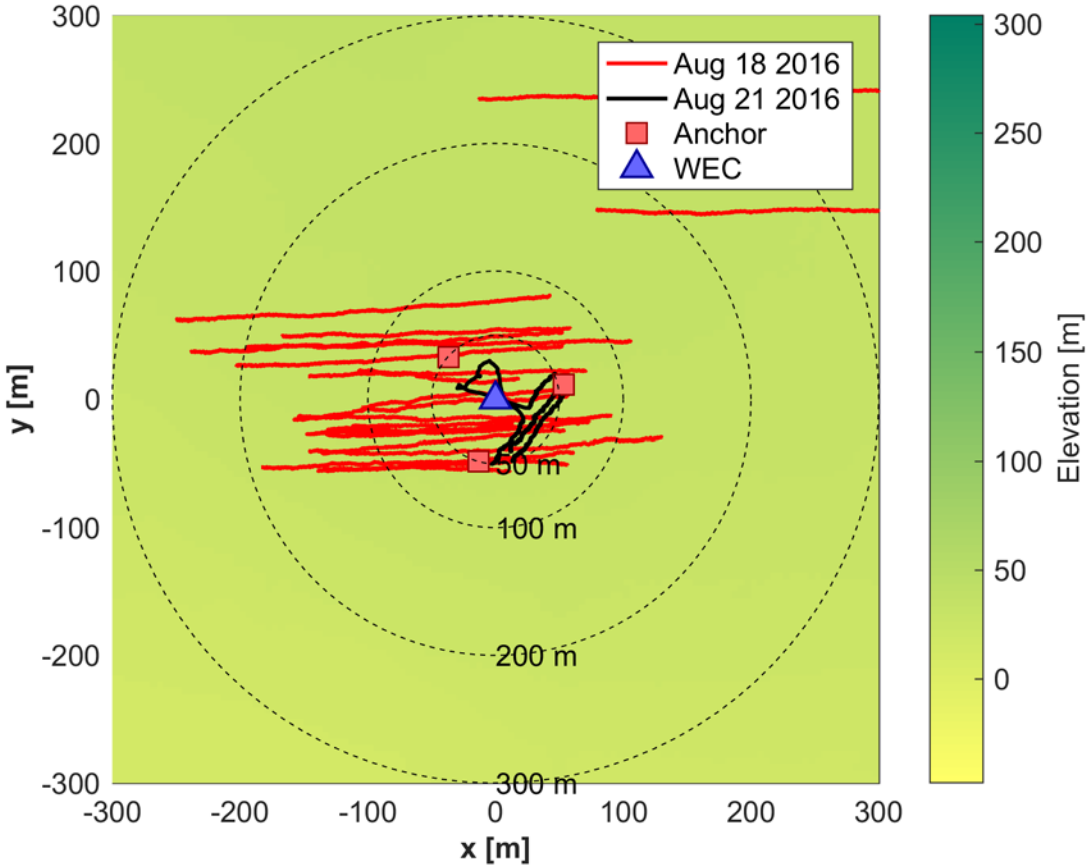

Figure 2 – Drifter track density around Azura WEC. Coordinate system relative to the location of the Azura.
Acoustic Measurements

2.1.1 Hydrophone Calibration

Hydrophones were field calibrated using a GeoSpectrum M351 calibrator. Average results for pre- and post-drift calibrations were used to construct a low-frequency (< 250 Hz) receive voltage sensitivity (RVS) curve for each hydrophone, while the manufacturer-supplied calibration was used for higher frequencies. Low-frequency sensitivity was consistent drift-to-drift and with previous surveys (±2 dB). Frequency-dependent calibration curves are applied to all acoustic data presented in this report.

2.1.2 Data Processing

Acoustic data sampled continuously at 256 kHz was buffered into samples consisting of 2^{15} points with 50% overlap between samples to improve time resolution of lower frequency events. Because of evidence for high-frequency sound associated with the Lifesaver, a subset of drifts were conducted with a sample rate of 512 kHz, which were buffered into samples of 2^{16} points to maintain frequency resolution while increasing the maximum resolvable frequency. Each window was linearly detrended, a hamming filter applied, and processed with a fast fourier transform (FFT). Resulting spectra have a frequency bandwidth of 8 Hz and are further merged, either in frequency or time, to produce spectra with acceptable confidence intervals.

2.1.3 Data Quality Assurance

Acoustic data were visually reviewed by stepping through 30 s spectrograms and "quarantining" periods contaminated by obvious vessel traffic or precipitation. Representative spectrograms containing these types of sound are shown in Figure 3, as compared to an ambient reference case. The case of vessel noise associated with the operation of the rigid inflatable AMBAR is dramatically different from the ambient reference. The example of precipitation (a rain shower) is dominated by broadband elevated sound, while the actual consequence of rainfall is in mild elevation in received levels around 10 kHz.

The processing algorithms developed to automatically quarantine flow-noise and self-noise in measurements of the NWEI Azura were found to identify sound in the vicinity of the Lifesaver as flow-noise or self-noise and incorrectly exclude a high percentage of sequences. A Lifesaver-specific automatic processing algorithm is planned for future development. Manual review of subsets of data were also performed to relate spectral signatures to underlying sound sources.

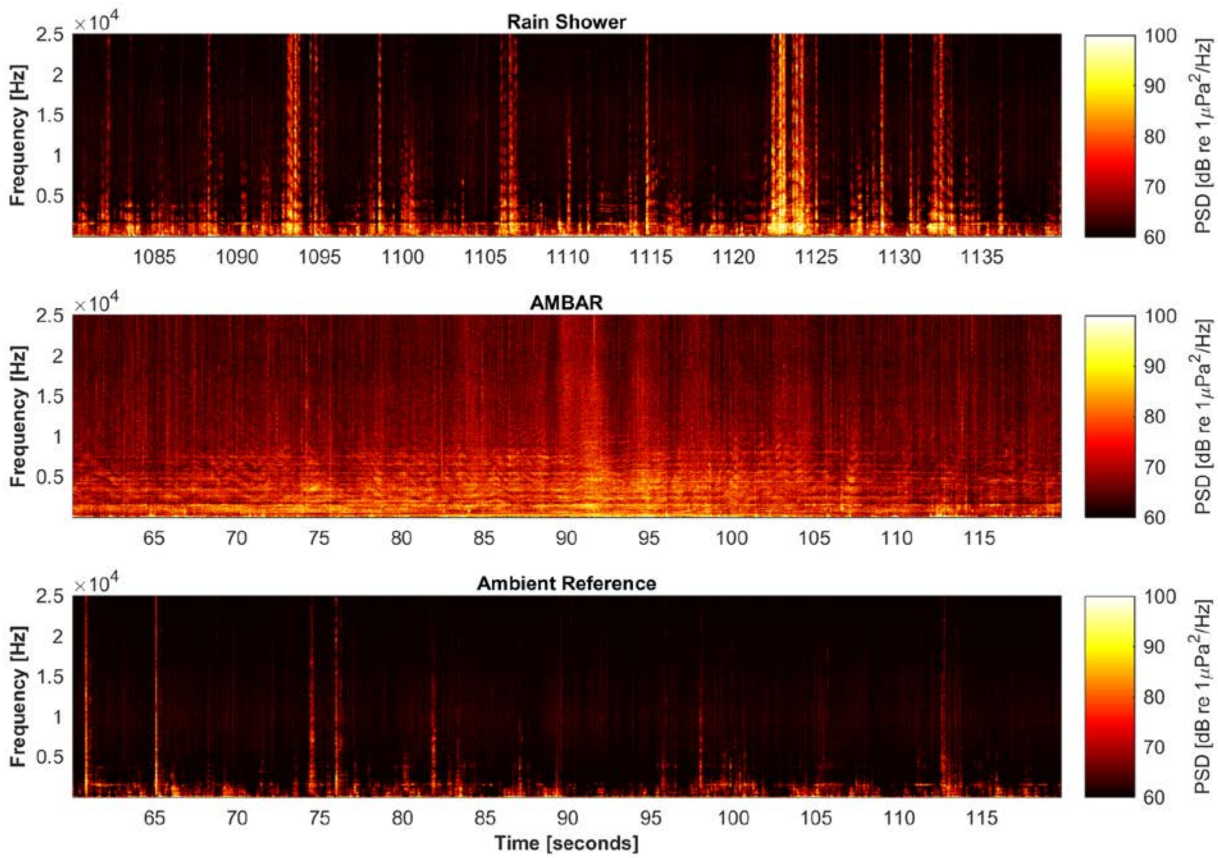

Figure 3 – Spectrograms of vessel noise (AMBAR rigid inflatable), light precipitation, and ambient reference. Both the vessel noise and precipitation examples are obtained at a distance of approximately 500 m from the Lifesaver, while the ambient reference is approximately 600 m from the Lifesaver.

2.2 Sound Attributable to the Lifesaver WEC

The frequencies of sound attributable to the Lifesaver were estimated by comparing the mean spectra at ranges between 75 and 125 m from the WEC to a reference ambient condition in similar water depth at a range of 600 m. The representativeness of the acoustic reference site was tested by comparison to two other candidate reference sites, also at a range of 600 m, but at different bearings and is discussed in the results.

In addition, sound levels attributable to the WEC were plotted as a function of range from the Lifesaver, using a 30 s integration time. These were evaluated over three bands:

- 200 – 100,000 Hz: frequencies of sound recorded around the Lifesaver that substantially exceeded the ambient reference. The 200 Hz lower limit corresponds to the lower limit of self-noise for the A-SWIFT.
- 5000 – 100,000 Hz: frequencies of sound in excess of those attributable to the Azura, to evaluate the contribution of these higher frequencies to broadband levels.

2.3 Methods to Attribute Sound to a WEC

A key challenge in the acoustic characterization of WECs is how to distinguish between the sound produced by a WEC and other sources of ambient noise. To date, drifting surveys at WETS have relied on comparisons between measurements obtained near a WEC and those beyond the range of its acoustic influence. One concern with using a “reference site” to identify WEC sound is that acoustic conditions may vary substantially throughout an area. To explore this concern, three A-SWIFTs were spread around the Lifesaver, at a range of 600 m, likely at or beyond the acoustic extent of the WEC. Spectra from the three drifts were compared to each other and to spectra at close range to the Lifesaver.

2.4 Flow-shield Testing

Prior comparisons have suggested that at frequencies less than 100 Hz, flow-noise associated with relative hydrophone motion has a high likelihood of masking propagating sound. While large (e.g., several meters in diameter) flow-shields are common in naval applications, there has been limited work to date on developing flow shields compact enough for marine energy acoustic measurement. The idea behind a flow-shield is to move the turbulence that produces flow-noise away from the hydrophone element. However, in doing so, it is important to choose a flow-shield design that does not attenuate propagating sound.

As shown in Figure 4, two types of flow-shields were tested against the standard hydrophone configuration: an annulus of open-cell foam, similar to the design of flow-shields used previously in Admiralty Inlet, WA in tidal energy applications, and a thin-walled plastic bucket. For flow-shield testing, three A-SWIFTs were simultaneously released in relatively close proximity for 10 minute drifts. The pressure-average spectra from two shields were then compared to the spectra from the standard configuration. A comparison was also made to the spectra after automatic flow-noise and self-noise identification algorithms had been applied.

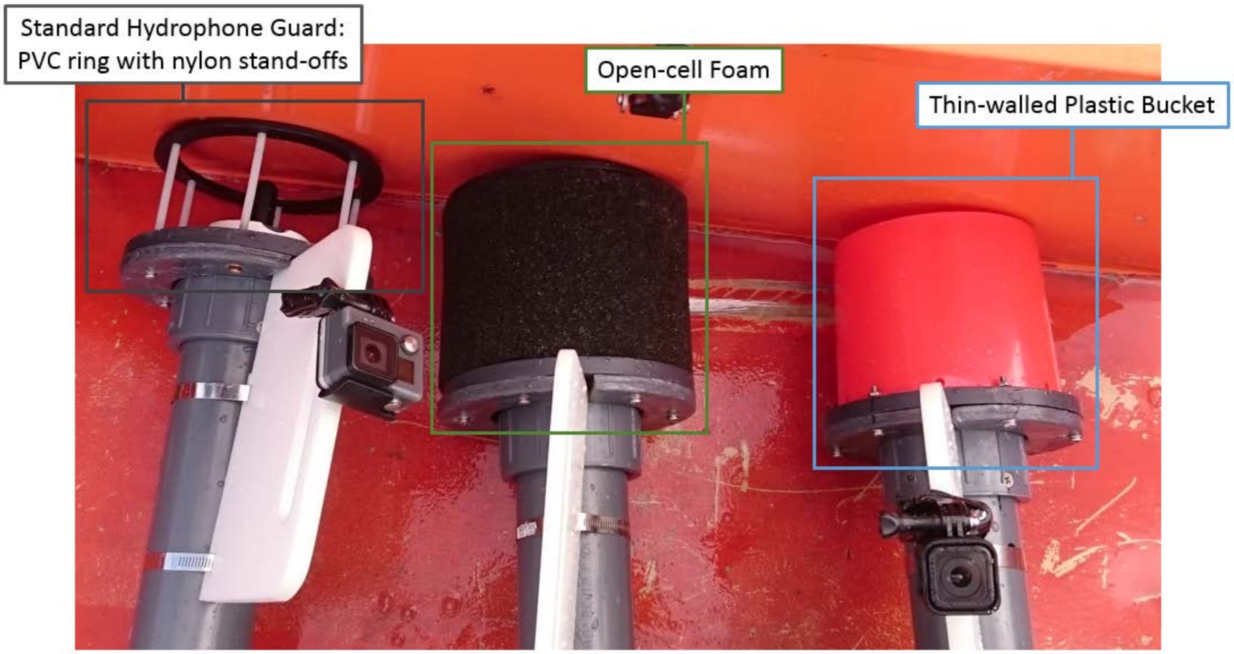

Figure 4 – Flow-shield configurations

2.5 Metocean Conditions

Metocean conditions were generally uniform over the study period. Winds were sustained from the east throughout operations. One rain shower occurred on August 21st and is quarantined from reported acoustic data. The significant wave height varied from 1.4 – 1.8 m and the energy period was approximately 6 s.

The sound velocity profile was measured on August 18th, 19th, and 21st with a Valeport mini-SVP (acoustic time of flight measurement). As shown in Figure 4, sound velocity is relatively consistent over the upper water column, with an indication of a mixed layer at greater depth closer to shore (Figure 5, red dot).

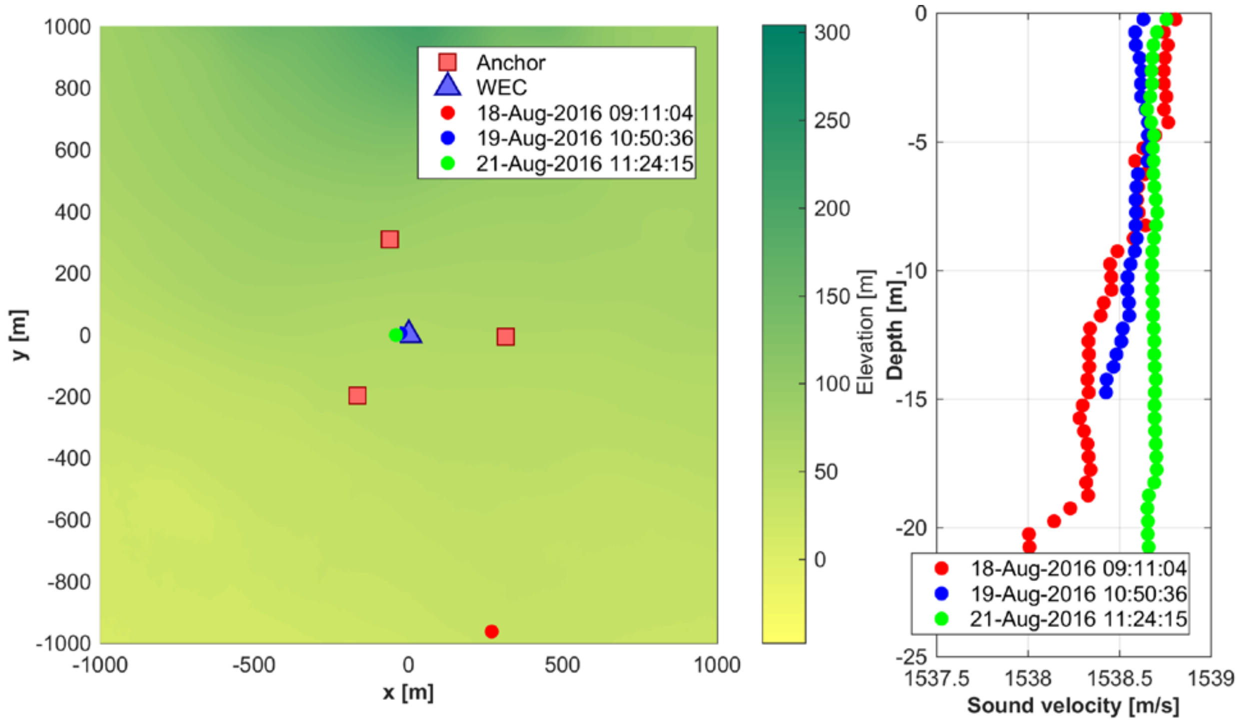

Figure 5 – Sound velocity profiles (referenced to the Lifesaver WEC). Note: Casts on the 19th and 21st are nearly co-spatial just east of the Lifesaver WEC.

3 Results

3.1 Sound Attributable to the Lifesaver

In manually reviewing the recordings around the Lifesaver, the dominant sound is a loud rattle, reminiscent of shaking an aerosol bottle. The sound is similar to the distant clang of chain audible around the Azura, but broader-band in nature and more frequent. No sound associated with the air-side PTO is apparent. Discussions with staff at Fred Olsen and Sea Engineering have not conclusively identified the source of the sound. While it is not likely originating from the Lifesaver hull, neither the PTO bands, PTO band mooring, Navy moorings, nor Waverider mooring have a clearly identifiable physical mechanism that would produce this type of sound.

Figure 5 shows a spectrogram from a single drift in the general vicinity of the deployment site (~400 m distance) prior to installation, one following installation at closer range (~50 m distance), and the ambient reference (co-temporal with post-installation measurement at ~600 m distance). The pre-installation significant wave height was 1.6 m, in the mid-range of significant wave heights during post-installation measurements. The frequency band at which chain noise is most prevalent in the pre-installation and ambient reference drifts is highlighted by a grey box. While these frequencies are still present in close proximity to the Lifesaver, they are accompanied by the broader band sounds (e.g., the "aerosol bottle" rattle).

Figure 6 shows a periodogram from all drifts around the Lifesaver (range of 75 – 125 m during similar sea states) as compared to an ambient reference and pre-installation measurement[1]. Pressure spectra

[1] Note that the pre-installation measurement was obtained in significantly deeper water than at the Lifesaver deployment site. As discussed later in this report, deeper water reduces the intensity of snapping shrimp sound,

densities from the Lifesaver exceeded the ambient reference for all frequencies above the A-SWIFT self-noise and flow-noise floor (200 Hz). The high-frequency sound is hypothesized to be associated with the collapse of entrained air bubbles around the Lifesaver. The Lifesaver has a shallow draft (~0.5 m), causing waves to continually break around it in the observed sea state. Video footage collected from GoPro cameras at the base of the A-SWIFT spars showed bubble clouds around the perimeter of the WEC of sufficient density to visually obscure its hull. Bubble collapse is a broadband monopole sound source and an efficient radiator of sound. However, this feature of operation may also serve to attenuate PTO sound, much in the same manner as a bubble curtain around pile driving.

