Integrated Measurement of Naval Sonar Operations and Precise Cetacean Locations
Final Report

Project Number: RC-201304

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14. ABSTRACT

A GPS enabled, low impact, minimally percutaneous electronic transmitter (LIMPET) tag for the in-situ study of cetaceans was developed. The tag is dart attached to individual animals at-sea using a neumatic rifle. The tag provides GPS and dive data in real-time via the Argos satellite system. The tag was successfully developed and deployed on a number of species including Cuvier's beaked whales ("Ziphius cavirostris") on the Southern California Offshore Range (SCORE).

A generic sonar detector was also developed and tested in-situ at SCORE with mid-frequency active sonar. The detector was integrated into the Marine Mammal Monitoring on Navy Ranges (M3R signal processor) and is capable of monitoring over 200 hydrophones in real-time. It is currently being used on the three major Navy ranges including the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, SCORE, and the Pacific Missile Range Facility (PMRF) in Hawaii.

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4. Acronyms

AUTEC: Atlantic Undersea Test and Evaluation Center

dBV_{rms}: Root mean squared decibel volts

FA: False alarm

FFT: Fast Fourier transform

GPS: Global Positioning System

LIMPET: Low impact minimally percutaneous electronic transmitter

Km: Kilometers

M3R: Mammal Monitoring on Navy Ranges

Me: *Mesoplodon europaeus*

Md: Mesoplodon densirostris

MFAS: Mid-frequency active sonar

PD: Probability of detection

PMRF: Pacific Missile Range Facility

SCORE: Southern California Offshore Range

Zc: *Ziphius cavirostris*

5. Acknowledgements

We thank the ESTCP program for allowing us this opportunity.

Thanks to the staffs at SCORE, AUTEC, and PMRF for affording access to the hydrophone arrays, their on-going logistics support, and for answering a myriad of our unending questions. In particular, we would like to thank all the personnel at SCORE, AUTEC, and at PMRF for their continued support.

We gratefully thank the staff at Wildlife Computers, and Daniel Webster and Robin Baird of Cascadia Research Collective for assistance in tag deployments. We also thank Brenda Rone of Marine Ecology and Telemetry Research for assistance with tag deployments. We thank Dianne and Bernardo Alps for assistance in tag whale follow up. Tagging was conducted under NOAA OPR permits 15330, 16111, and 17086, with approval from Cascadia Research Collective's Institutional Animal Care and Use Committee. We thank Kylie Owen for assistance. The dwarf minke whale tagging was conducted in collaboration with Dr. Alastair Birtles, James Cook University, and John Rumney, Eye to Eye Marine Encounters, and was approved by the James Cook Animal Ethics Committee and the Great Barrier Reef Marine Park Authority. Tagging of the other species was conducted by Cascadia Research Collective and collaborators, primarily

Greg Schorr, Daniel Webster and Robin Baird, under NOAA OPR permits # 15330 and 16111, with approval from the Cascadia Research Collective and Alaska SeaLife Center institutional animal care and use committees

6. Executive Summary

This project addresses the Navy's need to develop technology that enables the monitoring of cetacean populations that are routinely exposed to mid-frequency active sonar (MFAS). Navy anti-submarine warfare (ASW) training, and research and development are centered on the three major undersea NAVY ranges: the Atlantic Undersea Test and Evaluation Center (AUTEC), the Southern California Offshore Range (SCORE) off San Diego, and the Pacific Missile Range Facility (PMRF) off the island of Kauai. At each range, MFAS is routinely used.

Stranding of marine mammals, in particular Cuvier's and Blainville's beaked whales have been associated with MFAS operations. This has led to a focused effort to understand the effect of MFAS on beaked whale species and led to court mandated monitoring of the effect of sonar in areas of MFAS use. Cuvier's beaked whales have been documented at AUTEC and SCORE while Blainville's beaked whales have been documented at AUTEC and PMRF. At each facility, local populations of these species are routinely subjected to MFAS. Assessing the impact of MFAS on these animals required documenting the presence of sonar and the reaction of the animals to MFAS exposure.

The objective of this project is to

1. Develop and implement a sonar detection algorithm on each of the Navy's undersea ranges
2. Integrate GPS into a tag that can be used to more precisely monitor the movement of cetaceans with and without sonar present.

To meet these objectives a sonar detection algorithm was developed and implemented on Marine Mammal Monitoring on Navy Ranges (M3R) signal processors that are installed at AUTEC, SCORE, and PMRF. Each range includes large-scale, bottom-mounted, hydrophone arrays that allow acoustic monitoring over broad (> 1,000 km^2) spatial scales. The M3R signal processors are used to detect cetacean vocalizations in real-time on a continual basis. A sonar detection module was developed and installed at each Navy range. Detection reports of sonar pings are collected and integrated into archives of cetacean detections including beaked whales. In addition, a tool was also developed that allows detection of sonar pings in archived fast Fourier transform-based (FFT-based) detection data that has been collected for over ten years. These tools provide automated detection of sonar pings in real-time and historic data and have eliminated labor intensive manual post-processoing.

The sonar detection performance was measured in-situ at SCORE. In addition to Cuvier's beaked whales, SCORE is home to multiple delphinid species including a large population of common dolphins whose whistles potentially fall into the sonar bandwidth. Thus SCORE represents the most difficult acoustic environment of all three Navy ranges. As anticipated, the probability of sonar detection (PD) for sources within the hydrophone array was 1. For periods with no sonar present, a false alarm rate (FA) of approximately one per 3,600 seconds was measured. These values well exceeded the goal of a PD of .7 and a FA of one per 1,000 seconds in the most challenging of environments.

The sonar data are being combined with data collected on ARGOS tags placed on animals exposed to sonar including "sonar sensitive" beaked whales. In the past, these tags depended on in-accurate ARGOS localizations. The lack of precision made analysis of the combined acoustic and tag data difficult. This program integrated Fastloc® GPS into a small, Low Impact Minimally Percutaneous Electronic Transmitter (LIMPET) tag. This allowed calculation of precise (<163m, four satellites) locations from tags deployed on various species including beaked whales which exceeded the 200m goal. Nine tags were deployed including three on Cuvier's beaked whales, two on pilot whales, two on fin whales and one on a false killer whale which exceeded the goal of 6 total deployments. A mean update rate of 18.6 updates per day was recorded for Cuvier's beaked whales which exceeded the 18 updates per day goal. The tag is now commercially available from Wildlife Computers Inc. (https://wildlifecomputers.com/applications/cetacean-limpet/) and is being used in on-going Navy studies in Southern California, Hawaii, and off the East Coast.

8.0 INTRODUCTION

8.1 BACKGROUND

Multiple events involving the stranding of marine mammals, apparently after exposure to mid-frequency active sonar, have resulted in strict requirements for marine mammal monitoring on all Navy undersea ranges including the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, the Southern California Offshore Range (SCORE), and the Pacific Missile Range Facility (PMRF) off Kauai, HI. Mid-frequency active sonar (MFAS) operations occur repeatedly on Navy ranges that are known to include populations of Blainville's beaked whales (*Mesoplodon densirostris, Md*) , Cuvier's (*Ziphius cavirostris, Zc*), and Gervais' (*Mesoplodon europaeus, Me*) beaked whales. All three Navy ranges are known to have local populations of beaked whales present: *Md* at the at AUTEC and PMRF and *Zc* at SCORE and at AUTEC [1, 2, 3, 4]. Monitoring the long-term health of these populations, that are repeatedly exposed to sonar, is important for the continued operational integrity of these ranges.

The current Navy policy is to operate on range complexes with so-called "take permits" granted through the NOAA National Marine Fisheries Service (NMFS). The take permits attempt to quantify the level of disruption and harm to marine mammals. The Navy must also conduct long-term species monitoring to assess effects and impacts of range operations on resident marine mammal populations. Thus, tools to enable such monitoring are required to provide a means of long-term assessment of the health of cetacean populations on major Navy ranges as part of mandated environmental compliance requirements.

8.2 OBJECTIVE OF THE DEMONSTRATION

The objectives of this demonstration project are

1. To integrate a real-time sonar detector into existing passive acoustic Navy range monitoring systems.

2. To integrate Fastloc^{TM} GPS into a remotely deployed medium-duration dart tag suitable for attachment to a beaked whale.

These technologies were validated in both the laboratory and the field. Initially, Receiver Operator (ROC) Curves against white noise were measured to validate basic system performance. The software was then validated against recorded data from the Ranges to provide a realistic measure of performance in real-world environments.

The GPS based tag was tested to destruction on land as a measure of survivability and the ballistic integrity of the modified tags was verified. Tags were deployed in the field and the positional accuracy and update rate were measured. The focus was on the placement of tags on Cuvier's (*Ziphius cavirostris*) beaked whales but surrogate species such as fin (*Balaenonptera physalus*) whales were also tagged when encountered to assure adequate field testing.

The most recent tests prove placement of tags on Cuvier's beaked whales is within the scope of the program and is possible given reasonable sea-state conditions. Three GPS enabled tags were placed on beaked whales and provided real-time uplink data through the Argos satellites. In addition, the installation of a shore-based receiver on San Clemente Island proved highly successful at delivering transmitted data and significantly enhanced the analysis of tag data including GPS.

8.3 REGULATORY DRIVERS

The Navy operates under Environmental Impact Statements that access the effect of operations on cetacean populations. To issue the necessary permit, NMFS must reach a "negligible impact" determination. Determining the impact of exposure to MFAS requires monitoring of both cetacean populations and sonar in an effort to understand both the acute and long-term the "cause and effect" relationship. This project focused on providing tools that are being used to collect data necessary to measure such effect and inform the regulatory process

9.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

9.1 TECHNOLOGY/METHODOLOGY OVERVIEW

Each of the three major Navy undersea range facilities includes a broad field of bottom-mounted hydrophones spaced from 1-4 nm apart, which monitor ocean areas of 500-1,500 nm^2. These hydrophone fields were designed to track subsurface vehicles during active sonar anti-submarine warfare (ASW) exercises, but are also being used to detect and monitor vocalizing cetaceans before, during, and after MFA sonar operations [5, 6].

While evidence suggests that beaked whales are unusually sensitive to sonar [6, 7, 8, 2], several species have been documented in significant numbers on all three Navy ranges [3, 1, 2]. Range populations are being studied in-situ using a combination of passive acoustics, photo-ID and tag data. Interactions between tagged individuals and Navy sonar are being analyzed where the datasets overlap.

Beaked whales produce loud directional echolocation clicks only during foraging dives, detections of which can be used to estimate their spatial and temporal distribution on the range and as a proxy for their foraging behavior [9, 10, 11]. Passive acoustic detectors/classifiers for both Cuvier's and Blainville's beaked whales have been developed, and when possible, simultaneous detection data from multiple phones are combined to determine animal locations [12]. Location data are combined with detection reports in a comprehensive, time-synchronous archive.

Precise ship-track data can also be obtained from the ranges during MFA sonar exercises. However, the timing of sonar transmissions during these exercises had been laboriously extracted from multiple hydrophones through a manual inspection of associated detection archives, when available. The integration of a sonar detector in the existing hydrophone monitoring system allows each sonar ping to be detected and the received level directly measured in real-time. These data are stored along with the time-synchronous animal detections that are already being captured. The sonar detector algorithm has been implemented and integrated into the M3R signal processor on all three Navy Ranges. This allows the monitoring of all range hydrophones for Sonar pings in real-time. For example, 198 hydrophones are currently monitored at PMRF. Hydrophone data are digitized, packetized, time-tagged, and cast on a dedicated 1G-byte network. The sonar detector has been ported to a node and the data interface has been implemented.

At the same time, GPS modified LIMPET tags are being attached to beaked whales on the Navy ranges to monitor their behavior during MFA events. Previous LIMPET satellite tags only provided an ARGOS-based location estimate during the infrequent times when the whale surfaces and an overpass of an Argos-system satellite occur simultaneously. In contrast, there is always a sufficient number of GPS satellites overhead to allow a location to be calculated after every dive. Traditional GPS receivers require tens of seconds to acquire both range and ephemeral data, but most whales surface for too short of a time. The Fastloc™, as implemented in the tag, captures only the satellite ID and range information within ~ 300 ms and then those data are used for post-processed location calculations by the user.

