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Task 4: Environmental Impact Monitoring at WETS

Sea Spider Survey Field Reports

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Sea Spider Survey Report #1

Trial Deployment

REV 1.0 September 7, 2015

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1 Introduction

This report describes the initial deployment and recovery of a Sea Spider platform equipped with three recording hydrophones at the 30 m berth at the Wave Energy Test Site (WETS) in Kaneohe Bay, HI. This package underwent a trial deployment for two days in March 2015.

2 Deployment and Recovery

The Sea Spider was equipped with three Loggerhead DSG-ST recording hydrophones. Each hydrophone has 256 GB of on board storage, extended through the X3 lossless compression algorithm implemented on the onboard microprocessor. The hydrophones were configured to record continuously, beginning at 0800 on March 24, 2015. The recording rates was 96 kHz, allowing resolution of underwater sounds to 48 kHz.

The Sea Spider was deployed slightly before 0900 on March 24 at a location of 21 27’ 58.8635’ N, 157 45’ 8.4396’’ W, within approximately 5 m of the intended target at the 30 m test site. Conditions were flat calm and no complications were encountered during the deployment process.

The Sea Spider was recovered around 1100 on March 26. No difficulties were encountered in recovery, though the sea state was substantially higher than during recovery (approximately 2 m significant wave height).

3 Data Return

All instruments were operating at recovery. While only deployed for two days, data offload still required almost three hours to complete due to the high recording rate and slow transfer rate (USB 1.0).

4 Conclusions

The Sea Spider platform and Loggerhead DSG-ST recording hydrophones operated well during their trial deployment at WETS.

Sea Spider Survey Report #2

Azura Pre- and Post-Installation

REV 1.0 September 7, 2015

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1 Introduction

This report describes a three month recording hydrophone deployment at the 30 m berth at the Wave Energy Test Site (WETS) in Kaneohe Bay, HI. The hydrophones were deployed prior to installation of the Azura wave energy converter (WEC).

2 Deployment and Recovery

The Sea Spider was equipped with three Loggerhead DSG-ST recording hydrophones. Each hydrophone has 256 GB of on board storage, extended through the X3 lossless compression algorithm implemented on the onboard microprocessor. The hydrophones were configured to record continuously in a staggered manner to enable complete coverage over a three month period:

- S/N 806141979: Begin recording on 3/26/2015 at 1500
- S/N 805351455: Begin recording on 4/26/2015 at 1500
- S/N 805351449: Begin recording on 5/26/2015 at 1500

Recording rates was 96 kHz, allowing resolution of underwater sounds to 48 kHz.

The Sea Spider was deployed around 1600 on March 26 at a location of 21 27' 59.4329'' N, 157 45' 7.9897'' W, approximately 20 m from the intended target at the 30 m test site. Conditions were challenging for deployment, with significant wave heights of 2 m. It is unlikely that it would be possible to deploy a Sea Spider with greater accuracy in similar conditions.

The Sea Spider was recovered at 1700 on July 6, 2015. No difficulties were encountered in recovery, with relatively moderate seas. The hydrophone elements on all units were bent at a moderate angle by relative currents, either during deployment or recovery. All surfaces on the Sea Spider were heavily fouled by algal slime.

3 Data Return

Instrument data return was poor for this deployment:

- S/N 806141979: 3/26/2015 1500 – 4/6/2015 (11 days/30 days)
- S/N 805351455: 4/26/2015 1500 – 4/28/2015 (<2 days/30 days)
- S/N 805351449: 5/26/2015 1500 – 6/26/2015 (30 days/30 days – memory full)

Overall, this corresponds to < 50% data return relative to intended collection. The early shutdown on the first two hydrophones was not due to battery voltage; supply voltage was above instrument operating threshold at recovery. Loggerhead Instruments believes that the root cause is a write failure to the SD cards. While they have been able to replicate the failure through in-house testing, they have not been able to reliably reproduce it or determine the reason for the failure. Loggerhead Instruments continues to work towards a resolution to this failure mode and may be able to provide hardware for SD card testing prior to the next system recovery and redeployment.

4 Conclusions

The Sea Spider platform and Loggerhead DSG-ST recording hydrophones were deployed and recovered from the 30 m test berth at WETS. While data return was low due to unexpected hydrophone failures, the hydrophone that began recording when the Azura was deployed fortunately operated for its expected duration.

Two Sea-Spiders Field Survey Report #3
REV 1.0 June 20 2017
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1 Introduction

This report describes a three-month observation of the Fred Olsen Lifesaver wave energy converter (WEC) deployed at the 60 m berth of the US Navy Wave Energy Test Site (WETS) in Kaneohe, HI using a Sea Spider stationary package equipped with multiple hydrophones. It provides descriptions of measured sounds, their estimated source levels relative to regulatory thresholds, an analysis of the dependence of some sounds on sea state, and a review of stationary platform stability under wave loads.

2 Methodology

2.1 Measurement Platform and Instrumentation

Three DSG-ST recording hydrophones (Loggerhead Instruments) were configured for deployment on staggered duty cycles. Two hydrophones were set to deploy for 30 minutes every 90 minutes at a sample rate of 48 kHz (staggered), while the third recorded for 15 minutes every 90 minutes at a sample rate of 96 kHz and was deployed co-temporally with one of the lower sample rate hydrophones. Sample rates were chosen to balance the desire to increase total recording time, which improves the likelihood of measuring sound during infrequently occurring sea states, with an interest in resolving higher-frequency sound.

The hydrophones were deployed on a Sea Spider (Teledyne Marine), a fiberglass gravity anchored tripod (Fig. 1). The hydrophone elements of the DSG-STs had an approximate height of 0.9 m from the seabed. A 6-axis MAT-1 inertial measurement unit (IMU, Lowell Instruments) logging at 64 Hz was deployed to record motion of the Sea Spider that might be associated with wave forcing. Movement was suspected as a possible source for intermittent “scraping” sounds recorded in previous surveys.

Fig. 1: Sea Spider platform prepared for deployment.

2.2 Deployment and Recovery

The Sea Spider was deployed at the 60-m berth from the Sea Engineering, Inc. M/V *Huki Pono* at approximately 21.4736’ N, 157.7536’ W on December 6, 2016. This resulted in a transverse range from the Lifesaver of 72 m and a slant range of 94 m (Fig. 2).

