RAPIDLY DEPLOYABLE ACOUSTIC MONITORING AND LOCALIZATION SYSTEM BASED ON A LOW-COST WAVE BUOY PLATFORM

DE-EE0007822

Final Report

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ACRONYMS AND ABBREVIATIONS

BAR	broadband acoustic recorder
BP	budget period
COTS	commercial off-the-shelf
dB	decibel
DAISY	Drifting Acoustic Instrumentation SYstem
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
GTI	Geospectrum Technologies, Inc.
HDPE	high-density polyethylene
IMU	inertial measurement unit
ME	marine energy
MSL	Marine Science Laboratory (energetic testing site)
PNNL	Pacific Northwest National Laboratory
Q	quarter
SB2	Sequim Bay 2 (quiescent testing site)
SIO	Scripps Institution of Oceanography
TRL	technology readiness level
UW	University of Washington
VSA	vector sensor array
WEC	wave energy converter

EXECUTIVE SUMMARY

The primary objective of this project is to develop a cost-effective, fit-for-purpose environmental monitoring system, "NoiseSpotter®," that characterizes, classifies, and provides accurate location information for anthropogenic and natural sounds in near real-time. NoiseSpotter was developed to support the evaluation of potential acoustic effects of marine energy (ME) projects. By utilizing a compact array of three acoustic particle motion sensors, NoiseSpotter triangulates individual bearings to provide sound source localization to within 5% accuracy, allowing the ability to discern ME device sounds relative to other confounding sounds in the environment, while providing location estimates to nearby marine mammals for environmental mitigation purposes.

The ME industry needs proven solutions to meet environmental impact assessment needs. The NoiseSpotter® includes off-the-shelf, modular components that are easy to assemble and disassemble. Its acoustic particle motion sensors are commercially available and the data logger and real-time telemetry system is designed to be plug-and-play. The entire system is relatively compact and can be deployed from small vessels. NoiseSpotter's near real-time capability enables operational monitoring of ME sounds, particularly during early stages of technology adoption to facilitate mitigation of potential noise effects. Widespread adoption of the technology for acoustic monitoring of ME devices requires that it be cost effective; hence the anticipated commercial cost of system hardware is $35,000.

This project contributes to reducing barriers to ME testing through support of scientific research focused on reducing or mitigating environmental risks and lowering costs and complexity of environmental monitoring. This project has developed an acoustic monitoring system, NoiseSpotter® (U.S. Patent No. 11,156,734 and U.S. Registered Trademark No. 6,442,313), to detect and characterize baseline noise and sounds from ME operations and support geolocation of detected sounds. The intended outcome of the project is to mitigate concerns about the potential for ME device noise to alter marine mammal or fish behavior. NoiseSpotter® enables cost-effective, near real-time acoustic monitoring of an operational ME device relative to ambient environmental noise and provides a technical basis for ME developers seeking to navigate the permitting process in an efficient manner.

1 PROJECT GOALS AND OBJECTIVES

The overall goal of this project, "Rapidly deployable acoustic monitoring and localization system based on a low-cost wave buoy platform," (funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy [DOE EERE], Award No. DE-EE0007822) is to develop new acoustic monitoring technology to support evaluation of potential environmental effects of marine energy (ME) devices. We significantly improve upon traditional acoustic sensing techniques by developing a cost-effective compact array of acoustic particle motion sensors that characterizes, classifies, and provides accurate location information for anthropogenic and natural sounds.

Acoustic sensing techniques typically involve the use of hydrophones that measure acoustic pressure, a scalar quantity that provides no directional information as to the location of the source of sound. As a result, localizing the source of sound is typically achieved by large arrays consisting of multiple time-synchronized hydrophones. Further, for most deployments of acoustic instruments, data are stored onboard for the entire duration of the deployment. Data analysis following instrument recovery provides soundscape characterization, including information about the source of sound.

This project aims to use acoustic particle motion sensors that measure 3-D acoustic particle velocity in addition to acoustic pressure on a single sensor. This vector-based measurement inherently provides directional information regarding the source of sound. Unlike a hydrophone, a single particle motion sensor (commonly known as a vector sensor) provides a bearing to the source of sound. A vector sensor array (VSA) can therefore triangulate individual measured bearings to provide sound source localization, and thereby help characterize sound specific to a source. This localization ability is key to characterizing sounds from ME devices, which are expected to emit low intensity sounds on the order of 110–130 dB referenced to microPascal (re 1 μPA), with other sources of sound likely to be present in the vicinity, including boats, industrial activities, and natural sources, such as marine mammals, and breaking waves. In addition to providing the ability to localize and characterize sounds from ME devices, the project will develop the ability to process acoustic data in near real-time. Processed data metrics, such as source location, peak sound levels, signal to noise ratios, and ambient noise levels, will be compiled into a compact data digest for relay to a cloud-based data system.

At the end of this project, the resulting product is a fit-for-purpose acoustic sensing unit (called NoiseSpotter®) that consists of three acoustic particle motion sensors, a data logging/processing unit, and a surface buoy to relay acoustic data metrics in near real-time to a cloud-based storage system.

Specific objectives for each budget period were as follows:

- BP1: Formulation of in-water testing plan, demonstration of baseline and initial performance, and refinement of plans for performance and cost improvements.
- BP2: Design and engineering of NoiseSpotter® with post-processed location estimation. Second-phase in-water testing in collaboration with Pacific Northwest National Laboratory (PNNL) using the NoiseSpotter platform, with location estimates compared against known sources at known locations.
- BP3: Refine instrumentation of the NoiseSpotter along with testing, validation, and performance comparison against other awardees in an energetic environment representative of an ME device locale.

The actual accomplishments compared to project goals and objectives are described below. Integral Consulting Inc. (Integral) developed NoiseSpotter® (U.S. Patent No. 11,156,734 and U.S. Registered Trademark No. 6,442,313), which is a cost-effective, compact array of acoustic particle motion sensors that characterizes, classifies, and provides accurate location information for anthropogenic and natural sounds, thereby significantly improving upon traditional acoustic sensing techniques. NoiseSpotter represents the first passive acoustic monitoring system that can measure, characterize, and localize underwater sounds, all on a single platform. The ability to archive and process raw acoustic data onboard the system and relay – in near real-time – compressed data to a cloud-based server for further processing and reporting is unprecedented for acoustic particle motion-based systems.

The critical success factors that define the viability of the system include:

- Location estimation – the low levels of sound that ME devices are expected to produce necessitate location estimation to allow for the ability to distinguish ME sound from other ocean sounds. The project team successfully implemented beamforming techniques (among others) for accurate source location estimation in quiescent and energetic environments, with geolocation accuracy to within 5% of actual, with source-receiver separations that ranged from 50 m to 500 m (comparable to other methods such as the use of multiple tetrahedral arrays of hydrophones [Tessei et al., 2012]. This will allow the system to distinguish ME noise from surrounding environmental sounds.
- Flow noise removal – deployment of acoustic monitoring systems in energetic areas can result in degraded data quality from flow noise effects. Several iterations of the NoiseSpotter® platform design were necessary to mitigate flow noise effects. The final, validated design includes custom flow noise shields around each particle motion sensor that reduce turbulence associated with water flow over the sensors, resulting in flow noise reduction of more than 15 dB at frequencies below 200 Hz, which is the primary flow noise frequency band. This design allows for effective acoustic monitoring at energetic sites.
- Ease-of-operations and robustness – the ME industry needs proven solutions to meet environmental impact assessment needs. NoiseSpotter® includes off-the-shelf, modular components that are easy to assemble and disassemble. Platform materials are acoustically transparent to ensure high acoustic data quality. The acoustic sensors, data

logger, and real-time telemetry system are designed to be plug-and-play. A robust post-processing pipeline has been developed to create calibrated data files and provide an initial visualization of the data collected. More sophisticated analysis will likely require specific acoustic expertise that can be requested from Integral. The entire system is relatively compact and can be deployed from small vessels (e.g., 25 ft). Laboratory bench-top and in-water system testing and validation of NoiseSpotter demonstrated sustained, autonomous monitoring over 2+ week deployment periods.

- Near real-time reporting – operational monitoring of ME sounds, particularly during early stages of technology adoption, requires near real-time reporting to facilitate mitigation of potential noise effects. NoiseSpotter telemeters, in near real-time, compressed data digests to a cloud-based server that facilitates rapid characterization, classification, and geolocation of sources of sound in the environment. Final in-water testing demonstrated 0% data dropout over 8+ hours of monitoring.
- Target price of the system – widespread adoption of the technology for acoustic monitoring of ME devices requires that it is cost effective. The anticipated commercial hardware cost of NoiseSpotter is $35,000. Technical and cost performance analysis shows that the NoiseSpotter can achieve a 38% cost savings over current commercial off-the-shelf (COTS) technology.

Project accomplishments benchmarked against the original technical targets are shown in Table 1. Target technical performance metrics were met or exceeded with the exception of system needs for deployment and recovery. The original performance objective was hand-deployability/recovery by two persons from a small vessel without need for a winch or A-frame. In-water tests determined that the NoiseSpotter® platform requires a vessel A-frame or davit for safe and successful deployment and recovery. This is due to platform redesign from the original mid-water column mooring to a bottom platform to improve system stability and data quality.

Table 1. Project accomplishments benchmarked against original technical targets.
Scores are 0 to 10, with zero representing no issue and, e.g., 2 to 4 representing room for improvement.

Technical Performance Category	Final Score	Target Score
Detection frequencies	2 20 Hz – 20 kHz broadband, 10 Hz – 3 kHz particle motion	2 40 Hz to 5 kHz
Detection sensitivity	1 -194 dB – 230 dB	1 -194 dB – 230 dB
Ambient noise removal	1 Processing across multiple sensors suppresses incoherent ambient noise	1 Coherent processing across multiple sensors suppresses incoherent ambient noise
Horizontal flow noise removal	1 Flow noise shields reduce flow noise by >15 dB at <200 Hz and <1 dB signal loss at >200 Hz	2 Flow noise reduction of 2 dB at <200 Hz and <1 dB signal loss at >1 kHz

Vertical flow noise removal	1 <5° movement in pitch, roll, and yaw. Shock-mounted sensor configurations; bottom-mounted platform configuration	1 <5° movement in pitch, roll, and yaw. Shock-mounted configuration decouples buoy from surface wave motions
Data logger noise	2 NoiseSpotter® signals comparable to broadband acoustic recorder (BAR)	2 NoiseSpotter® signals comparable to BAR
Signal losses	0 <2 dB signal loss	0 <2 dB signal loss
Data quality	0 Zero dB degradation in signal to noise ratio	0 Zero dB degradation in signal to noise ratio
Clock	0 All sensors synchronized to GPS clock during start-up; all three sensors are logged synchronously	0 All sensors synchronized to GPS clock
Location estimation accuracy	1 Bearing estimates to within 2 m (within 5% of actual)	4 Bearing estimates <100 m
Data presentation and interpretation	1 Data digests @ 140 kB/digest from which peak exceedance levels, RMS sound pressure and location estimates can be computed.	1 Short data digests for decision-making; peak exceedance levels, RMS sound pressure, location estimates
Onboard data storage	1 1 TB	1 48 GB/day @ 25 kHz for 40 days
Data communication	2 >10 Mb/s throughput, cellular range: coastal, <1% data drop-outs, automatic data queuing, automatic system re-establishment	2 6 kb/s transmission of key data metric digest, satellite range: unlimited, <1% data drop-outs, automatic data queuing, automatic system re-establishment
Power budget	3 7 W; however NoiseSpotter® is designed with custom rechargeable 512 Ahr battery packs; therefore, its maximum deployment duration is not compromised	3 2 W of electrical power including acoustic sensors, analysis, storage
Operations	4 2 personnel and vessel assistance (e.g., A-frame) for deployment/recovery	2 2 personnel for deployment/recovery; no vessel assistance
Operational duration	1 Autonomously for 35+ days	2 Autonomously for 7 days
Operational environments	0	0

	Any: inland waters, harbors, surf zone, coastal ocean, open ocean; low to high energy	Any: inland waters, harbors, surf zone, coastal ocean, open ocean; low to high energy
Cost	2 <$35,000	2 <$35,000

2 PROJECT ACTIVITIES

A summary of project activities for the entire period of funding is provided here, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results. Project activity descriptions are organized by budget period.

2.1 BUDGET PERIOD 1

Baseline technical and cost performance were determined through baseline and initial testing at PNNL with a COTS passive acoustic sensor and known sources. Detailed, refined design and engineering plans for NoiseSpotter® were completed, with the goal of performance (including flow-noise removal) and cost improvements. An in-water testing plan for the NoiseSpotter was developed in collaboration with PNNL.

2.1.1 Tasks and Milestones

Task 1.0: Develop in-water testing plan. Work with PNNL to coordinate field-testing with known acoustic sources and other DOE EERE awardees to enable the establishment of baseline performance and quantitative analysis of technical and cost performance improvements during project progress.

Milestone 1.0: In-water testing plan submitted to and approved by DOE.

Task 2.0: Demonstrate COTS passive acoustic sensor (baseline) and linear particle motion sensor array (initial) performance at PNNL's Marine Sciences Laboratory (now Marine and Coastal Research Laboratory) in Sequim Bay, WA using known acoustic sources. Perform baseline and initial technical and cost performance analysis.

Milestone 2.1: Particle motion sensor array rigid frame mount designed and constructed for tethering to buoy-mooring system.

Milestone 2.2: Initial testing completed. Baseline and initial technical and cost performance report. Particle motion sensor array-measured pressure should be within 5 dB of expected received pressure for the known source. Signal to noise ratios measured on the particle motion sensor array will be within 3 dB of those measured at similar frequencies on the broadband acoustic recording unit.

Task 3.0: Develop and refine plans for performance and cost improvements for acoustic characterization, classification, and accurate location determination for anthropogenic and natural sounds. The engineering plans will include integration of an array of three 3-D acoustic vector sensors with buoy platform hardware, firmware, and software, including power and data transmission systems.

Milestone 3.0: Identify performance enhancement plan and cost reduction criteria in a report to be submitted to and approved by DOE.

2.1.2 Accomplishments

Summary of key accomplishments during BP1 (also see Table 2):

- Formulated a successful in-water test plan for baseline and initial system testing
- Designed and constructed an array frame to house acoustic particle motion sensors
- Conducted array frame motion and flow noise removal tests
- Initiated acoustic propagation modeling in support of algorithm development
- Completed baseline and initial system testing of a broadband acoustic recorder (BAR) and the vector sensor array (VSA).
- Completed technical and cost performance analysis and technical performance enhancement and cost reduction plan

Table 2. Summary of BP1 tasks and milestones.

Task / Milestone	**End Date**	**Date Completed**	**Description**
Task 1.	3.31.17	3.31.17	Develop in-water testing plan, coordinated with PNNL, to enable the establishment of baseline performance and quantitative analysis of technical and cost performance improvements during project progress.
Milestone 1.0	3.31.17	3.31.17	In-water testing plan submitted to and approved by DOE.
Task 2.	9.30.17	9.20.17	Demonstrate COTS acoustic sensor (baseline) and VSA (initial) performance in Sequim Bay, WA, using known acoustic sources. Perform baseline and initial technical and cost performance analysis.
Milestone 2.1	6.30.17	6.30.17	NoiseSpotter® rigid frame mount designed and constructed.
Milestone 2.2	9.30.17	9.20.17	Initial testing completed. Baseline and initial technical cost performance report. NoiseSpotter-measured pressure should be within 5 dB of expected received pressure for the known source. Signal to noise ratios measured on the NoiseSpotter will be within 3 dB of those measured at similar frequencies on the broadband acoustic recording unit.
Task 3.	10.31.17	10.17.17	Develop and refine plans for performance and cost improvements for acoustic characterization, classification, and accurate location determination for anthropogenic and natural sounds. The engineering plans for the final NoiseSpotter® product will include integration of an array of three 3-D acoustic particle motion sensors with the hardware, firmware, and

Task / Milestone	End Date	Date Completed	Description
			software, including power and data transmission systems, of a surface buoy platform.
Milestone 3.0	10.31.17	10.17.17	Identify performance enhancement plan and cost reduction criteria in report to be submitted to and approved by DOE.

During Quarter 1 (Q1), a comprehensive in-water testing plan to demonstrate baseline and initial performance of the acoustic sensing system was developed jointly with PNNL scientists. The testing plan detailed the use of two controlled acoustic sources (low frequency and high frequency) to measure the performance and sensitivity of the baseline system (COTS BAR). The in-water testing plan also formulated an initial demonstration of the viability of making particle motion measurements to enable location estimation.

The NoiseSpotter® frame was designed, constructed, and tested during Q2, following a modular design to accommodate three particle motion sensors and a BAR. The lightweight anodized aluminum frame allows for ease of deployment, while facilitating the suspension of the sensors within the cage. The NoiseSpotter frame was moored in quiescent conditions to evaluate stability. The BAR was calibrated within a test tank using a controlled, high-frequency source, and a preliminary in-water flow noise removal system was tested. An acoustic propagation model of Sequim Bay, WA, was developed to quantify expected detection distances between sound sources and receivers (BAR and VSA) as outlined in the in-water testing plan.

Q3 activities included the first round of field testing of the BAR and VSA in Sequim Bay, baseline and initial technical and cost performance analysis, and development of plans for performance and cost improvements for acoustic characterization, classification, and accurate location determination for anthropogenic and natural sounds. Preliminary algorithm development for location estimation using NoiseSpotter® data were completed as part of Bridge Task 1.

2.1.3 Significant Findings and Departures

Major findings and deviations from planned objectives resulting from BP1 activities are reported here, with key efforts during BP1 summarized in

Table 3 and described in Sections 2.1.3.1. Section 2.1.3.2 presents the BP1 cost performance analysis for baseline (BAR), initial (non-real-time NoiseSpotter®), and improved technology (near real-time NoiseSpotter).

Table 3. Significant efforts and key findings during BP1

Significant Finding
In-water testing plan to establish baseline (COTS BAR) and initial (VSA) system performance formulated. *Controlled low- and high-frequency sources deployed at various distances (10 m to 1 km) from sensors.*
NoiseSpotter array frame designed and constructed. *Lightweight aluminum frame allows for ease deployment, and provides a compact stable sensor mount.*
Investigation of NoiseSpotter stability in shallow water. *Frame found to be stable with respect to higher frequency motions.*
Investigation of preliminary flow noise removal system. *Open cell foam block found to attenuate not only low-frequency flow noise, but higher frequency signals of interest as well.*
Acoustic propagation model development for Sequim Bay, WA. *Significant transmission loss expected beyond 1 km.*
In-water testing of BAR and VSA in Sequim Bay, WA. *Pressure measured on VSA within 5 dB of that measured on BAR.*
Technical and cost performance analysis. *Significant performance and cost improvements found when using an array of particle motion sensors for source localization and characterization.*
Proposed changes to statement of project objectives. *Suggested that cage be lowered to bottom platform, with processing collocated with cage to minimize cable loss and allow increased safety and ease of deployment.*

2.1.3.1 BP1 Field Testing

Initial and baseline performance of the system was successfully demonstrated during a series of field tests in Sequim Bay, WA, in collaboration with PNNL, during the week of July 10, 2017. The NoiseSpotter® V1 mooring with BAR (MicroMARS by Desert Star Systems), and a three-element VSA (three M20 particle motion sensors from Geospectrum Technologies, Inc.; GTI) was deployed in approximately 25 m deep water at the SB2 mooring location in Sequim Bay (**Error! Reference source not found.**). NoiseSpotter® V1 consisted of a mid-water column array frame that housed the acoustic sensors (**Error! Reference source not found.**). Sensors were located at 15 m water depth and tethered via a mooring line and data cables to a COTS data logger and battery pack, located in a surface buoy (Figure 3). Testing consisted of transmission of low frequency (100 Hz to 2.2 kHz) and high frequency (10 kHz to 30 kHz) controlled acoustic signals for 15-minute periods; acoustic sources (Ocean Sonics icTalk) were located at a depth of 3 m. The in-water testing quantified the performance of the BAR and VSA by comparing expected pressure levels at source-receiver separations of 10 m, 50 m, 100 m, 200 m, 500 m, and 1 km.

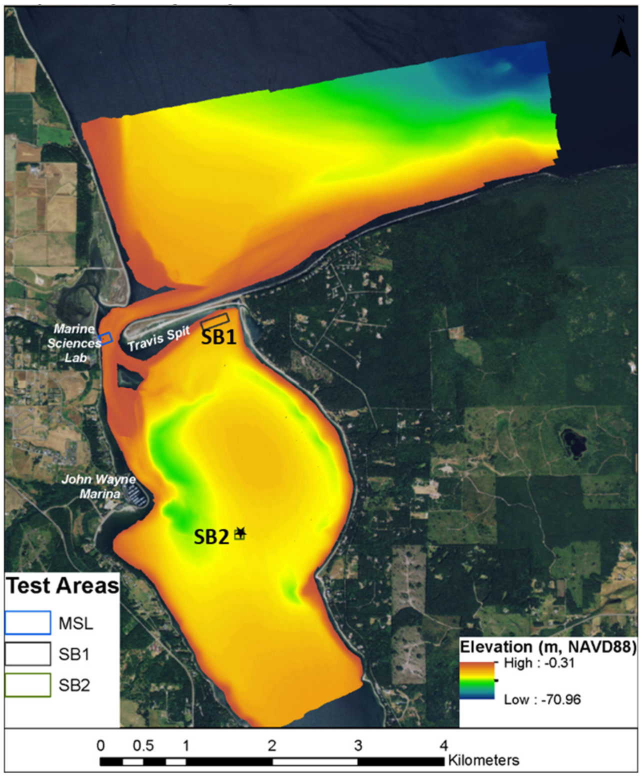

Figure 1. Sequim Bay, Washington, bathymetry and test locations.

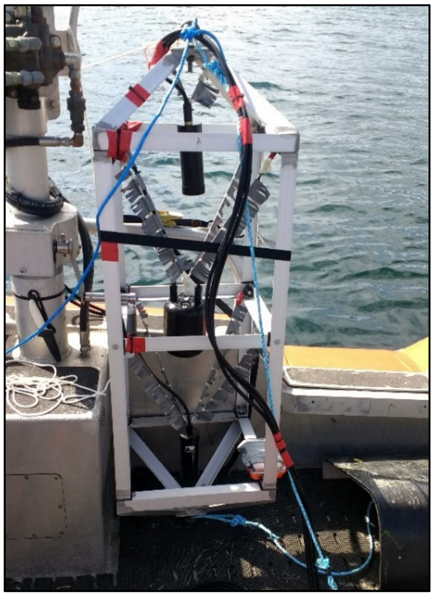

Figure 2. NoiseSpotter® V1 with linear array of particle motion sensors.