The roll-off in intensity of the 1.5 kHz peak associated with chain noise between the WEC and ambient reference is consistent with the source of this sound being in close proximity to the WEC. This sound is ubiquitous throughout WETS, including at the 30 m site. Because this sound pre-dates the installation of the Lifesaver, these observations suggest that this sound likely originates from either the Navy moorings or Waverider at the 60 m site. The elevation of the primary chain sound during pre-installation measurements were obtained to the northeast of the 60 m berth (i.e., closer to the Waverider), which might suggest that this sound originates from that sensor's mooring. However, the Waverider mooring has only two, relatively short (2 m) lengths of chain, neither of which is likely to produce significant sound. On the other hand, when the Navy moorings are unoccupied, the chain in these moorings hangs vertically below the surface buoys and has the potential to bang and rub against itself. While these moorings are under higher tension with the Lifesaver installed, they are still below their design load, and overlapping links of chain remain probable. Further information is required to make a conclusive determination, but the attribution of this sound to the Navy moorings seems most plausible.

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such that these measurements should not be compared to the Lifesaver or ambient reference spectra at frequencies above a few kHz.

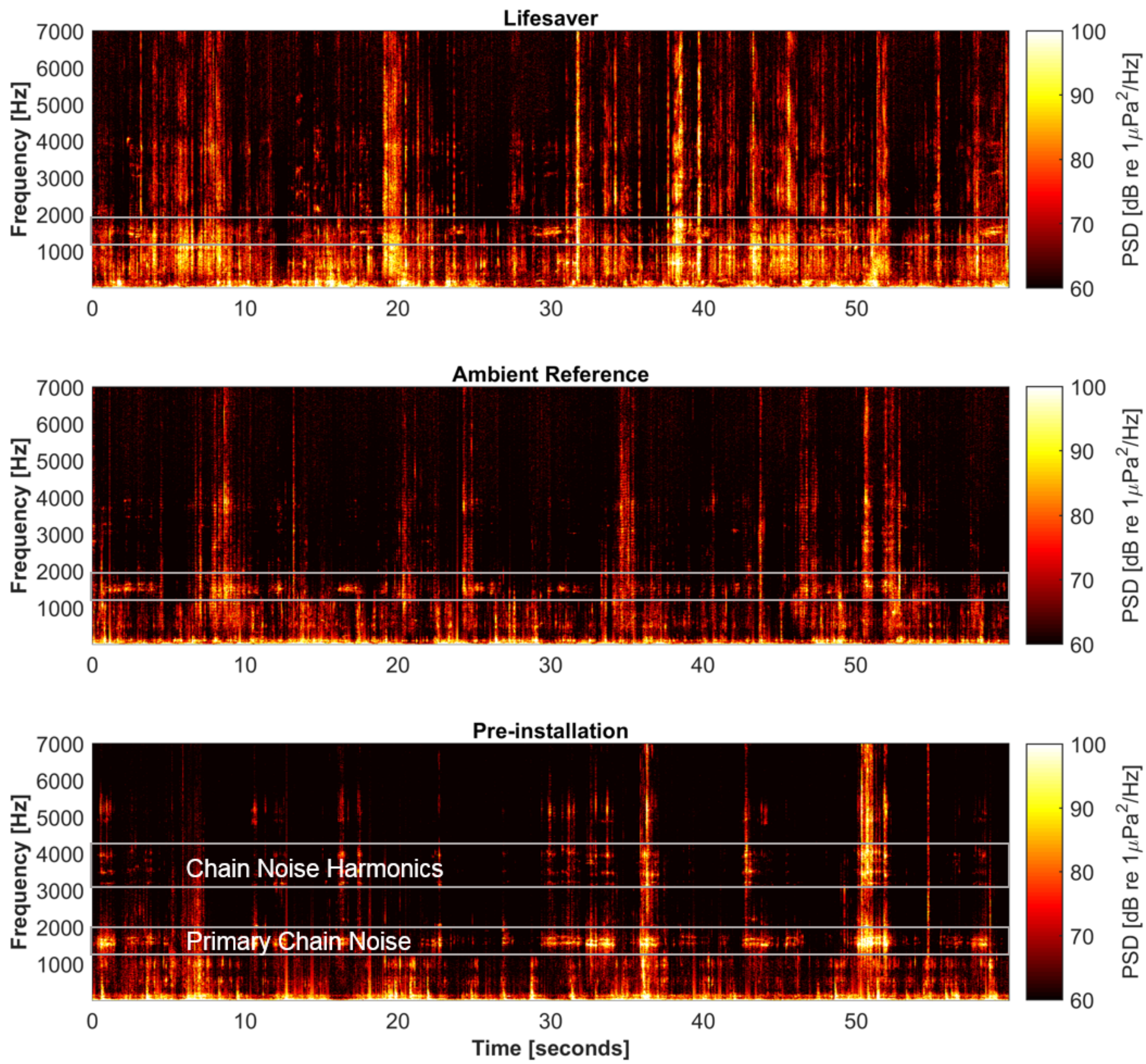


Figure 6 – Annotated spectrogram around Lifesaver. Acoustic spectra around the Lifesaver include A-SWIFT flow-noise and self-noise, which are most intense at frequencies below 200 Hz and around 1 kHz.

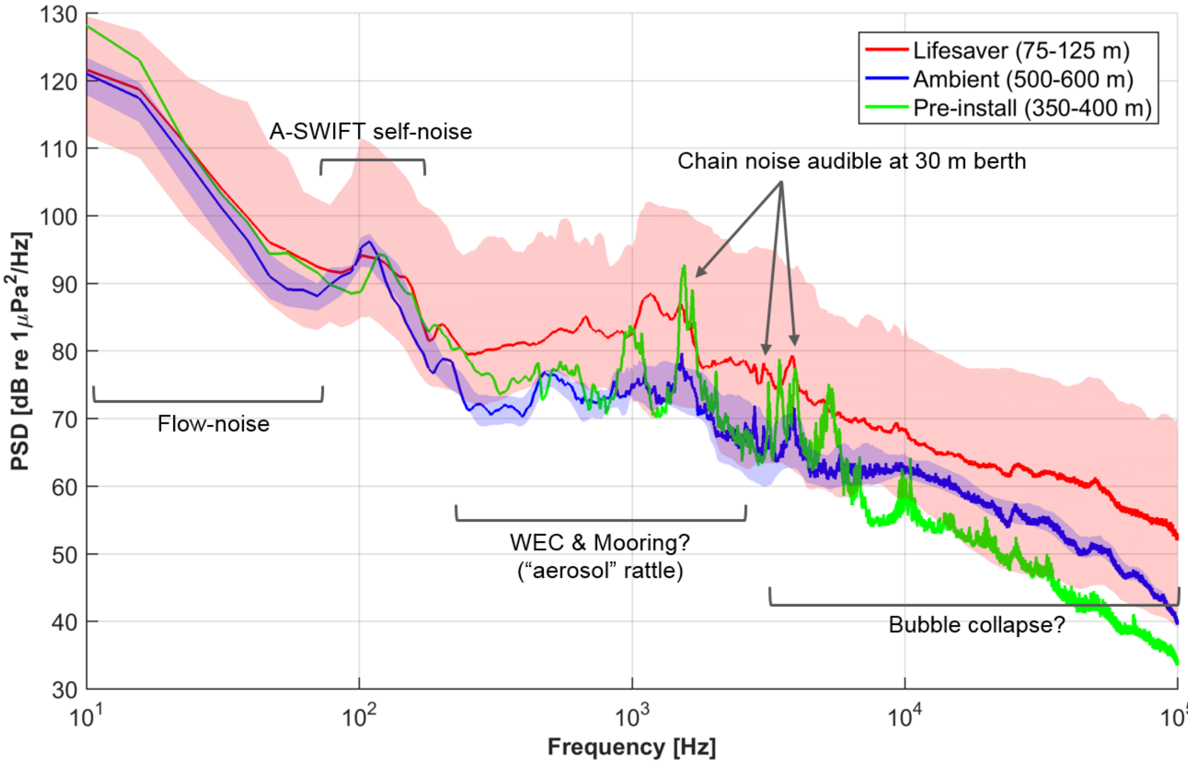


Figure 7 – Periodogram of A-SWIFT drifts at a range of 75-125 m of the Lifesaver as compared to an ambient reference location. Acoustic spectra around the Lifesaver have not been adjusted to minimize A-SWIFT flow-noise and self-noise which are most intense at frequencies below 200 Hz and around 1 kHz. The ambient reference spectra and pre-installation spectra have been corrected. Shading shows the smoothed range of minimum and maximum values.

Figure 7 shows spatial patterns in sound pressure levels around the Lifesaver. Sound levels are generally elevated in the vicinity of the Lifesaver, though do not result in as clear a spatial pattern as is observed in the vicinity of the Azura, as documented in previous reports. Further analysis and drifts originating at greater range may be required to understand the presence of spatial patterns, particularly asymmetry in sound at higher frequencies, which are more intense to the south of the Lifesaver than to the north. This spatial variability manifests in the broad range of observed sound at a given frequency and range from the Lifesaver (i.e., pink shaded area in Figure 6).

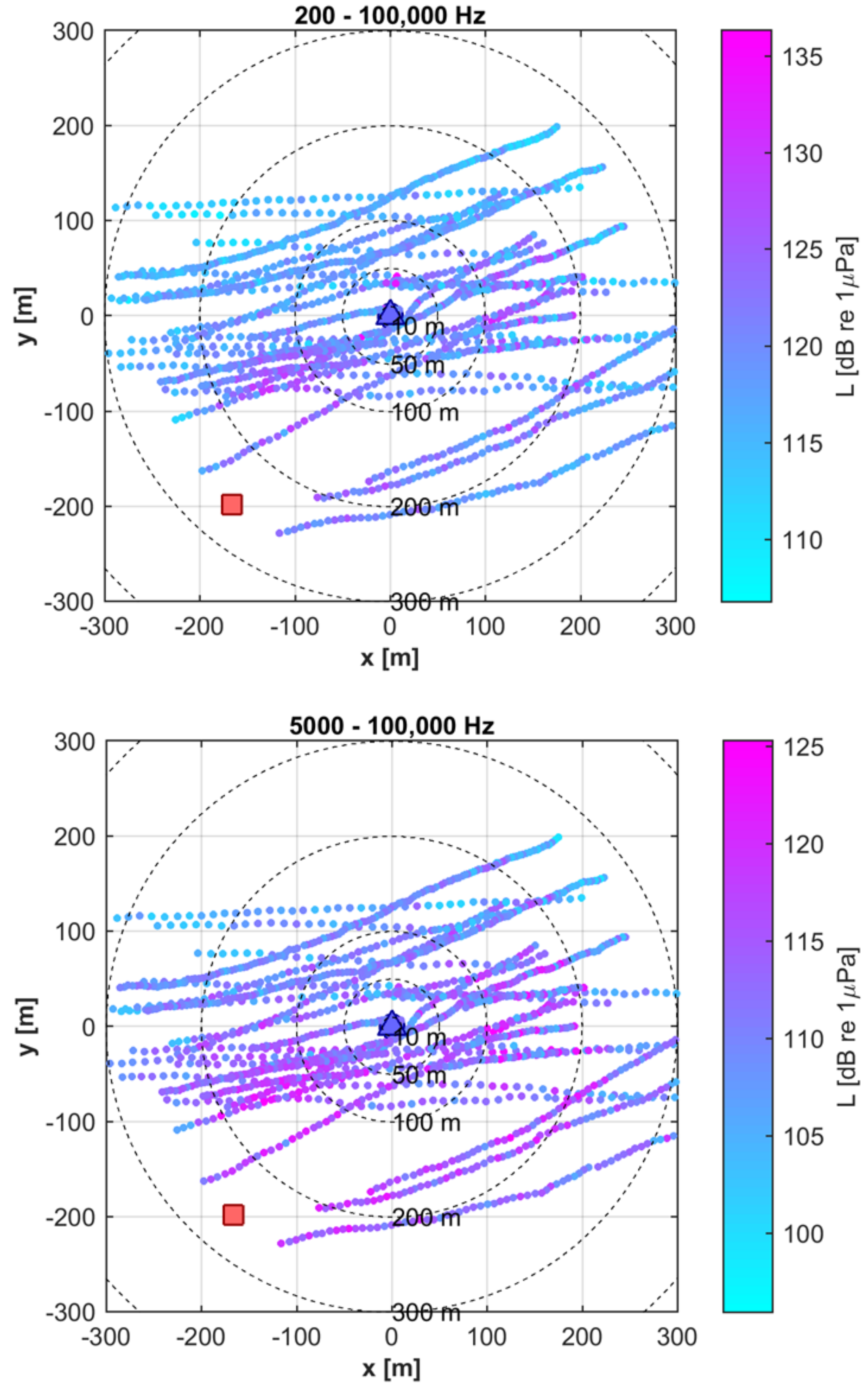
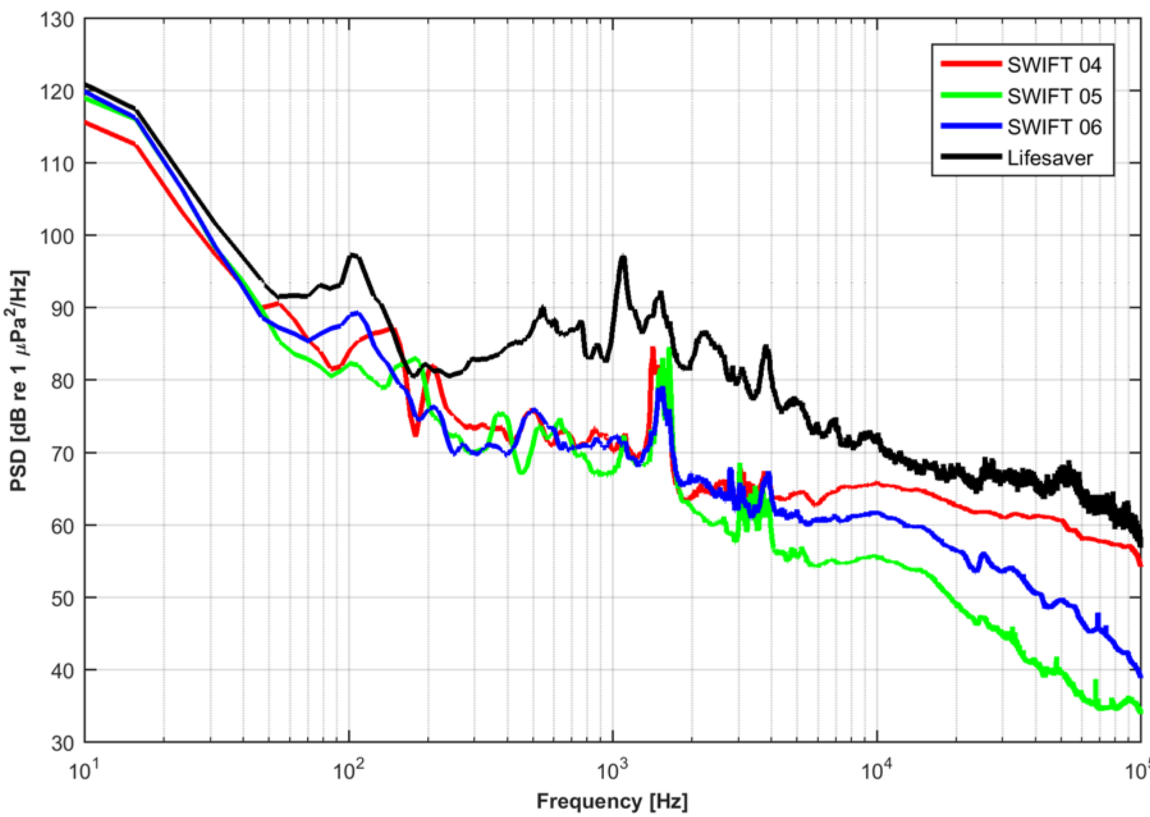


Figure 8 – Spatial patterns in sound pressure levels around the Lifesaver in two frequency bands.

3.2 Methods to Attribute Sound to a WEC

Figure 8 shows periodograms from drifts obtained at approximately 600 m distance from the Lifesaver relative to a measurement obtained at close range. The ambient cases have been adjusted to exclude sequences automatically identified as having significant contamination by flow-noise and/or self-noise. Results show relatively large variability in ambient noise around WETS at f > 2 kHz. This is consistent with a hypothesis of spreading snapping shrimp noise. SWIFT 04 (red) is in the shallowest water (closest to the shrimp, additional breaking waves with entrained bubbles) and shows the highest intensities at these frequencies, while SWIFT 05 (green) is in the deepest water and shows the lowest intensities at these frequencies. Variations below 2 kHz are more limited, suggesting that the choice for the location of the ambient reference for a WEC like the Azura, which does not produce high-frequency noise, is not a sensitive one.

The 1.5 kHz peak associated with chain noise has relatively similar intensity across locations, consistent with the hypothesis that this sound originates from the vicinity of the 60 m berth. The divergence in acoustic spectra above a few kHz also suggests that, at a range of 600 m, the Lifesaver does not dominate over other ambient noise at these frequencies. Finally, any choice of ambient reference leads to the identification of Lifesaver sound over an identical set of frequencies. While the extent by which Lifesaver sound exceeds the ambient reference is a function of the chosen reference, the identification of relevant frequencies is agnostic to the choice.



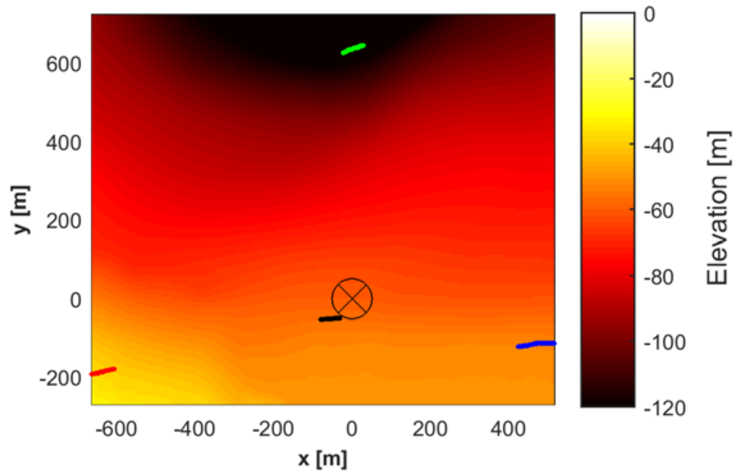


Figure 9 – (upper panel) Periodogram of baseline measurements obtained at similar range, but three bearings relative to the Lifesaver compared to a measurement at closer range. (lower panel) Location of drifts.