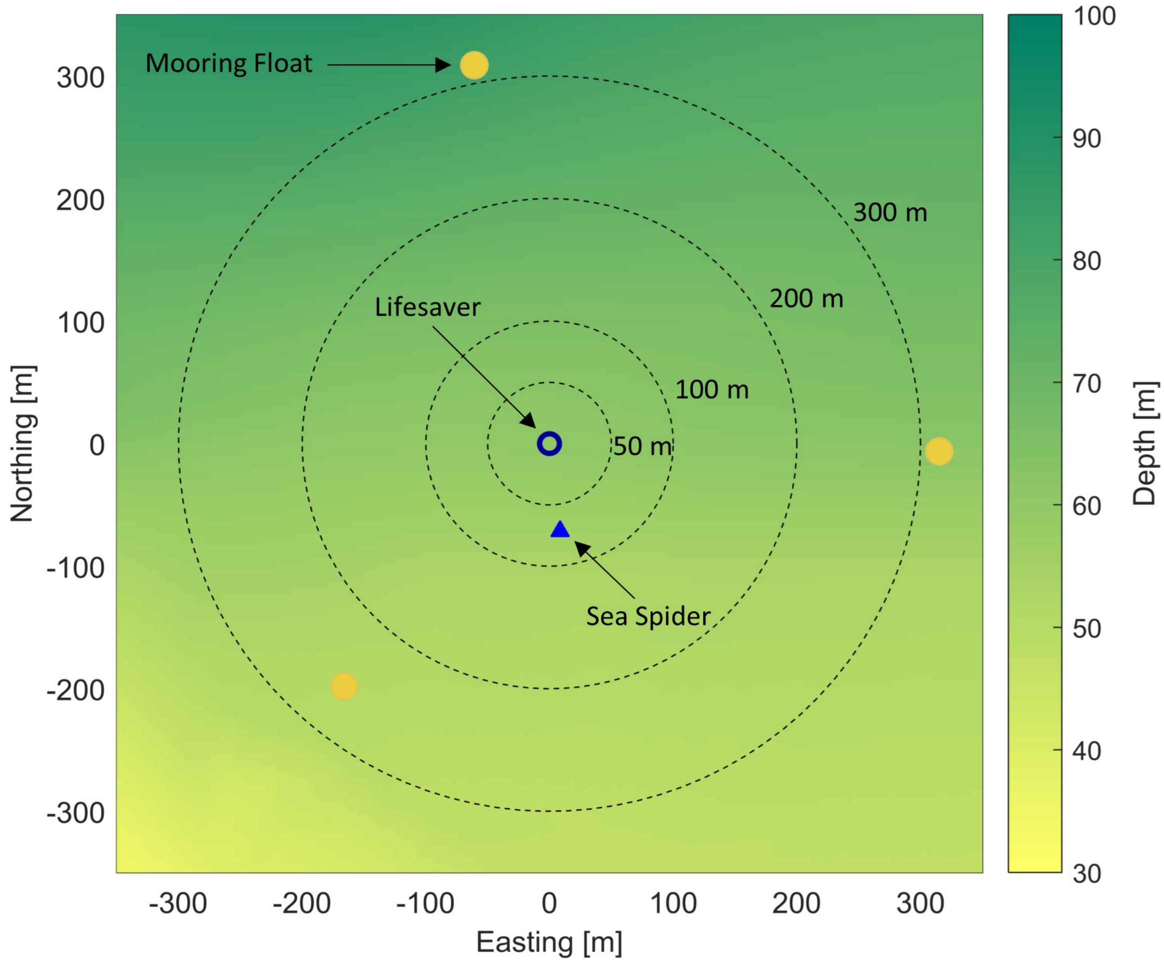

Fig. 2: 60 m berth with Lifesaver, permanent mooring floats, and Sea Spider bottom platform.

After 93.2 days, the Sea Spider was recovered on March 8, 2017 with 68.2 days of acoustic data onboard, indicating no loss of data from instrument malfunction. As in previous deployments, the stems of the hydrophone elements were bent by either currents or repeated wave forcing throughout the deployment, or at some point during deployment or recovery. Their surfaces were lightly covered with biomass but retained a thin layer of a UV blocking coating applied before deployment (Fig. 3).

Fig. 3: Hydrophone stem observed to be bent at recovery from the 60 m berth.

2.3 Data Processing

2.3.1 Hydrophone Calibration

Hydrophones were calibrated at low frequencies (<250 Hz) using a GeoSpectrum M351 calibrator prior to deployment. Because calibration of this type used sound measured by the hydrophones as deployed and saved internally to the DSG-ST boards, calibration results were specific to the unique combination of DSG-ST and the hydrophone element deployed with it. New calibration data were averaged with data from prior calibrations of the same DSG-ST/hydrophone combination in units of pressure squared. High frequency calibrations (>10 kHz) were provided by the manufacturer. Linear interpolation was used between calibration frequencies to produce a receive voltage sensitivity (RVS) curve for each DSG-ST/hydrophone element pair. Frequency-specific calibration was applied to all acoustic data presented in this report.

2.3.2 Acoustic Data Processing

Acoustic data sampled at 96 kHz were windowed into intervals of 12,288 points, while data sampled at 48 kHz were windowed into intervals of 6144 points, each resulting in spectra with frequency resolution of 8 Hz and temporal resolution of 64 ms. These window sizes were chosen such that the frequency and temporal resolution of spectra from stationary measurements would be equivalent to that of spectra from drifting measurements (discussed in SWIFT Surveys 4 - 6). Windows were detrended, overlapped by 50%, multiplied by a Hamming window, and processed using a fast Fourier transform (FFT). Frequency-specific calibration was applied to the resulting spectra and estimates of pressure spectral density were then calculated. Acoustic spectra are presented as pressure spectral densities (PSD) in units of dB re 1µPa^2/Hz. Broadband and band-limited levels are given in units of dB re 1µPa.

2.3.3 Source Level Estimation

Broadband (0 - 20 kHz) source levels (SL) were estimated from received levels (RL) at the hydrophones using the sonar equation under the assumption of practical spreading. An assumption of "practical spreading" may be used to estimate transmission losses in underwater environments in which the true transmission loss is unknown or difficult to model accurately, often as a result of incomplete information about bottom composition. Transmission loss under practical spreading, *TL*, is given as

$$TL = 15\log_{10} r \qquad \textbf{Eq. 1}$$

where *r* is the slant range from the source to the receiver. Thus, practical spreading is midway between cylindrical and spherical spreading.

Flow noise, a form of non-propagating pseudo-sound, can dominate at frequencies below 100 Hz during high sea states. Because flow noise does not originate with the WEC, the sonar equation would overestimate WEC source levels in the presence of flow noise. However, the removal of bands contaminated by flow noise would potentially remove sounds produced by the WEC. In the interest of conservatively reporting source levels, the sonar equation was applied across all frequencies[1].