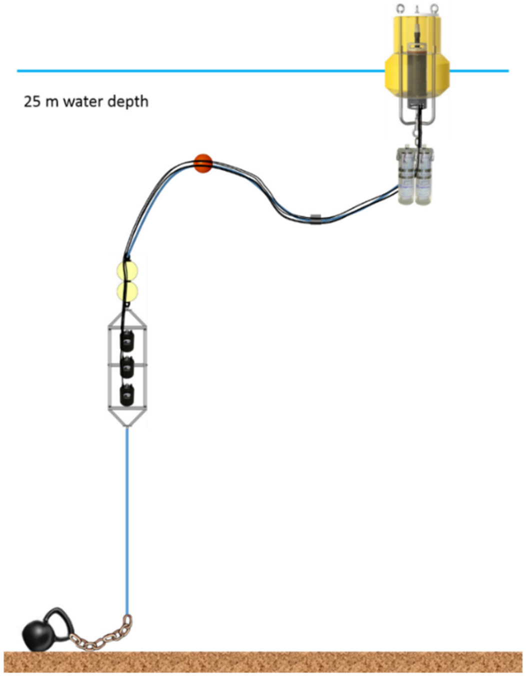

Figure 3. NoiseSpotter® V1 mooring diagram.

The sensors were powered by dual surface battery packs tethered to a surface buoy. A COTS data logger was mounted to the surface buoy. Four ¾-inch thick cables of 15 m length connected the VSA to the surface buoy, in addition to the mooring line.

NoiseSpotter® V1, an easily deployable moored array frame capable of housing three particle motion sensors and a BAR, was designed, fabricated, and deployed to demonstrate baseline and initial system performance. Data were simultaneously gathered on particle motion sensors and synchronously logged. A series of tests was conducted using low- and high-frequency acoustic sources, and the NoiseSpotter was shown to perform promisingly. Key issues for consideration were the stability of the array frame, efficacy of the initial attempt at flow noise removal, ease of system deployment, particle motion sensor data quality, data logger self-noise, and feasibility of making location estimates using BP1 field data:

- The NoiseSpotter® in the BP1 system required four thick cables to transmit power from the surface buoy to the acoustic sensors as well as to relay acoustic data from the underwater moored array up to the surface buoy (Figure 3). These 15-m long cables resulted in acoustic signal losses of 8 dB and challenges associated with deployment and recovery. Therefore, a new design was considered to lower the array frame, processor, and batteries onto a bottom platform and one cable to relay data digests up to the surface buoy for telemetry.
- The COTS multichannel data logger, while easy to configure and deploy, contributed to unnatural artifacts in the data. There were frequency sweeps and spectral lines observed that were conspicuously absent in the BAR data (Figure 4 and Figure 5). A custom low-noise, low-power data logging unit was developed in BP2 by Proteus Technologies.

- The flow noise removal system was also shown to be effective in reducing noise in the flow noise frequency band (<200 Hz). However, the choice of an open-cell foam block resulted in attenuation of sound across a wide bandwidth that included frequencies of potential interest. Flow noise removal was a BP2 milestone.
- The availability of time-synchronized multichannel particle motion sensor data enabled development of location estimation algorithms.

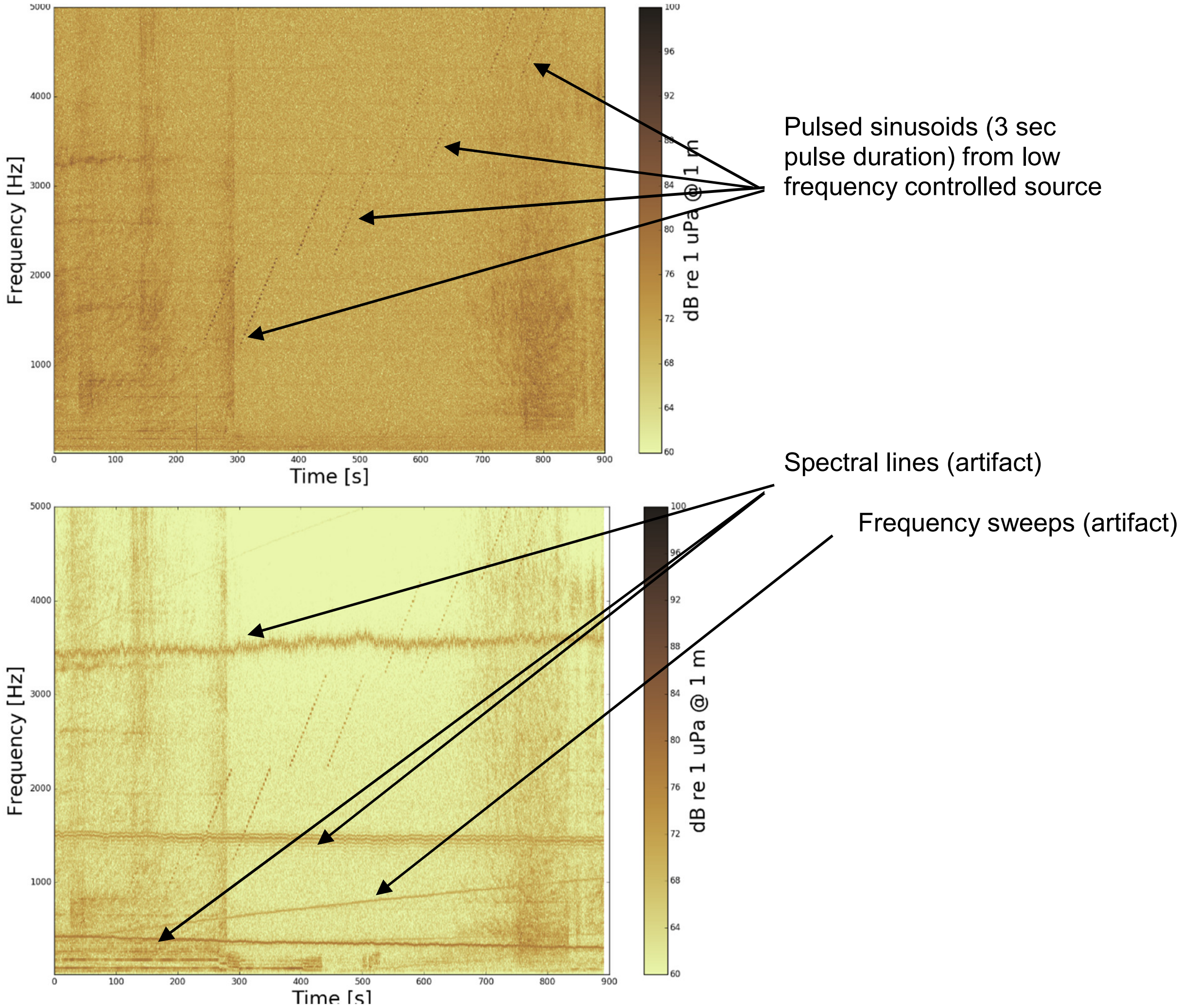

Figure 4. Comparison of BAR (top) and particle motion (bottom) spectrograms.

The low-frequency pulsed sinusoids between 100 Hz and 5 kHz as transmitted by the controlled low-frequency source (100 m distance) are visible in both panels. Artifacts arising from data logger self-noise are identified in the lower panel as spectral lines and frequency sweeps.

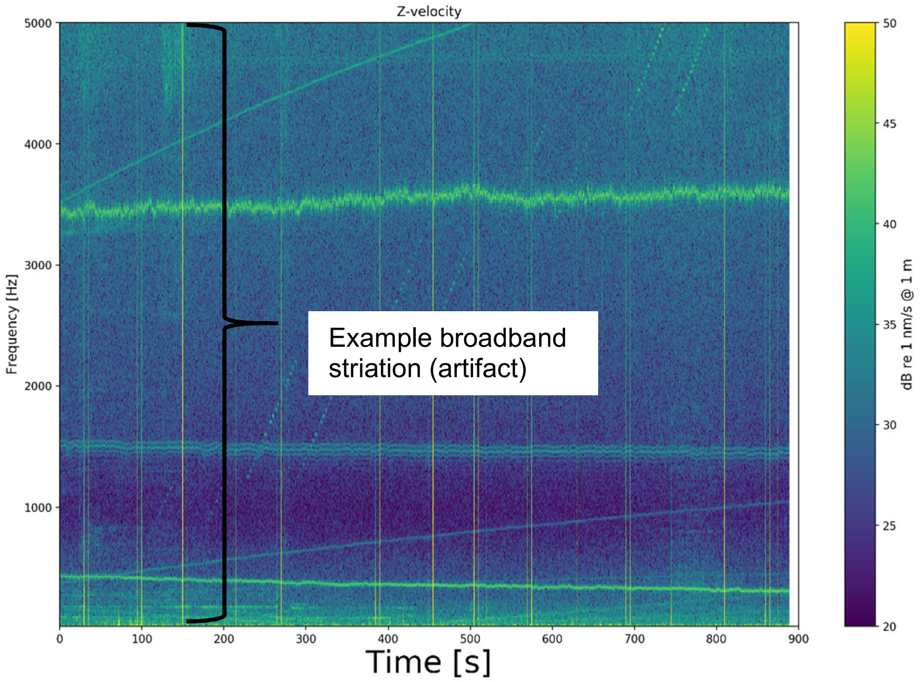

Figure 5. Particle velocity in the z-direction, measured by the M20-100.

The low-frequency pulsed sinusoids between 100 Hz and 5 kHz as transmitted by the controlled low-frequency source are visible. Artifacts from data logger self-noise are identical to the spectral lines and frequency sweeps in Figure 4. Broadband striations (vertical lines) are indicative of array motion.

2.1.3.2 BP1 Cost Performance Analysis

The BP1 cost performance analysis was prepared by estimating budgets for baseline, initial, and improved (

Table 4) acoustic technology testing over a period of 90 days with the objective of location estimation of natural and anthropogenic noises. It was assumed that all baseline, initial, and improved technology tests are conducted at Sequim Bay, Washington, with mobilization and demobilization facilities provided by PNNL but no vessel support. Differences between baseline, initial, and improved costs are shown in Table 5 and Table 6.

Baseline technology is assumed to be self-logging, high fidelity BARs (e.g., icListen instruments). Because these devices only measure acoustic pressure, an array of three moorings are necessary for triangulation and location estimation. Further, although all data are autonomously collected continuously, no real-time telemetry is possible without an undersea cable connection to shore; hence, data post-processing is necessary for location estimation. Over the 90-day continuous data collection, data storage and power requirements become an issue with BARs; therefore, 2-week mooring turnarounds are necessary to download data and exchange batteries. Without extensive technological development efforts to increase data logging and power capabilities, this 2-week mooring turnaround for BARs is unavoidable. Travel costs thus include the following: initial deployment (3 days plus travel days, 3 personnel), mooring servicing (×5; 2 days plus travel, 2 personnel), and final recovery (2 days plus travel, 3 personnel).

Initial technology includes an array of three acoustic particle motion sensors and a BAR. All sensors log and store data onboard for post-processing (i.e., no real-time telemetry). The initial technology enables geolocation algorithm development and, hence, only one mooring is necessary for acoustic monitoring. The initial technology supports approximately 2 weeks of continuous data logging (limited by data storage and power) and thus requires 2-week mooring servicing, similar to baseline technology testing. However, because only one mooring is required, only 2 personnel are needed for all mooring operations.

Improved technology is the NoiseSpotter® system—an array of three acoustic particle motion sensors that log, store, and process data onboard, and that transmit in near real-time, data digests with underwater soundscape and geolocation information. The improved custom, built-for-purpose, data logging system will enable 4+ weeks of data storage and system power, and thus will require only three mooring servicing trips. Importantly, estimated costs for data post-processing are eliminated.

Table 5 indicates that a 20% reduction in costs is achieved between baseline and initial technology testing, with the majority of cost savings associated with the decrease in the number of required moorings from three to one and subsequent decrease in the number of personnel required for at-sea operations. Nearly $13,000 is saved through purchase of a lower-fidelity BAR and the acoustic particle motion sensors and one mooring system as compared with the three mooring systems and high-fidelity BARs required for baseline testing. A lower-fidelity BAR is sufficient because the acoustic particle motion sensors provide high fidelity measurements of acoustic pressure. Further, over $15,000 in cost savings is realized through reduced vessel support and personnel requirements for mooring servicing.

Further cost improvements are determined for the NoiseSpotter® technology testing, primarily in labor costs associated with geolocation estimation. NoiseSpotter technology will employ automatic onboard data processing and near real-time telemetry of the data digests, thereby eliminating the need for hundreds of hours of labor data processing time. Additionally, the custom, built-for-purpose data logger will extend the period over which the technology can be deployed and thus reduces costs associated with labor, travel, and vessel services for mooring servicing. A 44% reduction in total costs is targeted between improved and initial technology testing (Table 6).

Table 4. Baseline, initial, and improved (NoiseSpotter®) technology cost performance analysis. These are cost estimates performed during BP1 and NoiseSpotter® costs are target costs.

Budget Categories	**Project Expenditures**		
	Baseline	**Initial**	**NoiseSpotter®**
a. Personnel	**$ 72,192**	**$ 62,524**	**$ 29,092**
Project Coordinator	$ 3,072	$ 3,072	$ 3,072
Scientist	$ 38,400	$ 29,920	$ 5,920
Scientist	$ 13,680	$ 12,492	$ 9,540
Managing Scientist	$ 13,680	$ 13,680	$ 8,880
Principal	$ 3,360	$ 3,360	$ 1,680
b. Fringe	**$ 39,706**	**$ 34,388**	**$ 16,001**
c. Travel	**$ 24,652**	**$ 12,050**	**$ 9,898**
Airfare/ppl	$ 6,400	$ 3,600	$ 2,800
Lodging/day/ppl	$ 7,776	$ 3,600	$ 3,024
Ground Transportation/day/ppl	$ 6,480	$ 3,000	$ 2,520
Meals Per Diem/ppl	$ 3,996	$ 1,850	$ 1,554
d. Equipment	**$ 24,000**	**$ 12,000**	**$ 12,000**
Broadband Acoustic Recorder	$ 24,000	$ -	$ -
Acoustic vector sensor M20-100	$ -	$ 12,000	$ 12,000
e. Supplies	**$ 16,800**	**$ 15,900**	**$ 15,100**
Broadband Acoustic Recorder	$ -	$ 3,500	$ 3,500
Acoustic vector sensor M20-40	$ -	$ 8,000	$ 8,000
Mooring gear and array frame	$ 6,000	$ 2,000	$ 2,000
Batteries & Electronics	$ 10,800	$ 2,400	$ 1,600
f. Contractual	**$ 30,000**	**$ 23,750**	**$ 16,250**
Vessel Support/boat/day	$ 30,000	$ 23,750	$ 16,250
g. Construction	**$ -**	$ -	**$ -**
h. Other	**$ 1,200**	**$ 600**	**$ 600**
Shipping (round-trip)	$ 1,200	$ 600	$ 600
i. Total Direct Charges	**$ 208,550**	**$ 161,212**	**$ 98,941**
j. Indirect Charges	**$ 103,235**	**$ 89,409**	**$ 41,602**
k. Totals (i+j)	**$ 311,784**	**$ 250,622**	**$ 140,542**

Table 5. Estimated/projected differences between baseline and initial costs.

Budget Categories	**Differences**	
	Baseline - Initial	**Percentage below baseline**
a. Personnel	$ (9,668)	13%
Project Coordinator		
Scientist		
Scientist		
Managing Scientist		
Principal		
b. Fringe	$ (5,318)	13%
c. Travel	$ (12,602)	51%
Airfare/ppl		
Lodging/day/ppl		
Ground Transportation/day/ppl		
Meals Per Diem/ppl		
d. Equipment	$ (12,000)	50%
Broadband Acoustic Recorder		
Acoustic vector sensor M20-100		
e. Supplies	$ (900)	5%
Broadband Acoustic Recorder		
Acoustic vector sensor M20-40		
Mooring gear and array frame		
Batteries & Electronics		
f. Contractual	$ (6,250)	21%
Vessel Support/boat/day		
g. Construction		
h. Other	$ (600)	50%
Shipping (round-trip)		
i. Total Direct Charges	$ (47,338)	23%
j. Indirect Charges	$ (13,826)	13%
k. Totals (i+j)	$ (61,162)	20%

Table 6. Target differences between initial and improved (NoiseSpotter®) costs.

Budget Categories	Differences	
	Initial - NoiseSpotter®	Percentage below Initial
a. Personnel	$ (33,432)	53%
Project Coordinator		
Scientist		
Scientist		
Managing Scientist		
Principal		
b. Fringe	$ (18,388)	53%
c. Travel	$ (2,152)	18%
Airfare/ppl		
Lodging/day/ppl		
Ground Transportation/day/ppl		
Meals Per Diem/ppl		
d. Equipment	$ -	0%
Broadband Acoustic Recorder		
Acoustic vector sensor M20-100		
e. Supplies	$ (800)	5%
Broadband Acoustic Recorder		
Acoustic vector sensor M20-40		
Mooring gear and array frame		
Batteries & Electronics		
f. Contractual	$ (7,500)	32%
Vessel Support/boat/day		
g. Construction		
h. Other	$ -	0%
Shipping (round-trip)		
i. Total Direct Charges	$ (62,272)	39%
j. Indirect Charges	$ (47,808)	53%
k. Totals (i+j)	$ (110,079)	44%

2.2 BUDGET PERIOD 2

2.2.1 Tasks and Milestones

Task 4.0: Integration of VSA with surface buoy. Continued development of location estimation algorithms based on NoiseSpotter® data.

Milestone 4.0: BP2 in-water testing plan submitted to and approved by DOE. A second round of initial testing will take place during Q1 of BP2. Specific objectives to be addressed by this round of testing include

- Sensitivity limits of the system when deployed mid-water column versus on the bottom
- Minimization of impulsive vertical NoiseSpotter motion
- Improvements in data logger signal quality, reduction of cable losses
- Changes in flexibility of deployment
- An evaluation of flow noise in a tidal channel.

Improvements will be compared to BP1 quantitative technical performance metrics. The technical performance analysis will be updated following this round of testing. The data collected in this round of field-testing will continue to contribute to location estimation algorithm refinement.

Milestone 4.1: Flow noise removal system custom integration with NoiseSpotter®. Laboratory tank tests will show reduction of flow noise by 2 dB.

Milestone 4.2: Development of self-powered seabed data logging in collaboration with PNNL and Proteus Technology. The data logging system will be capable of ingesting at least 12 channels of data at 20 kHz, 24 bits. It will have enough onboard power to operate for 2 weeks without servicing and store at least 2 weeks of data onboard. The data logging system will be consolidated into a pressure housing with short cable lengths for sensor, with an optional digital output to the surface.

Milestone 4.3: Continued development of location estimation algorithm. Post-processed data from initial testing will show bearing estimates toward known source of within 100 m.

Task 5.0: Not pursued.

Task 6.0: Technical and cost performance data collected during second round testing at PNNL will be analyzed against baseline and initial data collected during BP1 testing. Quantitative metrics such as pressure and bearing estimates, and system costs will be compared.

Milestone 6.0: Evaluate technical and cost performance enhancement relative to criteria in BP1 report. Results reported to and approved by DOE.

2.2.2 Accomplishments

Summary of key accomplishments during BP2 (also see Table 7):

- Formulated a successful in-water test plan for initial system testing
- Designed, constructed, and validated an effective flow noise shield to reduce flow noise by more than 15 dB at frequencies <200 Hz while not attenuating sounds of interest at higher frequencies, which exceeded our technical target of 2 dB flow noise reduction at low frequencies.
- Designed and implemented an onboard power and data storage and logging system and tested the integrated NoiseSpotter® system in quiescent, energetic, and deep water sites
- Developed and validated a location estimation algorithm capable of estimating sounds to within 4 m of a known acoustic source at 200 m range (2% accuracy) using beamforming techniques. Other systems such as the tetrahedral array developed by Tessei et al (2012) demonstrated 7% accuracy at a range of 250 m.
- Completed initial system testing of a BAR and the VSA on a redesigned, stable, bottom-mounted platform
- Completed technical and cost performance analysis and technical performance enhancement and cost reduction plan.

Table 7. Summary of BP2 Tasks and Milestones

Task / Milestone	End Date	Date Completed	Description
Task 4.	9.30.18	9.30.18	Hardware integration and continued development of location estimation algorithms
Milestone 4.0	3.31.18	3.31.18	BP2 in-water testing plan submitted to and approved by DOE
Milestone 4.1	3.31.18	3.31.18	Flow noise removal system custom integration with NoiseSpotter® showing reduction of flow noise by 2 dB
Milestone 4.2	6.30.18	6.30.18	Development of self-powered seabed data logging capable of ingesting at least 12 channels of data at 20 kHz, 24 bits and onboard power to operate with 2 weeks and store at least 2 weeks of data onboard. The data logging system consolidated in a pressure housing with short cable lengths.
Milestone 4.3	9.30.18	9.30.18	Continued location estimation algorithm development. Post-processed data show bearing estimates to known source of within 100 m.
Task 5.			Not pursued due to NEPA review.
Task 6.	10.31.18	10.17.18	Technical and cost performance data collected during second round testing at PNNL analyzed against baseline and initial data collected during BP1 testing. Quantitative

Task / Milestone	End Date	Date Completed	Description
			metrics such as pressure and bearing estimates, and system costs compared.
Milestone 6.0	10.31.18	10.17.18	Evaluate technical and cost performance enhancement relative to criteria in BP1 report. Results reported to and approved by DOE.

During BP2 Q1, a number of project milestones were achieved:

1. Completion of the first of two rounds of BP2 in-water field-testing.
2. Design of a flow noise removal system.
   The effectiveness of a number of different materials (fiberglass mesh, burlap, canvas, and ballistic and ripstop nylon) was evaluated. It was determined that canvas and ballistic nylon were the most suitable for flow noise removal while maintaining acoustic transparency.
3. Continued development of location estimation algorithms to locate a known acoustic source based on data collected during two rounds of BP2 in-water field-testing.
   Bearing estimates were computed using the methodology described by Thode et al. (2010). While results were generally successful (estimates to within 100 m of the source), signal-to-noise ratios were oftentimes degraded (< 20 dB) due to off-the-shelf data logger self-noise, which occasionally masked the ability to distinguish controlled source sounds from logger self-noise.

BP2 Q2 activities focused on design of the custom low power, low noise data logging system and its custom submersible pressure housing. The system was developed to ingest 12 channels of data at a sampling rate of 20 kHz with 16 bit analog to digital conversion depth and have enough power and onboard data storage to operate for at least two weeks without servicing. Additional Q2 activities included biofouling tests for the flow noise removal shields at PNNL to evaluate long-term efficacy of materials with and without application of antifouling paint, updating the technical performance analysis, and continued location estimation algorithm development using beamforming algorithms.

