Localization of Southern Resident Killer Whales Using Two Star Arrays to Support Marine Renewable Energy

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***Abstract*—Tidal power has been identified as one of the most promising commercial-scale renewable energy sources. Puget Sound, Washington, is a potential site to deploy tidal power generating devices. The risk of injury for killer whales needs to be managed before the deployment of these types of devices will be approved by regulating authorities. A passive acoustic system consisting of two star arrays, each with four hydrophones, was designed and implemented for the detection and localization of Southern Resident killer whales. Performance evaluation of the passive acoustic system was conducted at Sequim Bay, Washington. A total of nine sound source locations were chosen, within a radius of 250 m around the star arrays, to evaluate the accuracy of our localization approach. A localization algorithm, a least square solver, was applied to obtain a bearing location to a sound source from each star array. The sound source location was estimated by the intersection of the bearings from the two star arrays. Bearing and distance errors were computed to compare calculated and true (from Global Positioning System) sound source locations. Observed bearing errors were within 1.04º for eight of the nine test locations; location 3 had bearing errors slightly larger than expected due to a high level of background noise. The distance errors for six of the test locations were between 1.91 and 32.36 m. The other two test locations, 8 and 9, were near the line passing through the centers of the two star arrays, where large errors were expected based on theoretical sensitivity analysis results.**

***Index Terms*—Passive acoustic system, localization, star array, bearings.**

I. INTRODUCTION

With increasing interest in renewable energy during the last decade, the ocean has been recognized as an enormous renewable energy source. Tidal turbines, using the kinetic energy present in marine tidal currents, are widely considered as one of the most attractive means for extracting energy from the ocean [1]. However, there currently are no tidal-power generating stations in the United States. The Federal Energy Regulatory Commission (FERC) is considering an application by Snohomish County Public Utility District (SNOPUD) to deploy tidal turbines in Puget Sound, Washington. SNOPUD selected a site near Admiralty Island in Puget Sound because of strong tidal currents at the site. In addition to FERC approval, permission from regulatory authorities with responsibility to protect the safety of marine animals, especially those under the special protection of the *Endangered Species Act of 1973* (ESA) and the *Marine Mammal Protection Act of 1972* (MMPA), also is required for deployment of prototype tidal turbines.

Southern Resident Killer Whales (SRKW, Orcinus orca) constitute a distinct population of killer whales inhabiting the coastal waters of Washington state and British Columbia. SRKW were listed as an endangered species under ESA in 2005. As of July 2008 only 85 SRKW were reported to exist. The SRKW occur primarily in the Georgia Basin and Puget Sound from spring to fall [2-6]. Contact with tidal turbines is thought to pose a potential danger to SRKW.

A team from Pacific Northwest National Laboratory (PNNL) has designed and tested the Marine Mammal Alert System (MMAS) to manage the risk of injury, mortality, or harassment to SRKWs from tidal turbine contact. The MMAS has been designed as a monitoring device for detecting and localizing SRKWs when they are within high-risk zones of the tidal turbines and to alert turbine operators when SRKWs are near the turbines so that the turbines can be temporarily shut down or other mitigation initiated.

Both active and passive acoustic systems were considered for the MMAS [7-8]. Passive acoustic systems have been studied extensively for detection of SRKWs in recent years because SRKWs are known to vocalize frequently [9-10]. The primary focus of the PNNL study was on the detection and localization of SRKWs. An algorithm for passive acoustic detection and a method for evaluating passive acoustic system operational performance were described by Matzner et al. [11]. The MMAS consists of two star arrays separated by a distance of 20 m between the central hydrophones of each array. The separation between arrays was selected so that the arrays would fit within the perimeter of a tidal turbine's foundation to enable the arrays to be deployed with the turbine and have power and data transmission capability available. For each star array, four hydrophones are arranged as a symmetrical star [12]. The four-

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channel acoustic receivers connected to a star array are based on the acoustic telemetry receivers developed for the U.S. Army Corps of Engineers for tracking juvenile salmonids [13-14]. This paper describes the SRKW localization algorithm and the field evaluation of the performance of the passive acoustic system.

