Final Report

Assessing Odontocete Exposure and Response to Mid-Frequency Active Sonar during Submarine Command Courses at the Pacific Missile Range Facility: 2016 through 2018

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Prepared by:

Robin W. Baird[1], E. Elizabeth Henderson[2], Stephen W. Martin[3] and Brandon L. Southall[4]

[1]Cascadia Research Collective, 218 ½ W. 4th Avenue, Olympia, WA 98501

[2]Naval Information Warfare Center, 53560 Hull Street, San Diego, CA 92152

[3]National Marine Mammal Foundation, 2240 Shelter Island Drive, San Diego, CA 92152

[4]Southall Environmental Associates, Inc., 9099 Soquel Drive, Suite 8, Aptos, CA 95003

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HDR

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Cover Photo Credit:

Short-finned pilot whale (*Globicephala macrorhynchus*) with a Fastloc-GPS tag, off Kaua‘i. Photograph taken by Colin J. Cornforth under National Marine Fisheries Service permit no. 20605.

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Acronyms and Abbreviations

BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range Expansion
dB re: 1 μPa RMS	decibels referenced to 1 microPascal root mean square
GMT	Greenwich Mean Time
GPS	Global Positioning System
h	hour(s)
km	kilometer(s)
LC	location class
m	meter(s)
MFAS	mid-frequency active sonar
PMRF	Pacific Missile Range Facility
RLs	received levels
SCC	Submarine Command Course
SD	standard deviation
SPL	Sound Pressure Level
SSSM	Switching state space model

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1. Executive Summary

A number of species of resident and non-resident odontocetes use the waters of the Kaulakahi Channel between Kauaʻi and Niʻihau, overlapping with the Pacific Missile Range Facility (PMRF). Submarine Command Courses (SCCs) held at PMRF provide an opportunity to assess exposure and measure odontocete reactions to mid-frequency active sonar (MFAS) being used in realistic training scenarios. The primary goal of this assessment was to estimate MFAS received levels (RLs) for satellite tagged odontocetes and determine whether any large-scale movements occurred in response to hull-mounted surface ship MFAS exposure. Two prior reports have used odontocete satellite tag data and information on MFAS use to estimate RLs for animals tagged in 2011 through 2015.

This study continues and extends the earlier efforts using data from three species of odontocetes satellite tagged prior to SCCs in August 2016, February 2017, and August 2018. Methods in the current analyses were consistent with prior methods to allow for comparison, using filtered satellite tag data, the locations of ships transmitting MFAS, and the times of sonar transmissions from PMRF range hydrophones. However, several key improvements were made in data collection and the ability to quantify received noise exposure and describe various sources of error. One (in 2016) or two (in 2017 and 2018) land-based Argos receiving stations were used to supplement satellite tag data received through the Argos satellite system. RLs were estimated at the nominal location of tagged individuals and variability in RL estimates were assessed using information on the accuracy of locations, for locations received within one hour of MFAS transmissions. For each exposure, multiple metrics (mean, SD, minimum, maximum) of estimated RLs (measured as dB re: 1µPa RMS) were calculated, both near the surface (10 m depth) and at depths meant to represent typical foraging depths for each species. When available, information on diving and surfacing behavior of tagged individuals before, during and after MFAS use was also compared to assess potential reactions to MFAS.

From the 2016-2018 SCCs data for estimating RLs and examining potential responses were available for three short-finned pilot whales, *Globicephala macrorhynchus* (one from the resident population and two from a non-resident population), two rough-toothed dolphins, *Steno bredanensis* (both from the resident population), and two melon-headed whales, *Peponocephala electra* (both from an offshore population). The three short-finned pilot whales (in two different groups) were exposed to MFAS at estimated distances of 27.2 km to 145.5 km, with estimated mean RLs ranging from 122.6 to 145.0 dB at 10-m depth. Estimated RLs at 500 m depth for these individuals were typically 10-20 dB lower. The two pilot whales in the same group were traveling together before, during and after the August 2016 SCC, and were thought to be from a non-resident population. Prior to the start of surface ship MFAS use the two individuals had moved off PMRF. After the start of MFAS use these individuals moved away from the source for approximately 24 hours (to approximately 127 km from the source), then moved back towards PMRF to approximately 44 km from the source, moving from an area with estimated RLs of approximately 122 dB to 145 dB. Changes in diving behavior over the three sonar exposure periods (before, during, after the SCC) were documented for both individuals, but the patterns were not consistent between them, suggesting that some factor other than

MFAS exposure may have been influencing the diving behavior of one or both individuals. The other individual, tagged prior to the August 2018 SCC, was a member of the resident population. At the start of surface ship MFAS use this individual was 32.9 km from the MFAS source in an area with an estimated median RL of 133.3 dB, and over the next six hours moved to 52.4 km from the MFAS source into an area with an estimated median RL of 130.6 dB.