A second round of BP2 in-water field tests was completed in Q3, which tested the NoiseSpotter® sensors integrated with flow noise shields and custom data logger. Field tests were conducted in quiescent and energetic conditions to evaluate flow noise mitigation and the data logger's signal quality, power consumption, data storage, and operability. Technical and cost performance enhancement relative to BP1 criteria were reevaluated and updated based on BP2 field tests. Additionally, the NoiseSpotter location estimation algorithm was demonstrated to estimate location to within 4 m of a known source with pressure estimates with 3 dB of expected source pressure levels using beamforming techniques.

2.2.3 Significant Findings and Departures

Major findings resulting from BP2 activities are reported here, with key efforts during BP2 summarized in Section 2.2.3.5 presents the updated cost performance analysis from BP2.

Table 8. BP2 flow noise shield development, data logger development, in-water field-testing, and location estimation efforts and results are detailed in Sections 2.2.3.1, 2.2.3.2, 2.2.3.3, and 2.2.3.4. Section 2.2.3.5 presents the updated cost performance analysis from BP2.

Table 8. Significant efforts and key findings during BP2

Significant Finding
BP2 round 1 field-testing completed. *Sensor motion no longer observed in data for bottom deployments. Flow noise effects seen to exhibit depth dependence at an energetic site.*
Flow noise shield development. *Canvas and ballistic nylon effectively reduce flow and are acoustically transparent.*
Bearing estimates computed using triangulation method (Thode et al., 2010). *Estimates for BP2 field data are generally within 100 m of known acoustic source; however methodology is highly dependent on signal-to-noise ratio, which was often degraded due to off-the-shelf logger self-noise.*
Custom low power, low noise data logging system with housing designed. *Proteus Technologies designed and bench tested the data logger with multichannel vector sensor data; results indicated no system flaws. Power and data budget analysis indicated two to three week autonomous operation.*
Flow noise shield biofouling tests conducted. *Bare ballistic nylon suitable for two to three week deployment; longer-term deployments would benefit from a single coat of antifouling paint.*
Bearing estimates computed using beamforming methods. *Beamforming method showed greater precision than triangulation but initial approach is computationally intensive. Location estimates for BP2 field data to within 2 m from a known source at 50 m source distance.*
NoiseSpotter® sensors and custom data logger tested in quiescent and energetic sites during BP2 round 2 field-testing. *NoiseSpotter design is effective in all environments; design is nearly final. Data logger signal quality is high; power and storage capabilities appear suitable for two to three week deployments.*
Flow noise screen tested in energetic environment. *Ballistic nylon flow noise screen effective for reducing flow noise by 15 dB with no apparent signal attenuation at frequencies higher than 200 Hz.*
Computational efficiency gains in beamforming methods for bearing estimates. *Location estimates for BP2 field data to within 4 m from a known source at 200 m source distance.*
Technical and cost performance analysis updates. *Significant performance and cost improvements found when using an array of vector sensors for source localization and characterization.*

2.2.3.1 Flow Noise Shield Development

Subcontractor, Noise Control Engineering (NCE), evaluated the effectiveness of various materials for flow noise removal. A number of different types of materials was tested: fiberglass mesh, burlap, canvas, 1680 ballistic nylon, 1050 ballistic nylon, and ripstop nylon. Testing involved measuring flow and acoustic pressure in a controlled test tank with and without flow noise screens to evaluate acoustic transparency and reduction of flow noise. Acoustic recordings were made with the acoustic particle motion sensors.

Results indicated that the fiberglass mesh screen had little to no effect on flow or flow noise and hence it was not evaluated further. Also, burlap longevity in seawater is questionable; therefore it was not evaluated further. The acoustic transparency of canvas, 1050 ballistic nylon, ripstop, and 1680 ballistic nylon with and without Micron Extra and Seahawk Islands 77 anti-biofouling paints was evaluated (Figure 6). In Figure 6, negative values represent reduction in noise level and positive values represent amplification. The ideal flow screen would be zero different across the entire frequency range. Slight noise attenuation was observed for all unpainted and painted materials (Figure 6; unpainted results shown); however the larger sound pressure differences recorded for the 1050 ballistic nylon are believed to be related to variations in the source output over the course of the testing day.

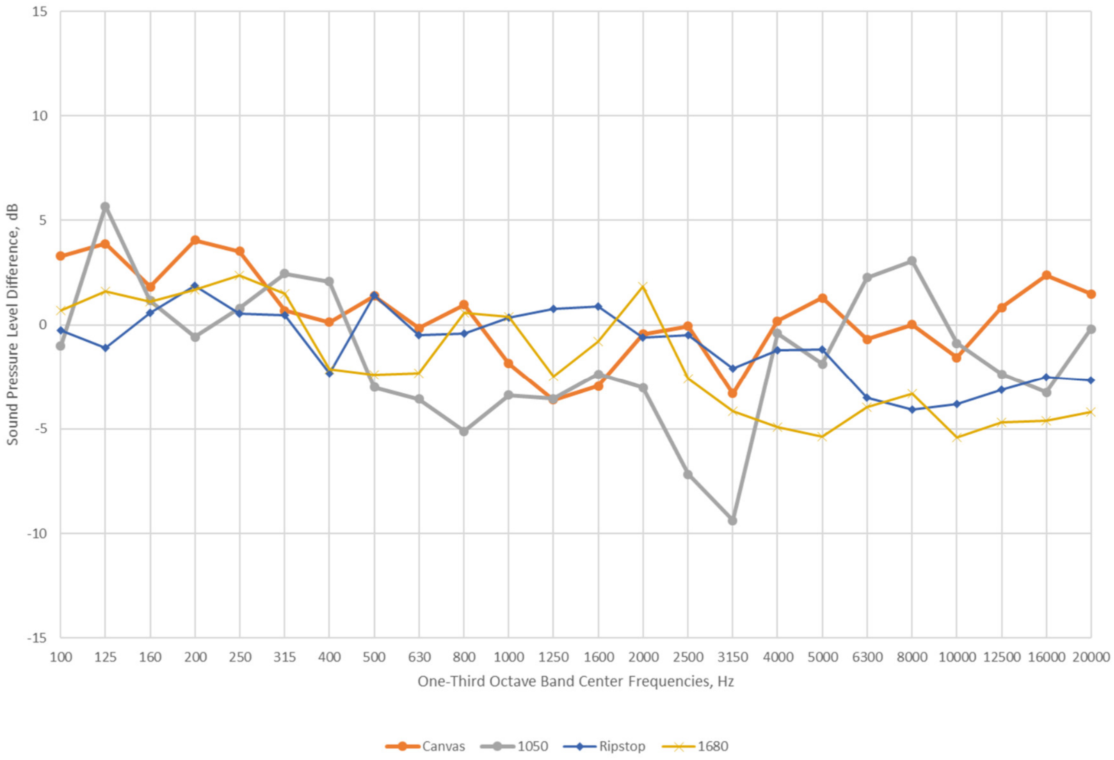

Figure 6. Acoustic transparency of different nylon materials.

A summary of flow removal efficiency of various materials is shown in Table 9. Flow reduction was quantified using simple measurements of flow. Various flow noise shield materials were stretched over a bucket and water was sprayed at the material from a distance of 1 foot, at a rate of 12 gallons per minute. Using a scale, the weight of the water in the bucket was assessed after 30 seconds, and compared to the weight of water sprayed over the course of each test. The result was a percent reduction in flow. Ballistic nylon (1050) with or without anti-biofouling paint was the material of choice for the flow noise shield due to flow reduction performance, acoustic transparency, availability, and cost considerations.

Table 9. Flow removal efficiency.

Material	Flow reduction
Canvas	90%
Ripstop self-wicking nylon	97%
1050 and ballistic nylon	100%
1050 ballistic nylon with Seahawk Islands 77	100%

During Q2 of BP2, the anti-biofouling properties of the canvas and 1050 ballistic nylon materials were assessed using one and two coats of Seahawk Islands 77 paint. Two swatches each of canvas and 1050 ballistic nylon were wrapped around four small PVC tubes, and the tubes were placed in a line on a 2′ x 4′ piece of lumber with a spacer between each PVC tube (Figure 7). Divers from PNNL secured the unit to an outflow pipe next to the MSL dock on May 7, 2018. Water depths at the site range from three feet on a low tide to about 10 feet on a high tide, allowing for variable solar radiation levels and consequent modulation of algal growth.

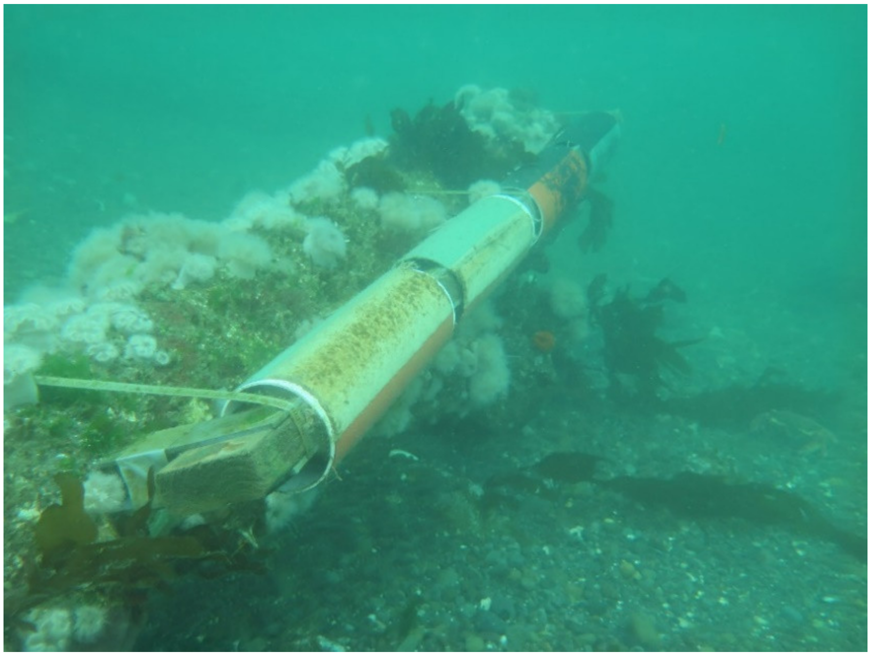

Figure 7. Flow noise shield biofouling test setup.

Lumber with 4 PVC tubes wrapped with 1050 ballistic nylon and canvas with one and two coats of Seahawk Islands 77 paint.

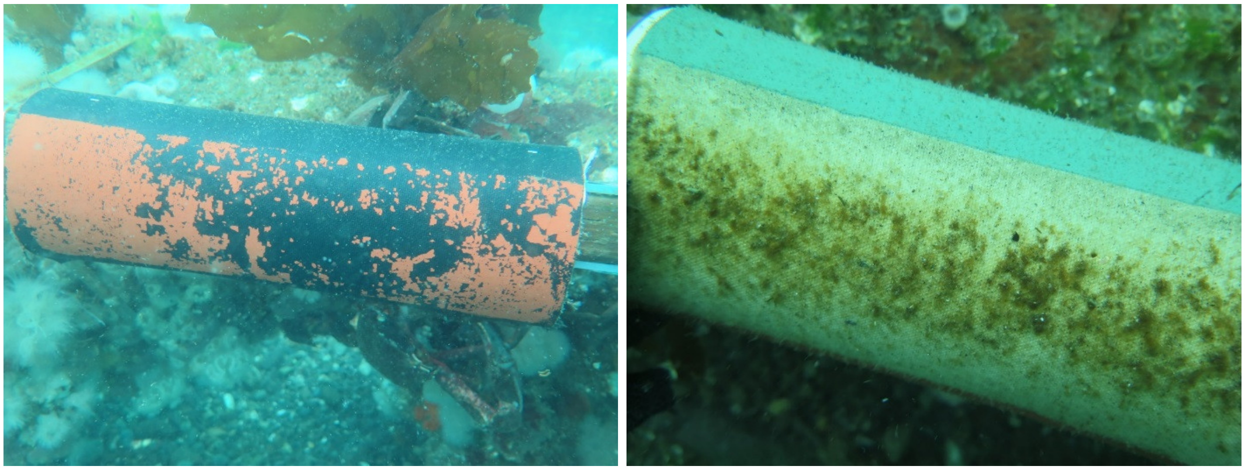

Figure 8. Long-term flow noise shield biofouling test results.

Left: Little to no growth observed on 1050 ballistic nylon with two coats of anti-biofouling paint, which showed substantial chipping. Right: Growth observed on canvas with two coats of paint after chipping. Both photos taken on May 24, 2018.

The units were checked during follow-up dives (photos taken on May 24; Figure 8) and finally recovered on July 20, 2018. Initial observations were that there was little growth on the 1050 ballistic nylon or on most of the painted sections. The canvas (and some of the painted canvas) had some accumulation of either algal growth or debris caught by the material (or both algae and debris). There was chipping of the paint, especially on the 1050 nylon. There also did not appear to be much of a difference between one and two coats of paint in anti-biofouling effectiveness, but the two coats seemed to chip off more, at least on the 1050 nylon. Assessments of the units following final recovery in July revealed that the unpainted surfaces appear to have attracted considerable biological growth, while the paint appeared to have effectively retarded algal growth. The results of this study indicate that 1050 ballistic nylon with no antifouling paint is suitable for a two to three week deployment, while longer deployments would benefit from a single coat of antifouling paint in terms of flow noise removal efficiency, acoustic transparency, and resistance to biofouling. The target deployment length for NoiseSpotter® operations is two to three weeks.

2.2.3.2 Custom Data Logger

The previously configured COTS data logging unit, while suitable for initial testing and system demonstration, was limited in its ability to operate autonomously for the two to three weeks envisioned for operational NoiseSpotter® deployments. Further, data quality from the COTS data logger was not consistent for accurate location estimation without statistical pre-filtering. Hence, a custom data logging unit was designed and engineered by subcontractor Proteus Technologies in collaboration with PNNL, with the goal of meeting the following objectives:

- Autonomous operation over a two to three week deployment period using available submersible rechargeable battery packs

- Time-synchronized data logging of 12 analog channels of data (four channels per sensor), using a bit depth of 24 bits
- Logging of one digital channel consisting of orientation measurements

Multichannel data from the three particle motion sensors that constitute the NoiseSpotter® are stored on the data logger as one-minute long files, with each file consisting of a file header that stores Year, Julian Day, and Time that the file is created, File Number, and Mission ID measured onboard the analog to digital converter. The file record is followed by an acoustic record that contains pertinent acoustic header information, followed by the sampled data. The last record in the file is the orientation record that contains array orientation information as measured by the IMU on board the M20-100 vector sensor. Analysis of the power budget for the custom data logger revealed that the system can operate autonomously for three weeks using three Sartek Industries submersible rechargeable battery packs. For reference, the previously used data logger operated for approximately 24 hours on a single Sartek battery.

The custom data logger circuit boards were encased in a custom stainless steel waterproof housing with maximum operating depth of more than 200 m (the sensors' depth rating). Inputs to the housing consist of one analog cable from each particle motion sensor (total three analog inputs), one digital cable from the M20-100 sensor that carries digital compass data, and two additional inputs for external power. Outputs from the housing consist of one to operate the logger via a computer interface and one to the processing and telemetry unit that was designed in BP3.

2.2.3.3 BP2 Field Testing

The specific objectives addressed by two rounds of BP2 in-water field-testing in collaboration with PNNL in Sequim Bay, WA included:

Round 1
- Evaluate sensitivity limits of the system when deployed mid-water column versus on the bottom
- Minimize impulsive vertical NoiseSpotter® motion
- Improve data logger signal quality and reduce cable-induced signal losses
- Improve flexibility of deployment
- Evaluate flow noise in an energetic tidal channel.

Round 2
- Test the newly developed submersible custom data logger
- Evaluate the effectiveness of custom flow noise shields
- Gather additional data for geolocation estimation algorithm development in different environmental conditions.

During Round 1 in-water field-testing, various configurations of the NoiseSpotter® were tested at Sequim Bay (Figure 1) in January 2018. In all configurations, three acoustic particle motion sensors were suspended vertically within PVC tubing, with the M20-100 (with digital compass) located in the center of the vertical array, and M20-40 sensors above and below. At times, the entire PVC tube, or a portion of the tube was wrapped in a preliminary flow noise screen, which was constructed with acrylic/Lycra material, and housed within an aluminum cage for additional protection (Figure 9). All acoustic particle motion sensors were hard-wire cabled to the COTS data logger and battery pack (the same types used during BP1 testing) that were placed within pressure housing and co-located with the VSA. A BAR was also deployed; co-located with the VSA.

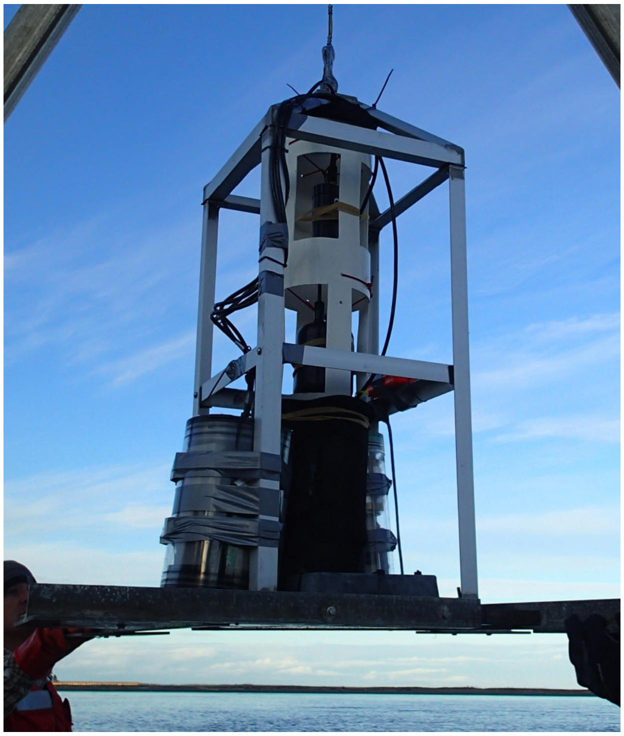

Figure 9. NoiseSpotter® V2 bottom platform with vertical sensor array.

NoiseSpotter® V2 field-testing results indicate that:

- Cable-induced signal losses were no longer observed.
- For data collected at the quiescent location (SB2), much of the sensor motion (yanking) seen in the particle velocity data collected during BP1 is no longer present because of the stable bottom-mounted system configuration.
- Flow noise effects were seen to exhibit a depth dependence with increasing flow noise closest to the sea bottom (Figure 10).

- The preliminary flow noise screen was seen to be effective in reducing flow noise on the pressure channel, but somewhat less effective at reducing flow noise on the velocity channels where significant bedload transport was observed.

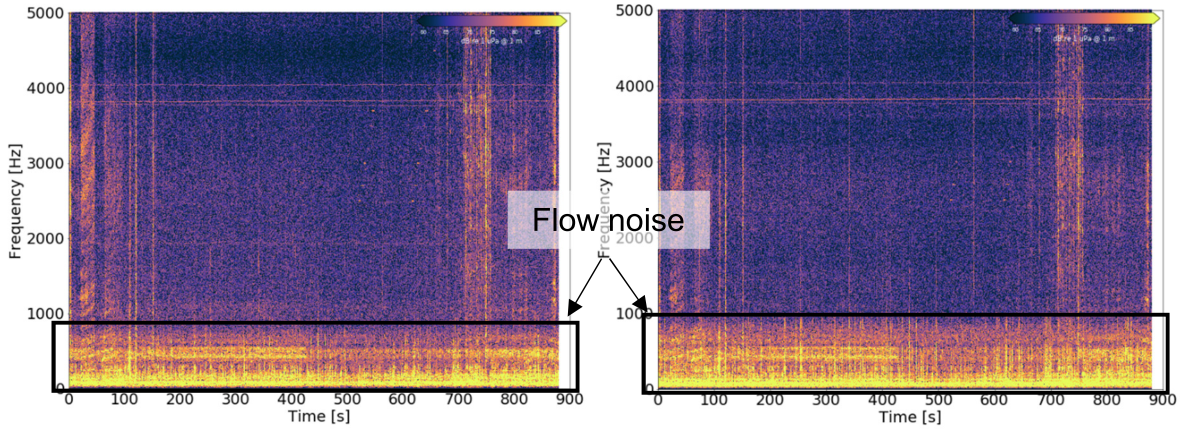

Figure 10. Uppermost M20-40A (left) and lowermost M20-40B (right) measurements.

The performance of the NoiseSpotter® V3 was evaluated in and near Sequim Bay, WA in a second round of in-water testing. NoiseSpotter V3 consisted of three separate low-cost, lightweight, modular cages of varying heights encompassing each of the three vector sensors (Figure 11). Each sensor was separated by 0.25 m in the vertical direction and 1 m in the horizontal direction, which facilitates location estimation. Further, the lowermost sensor was 0.5 m above the bed, thereby minimizing the effects of sediment impact (i.e. bedload transport). The operational environments for this new design (NoiseSpotter frame at seabed with three separate cages) is not different from the previous bottom-mount design and the modularity of the platform enables rapid reconfiguration of the NoiseSpotter depending on environmental conditions, e.g., increasing or decreasing the distance between the sensors and the seabed and between the sensors themselves.

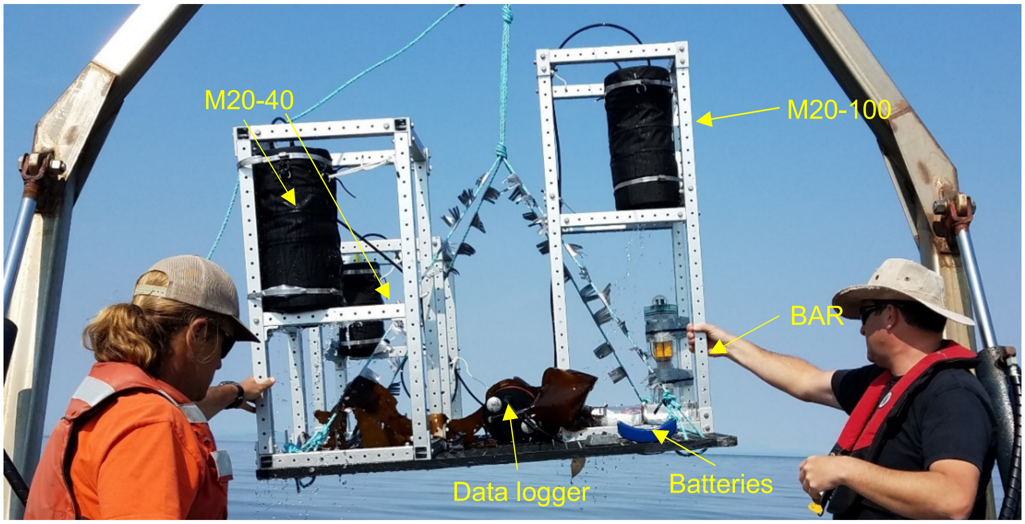

Figure 11. NoiseSpotter® V3 bottom-mount platform with flow noise screens.
Custom flow-noise shields encompass each of the three particle motion sensors, which were housed in separate lightweight, modular cages separated by 0.25 m vertically and 1 m horizontally. The custom data logger is mounted directly to the bottom platform.