II. METHODS

A. Overview

The acoustic receivers simultaneously sample the output of the four hydrophones in a star array at a 1 MHz sampling rate and perform a two-step SRKW call detection process in real time (Fig. 1). Time difference of arrivals (TDOAs) between the central hydrophone and the other hydrophones for each star array are calculated using cross correlation. The bearing of a sound source relative to each star array is obtained by two localization solvers—least square (LS) and approximate maximum likelihood (AML) solvers [15-19]. The results presented in this paper were obtained using the LS solver because it had better performance than the AML solver. The intersection of the two bearing estimates from the star arrays is computed to estimate the location of a sound source. From this point forward, this localization method will be referred to as the bearing method.

B. Error Analysis

A theoretical error analysis was performed for a 500 m× 500 m area with the center of the midpoint of the two star arrays at the origin. The bearing error was defined as the angle between two lines: a line from the origin to the true (Global Positioning System [GPS]) location of a sound source and a line from the origin to the source's calculated location. The distance error was defined as the distance between the true and calculated locations. The range error was defined as the difference between the distance from origin to the calculated location and the distance from origin to the GPS location. Two configurations were analyzed (Fig. 2)—one was a 2D array in which the four hydrophones were located in the same plane; the other was a 3D array in which the center hydrophone was 5 m higher than the outer hydrophones, which were located in the same plane. The same TDOA error, which was on the order of 10^{-5} s, was simulated for both star array geometries. Depths of 0 m and 50 m above the hydrophone plane, respectively, were chosen for the comparison. For each depth, the computed bearing and distance errors are shown in Figs. 3 and 4. Each panel of the figures illustrates the estimated errors in the *x-y* plane at a fixed depth. The maximum value on the color scale is 20° for the bearing error and 50 m for the distance error. It can be seen that the 2D star arrays have, in general, better performance than 3D star arrays, and the errors were often more uniform at greater depth. For this reason, the 2D star array geometry was used for the build of the passive acoustic system deployed for performance evaluation.

C. Validation Experiment

The in-field performance of a pair of 2D star arrays was conducted in Sequim Bay, Washington, to assess the accuracy of localization of a sound source and to validate the function of the bearing angle solvers. Nine test locations for a sound source were chosen within a radius of 250 m from the center of a line connecting the star arrays. The two red triangles shown in Fig. 5 are the central locations for each of the 2D star arrays, and the numbers highlighted in yellow are the test locations for the sound source. For each test location, an acoustic beacon (Model AAE 319, Applied Acoustic Engineering Limited, Great Yarmouth, UK) with a source level of 180 dB relative to 1 μPa at 1 m was placed at a depth of 2 m. After reception of beacon signals was verified for each, source location, an ensemble of six different types of whale calls was transmitted using a high-power broadband piezoelectric underwater transducer (Model LL9162T, Lubell Labs Inc., Columbus, Ohio, USA) deployed from an anchored silent vessel. The whale calls were obtained from a SRKW call library provided by the Sea Mammal Research Unit and were transmitted at source levels of 150 dB and 160 dB relative to 1 μPa at 1 m. The locations of the sound sources, which were later compared with the location estimated obtained using the paired star array, were determined using a GPS receiver.