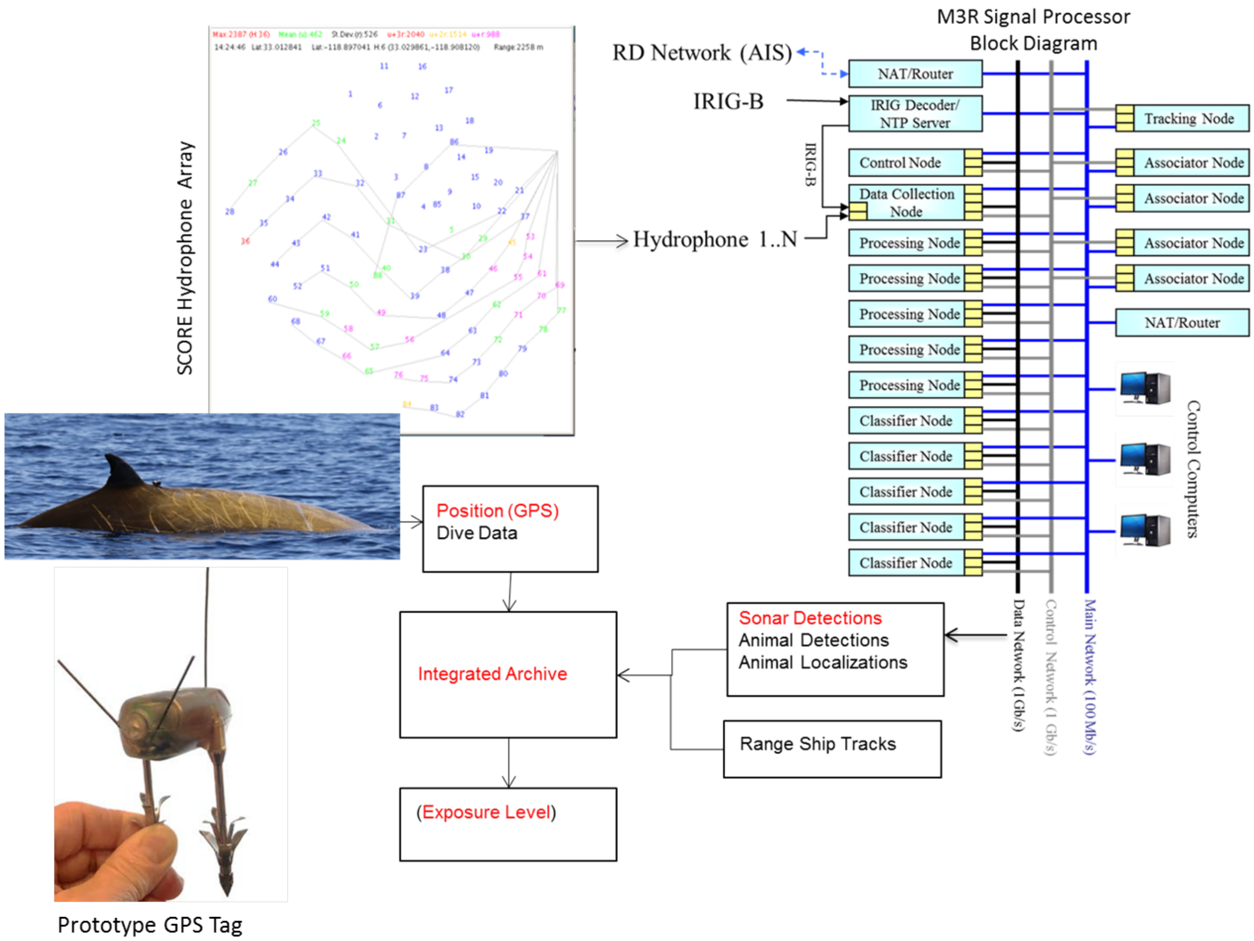

Figure 1. System Block Diagram

The sonar detector is available at all three Navy ranges and is being used to document the use of sonar and when combined with passive acoustic detections and tag data, estimate the animals' exposure levels. In addition, a variant of the algorithm is available for post-processing of an extensive archive of M3R FFT-based detection archives. The software is also available for analysis of data from portable recording devices including recording buoys under development by the Living Marine Resources Program.

The new GPS LIMPET tag has been bench-tested and field-tested on multiple species including beaked whales and is now commercially available from Wildlife Computers. It is currently in use on the SCORE Range as part of the U.S. Navy's monitoring program. It is also being used by the East Coast Behavioral Response Study off North Carolina and at PMRF in Hawaii. A land-based receiver on SCI provides a significant increase in received data and is also commercially available from Wildlife Computers.

9.2 TECHNOLOGY/METHODOLOGY DEVELOPMENT

9.2.1 Sonar Detector

A “generic” sonar detector was developed. The algorithm allows the user to detect energy over a threshold, in a band of interest, over a specified time period. The algorithm designed to run in real-time on a quad-processor node and process up to 300 hydrophones at a sample rate of 96 kHz. The software was written in C and ported to the Marine Mammal Monitoring on Navy Range (M3R) signal processor.

Prior to field deployment, the algorithm performance (PD, FA) was measured in the lab with a synthetic sonar signal and additive Gaussian white noise.

9.2.1.1 Test Configuration

The laboratory configuration included the hardware setup for transmitting Gaussian white noise and sonar signals to the sonar detector.

Noise was summed with playbacks of an analog sonar upsweep, and the signals were injected into M3R signal processor (Figure 1) for analog to digital conversions and transmission of the digitized signal across the data network to a node for sonar processing. The signal to noise ratio was directly measured on a signal analyzer at the input to the signal processor.

The sonar detection parameters can be set to detect a variety of signal types. For the purposes of pre-deployment testing, the system was set for the detection of Navy 53C sonar. A “characteristic” 53C sonar signal was used for the testing. This is the same signal that was used in Navy funded Behavioral Response Studies (BRS). The signal consists of an1.6 second upsweep from 3445 Hz to 4134 Hz peak frequency (Figure 2). The upsweep is composed of three 0.5 second pulses at approximately 3550 Hz, 3750 Hz, and 4050 Hz with a 0.1 second gap between the second and third pulses. To identify this upsweep, the sonar detector was configured for “SONARA”. The starting frequency (SONARFREQSTART) was defined to be 2200 Hz, and the ending frequency (SONARFREQEND) 4800 Hz. The pulse was required to remain at least 6.0 dB above the background level (SONARPWRDB) for 75 consecutive detections (CONSECDETS). At the 96 kHz sampling rate, this corresponds to a duration of 0.8 seconds. 2.5 seconds without detections (BLANKTIMESEC) were required between pulses. The background constant (BACKGROUNDCONSTANT) was specified at 0.99.

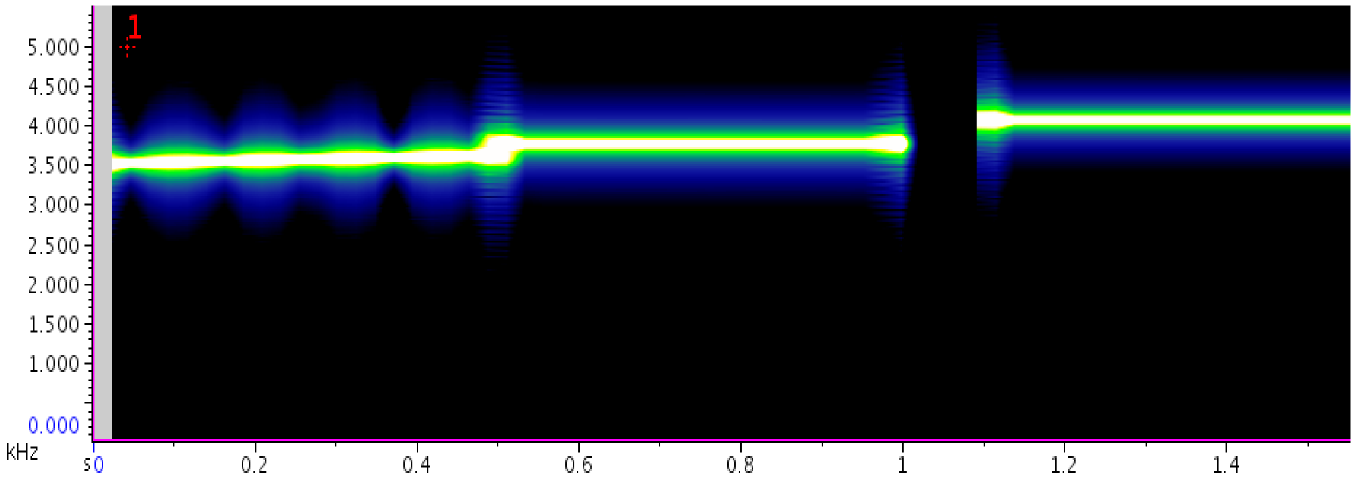

Figure 2. This spectrogram illustrates the 53C sonar signal that was used to test the sonar detector. The spectrogram was generated using a Hann window with 2048 samples and 50% overlap between windows. Time in seconds since the start of the signal is along the horizontal axis.

9.2.1.2 Signal intensity measurements

The amplitude of the noise, sonar ping, and mixed signal was measured immediately prior to entering signal processor. All values reported in this section are are in root-mean squared decibel volts (dBV_{rms}) with a measurement bandwidth of 95.485 Hz on the spectrum analyzer used in the analysis. The amplitude of the noise was quantified as the RMS average of 4096 samples. The average noise level was -51.55 at 3550 Hz, -51.23 at 3750 Hz, and -50.73 at 4050 Hz.

For the sonar measurements, the peak value at each frequency was used. The buffered signal output was passed through an attenuator, and measured at the input to the signal processor (Table 1). Levels were set by adjusting the attenuator for the desired output and comparing the input level to the level reported by the detector.

dB Atenuation	Frequency	Trial					μ±σ
		1	2	3	4	5	
0	3550	-8.65	-8.35	-8.31	-8.31	-8.44	-08.41±0.142
	3750	-8.32	-8.32	-8.32	-8.58	-8.32	-08.37±0.116
	4050	-8.59	-8.33	-8.33	-8.33	-8.58	-08.43±0.140
20	3550	-24.88	-24.84	-24.82	-24.82	-24.82	-24.84±0.026
	3750	-24.85	-24.84	-24.84	-24.83	-24.66	-24.80±0.081
	4050	-25.11	-24.84	-24.84	-24.84	-24.84	-24.89±0.121
21	3550	-25.79	-25.79	-25.81	-25.78	-25.78	-25.79±0.012
	3750	-25.8	-25.8	-25.8	-25.8	-25.8	-25.80±0.000
	4050	-25.8	-25.8	-25.81	-25.8	-25.8	-25.80±0.004
22	3550	-26.79	-26.78	-26.78	-26.8	-26.92	-26.81±0.060
	3750	-26.79	-26.79	-26.79	-26.79	-26.79	-26.79±0.000
	4050	-26.8	-26.8	-26.8	-26.8	-26.79	-26.80±0.004
23	3550	-27.8	-27.78	-27.78	-27.78	-27.78	-27.78±0.009
	3750	-27.8	-27.8	-27.8	-27.8	-27.8	-27.80±0.000
	4050	-27.81	-27.81	-27.8	-27.8	-27.81	-27.81±0.005
25	3550	-29.79	-29.78	-29.79	-29.78	-29.78	-29.72±0.137
	3750	-29.71	-29.79	-29.79	-29.75	-29.79	-29.77±0.036
	4050	-29.79	-29.8	-29.79	-29.8	-29.79	-29.79±0.005
30	3550	-34.82	-34.94	-34.84	-35.17	-34.82	-34.92±0.149
	3750	-34.83	-34.83	-34.83	-34.83	-34.83	-34.83±0.000
	4050	-34.83	-34.83	-34.84	-34.73	-34.83	-34.81±0.046
40	3550	-44.95	-44.87	-44.79	-44.88	-44.8	-44.86±0.065
	3750	-44.77	-44.77	-44.76	-44.76	-44.8	-44.77±0.016
	4050	-44.8	-44.8	-44.78	-44.8	-44.77	-44.79±0.014
60	3550	-65.06	-64.91	-64.62	-64.69	-64.58	-64.77±0.205
	3750	-64.64	-64.47	-64.42	-64.62	-64.72	-64.57±0.125
	4050	-64.64	-64.84	-64.67	-64.8	-64.47	-64.68±0.146

Table 1. Signal power measurements at the input to signal processor. Five replicates measurements were made at each of 9 attenuation levels. Measurements were consistent across the 3 peak frequencies in the sonar signal (3550 Hz, 3750 Hz, and 4050 Hz). All measurements are reported in dBV.

9.2.1.3 False positive rates

The false positive rate was quantified as the number of detections per unit time with noise only as the input to the sonar detector. A variety of detection thresholds (SONARPWRDB) were tested to determine where the false positive rate could be effectively approximated as 0. For each test Gaussian noise was run through the sonar detector. The results were then normalized to the number of detections per hour.

With the given parameter setting, the false positive rate began at 419 ±38 detections/hr (mean +/- std.dev., n=19) at SONARP-WRDB=1.0, increased to a maximum of 749 ±16 detections/hr (n=90) at SONARPWRDB=4.0, then sharply decreased to 0 detections/hr by SONARPWRDB=6.0 (Figure 2). With SONARPWDDB >=6.0, no false positives were observed in 15 hours of testing.

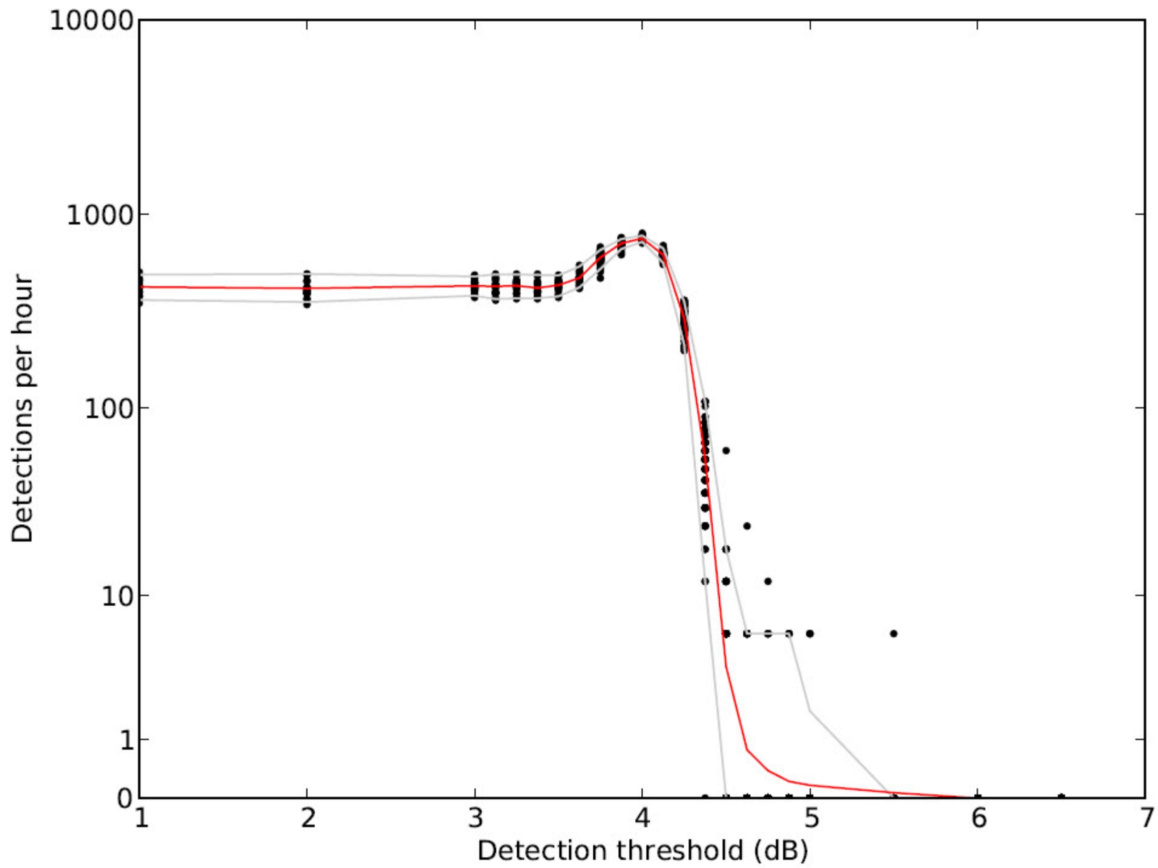

Figure 3. The false positive rate is presented as a function of the detection threshold (SONARP-WRDB). Each dot indicates the number of false positives from a single 10 minute window. The red curve indicates the mean false positive rate at each detection threshold, and the grey curves give the 2.5% and 97.5% quantiles.