3.3 Flow-shield Testing

Flow-shield testing yielded mixed results, as shown in Figure 10 First, considering the spectra without any automatic identification of self-noise and flow-noise (thick, solid lines), both flow shields significantly attenuated high frequency (i.e., > 1 kHz) propagating sound, with the foam flow-shield attenuation exceeding 30 dB at some frequencies. This may be a consequence of residual entrained air in the open-cell foam. When similar flow-shields were used in Admiralty Inlet, WA for tidal energy acoustic characterization, they had the benefit of deep (> 50 m) submergence for a multi-month period, which would likely expel nearly all bubbles from the foam. In contrast, submergence depth (1 m) and duration (up to 10 minutes) were insufficient to achieve a similar result when applied to A-SWIFT measurements. This flow-shield might, however, perform well on a SLOW mooring. At frequencies around 100 Hz, both flow-shields substantially increased self-noise relative to the baseline A-SWIFT. The reason for this is apparent in Figure 11. Namely, the elevation angle (i.e., the angle between the long-axis of the A-SWIFT and the horizon) changes more frequently than for the baseline A-SWIFT. This can be explained in terms of changes to the A-SWIFT hydrodynamics due to the flow-shields. The foam shield significantly increases the drag produced by the lower hull, while the bucket encloses a significant mass of water that increases the inertia of the lower hull. Both of these changes result in increased A-SWIFT motion and, consequently, elevated self-noise (e.g., hull creaking, splashing). Below 100 Hz, the foam appears effective at reducing flow-noise by 10-15 dB. Further, if one considers the spectra that have been processed with automatic flow-noise and self-noise identification algorithms (thin, dashed lines), one sees that, in the absence of contaminating sound, all three spars produce comparable results from approximately 100 Hz to 1000 Hz. This suggests that A-SWIFTs with the foam shield could be used to improve the low-frequency resolution limit for A-SWIFTs, provided that they are used in conjunction with unshielded A-SWIFTs capable of observing high-frequency sound. Perhaps the kindest thing that can be said of the thin-walled bucket shield is that this approach was as inexpensive as it was ineffective.

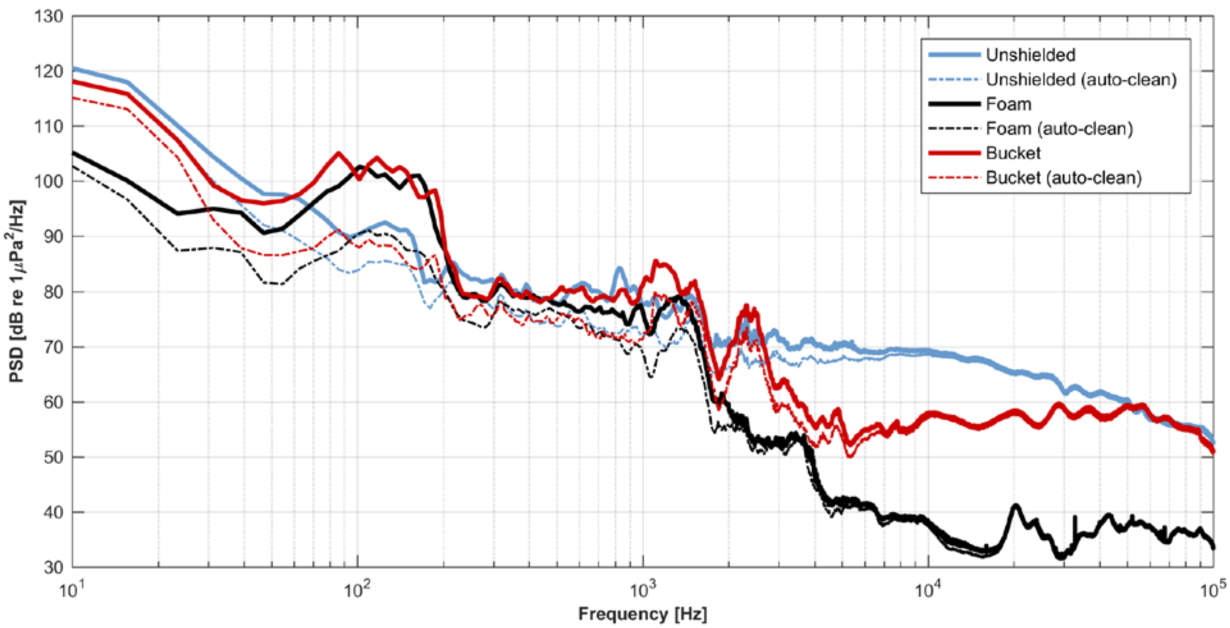


Figure 10 – Flow-shield periodograms obtained during co-temporal drifts. “Auto-clean” values refer to spectra that have been processed with an automatic flow-noise and self-noise identification algorithm.

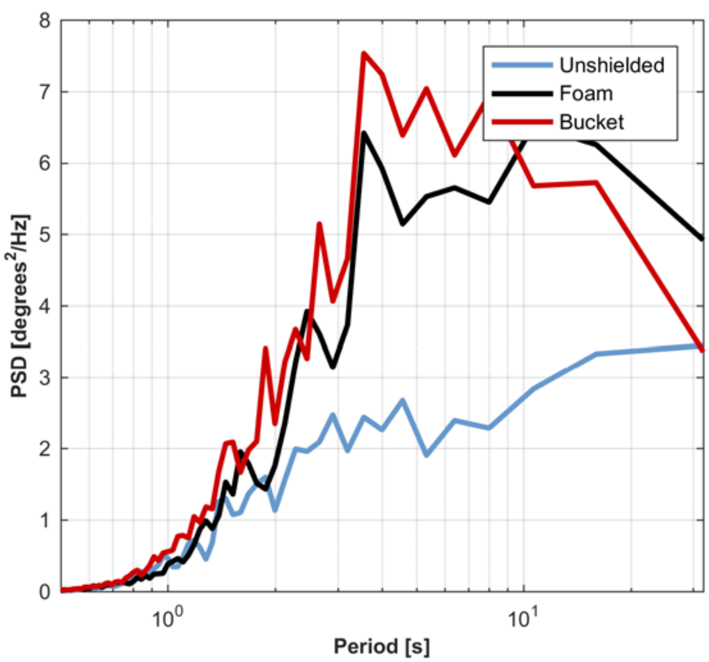


Figure 11 – Elevation angle periodogram for A-SWIFTs with flow-shields.

4 Conclusions

The Lifesaver produces sound at frequencies up to the upper limit of the observable range for the A-SWIFTs, likely as a consequence of bubble generation from breaking waves around its hull. This is significantly different than the Azura, which produces little sound above a few kHz. Below a few kHz, sound in the vicinity of the Lifesaver is dominated by chain noise, which is most likely originating from the Navy moorings. Spatial patterns in sound levels are non-intuitive and require further analysis. In addition to characterization of the Lifesaver, two types of flow-shields were trialed, neither of which performed adequately. However, the foam shield may be an effective measure to mitigate flow-noise on fixed, deeper-water moorings.

5 Acknowledgement

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SWIFT Field Survey #5
Compliantly-Coupled Hydrophone Systems
REV 2 December 14, 2016
(Deliverable No. 15)

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1 Introduction

This report describes drifting acoustic measurements using Acoustic Surface Wave Instrumentation Floats with Tracking (A-SWIFTs) at the US Navy Wave Energy Test Site (WETS) in Kaneohe, HI conducted from December 1 – 3, 2016. Surveys emphasized the testing of compliantly-coupled hydrophones, which were subsequently used to make additional surveys of the NWEI Azura and Fred. Olsen Lifesaver WECs. During these surveys, sea states were relatively moderate, ranging from 2.0 – 2.4 m significant wave height, with an energy period of approximately 8 s. On December 1, instrument deployment tests were conducted in the harbor entrance channel due to severe wave conditions and strong winds, while surveys were conducted at WETS on December 2 and 3 as metocean conditions improved.

2 Methods

2.1 SWIFT Drifters

WEC sound was measured by A-SWIFTs equipped with recording hydrophones and supporting instrumentation, as summarized in Table 1. An icListen HF hydrophone was used to make acoustic measurements. A-SWIFT position was tracked by a QStarz GPS logger, recording position and horizontal velocity at 1 Hz. An Airmar weather station mounted to each A-SWIFT monitored wind speed, wind direction, and temperature. The Airmar stations also recorded buoy position (a backup to the primary GPS logger) and buoy orientation (heading, pitch, and roll). All quantities were recorded at a rate of 1-2 Hz. Each A-SWIFT was also equipped with a Lowell Instruments MAT-1 Data Logger, a 6-axis IMU recording at 64 Hz. Finally, GoPro Hero 3 cameras were attached to the submerged portion of some of the A-SWIFTs to provide visual metadata.

Table 1 – A-SWIFT Instrumentation

Instrument	Model	Measurement
Hydrophone	OceanSonics icListen HF	Underwater sound
GPS	QStarz BT-Q1000eX	Spar position and speed (high res)
Weather Station	Airmar PB200	Wind velocity, air temperature, air pressure Spar position, orientation, and speed (low res)
Inertial Motion Unit (IMU)	Lowell Instrument MAT-1	Spar acceleration and orientation (high res)
Camera	GoPro Hero 3	Visual metadata from surface

Drifts are summarized in Table 2. During this survey, three A-SWIFTs were deployed, each with a different coupling between the hydrophone and spar, as described in Section 2.2.

A drift sequence consisted of the following steps:

- Deploy A-SWIFT drifters from survey vessel
- Motor off survey vessel until at least 100 m from A-SWIFTs
- Disengage engine and drift dead ship
- Drift until A-SWIFTs reached end of desired survey track
- Restart engines and recover A-SWIFTs

Drifts were conducted successfully, with complete data return from all instruments. Winds were sustained on December 2 and relatively calm on December 3.

Table 2 – Daily drift summary

Date	No. of Drifts	Total Drift Time	Avg. H_s (m)	Avg. T_e (s)
12/2/2016	13	2 h 31 m	2.4	7.9
12/3/2016	16	3 h 8 m	2.0	8.3

2.1.1 Hydrophone Calibration

Hydrophones were field calibrated using a GeoSpectrum M351 calibrator. Average results for pre- and post-drift calibrations were used to construct a low-frequency (< 250 Hz) receive voltage sensitivity (RVS) curve for each hydrophone, while the manufacturer-supplied calibration was used for higher frequencies. Low-frequency sensitivity was relatively consistent drift-to-drift and with previous surveys (±2 dB). Frequency-dependent calibration curves are applied to all acoustic data presented in this report.

Figure 1 – Compliantly-coupled hydrophone configurations. Drogue and "holster" visible on right. Heave plate visible on left.

2.1.2 Data Processing

Acoustic data sampled continuously at 512 kHz[1] was buffered into samples consisting of 2^{16} points with 50% overlap between samples to improve time resolution of lower frequency events. Each window was linearly detrended, a hamming filter applied, and processed with a fast fourier transform (FFT). Resulting spectra have a frequency bandwidth of 8 Hz and are further merged, either in frequency or time, to produce spectra with acceptable confidence intervals.

2.1.3 Data Quality Assurance

Acoustic data were visually reviewed by stepping through 30 s spectrograms and "quarantining" periods contaminated by obvious vessel traffic. The processing algorithms developed to automatically quarantine flow-noise and self-noise in measurements around the NWEI Azura were applied to rigid spar observations around that WEC, but were not used at other locations.

2.2 Compliantly-Coupled Hydrophone Testing

In an attempt to reduce the prevalence of flow-noise and self-noise in measurements, several

[1] This sampling rate was higher than the standard 256 kHz sampling rate due to observations of higher-frequency sound around the Fred. Olsen Lifesaver in August 2016 that was produced by bubble collapse that was likely associated with breaking waves on and around the hull.

compliantly-coupled hydrophone arrangements were tested. These are, effectively, mass-spring-damper systems. Two types of damping elements were tested: a rigid heave plate roughly 0.6 m in diameter (custom build) and a fabric drogue with a characteristic diameter of 0.8 m (Pacific Gyre Microstar). The damping elements were coupled to a shortened surface float and hydrophone by a 5/16" diameter rubber cord. The hydrophone was deployed in a "holster" along with an IMU, pressure logger, and camera. Three configurations were tested for both damping elements:

- Surface spar – 2 m rubber cord – damping element – 2.5 m rubber cord – hydrophone (Figure 1)
- Surface spar – 2 m rubber cord – damping element – hydrophone
- Surface spar – 2 m rubber cord – 2.5 m rubber cord – damping element – hydrophone

The coupling between elements was made by shackles. Self-noise that could be caused by the contact between metal components (e.g., rattling of shackles and eyebolts) was almost entirely mitigated by heavy urethane cladding on eyebolts and on eyes spliced into the rubber cord.

2.3 Observations with Compliantly-Coupled Hydrophones

The compliantly-coupled hydrophones were deployed to re-characterize the NWEI Azura and Fred. Olsen Lifesaver. These were not intended to provide spatially-resolved drifts, only to obtain a higher-quality temporal snapshot. Future surveys will again emphasize spatially-resolved drifts with compliantly-coupled hydrophones. Based on prior experience, the Azura was characterized at a range of 10-20 m, while the Lifesaver characterized at a range of 50 – 100 m. In addition, a survey was conducted at the 80 m site to identify the origin of the omnipresent chain noise at WETS.

2.4 Sound Velocity

The sound velocity profile was measured at the 30 m berth (Azura), 60 m berth (Lifesaver), and 80 m berth on December 3 with a Valeport mini-SVP (acoustic time of flight measurement). As shown in Figure 2, sound velocity was relatively consistent throughout the site during these measurements, varying by < 1 m/s.

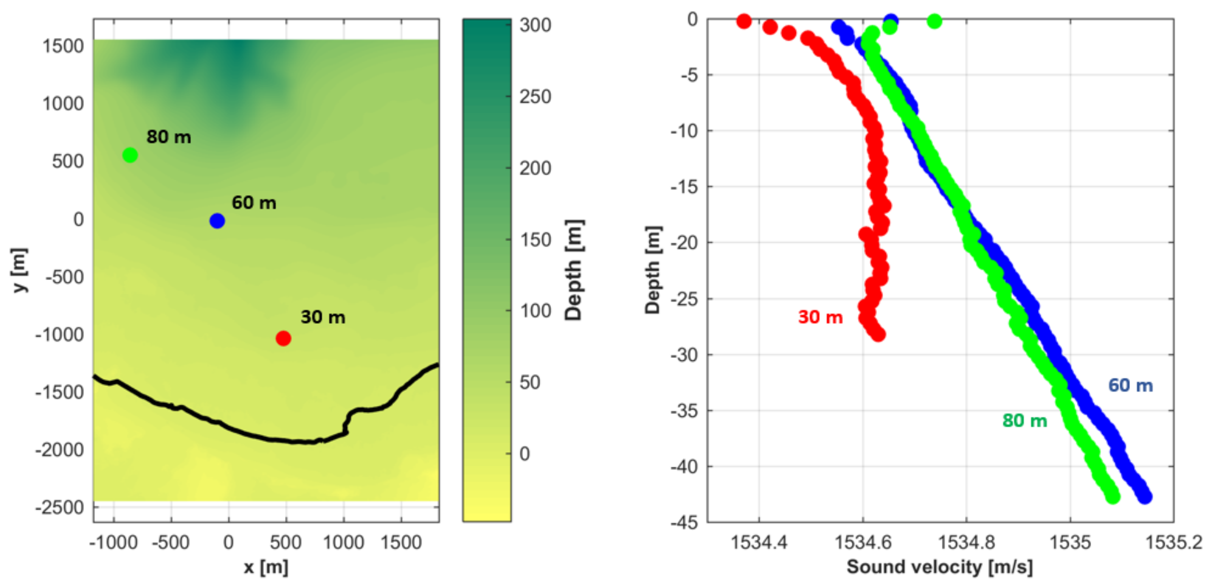


Figure 2 – Sound velocity profiles (distances relative to the Lifesaver WEC).

3 Results

3.1 Compliantly-Coupled Hydrophone Testing

Figure 3 shows periodograms from drifts conducted with the solid spar. These spectrograms are not annotated to indicate the source of particular sounds, but are associated with the 80 m berth and dominated by mooring chain noise (Section 3.2.3). The spectra suggests that at frequencies below 1 kHz, which were the focus of this survey, acoustic conditions were statistically stationary. At higher frequencies, the variation in sound intensity is likely associated with diel patterns of snapping shrimp noise. Figure 4 and Figure 5 show periodograms of spectra for the various drogue and heave plate configurations, respectively. In general, configurations with the damping element "sandwiched" between lengths of rubber cord appears most effective at reducing flow-noise and self-noise, as indicated by the elevated spectral intensity for alternative configurations. Figure 6 shows a comparison between the best performing drogue and heave plate cases and the standard solid spar. In general, either compliant coupling significantly reduces the noise floor for the drifting system and produces comparable results (to within a 1 dB) at frequencies down to 100 Hz. At lower frequencies the drogue-coupled hydrophone produces more self-noise than the heave plate-coupled hydrophone, but below 30 Hz the heave plate-coupled hydrophone appears to be more affected by flow-noise. For this reason, the heave-plate coupling will likely be used in future surveys. These acoustic results are confirmed by camera metadata, which show significantly more hydrophone motion in cases with elevated self-noise and/or flow-noise spectra.

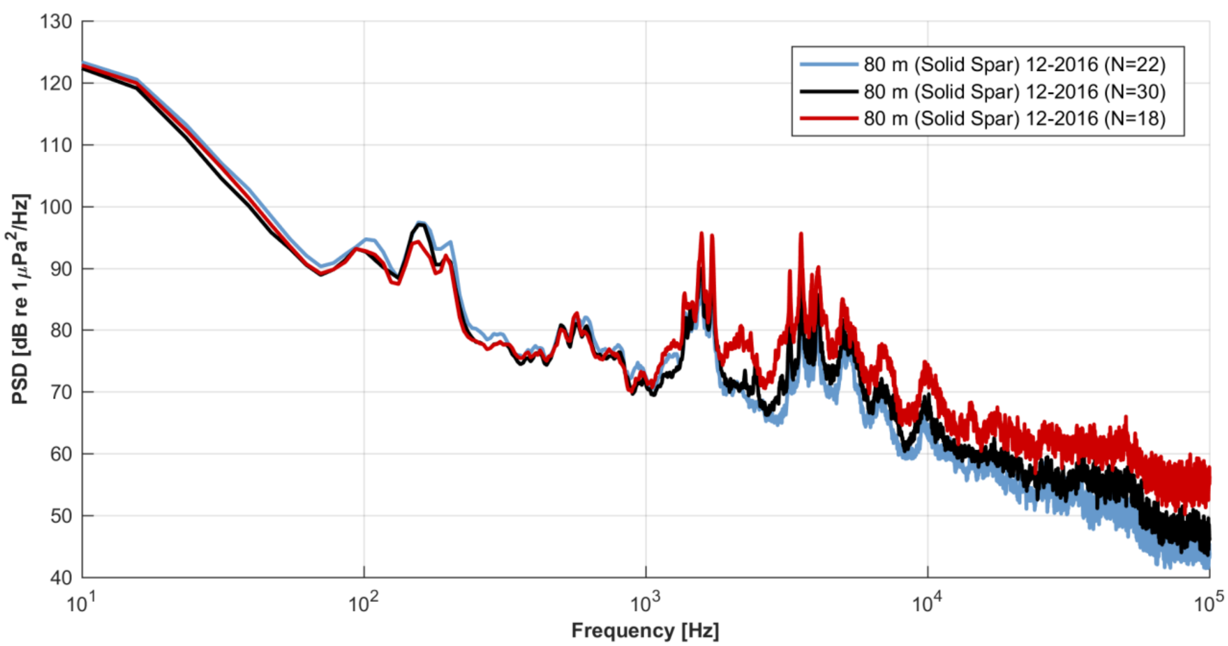


Figure 3 – Periodogram of A-SWIFT drifts with the solid spar configuration.