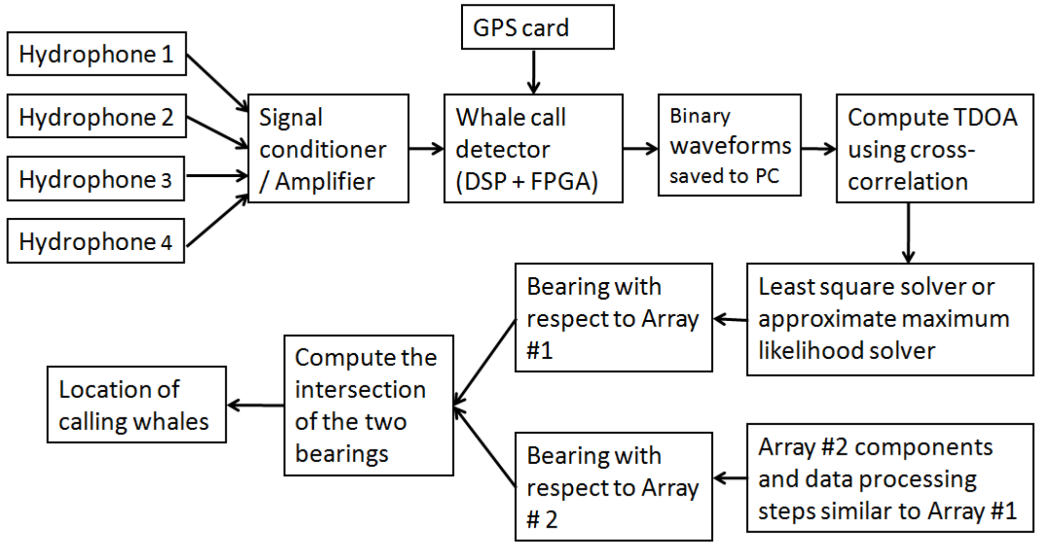

Fig. 1. Main components and signal processing flow for the approach to sound source localization performed by the paired star array passive acoustic system.

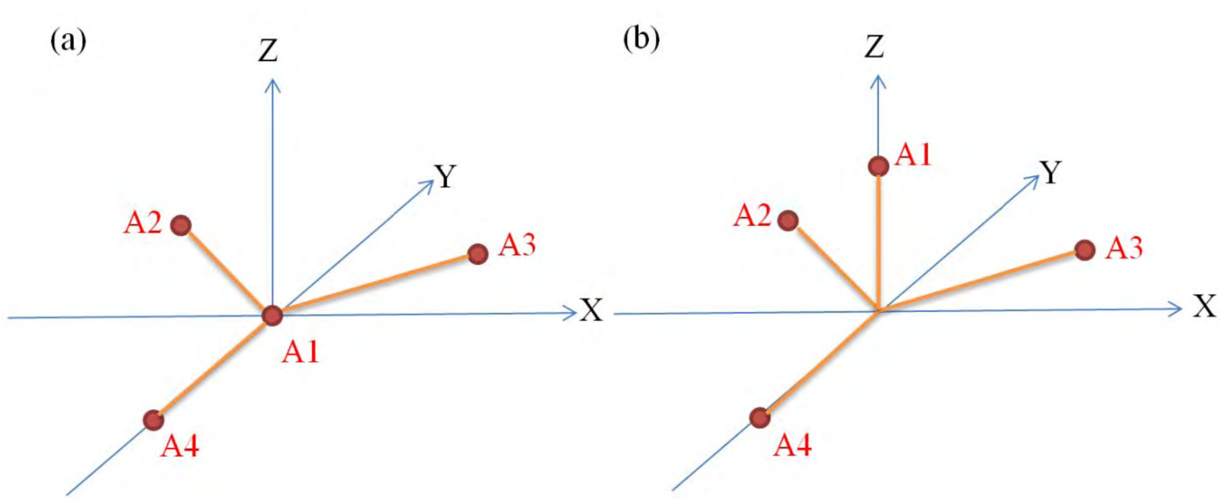

Fig. 2. Hydrophone geometry for 2D and 3D star arrays: (a) 2D; (b) 3D.