9.2.1.4 Detection rates

A set of trials was conducted to evaluate the ability of the sonar detector to identify sonar signals in the presence of noise. Each trial lasted 10 minutes. For the first and last 50 seconds, only noise was fed into the sonar detector to allow the thresholds to settle. During the middle 8 minutes and 20 seconds, a set of 100 repetitions of the sonar signal were input into the signal processor and the detection reports were archived. All units are given in dB using a 1 Hz bandwidth.
The probability of detecting the signal may be approximately modeled as a logistic function

$$P(detection) = e^{B_0+B_1x}(1+e^{B_0+B_1x})^{-1}$$

where x is the signal to noise ratio, B_0 = -43:2 ± 18:90 (estimate±std. dev.), and
B_0 = 1.44 ±0.663 (Figure 3). At a signal to noise ratio of 30 dB, the probability of detecting the signal is 0.5. Note the threshold is set assuming a source within the hydrophone field where the anticipated minimum sonar receive level at the nearest hydrophone from a MFAS source is 140 dBreµPa, the maximum hydrophone input level.

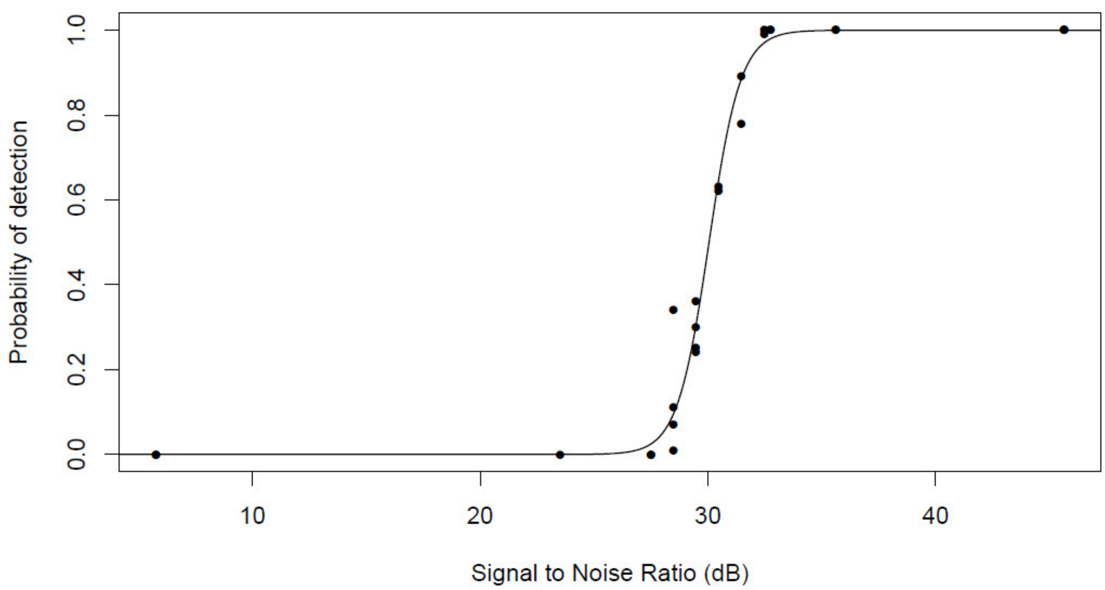

Figure 4. The probability of detection versus the signal to noise ratio (SNR). Each dot indicates a single 10 minute trial, and the line indicates the fitted logistic regression model.

9.2.1.5 Field Installation

In 2017, the sonar detector was installed on the M3R signal processor at SCORE, AUTEC, and PMRF. A signal processor node was added to the system and the software was incorporated into the system build. The sonar software is being used to monitor all hydrophones on each of the ranges. Upon detection of a sonar ping, a detection report is generated and is recorded as part of the system integrated archives. This allows all pertinent time-stamped data to be incorporated into a single archive including cetacean and sonar detection and localization reports.

From the data sonar detection times and levels are stored and are being used in analysis along with the coincident cetacean detection archives with a focus on sonar-sensitive beaked whales (Figure 5) .

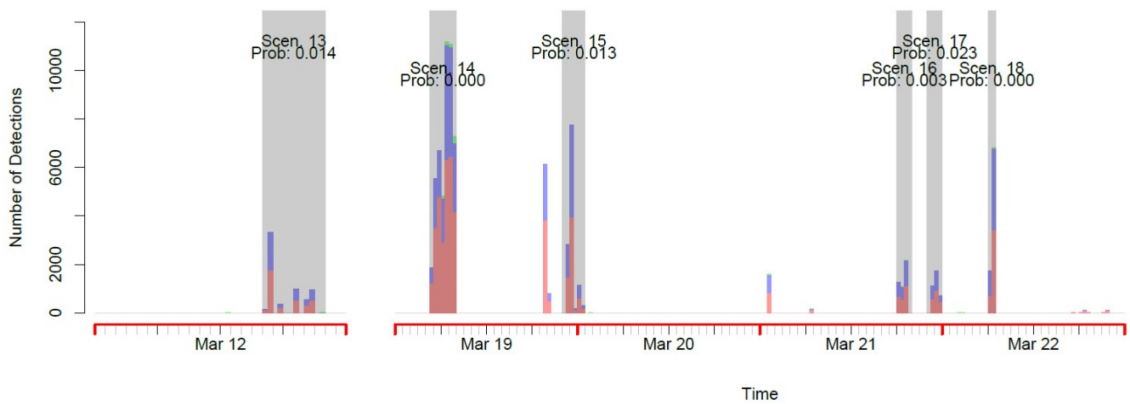

Figure 5. The processed March sonar detector output. The total height of each bar indicates the number of sonar detections that occurred during a 1/2 hour window. The bars are colored according to the detection band. Red ticks on the horizontal axis indicate breaks in days, black indicate 6 hour intervals, and gray ticks are hourly.

9.2.1.6 In-situ false alarm and probability of detection

To determine the false alarm rate, a 4-hour period with no sonar operations on range was selected. All 177 range hydrophones were examined. A false alarm rate of .88 detections/hour was measured. This rate is well below the performance objective of 1/1,000 sec.

This number should be interpreted with caution. The ocean presents a non-stationary noise background. In particular, the rate of interfering cetacean vocalizations can vary wildly depending on the species present and their distribution. However, SCORE represents a biologically rich area with many animals present, particularly common dolphins.

Multiple archives with sonar on range have been examined. The probability of detection if the source is over the hydrophone field is 1, well above the goal of .7. This is expected since the receive level at the hydrophone from a “low level” dipping helicopter source is approximately 140 dBreμPA on the closest hydrophone.

A secondary sonar detector for use in processing FFT-based M3R archives was also developed. This allows post-analysis of sonar events and analysis of over 10 years of archived data from the three Navy ranges. FFT-based detections are analyzed based on user criteria for up to three frequency bands and ping duration. A comparison of the real-time and FFT-based detector is provided in **Figure 6**.

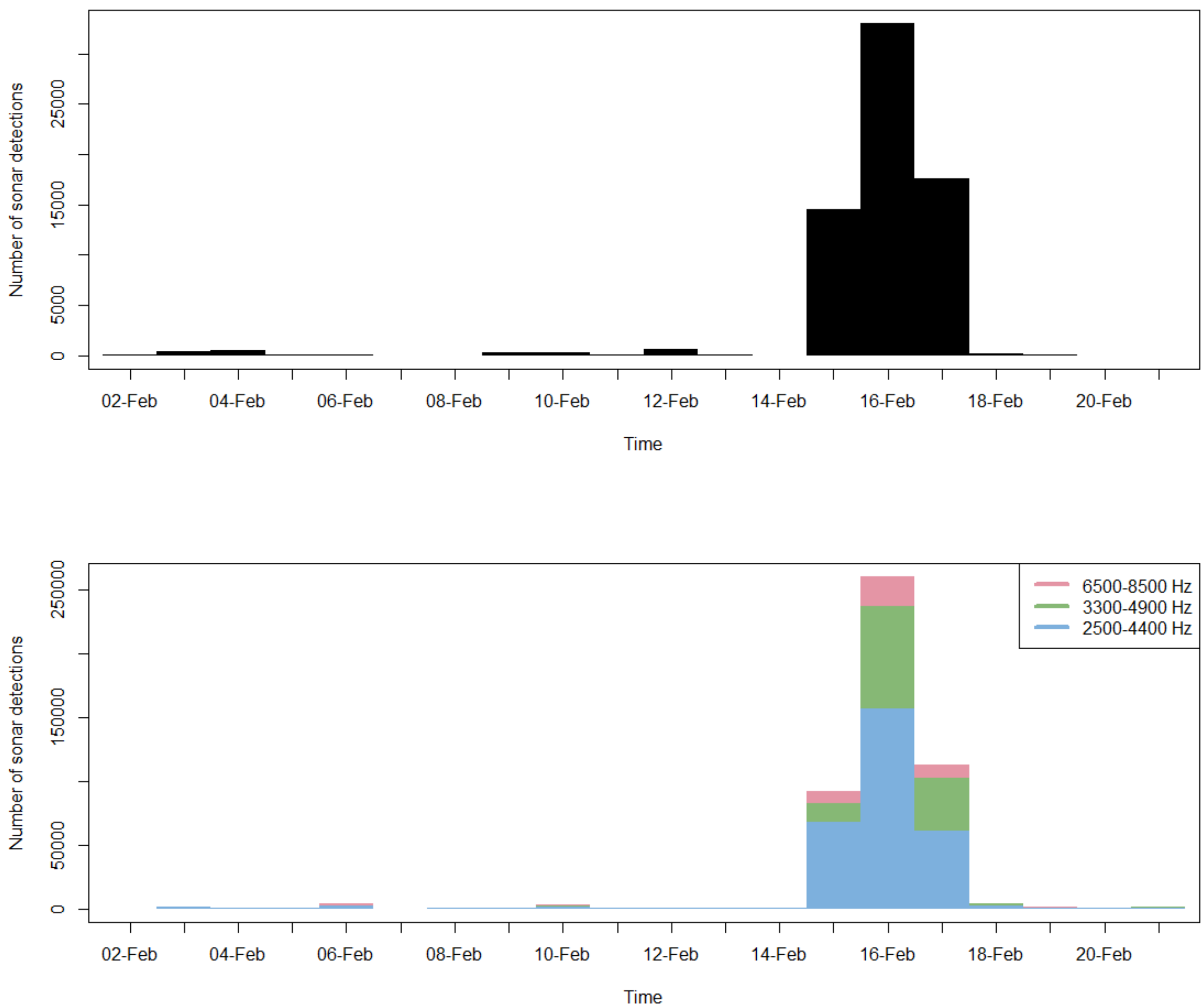

Figure 6. Sonar detector outputs for a three-day multi-ship sonar exercise at PMRF. The upper panel presents a histogram of the real-time sonar detector reports. The lower panel presents the output of the post-exercise, FFT-based analysis tool

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9.2.2 GPS enable LIMPET tag

9.2.2.1 Background

While LIMPET tags are currently being applied to beaked whales on Navy ranges to monitor their behavior during MFA events [13, 14, 2], limitations inherent in spatial data derived from the Argos system have presented challenges to the data analysis. The current LIMPET satellite tags can only provide a location estimate during the infrequent times when the whale surfaces and an overpass of an Argos-system satellite occur simultaneously. In contrast, there is always a sufficient number of GPS satellites overhead to allow a location to be calculated after every dive. Traditional GPS receivers require tens of seconds to acquire both the range and the ephemeral data needed to calculate a position, but most whales surface for too short of a time for that amount of data collection. The Fastloc® system, however, captures a small amount of the GPS satellite signals (snapshots) within ~ 300 ms for rapid calculation of pseudo-ranges and then those data are stored and subsequently transmitted for post-processed location calculations, now allowing GPS receivers to be incorporated into marine mammal tags (e.g Witt et al. 2010, Dujon et al. 2014).

The design of the Fastloc-GPS Low Impact Minimally Percutaneous External-electronics Transmitting (hereafter GPS-LIMPET) tag was completed and tested. The tag, identified by the mold AM-333B-AF, includes a v-dipole GPS antenna design (Figure 1). This tag underwent rigorous impact and ballistics testing and was been deployed on free ranging whales.

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Figure 7. A) Fastloc GPS-LIMPET tag in the SPLASH10-F-333B configuration. B) GPS-LIMPET deployed on an adult male Cuvier's beaked whale (ZcTag053).

The Fastloc GPS LIMPET tag was tested on land for robustness, accuracy, and ballistic capability prior to being used in the demonstration plan (see Appendix 1-3).

9.2.2.2 Land-based precision testing

Due to whale behavior and/or sea state conditions, long focal follows sufficient to assess accuracy could not be executed. Therefore, to assess the precision of the Fastloc-GPS locations in the v-dipole configuration in a manner that would replicate the field test, a land-based experiment was conducted. The tag was activated in a bucket of saltwater and was positioned 0.5 m away from the stationary Mobile Demand receiver.