Two rough-toothed dolphins were tagged in the same group prior to the February 2016 SCC, but had separated prior to the start of the SCC. Both individuals moved south of PMRF prior to the start of surface ship MFAS use. At the start of MFAS exposures the individuals were in areas with estimated median RLs of 143.4 and 147.3 dB. Some movements away from the MFAS source were documented for both individuals, although by the end of the SCC the individuals were in areas with estimated median RLs of 146.3 and 151.4 dB, respectively. Night-time dive depths and durations did differ significantly among the three sonar exposure periods for both individuals, but not in a consistent way, suggesting that some factor other than MFAS exposure may have been influencing the diving behavior of one or both individuals.

Two melon-headed whales tagged in the same group prior to the August 2017 SCC appeared to remain associated throughout the SCC. Both individuals moved off PMRF prior to the start of surface-ship MFAS use, and were almost 100 km from the MFAS source at the start of exposure, continuing to move away during the sonar exposure period. Only a few Argos locations were obtained within one hour of MFAS use for these individuals, so we undertook a preliminary exploration of a continuous-time animal movement model (a Bayesian switching state space model, SSSM) to generate locations at regular (one-hour) time intervals during the period of MFAS exposure. Using the modeled location data, estimated median RLs were in the range of approximately 75 to 105 dB. While we are confident in the magnitude of exposure for these individuals (i.e., that they were exposed at low RLs), further refinements and assessments of continuous-time movement models are needed for this type of application. Overall these analyses provide additional case studies of exposure and responses of three species of odontocetes to hull-mounted surface ship MFAS use, including individuals both from resident (rough-toothed dolphins, short-finned pilot whale) and non-resident populations (melon-headed whales, short-finned pilot whales). Six of the seven individuals had moved off PMRF prior to the start of surface ship MFAS use; the one individual which had not moved off PMRF prior was a short-finned pilot whale from the resident population. It is unknown whether or not such movements off PMRF may have been in response to surface or sub-surface Navy activities on the range prior to the start of surface-ship MFAS use. For the two pilot whales from the non-resident population, initial movements away from the MFAS source may have been a large-scale movement response to exposure. Movements back towards areas with higher RLs starting approximately 24 hours after the beginning of MFAS exposure may have indicated an increased tolerance of MFAS exposure. Alternatively, the exposure levels could have been too low to elicit a large-scale movement response and movements documented were in response to some other factor (e.g., prey patterns).

2. Introduction

As part of the regulatory compliance process associated with the Marine Mammal Protection Act and the Endangered Species Act, the U.S. Navy is responsible for meeting specific monitoring and reporting requirements for military training and testing activities. In relation to cetacean reactions to mid-frequency active sonar (MFAS), the marine species monitoring program addresses four broad topics: (1) cetacean *occurrence*; (2) MFAS *exposure*; (3) *responses* to MFAS; and (4) the population *consequences* of such exposure. Studies addressing the first three of these topics have been undertaken in the Kaulakahi Channel between Kauaʻi and Niʻihau, for cetaceans that use all or part of the waters on the Navy's Pacific Missile Range Facility (PMRF). These studies have used acoustic (e.g., Manzano-Roth et al. 2016) and boat-based methods (Baird et al. 2013, 2019). Studies of occurrence revealed the existence of resident populations of four species of odontocetes: rough-toothed dolphins (*Steno bredanensis*), bottlenose dolphins (*Tursiops truncatus*), spinner dolphins (*Stenella longirostris*), and short-finned pilot whales (*Globicephala macrorhynchus*) (Albertson et al. 2017; Baird et al. 2008, 2009, 2019; Baird 2016). These studies have also shown that other species off Kauaʻi, for example melon-headed whales (*Peponocephala electra*), belong to widely ranging populations that move among the islands and into offshore waters, only occasionally visiting the area around Kauaʻi (Aschettino et al. 2012; Baird 2016; Baird et al. 2019).

