PAPER

Design and Implementation of a Marine Animal Alert System to Support Marine Renewable Energy

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ABSTRACT

Power extracted from fast-moving tidal currents has been identified as a potential commercial-scale source of renewable energy. Marine and hydrokinetic (MHK) device developers and utilities are pursuing deployment of prototype tidal turbines to assess technology viability, site feasibility, and environmental interactions. Deployment of prototype turbines requires environmental review and permits from a range of regulatory authorities. Ensuring the safety of marine animals, particularly those under protection of the Endangered Species Act of 1973 and the Marine Mammal Protection Act of 1972, has emerged as a key regulatory challenge for initial MHK deployments. The greatest perceived risk to marine animals is from strike by the rotating blades of tidal turbines. Development of the marine animal alert system (MAAS) was undertaken to support monitoring and mitigation requirements for tidal turbine deployments. The prototype system development focused on the Southern Resident killer whale (SRKW), an endangered population that frequents Puget Sound, Washington, and is seasonally present in the part of the sound where deployment of prototype tidal turbines is being considered. Passive acoustics were selected as the primary means to detect the SRKWs because of the vocal nature of these animals. The MAAS passive acoustic system consists of a two-stage process involving the use of an energy detector and a spectrogram-based classifier to distinguish between SKRW calls and background noise. A prototype consisting of two 2D symmetrical star arrays separated by 20 m center to center was built and evaluated successfully in the waters of Sequim Bay, Washington, using whale-call playback.

Keywords: tidal power, Southern Resident killer whales, passive acoustics, renewable energy

Introduction

Marine and hydrokinetic (MHK) power sources in general, including tidal power, have been identified as a potential commercial-scale source for sustainable power (Ben Elghali et al., 2007). However, there currently are no tidal power generating stations in the West Coast of the United States. A number of tidal power developers and utilities are pursuing deployment of prototype tidal turbines to assess the viability of current designs and sites and to better understand potential environmental risks. Deployment of prototype turbines requires environmental review and permits from regulatory authorities with the responsibility to protect the safety of the marine environment, including marine animals. The most challenging aspect of selecting a site and permitting tidal turbines in U.S. waters is ensuring the safety of marine animals, particularly those under special protection of the Endangered Species Act of 1973 (ESA) and the Marine Mammal Protection Act of 1972 (MMPA). The National Oceanic and Atmospheric Administration (NOAA) Fisheries has responsibility for enforcing the MMPA and the ESA; NOAA regulators have stated that they will not allow deployment of tidal turbines unless they are assured that listed marine mammals are not at risk. Potential risk to other animals with special protection has not yet been addressed.

Snohomish County Public Utility District (SnoPUD) selected Admiralty Inlet in Puget Sound, Washington, as a potential site, because of its strong tidal currents, to deploy tidal power-generating devices near a major load center. SnoPUD received a preliminary permit from the Federal Energy Regulatory Commission to deploy two OpenHydro (Dublin, Ireland) tidal turbines. Puget Sound is home to the Southern Resident killer whales (SRKWs, *Orcinus orca*), which constitute a distinct population of killer whales inhabiting the coastal waters of Washington state and British Columbia (Krahn et al., 2009; Hanson et al., 2010). SRKWs, numbering fewer than 90 animals, were listed as endangered under the ESA in 2005 (NOAA Fisheries, 2008). The most critical permitting issue for the final licensing approval of the SnoPUD project involves determining and minimizing the risk to the SRKWs from turbine blade strike.

Pacific Northwest National Laboratory (PNNL) was tasked by the U.S. Department of Energy to develop technology using passive or active acoustics to assist the MHK industry in managing the risk of injury or mortality to animals from blade strike or other direct interaction with MHK devices. The primary purpose of the marine animal alert system (MAAS) technology is to monitor animals in the vicinity of the MHK devices; secondarily, the MAAS can assist with mitigating the risk to marine animals.