To simulate animal 'tracking', the tag was removed from the water to simulate a surfacing and then re-submerged. This was repeated 5-7 times over approximately 2 minutes to mimic typical Cuvier's beaked whale surface behavior. When the tag was out of the water, a position was marked with the Mobile Demand and the latitude/longitude was recorded in an Access database. The tag was out of the water for a few seconds each surfacing, reflecting the average amount of time a beaked whale dorsal fin is at the surface when the animal surfaces to breathe. Each two-minute experiment mimicked a "surface bout". Surface bouts were repeated several times throughout the day with a minimum of five minutes between each bout. A total of 94 GPS locations were recorded on the Mobile Demand and the distance between those locations were compared to each other to set a baseline location for the tag. The mean distance between locations collected by the stationary Mobile Demand was 1.1 m (SD = 3.2). This mean location was used to compare to all Fastloc-GPS snapshots from the tag.

Over the course of this experiment, the tag attempted 35 GPS snapshots in 25 'surfacings'. A total of 24 snapshots (69%) were successful in generating a location estimate (snapshots with ≥ 4 satellites). Fifteen of the snapshots (43% of the total) had five or more satellites and a residual of <30, generally considered to be the standard cutoff for high-quality location estimates. The mean distance of all successful snapshots from the actual tag location was 163 m (SD = 233.9). This dropped to 52 m (SD = 31) for snapshots with more than four satellites. A plot of the position estimates from the GPS-LIMPET tag compared to the Mobile Demand positions demonstrates the loss of precision when made with only four satellites (Fig. 2).

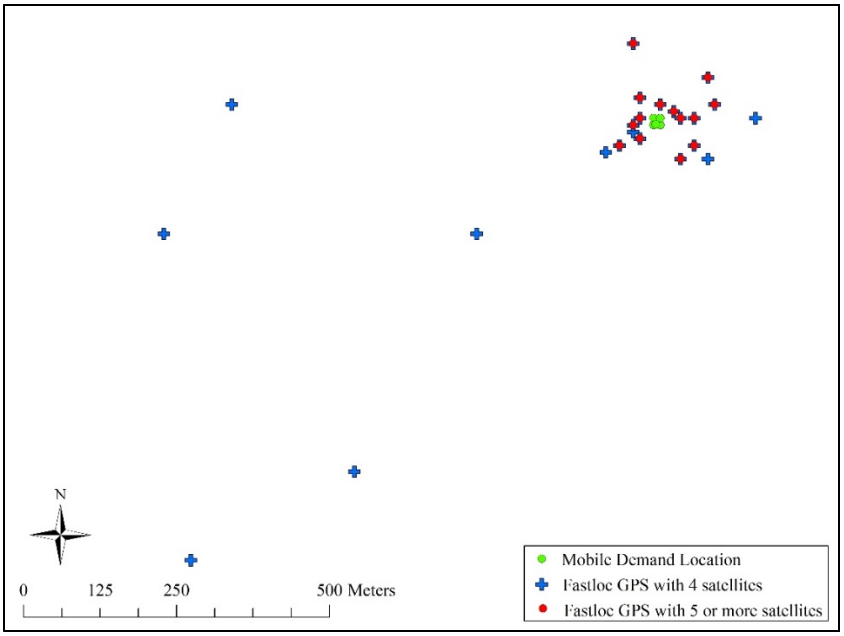

Figure 8. Scatter plot of position estimates generated during the precision test. The GPS-LIMPET tag was with 0.5m of the Mobile Demand during all portions of the test. GPS position estimates calculated with 5 or more satellites are much more precise than those generated with only 4 satellites.

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9.2.2.3 Field testing

During the project demonstration phase, sixteen days were spent on the water, surveying 2,258 km totaling 123.3h of effort (Figure 9, Table 2). Five days were lost due to poor weather conditions. During this effort, 61 sightings of 12 different species, including 11 sightings of Cuvier's beaked whales and 14 sightings of fin whales were recorded (Figure 4, Table 1). Five GPS-LIMPET tags were deployed, including three tags on Cuvier's beaked whales and two on fin whales (*Balaenoptera physalus)* (Table 2). One tag attempt was made on a Cuvier's beaked whale with the tag missing the whale and landing in the water. The tag was recovered for later use. Due to weather challenges and the lack of suitable target species in the demonstration area, we leveraged projects in Hawaii to deploy four additional tags for assessment of GPS performance (Table 2) including three tags on short-finned pilot whales (*Globicephila macrorynchus)* and one on a false killer whale (*Pseudorca crassidens*).

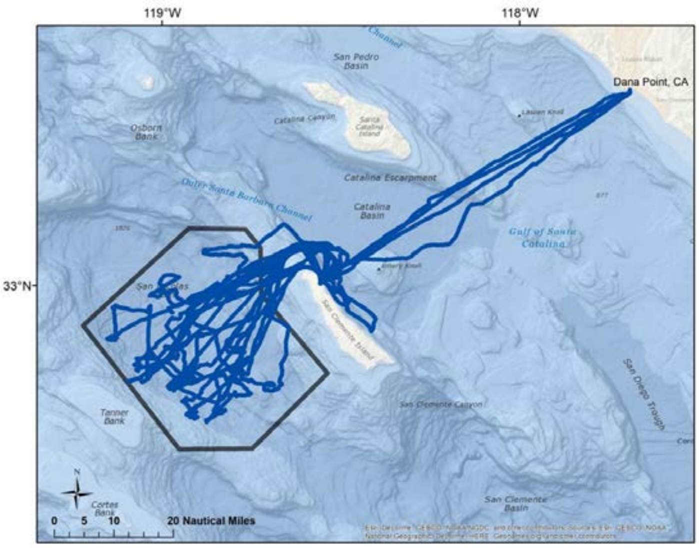

Figure 9. Vessel tracks (blue lines) showing on-water effort during the demonstration phase at SCORE. The black polygon represents the SOAR boundary.

Table 2. Effort and sighting information by day during the demonstration phase.

Date	Effort (h)	Distance (km)	# Sightings	# Species	# Biopsies	# Tags deployed
11/4/2016	3.8	102	0	0	0	0
11/7/2016	11.3	176	4	3	0	0
11/8/2016	9.1	172	4	3	0	0
11/9/2016	7.9	167	4	3	0	0
11/11/2016	11.3	193	7	3	0	1
11/12/2016	8.9	164	2	2	0	0
11/14/2016	2.3	95	0	0	0	0
1/5/2017	4.0	96	1	1	0	0
1/6/2017	9.1	141	3	3	0	0
1/7/2017	10.4	181	5	3	0	0
1/8/2017	11.6	174	9	4	1	1
1/9/2017	3.6	54	2	2	0	0
1/10/2017	9.8	177	7	4	4	1
1/12/2017	2.9	98	1	1	0	0
4/2/2017	7.3	115	7	4	1	1
7/25/2017	10.0	151	5	3	0	1

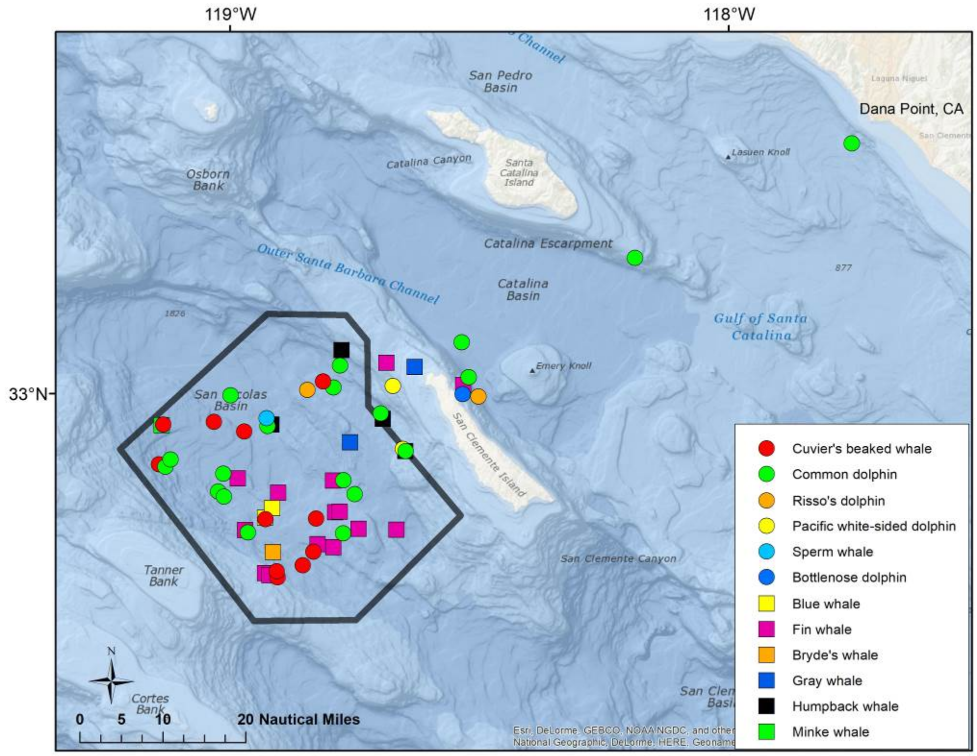

Figure 10. Map showing sighting locations by species. The black polygon represents the SOAR boundary.

9.2.2.4 GPS-LIMPET tag performance

Overall, GPS tag performance was good across a variety of taxa (Table 3). The percentage of successful versus failed snapshot attempts ranged from 37-83% (Table 4), depending on the species. The lowest rate of successful fixes was recorded by a fin whale, which is attributed to the location of tag deployment (dorsal fin) and the surfacing behavior of this species. Receiving a successful snapshot via Argos was the largest limiting factor; this can be attributed to satellite availability, which is limited except at high latitudes. For snapshots that were received, we compared the number of snapshots with four satellites versus five or more, in terms of the better accuracy of location estimates (Table 5) (e.g. Witt et al. 2010, Dujon et al. 2014 and the *land-based testing* section). The tag with the lowest percentage of successful GPS attempts, BpTag078 (Table 4), still had 66.7% of received locations with five or more satellites. The number of these optimal received locations went as high as 87.5% for ZcTag059, indicating that good snapshots were prevalent despite the challenges associated with data collection using these types of tags on free-ranging species.

Table 3. relevant tag programming parameters by Tag ID. Parameters where chosen (and modified) based on consideration of animal diving behavior, battery consumption, and study questions.

	Argos Settings				GPS Settings				
TagID	Fast Rep Rate (sec)	# hrs tx / day	Duty cycled?	Max # Daily Tx	Snapshot Interval (min)	Snapshot hrs / day	Duty cycled?	Max # successful snapshots/ hr	Max # successful snapshots/ day
BpTag077	15	16	No	700	8	24	No	7	180
BpTag078	15	16	No	700	30	24	No	2	50
GmTag169	15	21	Daily for 20 days, then every 5th day	750	30	24	Daily for 20 days, then every 5th day	2	96
GmTag170	15	21	Daily for 20 days, then every 5th day	750	30	24	Daily for 20 days, then every 5th day	2	96
GmTag171	15	21	Daily for 20 days, then every 5th day	750	30	24	Daily for 20 days, then every 5th day	2	96
PcTag055	15	21	Daily for 20 days, then every 5th day	750	30	24	Daily for 20 days, then every 5th day	2	96
ZcTag052	15	21	No	500	15	24	No	4	80
ZcTag053	15	21	No	500	20	24	No	3	48
ZcTag059	15	21	No	500	20	24	No	3	48

Table 4. GPS performance results from tags deployed during Task C. Tags with a * include GPS messages from the tags received by land-based Argos receiving stations (Motes, Wildlife Computers Inc., Redmond, WA).

TagID	Duration of data (Days)	# successful GPS attempts	# Successful attempts / # successful + failed attempts (%)	# GPS loc's received including Mote data	% GPS loc's received including Mote data	# GPS loc's received without Mote data	% GPS loc's received without Mote data
BpTag077*	15.1	1050	53.0%	48	4.6%	44	4.2%
BpTag078	67.3	2286	36.7%	N/A	N/A	356	15.6%
GmTag169	22.0	853	82.3%	N/A	N/A	526	61.7%
GmTag170	14.9	545	71.4%	N/A	N/A	258	47.3%
GmTag171*	23.0	841	67.2%	488	58.0%	485	57.7%
PcTag055	8.7	276	42.7%	N/A	N/A	166	60.1%
ZcTag052*	2.4	176	82.6%	72	40.9%	38	21.6%
ZcTag053*	11.7	479	81.3%	221	46.1%	89	18.6%
ZcTag059	10.3	354	78.0%	N/A	N/A	72	20.3%

Table 5. Assessment of the number of locations with more than four satellites, which lead to increased accuracy over location estimates with only four satellites. Tags with Mote data included are indicated by an asterisk (*).

TagID	Total # of GPS loc's received	Mean # Satellites per location	# GPS Locs with >4 satellites	% GPS Locs with >4 satellites
BpTag077*	48	5.3	32	66.7%
BpTag078	356	5	219	61.5%
GmTag169	526	5.3	372	70.7%
GmTag170	258	5	160	62.0%
GmTag171*	488	5	313	64.1%
PcTag055	166	5.3	109	65.7%
ZcTag052*	72	6.2	53	73.6%
ZcTag053*	221	5.4	165	74.7%
ZcTag059	72	6.8	63	87.5%

The daily update rate for each tag was assessed (mean number of locations received per day) for both GPS location estimates and Argos location estimates. In five of nine cases, the mean GPS update rate ranged from 43-106% greater per day than the Argos location update rate (Table 6). The two fin whales and two beaked whales had GPS update rates lower than those generated by Argos, although in the case of ZcTag053, with the addition of land-based Argos receiving stations, or Mote data (Wildlife Computers, Redmond, WA), GPS locations outweighed Argos locations by 136%. For these two species, update rate via GPS could be influenced by tag position on the body, surfacing behavior, sea state, or a combination of all three. If the tag is unable to collect a successful snapshot (four or more satellites), the tag will continue to try and collect a snapshot at the expense of a normal Argos transmission. Additionally, if the tag is transmitting an Argos message with GPS data included and the message is corrupted (e.g., the full 32-bit transmission is truncated), Argos may still be able to receive the signal well enough to ID the tag and use the uplink to generate a traditional location estimate.

Table 6. Location update rate of Fastloc-GPS versus Argos location estimates.