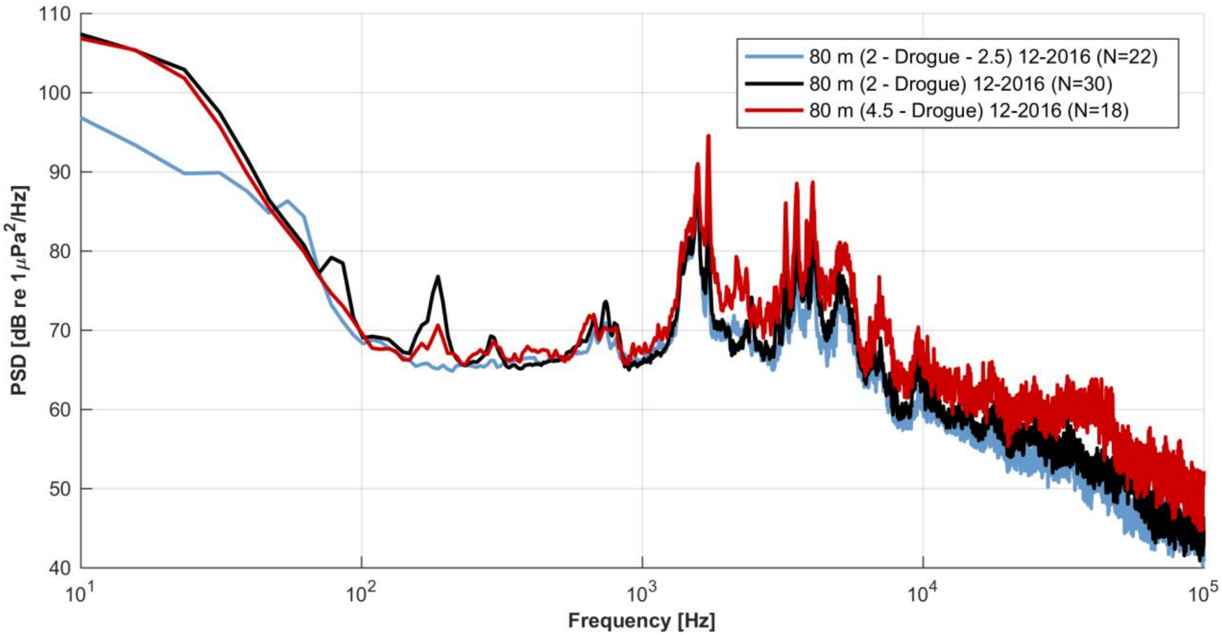


Figure 4 – Periodogram of A-SWIFT drifts with a drogue as a damping element.

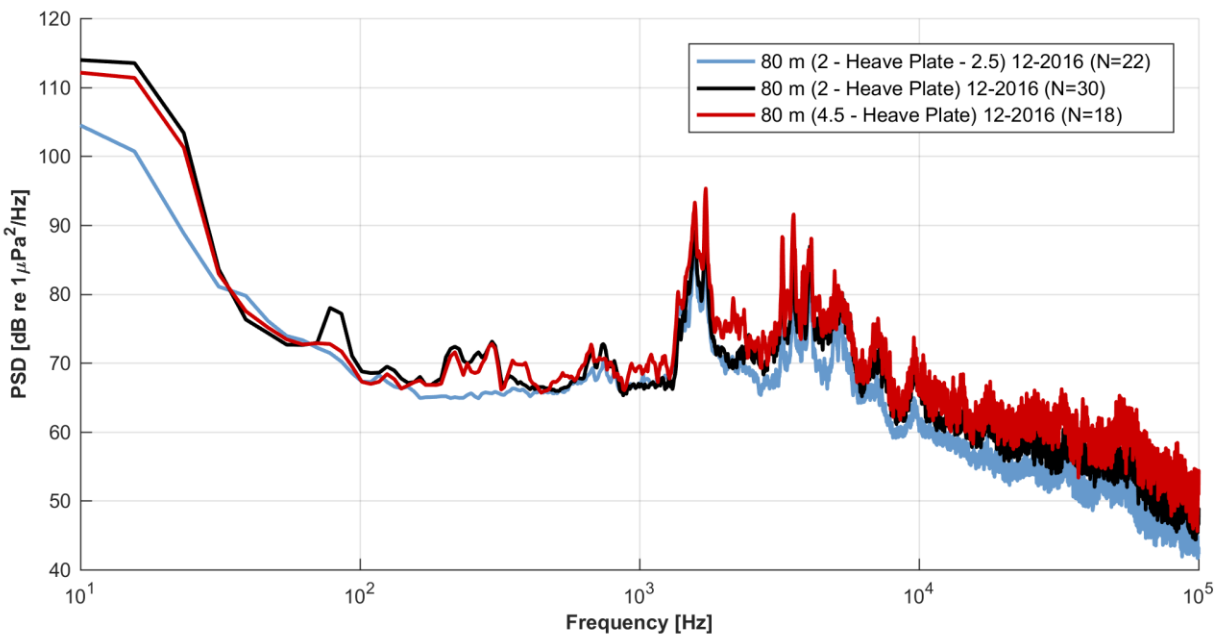


Figure 5 – Periodogram of A-SWIFT drifts with a heave plate as a damping element.

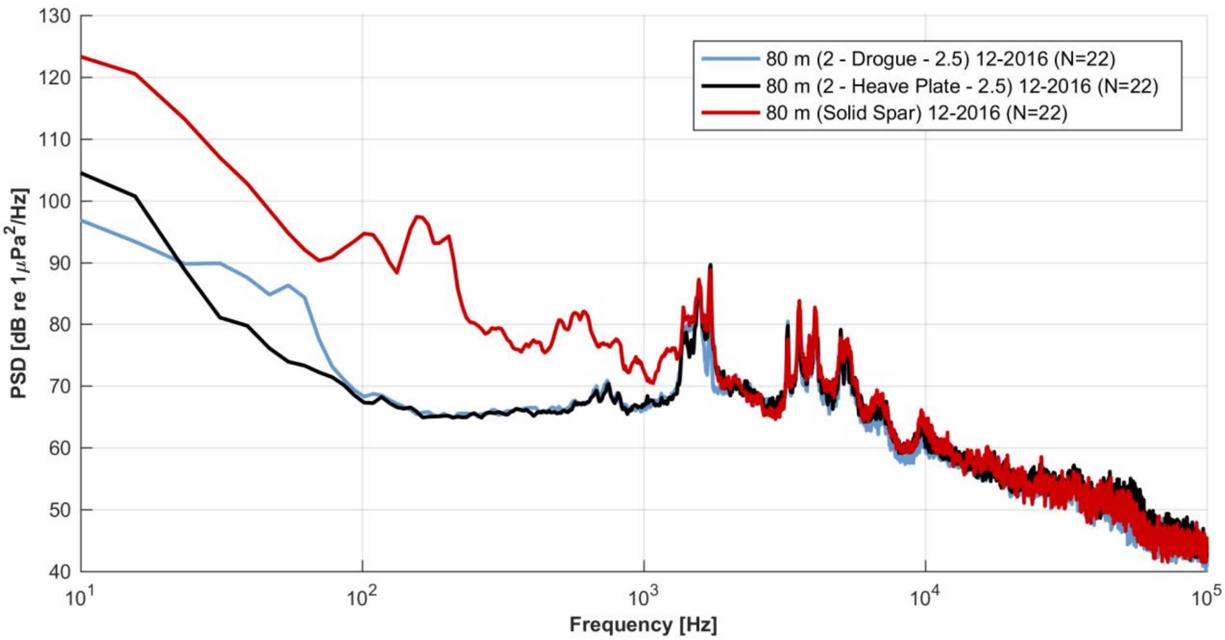


Figure 6 – Periodogram of A-SWIFT drifts comparing between best-performing cases.

3.2 Observations with Compliantly-Coupled Hydrophones

3.2.1 NWEI Azura

Figure 7 shows a periodogram from drifts around the NWEI Azura. Each line shows the median spectral density for drifts within a specified range of the WEC, with the shaded area denoting the 25th and 75th percentiles. The reference measurement is obtained approximately 600 m to the east. The type of A-SWIFT (drogue, solid spar, or heave plate) is included in the figure legend. The number of 30-s averages underlying each spectrum is also indicated by the legend. Comparison of measurements around the Azura to the reference spectrum suggests the following:

- With automatic identification and exclusion of flow-noise and self-noise, the solid spar A-SWIFT can resolve Auzra sound down to ~250 Hz, below which self-noise and flow-noise mask most sound produced by the WEC. This suggests that prior survey data has value in characterizing the Azura sound at frequencies above this threshold.
- The drogue-coupled hydrophone measurements continue to support the assertion that the Azura does not produce significant sound, relative to ambient levels, at f > 3 kHz.
- Between the March and December 2016 surveys, the sound produced by Azura was relatively consistent, even though the measurements were obtained from seas with somewhat different energy periods (see the Lifesaver discussion for a contrasting case).
- Though deeper in the water column than the solid spar, the drogue-coupled hydrophone measures more intense sound at equivalent frequencies. This cannot be explained simply by a variation in slant distance between hydrophones at different depth and may suggest that near-surface observations by the solid spars are being affected by proximity to the pressure release surface. This could be explored further through analytics, acoustic propagation modeling, and future field surveys.

- The Azura likely produces observable sound at frequencies at least as low as 30 Hz. While drogue self-noise is significant at frequencies less than 80 Hz, drogue self-noise is about 90 dB (Figure 6), whereas sound measured at these frequencies is about 100 dB.

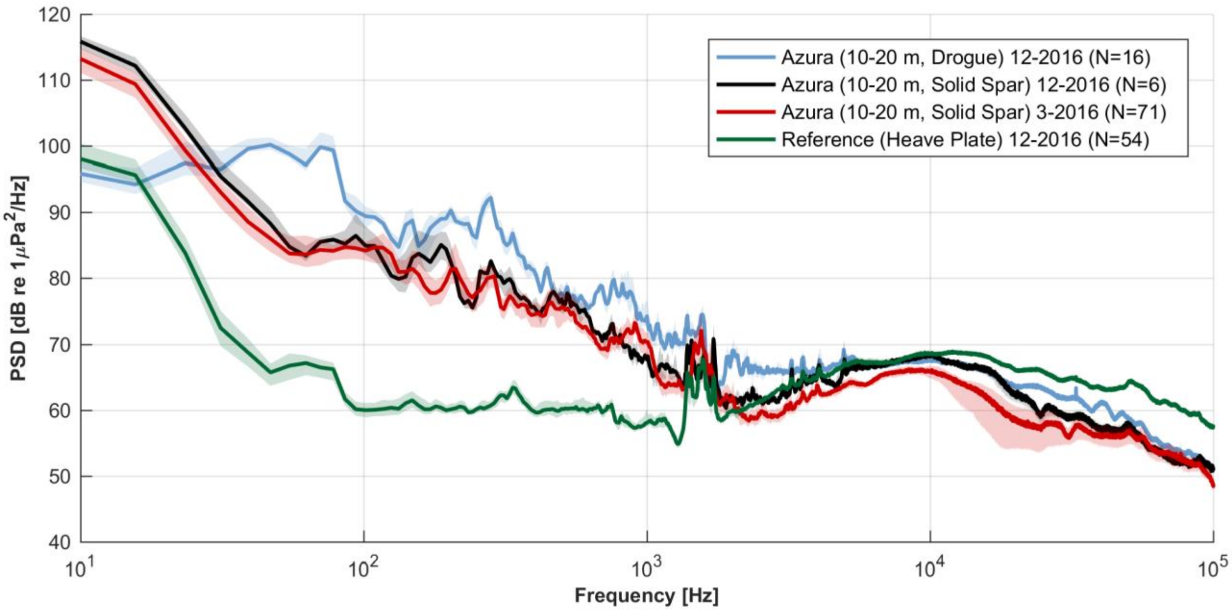


Figure 7 – Periodogram of measurements around the Azura in August and December 2016.

3.2.2 Fred. Olsen Lifesaver

Figure 8 shows a periodogram from drifts around the Fred. Olsen Lifesaver. The layout of this figure is identical to the discussion accompanying NWEI Azura. Comparison to the reference spectrum, obtained approximately 1000 m to the east, suggests the following:

- The high-frequency sound (e.g., f > 20 kHz) observed in the Lifesaver data during the August 2016 surveys (red line) is absent. The distinguishing feature between the two surveys is the wave period, which was 6.1 s in August, but 8.4 s in December. This reduces wave steepness, and consequently the likelihood of waves breaking around the Lifesaver hull which had produced sustained bubble clouds. This suggests that high-frequency sound production by the Lifesaver will be intermittent and will be characterized through stationary surveys.
- As for the Azura, the rigid spar A-SWIFT is able to characterize, with reasonable accuracy, Lifesaver sound down to ~250 Hz, below which self-noise and flow-noise mask most sound produced by the WEC.

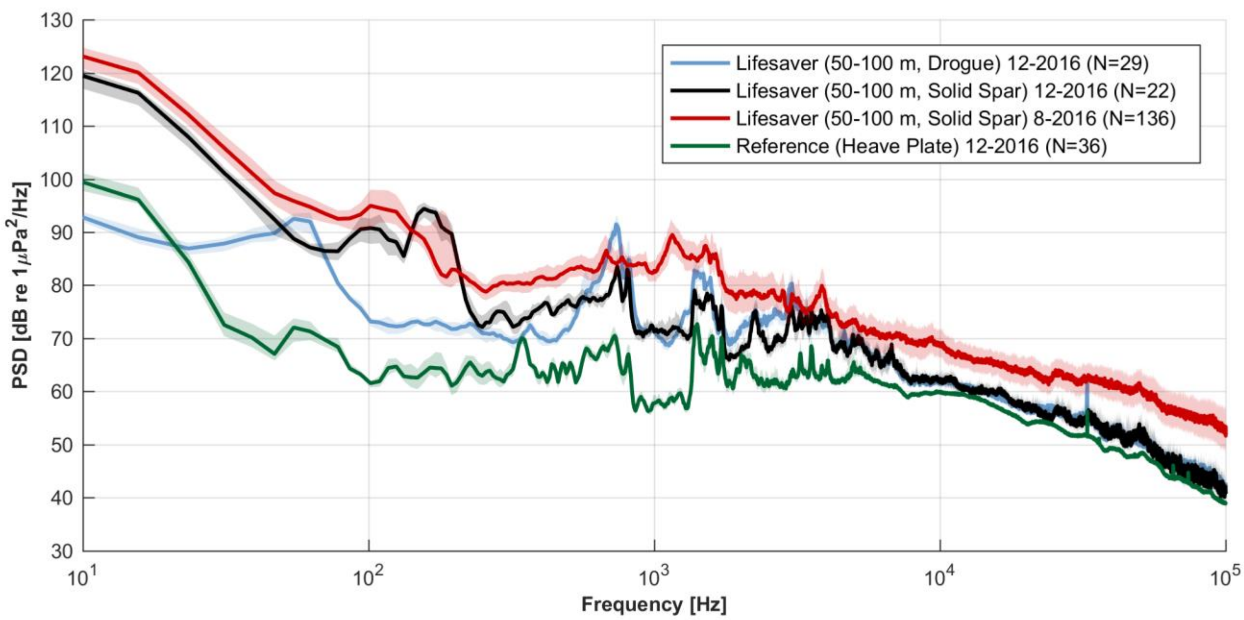


Figure 8 – Periodogram of measurements around the Lifesaver in August and December 2016.

Figure 9 shows an annotated periodogram of compliantly-coupled hydrophone measurements from December 2016. Several features are notable in describing the Lifesaver sound:

- Sound around the Lifesaver is only elevated above reference levels at *f* < 10 kHz, which is more in keeping with expected mechanical sound sources.
- The Lifesaver may produce observable sound at frequencies at least as low as 50 Hz. While drogue self-noise is significant at these frequencies, the shape of the spectrum is unlike that of the intercomparison between the heave plate and drogue-coupled hydrophones (e.g., here, the spectrum peaks around 60 Hz, then declines). An alternative explanatory hypothesis is that the Lifesaver does not produce significant sound at this sea state, but that the drogue-coupled self-noise is dependent on the sea state. Further analysis and field experimentation are likely required.
- The acoustic environment around the Lifesaver is presently dominated by the sound from a rubbing belt on PTO #2 (personal communication, Fred. Olsen). This is not a normal feature of operation and, at present appears to mask the majority of the mooring noise audible during the August 2016 survey (as discussed in the next section, this mooring noise appears to originate from the 80 m berth).

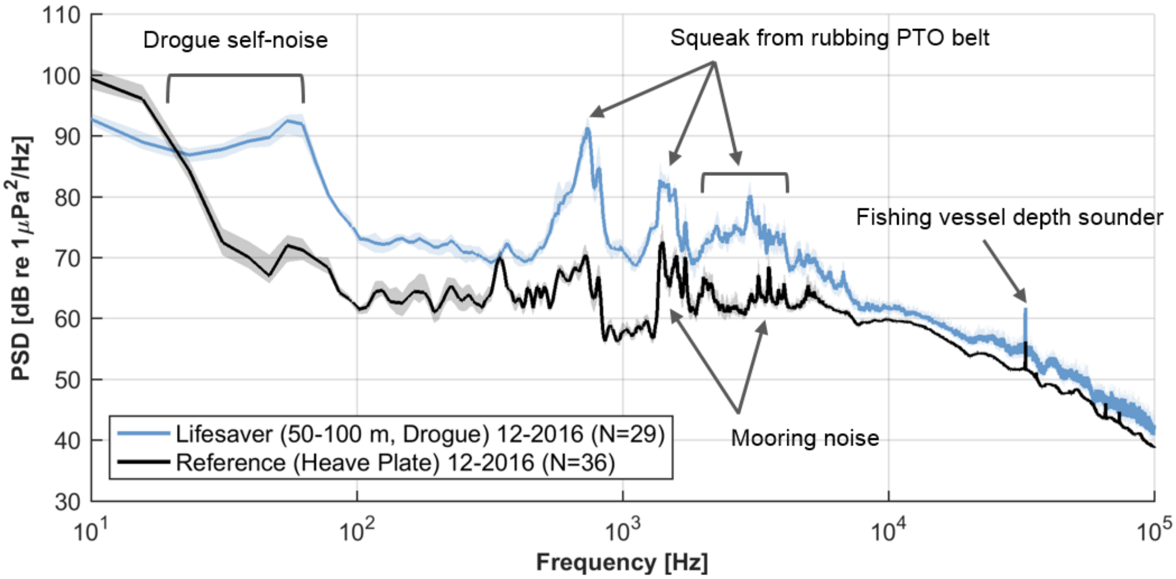


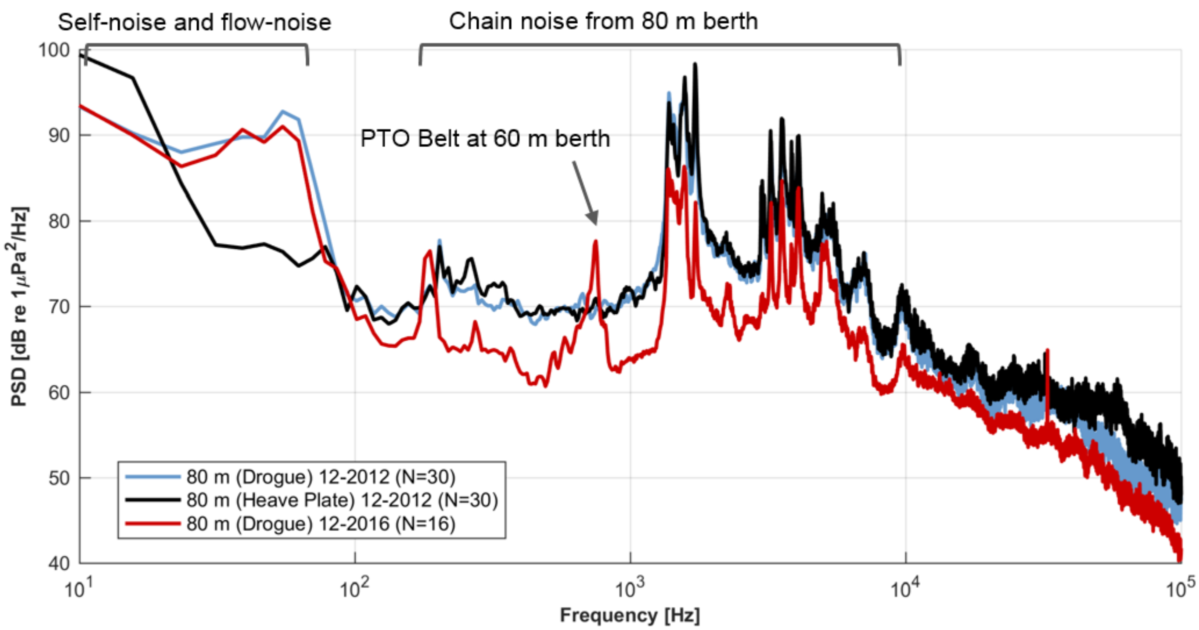
Figure 9 – Annotated periodogram of measurements around the Lifesaver in December 2016 with compliantly coupled hydrophones.