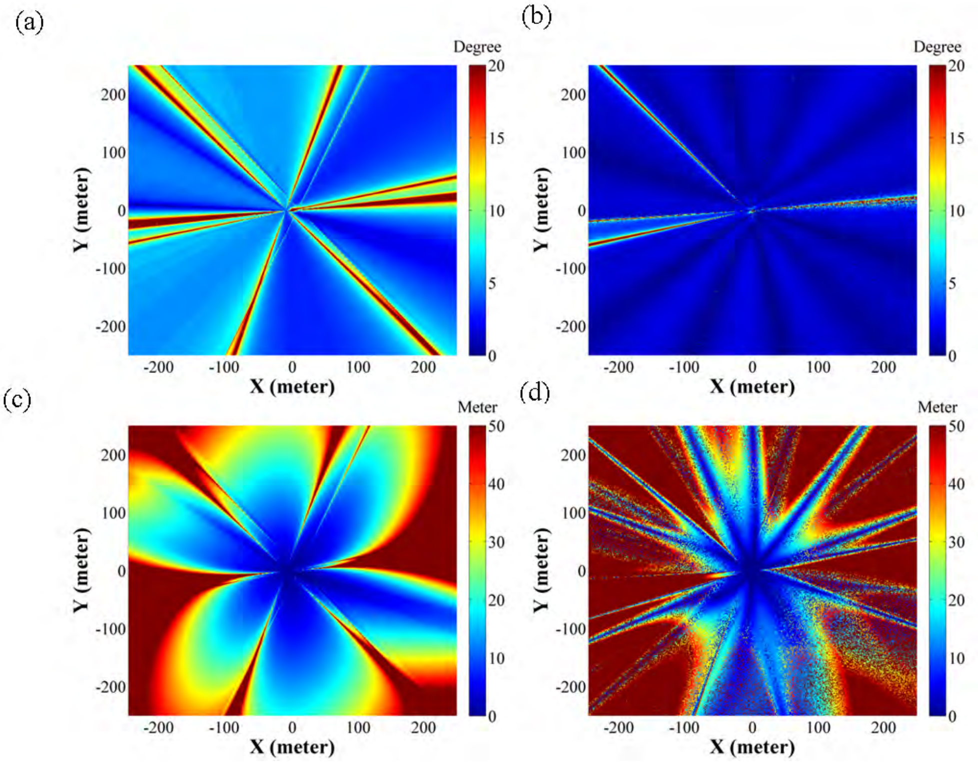

Fig 3. Sensitivity analysis for 2D and 3D arrays at z = 0 m. (a) bearing error of 2D array; (b) bearing error of 3D array; (c) range error of 2D array; (d) range error of 3D array.

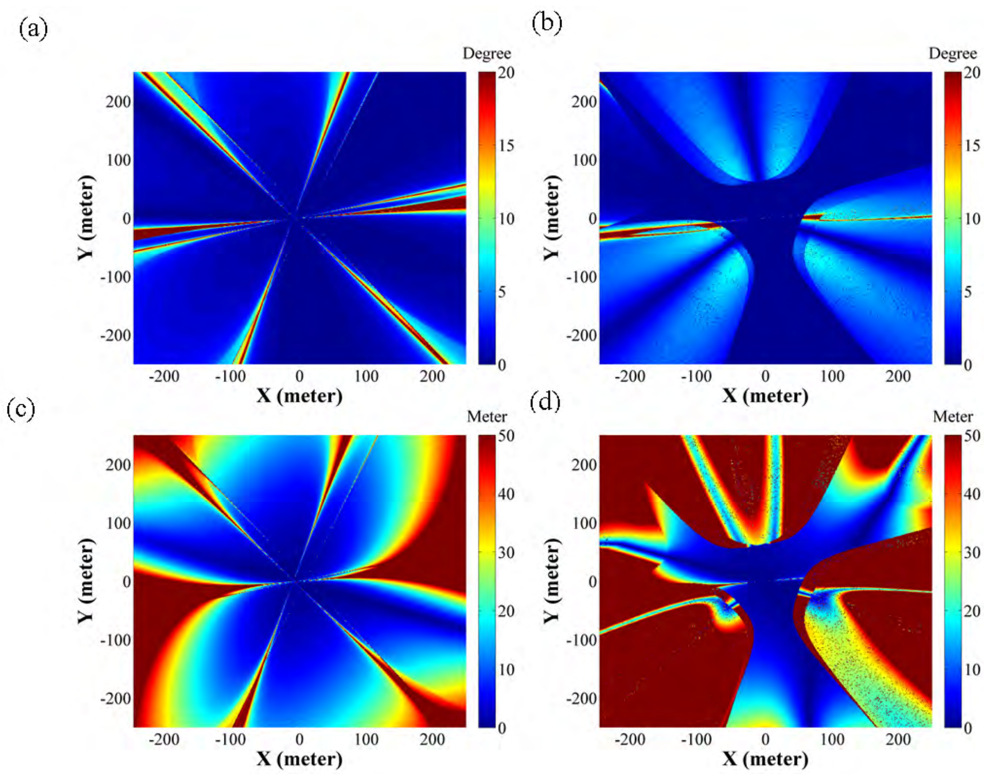

Fig 4. Sensitivity analysis for 2D and 3D arrays at z = 50 m. (a) bearing error of 2D array; (b) bearing error of 3D array; (c) range error of 2D array; (d) range error of 3D array.