Most of the field efforts examining occurrence questions have strategically occurred prior to the start of Submarine Command Courses (SCC), which are typically conducted in the area twice a year. Satellite tags deployed on a number of species of odontocetes have remained attached and transmitting through all or part of several SCCs, also allowing for initial, novel assessments of both exposure and response to MFAS for these species in this region (Baird et al. 2014, 2017a). Previous integrated occurrence, exposure, and response analyses have been conducted for 13 individuals of four species of odontocetes satellite tagged between 2011 and 2015: one bottlenose dolphin, one false killer whale (*Pseudorca crassidens*), five rough-toothed dolphins, and six short-finned pilot whales (Baird et al. 2014, 2017a). These assessments have included an integrated analysis of satellite-tag data, information on hull-mounted MFAS use, and acoustic propagation modeling. These methods build upon other opportunistic exposure and response analyses using received acoustic signals from vocalizing animals in combination with information on MFAS use (Martin and Kok 2011; Martin et al. 2018)

For our analyses of tagged whales in Hawaiʻi, we have used increasingly complex methods to account for positional uncertainty and spatial heterogeneity in sound fields from propagation modeling methods, and applied lessons learned from previous efforts and through related collaborations with other Navy-funded efforts. Estimated maximum received levels (RLs) from MFAS for individuals in our analyses to date have ranged from 130 to 168 decibels referenced to 1 microPascal root mean square (dB re: 1 μPa RMS; hereafter dB). Individuals showed no large-scale avoidance of areas with moderately high estimated MFAS received levels, although clear dive behavioral changes were quantified in one short-finned pilot whale for which detailed dive data were available (Baird et al. 2014, 2017a).

For the current analyses described here, satellite tagging was conducted in the Kaulakahi Channel prior to SCC events in February 2016, August 2017 and August 2018. During these efforts 23 individuals of four different species were satellite tagged (Baird et al. 2017b, 2018, 2019), seven of which remained in or near the Kaulakahi Channel and continued to transmit during the SCC. These include two rough-toothed dolphins, two melon-headed whales, and three short-finned pilot whales. The two rough-toothed dolphins and one of the short-finned pilot whales were known to be part of the resident communities with ranges centered around the Kaulakahi Channel, while the melon-headed whales and the other two short-finned pilot whales were both thought to be from populations that range more widely among the islands (Baird et al. 2017b, 2018, 2019). The purpose of this report is to extend the earlier analyses to these individuals satellite tagged from 2016 through 2018. As with the earlier analyses, we examine exposure to high-power, surface-ship MFAS sources only, and other MFAS sources (e.g., mid-power, helicopter-deployed, dipping sonars and sonobuoys) are not considered in this analysis. These analyses include both information on MFAS exposure and associated horizontal movements of the tagged individuals, as well as information on diving behavior of the individuals (i.e., potential changes in vertical movements). Odontocete movement patterns and diving behavior may be influenced by a variety of environmental factors, including time of day, lunar cycle, and season. All three species in Hawaiʻi exhibit variability in diving behavior in relation to one or more of these factors (Baird 2016; Owen et al. 2019; West et al. 2018). For example, all dive deeper and more frequently at night than during the day, and short-finned pilot whales are found farther offshore and dive deeper and longer during the full moon (Baird 2016; Owen et al. 2019; West et al. 2018). Thus, we undertake comparisons of diving behavior separately for day/night periods.

3. Methods

3.1 Tag Types, Programming and Tagged Individuals

Tags used (all manufactured by Wildlife Computers, Redmond, Washington) included SPLASH10 tags, that provided Argos locations and dive data (in all three years), SPOT5 and SPOT6 location-only tags (in 2017 and 2018), and SPLASH10-F tags that provided Argos locations as well as Fastloc-GPS (Global Positioning System) locations and data on diving behavior (in 2018). Tags were in the Low Impact Minimally Percutaneous Electronic Transmitter configuration, with attachment to the animals with two titanium darts with backward-facing petals, using either short (4.4-centimeter) or long (6.8-centimeter) darts (Andrews et al. 2008), depending on species (e.g., short darts for rough-toothed dolphins and melon-headed whales, long darts for short-finned pilot whales).

Of the seven tags considered in these analyses that were deployed in 2016–2018, six were SPLASH10 tags (on melon-headed whales, rough-toothed dolphins, and short-finned pilot whales), and one was a SPLASH10-F tag (on a short-finned pilot whale). The SPLASH10 tag programming varied by species and year, based on species-specific differences in diving and surfacing patterns, and on lessons learned during each successive year of deployments. SPLASH10 tags for short-finned pilot whales (only used in 2016) were programmed to transmit 17 hours/day with a maximum of 700 transmissions per day. SPLASH10 tags on melon-headed whales (in 2017) were programmed to transmit 14 hours/day, and on rough-toothed dolphins (in 2016) for 15 hours/day, with a maximum of 1,050 or 700 transmissions per day, respectively. The SPLASH10-F tag (in 2018) was set to transmit 17 hours/day up to 900 times per day. Hours chosen for transmission in all cases corresponded to hours with the best Argos satellite overpasses with hours spread throughout the 24-hour period to minimize temporal gaps in locations. The SPLASH10-F tag was set with Fastloc-GPS locations as high priority and behavior logs (i.e., dive data) as low priority, with a 6-day buffer. Behavior data and Fastloc-GPS locations were only collected up to 3.5 days past the scheduled end of the SCC, to maximize throughput of both location and behavior data during the period of interest (i.e., before, during, and after the SCC). For tags that remained transmitting after this period, this allowed for prioritization of transmitting existing tag data, rather than collection of new data, in order to minimize gaps in the location and dive record during the period of interest. Tags were programmed to record dives to at least 30 (in 2016 and 2017) or 50 (in 2018) meters (m) in depth, with depth readings of 3 m being used to determine the start and end of dives, thus dive durations are slightly negatively biased. Given typical odontocete descent and ascent rates of 1 to 2 m/second, dive durations recorded are likely only 3 to 6 seconds shorter than actual dive durations.