3.2.3 Mooring Noise

As noted since surveys began in 2015, chain noise is omnipresent throughout WETS, but theories about its origination have been difficult to prove out. Figure 10 shows a periodogram from drifts around the 80 m berth, which is currently unoccupied by a WEC. A pair of drifts with the drogue and heave plate-coupled hydrophones were conducted close to the surface floats, while a single drogue-coupled hydrophone was deployed further away a short time later. An examination of the spatial trends in the spectra suggests the following:

- The sound hypothesized to be associated with the PTO belt on the Lifesaver intensifies as one moves closer to that WEC. This suggests that, at a minimum, that sound originates from the 60 m berth.
- The sound hypothesized to be associated with chain noise at the 80 m berth decreases as one moves away from that site.

On this basis, the chain noise appears to be relatively broadband in nature, spanning nearly two decades from 100 Hz to 10 kHz. It is hypothesized that this sound is produced by the pile of chain on the seabed beneath untensioned surface floats. As the floats heave with the waves, the chain is picked up and set down on itself, producing sound. If this hypothesis is correct, prior to the Lifesaver installation, relatively high intensity chain noise would have been being produced at both the 60 m and 80 m sites.



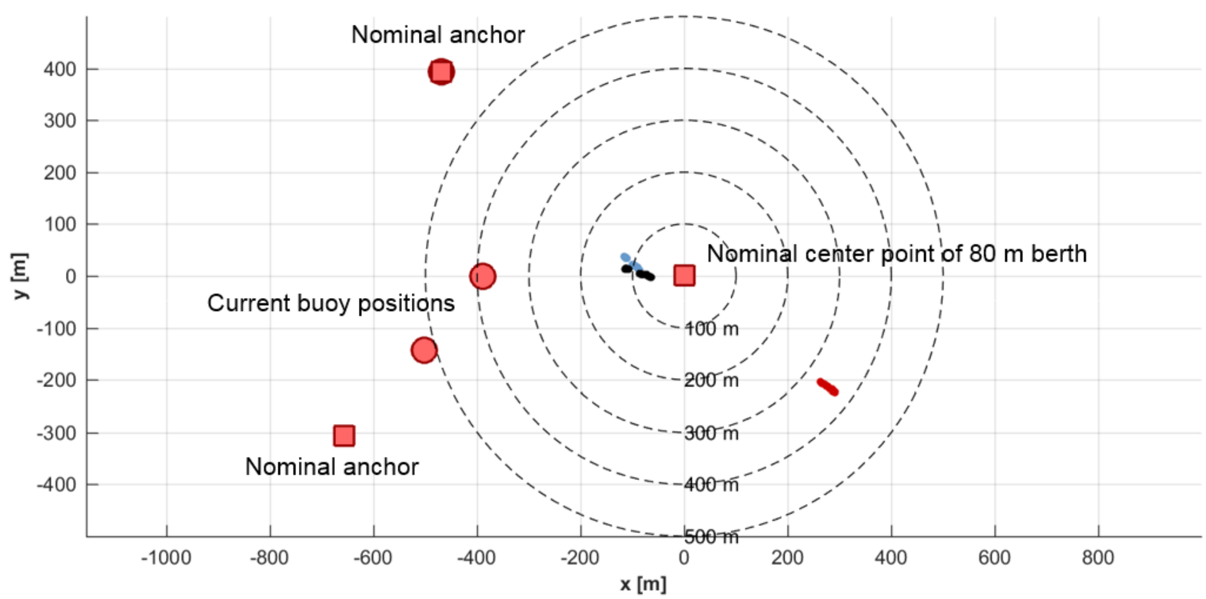


Figure 10 – (top) Annotated periodogram of measurements around the 80 m berth in December 2016 with compliantly coupled hydrophones. (bottom) Location of drifts (same color map).

4 Conclusions

Overall, the compliantly-coupled hydrophone experiment proved extremely effective at reducing self-noise and flow-noise, allowing observations of WEC sound at frequencies down to approximately 20 Hz. This provided new insight into the sound produced by both the Azura and Lifesaver WECs. For this reason, future surveys are likely to emphasize compliantly-coupled measurements, likely with the heave plate, given its superior noise floor at frequencies around 50 Hz. This does, however, need to be considered against the drogue's superior ultimate noise floor and ability to collapse on deck when not in use. The use of compliantly-coupled hydrophones will need to be balanced against limitations on A-SWIFT proximity to mooring lines and WECs during metocean conditions that could result in entanglement or collision.

5 Acknowledgement

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SWIFT Field Survey #7
Surveys around Fred. Olsen Lifesaver
REV 1 January 12, 2018
(Deliverable No. 17)

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1 Introduction and Overview

Drifting acoustic surveys were conducted at the US Navy's Wave Energy Test Site (WETS) in Kaneohe, HI on November 28 and 29th, 2018. These surveys made use of prototypes of second-generation Drifting Acoustic Instrumentation SYstems (DAISYs). These are referred to as "V2" DAISYs (i.e., "version 2") and are equipped with suites of integrated instrumentation on the surface expression. The lower hulls are "V1.5" DAISY hardware, with an autonomous sensors. Survey effort focused on the redeployed Fred. Olsen Lifesaver wave energy converter.

2 General Survey Methodology and Setting

Each DAISY consisted of a surface expression, 7 m rubber cord (10 mm diameter), 0.6 m diameter heave plate, 2.5 m rubber cord, and lower hull. The surface expressions were instrumented with a meteorological station (Airmar WX200), Garmin DC 50 tracking collars, and an integrated package with board-level GPS, 9-axis IMU, wireless and RF communication links, and condition health monitoring. The lower hull utilized independent sensors, with acoustic measurements were made by Ocean Sonics icListen HF hydrophones configured to sample at 512 kHz and supplemental metadata collected by pressure loggers (HOBO) and inertial measurement units (Lowell Instruments MAT-1).

The primary objective was to characterize the acoustic emissions from the redeployed Fred. Olsen Lifesaver wave energy converter (WEC), which was deployed at the 30 m berth. The spatial extent of the survey utilized a "zone" method, which is proposed for the IEC TC 114 technical specification on acoustic characterization of marine energy converters. In addition, reference drifts were undertaken at a location previously found to have similar acoustic characteristics to the 30 m berth to facilitate identification of frequencies with appreciable WEC sound and inter-comparison of individual DAISYs. One inter-comparison survey was also conducted at the 60 m berth. Survey locations are shown in Figure 1.

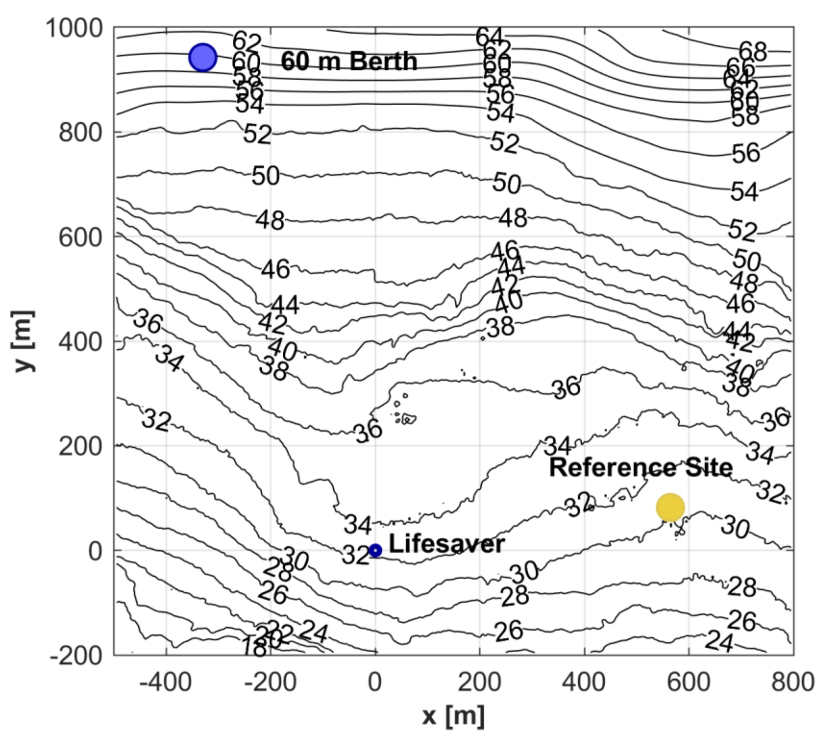

Figure 1: Survey locations

CTD surveys to evaluate the sound speed profile were conducted on November 28 and 29 using a Rushkin RBR XR provided by Sea Engineering. Survey locations and observed profiles are summarized in Figure 2. Sound velocity profiles were consistent between the days for the top 20 m of the water column, but, due to calming seas and attendant reduction in mixing on the 29th, a substantial gradient appeared between 20 and 30 m depth.

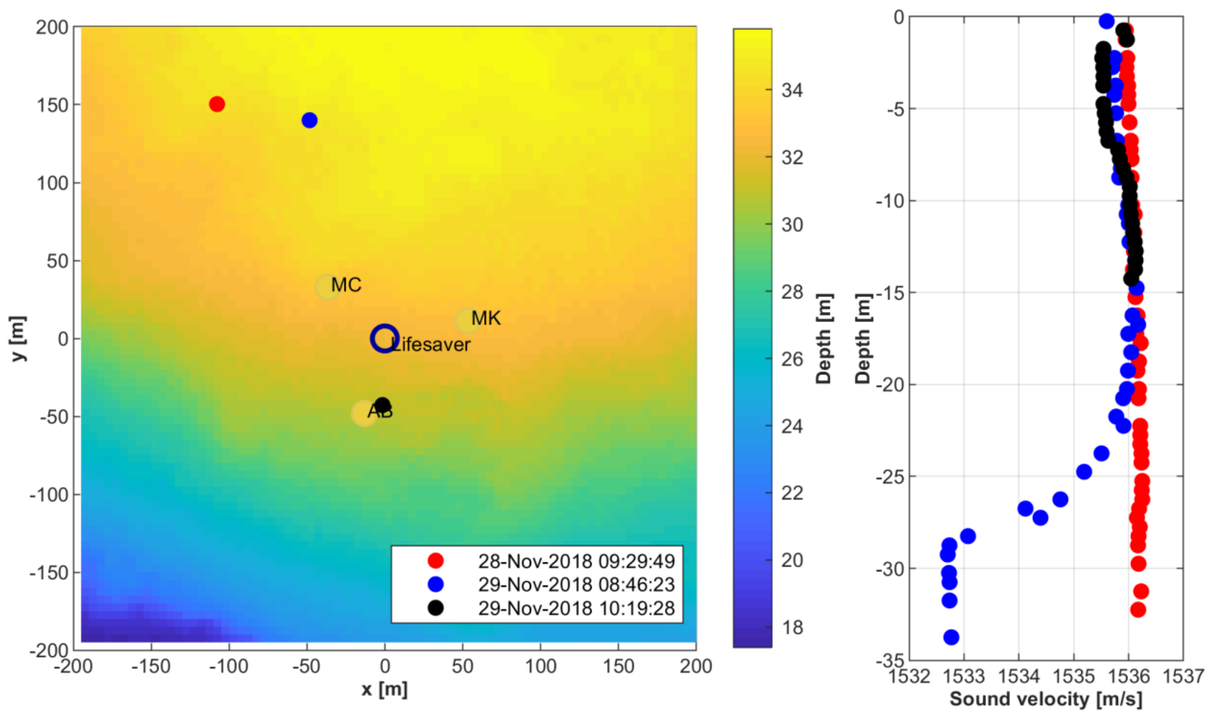

Figure 2: Sound velocity profiles

3 DAISY Inter-comparison

Prior to deployments to characterize acoustic estimations from the Fred. Olsen Lifesaver, the pair of DAISYs were deployed in close proximity at the nominal reference location 600 m to the east of the 30 m berth. These DAISYs were also deployed in close proximity at the 60 m berth. Periodograms for these drifts are shown in Figure 3 - Figure 5. Associated metadata is given in Table 1. The two DAISYs have a broadband offset of 2-3 dB at frequencies > 100 Hz, which departs from previous characterizations that showed close agreement to frequencies as high as 80 kHz. There are three potential explanations for the observed variation:

- *The sensitivity of one of the hydrophones has changed*. This is not supported by the agreement in the primary mooring noise peak observed in the drift at the 60 m berth (Figure 5).
- *The DAISY 02 assembly is producing broadband self-noise*. It does not seem plausible that this could occur over a broad range of frequencies in proportion to ambient noise.
- *Differences in hydrophone orientation*. This explanation appears to be the most plausible. The z-acceleration on the IMU on each "holster" suggests that for all drifts, DAISY 01 was at an angle of ~15° off vertical. Because each holster incorporates a PVC guard ring to protect the hydrophone while on deck, this would result in different reflections or shadowing for each DAISY. However, it is unclear why this would affect frequencies that have a wavelength much

greater than the size of the guard. Further, it is unclear why the holster drifted at an angle, as this has not been previously observed with V1.5 hardware, particularly given that the surface expressions were moving at similar speeds over ground.

Regardless of the source, this discrepancy means that when comparing data from the drifts around the Lifesaver, DAISY 01 measurements should be implicitly elevated by 2-3 dB relative to DAISY 02.