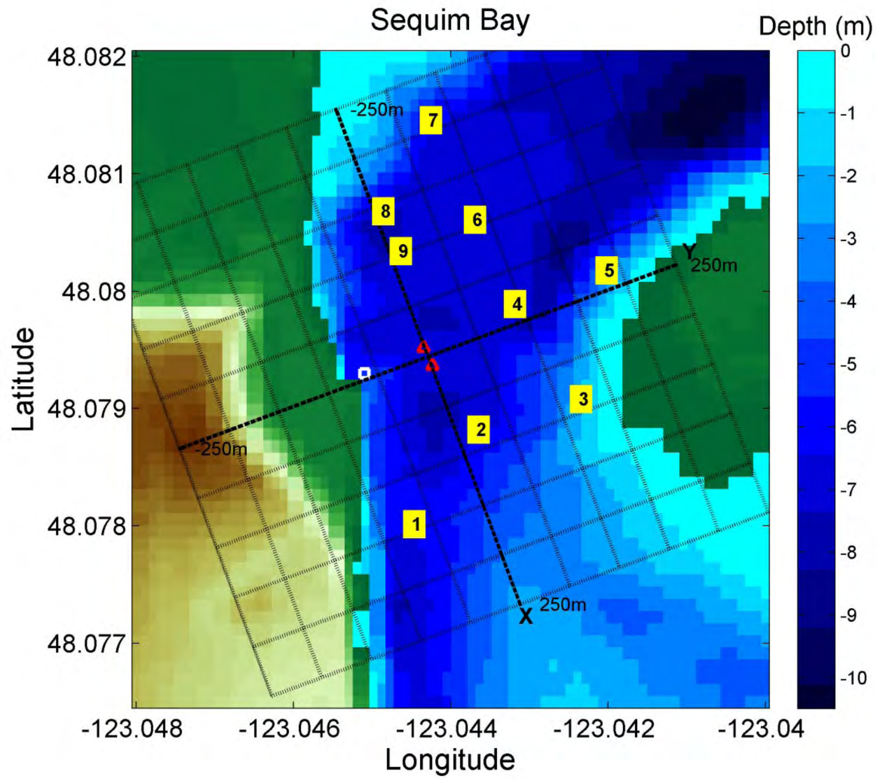

Fig. 5. The test site and test locations for the validation experiment at Sequim Bay

III. Results and Discussion

Only the results of analysis of beacon signal location estimates are presented in this paper. The estimate of the beacon source locations, using the bearing method and the error of those location estimates are illustrated in Fig. 6. For example, the first bearing to a sound source was obtained from star array 1 comprised of hydrophones A1, A2, A3, and A4. Bearing 2 to the source was obtained using star array 2, comprised of hydrophones A5, A6, A7, and A8. Only sound source locations for converging (acute) bearing angles were considered, thereby resolving the initial ambiguity for source location. The final sound source location is estimated by calculating the crossing point of the two bearing lines.

One beacon transmission was chosen at random for each test location to evaluate sound source location estimation accuracy (Table I). Cross-bearing errors were within 1°, and the distance errors were within 33 m for seven of nine test locations. Bearing errors were within 0.5° for six test locations. For location 3, the bearing and distance errors were increased because background noise reduced signal-to-noise levels. The poor signal-to-noise ratio resulted in large TDOA errors that, in turn, led to large localization errors [19]. Sound source test locations 8 and 9 were located near the *x*-axis in the localization coordinate system, where bearing crossing angles were expected to be very small with resulting distance errors greater than 50 m predicted from the sensitivity analysis. Although locations 8 and 9 had relatively small bearing errors (0.49° and 1.03°, respectively), because of the very small bearing crossing angles, the distance errors were large—90.17 m and 57.66 m, respectively. For location 7, the test position farthest from the array at a distance of 230 m, the bearing method still performed within expectations, with a bearing error of 0.34° and a distance error of 22.12 m.