One (in 2016) or two (in 2017 and 2018) shore-based Argos receiver stations were used to increase the amount of dive and surfacing data obtained from the location-dive tags, as well as the Fastloc-GPS locations. This system uses a Wildlife Computers MOTE (see Jeanniard-du-Dot et al. 2017) to record and transmit data to a Wildlife Computers interface for data access. One system was at 456 m elevation on Mākaha Ridge, Kauaʻi (22.13°N, 159.72°W) in all three years, with directional antennas oriented to the north and southwest, and one system (in 2017 and 2018) was at approximately 365 m elevation on the east side of Niʻihau (21.95°N, 160.08°W), with one directional antenna oriented to the north and one omnidirectional antenna.

Details on the field methods and general results are available elsewhere (Baird et al. 2017b, 2018, 2019). Tagged and companion individuals were photographed for assessment of age class and sex as well as individual identification. Photographs were compared to long-term photo-identification catalogs (Baird et al. 2008; Mahaffy et al. 2015), and information on association patterns of identified individuals was used to assess population identity (see Baird et al. 2017b, 2019). A skin biopsy of one of the tagged short-finned pilot whales was collected, and the sex of the individual was genetically determined at the Southwest Fisheries Science Center.

3.2 Tag Data Processing

Location data were first processed by Argos using a least-squares method, and subsequently filtered with the Douglas Argos-filter v. 8.5 (Douglas et al. 2012) to remove unrealistic locations using two independent methods: distance between consecutive locations, and rate and bearings among consecutive movement vectors. Each location is assigned a “location class” by Argos, which reflects the estimated precision of the location, with the most precise locations being classes 3 and 2. We set the Douglas Argos-filter to automatically retain location classes 3 and 2. Maximum rates of movement were set at 15 kilometers per hour for short-finned pilot whales and melon-headed whales and 20 kilometers per hour for rough-toothed dolphins. For individuals tagged within the same group, we measured the straight-line distance between pairs of locations received during the same satellite overlap to see whether individuals were acting independently.

Data obtained from the shore-based Argos MOTE receiver and from the Argos System were processed through the Wildlife Computers portal to obtain diving and surfacing data as well as Fastloc-GPS locations from the SPLASH10-F tag. Fastloc-GPS location data were filtered by removing locations with residual values greater than 35 (Dujon et al. 2014) and those with time errors >10 seconds. For two of the tagged individuals (both melon-headed whales), most of the Argos locations were more than 1 hour from MFAS transmissions. To better allow for assessing exposure of these individuals we undertook a preliminary assessment of a Bayesian switching state-space model (SSSM, R package *bsam* v. 1.1.2, see Jonsen et al. 2005) to process the filtered Argos locations, producing one SSSM location every hour.

Dive statistics (dive rates, percentage of time in surface periods, dive depths, dive durations) were calculated separately by day and night, given known diel differences in diving behavior for the species tagged (Baird 2016; West et al. 2018), and for three periods of time, corresponding to the periods before, during, and after MFAS use. The duration of these periods was variable depending on the duration of tag deployments, their timing relative to MFAS transmissions, and the length of the period of MFAS transmissions, each of which differed among individuals (see results). As there are often gaps in behavior data obtained through Argos (i.e., periods of time for which there is no information on either diving or surfacing), for each of the three periods we determined the percentage coverage to allow for an assessment of how robust comparisons are among the three periods. This was calculated by summing the durations of all dives and surface periods (referred to as “days surfacing/dive data) and dividing this by the total span of time (referred to as the "duration overall"). Preliminary examination of dive depth and duration data indicated they were non-normal (not shown), thus tests of significance for differences in dive depths and durations for the three periods used a Kruskal-Wallis test. Given how dive rates and percentage of time at the surface were calculated (i.e., single values for each of the three periods), no statistical comparisons were made.