NoiseSpotter® V3 field-testing results were successful. The custom data logger was demonstrated, with time-synchronized data streaming from three particle motion sensors that were sampled at a rate of 20 kHz. Power consumption and data storage calculations showed that the array can operate autonomously for up to three weeks. NoiseSpotter signal quality was comparable to the BAR data. No data quality degradation was observed in particle motion sensor signals when deployed in the tidal channel energetic environment.

The efficacy of the flow noise screens was evaluated at the MSL energetic tidal channel, where the NoiseSpotter® was first deployed at high slack tide with flow noise screens, then recovered at low slack tide after ~6 hrs and redeployed without flow noise screens for an additional ~6 hrs. While ambient noise conditions differed between the two NoiseSpotter® configurations, it was expected that flow noise at frequencies below 200 Hz would be similar at similar tidal phases. Flow noise screen evaluation results show a >15 dB reduction in flow noise (Figure 12). Ambient noise levels did indeed differ between the two test periods, with elevated noises at frequencies >3500 Hz during the flood tide period; however data collected between 300 Hz and 1600 Hz show comparable signals with and without flow noise shields.

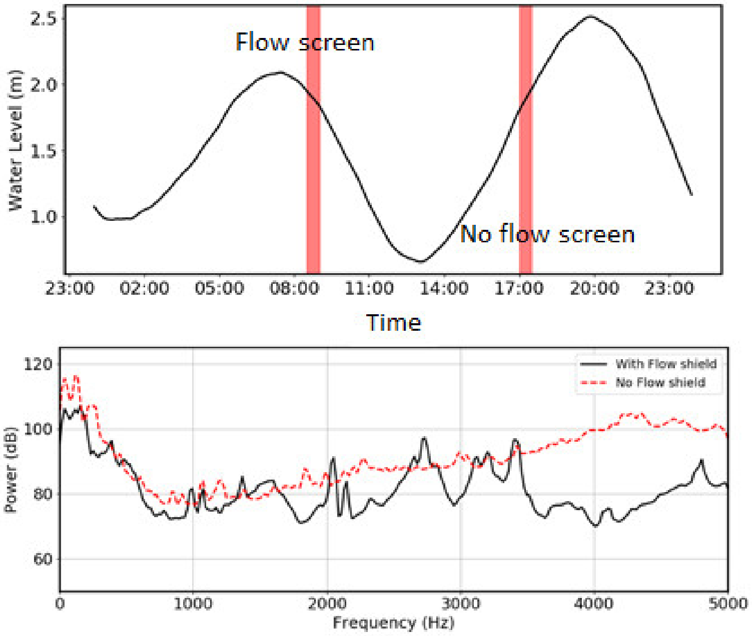

Figure 12. Flow noise shield evaluation test results.

Upper: Tidal variability during flow noise shield evaluation tests. Lower: particle velocity spectra collected with (black) and without (red) flow noise shields.

2.2.3.4 Bearing Estimates with Beamforming

A beamforming location estimation algorithm was implemented, which provide 3-D bearing estimates to the controlled source of sound by synchronously utilizing data from the three particle motion sensors. During BP2, improvements were made to computational efficiency to allow for eventual transfer to onboard processing. The custom low-noise data logger and flow noise shields developed during BP2 allowed for improved location estimation accuracy relative to previous analysis. Example results are shown in Figure 13, where the beamforming algorithm was applied to a 5-min segment of data at 2000 Hz. Here, controlled source pulses were observed at approximately 60 seconds, 130 seconds, and 200 seconds. Despite other noise in the environment surrounding the source pulses, the desired acoustic signals were accurately estimated, while noise sources at all other times, despite occupying the same frequency band, were correctly not associated with the controlled acoustic source.

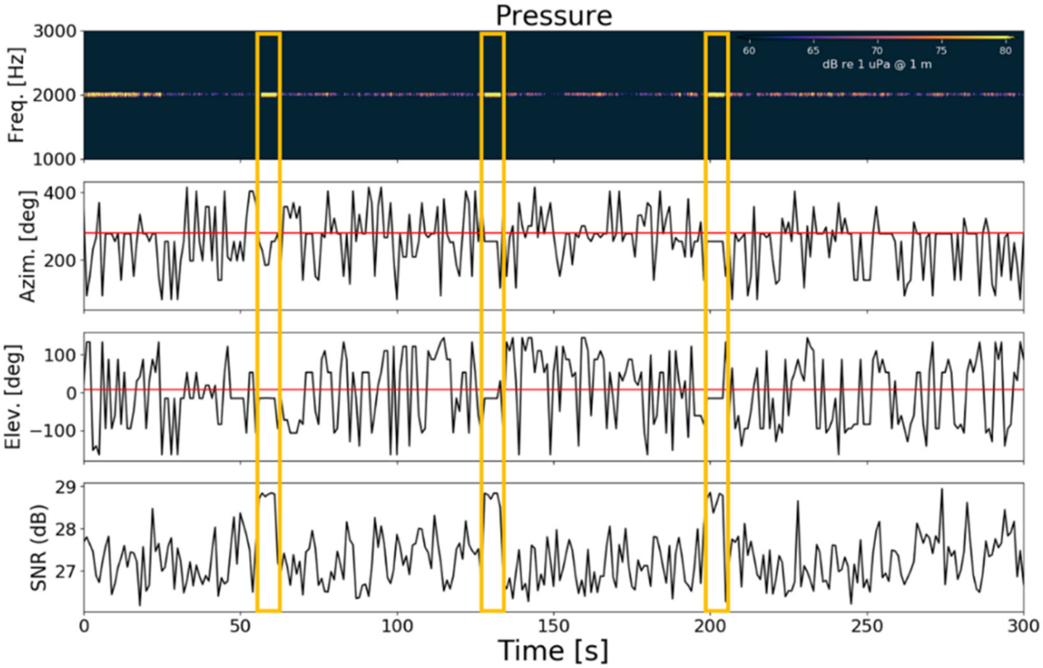

Figure 13. Beamforming algorithm applied to a 5-min data segment.

Figure 14 shows the source and NoiseSpotter® V3 locations obtained following the beamforming process, along with the estimate of the source location using the beamforming algorithm. Results indicate that the estimated location is within 3.6 m of the actual source location, over a range of 200 m (within 2% of the separation distance).

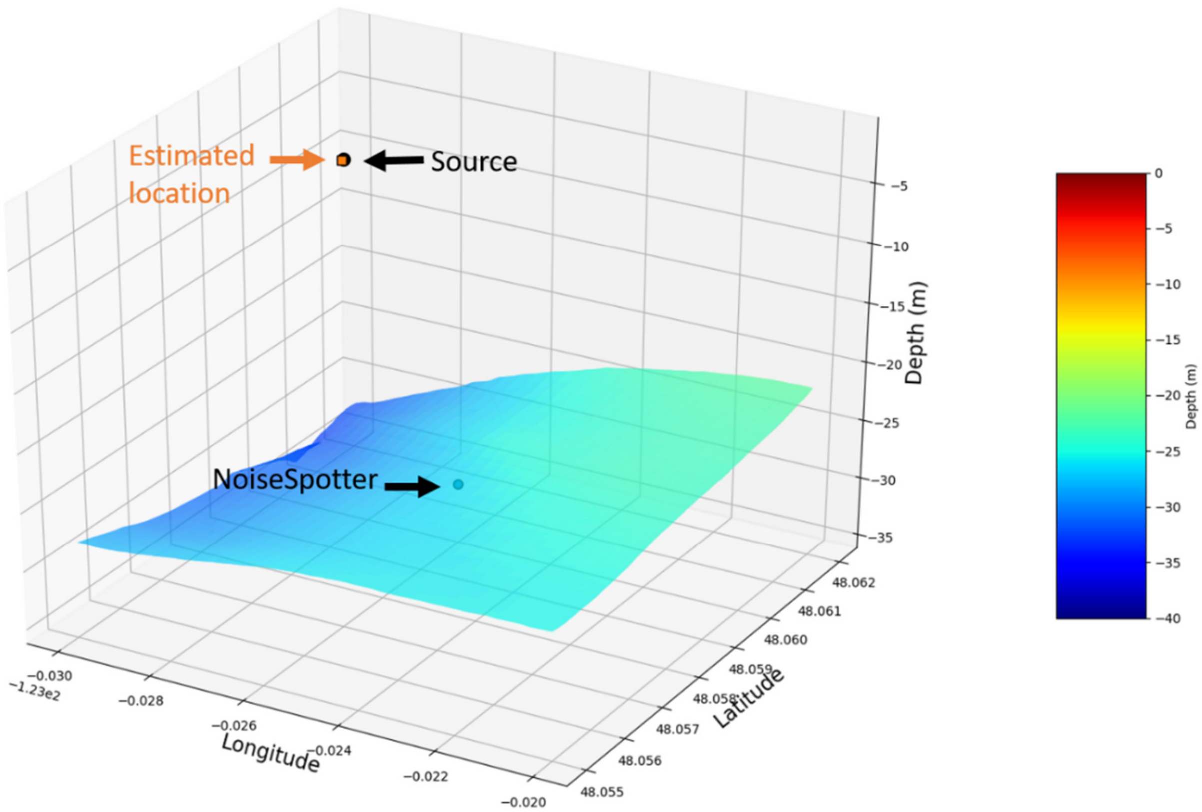

Figure 14. True and estimated source locations using the NoiseSpotter®.

2.2.3.5 Cost performance analysis

The cost performance analysis was updated based on the BP2 technology development and in-water testing activities. BP2 cost performance was identical to that determined for BP1 with the exception of $1,800 of added costs for each of the 4 sets of batteries (

Table 10) needed to extend the autonomous deployment life of the NoiseSpotter® to 3+ weeks. Even with these additional hardware costs, a 38% reduction in costs is achieved between initial and improved technology.

Table 10. Updated (BP2) improved technology (NoiseSpotter®) cost performance analysis.

Improved Budget Categories	**Project Expenditures**		
	Rate	**Number**	**Total**
a. Personnel			**$29,092**
Project Coordinator	$24.00	128	$3,072
Scientist	$40.00	148	$5,920
Scientist	$36.00	265	$9,540
Managing Scientist	$60.00	148	$8,880
Principal	$70.00	24	$1,680
b. Fringe			**$16,001**
c. Travel			**$9,898**
Airfare/ppl	$400	7	$2,800
Lodging/day/ppl	$144	15	$3,024
Ground Transportation/day/ppl	$120	15	$2,520
Meals Per Diem/ppl	$74	15	$1,554
d. Equipment			**$12,000**
Broadband Acoustic Recorder	$8,000	0	$0
Acoustic vector sensor M20-100	$12,000	1	$12,000
e. Supplies			**$29,500**
Broadband Acoustic Recorder	$3,500	1	$3,500
Acoustic vector sensor M20-40	$4,000	2	$8,000
Mooring gear and array frame	$2,000	1	$2,000
Batteries & Electronics	$2,000	4	$16,000
f. Contractual			**$16,250**
Vessel Support/boat/day	$2,500	7	$16,250
g. Construction			**$0**
h. Other			**$600**
Shipping (round-trip)	$600	1	$600
i. Total Direct Charges			**$113,341**
j. Indirect Charges			**$41,602**
k. Totals (i+j)			**$154,942**

2.3 BUDGET PERIOD 3

2.3.1 Tasks and Milestones

Task 7.0: Finalize and validate NoiseSpotter® design with in-water field tests in Sequim, WA. The NoiseSpotter V4 design, based on BP1 and BP2 in-water field tests, will be a stable bottom-mount system with modular components to enable rapid reconfiguration to suit a variety of environmental conditions. Components will be relatively low cost (total material costs not exceeding $10,000, not including sensors) and lightweight (total system not exceeding 100 kg).

Milestone 7.0: The finalized NoiseSpotter® design will be validated in Sequim, WA in collaboration with University of Washington (UW). The NoiseSpotter will be deployed, collocated with other acoustic devices working with PNNL, in quiescent (SB2) and energetic (MSL) environments, where controlled acoustic transmissions will be ranged and post-processed geolocation algorithms will be implemented.

Task 8.0: Real-time hardware design and implementation and final NoiseSpotter® field validation in an energetic environment. Repeated range testing and re-evaluation of location accuracy around ME device in a variety of environmental conditions relevant to ME. Field test results will include documentation of location estimation accuracy, robustness of NoiseSpotter array, transmission data rates including data loss, efficiency of flow noise removal system, and range from wave energy converter (WEC) beyond which WEC noise is undetectable.

Milestone 8.1: Optimized C-libraries integrated with NoiseSpotter® software for rapid, near real-time onboard processing.

Milestone 8.2: Data digests, consisting of location estimates and acoustic metrics of interest will be transmitted in near real-time to a shore-based receiver station. Data transmissions will be performed with <5% data dropouts over a land-based testing period of at least 24 hours.

Milestone 8.3: Field-testing in an energetic environment will be completed.

Task 9.0: Final reporting. A final report will be drafted including project progress between BP1 and BP3, comparison of technical and cost performance between project phases and with COTS results, and technical instruction manual for developed technology. Technical and cost performance data collected during third round of testing at a ME site will be analyzed against baseline and initial data collected during BP1 testing and BP2 testing.

Milestone 9.0: Quantitative metrics such as pressure and bearing estimates and source identification, and system costs will be compared between BP1, BP2, and BP3 field tests.

Milestone 9.1: Final report submitted to DOE.

2.3.2 Accomplishments

Summary of key accomplishments during BP3 (also see Table 11):

- Finalized the NoiseSpotter® design and validated it in quiescent and energetic environments.

- Deployed NoiseSpotter® in an energetic environment and characterized sounds generated by an ME device – the CalWave WEC.
- Compared quantitative metrics and system costs between BP1, BP2, and BP3 in-water field tests.
- Submitted the final project report to the DOE.

Table 11. Summary of BP3 Tasks and Milestones

Task / Milestone	End Date	Date Completed	Description
Task 7.	3.31.19	8.31.19	Finalize NoiseSpotter® design.
Milestone 7.0	3.31.19	8.31.19	Finalized NoiseSpotter design validated in Sequim, WA. The NoiseSpotter was deployed, collocated with other acoustic devices at SB2 and MSL.
Task 8.	12.31.21	11.23.21	Real-time hardware design and implementation of final NoiseSpotter field validation in an energetic environment with a WEC.
Milestone 8.1	12.31.21	11.23.21	Integrate onboard near real-time data processing.
Milestone 8.2	12.31.21	11.23.21	Transmit near real-time data digests with <5% data dropouts.
Milestone 8.3	12.31.21	11.23.21	Deploy NoiseSpotter to measure WEC sounds.
Task 9.	12.31.22		Final reporting.
Milestone 9.0	12.31.22		Quantitative metrics (e.g., pressure and bearing estimates) and system costs compared between BP1, BP2, and BP3 field tests.
Milestone 9.1	12.31.22		Final report submitted to DOE.

2.3.3 Significant Findings and Departures

2.3.3.1 Finalized NoiseSpotter® Design

The performance of the final NoiseSpotter® design was evaluated in Sequim Bay, WA during BP3. The primary goals of this final phase of in-water testing were to:

1. Test design changes to the moored array of vector sensors and its ability to operate in energetic environments.
2. Evaluate the performance of the high-density polyethylene (HDPE) frame with respect to acoustic transparency.
3. Evaluate the effectiveness of the flow noise shield.
4. Design, test, and validate the real-time processing and telemetry system in Sequim Bay, WA.

1\. *Design change evaluation.* The NoiseSpotter® V4A (non-real-time) consists of a modular array of three GTI acoustic particle motion sensors (one M20-100 with integrated digital compass and two M20-40s) enclosed in custom 1050 ballistic nylon flow noise shields wrapped around PVC pods and one BAR, each mounted on HDPE posts that are braced onto a bottom platform (Figure 15). The data logger and battery packs are mounted directly onto the bottom platform on HDPE brackets. The PVC pods are easily adjustable in the vertical directions, enabling rapid reconfiguration of the system depending on desired measurements. The weight of the NoiseSpotter with sensors is approximately 30 kg and the total material costs of the NoiseSpotter platform is approximately $1,500, not including the particle motion sensors. The lightweight and modular frame was assembled and mobilized for deployment in less than one hour. The frame was deployed and recovered at the quiescent location (SB2) and the energetic tidal channel at mouth of Sequim Bay (MSL) in approximately 15 minutes per site, demonstrating the ability of the system to be rapidly deployed.

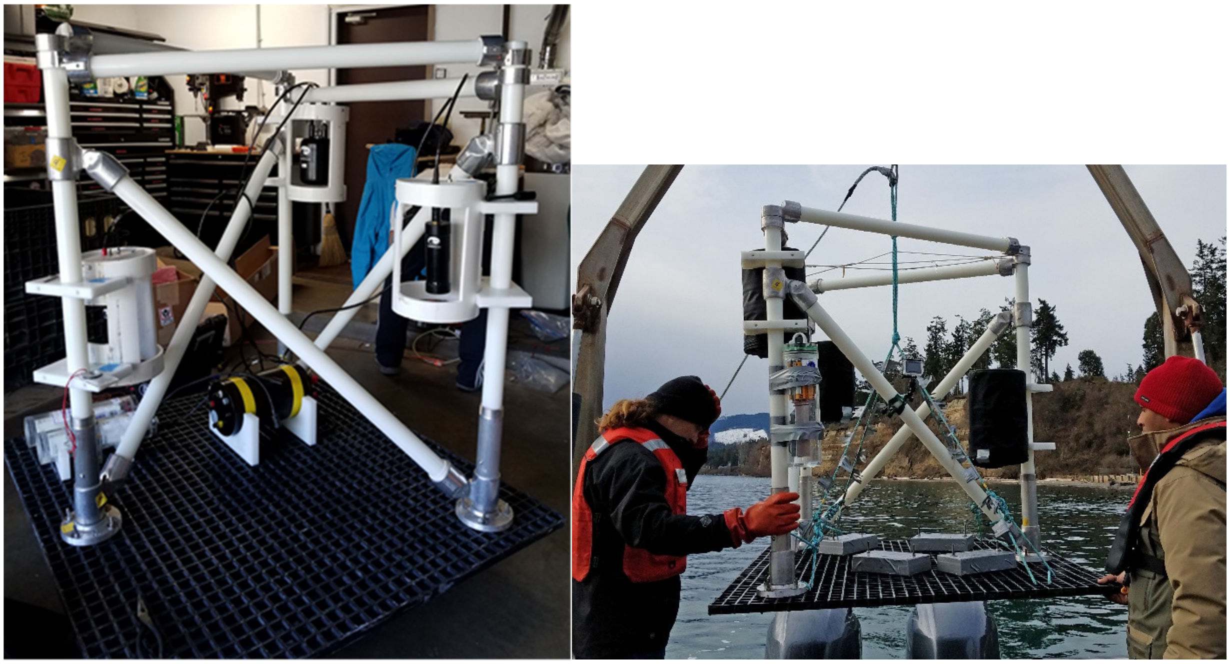

Figure 15. NoiseSpotter® V4A without (left) and with (right) flow noise shields.

2. *HDPE performance.* HDPE was chosen because it is nearly acoustically transparent in water, with an acoustic impedance of 2.9 g/cm^2 s (similar to PVC; water's acoustic impedance is 1.51 g/cm^2 s), compared to that of aluminum, which 17 g/cm^2 s. Also, the HDPE design is simple to construct and demobilize, is relatively lightweight and easy to deploy, and is modular. The individual particle motion sensor "pods" can easily be moved laterally and vertically on the bottom mount platform . The newly designed HDPE platform was deployed in SB2 and broadband acoustic recordings of controlled sound sources (from a low-frequency icTalk) were made in conjunction with UW Drifting Acoustic Instrumentation SYStem (DAISY) drifts. Controlled source transmissions were conducted for approximately 30 minutes following which the HDPE frame was recovered. The aluminum frame platform was then deployed immediately

after recovery of the HDPE NoiseSpotter platform to investigate potential effects of acoustic scattering from aluminum. Figure 16 shows frequency spectra computed over 30 minutes using the BAR data with the BAR deployed on the HDPE frame, compared to that recorded when deployed on the aluminum frame. While the spectra look mostly similar, the resonance peak at 500 Hz when using the aluminum frame corresponds to a half-wavelength of 1.5 m, which is the length of the tallest aluminum tower on the platform. These results indicate that there is little, yet measurable evidence of acoustic scattering by aluminum and no large-scale signal degradation when using an aluminum frame.

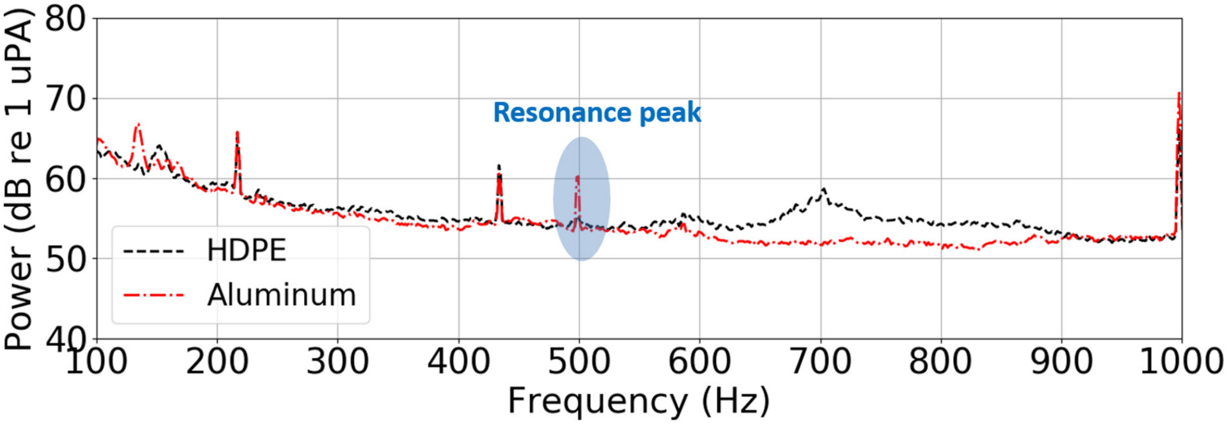

Figure 16. Comparison of acoustic scattering by aluminum versus HDPE.