We focused on the proposed tidal development in Puget Sound and SRWK monitoring and detection. Initially both passive and active acoustics were considered. However, NOAA Fisheries expressed concern that the effective range of 200-kHz sonar systems under consideration could cause behavior change of actively migrating SRKWs. Subsequently, we confirmed the presence of sufficiently high energy levels of sideband sound generated by 200-kHz echo sounders to be heard by SRKWs at distances up to several hundred meters from the echo sounders. We discontinued development of the active acoustic element of the MAAS pending action on the part of regulatory authorities to provide guidance for permitting the use of active acoustics to observe marine mammals. Our focus turned to passive acoustics as a means to detect the presence of SRKWs, as these animals are very vocal. SRKWs use echolocation to find and hunt for prey, communicate and navigate, using a variety of calls (Ford, 1991). Several existing marine animal detectors (Mellinger & Clark, 2000; Erbe & King, 2008; Gillespie et al., 2008; Baumgartner & Mussoline, 2011) were evaluated but were found to be unsuitable for this study because they could not meet requirements for high detection efficiency and real-time monitoring while minimizing false alarms. In this paper, we describe the design, implementation, and performance of the passive acoustic portion of the MAAS.

Whale Call Characteristics From a Whale Call Library

The underwater vocalizations of killer whales are usually categorized into three classes: clicks, whistles, and pulsed calls. The clicks consist of a short sequence of pulses in varying frequencies. The whistles show continuous waveforms with little or no harmonics in the spectrogram. The pulsed calls are the most complex signals produced by killer whales, with varying harmonics (Ford, 1989; Brown et al., 2006). Pulsed calls from the majority of calls heard during activities such as traveling and foraging, the most commonly observed whale activities, and the call source levels are in the range of 160 dB re 1 μPa at 1 m (Riesch et al., 2008).

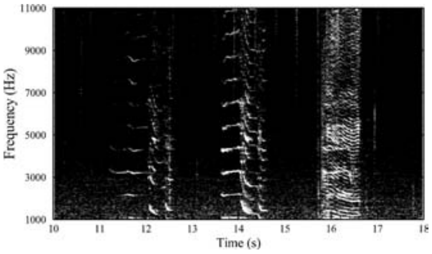
The whale calls used in this study are pulsed calls. A statistical characterization was performed on the calls in the SRKW call library provided by the Sea Mammal Research Unit (SMRU). This library contains 1-min sound files of whale calls recorded from July 2 to August 17, 2010. There are 482 human-annotated calls, of which 460 are pulsed calls, which cover about 40 different call types such as S1, S3, buzz, and aberrant. For each whale call, the annotation includes the call starting time, duration, and type. The annotated calls were analyzed in the time and frequency domains. Every call type was included in the characterization.

The average call duration of the 460 annotated pulsed calls was 0.85 s with a standard deviation of 0.53 s, and the median was 0.76 s. The maximum call duration was 4.21 s from a type S10 call, and the minimum was 0.09 s from an unknown harsh call. These observations are consistent with the findings by Ford (1989).

For the analysis in the frequency domain, the whale calls were extracted according to the annotated starting and ending times. The signal of the corresponding background noise was extracted 1 s prior to the whale call. The fast Fourier transform (FFT) was applied to the calls and background noise signals, followed by the frequency bands of the whale calls and background noise signals being determined by detecting the peak frequencies. Peak frequency detection showed that most of the peaks obtained from the whale-call signals were within the range of 1–6 kHz. The peaks of the background noise signals are approximately 1.5 kHz or less. This led to selection of a lower frequency bound of 1 kHz for whale calls. Furthermore, some of the signals had peaks between 8 and 11 kHz. Peaks of whale calls and noise rarely appeared over 20 kHz. To detect most of the whale calls, the upper frequency bound of the whale calls was set at 11 kHz. To verify the frequency band determined from the frequency domain analysis, spectrograms in the frequency-time frame were generated for all the annotated signals. Figure 1 shows an example of three annotated calls that can

FIGURE 1

Spectrogram of a call in the SRKW call library provided by the Sea Mammal Research Unit.



be clearly identified on the spectrogram within the frequency band of 1–11 kHz.