2.3.4 Sea State Dependence of Acoustic Data

Acoustic data were binned by significant wave height and wave energy period with bin resolutions of 0.5 m and 1 s, respectively. Acoustic data were randomly selected in 30-second samples from the total data available at a given sea state. Random selection increased the distribution of samples over the available data within a sea state bin to increase the temporal diversity of samples used in the analysis. However, a few sea states occurred infrequently during the deployment, such that data representing those sea states may be derived from temporal clusters, rather than dispersed over the duration of the deployment. Each sample was manually reviewed and samples contaminated by boat noise or self-noise were excluded. Ten samples were selected for each sea state bin for a total of 300 seconds of data. Estimates of mean PSD were calculated for each sample and an ensemble average of samples was then calculated in units of pressure squared per Hertz for each sea state bin. Finally, each PSD estimate was integrated into band-limited sound pressure levels (SPL).

2.3.5 Sea State Dependence of WEC Power Output

The mean power of each PTO was measured over 20 minute periods during the Lifesaver's deployment. This data was interpolated using a nearest neighbor method and sampled to estimate the mean power of the Lifesaver over 30-second samples co-temporal with manually reviewed acoustic data. Data from active PTOs were then summed for each 30-second sample to produce an estimate of mean total power output, which was subsequently binned by significant wave height and wave energy period with bin resolutions of 0.5 m and 1 s, respectively, and then averaged to produce mean total power as a function of sea state. This is a WEC performance matrix corresponding to the acoustic measurements and should not be interpreted as a general WEC performance matrix compliant with international standards.

3 Results

3.1 Description of Sounds

Several distinct sound sources are present in the acoustic data. A "bearing warble" associated with a damaged PTO component appears as successive short duration tones with fundamental frequencies of approximately 790 Hz and higher order harmonics that extend beyond 20 kHz (Fig. 4, Fig. 5Fig. 6). "Humpback whistles", which appear as short tonal sweeps from 500 – 1000 Hz, and "Humpback moans", which are typified as narrow-band tones with center frequencies that varied between 100 and 600 Hz, are easily identified by manual review (Fig. 4,Fig. 6 and Fig. **7**). A distinct sound that rose in frequency from 50 to 500 Hz was present during high sea-states, however it was not clear if the sound originated

[1] A more detailed discussion of this calculation is provided in a previous report, "Broadband Azura Analysis".

with a marine mammal or a mechanical source on the WEC or mooring system (Fig. 5). A correlation between biological activity and sea state seems less likely, which suggests a mechanical origin. Flow noise caused by wave orbital motion was present when significant wave height exceeded 3 m and elevated sound levels at frequencies up to 600 Hz (Fig. 7). In the case shown, sound levels below 50 Hz were continuously elevated. An impulsive chain noise (“chain impulse”) was intermittently present in much of the data and appeared as successive broadband impulses with durations less than 500 ms. Other sources of sound included chain noise from the unoccupied 80 m berth, as well as snapping shrimp sound, which elevate levels above approximately 10 kHz and vary in intensity on a diurnal cycle. Periodograms showing the average spectra from Fig. 6 (T_e = 7.8 s, H_{m0} = 1.61 m) and **Fig. 7** (T_e = 11.8 s, H_{m0} = 3.57 m), are shown in Fig. **8**. Comparing these periodograms to their corresponding spectrograms shows that intermittent flow noise can elevate spectral density levels by over 10 dB, if calculated over relatively long (30 second) windows containing multiple flow noise events. It should be noted that the wave steepness during both events is relatively similar (estimated as H_{m0} relative to a wavelength based on the energy period). The general elevation in sound between 100 Hz and 600 Hz likely originates from surface processes (e.g., spray), given the general correlation of elevation in this frequency band and elevation at lower frequencies associated with wave orbital flow noise (Fig. 7).

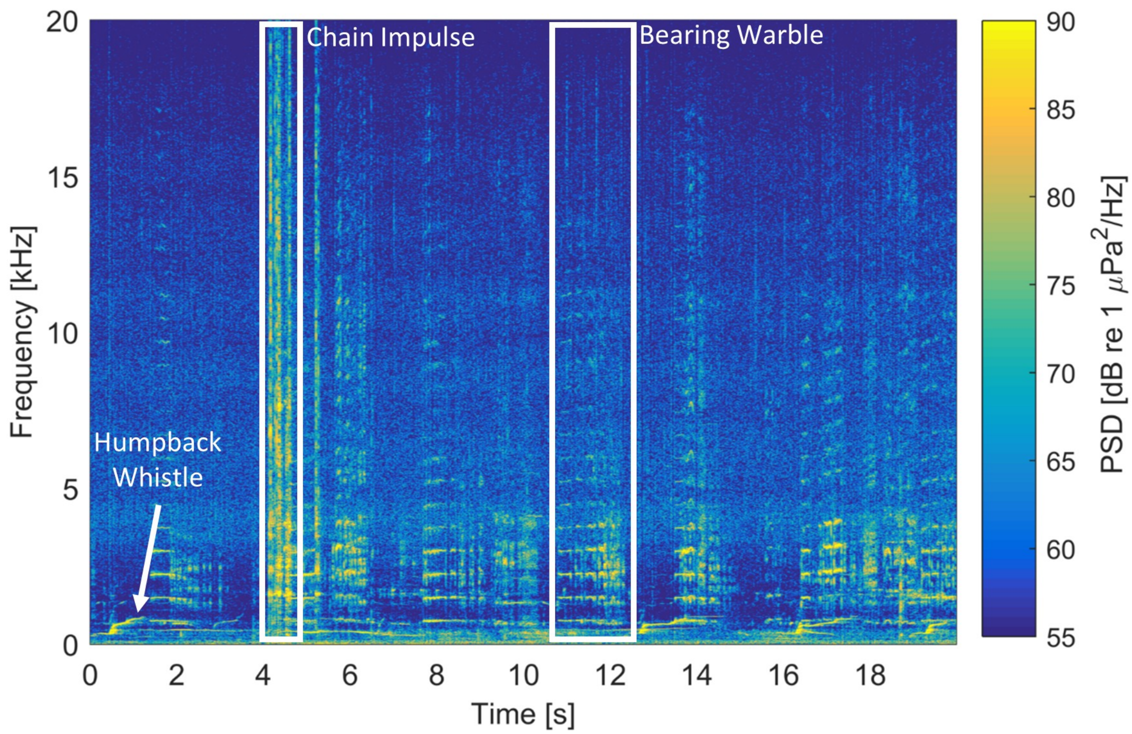

Fig. 4: Example of recorded sounds, T_e = 7.2 s, H_{m0} = 2.0 m, 01 March 2017 06:05:20.