3. *Flow noise shield effectiveness.* An evaluation of flow noise removal efficiency was conducted at the MSL location where two BARs were deployed, one inside a flow shield and the other with no flow shield. UW's icListen was deployed inside the flow shield, while the Integral BAR (also referred to as the 'CRT') was deployed outside the flow noise shield. Each sensor is a COTS system that has undergone testing by the manufacturer and comes with sensor-specific calibration curves. Once each data stream in calibrated, there was no reason to expect measurements on each sensor in identical conditions to be more than 0.5-1 dB different. The recorders were deployed over a half-day period, which allowed for acoustic characterization over a full tidal oscillation. Figure 17 shows a comparison of frequency spectra computed over a two-hour period when the flow velocity through the tidal channel was strongest. Significant improvements are seen with the flow shield in place. Flow noise is reduced uniformly across the 0-1000 Hz frequency band by up to 15 dB, consistent with earlier improvements seen with the use of flow shields on vector sensor measurements in BP2.

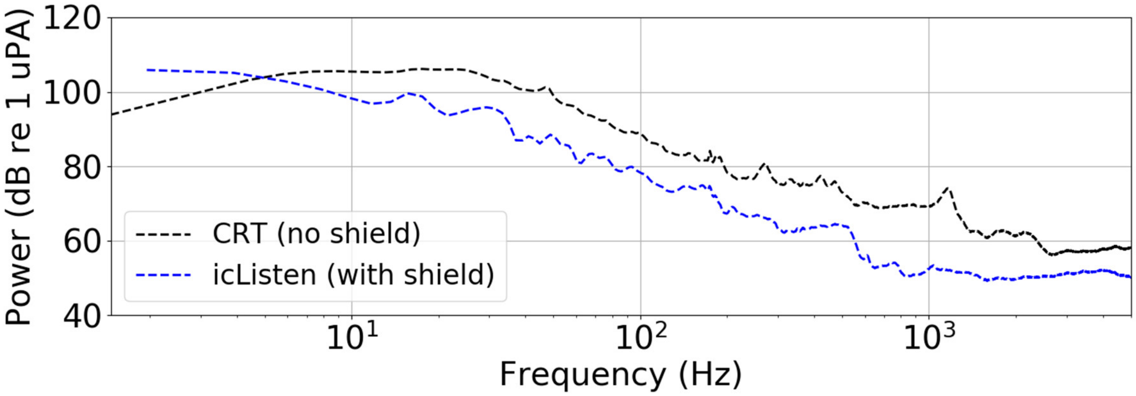

Figure 17. Frequency spectra with and without the flow shield.

In addition to the above tests where flow noise removal on the NoiseSpotter® was considered, a series of drifts were performed over the bottom-mounted NoiseSpotter using the UW DAISY acoustic recording system (Figure 18). Repeated drifts were conducted on the rising tide. Frequency spectra were computed over the period of one drift when the DAISY was within a 10 m bounding box around the NoiseSpotter, the duration of which was 6 seconds (Figure 19). The noise floor at frequencies less than 10 Hz are similar between the two systems, but significant differences of around 30 dB are observed between 10 Hz and 400 Hz. These large differences are unlikely to be flow noise effects, and are more likely due to differences in acoustic propagation between the near surface DAISY and bottom-mounted NoiseSpotter.

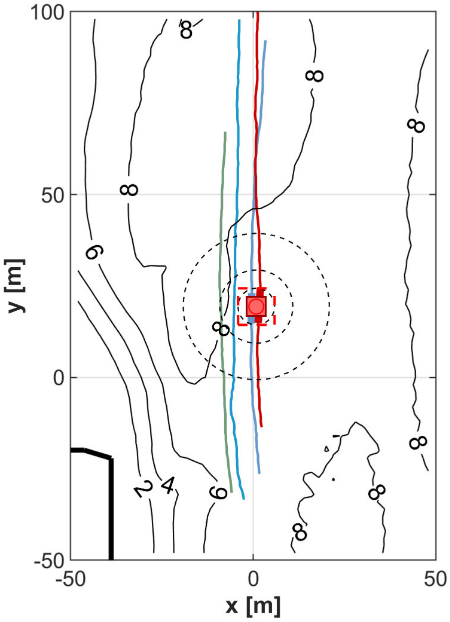

Figure 18. UW DAISY drifts (colored lines) over the NoiseSpotter® (red square). Dashed circles represent the 5m, 10 m and 20 m contours.

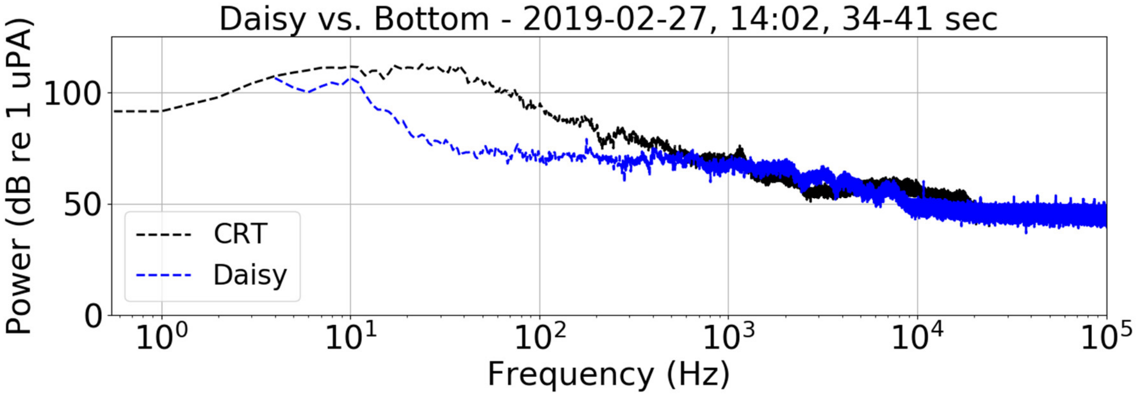

Figure 19. Drifting DAISY and the fixed NoiseSpotter® frequency spectra.

4. *Near real-time NoiseSpotter® testing*. To facilitate rapid decision-making and undertaking of any corrective actions in response to anomalous recorded sounds (i.e. mitigation), the final NoiseSpotter® V4B product features near real-time telemetry of key acoustic parameters in addition to information required to geolocate sounds of interest (Figure 20). In-water testing was conducted during BP3 to evaluate the near real-time NoiseSpotter® (Figure 20 and Figure 21). Onboard processing is accomplished using a surface buoy-based Teensy 3.6 data processor that implements optimized C-libraries to create data digests. Near real-time data telemetry is accomplished using an Ethernet connection that relays raw data from the data logger (where data are also logged and archived) to the Teensy data processor, and then to cloud-based data server via cellular modem telemetry. A successful near real-time NoiseSpotter is defined as one where data streams from the three particle motion sensors to the custom data logger where all data are synchronized and time-stamped at a sampling rate of at least 10 kHz. NoiseSpotter data are logged onboard in 1-minute segments. Further, particle velocity data stream near-continuously via Ethernet cable to the Teensy, which is located in the surface buoy (Figure 21). The Teensy accumulates a packet of data, implements optimized C-libraries, and creates data digests. Data digests are transmitted to a cloud server via cellular modem technology with <5% dropout rate.

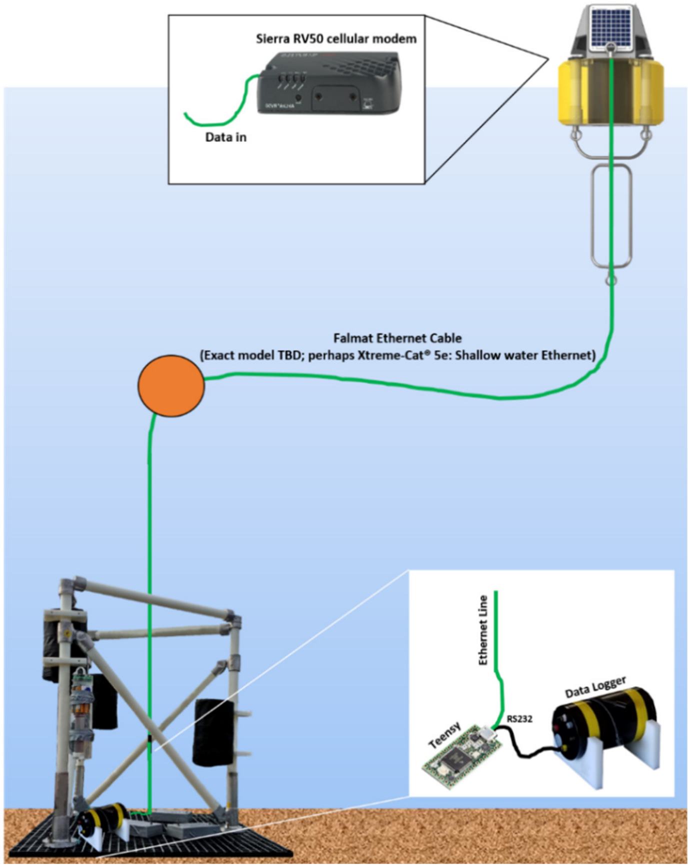

Figure 20. NoiseSpotter® V4B (near real-time) system.

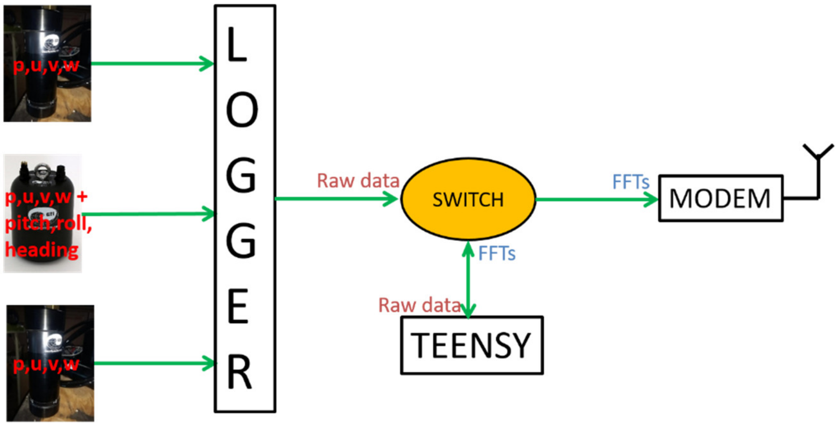

Figure 21. Near real-time NoiseSpotter® V4B schematic diagram.

Field testing activities in BP3 were similar to NoiseSpotter® tests that were completed at the permitted quiescent SB2 and energetic MSL tidal channel deployment sites (Figure 22). During land-based testing in the PNNL parking lot, the near real-time NoiseSpotter system immediately worked as planned. One-minute segments of data (parking lot noise signals), in the form of data digests, populated the designated NoiseSpotter folder on the Integral server, one after the other. The near real-time NoiseSpotter was field deployed, and data digests were telemetered to a cloud-based server using a cellular (Verizon LTE) telecommunication link. The hardware system was robust; minute-long data digests were received on Integral's NoiseSpotter server with only one data dropout over approximately 4 hours of testing (<5% data dropout). The one data dropout was likely due to sustained (longer than 30 s) cellular interruption.

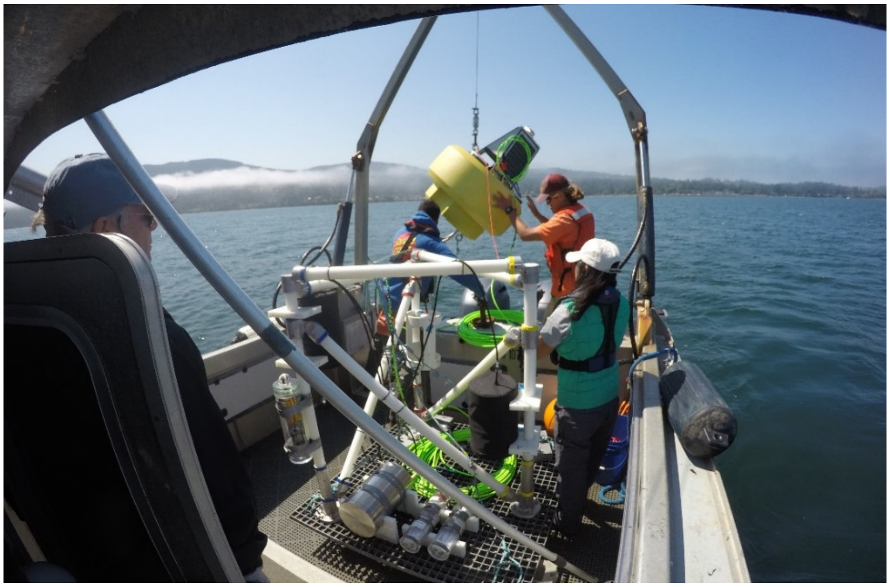

Figure 22. Deployment of the real-time NoiseSpotter® V4B.

2.3.3.2 Final NoiseSpotter® Field Validation near a WEC

The NoiseSpotter® was deployed offshore of the Scripps Institution of Oceanography (SIO) Pier, San Diego, California in November 2021. The specific goal of this final round of testing was to demonstrate NoiseSpotter performance near an operational WEC. As part of this demonstration, the NoiseSpotter was deployed in ~30 m deep water during multiple deployments over an approximate 10-day period. Field-testing consisted of:

1. A drifting configuration of the NoiseSpotter (Figure 23), where a particle motion sensor was coupled with the UW DAISY subsurface hardware.
2. Deployments of the NoiseSpotter® V4B (Figure 20) over periods of 4-6 hours, approximately 70 m from the CalWave WEC to demonstrate near real-time telemetry.
3. Shorter-term deployments of the NoiseSpotter® V4A (Figure 24) approximately 100 m and 200 m from the CalWave device at the four cardinal directions from the WEC.
4. A multi-day autonomous deployment of the NoiseSpotter® V4A (Figure 24) to demonstrate longer-term acoustic monitoring ability.

During the deployments, the NoiseSpotter monitored for operational sounds from the CalWave device, boat traffic, and marine mammals in the frequency band 50 Hz to 3 kHz. A detailed log of field activities is available in Section 5-2.

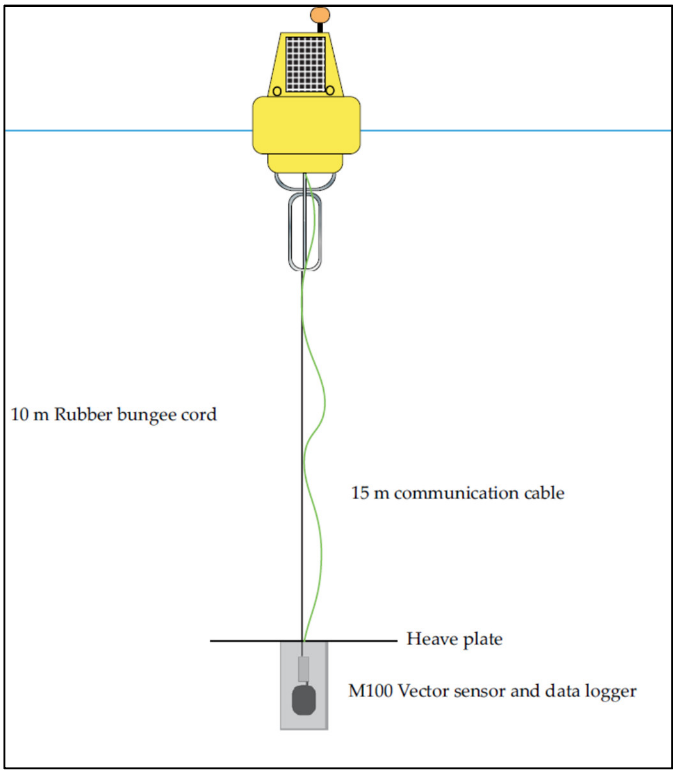

Figure 23. Drifting NoiseSpotter® design.

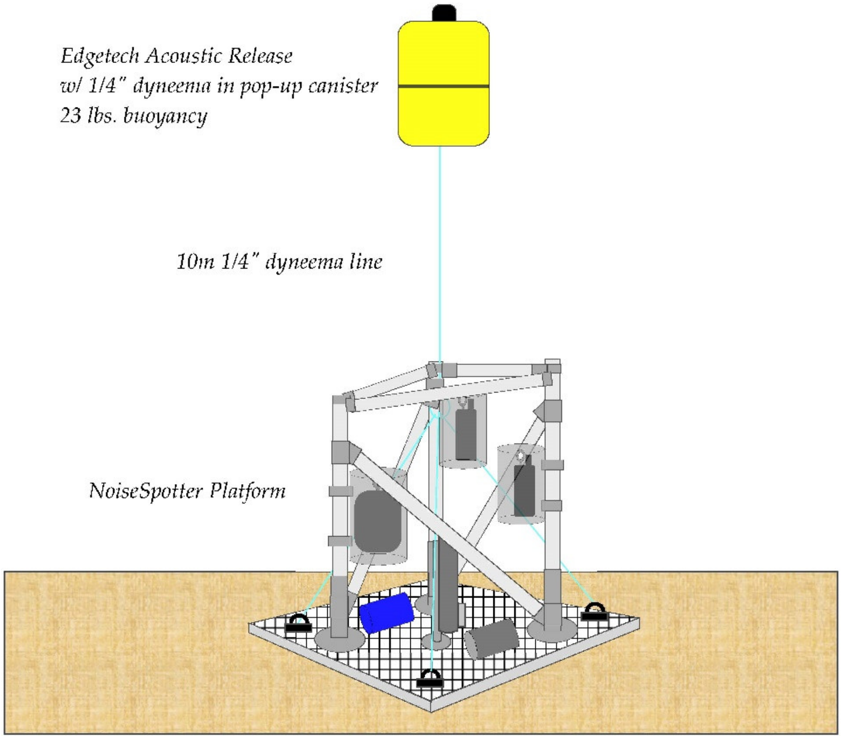

Figure 24. Autonomous NoiseSpotter® V4A with subsurface mooring.

Drifting NoiseSpotter®

A series of five drifts were conducted on November 14, 2021 with the drifting configuration of NoiseSpotter® and a UW DAISY (Figure 25). Both units were released from the vessel and retrieved up to 60 min later (Appendix A).

Figure 25. DAISY (left) and drifting NoiseSpotter® (right).

As indicated in Figure 26, the NoiseSpotter® drifts occurred over distances of 30 m to 500 m from the WEC, over multiple drifts. Surface currents were generally weak, and each drift occurred over a 30 minute period after which the buoy was towed back towards the WEC and re-released.

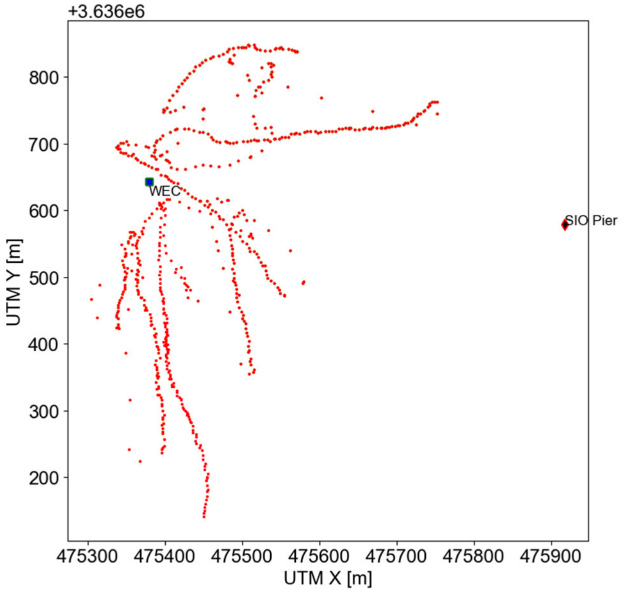

Figure 26. GPS tracks of drifting NoiseSpotter® on November 14, 2021. The sparsely separated points alongside each drift track indicate the tow back of the buoy before a re-release. Also shown for reference are the WEC and SIO Pier locations.

Pressure and particle velocity measurements during the drifts generally show good data quality (Figure 27). However, artifacts due to motion of the particle motion sensor are clearly visible as periodic spikes in both pressure and z-velocity. The spikes are seen to occur roughly every 10 seconds, consistent with wave periods during this period that ranged from 9.5 s to 11.1 s[1].

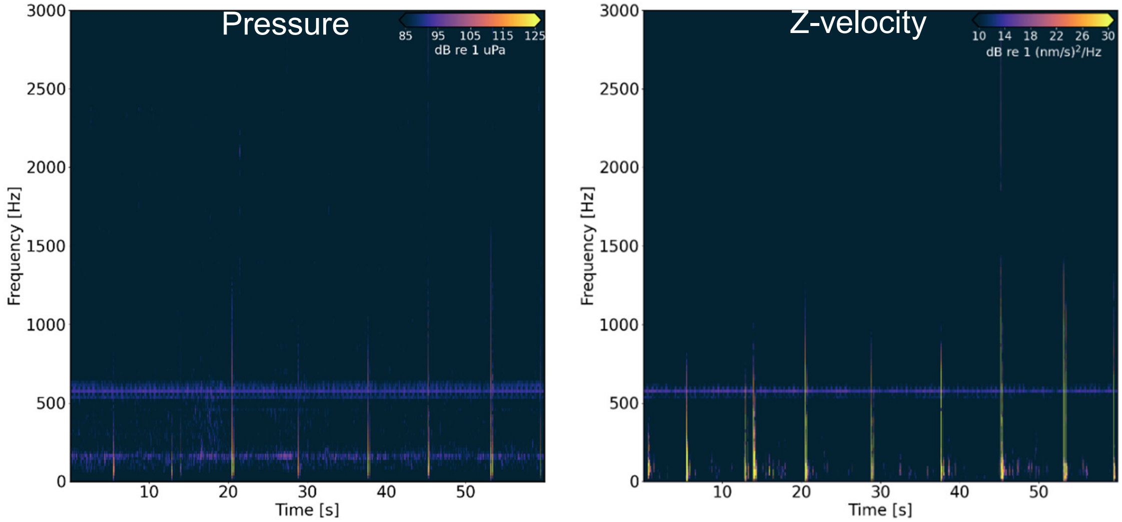

Figure 27. Example of acoustic pressure (left) and z-velocity (right) measured during NoiseSpotter drifts.

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[1] http://cdip.ucsd.edu/themes/?pb=1&d2=p70&u2=s:073:st:1:v:parameter:dt:202111

Motion of the sensor indicates that the compliant cord and heave plate, borrowed from the DAISY, are not quite suited to the NoiseSpotter's vector sensor, which is bigger in size and heavier. Therefore, a less stiff compliant cord would likely be required in future iterations of the drifting NoiseSpotter® to minimize motion of the sensor relative to the sea surface.