TagID	Mean # GPS snapshots received / day without Mote data	Mean # GPS snapshots received / day including Mote data	Mean # Argos location estimates / day
BpTag077	2.9	3.2	7.6
BpTag078	5.3	NA	11.6
GmTag169	23.9	NA	11.6
GmTag170	17.7	NA	10.1
GmTag171	21.1	21.2	14.7
PcTag055	19.1	NA	10.9
ZcTag052	15.8	30.0	9.5
ZcTag053	7.6	18.9	8.0
ZcTag059	7.0	NA	9.1

9.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

9.3.1 Sonar detector

The sonar detector is relatively simple to implement but demands the requisite hardware. In the case of Navy ranges, large arrays of hydrophones provide coverage over broad areas. For portable applications, the detector is available for implementation within a buoy for instance of for post-processing of recording data. On the major Navy ranges, given the hydrophone density and high MFAS source level, detection of a sonar ping within the array is guaranteed and in-fact localization of the source based on time-differences of arrival on multiple hydrophones is relatively straight forward. However, for sources off-range, MFAS signals may be detected but localization is difficult if outside a direct-path hearing radius.

The false alarm rate is highly dependent on the density of interfering signals, especially those from cetacean species. For instance, minke whales are common on the PMRF range. The animals produce a 1.5 kHz, >1 second tonal call whose third harmonic falls within the sonar band and closely mimics MFAS. At SCORE, common dolphins produce steady whistles that may reach into the MFAS band. Such biologic interferers vary both temporally and spatially.

9.3.2 GPS tag

While the GPS tag provides far more accurate location estimates than location estimates generated by the Argos system, there are some trade-offs that must be assessed when selecting a tag for a particular study. Battery life, importance of dive data versus position update rate and accuracy, ability to get close to your target animal, Argos availability, and cost, among others must be assessed for each study.

As an example: for beaked whales in the Southern California Bite (SCB), the mean time at the surface from the first to last breath for a beaked whale is 1.9 minutes with an mean of 21 minutes between shallow dives (Schorr et al. 2014). To best balance battery performance with Argos transmission performance for beaked whales, we program tags to transmit every 15 seconds, meaning the tag will only be available to transmit on average seven times per surfacing series (irrespective of Argos satellite availability). After collecting a GPS snapshot, the tag is unable to transmit for ~20 seconds while determining if the snapshot is 'successful' meaning 4 or more satellites were received during the snapshot. This process means that, at a minimum, two chances, out of seven, for an Argos transmission within a surface series were lost for Cuvier's beaked whales in the SCB. If the snapshot is good, the tag can immediately begin to transmit data: however, the tag now has GPS location data to transmit in addition to any dive data that may be collected. Therefore, at best, a researcher needs to assume a relatively large reduction in ability to transmit dive data over the SPLASH10 tag.

In the case of Cuvier's beaked whales within the SCB where studies have demonstrated that disturbance from Navy sonar may be assessed as a function of the time between deep (foraging) dives (Falcone et al. 2017), we modified our behavior log data collection to only capture deep dives, with the time between recorded deep dives as 'surfacings'. This increased the probability of receiving a complete temporal summary of deep diving behavior, while increasing number of available messages for transmission of GPS snapshots.

Upon review of the behavior log for these three whales with tags programmed to collect only dives greater than 40 minutes, it was determined that a mean of 2.2 behavior log messages per day were needed to capture the entire day of diving behavior. Each of these messages was received via Argos an average of 2.4 times per day; therefore, a tag could in theory increase the number of received GPS location estimates by ~ 4.8 per day by excluding the collection of behavior log dive data. However, if higher-resolution diving behavior is more important than high-resolution location data, and diving behavior would generate a larger number of behavior log messages per day, which illustrates why researchers should consider the trade-offs of the tag types carefully.

10.0 PERFORMANCE OBJECTIVES

Table 7 provides a summary of the performance objectives. The objectives are divided between the sonar detector and the GPS tag. Three objectives are set out for the sonar detector, the in-situ probability of detection, the false alarm rate, and also the accuracy of the measured sonar level at the face of the hydrophone.

The sonar detector exceeded each success criteria. It should be noted, that the false alarm rate was measured using in-situ data during a period with no sonar present on SCORE. However, the false alarm rate is heavily dependent on the presence or absence of vocalizing cetaceans which is highly temporally and spatially variable, and site-dependent. While the sonar bands are generally below that recorded for most cetaceans, there is at times vocalization energy in the sonar band that mimics a sonar signal. SCORE however, is the most vocally active of the three major Navy ranges and the false measured false alarm rate was on-average well within acceptable limits.

For the GPS tag, objectives for survival upon impact, the total number of attachment days, the number of GPS position updates provided per day, and the accuracy of those positional updates are set forth. The number of updates per day for beaked whales met the performance criteria. The overall rate (16 per day) was just below the goal of 18 updates per day. The number of updates is highly dependent on tag placement on the dorsal fin or high on the dorsal ridge. A low placement on a fin whale resulted in an update rate of but 3 per day since the tag did not come out of the water for the majority of the animal’s surfacing.

A table of performance objectives is provided below. These represent quantitative measures of performance for both the sonar detector and GPS-based tag.

Table 7. Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Final Result
Quantitative Performance Objectives				
Provide integrated sonar detector to M3R range monitoring signal processor	Probability of Detection	SCORE Range Recorded Data	70% correct detection/classification rate when interfering species present	100% (For sonar sources within SOAR)
	False Alarm Rate	SCORE Range Recorded Data	1 per 1000 seconds	~1 per 3,600 sec
	Measure Signal Level	Controlled signal in Gaussian white noise	+/- 10% of measured value (dBV)	< +/- 10%
Provide satellite tag with embedded GPS	Impact survival	Data collected with land-based targets	<10% failure in extreme tests that exceed expected force in field	0% Failure Rate
	Successful attachment and function	Data from tags attached to animals	Six tags must be attached to and function (for at least 2 days) on beaked whales or surrogate species*	**9 tags attached** 19.49 days mean attachment duration
	Update Rate	Data from tags attached to animals	18 per day	16.2/day overall Min 3.2/day *Bp* Max 30/day *Zc* **Zc mean = 18.6/day**
	Positional Accuracy	Data from tags tested at sea fielded on RHIB and animals compared to vessel-based tracks	90% < 200 m error	**Overall 163 m (SD = 233.9) >=4 satellites** 52m (SD 31m) w/ >= 5satellites

*Surrogate species for beaked whales could include Risso’s dolphins or fin whales.

11.0 PERFORMANCE ASSESSMENT

The sonar detector has been successfully integrated into the M3R software build and is fully running on all three major U.S. Navy Ranges. The software monitors up to 200 hydrophones at SCORE and PMRF and 92 hydrophones at AUTEC in real-time, on a continuous basis.

Probability of detection and false alarm statistics were measured in the lab in a Gaussian white noise environment (Table 7). With the parameter settings tested in the laboratory, the software was tested in-situ at SCORE. With a "lower" source level dipping helicopter MFAS within the confines of the hydrophone array, the probability of detection was 1. With no sonar present, the false alarm rate was 1 per hour which was significantly less than the objective (1 per 1,000 sec). It must be emphasized that the noise background is non-stationary and is highly influenced by the nature of interfering signals, primarily cetacean vocalization, present at any given time. SCORE was chosen in part because of its extremely high cetacean density and therefore interferers. Despite this challenging environment, the false alarm rate exceeded the objective.

The GPS-LIMPET tag was successfully deployed on target species including "sonar sensitive" Cuvier's beaked whales. Finding and tagging these animals is extremely challenging, but over the course of the tests, 3 tags were deployed on Cuvier's. A total of nine tags were attached, which exceeded the goal of 6 attachments. The mean attachment time (19 days) also exceeded the 10 day attachment goal. The three beaked whale tags provided 18.6 uplinks per day, which exceeded the goal of 18 per day. The overall rate of 16 uplinks per day was slightly under this goal but was attributed to suboptimal attachments, low on the animal's body which did not allow the tag to clear the water during the majority of surfacing. The overall location accuracy of 163 m exceeded the 200m goal. With 5 satellites, the position accuracy increased to 52 m. All tags survived destruction testing at forces that significantly exceeded those anticipated during actual deployments.

12.0 COST ASSESSMENT

Implementation of the sonar detector is low cost. The software is available at no cost from NUWC. However, integration into a real-time system will incur software development costs and depend on the particular application. For shore-based systems, a single quad-core node will service up to 200 channels in real-time at an input sample rate of 96 kHz.

The GPS-LIMPET tags are commercially available from Wildlife computers for a cost of approximately $7K each. A land-based MOTE receiver is available at a cost of approximately $15K.

The cost of on-water operations is extremely variable and depends on the test design and is highly site and species specific.

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14.0 Appendices

14.1 Appendix 1: Summary of work completed Contract No. N66604-14-C-2438, Task A 03 September 2014 to 04 August 2015

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The prototype GPS LIMPET tag was developed and built in collaboration with Wildlife Computers and Russ Andrews of the Alaska SeaLife Center. Twenty of the prototype tags were fired into a dorsal-fin simulating hard rubber target at 2 meters and withstood the impact. All tags survived pressure testing to 2000 meters, post impact testing (see N66604-14-C-0144_Andrews_ProgressReport_03Jul2015 submitted to NUWC).

The Fastloc GPS LIMPET tag in the current configuration was shot at ranges of 10 and 15m to assess flight characteristics and accuracy. The target was overlaid with a 5cm x 5cm grid pattern to facilitate elevation and windage measurements. A green-dot laser sight was affixed to the tagging rifle and the sight was adjusted to as close to center as possible in a series of practice shots at 10m. The rifle was positioned 1.5m above the target height, simulating the approximate height a tagger would be above a whale during tag deployments from a small vessel. Elevation and windage readings were captured by comparing the location of the tag impact to the position of the laser dot on the target using a high speed video camera. To asses precision of shots at each range, the average elevation and windage from the group of shots was subtracted from each shot's elevation and windage, effectively placing the sight at the center of the group of shots (aim point). To assess the difference in elevation between 10 and 15m, the laser sight was left zeroed in at 10m, and the difference of elevation between the two ranges was compared.

Precision of shots with the aim point at 10 and 15m.

At 10 m, the Fastloc GPS LIMPET tag flew similar to the SPLASH10 tag currently in use. While the grouping of shots was not quite as tight, the standard deviation for both elevation and windage was less than 3.5cm at 10 m, and less than 5.8 cm at 15m (Table 1, Figure 1).

Table 1. Comparison of the precision of tag impacts between the prototype Fastloc GPS and the production SPLASH10 LIMPET tag at 10 and 15 meters.

Tag Type	Range (m)	n	Elevation Sd (cm)	Windage Sd (cm)
SPLASH10	10	51	1.6	2.1
Fastloc	10	29	3.2	2.4
SPLASH10	15	72	3.3	3.7
Fastloc	15	20	5.7	4.6

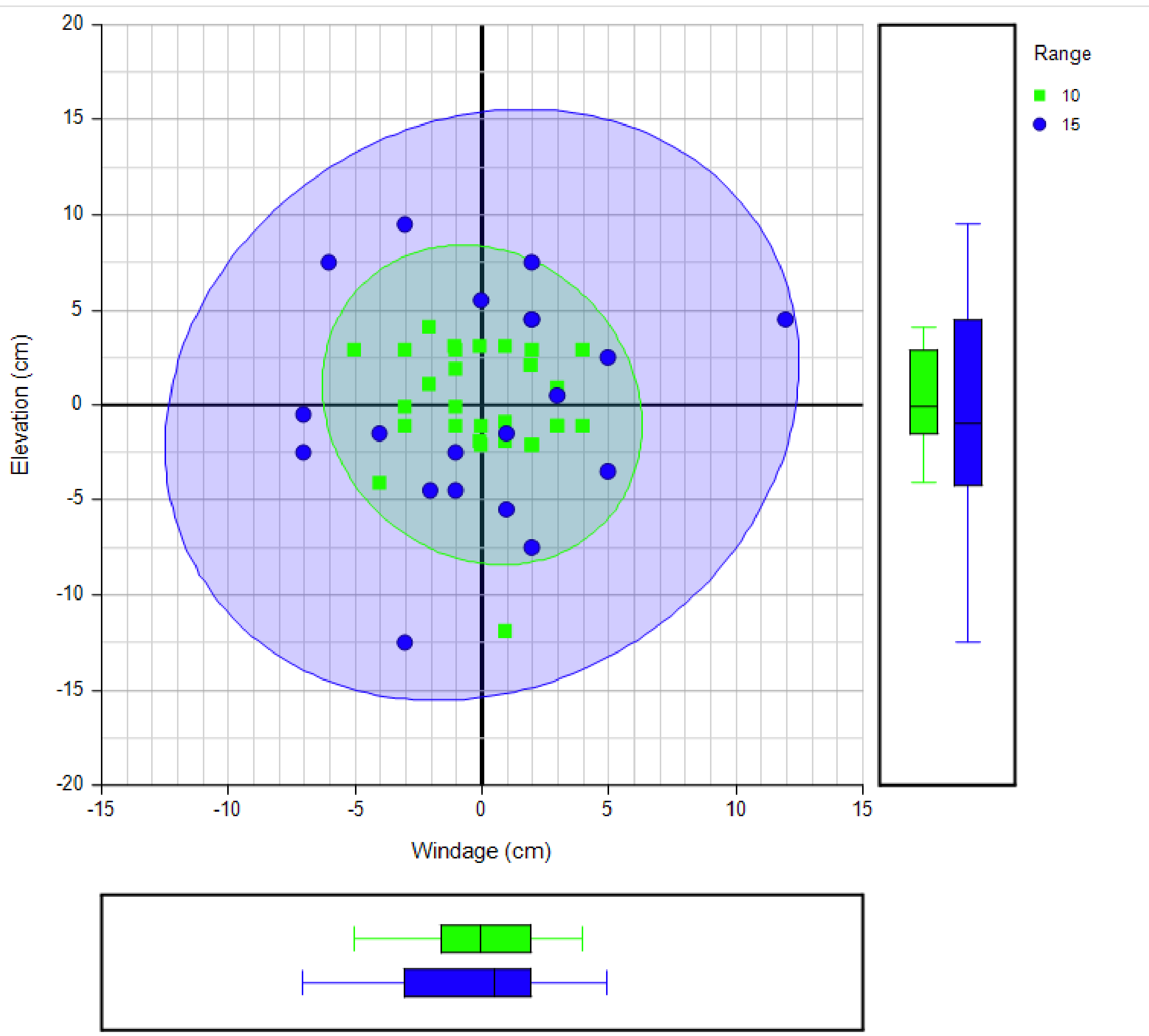

Figure 1. Scatter plot of Fastloc GPS LIMPET tag impact locations relative to the aim point at 10 (green) and 15 (blue) meters. In this figure, the aim point was adjusted to the center of the target at each range. The colored ellipses represent the 100% probability ellipse (assuming a bivariate normal distribution) at each range. The border box plots illustrate the median and inter-quartile range, with whiskers at 1.5 times the inter-quartile range for both elevation (right) and windage (bottom).