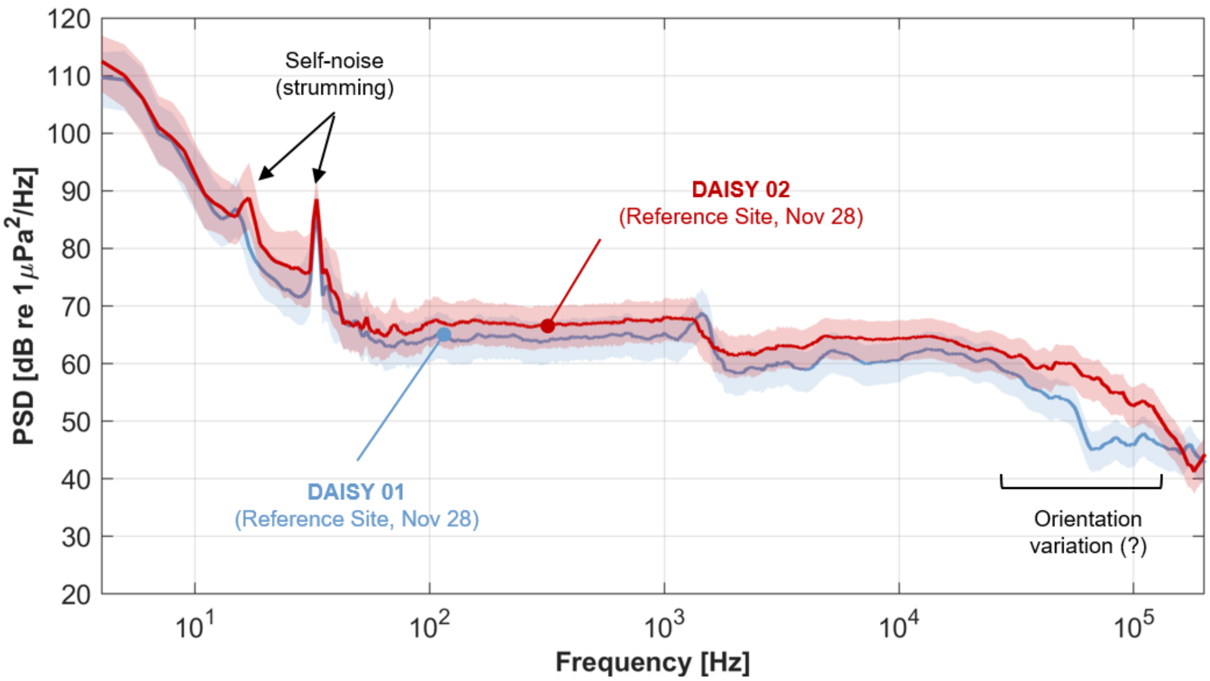

Figure 3: Comparison between received levels at reference site on November 28

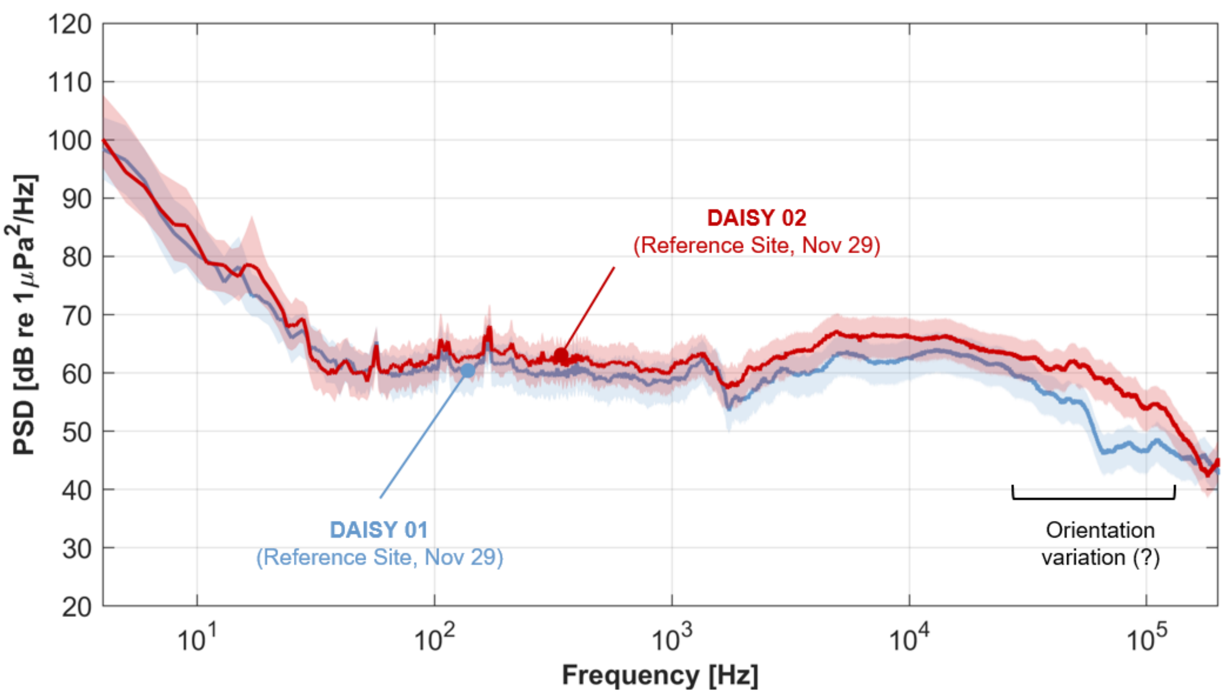

Figure 4: Comparison between received levels at reference site on November 29

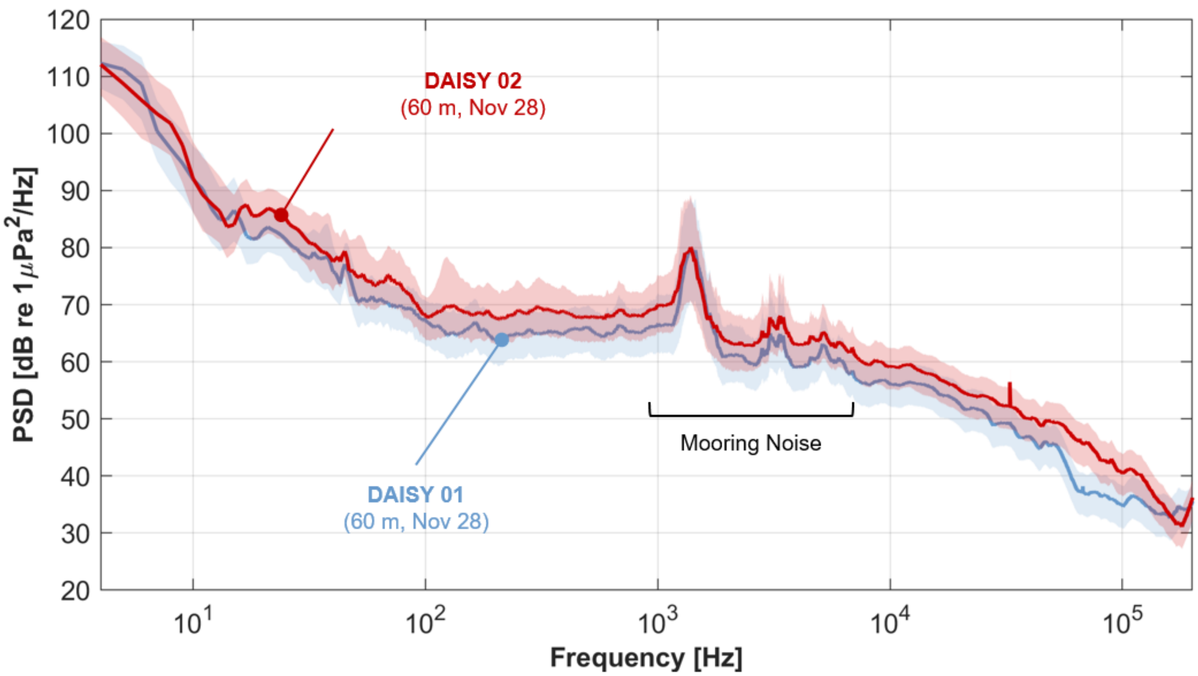

Figure 5: Comparison between received levels at 60 m berth on November 28

Table 1: Metadata for DAISY inter-comparison drifts

Drift	DAISY	Location	SOG [m/s]	Wind Speed [m/s]	Depth [m]	a_z [m/s²]	H_s [m]	T_e [s]	Steepness
342	01	Reference	-	5.7 ± 1.3	13 ± 0.12	-9.6 ± 0.16	2.0	7.5	0.023
343	02	Reference	0.37 ± 0.3	5 ± 1.5	13 ± 0.12	-9.9 ± 0.18			
356	01	Reference	0.2 ± 0.2	0.93 ± 0.25	13 ± 0.09	-9.6 ± 0.11	1.4	7.4	0.017
357	02	Reference	0.25 ± 0.2	0.73 ± 0.33	13 ± 0.1	-9.9 ± 0.14			
354	01	60 m	0.32 ± 0.4	6.2 ± 0.97	13 ± 0.1	-9.5 ± 0.17	1.9	7.4	0.022
355	02	60 m	0.34 ± 0.3	3.8 ± 0	12 ± 0.11	-9.8 ± 0.2			

4 Fred. Olsen Lifesaver Surveys

4.1 Observations

Surveys around the Fred. Olsen Lifesaver were conducted on November 28 and 29th, 2018. These measurements utilized a “zone” method, as designated in Figure 6. Zones 1-4 correspond to 100 m stand-offs (±12.5 m in any direction) from the Lifesaver in the along-wave and across-wave orientations and are consistent with measurement zone specifications for Level A and B characterization under IEC TC 114 62600-40 Draft Technical Specification. Zones 1A-4A correspond to 25 m stands-off (±12.5 m in any direction).

Zone 1 corresponds to the Sea Spider deployment target for the 30 m berth and so was the primary focus of surveys. The “A” zones are closer to the source and more likely to resolve sounds produced by the Lifesaver, but present a significant entanglement risk due to the hawsers running from the Lifesaver to the MC, MK, and AB sub-surface moorings. Given the prevailing DAISY drift direction, inner zone surveys were restricted to 2A.

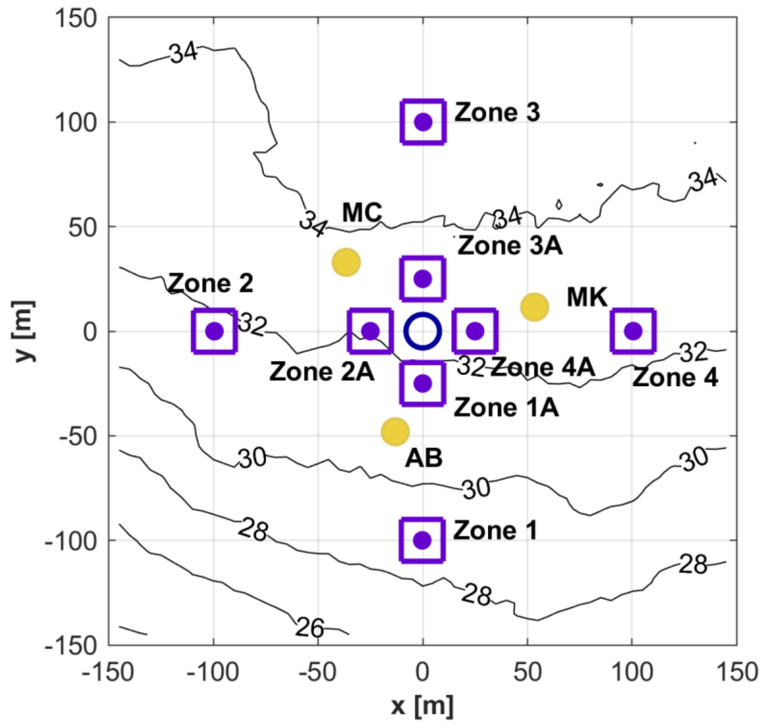

Figure 6: Survey zones around the Fred. Olsen Lifesaver

Figure 7 shows a comparison between measurements obtained at 25 m and 100 m stand-offs from the Lifesaver, as compared to measurements at the reference site. Drift metadata are summarized in Table 2 and suggest the same likely "tilt" artifact for DAISY 01 as observed in the inter-comparison drifts. Meaningful range dependence (i.e., sound that could be attributable to the WEC) is observed for frequencies from 30 Hz to 1 kHz. Variations at higher frequencies are likely reflective of time-variation in snapping shrimp behavior and variations at lower frequencies are likely reflective of variation in wave breaking and other low-frequency ambient noise.

With this knowledge, the frequencies of sound produced by the Lifesaver are apparent at a range of 100 m, but the signal-to-noise ratio is approaching the same order as inter-instrument variability. This mirrors the experience with a similar methodology around the NWEI Azura, in which identification of WEC sound at 100 m was facilitated by measurements at closer range.

The sound produced by the Lifesaver has a local tonal maxima around 100 Hz, consistent with observations made by another research group while the Lifesaver underwent field trials at FabTest in the UK. This is substantially reduced relative to sound observed during the prior deployment at the 60 m berth when a failing bearing dominated the soundscape over a wider range of frequencies.

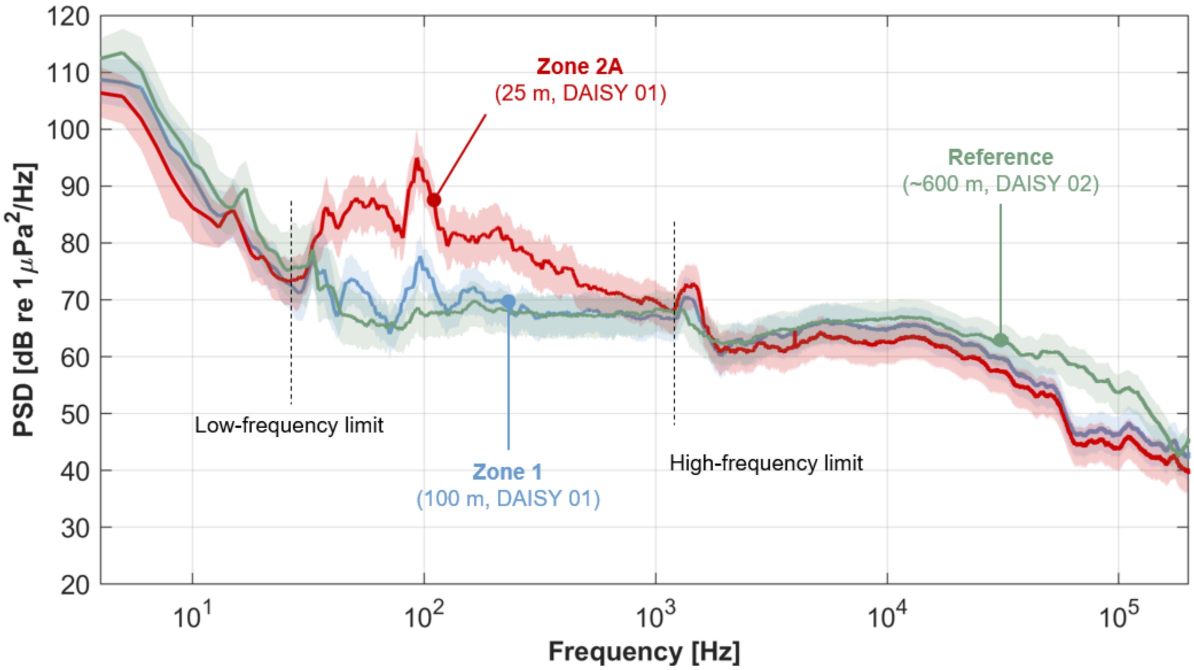

Figure 7: Comparison between received levels at 25 m and 100 m range from Lifesaver and reference site on November 28

Table 2: Metadata for November 28

Drift	DAISY	Location	SOG [m/s]	Wind Speed [m/s]	Depth [m]	a_z [m/s²]	H_s [m]	T_e [s]	Steepness
346	01	Zone 1	0.2 ± 0.05	6.7 ± 1.2	13 ± 0.09	-9.5 ± 0.1			
352	01	Zone 2A	0.25 ± 0.2	5.9 ± 0.91	13 ± 0.09	-9.6 ± 0.1	1.9	7.4	0.023
347	02	Reference	0.27 ± 0.2	6.6 ± 2.5	13 ± 0.12	-9.9 ± 0.2			

As shown in Figure 8, surveys on November 28 during a slightly weaker sea state show similar trends. Each solid line denotes a single drift that passed through Zone 1 during a 1 hour period. During that time, the five drifts accumulated sufficient time inside the zone (> 10 minutes) to satisfy the requirements of a Level B IEC survey. As indicated by the similarities between individual drifts, received levels were consistent within the zone and across drifts. Though the sea state was slightly less energetic than on November 28 (1.5 m significant wave height vs 1.9 m significant wave height, similar energy period), the received levels in Zone 1 are slightly higher (by a few dB). The reasons for this are uncertain.

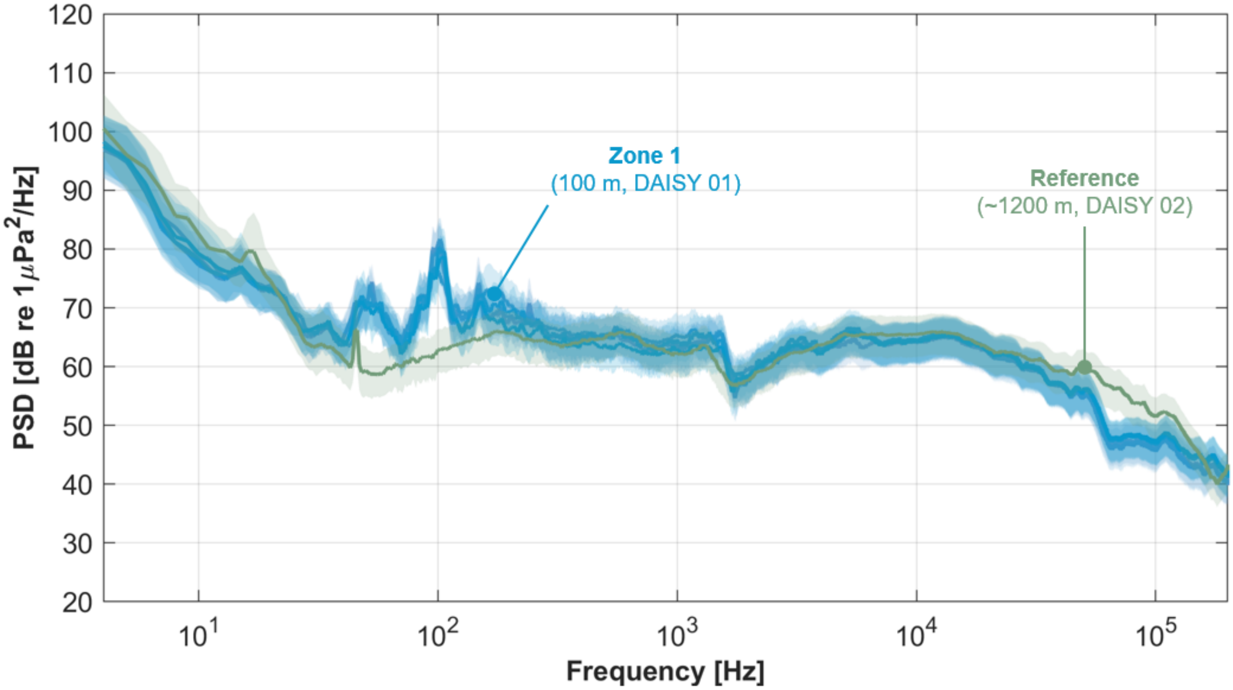

Figure 8: Comparison between received levels at 100 m range from Lifesaver and reference site on November 29

4.2 Source Level Occurrence

Table 3 summarizes occurrence levels for a roughly estimated broadband (4 Hz – 200 kHz) source level, as stipulated by WETS regulatory reporting requirements. The propagation model is the basic sonar equation

$$SL(f) = RL(f) + N \log D$$

where *SL(f)* is the source level as a function of frequency, *RL(f)* is the received level, *N* is a propagation loss coefficient, and *D* is the slant distance between the source (i.e., Lifesaver) and receiver (i.e., DAISY). Here, we assume that all sound originates from just below the surface at the Lifesaver's reported location. A "practical" propagation loss coefficient of 15 is used, reflecting that spreading is likely to be somewhere between cylindrical and spherical. Source level estimation is applied only to drift data within Zone 2A to minimize errors associated with the coarse model for propagation loss.

As discussed, the Lifesaver likely produces sound at frequencies between 30 Hz and 1 kHz. Consequently, the propagation model is applied only to those frequencies to avoid unrealistically inflating source levels at frequencies outside of this range. Broadband source levels are, therefore, integrated over specific frequency bands, using the following data sources:

- 4-30 Hz: received levels at DAISY position
- 30 Hz – 1 kHz: estimated source levels given DAISY slant distance to source
- 1 kHz – 200 kHz: received levels at DAISY position

This model for the Lifesaver source level suggests that broadband source levels exceeded 120 dB continuously during these measurements, but never exceeded the regulatory thresholds at 154 dB or 180 dB.

Table 3: Regulatory reporting for Lifesaver surveys

Limit (at source dB)	Occurrence (%)	Instrument	SPL (at instrument)	WEC	Propagation Model
<120	0%	DAISY	~25 m horizontal distance ~13 m depth ~ 2 minutes at 512 kHz	Lifesaver	15log spreading for frequencies of sound produced by WEC
120	100%	DAISY			
154	0%	DAISY			
180	0%	DAISY			

5 Conclusions

These surveys indicate that during normal operation the Fred. Olsen Lifesaver is quiet and will be difficult to detect at a range of 100 m on the Sea Spider platform. Acoustic emissions appear to vary slightly with sea state. Surveys also highlighted a variation in received levels between V1.5 DAISYs. While the source of this variation is unknown, the pending transition to V2 DAISY hardware should address this concern.

6 Acknowledgements

Many thanks for the field support provided by Sea Engineering and to Emma Cotter, Corey Crisp, and James Joslin for survey execution.

SWIFT Field Survey #8

Surveys around Fred. Olsen Lifesaver

REV 2 March 13, 2019

(Deliverable No. 18)

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1 Introduction and Overview

Drifting acoustic surveys were conducted at the US Navy's Wave Energy Test Site (WETS) in Kaneohe, HI on February 5th and 7th, 2019. These surveys utilized prototypes of complete second-generation Drifting Acoustic Instrumentation SYstems (DAISYs). These are referred to as "V2" DAISYs (i.e., "version 2") and are equipped with suites of integrated instrumentation on the surface and sub-surface expressions. Effort focused on attempting to resolve an issue with line strum that appeared during a prior deployment, a general shake-down the V2 prototypes in energetic wave conditions to identify any remaining issues, and making acoustic measurements around the Fred. Olsen Lifesaver wave energy converter, which was not generating power at the time of the survey.