Near real-time NoiseSpotter®

The final demonstration of the near real-time NoiseSpotter® system (V4B; Figure 28) was demonstrated on November 15 and 16, 2021. NoiseSpotter V4B was deployed within 100 m of the CalWave device over an approximate 6-hr period on November 15 and an approximate 4-hr period on November 16. The vessel remained on-site, and field personnel noted the passage of several small vessels and large aircraft near the WEC and NoiseSpotter over the periods of both deployments.

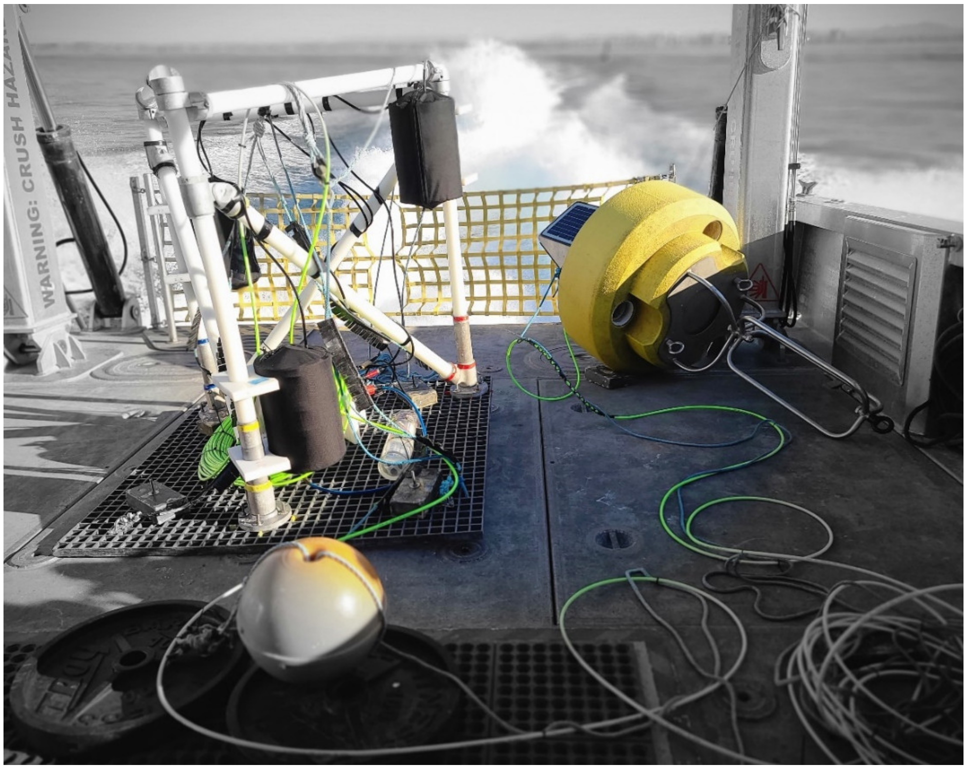


Figure 28. NoiseSpotter® V4B.

Near real-time system demonstration was successful, with 0% data dropout over the 10-hr total monitoring period. The telemetry unit transmits average spectra computed using approximately 10 seconds of data every minute. A 2048-point Fast Fourier Transform (FFT) is computed on each of 100 2048-sample time series as they stream out of the data logger, and the average spectra computed using these 100 time series is transmitted on the minute. A comparison of spectra computed using 10 seconds of data stored on the logger against that transmitted by the telemetry unit (Figure 29) shows a good comparison between the two. Discrepancies, however, do arise due to offsets in timing and limited-precision processing on the low-power Teensy processor.

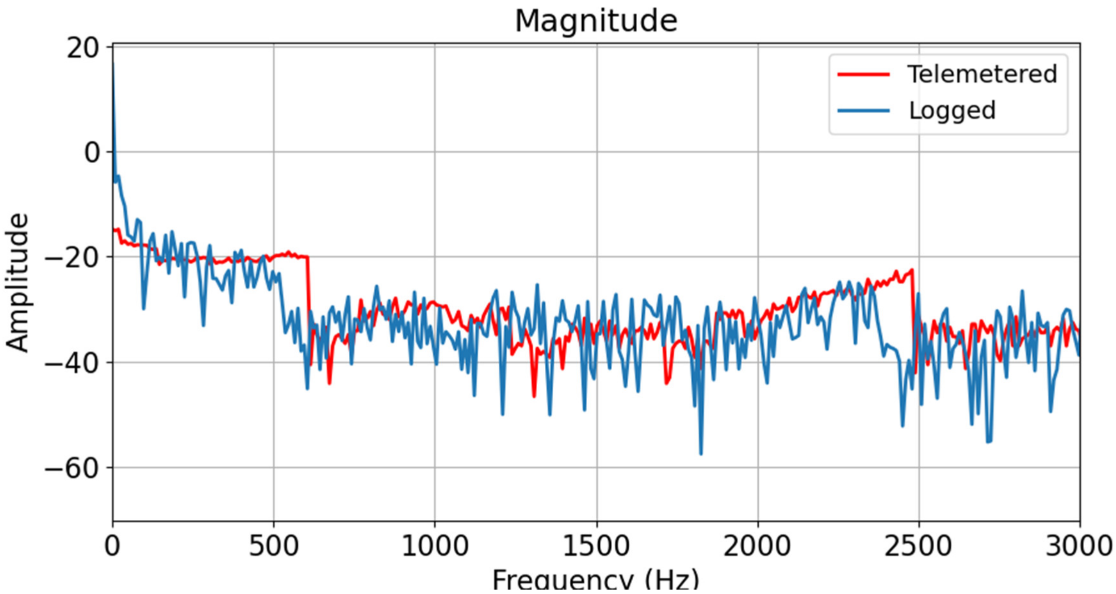


Figure 29. Comparison of telemetered spectra versus that computed from data stored on board the data logger.

Non-real-time NoiseSpotter® at four cardinal directions from WEC

Operational sounds from the WEC were characterized at two distances (100 m and 200 m) from the CalWave device, at four cardinal directions over the course of two field days (November 17-18, Figure 30). Autonomous acoustic data collection was demonstrated, with the NoiseSpotter® V4A bottom platform configured as a self-contained subsurface system without real-time telemetry (Figure 31). This effort represents a comprehensive characterization of WEC sounds as a function of distance, along with a characterization of the anisotropy of WEC sounds to aid in future three-dimensional acoustic propagation modeling. This characterization effort was conducted in collaboration with CalWave, who activated the device’s geometric actuator controls to open and close the flaps at the top of the device, as well as change its submergence depth multiple times during NoiseSpotter demonstration deployments (Figure 32).

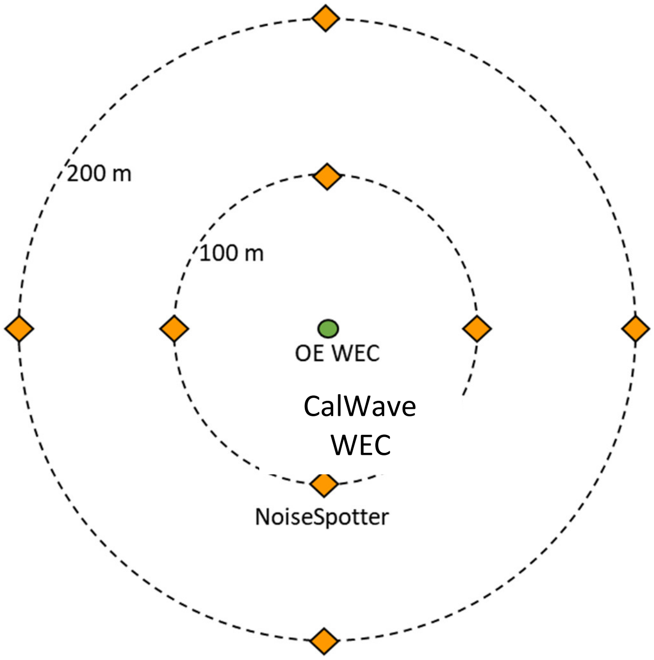


Figure 30. NoiseSpotter® V4A deployment locations around the CalWave device.

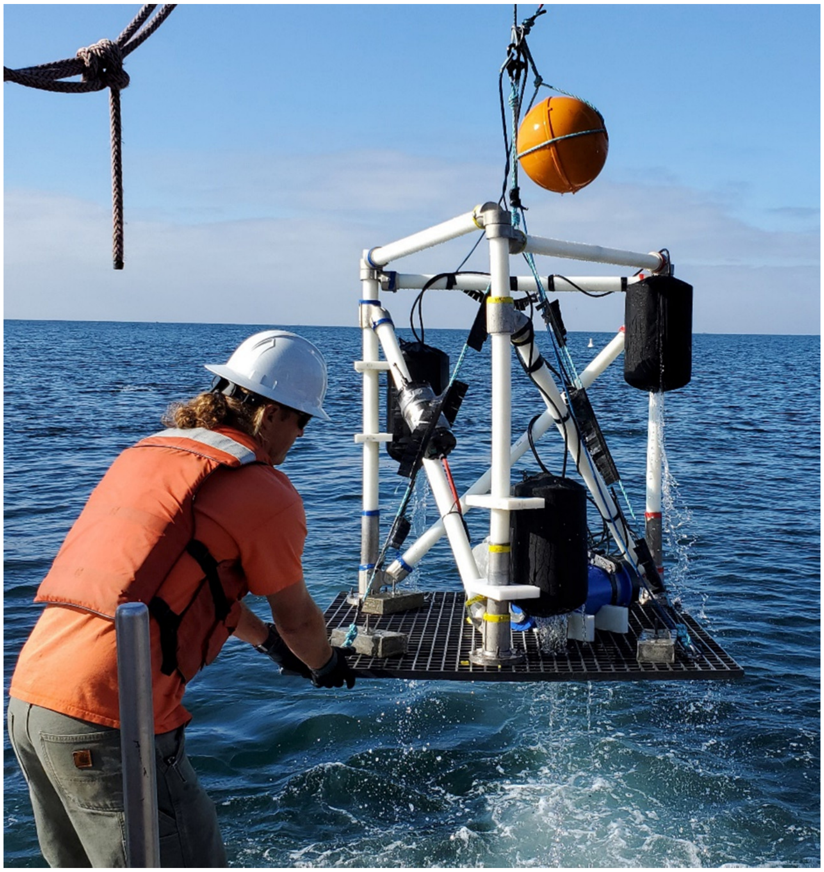


Figure 31. NoiseSpotter® V4A deployment.

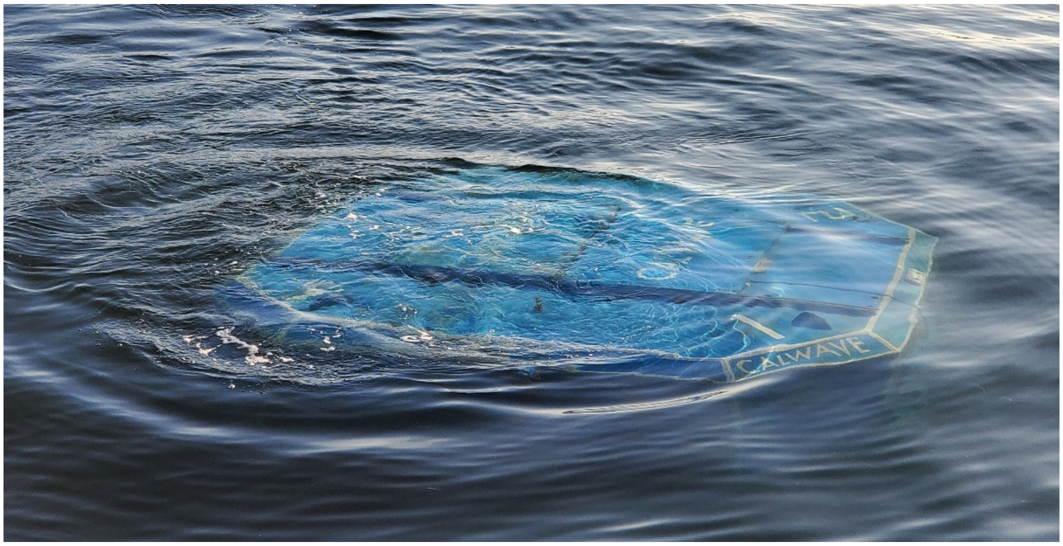


Figure 32. CalWave device at sea surface with hatch closed.

A variety of sounds were measured around the CalWave WEC that included sounds from a hovering helicopter, small boats and the opening/closing of the hatch on the WEC. Directional processing was applied to pressure and particle motion data following the methods described by Thode et al., 2019. These directional processing algorithms provide an 'azigram' for each minute of data, which shows the conventional spectrogram in addition to the frequency- and time-dependent azimuthal and elevation angles. Azimuth and elevation angles obtained from the particle motion sensor data are corrected using digital compass data such that the bearings displayed in the azigrams are in true earth coordinates, i.e. 0°, 90°, 180° and -90° indicate true north, east, south and west respectively.

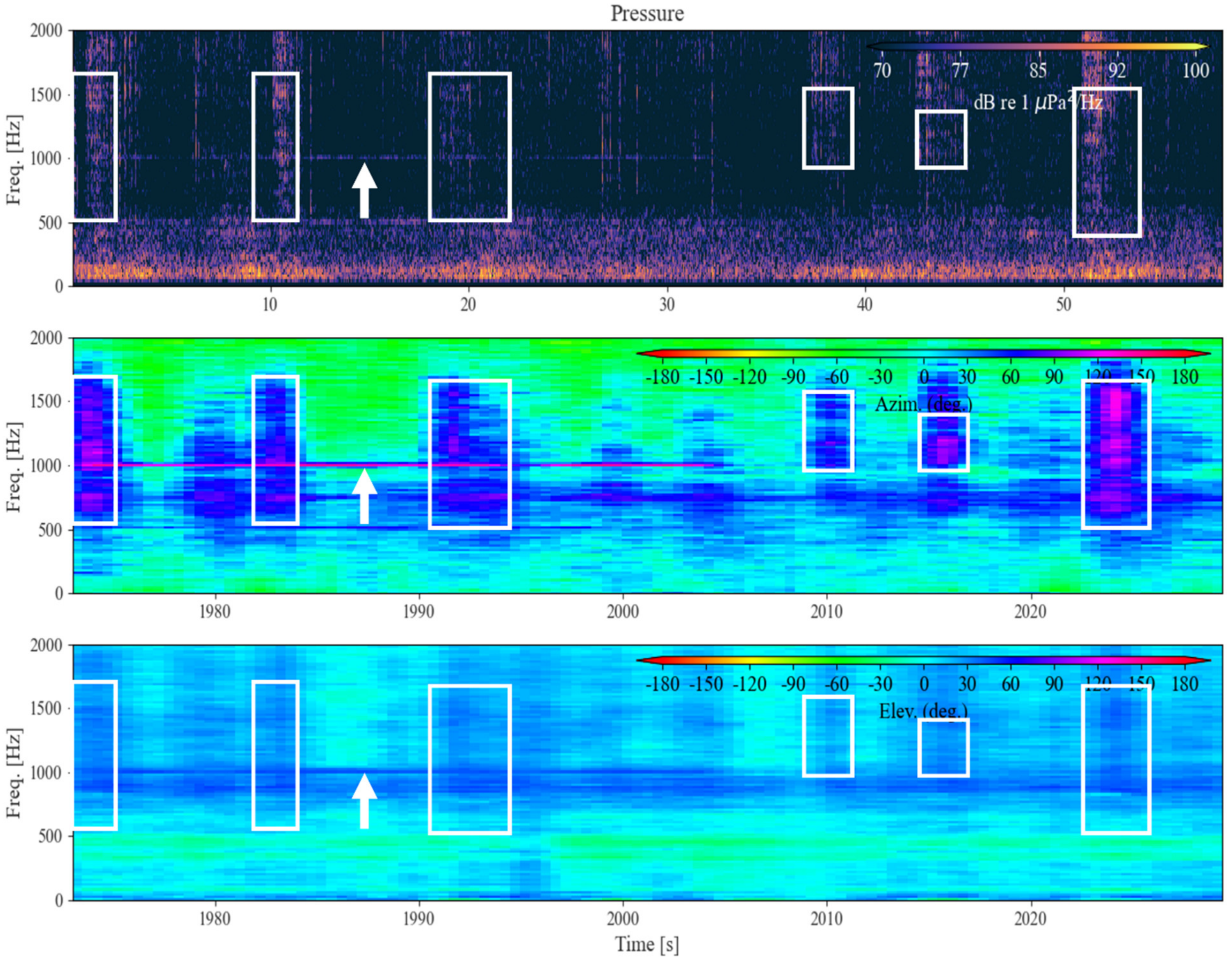


Figure 33. 'Azigram' of measured WEC sounds showing spectogram of acoustic pressure (top panel), azimuthal angle (middle panel) and elevation angle (lowest panel) for a 1-minute segment of data. WEC sounds are identified as those arriving from the 60-90° azimuthal bin. The white boxes and arrow show identified WEC sounds based on the azimuthal angle (middle panel) to the known WEC location.

As seen in Figure 33, directional processing can help identify specific signals of interest from other potentially confounding signals. In this particular case, it was known that the WEC was located due east of the NoiseSpotter® (90° azimuth). Therefore, WEC sounds are directionally identified as those colors associated with the 90° azimuth in the azigram. Similarly, the elevation angle associated with the WEC sounds is between 15-20°, close to the true elevation angle of 14° in 25 m water depth, at a distance of 100 m from the WEC.

Other sounds of interest measured on the NoiseSpotter during this deployment include those by a passing boat, helicopter and whale. Figure 34 shows the azigram for a passing boat. A typical Lloyd's mirror pattern is observed in the spectrogram, associated with the interference between the direct and reflected paths between the boat and measurement location. The azimuthal angle further shows the evolution of the azimuth as the boat transits by the

NoiseSpotter, while the elevation angle shows the angles associated with the direct (+60°) and bottom reflected (-60°) paths.

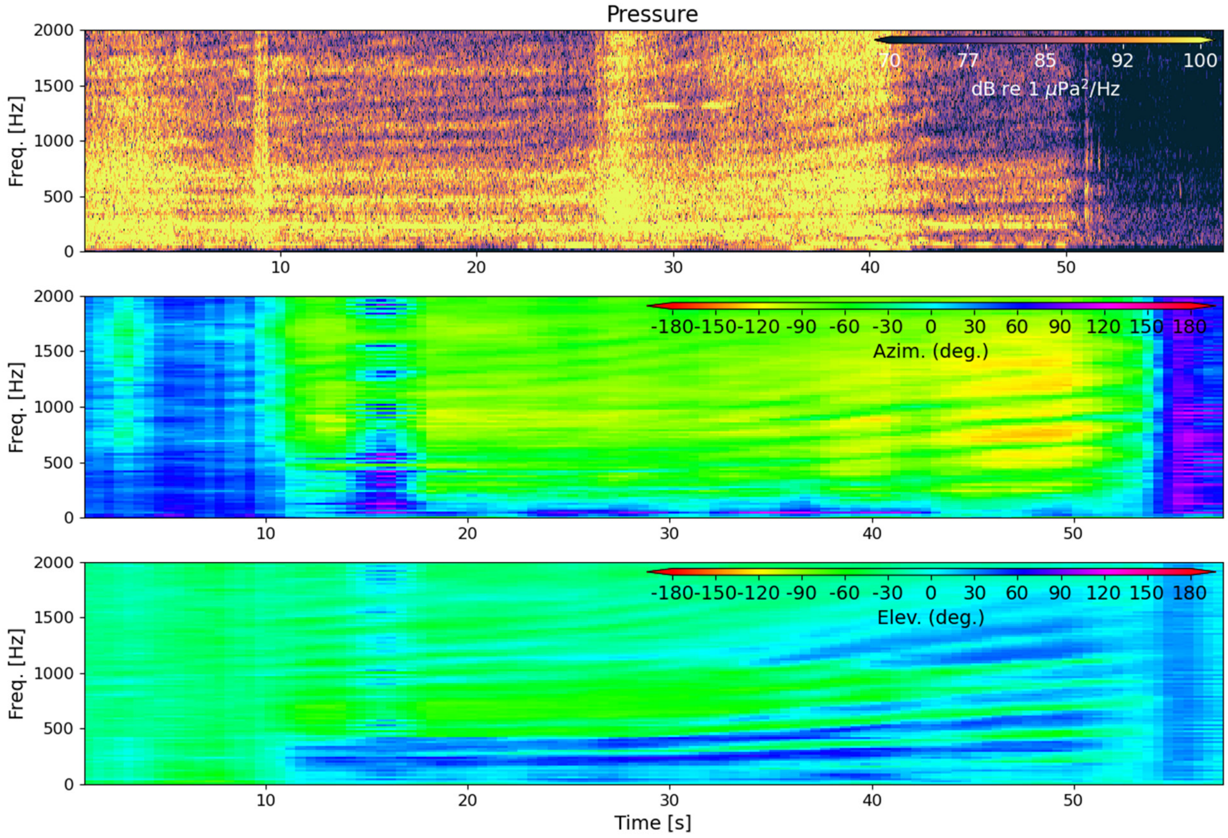


Figure 34. Azigram associated with a passing boat.

Underwater sound from a passing helicopter was also measured (Figure 35) during the deployment period. In contrast to the sounds from the WEC and boat, helicopter sounds are marked by distinct tonals associated with the rotor blade rotation. Further, azimuthal angles associated with the helicopter sounds are almost identical to those from the WEC, suggesting that the horizontal bearing of the two sounds are similar. This represents a potential limitation in the use of bearing angle to discriminate similar sounds of interest (either both continuous or both impulsive) when the sounds lie on the same bearing angle. However, more advanced signal processing and machine learning techniques can be leveraged in future efforts to further isolate WEC sounds in addition to the directional processing shown.

Sound exposure levels associated with various sounds measured during the deployment are listed in Table 12. The sound exposure level is computed as the average power over a 60 second window, and is a useful metric to compare chronic exposure of animals to continuous sounds. Other metrics such as peak sound pressure levels compare peak levels associated with more impulsive sounds, and can show greater differences between various sounds, but are somewhat less useful in terms of effects on marine mammals. The table of SELs shows that the anthropogenic sounds associated with the WEC are comparable to those from marine mammals, and 8 dB lower than those from a boat.