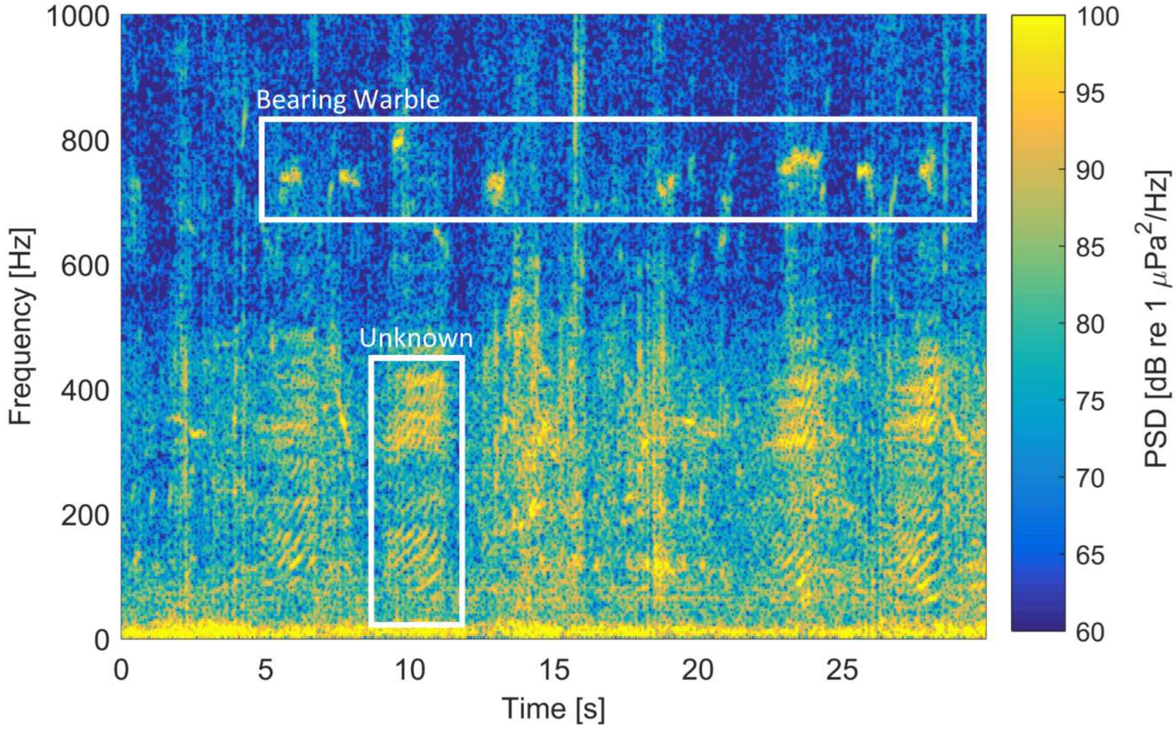

Fig. 5: Example of recorded sounds, T_e = 11.8, H_{m0} = 3.9, 01 February 2017 19:03:35

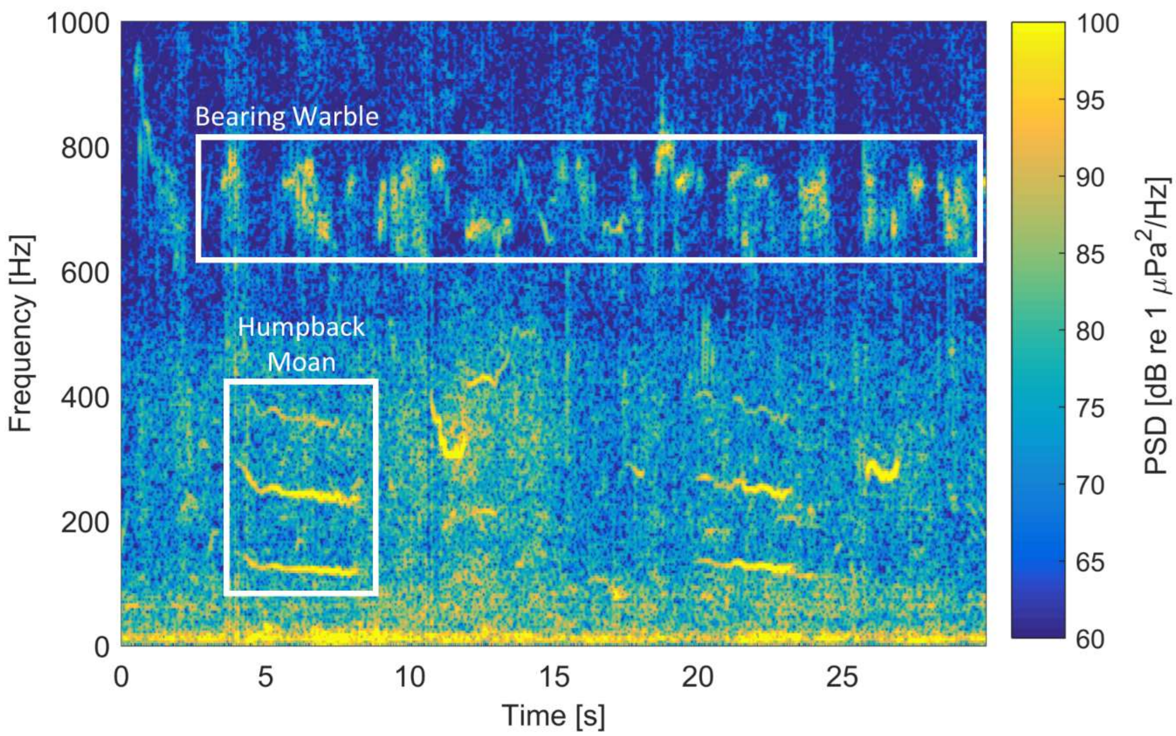

Fig. 6: Example of recorded sounds, T_e = 7.8 s, H_{m0} = 1.6 m, 25 February 2017 05:37:35.