Southern Resident Killer Whale Call Detection

The MAAS detection system has two stages (Figure 2). In the first stage, an energy detector detects whether a sound, which may be a SRKW call, is present. If a candidate sound is detected, it is captured for the second stage of processing. In the second stage, the candidate sound is processed to determine if it has the characteristics of a SRKW call or if it may be another sound, such as vessel noise, not produced by a SRKW.

The energy detector was modified from the Juvenile Salmon Acoustic Telemetry System (JSATS) cabled system, a nonproprietary sensing technology deployed system-wide in the lower Columbia River basin for evaluating the behavior and survival of migrating juvenile salmon and other endangered species passing through hydroelectric dams (McMichael et al., 2010; Deng et al., 2011; Weiland et al., 2011). The processing flow for the MAAS whale call energy detector is shown in Figure 3. Audio signals entered the detector from the system hydrophones in the form of a data packet, which contained 5 million samples of raw data, with a duration of 5 s at the 1-MHz sampling frequency. The signals were filtered to a band known to contain most of the energy in SRKW calls, and the signals were squared to compute energy within a predefined window length of 0.4 s (or about half the typical duration of a SKRW call). Two thresholds were used for detection analysis. The first threshold (E) is a function of background noise, usually set at one to two times the background noise. The second threshold (TH) is the number of samples above the first threshold with the computed energy value at these samples monotonically increasing. If both thresholds were met, then a candidate whale call was detected and the packet was saved to the host computer. For example, Figure 4 shows an audio signal of the SMRU library and the response of the detector to segments within the sample that contain known SRKW calls. Also shown are audio signal segments that satisfy detector criteria but contain only noise; these signal segments are identified as candidate whale calls and captured for further processing. Figure 5 shows another example of the detection process. The first threshold was set to 1.2 times the background noise and the second threshold to 100,000 samples. The number of samples above the first threshold with the correlation values monotonically increasing is 195,000, larger than the second threshold. Therefore, this packet was determined to be a candidate and saved to the host computer for second-stage processing. The window length and the two detection thresholds are user-definable and are configured to optimize detection efficiency while filtering out sound that is not produced by a SRKW.

Candidate whale calls were further processed to reduce the occurrence of false detections while preserving true detections. The processing flow for the classification stage of the whale call detector is shown in Figure 6. The first step in processing a candidate whale call was to obtain a spectrogram by using short-time Fourier transform (STFT). The spectrogram was filtered

FIGURE 2

Major elements of the detection and classification component of the MAAS passive acoustic system.

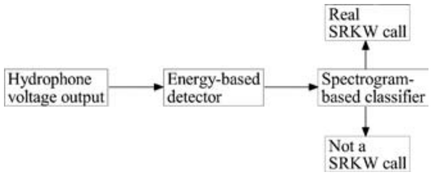


FIGURE 3

Processing flow diagram for the MAAS whale call energy detector.

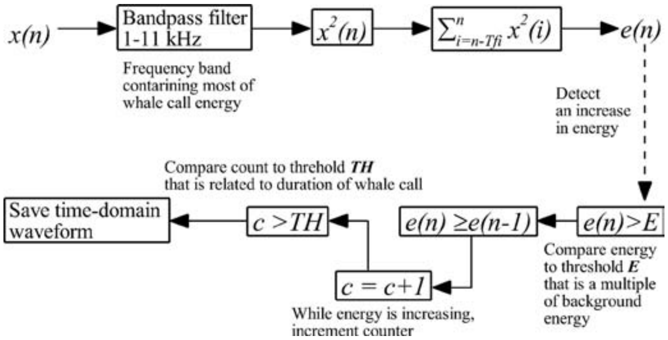


FIGURE 4

Audio signal from a star array hydrophone (upper panel) and corresponding output of the whale call detector (lower panel). Known whale calls are highlighted in green in the upper panel. In the lower panel, green highlights are segments of the detector output that correspond to the known whale calls. Segments circled in red are false whale calls that passed the energy detector. (Color versions of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2013/00000047/00000004.)