A pseudotrack was developed with a straight line between locations, using GPS locations (for the SPLASH10-F tag) or the Douglas-filtered Argos locations. Positions for each dive and surfacing period were interpolated along this track and the time and location information from interpolated locations were used to determine moon-illuminated fraction (to assess potential effects of lunar cycle, see Owen et al. 2019) and estimate bottom depth for each dive, to allow for an assessment of whether those factors influenced diving patterns. Moon-illuminated fraction (i.e., the fraction of the lunar disk that is illuminated at local midnight) was determined with the r-package *oce* v. 1.1-1 (Kelly and Richards 2016). For individuals with the largest sample size of both dive data and exposure calculations (i.e., GmTag152 and SbTag018) within the "during SCC" period, selected dive statistics were compared during blocks of MFAS use and periods between MFAS blocks. For the purposes of the percentage of time spent in surface blocks by day/night, surface periods that spanned sunrise or sunset were split with time allocated to either day or night as appropriate.

3.3 Exposure Analysis

Analyses were undertaken to be consistent with previous analyses of satellite tag data (Baird et al. 2014, 2017b). The basic method for estimating RL for tagged individuals requires: 1) the locations of ships transmitting MFAS (provided as standard data products from PMRF); 2) times of sonar transmissions (obtained from passive acoustic monitoring by PMRF range hydrophones); and 3) time and estimated location for each tagged animal position (using filtered Argos, Fastloc-GPS, or estimated locations from the SSSM) at which exposures were estimated to occur (Baird et al. 2014, 2017b). Analyses were undertaken and data presented in a way to ensure that no classified information was revealed. However, this necessarily resulted in greater uncertainty in terms of MFAS operations. For example, sources were assumed to have no directionality in azimuth angles, and only limited directionality in elevation angles by the propagation model (nominally +/- 45 degrees from horizontal) for the analysis.

Tagged animal locations were obtained intermittently and irregularly based on the behavior of tagged individuals and other factors such as the timing and location of satellites. Only animal locations where the time difference between the sonar transmission and animal tag update was less than 60 minutes were used for estimating RLs. Potential animal movement over this time difference was not considered in the current analysis, which was done specifically to be consistent with prior analyses (Baird et al. 2014, 2017b). We acknowledge that there is considerable three-dimensional variability in MFAS sound fields and to address this we modelled sound pressure levels (SPLs) to estimate RLs at two different depths and attempt to account for positional uncertainty in tagged animal locations. In terms of depth, we estimated RLs near the surface (10 m ± 5 m) for all individuals, as well as species-specific typical dive depths (also +/- 5 m), based on data collected for these species in Hawaiian waters (see Baird

2016; West et al. 2018). The deeper dive depths used in this analysis for each species were: rough-toothed dolphins – 50 m; melon-headed whales – 200 m; and short-finned pilot whales – 500 m. The depth of the MFAS source was fixed as the nominal depth of the sonar dome of the MFAS ship. The primary U.S. Navy surface-ship sonar system used at PMRF, AN/SQS-53C sonar, has a nominal source level of 235 dB at a center frequency of approximately 3 kilohertz (U.S. Department of the Navy 2013).

Variability associated with animal location accuracy estimates for the ARGOS satellite location classes (LC3, LC2, LC1, LC0, LCB and LCA) was explicitly integrated into RL estimates. Specific location class accuracies (from Costa et al. 2010) utilized were: LC3 – 0.49 kilometers (km), LC2 – 1.01 km, LC1 – 1.20 km, LC0 – 4.18 km, LCA – 6.19 km, and LCB – 10.28 km. For each tagged animal location, 1,000 estimated RLs were calculated for both near-surface and deeper dive depths at evenly distributed positions along a single radial from the MFAS source location through the estimated location with the radial length on either side of the location equal to the distance associated with the location code accuracies noted above. The RL at each of these 1,000 locations for each depth was estimated using the parabolic equation propagation model Peregrine (Heaney and Campbell 2016). For example, with LC3 locations, 1,000 estimated RLs were calculated at 10 m and either 50, 200, or 500 m depths (for rough-toothed dolphins, melon-headed whales or short-finned pilot whales, respectively) along a two-dimensional radial extending from the tagged animal location 0.49 km towards and 0.49 km away from the vessel using MFAS. In addition, RLs for each tagged animal location often were calculated for more than one MFAS exposure if there were MFAS transmissions within the 1-hour time window both before and after the tagged animal location was obtained, each with corresponding distance between the MFAS transmitting vessel and the tagged animal location. For example, for the first location of GmTag153 when there was a MFAS transmission within an hour, two RLs (and associated distances) were calculated, for a MFAS transmission 20 minutes prior to the tagged animal location, and one for a transmission 34 minutes after the tagged animal location. For each set of estimated RLs, we calculated the mean, median, standard deviation, minimum, and maximum values and compared values to assess how variable the estimates were.