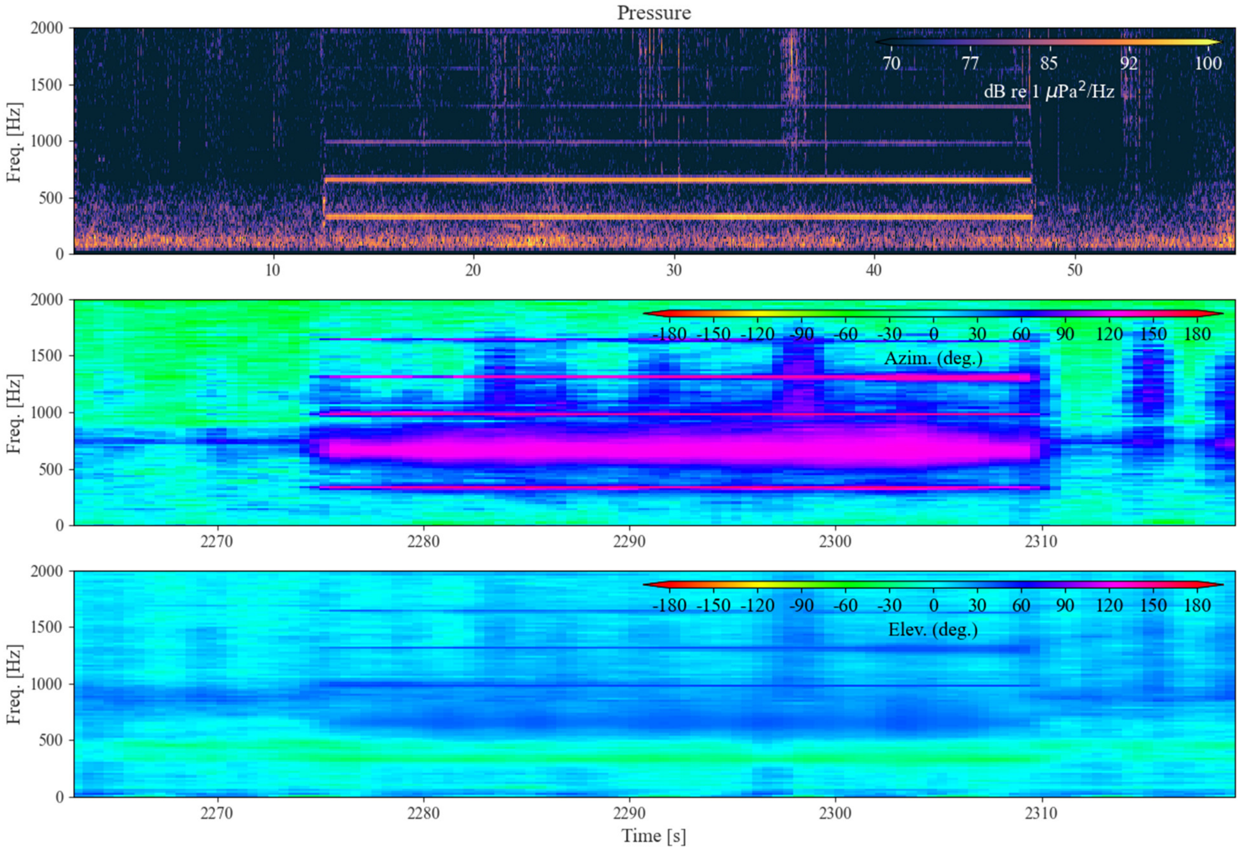


Figure 35. Azigram associated with a hovering helicopter.

Table 12. Sound exposure levels computed over minute-long data segments for various sounds measured during the deployment.

Source	$L_{E,60\ s}$ (dB re 1 µPa^2 s)
WEC	139 dB re 1 µPA
Boat	147
Helicopter	140
Gray Whale	138 dB

Multi-day non-real-time NoiseSpotter®

The robustness of the NoiseSpotter® system was demonstrated during a multi-day deployment (non-real-time; no surface expression) between November 19 and 21, 2021 (Figure 37).

A wide variety of sounds, including those from WEC operations (opening and closing of the hatch), boats and marine mammals were observed during this longer deployment. Figure 36 shows what appear to be humpback whale vocalizations (cusps in the spectrogram between 27-60 s). While the signals appear to be clearly visible in the spectrogram, they do not appear to be tracked in the estimates of azimuthal and elevation angles. This is likely due to lower signal to noise ratios associated with the relatively short duration of each call.

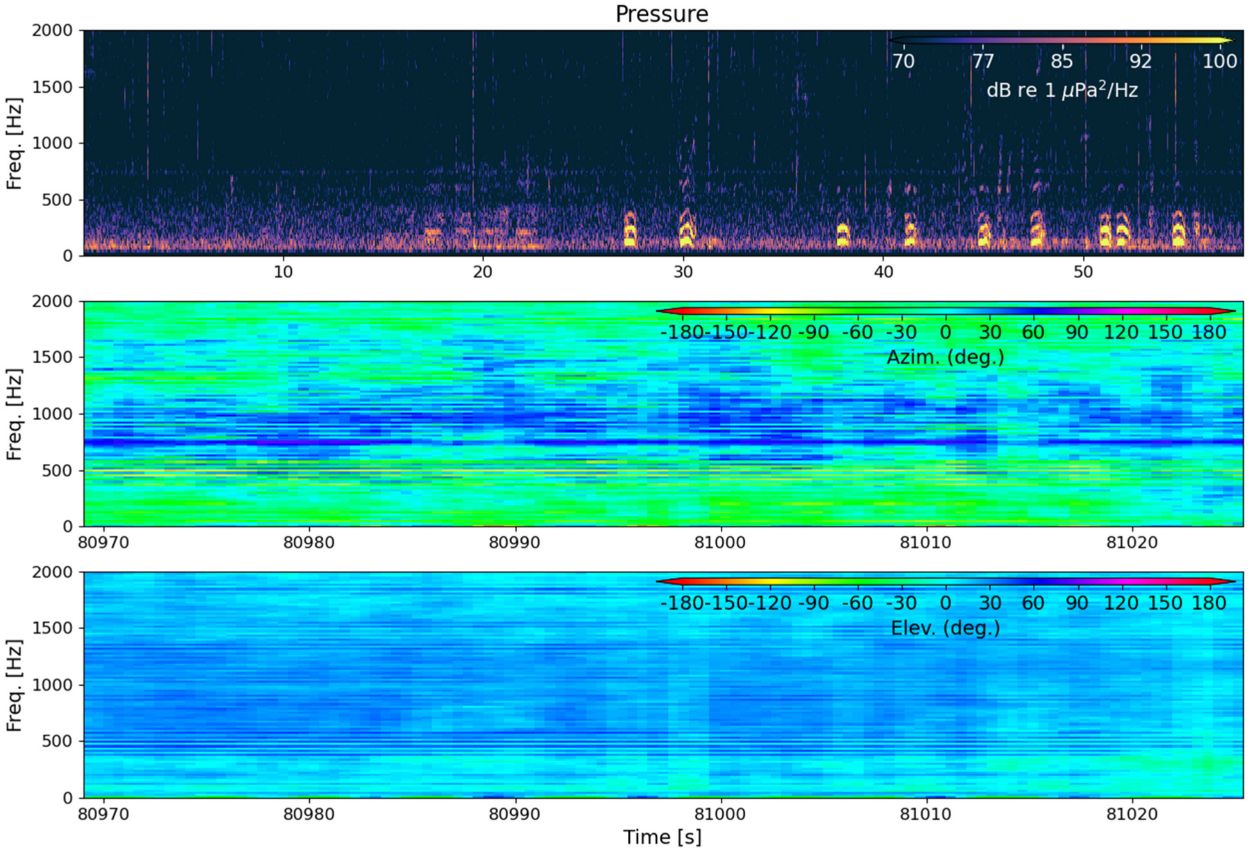


Figure 36. Azigram of what appear to be humpback whale vocalizations.

A juvenile gray whale was observed, exhibiting feeding behavior, in close proximity to the WEC and NoiseSpotter® upon arrival for recovery on November 21 (Figure 38).

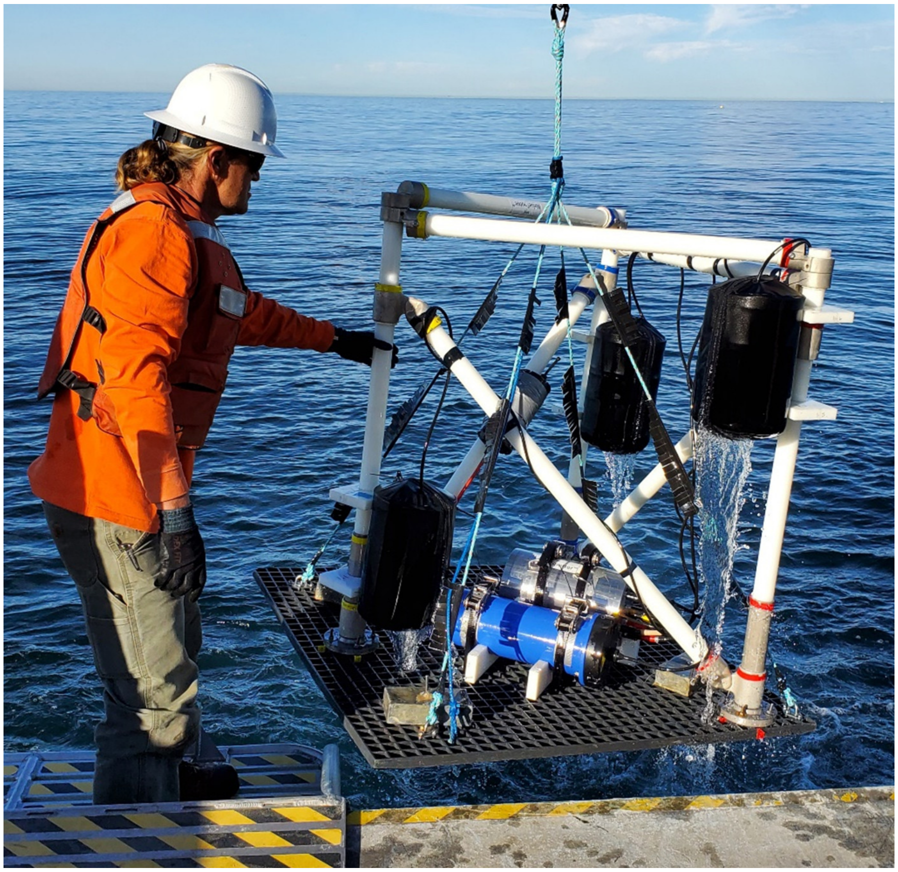


Figure 37. NoiseSpotter® V4A upon recovery after a multi-day deployment.

Figure 38. Gray whale observed in close proximity to the CalWave device.

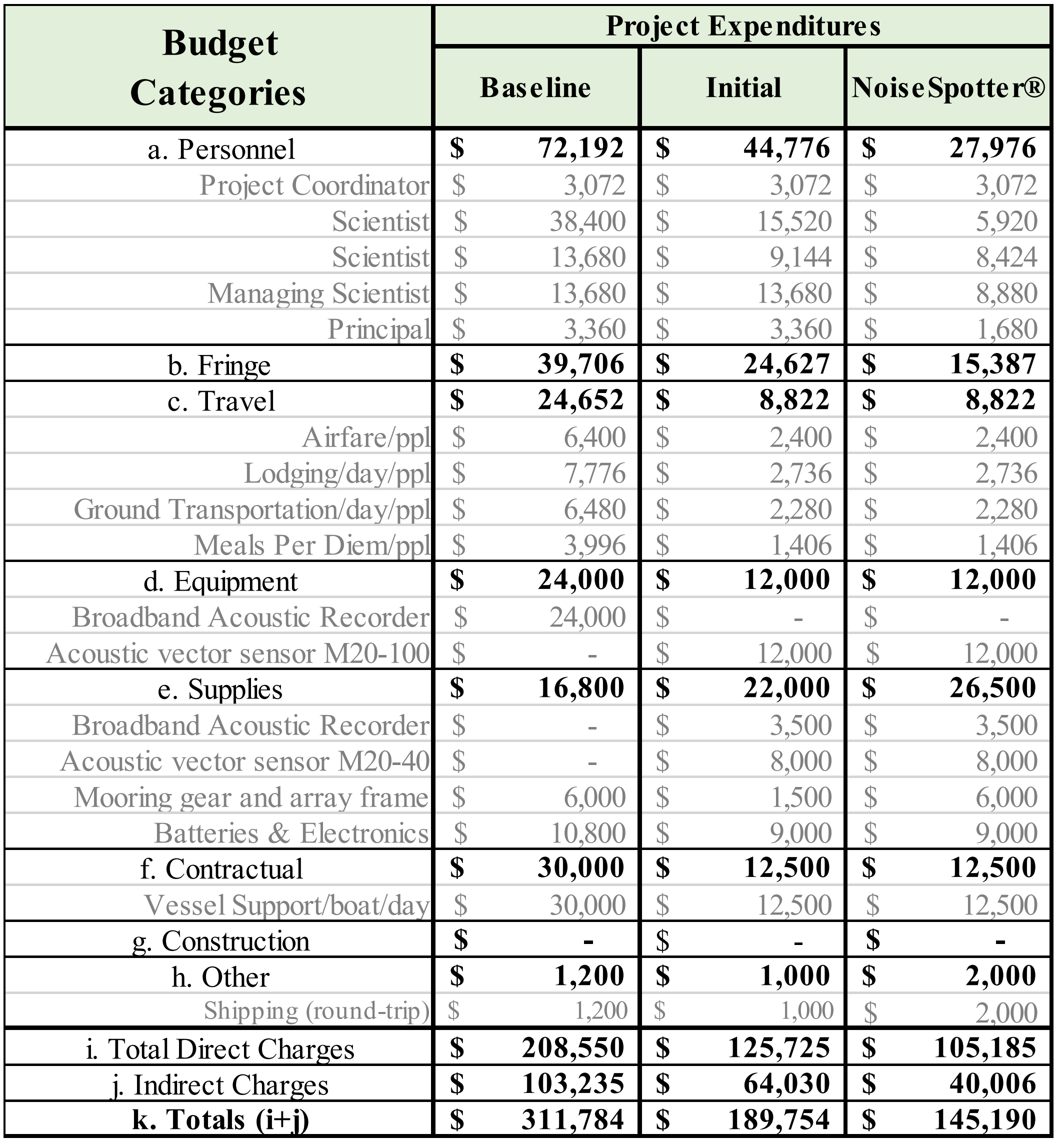
2.3.3.3 Final Technical and Cost Performance Analysis

NoiseSpotter® is the first passive acoustic monitoring system that can measure, characterize, and localize underwater sounds in near real-time, all on a single platform. NoiseSpotter is relatively compact, easy to assemble and disassemble, and can be deployed from small vessels. In-water deployments of NoiseSpotter demonstrated sustained, autonomous monitoring over 3+ week deployment periods and near real-time data telemetry was demonstrated with less than 5% data dropout over a 10+ hour monitoring period. NoiseSpotter acoustic pressure and particle velocity data are of high quality, comparable to COTS BAR data. Using through custom designed shields, flow noise is reduced by more than 15 dB at frequencies below 200 Hz, while not attenuating sounds of interest at higher frequencies. Beamforming techniques were developed and implemented for accurate sound source location estimation in quiescent and energetic environments, with geolocation accuracy to within 5% of actual. Final technical performance metrics benchmarked against target metrics are presented in Table 1. The iterative development process allowed for continuous improvements in data quality over each budget period. For example, electronic and motion-induced noise in BP1 was mitigated in BP2 by lowering the sensors onto a stable bottom platform and by designing a custom low-noise data logger. Improvements in data quality and sensor stability led to consequent improvements in location estimation performance from source detection withing 100 m to that within 2 m.

The final NoiseSpotter® cost performance analysis was prepared by updating the BP1 cost estimates for initial (non-real-time; Table 13) and improved (near real-time; **Error! Reference source not found.**) acoustic technology to actual costs involving testing over a period of 90 days with the objective of location estimation of natural and anthropogenic noises. Baseline technology costs were not updated from BP1 estimates (Table 13). Notable changes to the BP1 and BP2 estimated and actual costs for initial and improved technologies were decreases to labor and travel budgets for at-sea equipment maintenance and increases to the cost of batteries and mooring gear (improved technology only). Previous initial and improved technology cost estimates assumed 2-week deployment periods; final NoiseSpotter validation indicates 4+ deployment periods are possible. The result is an approximate $60,000 decrease in initial technology cost estimates. The updated improved technology cost estimate is approximately $5,000 greater than BP1 and BP2 estimates, largely due to previously unbudgeted data communication costs (e.g., surface buoy and Ethernet cable).

The final NoiseSpotter® cost performance analysis indicates 39% cost savings from baseline to initial (BP1 estimates were a 20% reduction), 23% cost savings from initial to improved (previous was 44%), and 53% reduction in costs from baseline to improved technology (BP1 estimate was 55%). The majority of cost savings from baseline (array of three BARs) to NoiseSpotter technology (non-real-time and near real-time) was associated with the decrease in the number of required moorings from three to one, increase in length of autonomous deployment (2 weeks to 4+ weeks), and subsequent decrease in labor hours required for at-sea operations. Further, labor costs associated with geolocation estimation facilitated by the near real-time NoiseSpotter resulted in more than 50% cost savings.

Table 13. Final cost performance analysis.



Budget Categories	**Project Expenditures**		
	Baseline	**Initial**	**NoiseSpotter®**
a. Personnel	**$ 72,192**	**$ 44,776**	**$ 27,976**
Project Coordinator	$ 3,072	$ 3,072	$ 3,072
Scientist	$ 38,400	$ 15,520	$ 5,920
Scientist	$ 13,680	$ 9,144	$ 8,424
Managing Scientist	$ 13,680	$ 13,680	$ 8,880
Principal	$ 3,360	$ 3,360	$ 1,680
b. Fringe	**$ 39,706**	**$ 24,627**	**$ 15,387**
c. Travel	**$ 24,652**	**$ 8,822**	**$ 8,822**
Airfare/ppl	$ 6,400	$ 2,400	$ 2,400
Lodging/day/ppl	$ 7,776	$ 2,736	$ 2,736
Ground Transportation/day/ppl	$ 6,480	$ 2,280	$ 2,280
Meals Per Diem/ppl	$ 3,996	$ 1,406	$ 1,406
d. Equipment	**$ 24,000**	**$ 12,000**	**$ 12,000**
Broadband Acoustic Recorder	$ 24,000	$ -	$ -
Acoustic vector sensor M20-100	$ -	$ 12,000	$ 12,000
e. Supplies	**$ 16,800**	**$ 22,000**	**$ 26,500**
Broadband Acoustic Recorder	$ -	$ 3,500	$ 3,500
Acoustic vector sensor M20-40	$ -	$ 8,000	$ 8,000
Mooring gear and array frame	$ 6,000	$ 1,500	$ 6,000
Batteries & Electronics	$ 10,800	$ 9,000	$ 9,000
f. Contractual	**$ 30,000**	**$ 12,500**	**$ 12,500**
Vessel Support/boat/day	$ 30,000	$ 12,500	$ 12,500
g. Construction	**$ -**	$ -	**$ -**
h. Other	**$ 1,200**	**$ 1,000**	**$ 2,000**
Shipping (round-trip)	$ 1,200	$ 1,000	$ 2,000
i. Total Direct Charges	**$ 208,550**	**$ 125,725**	**$ 105,185**
j. Indirect Charges	**$ 103,235**	**$ 64,030**	**$ 40,006**
k. Totals (i+j)	**$ 311,784**	**$ 189,754**	**$ 145,190**

3 PRODUCTS DEVELOPED

3.1 TECHNOLOGY: NOISESPOTTER®

NoiseSpotter®, U.S. Patent No. 11,156,734 and U.S. Registered Trademark No. 6,442,313, is a passive acoustic monitoring device designed to characterize, classify, and provide accurate location information, in near real-time, for underwater anthropogenic and natural sounds. It improves upon traditional acoustic monitoring technologies through integration of a compact array of acoustic particle motion sensors that measure acoustic pressure and 3-D particle velocities associated with the propagation of an acoustic wave, enabling triangulation of individual bearings and sound source localization.

3.1.1 NoiseSpotter® Commercialization

The NoiseSpotter® initial design (NoiseSpotter V0), technology readiness level (TRL) 4 (laboratory testing of components), was an array of particle motion sensors consisting of three GTI sensors: two M20-40s and one M20-100.

NoiseSpotter® design challenges to progress from TRL 4 to TRL 8 (pre-commercial demonstration) were related to:

- Data logging and transmission
    - Synchronous logging and transmission of 12-channels of acoustic data and ancillary IMU information
    - Continuous collection of acoustic pressure and particle velocity data at 20 kHz (~1.7 GB/day)
- Data quality
    - Minimal electronic noise, system self-noise, and acoustical disturbances from water flow around transducers (i.e., flow noise)
    - Reduced acoustic interferences from system hardware components (e.g., acoustic reflectance)
    - Maximum detection sensitivity (-194 dB - 230 dB)
    - Performance of location estimation algorithm
- Power budget
    - Low system power requirements to achieve autonomous operation for at least 14 days
- Field operations
    - Portable system to enable field deployments from a small vessel (e.g., 8 m) by two persons
    - Modular configuration of the particle motion sensors to support location estimation of sounds at multiple frequencies
    - Robust system components for operations in a wide range of environments

Table 14. Evolution of NoiseSpotter® design across different versions.

NoiseSpotter® Version	Key Features
V1	• Linear array of three mid-water column particle motion sensors. • Data logger located on surface buoy • Subject to data degradation from sensor motion and cable loss
V2	• Bottom-mounted linear array of sensors • No sensor motion issues like in V1, but subject to flow noise and data logger self-noise
V3	• Bottom-mounted 3D array, with each sensor mounted inside individual aluminum cage • Custom low-noise data logger • Issues include acoustic reflections from aluminum cages and time-consuming mobilization
V4A,B	• Bottom-mounted 3D array, with each sensor on vertical members of an acoustically transparent HDPE frame • Real-time and non-real time versions (A, and B respectively) • Modular system, with ease of mobilization and recovery

A series of five field-tests were conducted at SB2 and MSL in Sequim Bay, WA to overcome NoiseSpotter® design challenges. Field-tests involved moored deployments of the NoiseSpotter and controlled acoustic source signal transmissions spanning the frequency range 100 Hz - 3 kHz, over a range of source-receiver separation distances of 50 - 1000 m.

NoiseSpotter® V1 (TRL 5) consisted of a linear array of particle motion sensors on a mid-water column mooring (Figure 39A). Each sensor was hard-wired (cabled) to an off-the-shelf data logger and battery pack, housed in a surface buoy. NoiseSpotter V1 was field-tested at SB2 and resulted in identification of a number of issues, primarily stemming from the mid-water column design. These included system instability and acoustic contamination in the vertical channels; signal losses of 8 dB over 15 m cables; and difficulties with deployment and recovery due to unwieldy cables. Data logger self-noise was also observed at multiple frequencies and acoustic interference was detected at low frequencies (<200 Hz), indicative of flow-noise.