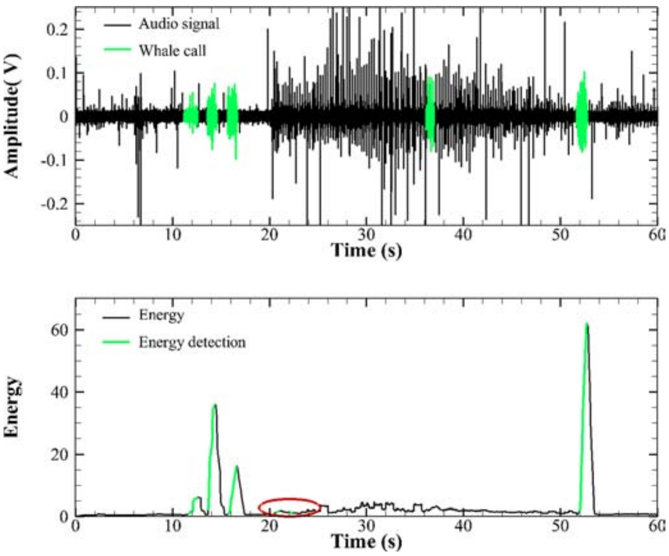
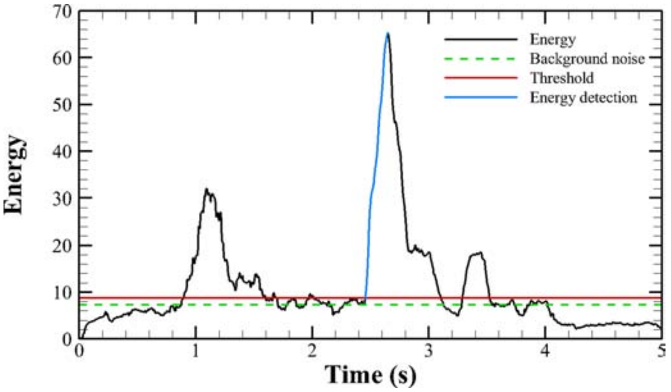


FIGURE 5

Computed energy of a candidate whale call that passes the first-stage detector.



by Gaussian filter to remove noise pixels; then, a noise suppression method proposed by Boll (1979) was applied along each frequency bin and time bin to suppress background noise. All possible whale call pixels were kept, and all background noise pixels were converted to white pixels after these two filters. Next, all connected remaining pixels were grouped into segments. For each segment, the mean and standard deviation (STD) were calculated; pixels in a segment were converted to white pixels when they were less than the mean minus 0.5 times STD. The segments were removed if they met any of the following criteria: (1) segments were not overlapping with detection time of the energy detector; (2) the number of pixels in the segment was greater than 25% of the size of the segment; (3) the segments were small (having fewer than 8 pixels); (4) the segments were large (having more than 400 pixels); and (5) segment width was less than 8 pixels. After segments were cleaned, the candidate whale call was classified as a valid whale call if more than one segment existed.

Figure 7 shows a series of spectrograms at various stages of processing the classification for a candidate whale call. The original spectrogram (Figure 7a) was obtained by applying the STFT to the candidate whale call. The second spectrogram (Figure 7b) displays results of the original spectrogram smoothed by Gaussian filter, which was achieved by convolution. One of the main justifications for using a Gaussian filter is the frequency response, as most of the convolution-based smoothing filters act as low-pass filters. The final filtered spectrogram (Figure 7c) illustrates the smoothed spectrogram filtered along both frequency and time bins by using the noise suppression reduction (Boll, 1979). In the time bin direction, the median value was calculated using a sliding window of 400 Hz instead of the entire dataset from 1 to 11 kHz. In this case, each pixel was compared with its own median, creating more accurate noise reduction. The filtered spectrogram was then segmented. The segments were eliminated according to the characteristic of whale calls. Figure 7d presents the segments after the removal of those not overlapping with the time period from energy detector. Then the small and narrow segments were removed (Figure 7e). Each segment was checked based on the number of pixels in the frequency band and the unqualified pixels removed. The remaining segments presented in

FIGURE 6

Steps in processing a candidate whale call detection to decide if it is a valid call.