Effect of range on flight path between 10 and 15m

To assess the effect of range on the ballistic path of the tag, we left the sight zeroed in at 10 m, then shot at 15m. This resulted in tags striking the target at a group mean distance of 30cm below tags shot at 10m (Figure 2). For comparison, a drop of 28 cm is observed in the existing SPLASH10 LIMPET tag without the GPS component, so the ballistics of the Fastloc GPS LIMPET tag should be readily comparable to existing tags during field deployments. The additional 2cm of drop is likely a function of the increased weight of the FastLoc GPS LIMPET.

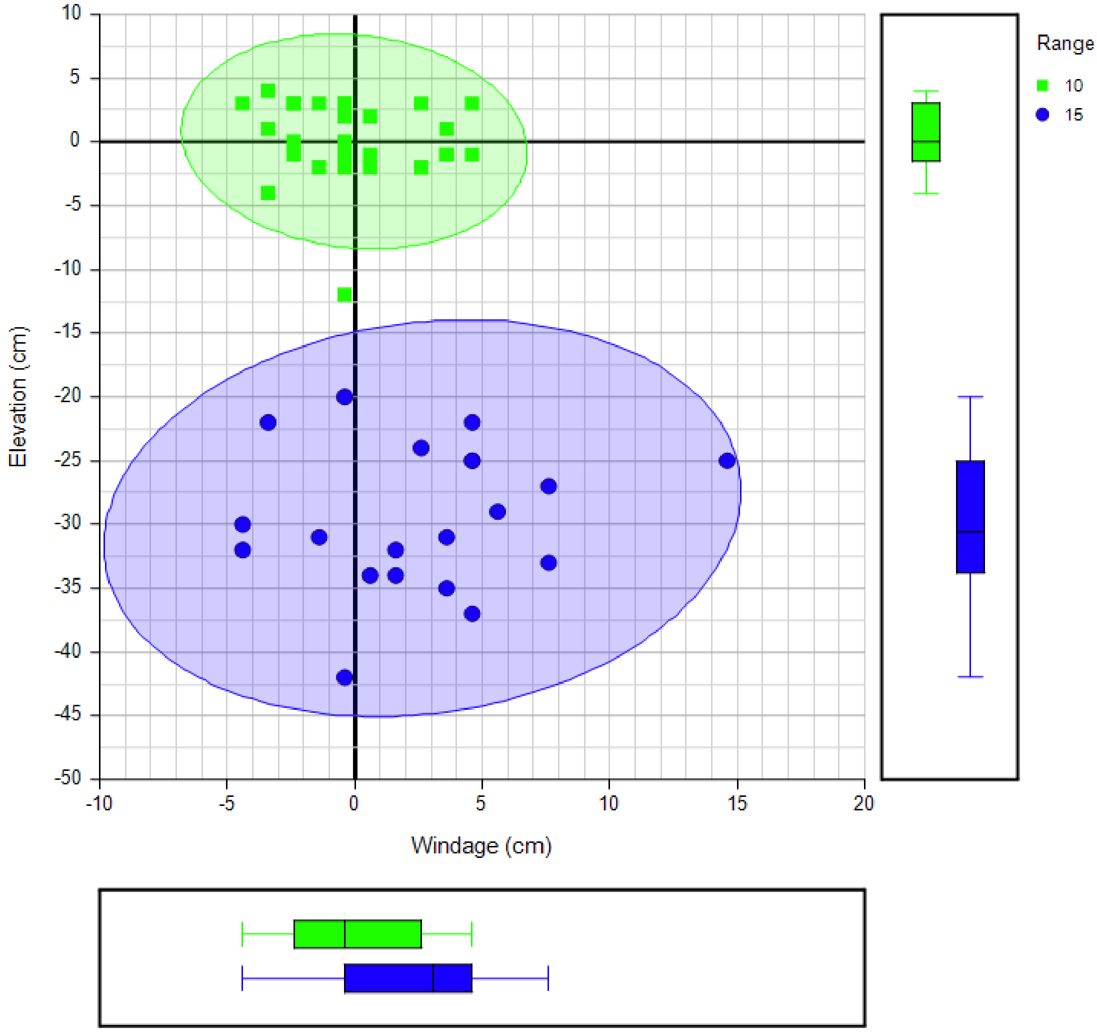

Figure 2. Scatter plot of Fastloc GPS LIMPET tag impact locations at 10 (green) and 15 (blue) m. In this experiment, the laser was sighted in at 10m, and not compensated for with the 15m shots. The colored ellipses represent the 100% probability ellipse at each range. The border box plots illustrate the median and inter-quartile range, with whiskers at 1.5 times the inter-quartile range for both elevation (right) and windage (bottom).

14.2 Appendix 2: Summary of work completed under Task B, contract Number: N66604-14-C-2438

Gregory S. Schorr and Erin A. Falcone

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Project Summary

The objective of this project is to integrate a FastlocTM GPS into a remotely-deployed, dart-attached, medium-duration satellite tag suitable for attachment to a beaked whale. This modification will allow for opportunistic monitoring of the reaction of cetaceans, including sonar-sensitive Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) beaked whales, to Mid-Frequency Active (MFA) sonar operations over the medium-term (weeks to months) with a high degree of spatial precision not currently available with existing satellite tags. These data, which will include precise localizations, and the presence or absence of deep foraging dives before, during, and after sonar exposure, are critically needed inputs for the Population Consequences of Disturbance (PCoD) model that is being developed to measure the health of animal populations. The project will be executed in three phases.

Task A Objective: The objective of Task A is to integrate the FastlocTM GPS receiver into the Low Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) style package and conduct land-based testing. Satisfactory completion of the testing will be the go/no-go criterion to exercise Task B.

Task B Objective: The objective of Task B will be to conduct field tests of the GPS LIMPET tags on several species of cetaceans to assess tag performance. Successful completion of field testing will be the go/no-go criterion for exercising Task C.

Task C Objective: The objective of Task C will be to deploy the final variant of the GPS LIMPET tag at SCORE prior to a Naval MFA sonar exercise.

Tasks included in this reporting period

Task B-Option. Please note that this work was completed in collaboration with Russ Andrews from the Alaska SeaLife Center, and David Moretti from the Naval Undersea Warfare Center, and this report compliments reports for this project submitted by these collaborators.

Summary of work completed

In order to increase the performance of the GPS, a dipole antenna was added to the tag (described in the report submitted by co-PI Russel D. Andrews). Additionally, extra epoxy was added between the transducer board and the main body of the tag in order to reinforce the board. These changes added approximately 2 grams of weigh to the tag. Ballistic testing at 13 meters indicated a standard deviation of just 0.29 cm elevation difference across test shots, indicating that the new tag can fly with sufficient accuracy at the typical ranges beaked whales are tagged. The dipole tag was then successfully deployed on three different species of cetaceans, including a pilot whale, fin whale, and Risso's dolphin (Figure 1) and an additional mono-pole version of the tag was deployed on a Risso's dolphin.

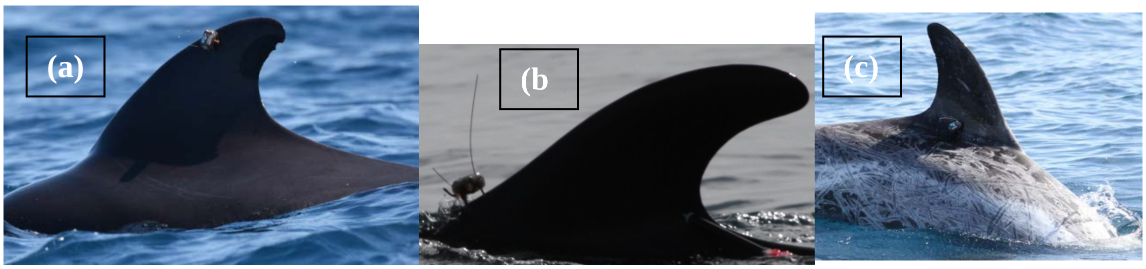

Figure 1. Photographs of the GPS LIMPET tag attached to: (a) short-finned pilot whale, (b) fin whale, and (c) Risso's dolphin. Photo credits are Danielle M. Waples (Permit #17086), Bernardo Alps (Permit #16111), Gregory S. Schorr (Permit # 16111)

While focal follows of tagged whales were not conducted to compare whale GPS locations to vessel GPS locations (as will be done under Task C), for the two tagged pilot whales we compared the Fastloc GPS locations with Argos position estimates of Location Classes (LC) 1, 2, and 3 that were acquired within 20 minutes of each other. The Argos error estimates for these LC positions are that 66% will be within 1500m, 500m, and 250m of the real location for LC 1, 2 and 3 positions. This resulted in 233 comparable position estimates with a median time difference of 9.41 minutes (range = 0.21 – 19.98 min). Overall median distance between Argos position estimates and concurrent Fastloc GPS position estimates was just 1.26 Km, though the distance varied by location class, as expected (Figure 2). For Argos location class 3 position estimates, the median distance from a GPS location within 20 minutes was just 0.90 km (range = 0.07-3.97, n = 52). The median distance between Argos location classes 0, A, and B position estimates and a corresponding GPS location within 20 minutes (n = 216) was more than 4 times greater (median = 4.92 km). Assuming the Fastloc GPS position estimates are accurate within even several hundred meters of the true position, the new tag will generate much better positional accuracy compared the lower location classes provided by Argos alone. This is particularly important for potential use on species, such as beaked whales, that generate a disproportionate number of lower class Argos positions during a typical deployment.

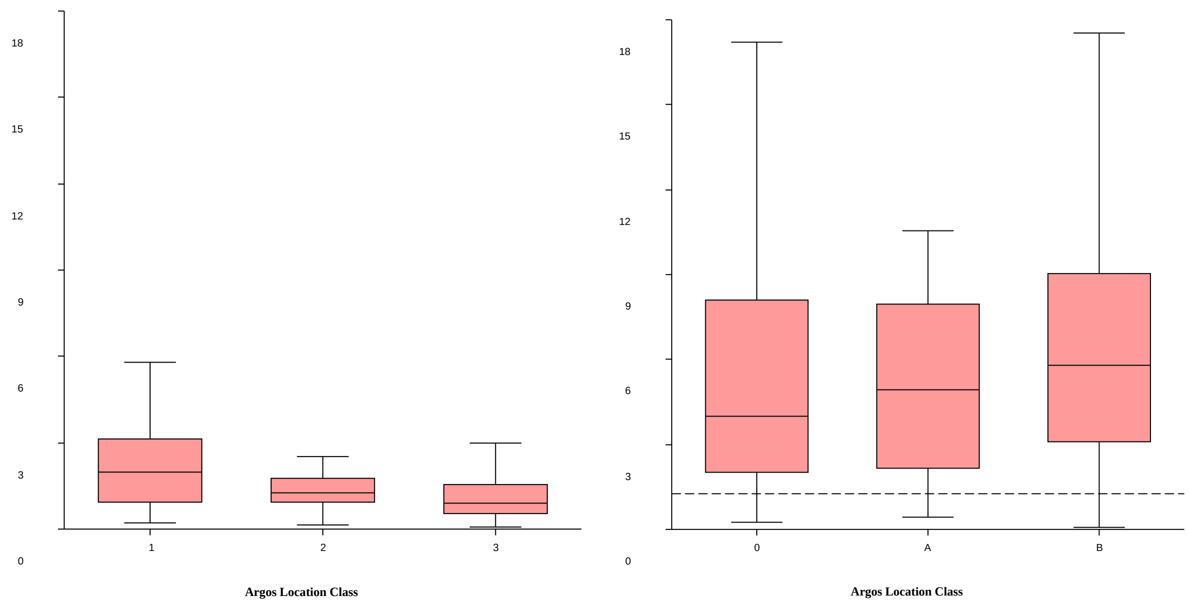

Figure 2. Box plots of the distances between Argos position estimates and GPS Fastloc position estimates obtained within 20 minutes of each other, by Argos location class. Left plot shows distance between Argos position estimates of LC 1, 2, and 3, right plot is Argos position estimates of LC 0, A, and B, with the dashed line representing the median distance between for LC 1, 2, and 3 location estimates. Note that all Fastloc positions were included in this analysis.

Conclusions

Task B allowed for additional refinement, improvement, and testing of the GPS LIMPET tag. The new version, model 333B, resulted in an increased performance (see report from R. D. Andrews), and passed both land and field testing. The current version meets the requirement of being deployable on individuals with smaller dorsal fins (Risso's dolphin and fin whales), and was successfully deployed on three different species during this task. We therefore feel that option 1 (Task B) was successfully completed and propose to move onto option 2 (Task C).

Acknowledgements

We gratefully thank the staff at Wildlife Computers, and Daniel Webster and Robin Baird of Cascadia Research Collective for assistance in tag deployments. We also thank Brenda Rone of Marine Ecology and Telemetry Research for assistance with tag deployments. We thank Dianne and Bernardo Alps for assistance in tag whale follow up. Tagging was conducted under NOAA OPR permits 15330, 16111, and 17086, with approval from Cascadia Research Collective's Institutional Animal Care and Use Committee.