To mitigate issues with data quality and ease-of-deployment, the NoiseSpotter® was redesigned such that the linear array of sensors, data logger, and batteries were mounted on a stable bottom platform (Figure 39B); cable lengths were reduced to less than 1 m. Field-tests of the NoiseSpotter V2 (TRL 5) at the SB2 and MSL sites demonstrated simplified deployment, zero cable-induced signal losses, and no vertical motion observed in IMU or acoustic data.

However, flow-noise and data logger self-noise continued to be detected in data collected at both field-test sites.

The NoiseSpotter® V3 (TRL 6) included the design and engineering of a custom, low-power, low-noise, high-capacity data logger and custom flow-noise shields, constructed of 1050 ballistic nylon. Particle motion sensors with flow-noise shields were mounted in modular aluminum cages, vertically and horizontally separated on the bottom platform (Figure 39C). This allowed for sufficient spacing of the sensor array for accurate geolocation estimation. Field-test results at SB2 and MSL indicated little to no data logger self-noise, lower power requirements (0.36A versus 0.45A for the off-the-shelf logger), higher data storage (2 TB compared to 32 GB), and flow-noise reduction of ~15 dB. The remaining issues for the NoiseSpotter design included mitigating potential acoustic reflectance from the aluminum cages and time-consuming system mobilization.

The NoiseSpotter® V4A,B (TRL 7 and 8) was redesigned with modular HDPE frames to house each flow-noise shielded vector sensor (Figure 39D). The acoustic impedance ratios of HDPE indicates greater than 5-fold reduction in acoustic reflectance potential. NoiseSpotter V4B included onboard near real-time data processing and telemetry of acoustic data metrics via cellular link to a cloud server. Field-tests of NoiseSpotter V4A,B at SB2 and MSL demonstrated ease of assembly and disassembly of the HDPE frame design, rapid adjustment of the horizontal and vertical spacing of the vector sensors, and near real-time assessments of underwater sound. NoiseSpotter V4 field-tests were conducted with the UW DAISY.

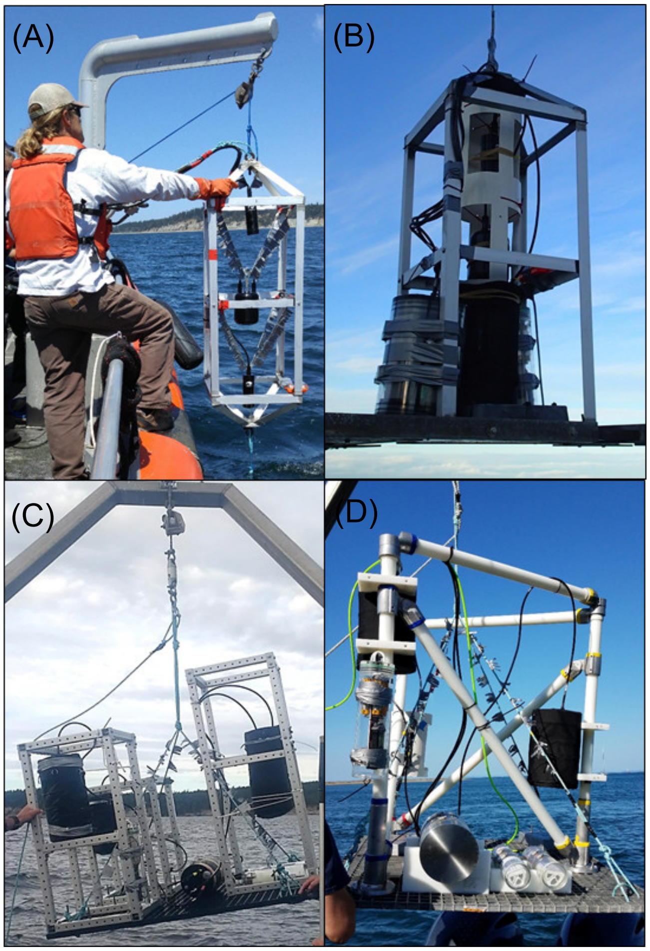


Figure 39. NoiseSpotter® design iterations. (A) V1, (B) V2, (C) V3, (D) V4A,B.

In addition to the final demonstration of NoiseSpotter®, collocated with the CalWave WEC in San Diego, CA, the technology was deployed commercially to measure sound pressure and particle velocity generated during oil platform decommissioning activities and during seismic surveys. For example, the NoiseSpotter® has been deployed in Santa Monica Bay to measure underwater sounds from aircraft, off Redfish Banks Marine Reserve (Port Orford, OR) to measure particle motion levels from seismic airgun surveys, off Point Conception (CA) to measure underwater sound from a rocket launch, and operationally in the Santa Barbara Channel to measure sound from conductor cutting operations associated with oil platform decommissioning.

3.2 PEER REVIEWED PUBLICATIONS

Chang, G., G. Harker-Klimeš, K. Raghukumar, B. Polagye, J. Haxel, J. Joslin, F. Spada, and G. Staines. 2021. Clearing a path to commercialization of marine renewable energy technologies through public-private collaboration. *Front. Mar. Sci.*, 8, 669413. doi: 10.3389/fmars.2021.669413.

Raghukumar, K., G. Chang, F. Spada, and C. Jones. 2020. A vector sensor-based acoustic characterization system for marine renewable energy. *J. Mar. Sci. Eng.* 8(3):187. doi:10.3390/jmse8030187.

Raghukumar, K., G. Chang, F.W. Spada, and C.A. Jones. 2019. NoiseSpotter: A rapidly deployable acoustic monitoring and localization system. D. Vicinanza et al. (eds), Proc. of the 13th European Wave and Tidal Energy Conference, Naples, Italy.

Raghukumar, K., G. Chang, F. Spada, C. Jones, J. Spence, S. Griffin, and J. Roberts. 2019. Performance characteristics of a vector sensor array in an energetic tidal channel. pp. 653–658. J.S. Papadakis (ed), Proc. of the Fifth Underwater Acoustics Conference and Exhibition, Crete, Greece.

Raghukumar, K., G. Chang, F.W. Spada, and C.A. Jones. 2019. Performance characteristics of the NoiseSpotter: An acoustic monitoring and localization system. A. Cooper and P. Gibbs (eds), Offshore Technology Conference, Houston, TX. doi:10.4043/29425-MS.

3.3 CONFERENCE PRESENTATIONS

Raghukumar, K., F. Spada, G. Chang, and C. Jones. 2021. Performance of an acoustic sensing array in an energetic channel. Poster presentation at the International Conference on Ocean Energy (ICOE). Virtual. April 28–30.

Spada, F., K. Raghukumar, G. Chang, and C. Jones. 2020. NoiseSpotter: Real-time underwater acoustic characterization in support of marine renewable energy projects. Poster presentation at the Ocean Sciences Meeting. Co-sponsored by the American Geophysical Union, the Association for the Sciences of Limnology and Oceanography, and The Oceanography Society, San Diego, CA. February 16–21.

Raghukumar, K., G. Chang, F.W. Spada, and C.A. Jones. 2019. NoiseSpotter: A rapidly deployable acoustic monitoring and localization system. Oral presentation at the 13th European Wave and Tidal Energy Conference, Naples, Italy. September 1-6.

Raghukumar, K., F.W. Spada, G. Chang, and C. Jones. 2019. Characterization of near-bed particle motion by the NoiseSpotter: A three-dimensional vector sensor array. Poster presentation at the Fifth International Conference on the Effects of Noise on Aquatic Life. Den Haag, The Netherlands. July 7–12.

Raghukumar, K., G. Chang, F. Spada, C. Jones, J. Spence, S. Griffin, and J. Roberts. 2019. Performance characteristics of a vector sensor array in an energetic tidal channel. Oral presentation at the Underwater Acoustics Conference and Exhibition Series, Crete, Greece. June 30–July.

Raghukumar, K., G. Chang, F. Spada, and C. Jones. 2019. NoiseSpotter: New technology for underwater acoustic characterization. Poster presentation at 7th Annual Marine Energy Technology Symposium, Washington, DC. April 1–3.

Raghukumar, K., F. Spada, G. Chang, and C. Jones. 2018. Initial field trials of the NoiseSpotter: An acoustic monitoring and localization system. Oral presentation at the 6th Annual Marine Energy Technology Symposium, Washington, DC. April 30–May 2.

3.4 INTERNET SITES

The NoiseSpotter® has been featured on two Integral Consulting Inc. website news posts, released on March 24, 2020 and July 19, 2021 (https://www.integral-corp.com/acoustics-integral-scientists-coauthor-article-in-journal-of-marine-science-and-engineering/ and https://www.integral-corp.com/how-does-noise-affect-fish-integral-investigates-loud-impulsive-sounds-with-noisespotter/). PNNL maintains two websites that highlight NoiseSpotter technology, one as part of the Triton program (https://www.pnnl.gov/projects/triton/integral-noisespotter) and the other as a research study in the Tethys Knowledge Base (https://tethys.pnnl.gov/research-studies/integral-noisespotter). Other internet sites that present NoiseSpotter include journal websites at which NoiseSpotter research has been published (see Section 3.2).

3.5 COLLABORATIONS FOSTERED

Regular outreach throughout the project performance period has resulted in ongoing collaborations with teams from industry, academia and government agencies. Most recently, Integral is a subcontractor to the University of Washington on DOE grant EE0009959 to infer acoustic source functions of wave energy converters at the PacWave site, and to Oregon State university on an NSF grant to relate seismic airgun sounds to behavioral changes in demersal and semi-pelagic fishes. Integral is also working with CalWave on relating NoiseSpotter® measurements to operational sounds from the WEC.

In addition to ongoing funded collaborations, regular outreach has resulted in several proposal efforts to either use the NoiseSpotter® in operational settings, modify/enhance the system, or develop new technology based on the NoiseSpotter®. A current TEAMER proposal with UW and PNNL as project partners aims to utilize the NoiseSpotter® to measure and localize sound from UW's prototype tidal turbine. A pending proposal to Gardline Ltd. will conduct operational measurements of particle motion associated with pile-driving for offshore wind turbines. Finally, a proposal was recently submitted to NOAA Office of Exploration Research, teamed with Seatrec Inc., the Naval Postgraduate School, Monterey Bay Aquarium Research Institute and Scripps Institution of Oceanography to develop an Ocean Thermal Energy Conversion-powered profiling float capable of directional acoustic measurements.

The team also has regular ongoing conversations with Applied Ocean Sciences Inc., BioSonics Inc., Florida Atlantic University, and MarineSitu to identify opportunities to collaborate on.

4 REFERENCES

Tesei, A., Fioravanti, S., Grandi, V., Guerrini, P. and Maguer, A., 2012, July. Localization of small surface vessels through acoustic data fusion of two tetrahedral arrays of hydrophones. In *Proceedings of Meetings on Acoustics ECUA2012* (Vol. 17, No. 1, p. 070050). Acoustical Society of America.

Thode, A., Skinner, J., Scott, P., Roswell, J., Straley, J. and Folkert, K., 2010. Tracking sperm whales with a towed acoustic vector sensor. *The Journal of the Acoustical Society of America*, *128*(5), pp.2681-2694.

Thode, A.M., Sakai, T., Michalec, J., Rankin, S., Soldevilla, M.S., Martin, B. and Kim, K.H., 2019. Displaying bioacoustic directional information from sonobuoys using "azigrams". *The Journal of the Acoustical Society of America*, *146*(1), pp.95-102.

5 APPENDIX A. FINAL FIELD DEMONSTRATION FIELD LOG

Time (PST)	Activity / Notes
11.14.21 -- Drifting	
DRIFT #1	CalWave device submergence depth was 15-20 ft, normal operations
09:15	Drifting NoiseSpotter® deployed
09:18	DAISY deployed
09:19	Vessel engine off
09:35	Vessel engine on for recovery
09:38	DAISY recovered
09:42	Drifting NoiseSpotter® recovered
DRIFT #2	CalWave device submergence depth was 15-20 ft, normal operations
09:48	Drifting NoiseSpotter® deployed
09:50	DAISY deployed
09:50	Vessel engine off
10:27	Vessel engine on for recovery
10:30	DAISY recovered
10:32	Drifting NoiseSpotter® towed behind vessel
DRIFT #3	CalWave device submergence depth was 15-20 ft, normal operations
10:38	Drifting NoiseSpotter® released from vessel
10:39	DAISY deployed
10:40	Vessel engine off
11:00	Sea lion calls audible toward the southeast
11:07	Vessel engine on for repositioning
11:08	Vessel engine off: twin prop plane overhead
11:25	Vessel engine on for recovery
11:28	DAISY recovered
11:31	Drifting NoiseSpotter® towed behind vessel
DRIFT #4	CalWave device submergence depth was 15-20 ft, normal operations
11:35	Drifting NoiseSpotter® released from vessel
11:36	DAISY deployed
11:36	Vessel engine off
12:08	Vessel engine on for repositioning
12:10	Vessel engine off
12:29	Vessel engine on for recovery
12:31	DAISY recovered
12:33	Drifting NoiseSpotter® towed behind vessel
DRIFT #5	CalWave device submergence depth was 15-20 ft, normal operations
12:39	Drifting NoiseSpotter® released from vessel
12:41	DAISY deployed

12:41	Vessel engine off
13:30	Vessel engine on for recovery
13:33	DAISY recovered
13:35	Drifting NoiseSpotter® recovered
11.15.21 – Near Real-Time NoiseSpotter®	
DEP #1RT	CalWave device submergence depth was 13 ft, actuation systems out of normal line and times were monitored by CalWave. Deployment location: 32°52.028′ N, 117°15.796′ W in 19.8 m water depth
09:32	NoiseSpotter® platform on bottom
09:35	NoiseSpotter® surface buoy deployed
09:58	Recovery line attached to support buoy
09:59	Vessel engine off
10:20	Vessel engine on for repositioning
10:27	Vessel engine off
10:44	Large bait ball ~300 m east of the WEC
11:24	Vessel engine on for repositioning
11:26	Vessel engine off
12:51	Two osprey aircraft passing overhead
13:07	Vessel engine on for repositioning
13:09	Vessel engine off
13:57	Helicopter circled the WEC overhead
14:12	Vessel engine on for repositioning
14:15	Vessel engine off
15:06	Helicopter overhead of the WEC
15:25	Vessel engine on for recovery
15:32	Surface buoy hooked
15:36	Start of platform recovery
15:50	NoiseSpotter® recovery operations completed
11.16.21 – Near Real-Time NoiseSpotter®	
DEP #2RT	CalWave device transitioning to more shallow submergence. Will be at 10 ft depth at 9:42 am. Deployment location: 32°52.028′ N, 117°15.796′ W in 19.8 m water depth
08:39	Start of deployment operations
08:52	NoiseSpotter® platform on bottom
08:57	Vessel engine off
09:04	Vessel engine on for repositioning
09:16	Vessel engine off
09:29	SIO small vessel passed from the Pier near WEC
09:43	Vessel engine on for repositioning
09:44	Vessel engine off

10:17	Vessel engine on to warn kayaker to stay away from WEC
10:26	Vessel engine off
10:32	Vessel engine on for repositioning
10:34	Vessel engine off
10:35	Helicopter overhead of WEC
10:41	Small vessel approaching WEC
10:57	Vessel engine on for repositioning
10:59	Vessel engine off
	CalWave device was at approximately 5 ft submergence
11:35	Vessel engine on for repositioning
11:37	Vessel engine off
12:24	Vessel engine on for repositioning
12:26	Vessel engine off
12:30	Small vessel passing by WEC
12:46	Vessel engine on for recovery
12:49	Buoy hooked
12:53	NoiseSpotter® platform recovered
12:57	Surface buoy recovered
11.17.21 – Non-Real-Time NoiseSpotter® [Note that the vessel GPS antenna is 8 m from the A-frame location]	
DEP #1NRT	CalWave device was at 6 ft submergence until 10:25 am 100 m east of WEC; boat heading is 90° Deployment location: 32°52.056′ N, 117°15.724′ W in 20 m water depth
08:39	NoiseSpotter® deployed
08:41	Engine off
09:23	Engine on for recovery
09:26	Buoy hooked
09:30	NoiseSpotter® recovered
DEP #2NRT	200 m east of WEC; boat heading is 90° Deployment location: 32°52.032′ N, 117°15.665′ W in 19.3 m water depth
09:41	NoiseSpotter® deployed and engine off
10:03	Engine on for repositioning
10:05	Engine off
10:25	CalWave device submergence depth moved to 3 ft until ~noon
10:27	Engine on for recovery
10:35	NoiseSpotter® recovered
DEP #3NRT	100 m south of WEC; boat heading is 60-70° Deployment location: 32°52.003′ N, 117°15.787′ W in 18.5 m water depth
10:48	Large helicopter hovered over the CDIP buoy (west of WEC)
10:50	NoiseSpotter® deployed and engine off

11:10	Airplane overhead
11:31	Engine on for recovery
11:38	NoiseSpotter® recovered
DEP #4NRT	200 m south of WEC; boat heading is 60-70° Deployment location: 32°51.949′ N, 117°15.792′ W in 18.3 m water depth
11:48	NoiseSpotter® deployed and engine off
12:00	CalWave device submergence depth moved to 2.5 ft.
12:29	Engine on for recovery
12:36	NoiseSpotter® recovered
DEP #5NRT	Device has geometric actuator controls that open and close flaps. CalWave to start actuator changes. 100 m west of WEC; boat heading is 250-260° Deployment location: 32°52.058′ N, 117°15.859′ W in 23.9 m water depth
12:54	NoiseSpotter® deployed and engine off
12:59 – 13:00	CalWave actuator controls activated (moonpool/hatch opened?)
13:01	Helicopter overhead
13:08	CalWave actuator controls activated (moonpool/hatched closed?)
13:12 – 13:15	CalWave actuator controls activated (moonpool/hatch opened?)
13:17	CalWave actuator controls activated (moonpool/hatched closed?)
13:22	Airplane overhead
13:26	CalWave actuator controls activated
13:35	Helicopter overhead and engine on for recovery
13:46	NoiseSpotter® recovered
DEP #6NRT	200 m west of WEC; boat heading is 290° Deployment location: 32°52.057′ N, 117°15.921′ W in 31.2 m water depth
13:56	NoiseSpotter® deployed and engine off
14:36	Engine on for recovery
14:45	NoiseSpotter® recovered
DEP #7NRT	100 m north of WEC; boat heading is 350° Deployment location: 32°52.114′ N, 117°15.786′ W in 26.6 m water depth
14:54	NoiseSpotter® deployed and engine off
15:28	Engine on for repositioning
15:28	Engine off
15:34	Engine on for recovery
15:42	NoiseSpotter® recovered
DEP #8NRT	200 m north of WEC; boat heading is 180° Deployment location: 32°52.167′ N, 117°15.792′ W in 26.5 m water depth
15:49	NoiseSpotter® deployed and engine off
16:29	Engine on for recovery
16:36	NoiseSpotter® recovered

11.18.21 – Non-Real-Time NoiseSpotter® [Note that the vessel GPS antenna is 8 m from the A-frame location]	
DEP #9NRT	CalWave device was at 13 ft submergence. 100 m north of WEC; boat heading is 0° Deployment location: 32°52.114′ N, 117°15.786′ W in 26.6 m water depth
08:18	NoiseSpotter® deployed and engine off
08:32	CalWave starting process to further submerge the WEC
08:42	Acoustic release unit undergoing testing on vessel deck
08:44	Acoustic release unit testing stopped
08:44	Helicopter overhead, to west of WEC
08:57	Small vessel near WEC
09:05 – 09:11	WEC performs a full self-check and reports generation. Expected to take 6 minutes to complete.
09:15	Engine on for repositioning
09:16	Engine off
09:18	WEC submergence is 20 ft
09:20	WEC moonpool/hatch changes from closed to opened
0923 – 09:56	WEC moonpool/hatch is opened and closed five times
09:54	Acoustic release unit undergoing testing on vessel deck
09:57	Engine on for recovery
10:07	NoiseSpotter® recovered
DEP #10NRT	200 m north of WEC; boat heading is 0° Deployment location: 32°52.167′ N, 117°15.792′ W in 26.5 m water depth
10:15	NoiseSpotter® deployed and engine off
10:30	Start of CalWave actuator tests
11:08	End of CalWave actuator tests
11:20	Engine on for recovery
11:28	NoiseSpotter® recovered
DEP #11NRT	200 m west of WEC; boat heading is 0° Deployment location: 32°52.057′ N, 117°15.921′ W in 31.2 m water depth
11:37	NoiseSpotter® deployed and engine off
11:48	Engine on for recovery
11:55	NoiseSpotter® recovered
DEP #12NRT	100 m west of WEC; boat heading is 0° Deployment location: 32°52.052′ N, 117°15.868′ W in 24.0 m water depth
12:06	NoiseSpotter® deployed and engine off
12:36	Engine on for recovery
12:45	NoiseSpotter® recovered
DEP #13NRT	100 m south of WEC; boat heading is 0° Deployment location: 32°52.003′ N, 117°15.787′ W in 18.5 m water depth

12:52	NoiseSpotter® deployed and engine off
13:13	Engine on for recovery
13:20	NoiseSpotter® recovered
DEP #14NRT	200 m south of WEC; boat heading is 0° Deployment location: 32°51.949′ N, 117°15.792′ W in 18.3 m water depth
13:25	NoiseSpotter® deployed and engine off
13:40	Vessel observed to the west of the WEC
13:45	Engine on for recovery
13:52	NoiseSpotter® recovered
DEP #15NRT	100 m east of WEC; boat heading is 0° Deployment location: 32°52.056′ N, 117°15.726′ W in 20.0 m water depth
13:59	Helicopter fly-by (NoiseSpotter® in water but engine still running)
14:00	NoiseSpotter® deployed and engine off
14:20	Engine on for recovery
14:27	NoiseSpotter® recovered
DEP #16NRT	200 m east of WEC; boat heading is 0° Deployment location: 32°52.032′ N, 117°15.665′ W in 19.3 m water depth
14:34	NoiseSpotter® deployed and engine off
14:38	Vessel in area
14:55	Engine on for recovery
15:02	NoiseSpotter® recovered
11.19.21 – Multi-Day Non-Real-Time NoiseSpotter® [Note that the vessel GPS antenna is 8 m from the A-frame location]	
Deployment	100 m south of WEC Deployment location: 32°52.003′ N, 117°15.787′ W in 18.5 m water depth
09:12	NoiseSpotter® deployed and engine off
09:14	Pinging acoustic release with deck box
09:21	Engine on, departing area
11.21.21 – Multi-Day Non-Real-Time NoiseSpotter®	
Recovery	100 m south of WEC Deployment location: 32°52.003′ N, 117°15.787′ W in 18.5 m water depth
08:00	Arrival on-site. Juvenile gray whale circling WEC and vessel. Exhibiting feeding behavior
08:07	Subsurface buoy released
08:20	NoiseSpotter® recovered
END OF FIELD LOG	