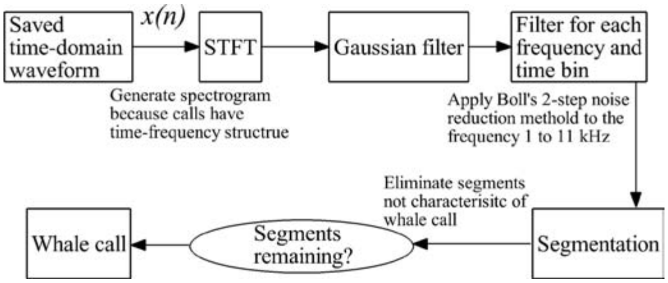


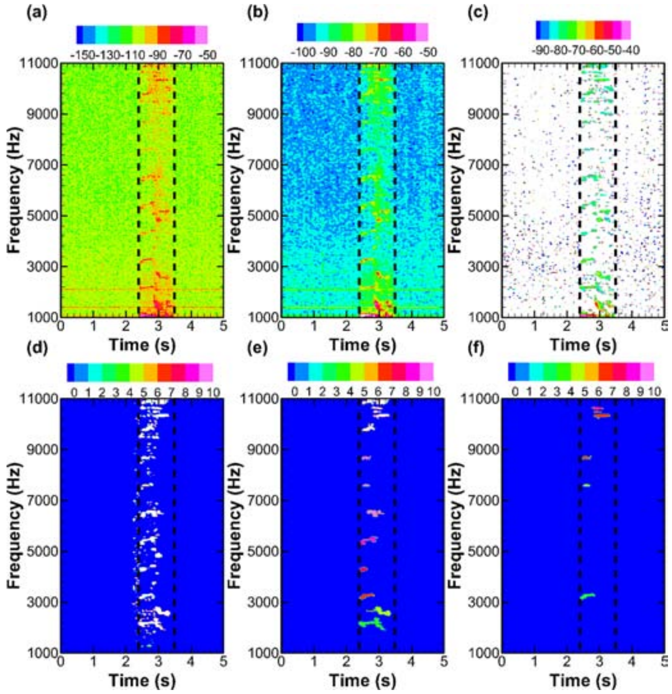
Figure 7f indicates the whale calls verified by the classification.

System Implementation

Both the hardware and software components of the MAAS passive acoustic system were packaged for field deployment (Figure 8). The in-water portion of the system included two star arrays, modified from the star array used by Au and Herzing (2003) to track the Atlantic spotted dolphin. Each 2D star array consisted of four hydrophones (Model TC4032, RESON A/S, Slangerup, Denmark) in a symmetrical star configuration (Figure 9). One hydrophone was located in the center of the array; the other three hydrophones were set on 2-m-long extensions at an angle of 120° from one another. The TC 4032 hydrophone (Figure 10) is a sea-state zero hydrophone with low noise and a flat frequency response up to 120 kHz, with a built-in 10-dB preamplifier that amplifies the low analog voltage signal out of the hydrophone's piezoelectric element. The hydrophones were connected to a cable junction box on the shore. The preamplified analog signal was then transmitted to a signal conditioner (Model VP2000, RESON A/S, Slangerup, Denmark) for further amplification and conditioning prior to input to a DSP + FPGA card (digital signal processor TMS320C6713 and field programmable gate array Xilinx XC3S1000, Innovative P25M; Innovative Integration, Simi Valley, CA) resident in the data acquisition computer for detection analysis. Both the signal conditioning interface and the detector were designed to simultaneously process the data from the four hydrophones of one star array.

FIGURE 7

Spectrograms illustrating the treatment of the spectral information in the whale call candidate signal to prepare the sample for classification: (a) original spectrogram; (b) smoothed by Gaussian filter; (c) after Boll's two-step noise reduction; (d) segments after removal of those not overlapping with the time period from energy detection; (e) after small and narrow segments are removed; (f) final segments after unqualified points are removed.