2 General Survey Methodology and Setting

The standard DAISY configuration consisted of a surface expression, 7 m rubber cord (10 mm diameter), 0.6 m diameter heave plate, 2.5 m rubber cord, and lower hull. The surface expressions were instrumented with a meteorological station (Airmar WX200), Garmin DC 50 tracking collars, and an integrated package with board-level GPS, 9-axis IMU, wireless and RF communication links, and condition health monitoring. The sub-surface expression was instrumented with an integrated package with a board-level GPS, 9-axis IMU, pressure sensor, and an acoustic data acquisition system built around an HTI-99-UHF hydrophone. Hydrophone data were acquired at 512 kHz, while metadata from the GPS was acquired at 1 Hz and data from the IMUs and pressure sensors were acquired at approximately 50 Hz.

For surveys around the Fred. Olsen Lifesaver wave energy converter (WEC) at the 30 m berth, we utilized a "zone" method, which is proposed for the IEC TC 114 technical specification on acoustic characterization of marine energy converters. Data were collected at the IEC-specified stand-off distance of 100 m, as well as at a stand-off distance of 25 m to increase the signal-to-noise ratio of the WEC relative to ambient sources. Acoustic data collected around the Lifesaver was also compared to a reference location approximately 600 m to the east. Comparisons between different line types of minimize strum were conducted further west to minimize transit time. Survey locations are shown in Figure 1.

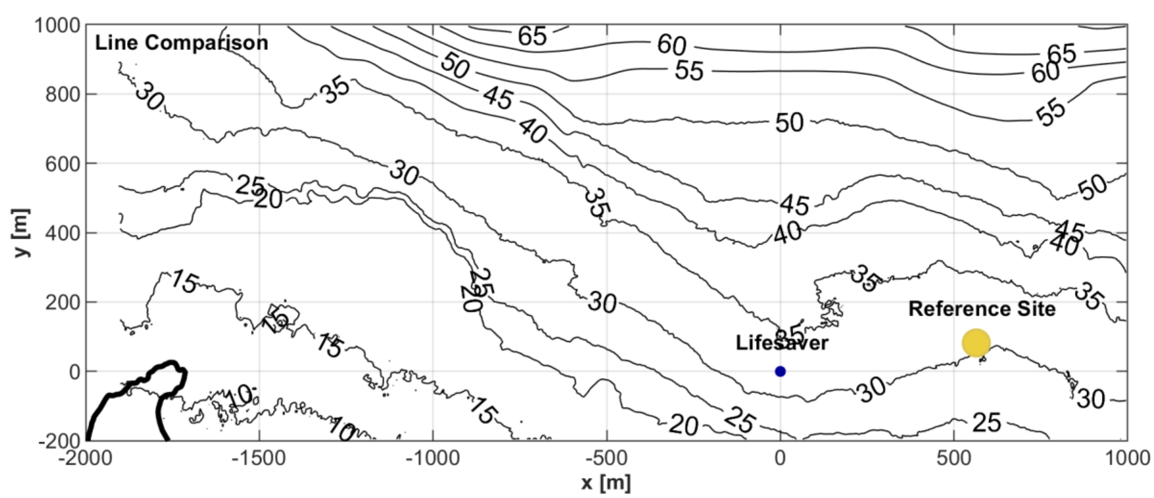

Figure 1: Survey locations

CTD surveys to evaluate the sound speed profile were conducted on February 5th and 7th using a Rushkin RBR XR provided by Sea Engineering. Survey locations and observed profiles are summarized in Figure 2. Sound velocity profiles were consistent between the days for all but the top 5 m of the water column, potentially indicating that stratification was beginning to set up due to reduced wave action between the 5th and 7th.

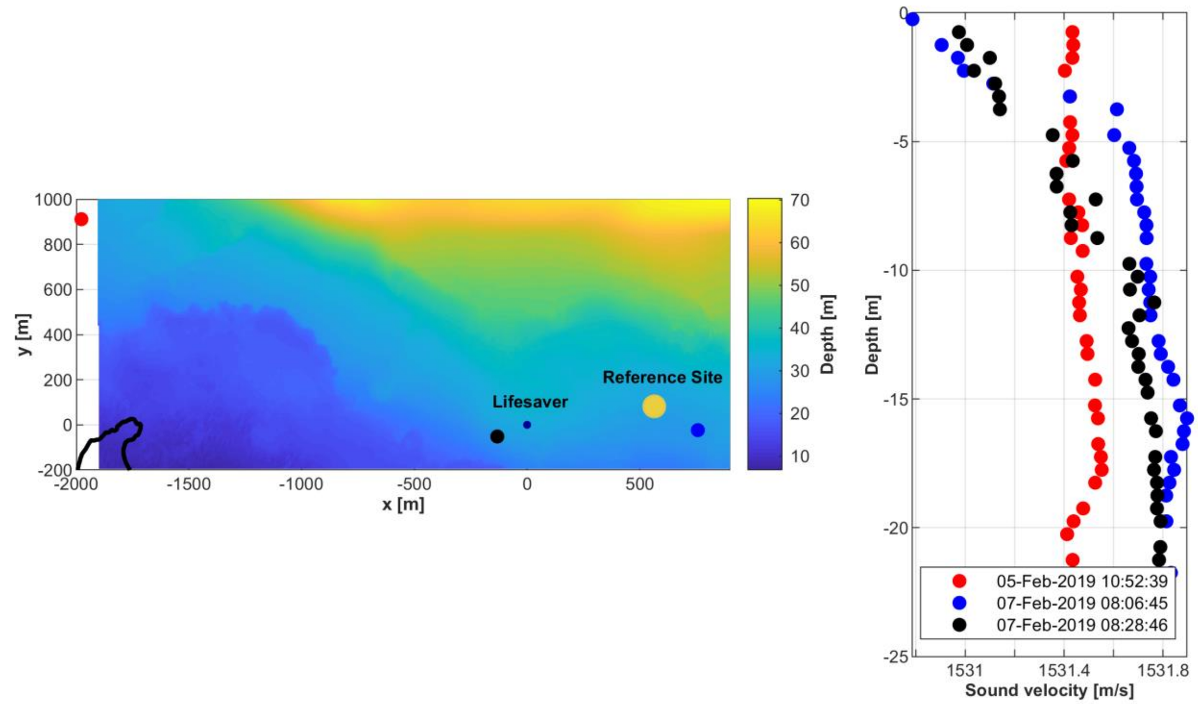

Figure 2: Sound velocity profiles

3 DAISY Inter-comparison

Three types of inter-comparisons were conducted:

- Two V2 DAISYs to evaluate inter-unit variability;
- A V2 DAISY and a V1.5 DAISY to evaluate the performance of the new hydrophones and lower housings compared to the prior arrangement (an autonomous icListen HF hydrophones with pressure logger and IMU);
- V2 DAISYs with different connections (e.g., static line, fuzz fairing) between the heave plate and lower housing to evaluate the potential for strum reduction identified during a prior survey.

Figure 3 shows a co-temporal and co-spatial (< 25 m separation) drift involving a pair of V2 DAISYs. From 10 Hz to > 100 kHz we observe that the two systems are in agreement within 1-2 dB. Below 10 Hz we see a divergence up to 5 Hz of unknown source, but likely self-noise (e.g., a broad-banded strum). Above 10 kHz there are a sequence of narrowband artifacts at 10 kHz spacing associated with electrical self-noise from the system electronics. These may be reduced by a minor modification to the PCB that increases the electrical isolation between board layers, but their narrowband, continuous nature does not impair our ability to quantify sources of sound at WETS.

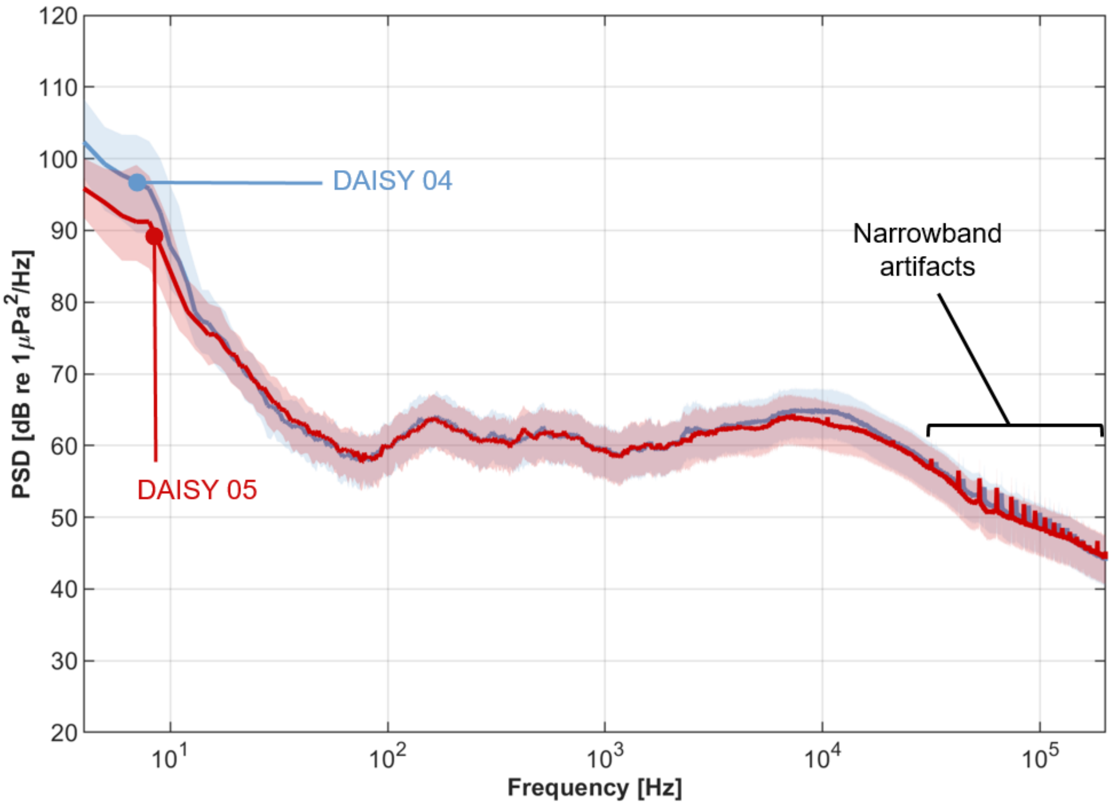

Figure 3: Co-temporal and co-spatial comparison of V2 DAISYs

Figure 4 shows a similar comparison between a V1.5 DAISY and V2 DAISY. The only difference between the two systems is the lower package: the V2 DAISY is built around an HTI hydrophone and custom acquisition system while the V1.5 DAISY is built around an off-the-shelf OceanSonics icListen HF. The following are notable:

- From 30 Hz to 1 kHz, there is extremely close agreement between the two DAISY versions
- Below 30 Hz, the V1.5 DAISY is affected by flow-noise, consistent with elevated acceleration on the horizontal axes of the IMU with a peak around 10 Hz.
- Above 1 kHz, the same general trends are apparent, but received levels routinely diverge by several dB. These are likely a consequence of two factors. First, the HTI hydrophone on the V2 DAISY has not been through a 3rd party high-frequency calibration[1]. Second, the manufacturer specification on the icListen suggests significant variations in azimuthal sensitivity at higher frequencies, such that some of the variation observed may be simply an artifact of this variability.
- The relatively abrupt change in received levels for the icListen around 1 kHz is most likely an artifact of its calibration, as this is around the transition point between the manufacturer calibration and a 3rd party calibration.

[1] 3rd party calibration has been conducted for both the HTI and icListen hydrophones at frequencies up to 800 Hz by the University of Victoria.

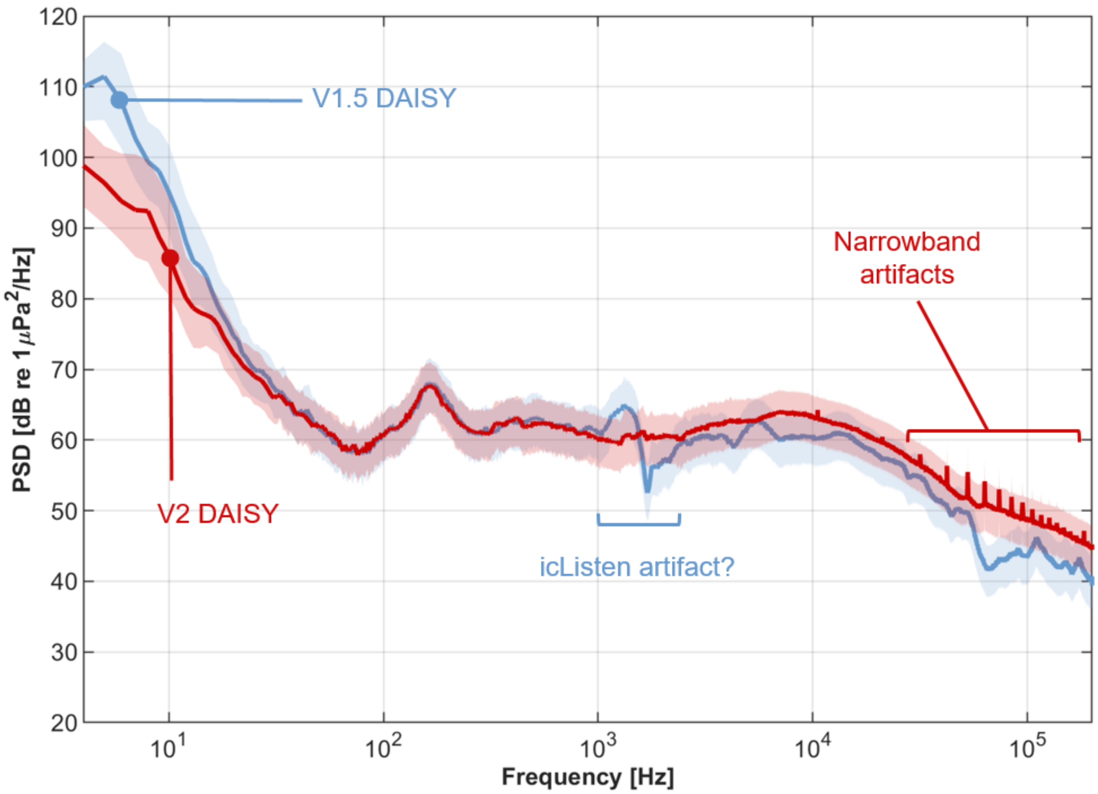

Figure 4: Co-temporal and co-spatial comparison of V1.5 and V2 DAISYs

Figure 5 shows a similar comparison between three types of connections between the heave plate and lower housing and Table 1 shows the associated metadata. During a prior survey, narrowband self-noise was identified during some drifts at frequencies between 10 and 30 Hz. The strongest explanatory hypothesis for this self-noise was line strum and potential mitigation measures included replacing the rubber line between the heave plate and lower housing with a static line – either smoothed or "fuzzed" to inhibit vortex-induced vibration. However, as demonstrated by Figure 5, differences between the line types were limited, more so than the inter-unit variability observed in Figure 3. While the fuzzed line resulted in somewhat reduced received below 10 Hz, the peak in the inter-quartile range at 20 Hz suggests that this configuration suffered from intermittent strum. There are two explanatory hypotheses: (1) that the wave state was insufficient to excite continuous strum for any of the line types or (2) the hydrodynamics of the V2 lower housings do not promote line strum[2]. This issue will be monitored in future surveys and, if it re-occurs, a similar evaluation of line types will be conducted.

[2] The version of the DAISY that experienced significant strum was a V2 prototype with a significantly larger lower housing and more limited righting moment.

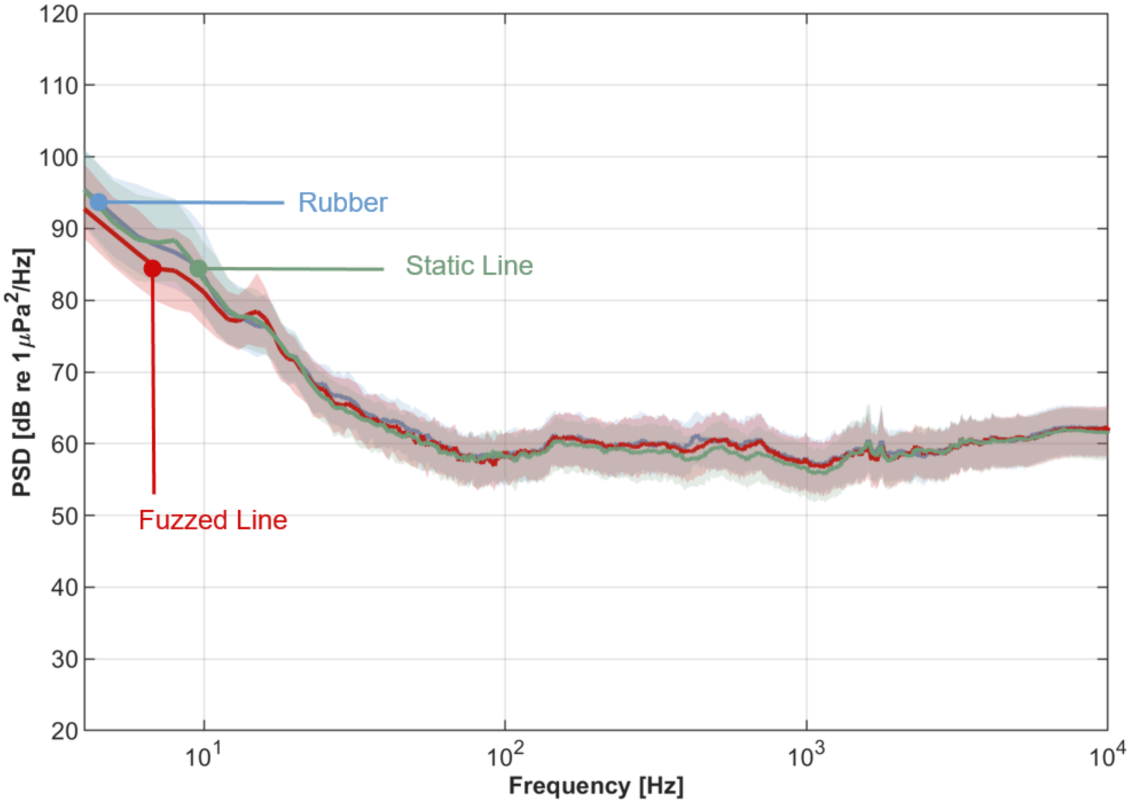

Figure 5: Co-temporal and co-spatial comparison of V2 DAISYs with alternative connections between heave plate and lower housing.

Table 1: Metadata for DAISY inter-comparison drifts

Drift	DAISY	Lower Connection	SOG [m/s]	Wind Speed [m/s]	Depth [m]	a_z [m/s²]	H_s [m]	T_e [s]	Steepness
375	04	Rubber	0.36 ± 0.28	1.5 ± 0.78	12.2 ± 0.2	-9.8 ± 0.2	1.9	8	0.019
374	05	Fuzzed Fairing	0.48 ± 0.33	3.8 ± 1.7	12.4 ± 0.1	-9.9 ± 0.2			
376	05	Static Line	0.46 ± 0.31	1.4 ± 0.78	12.5 ± 0.1	-9.9 ± 0.2	1.9	7.9	0.019

4 Fred. Olsen Lifesaver Surveys

4.1 Observations

Results of the measurements around the Fred. Olsen Lifesaver are shown in Figure 6, as compared to co-temporal measurements at a reference location, 600 m to the east. Metadata for these drifts are summarized in Table 2. For context, measurements from a similar distance while the Lifesaver was generating power are also shown. The specific trajectories of the close-range drifts are visualized in Figure 9. Zones 1-4 correspond to 100 m stand-offs (±12.5 m in any direction) from the Lifesaver in the along-wave and across-wave orientations and are consistent with measurement zone specifications for

Level A and B characterization under IEC TC 114 62600-40 Draft Technical Specification. Zones 1A-4A correspond to 25 m stands-off (±12.5 m in any direction) and are intended to identify lower-amplitude sound that is masked by ambient noise at longer range.