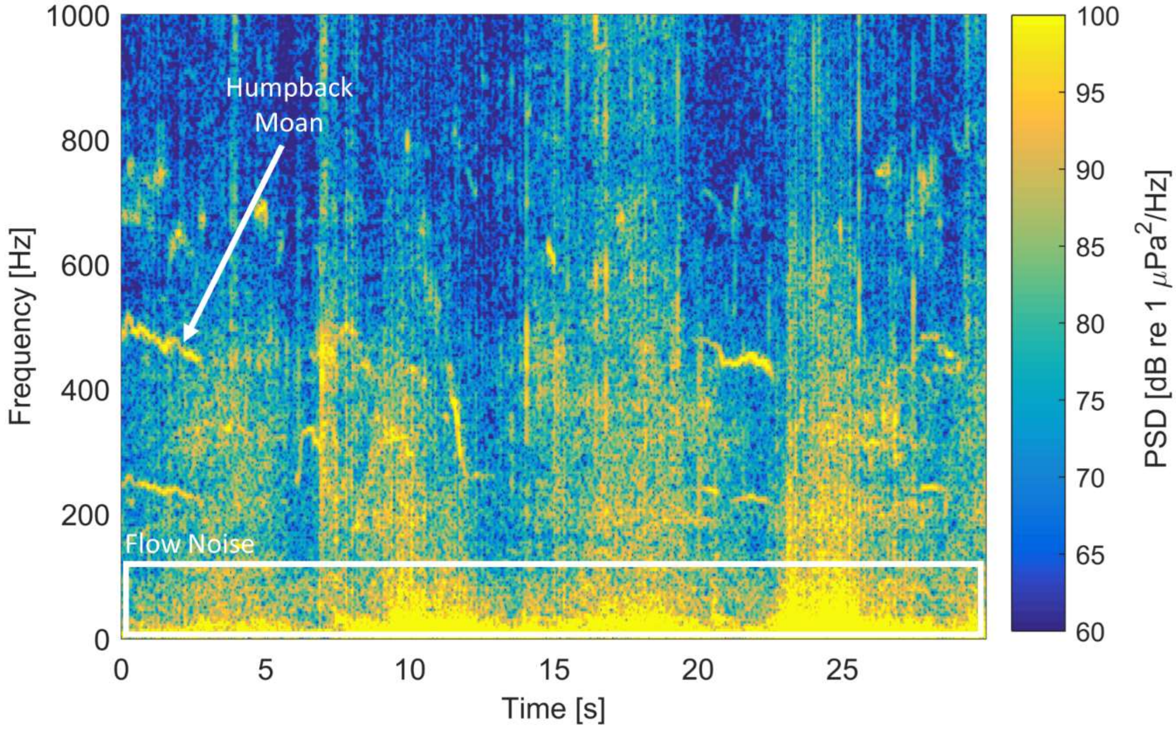

Fig. 7: Example of recorded sounds, T_e = 11.8 s, H_{m0} = 3.6 m, 01 February 2017 20:36:35.

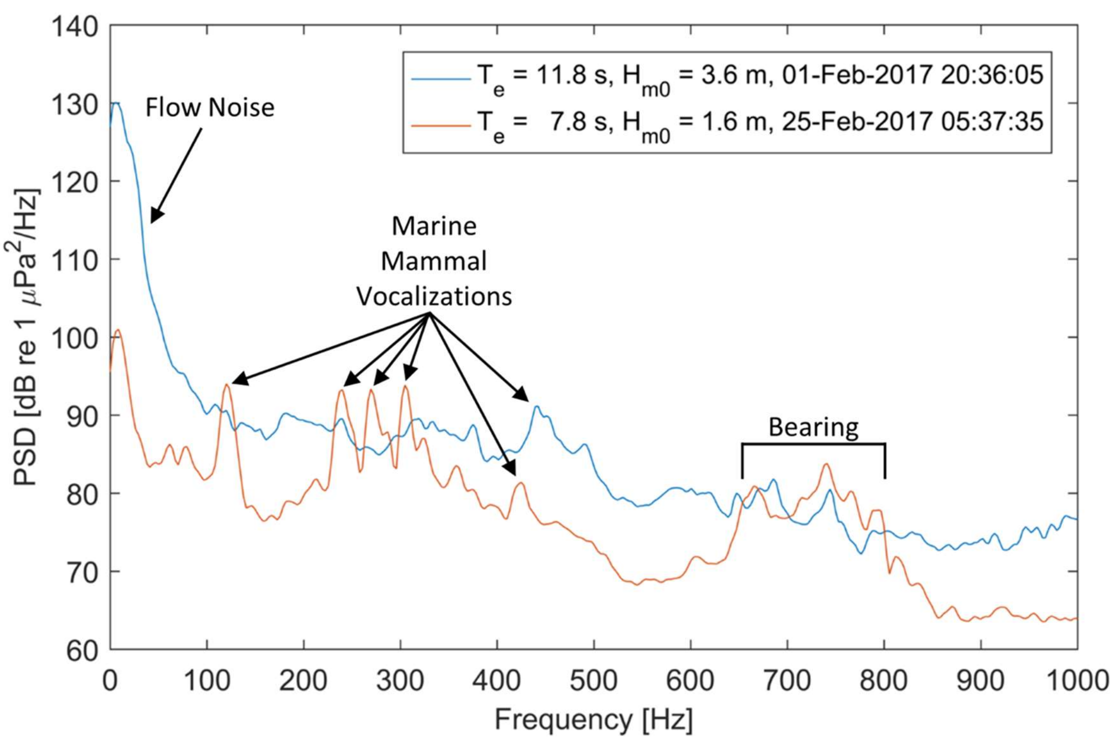

Fig. 8: Mean PSDs corresponding to Fig. 6 and Fig. 7.

3.2 Temporal Statistics of Received and Estimated Source Levels

A histogram of broadband received levels, calculated over 30 second periods from the complete 68.2 days of data, is presented in Fig. 9. The median broadband received level was approximately 114 dB re 1μPa. Although broadband levels as high as 159 dB re 1μPa were occasionally observed in the data, received levels exceeded 120 dB re 1μPa for only 1% of the total recording time.

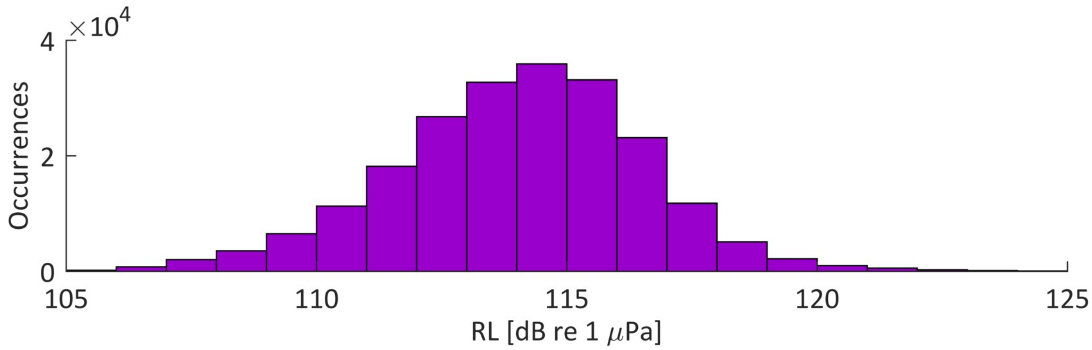

Fig. 9: Histogram of broadband received level.