The two arrays were operated independently but are synchronized to submicrosecond accuracy using Global Positioning System (GPS) receivers (Meinberg GPS 170PCI, Meinberg Funkuhren GmbH & Co. KG, Bad Pymont, Germany). A bearing to a detected sound source was determined for each array, and the source was localized using the intersection of the two bearings. This paper focuses only on the detection and classification of SRKWs because the localization aspect is being optimized and not yet been built into the hardware.

A user-friendly graphical user interface (GUI) was built to visually confirm calls detected by the energy detector (Figure 11), written in MATLAB (R2011b, 7.11) on Microsoft Windows 7. When the GUI is launched, the parameter setting window appears with default values. The

FIGURE 8

Marine animal alert system passive acoustic system hardware diagram.

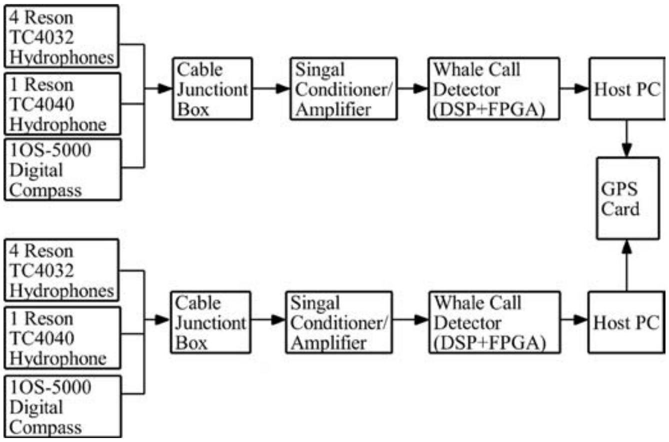


FIGURE 9

One 2D symmetrical star array (before hydrophones installation) deployed in Sequim Bay, Washington.

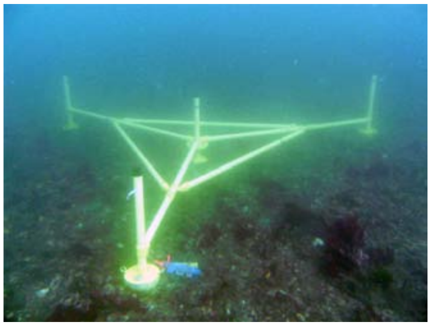
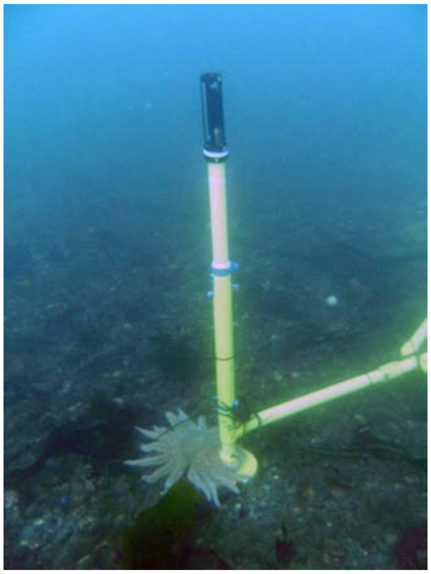


FIGURE 10

Hydrophone deployed in Sequim Bay, Washington.



parameters include the limit of processing delay time, the lower and upper bounds of the band-pass filter, and resolution settings. The user can modify the parameter values and save a new configuration. The main interface has separate blocks for the detected data folder path, process mode, process status, and results.