For the SSSM locations, output from the *bsam* model also includes a median (50 percent) location value. The difference between the predicted locations and the 50 percent locations were used in the exposure modeling to bound the 1,000 estimates RLs as noted above. We should note that we consider this use of SSSM locations for RL estimates to be a preliminary assessment of the approach to address long temporal gaps in tag data, and future analyses should consider a broader suite of methods and more fully explore estimated errors associated with SSSM locations.

We chose to not provide estimated RLs for certain situations, where there were known factors related to the statistical distribution of results that could lead to unrealistic or unrepresentative conclusions. When the distribution of RLs is not unimodal and has a large variation in terms of the differences between the maxima and minima and/or standard deviation, it is difficult to put single numbers on the estimated RL with any confidence. An example of this could be a bimodal distribution where one peak of estimates are near 120 dB with a second similar peak at near

145 dB, which could have very similar mean and median values (i.e., 132 dB) that do not represent the actual levels at all. Reporting this as either 120 or 145 dB also seems inappropriate. Also, when the estimated RL is near ambient noise levels and signals were thus expected to be inaudible to focal whales, we chose to not provide estimates. The cutoff value utilized for reporting RLs was based upon the Wenz curve for the upper limit of sea state noise around 3 kilohertz of 70 dB re 1μPa^2/Hz (Greene 1995).

4. Results

Data were obtained from seven tags from three different species that generally overlapped with three different SCCs (Table 1, 2). MFAS was used both on the Barking Sands Tactical Underwater Range (BARSTUR) and the Barking Sands Underwater Range Extension (BSURE) portions of PMRF. MFAS use varied considerably among the three different SCCs, in terms of the overall span during which MFAS was used (approximately 6 to 57 hours) and the amount of MFAS use within each period (Table 1). The August 2018 SCC was cut short due to the forecasted approach of Hurricane Lane; thus MFAS was used only for a period of approximately 1 hour over a 6-hour span, while in the August 2016 SCC, MFAS was used for approximately 27 hours over a 57-hour span.

For SCCs that were not cut short there are typically dozens of separate estimated RLs for satellite tagged individuals. Summary statistics for these results are provided in Tables 3 and 4, and maps showing filtered locations before, during and after MFAS periods are represented in Figures 1 through 5, with information presented on the estimated median RLs at the start and end of exposures along with the maximum estimated RLs received on the animals' track. For one of the three species, melon-headed whales, there were only three locations within 1 h of MFAS use. Therefore, an exploratory analysis was done to apply a continuous movement model (SSSM) to the melon-headed whale data only.

4.1 Short-finned pilot whales

For short-finned pilot whales, RLs were estimated for two individuals tagged in the same group in February 2016 that were thought to be either from a pelagic or eastern main Hawaiian Islands community (GmTag152, GmTag153), as well as one individual tagged in August 2018 from the western main Hawaiian Islands resident community (GmTag214; Table 2). The two short-finned pilot whales tagged in February 2016 included one individual that was either an adult female or small sub-adult male (GmTag152, based on relative size noted in the field as well as dorsal fin morphology), and one individual that was an adult male (GmTag153). The distance between the two individuals when locations were received during the same satellite overpass (median=1.62 km) indicate they were acting in concert. These individuals were tagged on PMRF but moved off the range to the northeast prior to the start of the SCC. Estimated ranges from the tagged individuals to the MFAS source over the entire period of exposure were from 44.3 to 145.5 km (Table 3). At the start of the SCC, the individuals were approximately 67 km east of PMRF with estimated median RLs of approximately 138 to 140 dB. Both generally moved east away from the range (to a maximum of approximately 117 km from PMRF) for the first approximately 24 hours of MFAS use, then moved west and southwest to an area approximately 33 km east of the range (Figure 1, Figure 2). This westward movement brought the tagged individuals from approximately 127 km from the MFAS source to approximately 44 km from the MFAS source, with an increase in estimated median RLs from approximately 122 dB to 145 dB. After the end of the SCC, the tagged whales remained off the range for approximately 24 hours, moved onto the northern part of the range for 7.5 hours, and then continued movements in offshore waters to the east of the range until the end of the tag transmissions. Received level estimates for the two individuals for all exposures were generally similar (Table 3).