Task B-Option. Please note that this work was completed in collaboration with Russ Andrews from the Alaska SeaLife Center, and David Moretti from the Naval Undersea Warfare Center, and this report compliments reports for this project submitted by these collaborators.

14.3 Appendix 3: **Integrated Measurement of Naval Sonar Operations and Precise Cetacean Locations: Integration of Fastloc GPS into a LIMPET tag.**

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Contract Number: N66604-14-C-0144, Mod. # P00005

Contractor:

Seward Association for the Advancement of Marine Science dba Alaska SeaLife Center

Reporting Period: 20 June 2014 to 22 August 2017

Project Summary

The objective of this project was to integrate a Fastloc® GPS into a remotely deployed medium-duration satellite dart tag suitable for attachment to a beaked whale. This modification will allow the opportunistic medium-term (weeks to months) monitoring of the reaction of cetaceans, including sonar-sensitive Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) beaked whales, to Mid-Frequency Active (MFA) sonar operations with a high degree of spatial precision not currently available with medium-term satellite tags. These data, which will include precise localizations, and the presence or absence of deep foraging dives before, during, and after sonar exposure, are critically needed inputs for the Population Consequences of Disturbance (PCoD) model that is being developed to measure the health of animal populations. The project consisted of three phases.

Task A Objective: The objective of Task A was to integrate the Fastloc® GPS receiver into the Low Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) style package and conduct land-based testing. Satisfactory completion of the testing will be the go / no go criterion to exercise the Phase 2 option.

Task B Objective: The objective of Task B was to conduct field tests of the GPS LIMPET tags on several species of cetaceans to assess tag performance. Successful completion of field testing will be the go / no go criterion for exercising the Phase 3 option.

Task C Objective: The objective of Task C was to provide ten of the final variant of the Fastloc-GPS LIMPET tags so our collaborator, NUWC contractor Cascadia Research Collective, could deploy them prior to a Naval MFA sonar exercise.

Summary of the Fastloc-GPS Tag Development Process, Test Results, and Lessons Learned

Task A

We worked with Wildlife Computers, Inc. (Redmond, WA) to design a LIMPET tag incorporating the Fastloc GPS receiver. The design specifications included small package size similar to the current dive-depth transmitting SPLASH LIMPET tag (SPLASH10-292B; length x width x height = 58 x 47 x 25 mm, mass = 63 grams), but including the Fastloc GPS capability and its necessary antenna. The original prototype is depicted in Fig. 1.

Figure 1. Drawings of the initial (2014) LIMPET tag incorporating the Fastloc-GPS with a monopole whip antenna, model AM-A333A-AF.

Our approach was to develop a tag that could meet the following physical criteria:

a. The tag shall withstand impact associated with striking a simulated whale after being launched from a Dan-Inject CO2 powered rifle at ranges as close as 2 meters with a failure rate of 10% or less.

b. The tag shall possess sufficient aerodynamic characteristics to permit consistent accuracy, striking within 10 cm of the point of aim at ranges from 3 to 20m.

c. The tag shall withstand pressurization equivalent to a depth of 2000m

All Fastloc-GPS prototype tags were initially tested at the manufacturer's facility to demonstrate proper functioning of all components and that the tags could withstand pressurization to the equivalent of 2000m seawater depth. After receipt at the Alaska SeaLife Center, tags were prepared with practice darts, which are 8.0 cm long titanium darts that penetrate 6.7 cm, without the usual backwards facing barbs, as shown in Fig. 2. Tags were impact-tested using the Dan-Inject CO_2-powered rifle to project the tags at a fiber-reinforced rubber target (Shore A hardness = 80 durometer). This hard rubber target is a reasonable simulation of dorsal fin tissue, although it requires approximately 50% more energy than would be required in whale dorsal fins for the darts to fully penetrate 6.7 cm. By using a hard target, we are simulating an impact more extreme than what would be expected when deploying a tag onto a live whale. Furthermore, the tags were projected at a distance of 2 meters from the target. In the field, we typically deploy tags at distances no closer than 3 meters, so these tests are simulating a more severe impact than would be expected in the field.

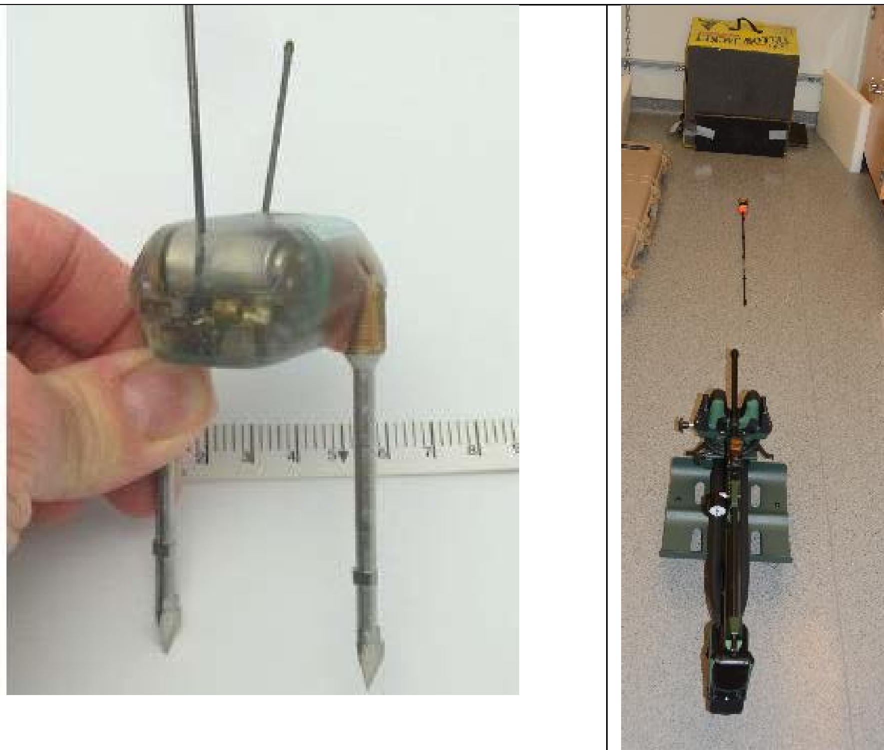

Figure 2. Photograph of an initial prototype (left) of the Fastloc-GPS with monopole whip antenna in the LIMPET configuration, equipped with practice darts for impact testing in the test setup shown in the right panel. The Dan-Inject CO_2-powered rifle was used to fire tags at an angle of 90 degrees from the flat surface of the hard rubber target at a distance of 2 meters.

Prototype tags were fired twice each, once at an angle of 90 degrees from the face of the flat target (Fig. 2), and once at an angle of 45 degrees. After the impact tests, functionality of all sensors and the GPS were verified at the Alaska SeaLife Center, and then the tags were returned to the manufacturer for further testing of sensors and functionality. All tags equipped with practice darts and subjected to our impact tests passed all subsequent functionality tests, including another round of pressurization equal to 2000 m sea water. However, testing did reveal that placement of the wet/dry sensors could lead to false surface readings, and therefore the design was modified and subsequent prototypes were built with an improved wet/dry sensor. The modified prototypes underwent the same impact and subsequent functionality tests and passed all tests.

The final criterion for determining success in the initial design stage based on land-based testing was that the tag must possess sufficient aerodynamic characteristics to permit consistent accuracy at ranges from 3 to 20m, to permit successful attachment to animals that can be difficult to tag, such as beaked whales. To test whether the current prototype Fastloc GPS LIMPET design can meet this standard, we conducted initial tests at the Alaska SeaLife Center, firing the tag at ranges from 3 to 20 meters and found that the flight trajectory matched expectations and that we could reliably hit a 10 cm target at those distances. After delivery of the final lot of prototypes, and after the tags successfully passed the impact and pressurization tests, the following tests were conducted in collaboration with Cascadia Research Collective (Olympia, WA). The Fastloc-GPS LIMPET prototype tags were prepared with normal length practice darts, as illustrated in Fig. 2, and fired from a rifle rest, but at distances of 10 to further assess flight characteristics and accuracy. The target was overlaid with a 5cm x 5cm grid pattern to facilitate elevation and windage measurements. A green-dot laser sight was affixed to the tagging rifle and the sight was adjusted to as close to center as possible in a series of practice shots at 10m. The rifle was positioned 1.5m above the target height, simulating the approximate height a tagger would be above a whale during tag deployments from a small vessel. Elevation and windage readings were captured by comparing the location of the tag impact to the position of the laser dot on the target using a high speed video camera. To assess precision of shots, the average elevation and windage from the group of shots was subtracted from each shot's elevation and windage, effectively placing the sight at the center of the group of shots (aim point).

Precision of shots with the aim point at 10 m.

At 10 m, the Fastloc GPS LIMPET tag flew similar to the SPLASH10-292B tag that was already in use for tagging beaked whales. Although the grouping of shots for the Fastloc-GPS LIMPET was not quite as tight, the standard deviation for both elevation and windage was less than 3.5cm at 10 m.

Table 1. Comparison of the precision of tag impacts between the prototype Fastloc GPS and the production SPLASH10-292 LIMPET tag at 10 meters.

Tag Type	Range (m)	n	Elevation SD (cm)	Windage SD (cm)
SPLASH10	10	51	1.6	2.1
Fastloc	10	29	3.2	2.4

At the conclusion of Year 1, we determined that the modified Fastloc-GPS LIMPET tag prototype was a good design. The tag prototypes were thoroughly tested, and the tags passed all three of our physical design criteria. The tags equipped with practice darts survived the extreme impacts that occurred in our tests firing the tags at a range of 2 meters into a target that is harder than any whale tissue. After the impact tests, all these tags passed the subsequent functionality tests, including pressurization to an equivalent depth of 2000 msw. Finally, the tags possessed sufficient aerodynamic characteristics to permit consistent accuracy when firing at ranges from 3 to 20m.

Task B

In Year 2, we tackled Task B, which consisted of a continuation of land-based testing and field testing at sea on several species of cetaceans. We worked with various collaborators, primarily at Cascadia Research Collective, to deploy Fastloc GPS LIMPET tags on a variety of cetacean species. One of the tags with the monopole GPS whip antenna was deployed onto a dwarf minke whale on 03 July 2015. The tag transmitted for only 8.5 days, likely because of an attachment failure, which is not unexpected given the large variation in attachment duration of LIMPET tags in general.

The performance of the Fastloc GPS LIMPET tag was quite reasonable. The tag was programmed to attempt a GPS snapshot every 15 minutes, and on average it attempted a snapshot every 17.3 min (Table 2). Of those snapshot attempts, 66.3% were successful, meaning they included the necessary data from four or more GPS satellites. However, the Argos performance of this tag was not very good because it was placed rather low on the body, and we only received 29% of the good snapshots via the Argos telemetry system. This meant that the average number of GPS fixes per day was only 15.9. Improvements in the GPS performance won't really matter if we cannot transmit enough of the collected GPS information via the Argos system, so these results demonstrate the importance of good placement of the tag on the whale, as well as an animal that spends a reasonable amount of time at the surface to facilitate a greater number of Argos transmissions.

Table 2. Results from deployments of Fastloc GPS tags on multiple species of cetaceans.

	Dwarf Minke whale	**Short-finned pilot whale-Hawaii**	**Fin whale**	**Risso's dolphin**	**Short-finned pilot whale-Cape Hatteras**
Type of Fastloc GPS antenna	333A monopole	333A monopole	333A dipole	333A monopole	333B dipole
Duration (d) of data in analysis	8.5	19.6	28.7	6.4	11.3
% of snapshot attempts successful (>4 sats)	66.3	68.8	42.0	49.3	88.5
% of good snapshots received via Argos	28.9	81.9	5.4	9.1	76.2
# snapshots received	135.0	564.0	107.0	41.0	353.0
Mean received snapshot interval (minutes)	91.2	50.2	389.7	230.0	46.2
Mean # of GPS fixes per day	15.9	27.3	3.6	6.4	30.9

A second Fastloc GPS LIMPET tag with the 333A GPS monopole antenna was attached to a short-finned pilot whale off the west coast of the island of Hawaii on 05 November 2015. This tag was attached much closer to the target area of the middle of the dorsal fin, and its GPS and Argos performance were better. This tag was programmed to attempt a GPS snapshot every 30 minutes, and on average it attempted a snapshot every 30 min. Of those snapshot attempts, 68.8% were successful (> 4 GPS satellites). Of these good GPS snapshots, we received 82% via the Argos system, resulting in over 27 GPS fixes per day (Fig.3, Table 2).

A third 333A monopole GPS tag was deployed on Risso's dolphin in Southern California on 11 April 2016. Unfortunately, this tag attached below the base of the dorsal fin, much lower than our target. On average only half of the GPS snapshot attempts were successful, and we received less than 10% of those via the Argos system.