The percent of total recording time during which estimated broadband source levels exceeded regulatory thresholds is presented in Table 1. Because exceedance events were dominated by non-propagating flow-noise and other sources that did not originate with the Lifesaver (e.g., impulsive sound), actual source levels would be expected to be much lower. However, rigorous identification and isolation of Lifesaver sound and a validated site- and frequency-specific propagation model would be required for a more robust estimate.

Table 1: Percent occurrence of source level limit exceedance.

Limit (dB at Source)	**Occurrence** (%)	**Instrument**	**Distance From WEC (m)**	**Record Length (hr)**	**WEC**	**Propagation Model**
120	100.000	Sea Spider, DSG-ST	Slant Range = 94 ± 2.0 Transverse Range = 72 ± 2.5 Depth = 60	1636.8	Lifesaver	Practical: 15log*(r)*
154	0.285					
180	0.057					

3.3 Sea State Dependence

3.3.1 PTO Mean Power Output

Mean power output from each lifesaver PTO calculated over 20 minute periods unsurprisingly revealed correlations with wave energy period and significant wave height (Fig. 10).

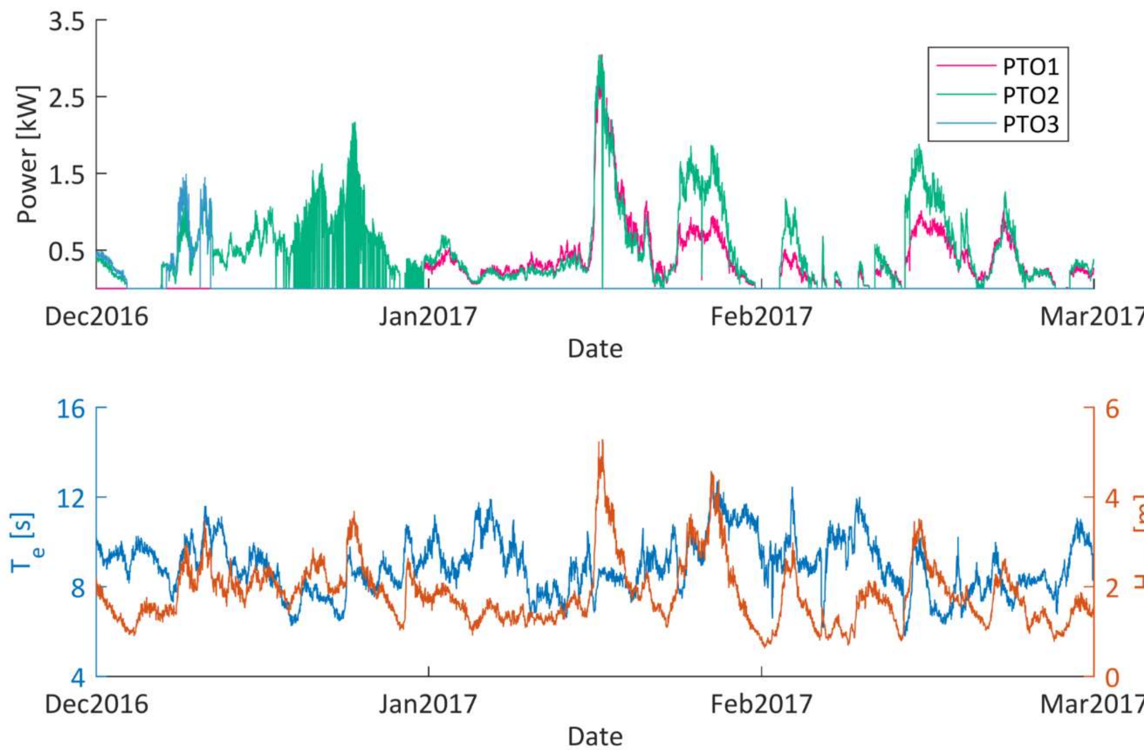

Fig. 10: Mean power output of Lifesaver PTOs (top) and co-temporal significant wave height (H_{m0}) and energy period (T_e) (bottom) from December 2016 to March 2017.

In attempting to identify causal relationships between received levels and PTO activity (should one exist), analysis was restricted to periods during which PTO status was relatively invariant. The following analyses use manually reviewed data from January 2017 to March 2017, during which time PTOs 1 and 2 were consistently active and PTO 3 was consistently inactive (Note: the “bearing warble”, believed to be related to PTO motion, had already developed by January 2017).

Separation of co-temporal mean total power output from PTOs 1 and 2 by sea state shows that power generation was highest during periods of greatest significant wave height and when the wave energy period was less than 9 seconds (Fig. 11).

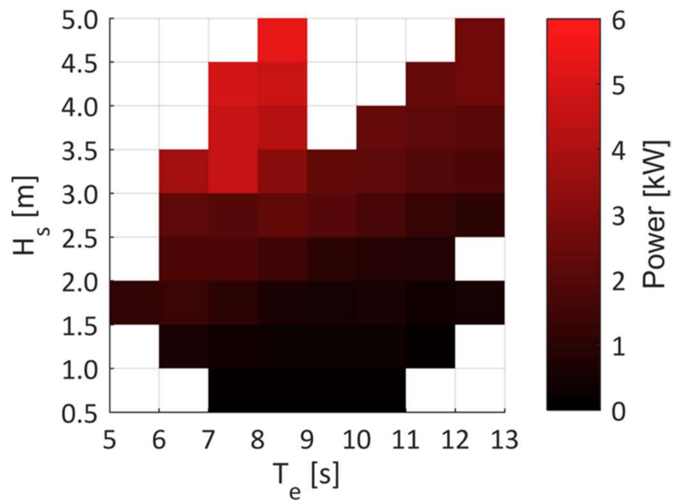

Fig. 11: Mean total power output from PTOs 1 and 2 corresponding to manually reviewed acoustic data.

3.3.2 Received Levels

Broadband received levels calculated over 30-second windows also correlate with significant wave height, suggesting that a significant portion of the measured sound originated with sources driven by wave motion, which could include flow noise, wave breaking, sediment transport, PTO motion, or other mechanical and impulsive sources (Fig. 12).