Table 1. Characteristics of hull-mounted MFAS used for Submarine Command Courses used in received level estimation.

Period	Span of hours from first to last MFAS use	Sum of blocks of hours of ship MFAS use	No. of blocks of MFAS use during SCC	Mean (SD) length of sonar blocks (hours)	Mean (SD) gap between MFAS blocks (hours)	Tagged animals with RL estimates
16–19 Aug 2016	56.92	27.27	27	1.01 (0.46)	1.58 (1.31)	GmTag152, GmTag153, SbTag017, SbTag018
15–18 Feb 2017	43.02	12.72	18	0.71 (0.55)	3.12 (2.87)	PeTag025, PeTag026
22 Aug 2018*	5.98	1.02	3	0.34 (0.43)	2.50 (1.60)	GmTag214

*SCC terminated early due to forecasted approach of Hurricane Lane. Gm=*Globicephala macrorhynchus* (short-finned pilot whale); Pe=*Peponocephala electra* (melon-headed whale); Sb=*Steno bredanensis* (rough-toothed dolphin).

Table 2. Details on odontocetes with tag data that overlap MFAS exposure for which received levels were calculated.

Tag ID	Date tagged (HST)	Age/sex	Encounter number	Population	Comparisons in relation to MFAS exposure
GmTag152	13 Feb 16	Adult female or sub-adult male	2	Pelagic or eastern community	Argos, dive
GmTag153	13 Feb 16	Adult male	2	Pelagic or eastern community	Argos, dive
GmTag214	19 Aug 18	Sub-adult male	1	Western community residents	Fastloc-GPS, dive
PeTag025	13 Aug 17	Adult unknown	3	Likely Hawaiian Islands	Argos, 1-hour SSSM locations
PeTag026	13 Aug 17	Adult unknown	3	Likely Hawaiian Islands	Argos, 1-hour SSSM locations
SbTag017*	14 Feb 16	Adult unknown	3	Kaua‘i/Ni‘ihau residents	Argos, dive
SbTag018*	14 Feb 16	Adult unknown	3	Kaua‘i/Ni‘ihau residents	Argos, dive

Encounter numbers were consecutive throughout day. Gm=*Globicephala macrorhynchus* (short-finned pilot whale); Pe=*Peponocephala electra* (melon-headed whale); Sb=*Steno bredanensis* (rough-toothed dolphin). *Although tagged in the same group, these individuals did not act in concert during the period of overlap (median distance apart=11.9 km, maximum=52.4km).

Table 3. Summary of MFAS exposure modelling for satellite-tagged individuals.

Tag ID	# locations within period MFAS used	# locations with estimated RLs	# exposures with estimated RLs	Range of distance to MFAS (km)	Range of estimated mean RL at 10-m depth (dB re 1μPa RMS)	Minimum estimated RL at 10-m depth (dB re 1μPa RMS) (Min/SD/LC)	Maximum estimated RL at 10-m depth (dB re 1μPa RMS) Max/SD/LC
GmTag152	34	25	27	44.4–145.5	122.6–142.8	120.2 / 1.3 / LC2	148.1 / 1.1 / LC0
GmTag153	44	22	25	44.3–127.6	125.4–145.0	123.9 / 0.8 / LCA	147.3 / 2.6 / LCB
GmTag214	6	6	6	27.2–52.4	126.0–133.3	112.9 / 4.3 / LC2	133.3 / 0.6 / GPS
PeTag025	1	1	1	126.3	83.3	73.6 / NA / LCB	88 / 3.3 / LCB
PeTag026	2	2	2	132.9–141.9	NA**	NA**	NA**
SbTag017	34	6	7	37.2–68.7	139.2–146.5	137.1 / 1.0 / LC2	148.3 / 0.5 / LC1
SbTag018	36	22	25	21.2–67.3	134.6–151.4	130.2 / 1.7 / LC1	155.9 / 1.1 / LC1

LC=location class; GPS=Global Positioning System; **no estimated RL values for Pe026 at 10 m depth above 70 dB

Table 4. Comparison of metrics of MFAS RL estimates at 10 m and at species-specific diving depths.