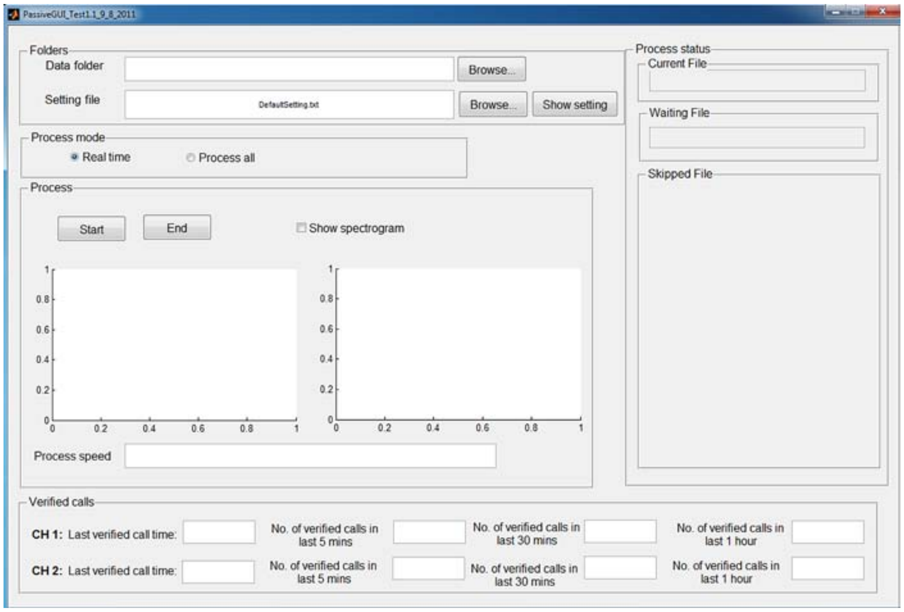
Two process modes may be selected—*Real time* or *Process all*. In the *Real time* mode, the classifier skips to the most recent recorded file, commonly when the processing speed is slow and too many files are waiting to be processed. Slowness is determined by the processing delay time parameter. Once the data folder is selected, the classifier automatically detects unprocessed files and starts the batch process according to the process mode. The *Process status* block displays the current file and the skipped files. The *Process* block shows the spectrogram for each channel of the signals. The detection results are marked on the spectrograms. The user can also choose to hide the spectrogram images for improved processing speed.

Field Validation

The two star arrays were deployed at a separation of 20 m and water depth of 10 m in Sequim Bay, Washington. Nine test locations for a sound source were chosen within a radius of 200 m from the center of a line connecting the star arrays (Figure 12). For each test

FIGURE 11

Main window of the spectrogram-based classifier graphical user interface.


PassiveGUI_Test1.1_9_8_2011

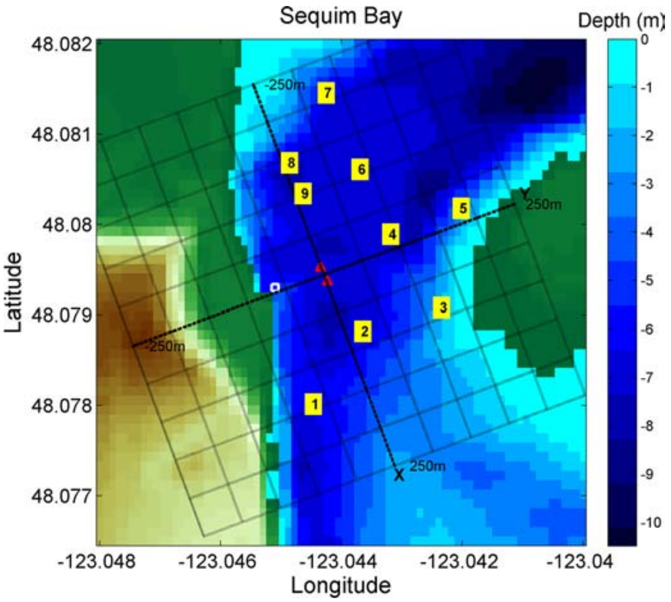
Setting file: DefaultSetting.txt

Process mode: ● Real time ○ Process all

☐ Show spectrogram

FIGURE 12

Test site and test locations for the validation experiment in Sequim Bay, Washington. The red triangles are star arrays and yellow squares are boat positions where simulated calls originated.



location, an acoustic beacon (Model AAE 319, Applied Acoustic Engineering Limited, Great Yarmouth, U.K.) with a source level of 180 dB relative to 1 µPa at 1 m was placed at a depth of 2 m. After reception of beacon signals was verified for each source location, an ensemble of six different types of whale calls was transmitted using a high-power broadband piezoelectric underwater transducer (Model LL9162T, Lubell Labs Inc., Columbus, OH) deployed from a silent anchored vessel. The whale calls were obtained from the SRKW call library provided by SMRU and were transmitted at source levels of 150 dB relative to 1 µPa at 1 m.