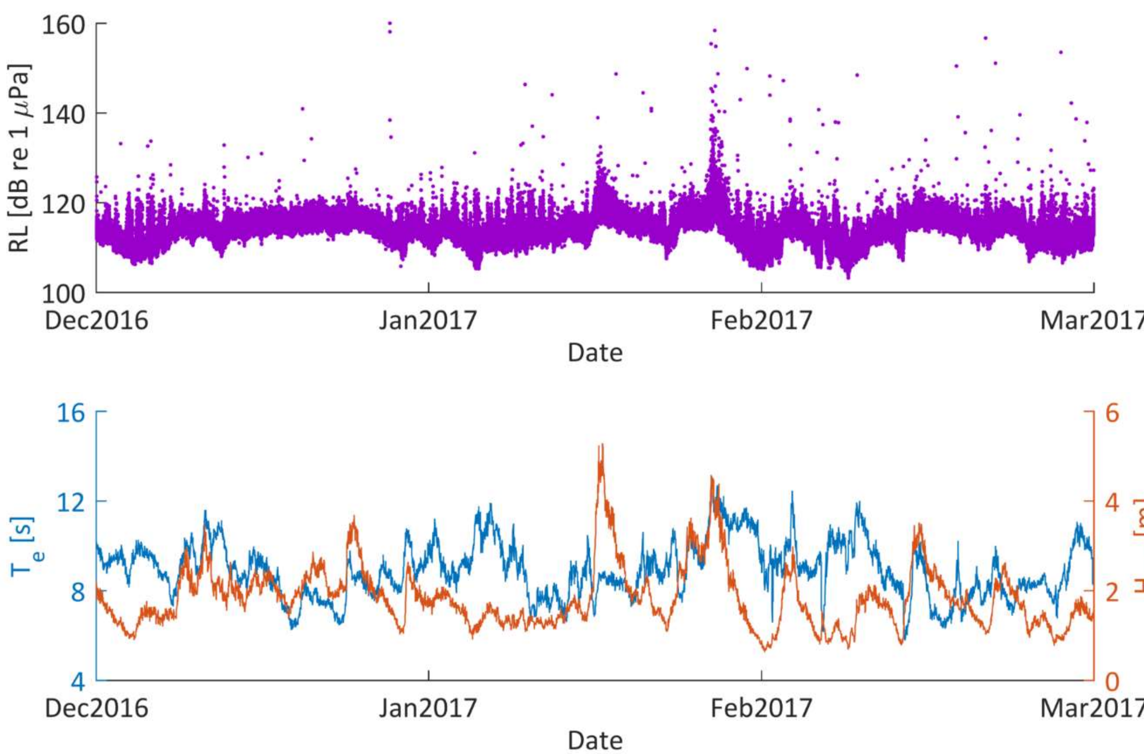

Fig. 12: Broadband received levels (RL) (top) and co-temporal significant wave height (H_{m0}) and energy period (T_e) (bottom) from December 2016 to March 2017.

Received levels were separated by frequency band and sea state parameters to examine the underlying mechanisms of sound production (Fig. 13). Sound below 10 Hz (b) was the dominant contributor to broadband levels and explains the majority of dependence on significant wave height. Specifically, the source of this sound was likely flow noise resulting from wave orbital motion. The “bearing warble”, which has a fundamental frequency of approximately 790 Hz, also exhibited a more limited sea state dependence (c). Sound between 5 and 20 kHz (d) was dominated by impulsive chain noise which, though excited by wave action, was infrequent and short in duration, such that aggregate statistics do not show a sea state dependence.

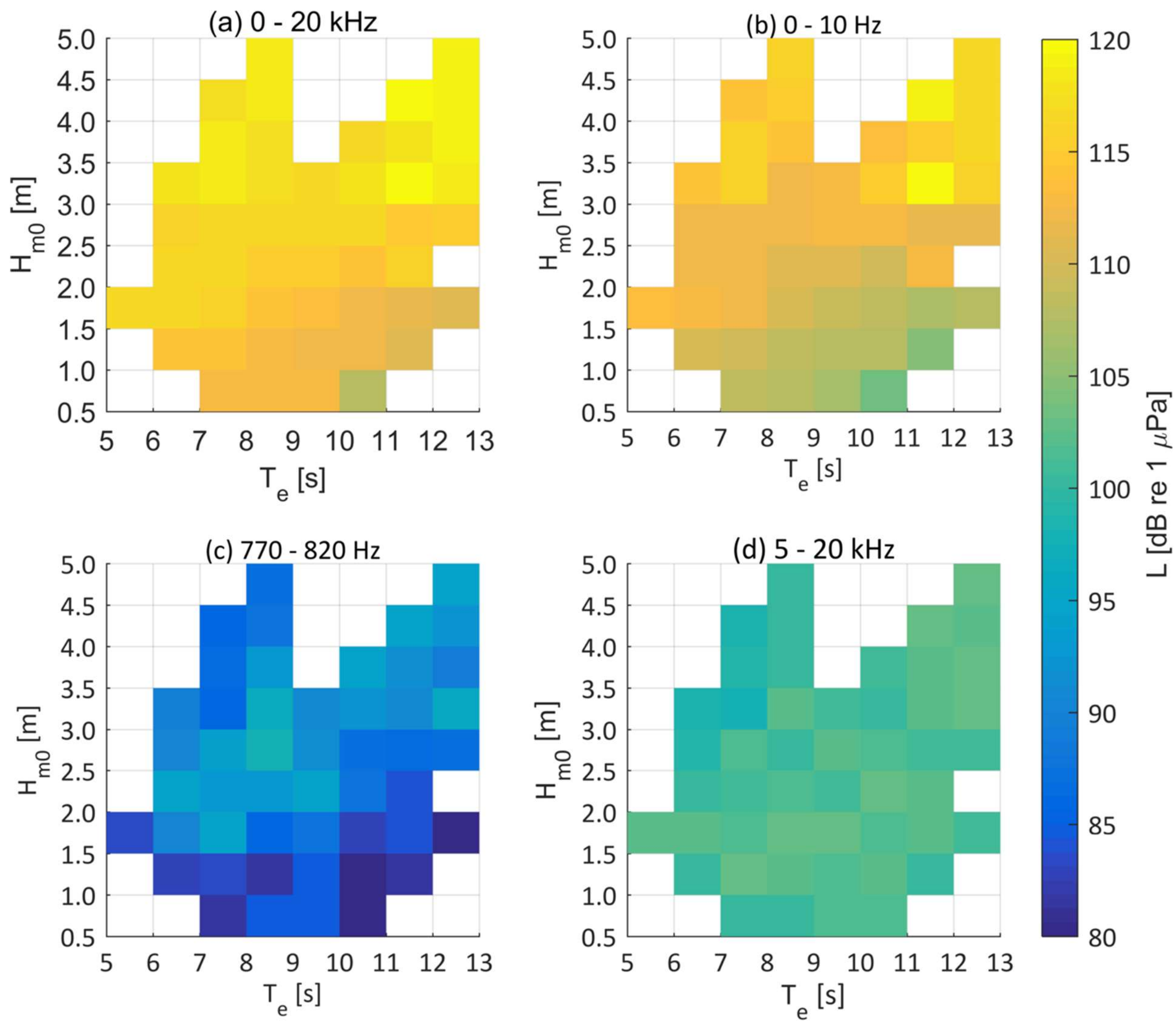

Fig. 13: Stationary platform received level as a function of sea state and frequency band. (a) broadband sound pressure levels (0 - 20 kHz), (b) band levels dominated by flow-noise (0 - 10 Hz), (c) band levels dominated by sound from damaged PTO bearing (770 – 820 Hz), (d) band levels dominated by metallic impulse from the permanent mooring.