Several aspects of the measured sound are notable:

- At a range of 100 m, the sound produced by the idle Lifesaver was nearly indistinguishable from ambient noise (i.e., the reference spectrum is within a few dB of the spectrum obtained within Zone 1);
- At closer range, even while idle, the Lifesaver still produces significant sound between 30 Hz and 300 Hz. There is limited directionality to this sound, as evidenced by common elevation of the measurements within Zones 1A and 4A relative to the reference site; and
- The sound produced while idle occurs at similar frequencies to those during power generation, but with substantially reduced amplitude.

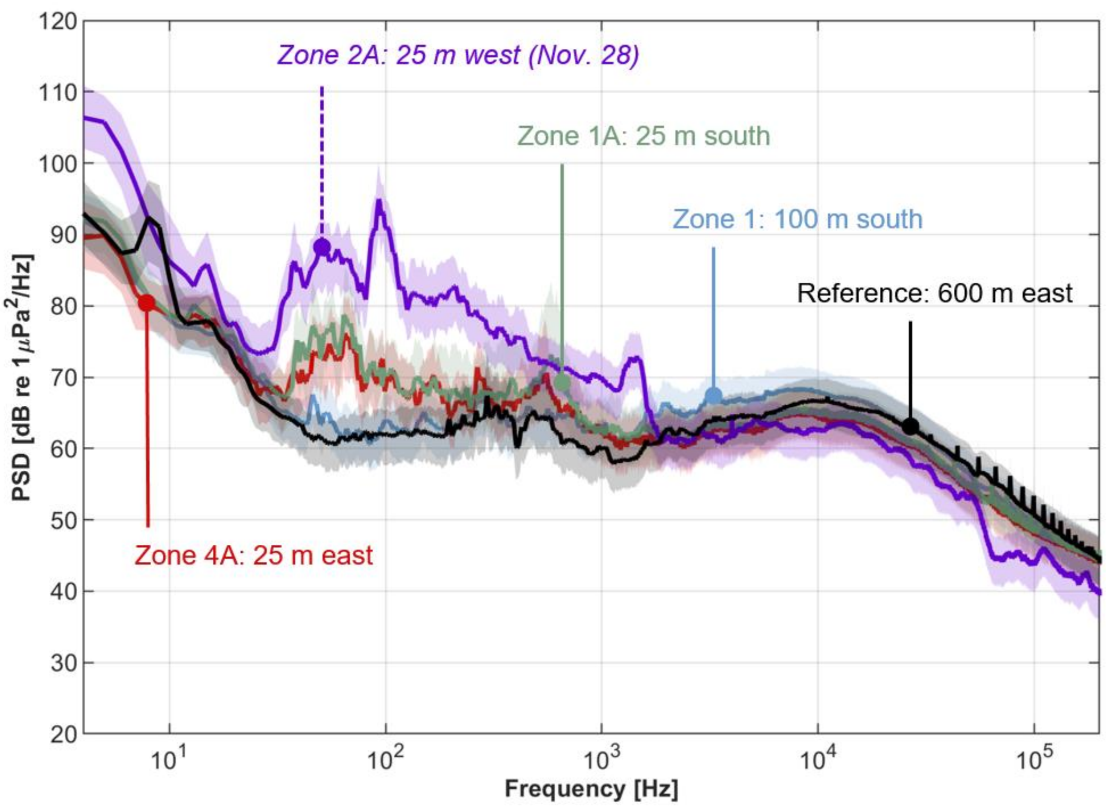

Figure 6: Comparison between Lifesaver zones and reference location. Measurements from Zone 2A were obtained while Lifesaver was active on Nov. 28.

Spectrograms for sound up to 1 kHz from co-temporal drifts at the reference site and through Zone 4A is given in Figure 7. The relatively high amplitude sound that is intermittently apparent between 300 Hz and 800 Hz is associated with humpback whale song, but, due its intermittency at any given frequency, does not appear in the median periodogram (Figure 6).

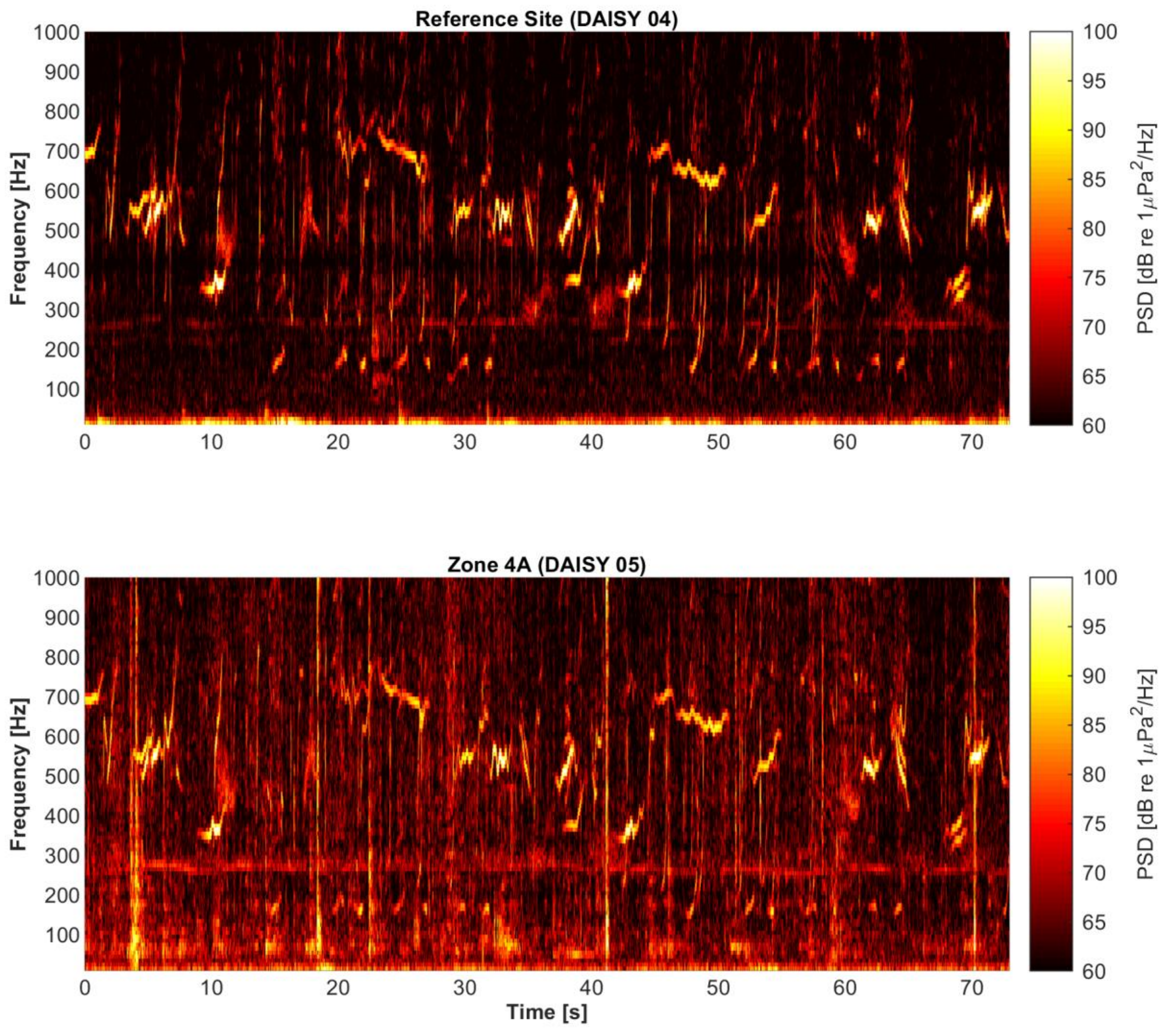

Figure 7: Spectrograms from co-temporal drifts at the reference site and in Zone 4A (25 m east of Lifesaver)

Figure 8 shows an annotated spectrogram from a portion of the drift in Zone 4A with a few highlighted features and their associated periodograms. The low-frequency limit for the periodograms is elevated relative to Figure 6 because these are constructed from time-resolved spectra (10 Hz resolution), rather than frequency-resolved spectra (1 Hz resolution). As noted previously, the whale song is obvious in the spectrogram, but has statistical characteristics that are nearly indistinguishable from the sequence median, as the elevated sound at any given frequency occurs for only a short time. The only discrete sound clearly attributable to the Lifesaver is the “bang” of a disconnected PTO float on the underside of the hull, which elevates sound relative to the median over a relatively wide range of frequencies. The elevation in received levels relative to the reference site (30 – 300 Hz) appears to be generalized and relatively continuous, possibly associated with breaking waves around the Lifesaver hull.

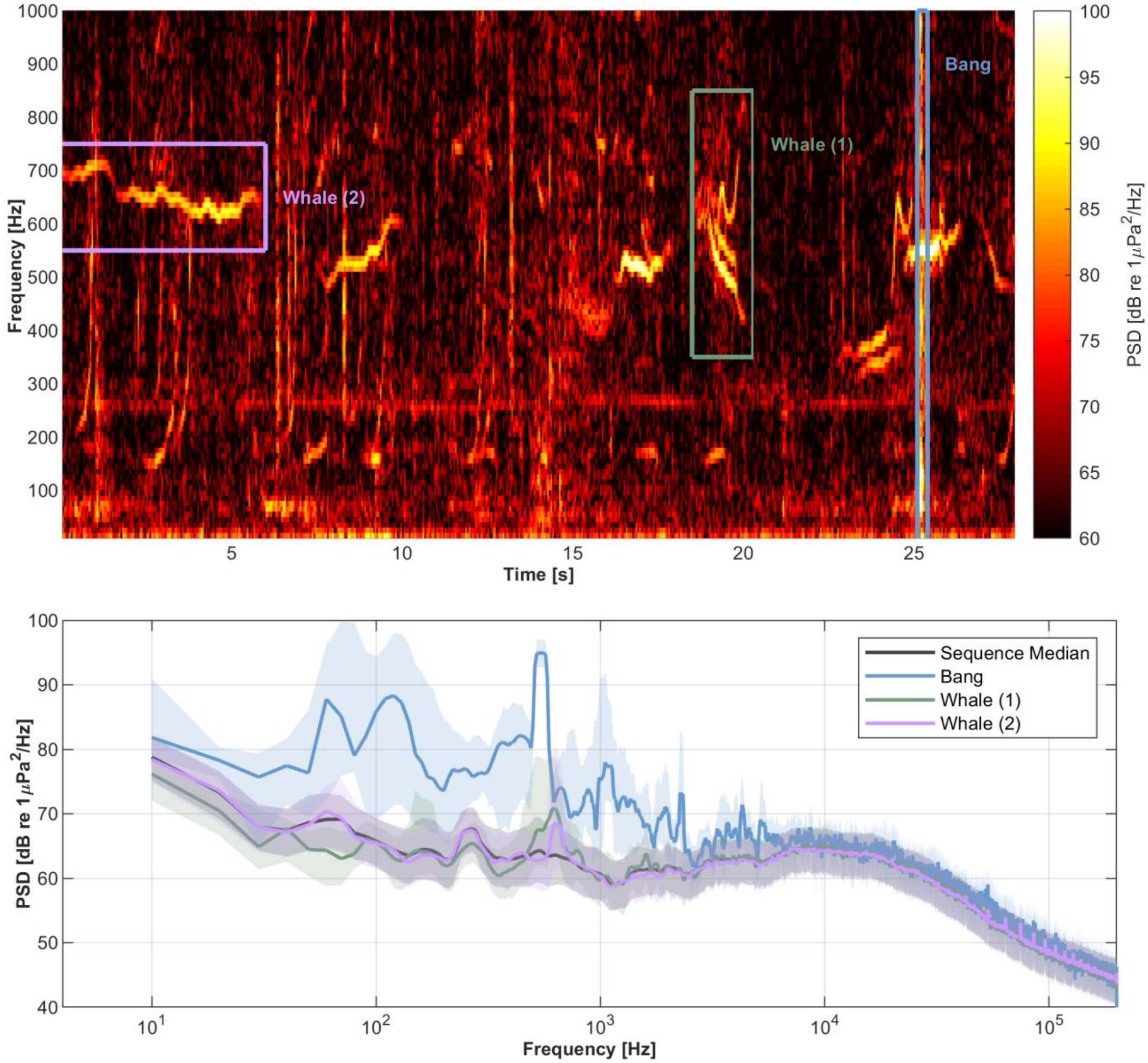

Figure 8: Annotated spectrogram (top) and periodograms of annotations (bottom) for drift in Zone 4A (25 m east of Lifesaver)

Table 2: Metadata for Lifesaver drifts

Drift	Location	Date	Lifesaver Status	SOG [m/s]	Depth [m]	a_z [m/s^2]	H_s [m]	T_e [s]
381	Zone 1	Feb 7	Idle	0.4 ± 0.2	12.2 ± 0.1	-9.8 ± 0.1	1.8	9.9
383	Zone 4A	Feb 7	Idle	0.4 ± 0.2	12.3 ± 0.1	-9.8 ± 0.2	1.8	10
385	Zone 1A	Feb 7	Idle	0.5 ± 0.3	12.9 ± 0.2	-9.8 ± 0.2	1.8	10
352	Zone 2A	Nov 28	Active	0.3 ± 0.2	12.9 ± 0.1	-9.6 ± 0.1	2	7.3
380	Reference	Feb 7	Idle	0.4 ± 0.3	12.2 ± 0.1	-9.9 ± 0.2	1.8	9.9

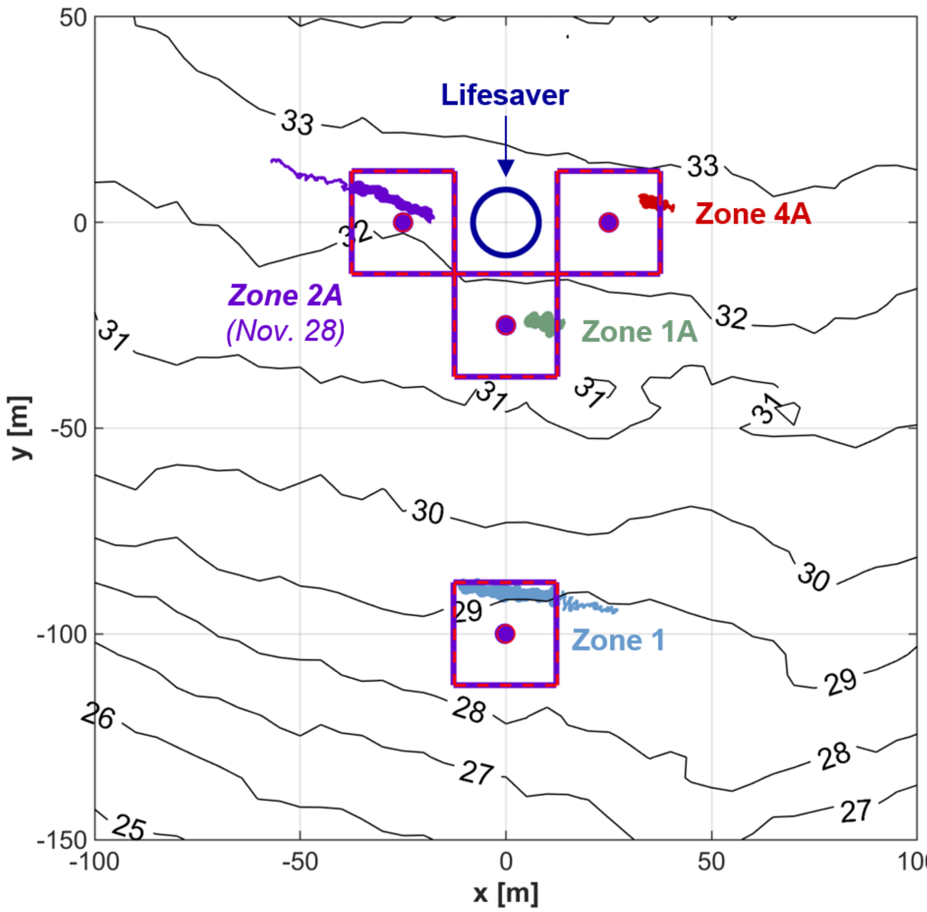

Figure 9: Measurements within survey zones around the Lifesaver

4.2 Source Level Occurrence

Table 3 summarizes occurrence levels for a roughly estimated broadband (4 Hz – 200 kHz) source level, as stipulated by WETS regulatory reporting requirements. The propagation model is the basic sonar equation

$$SL(f) = RL(f) + N \log D$$

where *SL(f)* is the source level as a function of frequency, *RL(f)* is the received level, *N* is a propagation loss coefficient, and *D* is the slant distance between the source (i.e., Lifesaver) and receiver (i.e., DAISY). Here, we assume that all sound originates from just below the surface at the Lifesaver's reported location. A "practical" propagation loss coefficient of 15 is used, reflecting that spreading is likely to be somewhere between cylindrical and spherical. Source level estimation is applied only to drift data within Zone 1A or 4A to minimize errors associated with the coarse model for propagation loss.

As previously shown, in operation, the Lifesaver likely produces sound at frequencies between 30 Hz and 1 kHz. Here, we apply the propagation model to those frequencies, as well, to those frequencies to avoid unrealistically inflating source levels at frequencies outside of this range and maintain consistency with prior evaluations. Broadband source levels are, therefore, integrated over specific frequency bands, using the following data sources:

- 4-30 Hz: received levels at DAISY position
- 30 Hz – 1 kHz: estimated source levels given DAISY slant distance to source
- 1 kHz – 200 kHz: received levels at DAISY position

As shown in Table 3, this model for the Lifesaver source level suggests that broadband source levels exceeded 120 dB during the majority of the measurements, but never exceeded the regulatory thresholds at 154 dB or 180 dB.

Table 3: Regulatory reporting for Lifesaver surveys

Limit (at source dB)	Occurrence (%)	Instrument	SPL (at instrument)	WEC	Propagation Model
≤ 120	14 %	DAISY	~25 m horizontal distance ~12 m depth ~ 2 minutes at 512 kHz	Lifesaver	15log spreading for frequencies of sound produced by WEC
> 120	86 %	DAISY			
> 154	0%	DAISY			
> 180	0%	DAISY			

5 Conclusions

These surveys indicate that even when the Lifesaver is in an idle state, there are acoustic emissions that are detectable at close range. These emissions are relatively low amplitude and are produced at similar frequencies to sounds associated with power generation. The most likely explanation for these sounds is wave breaking around the Lifesaver hull.

The V2 DAISYs performed well during these surveys, with indications of substantially reduced flow-noise at frequencies below 10 Hz. Attempts to mitigate strum that affected earlier V2 DAISY prototypes was ineffective because the strum overserved for prototype units could not be replicated.

6 Acknowledgements

Many thanks for the field support provided by Capt. Donald Bunnell of Sea Engineering, Nicholas Ulm of the University of Hawai'i, and to Corey Crisp for survey execution.