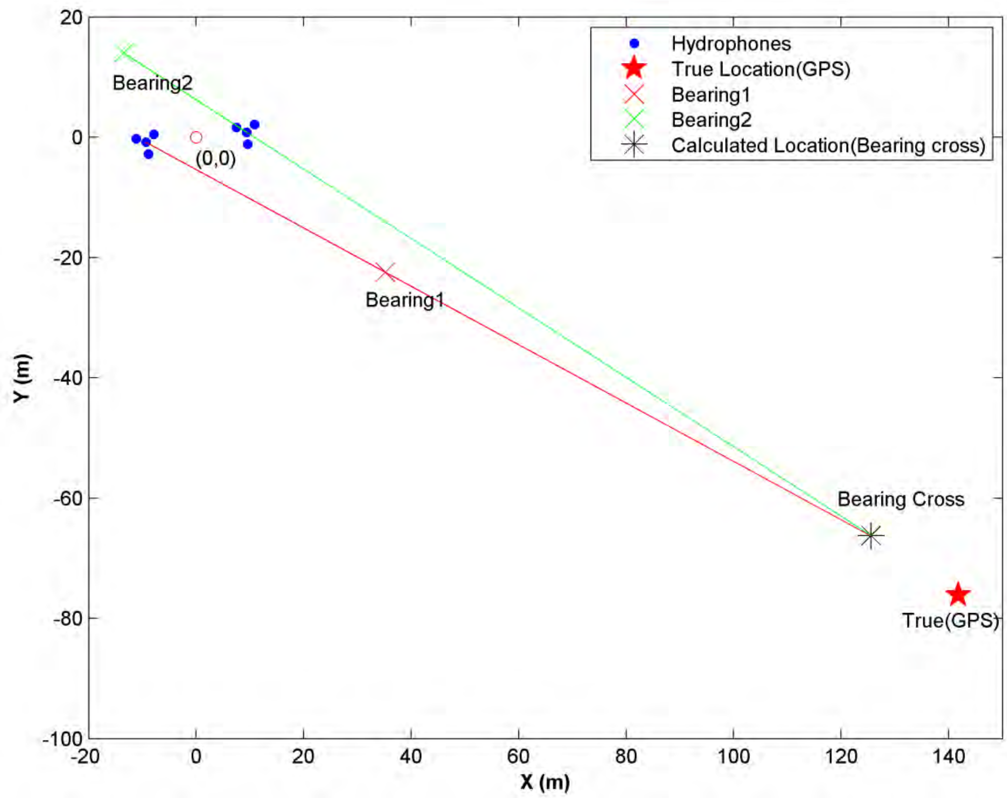

Fig. 6. An example of the use of the paired star arrays to estimate bearing and range to a sound source and how those estimates compare to the actual bearing and range of the sound source.

TABLE I. LOCALIZATION OF BEACON SIGNALS FOR EACH TEST LOCATION

Test Location	Distance (m)	Bearing 1 error (°)	Bearing 2 error (°)	Cross bearing error (°)	Distance error (m)	Range error (m)
1	159.73	0.11	0.60	0.33	17.80	17.78
2	80.02	0.81	1.39	1.04	14.48	14.42
3	143.28	1.12	3.29	2.13	82.95	82.67
4	90.12	0.04	0.20	0.09	1.91	1.91
5	181.29	0.02	0.25	0.11	7.93	7.92
6	135.21	0.52	0.50	0.03	32.36	32.36
7	224.16	0.47	0.22	0.34	22.12	22.09
8	146.58	0.18	0.91	0.49	90.17	90.17
9	105.42	0.21	1.48	1.03	57.66	57.64

IV. CONCLUSION

A passive acoustic monitoring system consisting of a pair of 2D star arrays was developed to detect and localize SRKW to support potential deployment of tidal turbines in Puget Sound, Washington. A theoretical analysis of the localization performance of the system was performed. The system was built and deployed in Sequim Bay, Washington, and the localization performance of the system evaluated. The system performed as expected, with bearing errors less than 1.04° for eight of nine sound source locations. Six sound source test locations had distance errors that ranged between 1.91 m and 32.36 m. Two test locations had large distance estimation errors because they were located near the line passing through the center of the two arrays, which resulted in very small bearing crossing angles, with the expected result of high probability of large sound source distance estimate errors. Overall, the preliminary results showed the localization method presented in this paper is promising for a passive acoustic monitoring system that can be deployed with a tidal turbine.

ACKNOWLEDGMENTS

This study was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Wind and Water Power Program. The study was conducted at Pacific Northwest National Laboratory (PNNL) in Richland, Washington, which is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830. The authors thank Brandon Southall (SEA, Inc.), Brian Polagye, Jim Thompson, Chris Bassett (University of Washington), and Jason Wood (Sea Mammal Research Institute, University of St. Andrews) for their help with this study. The authors are grateful for the contributions and input of many PNNL staff, including Tylor Abel, Charlie Brandt, Eric Choi, Andrea Copping, Andrea Currie, Jen Elster, Kate Hall, Michele Halvorsen, Mark Jones, Rhonda Karls, Chandler May, Sue Southard, Jennifer States, Andrew Stevens, John Vavrinec, and Mark Weiland.

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