The test results show that detection efficiency was, as expected, highest at the shortest range tested, 133 m (Table 1), and lowest at the longest range, 191 m (Table 2). The performance of the whale call detector was tested for all eight hydrophones in the receiving arrays. In practice, all of the hydrophones in the array would be scanned for detections of whale calls, and the performance of the complete array would be determined by valid detections of whale calls on at least one hydrophone in the array. In this context, the highest of the detection efficiencies at each range would be the best estimate of detector performance for the array. Therefore, the performance of the system to detect a whale call with a source level of 150 dB relative to 1 µPa would be on the order of 75% at a range of nearly 200 m and 100% at a range of 133 m.

When the performance of the first-stage detector was removed from the assessment, the whale call classifier correctly identified virtually 100% of the whale calls detected by the system. The combined detector-classifier performance at a source level of 150 dB relative to 1 µPa was on the order of 90% at 133 m and decreasing to approximately 60% at 191 m. The false

TABLE 1

Results for whale call detection and classification performance for all hydrophones in the paired star array, for an ensemble of whale calls with a source level of 150 dB relative to 1 µPa, at a range of 132 m from the receiving array.

Channel	Transmitted Signals	Signals Saved by Detector	Signals After Classifier	Valid Signals After Classifier	False Positive Rate (%)	System Detection Efficiency (%)
1	116	103	84	84	0	72.4
2	116	102	88	88	0	75.9
3	115	115	103	103	0	89.6
4	115	113	93	93	0	80.9
5	116	114	105	105	0	90.5
6	116	115	105	105	0	90.5
7	116	115	101	101	0	87.1
8	116	115	105	105	0	90.5

TABLE 2

Results for whale call detection and classification performance for all hydrophones in the paired star array, for an ensemble of whale calls with a source level of 150 dB relative to 1 μPa, at a range of 191 m from the receiving array.

Channel	Transmitted Signals	Signals Saved by Detector	Signals After Classifier	Valid Signals After Classifier	False Positive Rate (%)	System Detection Efficiency (%)
1	102	61	54	53	1.6	52.0
2	102	61	51	50	1.6	49.0
3	102	78	65	61	5.1	59.8
4	102	75	58	57	1.3	55.9
5	102	50	43	42	2.0	41.2
6	102	49	44	43	2.0	42.2
7	102	72	52	50	2.8	49.0
8	102	70	49	46	4.3	45.1

positive rates ranged from 1% to 6% at 191 m to no false positives at 133 m. For whale calls at a typical source level of 160 dB re 1 μPa at 1 m (Riesch et al., 2008), the combined detector-classifier efficiency would be over 90% at approximately 415 m and 60% at approximately 593 m, assuming spherical spreading (20 × log↓10 *R*) and an absorption loss of 0.38 dB/km using the formula proposed by Ainslie and McColm (1998).

Conclusions

Development of the MAAS was undertaken to support monitoring and mitigation requirements for tidal turbine deployments. The prototype system development focused on SRKWs, an endangered population of killer whales that appears seasonally in Puget Sound and is frequently present in the part of the region where deployment of prototype tidal turbines is being considered. A prototype of the passive acoustic portion of the MAAS was modeled, built, and deployed, and its performance was evaluated in Sequim Bay. The configuration build consisted of two 2D symmetrical star arrays separated 20 m center to center. The system was able to successfully acquire and process eight channels of data at a digital frequency of 1 MHz for each channel to perform detection of SRKW calls. At an assumed typical source level of 160 dB re 1 μPa at 1 m for whale calls, the combined detector-classifier efficiency would be higher than 90% at approximately 415 m and 60% at approximately 593 m. Overall, the results showed the MAAS passive acoustic monitoring system may potentially be deployed to obtain monitoring information to assist environmental review and permitting of ocean renewable energy devices.

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