In general, averaging sound pressure levels from many 30-second windows containing “episodic” events, such as impulsive mooring noise and bearing warble, reduced the contribution of these sound to the ensemble average, making it difficult to isolate their sea state dependence. Consequently, it is thought that isolation of shorter sample windows containing uncontaminated examples of WEC sound or chain impulse could further elucidate sea state dependencies. Although it is possible to undertake a manual analysis of this type for limited portions of the dataset, an approach utilizing machine learning would permit efficient analysis of the entire dataset. Furthermore, the process could reveal information about less frequent sounds that were not identified during the manual review process.

Recordings with drifting acoustic measurement systems have shown that PTO sound similar to that reported in observations of the Lifesaver in the UK was detectable above ambient sound levels at close range. However PTO sound was not conclusively identifiable in data from the stationary platform. It is possible that PTO sound during periods of high wave height may have been masked by flow noise, which is also correlated with wave height. In addition, because the bottom platform was considerably further away than drifting platforms, transmission losses could have reduced received levels below ambient.

It is also possible that PTO sounds were too similar to marine mammal vocalizations to conclusively identify them. The use of machine learning algorithms trained with samples of known marine mammal vocalizations may help to discover these sounds by process of elimination (i.e. after marine mammal sounds are clearly identified, the remaining unclassified sounds can be manually reviewed with greater scrutiny).

3.4 Platform Movement

Distinct changes in platform orientation were observed on the 13th and 15th of December 2016, at which times significant wave heights exceeded 2 m (Fig. 14). Unfortunately, the IMU's internal storage was entirely filled by late December, so it is unclear if orientation continued to change through March 2017, or if the platform settled into a stable orientation on the sea bottom. Future deployments should include a MAT-1 IMU logging at 1 Hz, which will be capable of logging for the entire deployment period. It is strongly recommended that the ballast be significantly increased prior to redeployment, particularly at the 30 m berth. This analysis from the 60 m berth suggests that the Sea Spiders would be marginally stable at the 30 m berth, which could explain the disappearance of one platform after an extended deployment with significant wave heights intermittently exceeding 3 m.

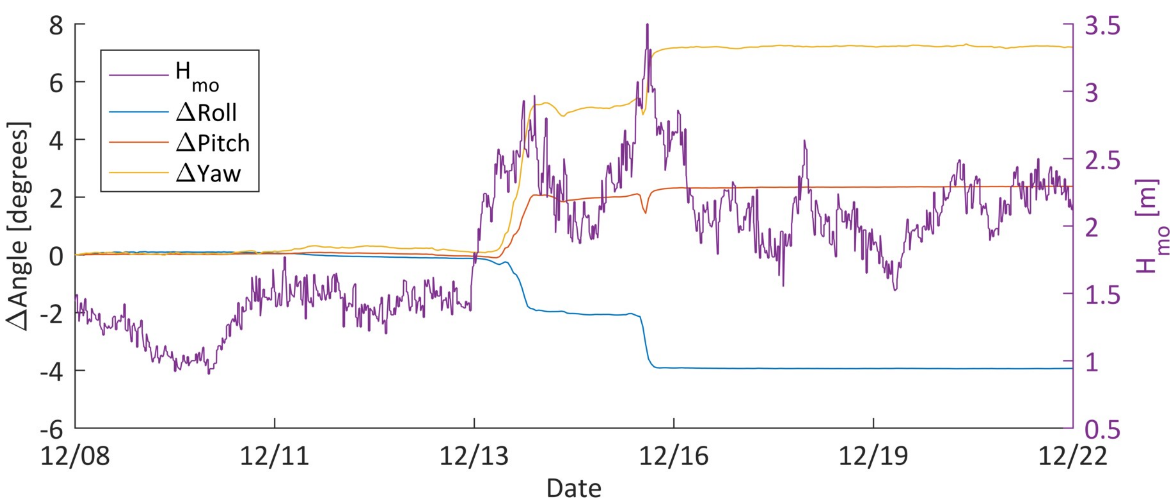

Fig. 14: Change in platform orientation principle angles and significant wave height (H_{m0}) over two weeks.

4 Conclusions

Broadband source levels estimated using a conservative assumption of practical spreading remained below 154 dB re 1µPa for over 99% of the recorded time. Because flow noise contributed significantly to exceedance events, it is believed that actual WEC source levels generally did not exceed the 154 dB regulatory threshold.

One sound in particular, the “bearing warble”, was shown to have a limited dependence on sea state. However, given the episodic nature of this sound (and of other sound sources at the site), 30 second spectral averages tend to decrease estimates its average SPL and mask its sea state dependence. All other episodic sounds were similarly affected. The use of shorter windows encapsulating each type of sound could provide more accurate, and possibly more revealing, results. As is the case with 30 second windows, it is feasible to manually review shorter windows of data which are representative of each sea state. However, an automated approach, such as one utilizing machine learning, could permit efficient isolation of windows containing various sounds, uncontaminated by vessel and flow noise, throughout the entire dataset.

Machine learning may also aid in the discovery of unknown sounds. For example, because it was difficult to distinguish suspected examples of PTO sound from marine mammal vocalizations, it was unclear if PTO sound was observed in the Sea Spider recordings. Using examples of marine mammal vocalizations from periods during which the WEC was not on site as “training” data, machine learning algorithms could isolate examples of marine mammal vocalizations. The remaining unclassified sounds could then be investigated to determine if the PTO or WEC are probable sources.

For machine learning to be effective, data features (in this case, episodic sound) must be parameterized in such a way that they are distinguishable from the rest of the dataset. For example, elevation of a narrow frequency band from neighboring bands could indicate a sound source. If elevated levels persists for multiple successive time windows, then the sound is tonal and of interest. Correlation with sea state parameters and time of day are also likely to help in distinguishing some sounds. Another method of parameterizing spectral data is to conduct principle component analysis on spectrograms, which may be effective for identifying flow noise or differentiating tonal sounds with particular “shapes”, such as moans and whistles, from one another.

5 Acknowledgement

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