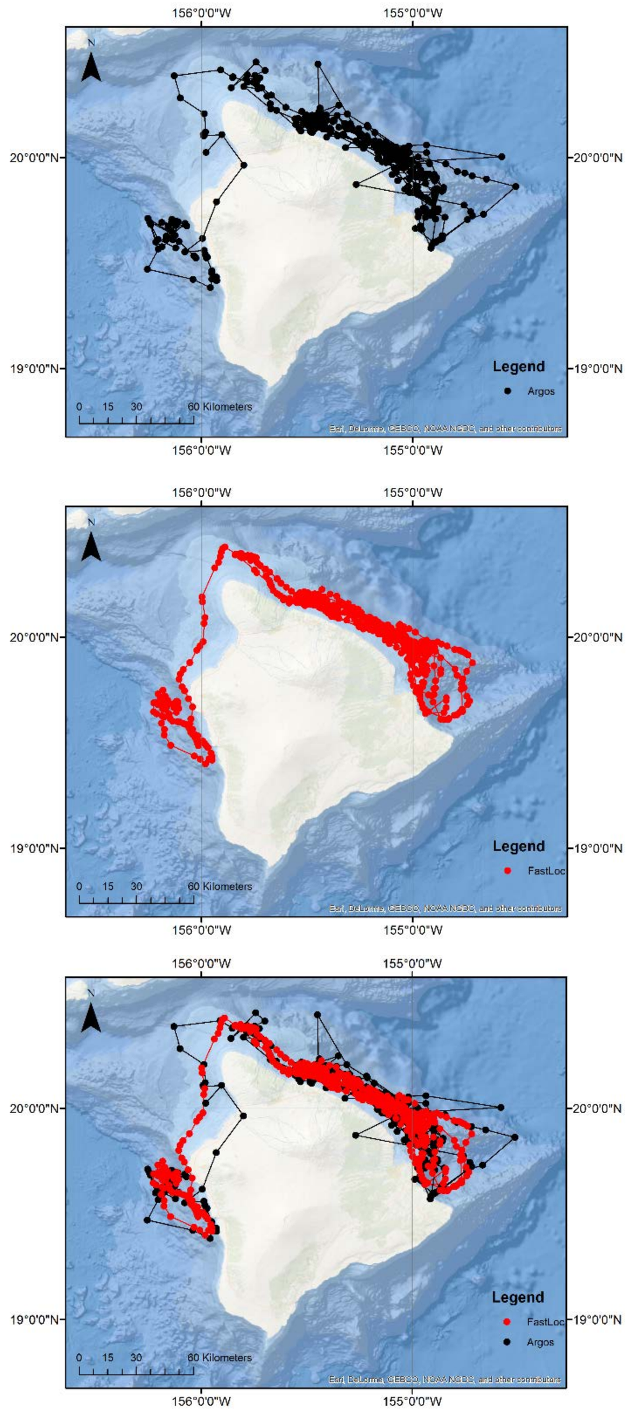

Fig. 3. Maps of position estimates for a short-finned pilot whale tagged with a monopole Fastloc GPS LIMPET tag. Top: Position estimates from the Argos Kalman process, filtered with the Douglas Argos Filter to remove outliers. Middle. GPS position estimates. Bottom: Plot of both the Argos (black) and GPS (red) position estimates.

Although the GPS performance of the model 333A Fastloc GPS LIMPET tag with a monopole GPS antenna on the short-finned pilot whale off Hawaii was quite good and far exceeded our goal of receiving at least 18 GPS fixes per day, we wanted to increase the percentage of GPS snapshot attempts that collected adequate signals from four or more GPS satellites. Therefore, we worked with Wildlife Computers to modify the Fastloc GPS LIMPET design to incorporate a dipole GPS whip antenna configuration instead of the monopole. These initial dipole prototypes were model 333A-dipole (Fig. 4). Although these tags contained the same internal electronics and external packaging, we nonetheless repeated all of our land-based impact testing to verify consistency. The new 333A-dipole tags were initially tested at the manufacturer's facility to demonstrate proper functioning of all components and that the tags could withstand pressurization to the equivalent of 2000m seawater depth. After receipt at the Alaska SeaLife Center, tags were prepared with practice darts and the tags were impact-tested following the same protocol detailed above. The new 333A-dipole prototype tags passed the impact and functionality tests, so we arranged for additional field testing.

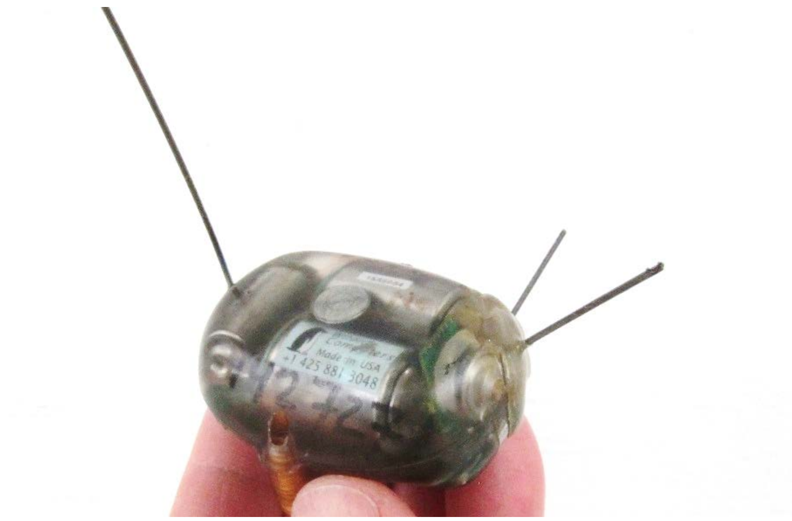

Figure 4. Photograph of the modified model 333A Fastloc GPS LIMPET with a dipole GPS whip antenna configuration, with one whip vertical and one whip horizontal.

A Fastloc GPS LIMPET tag with the 333A-dipole GPS antenna configuration was deployed on the fin of a Risso's dolphin in Southern California in February 2016, but the tag never uplinked through the Argos satellites. The tag was well attached, so the failure must have been in the tag electronics, which although rare, has occurred inexplicably with other models of Argos satellite tags. We have no indication of why this occurred, and all other lab tests and deployments have resulted in normal operation. We therefore feel this was an event that is unlikely to be repeated, and does not reflect the robustness of the overall design.

A Fastloc GPS LIMPET tag with the 333A-dipole GPS antenna configuration was attached to a fin whale in Southern California on 01 March 2016. This tag was attached at the base of the dorsal fin, slightly lower than the targeted area of the middle of the fin. This, combined with the fact that this whale rarely brought its fin to the surface resulted in very limited Argos transmissions, making assessment of the GPS performance difficult.

We did conduct extensive land-based testing of the GPS performance, using a simulated dorsal fin sitting on the surface of the ocean, and found that while the performance of the dipole GPS antenna was significantly better than the monopole, the initial dipole configuration with one GPS whip horizontal and one vertical could result in the lower horizontal whip contacting the fin. Therefore, we again worked with Wildlife Computers engineers to redesign the GPS dipole whip layout, producing the model 333B (Fig. 5). In addition to the GPS whip design change, the 333B tag included an extra 2 mm of epoxy behind the pressure transducer to further reinforce it, resulting in the total mass of the tag increasing by 2.8%, from 68.2 grams to 70.1 grams.

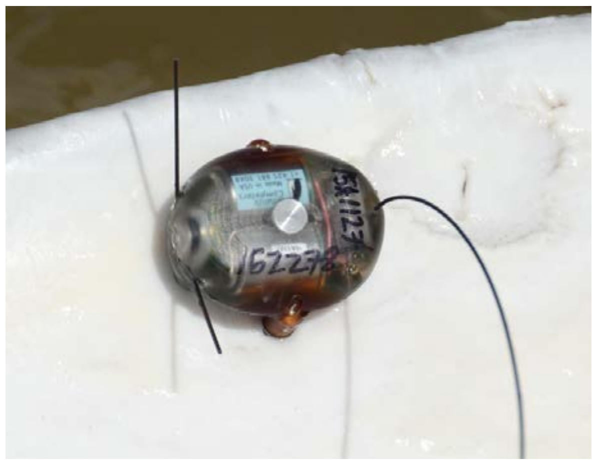

Fig. 5. Fastloc GPS LIMPET design model 333B with symmetrical V GPS dipole whip antenna configuration.

An additional 20 of these model 333B tags were built and subject to the same land-based testing as our original tags, including equipping them with the barbless practice darts and firing them two times into the dorsal-fin simulating hard rubber target at a distance of 2 meters. All tags survived the impact and passed the post-impact testing, including pressurization to a depth equivalent to 2000 meters. All tags survived the pressurization tests, and no tags showed any signs of water intrusion. Therefore, all 20 tags survived the extreme tests with darts, and all 20 tags passed the functionality and pressurization tests. The external packaging was not different from the earlier 333A designs that went through ballistics testing, but we did work with Cascadia Research Collective to ensure that the additional mass of approximately 2 grams did not cause an unacceptable impact on flight performance during deployment.

One of the improved Fastloc GPS LIMPET 333B GPS dipole tags was deployed on a short-finned pilot whale offshore of Cape Hatteras, NC on 26 May 2016. This tag performed exceptionally well and we have observed a significant improvement in the GPS performance of the new design with a symmetrical V dipole GPS whip antenna. This 333B tag was programmed to attempt a GPS snapshot every 30 minutes, and on average it attempted a snapshot every 31.1 min (Table 2). Of those snapshot attempts, 88.5% were successful (> 4 GPS satellites). Of these good GPS snapshots, we received 76% via the Argos system, resulting in an average of 31 GPS fixes per day.

Task C

The final objective of the Fastloc-GPS portion of our project, "Integration of Fastloc GPS into a LIMPET tag", was to continue to work with the commercial satellite tag manufacturer, Wildlife Computers (Redmond, WA), to produce a final design of the GPS LIMPET tag and to procure a final lot of 10 tags for testing at sea by Cascadia Research Collective collaborators working under their own NUWC contract in the overall ESTCP project's third year. The final design is the model 333B (officially the SPLASH10-F-333B), and is illustrated in figures 6 and 7, including the specifications sheet from Wildlife Computers: "SPLASH10-F-333B, Stacked Dart Finmount, 2-Lay, Extended depth range". Additionally, the Fastloc-GPS LIMPET tag is now offered as a standard, commercial product, by Wildlife Computers, along with the other variants of the LIMPET tag.

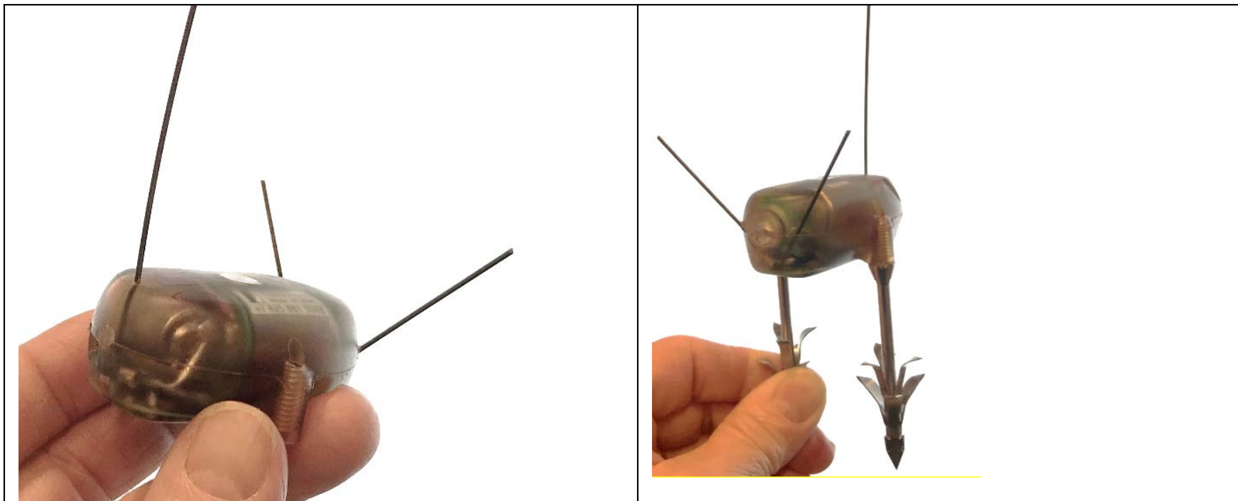

Figure 6. Photographs of the final Fastloc-GPS design (model SPLASH10-F-333B, Wildlife Computers) incorporating a dipole whip antenna, with (right) and without (left) attachment darts.

The final design of the Fastloc-GPS LIMPET model SPLASH10-F-333B, is characterized by the following physical specifications: maximum length (not including antennas): 55.9 mm; maximum width (not including antennas): 50.1 mm; maximum height (not including antennas): 27.2 mm; mass: 70.1 grams.

The details of the Fastloc-GPS tag deployments by Cascadia Research Collective will be summarized in their final report for their NUWC contract, which we will assist them in producing. A no-cost extension was requested and granted, and that report will be submitted at the end of December, 2017. Briefly, five Fastloc-GPS tags were deployed on Cuvier's beaked whales and a surrogate species, the fin whale (Table 3), in California.

Table 3. Details of Fastloc-GPS tag deployments performed by Cascadia Research Collective in California.

Species	TagID	Deployment date	Duration of data transmission (d)
Fin whale	BpTag077	10JAN2017	15.1
	BpTag078	02APR2017	67.3
Cuvier's beaked whale	ZcTag052	11NOV2016	2.4
	ZcTag053	08JAN2017	11.7
	ZcTag059	25JUL2017	10.3

The difficulties of working with unpredictable cetaceans and sometimes inclement weather combined to prevent our Cascadia Research Collective collaborators from deploying more tags on beaked whales. However, additional opportunities to deploy Fastloc-GPS tags on deep-diving odontocetes were presented by Cascadia Research Collective collaborators working with short-finned pilot whales off the island of Hawaii (Table 4). A Fastloc-GPS tag was also deployed there on a false killer whale.

Table 4. Details of Fastloc-GPS tag deployments performed by Cascadia Research Collective off the island of Hawaii.

Species	TagID	Deployment date	Duration of data transmission (d)
Short-finned pilot whale	GmTag169	06MAR2017	22.0
	GmTag170	13MAR2017	14.9
	GmTag171	13MAR2017	23.0
False killer whale	PcTag055	09MAR2017	8.7

Conclusion

Detailed analyses of the performance of the Fastloc-GPS tags, especially for whales tagged on a Navy range, will be presented in the Cascadia Research Collective final report for this project (Integrated Measurement of Naval Sonar Operations and Precise Cetacean Locations: Integration of Fastloc GPS into a LIMPET tag). The Cascadia Research Collective contract is Number: N66604-14-C-2438.

Acknowledgements

This project would not be possible without the excellent work of the staff at Wildlife Computers. We thank Kylie Owen for assistance. The dwarf minke whale tagging was conducted in collaboration with Dr. Alastair Birtles, James Cook University, and John Rumney, Eye to Eye Marine Encounters, and was approved by the James Cook Animal Ethics Committee and the Great Barrier Reef Marine Park Authority. Tagging of the other species was conducted by Cascadia Research Collective and collaborators, primarily Greg Schorr, Daniel Webster and Robin Baird, under NOAA OPR permits # 15330 and 16111, with approval from the Cascadia Research Collective and Alaska SeaLife Center institutional animal care and use committees.