Tag ID	Grand means of estimated RLs at 10-m depth (dB re 1μPa RMS)				Grand means of estimated RLs at species-specific diving depth* (dB re 1μPa RMS)			
	Min RL	mean RL	median RL	Maximum RL	Min RL	Mean RL	Median RL	Maximum RL
GmTag152	132.4	133.6	133.4	134.8	114.3	119.8	119.0	124.1
GmTag153	135.0	136.7	136.4	138.8	116.7	122.8	121.7	127.4
GmTag214	124.5	129.3	128.8	130.5	122.4	127.3	126.4	129.2
PeTag025	73.6	83.3	82.0	88.0	75.0	84.2	83.8	90.0
PeTag026	NA**	NA**	NA**	NA**	71.9	75.5	75.3	78.2
SbTag017	141.5	143.6	143.6	144.2	128.1	131.9	131.8	132.6
SbTag018	141.3	144.0	143.8	145.7	122.8	134.4	133.8	136.8

*500 m for short-finned pilot whales, 200 m for melon-headed whales, 50 m for rough-toothed dolphins; **no estimated RL values for Pe026 at 10 m depth above 70 dB

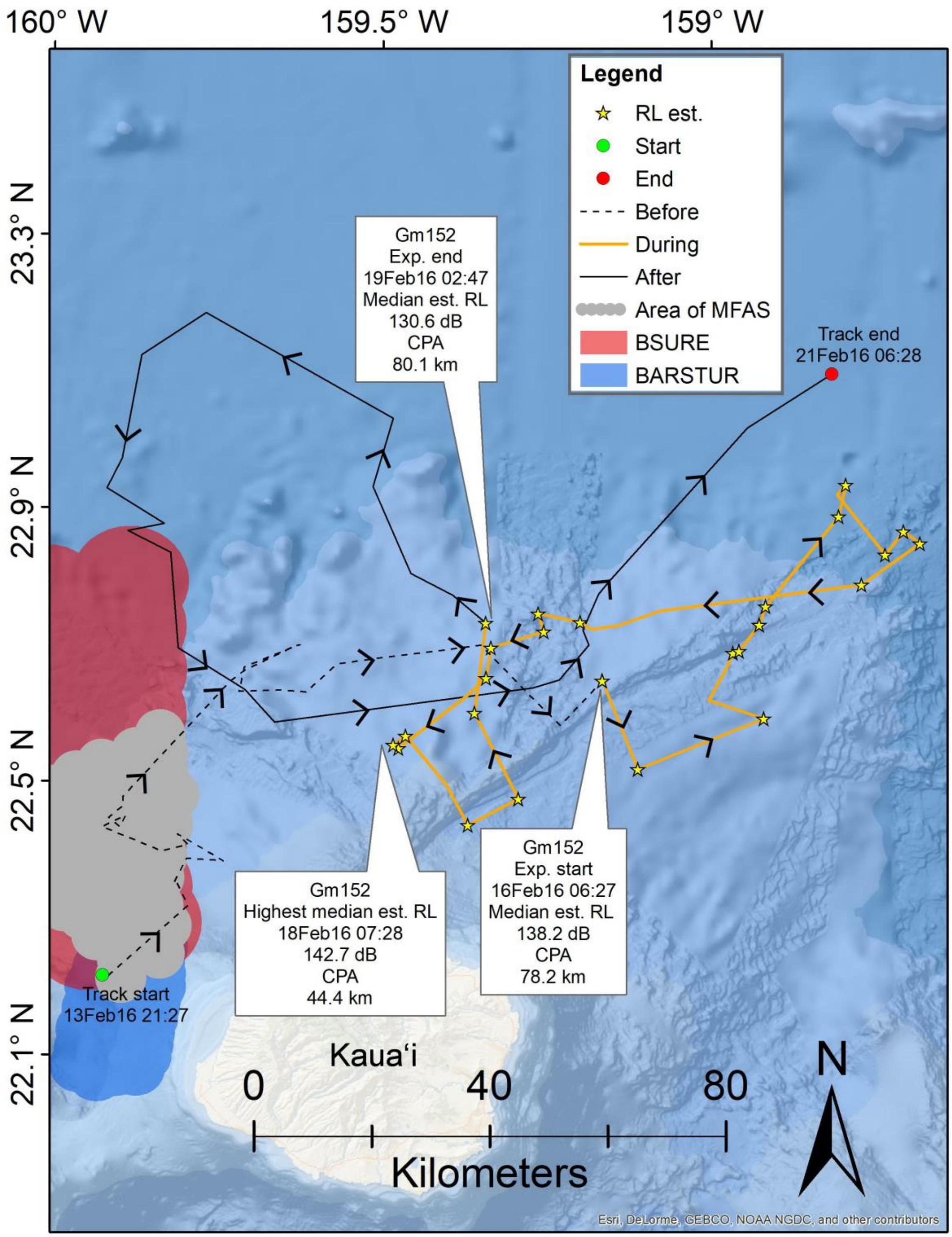

Figure 1. Filtered locations and interpolated track of short-finned pilot whale GmTag152 from 13 to 21 February 2016 prior to, during, and shortly after the end of a Submarine Command Course. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times are shown in GMT.

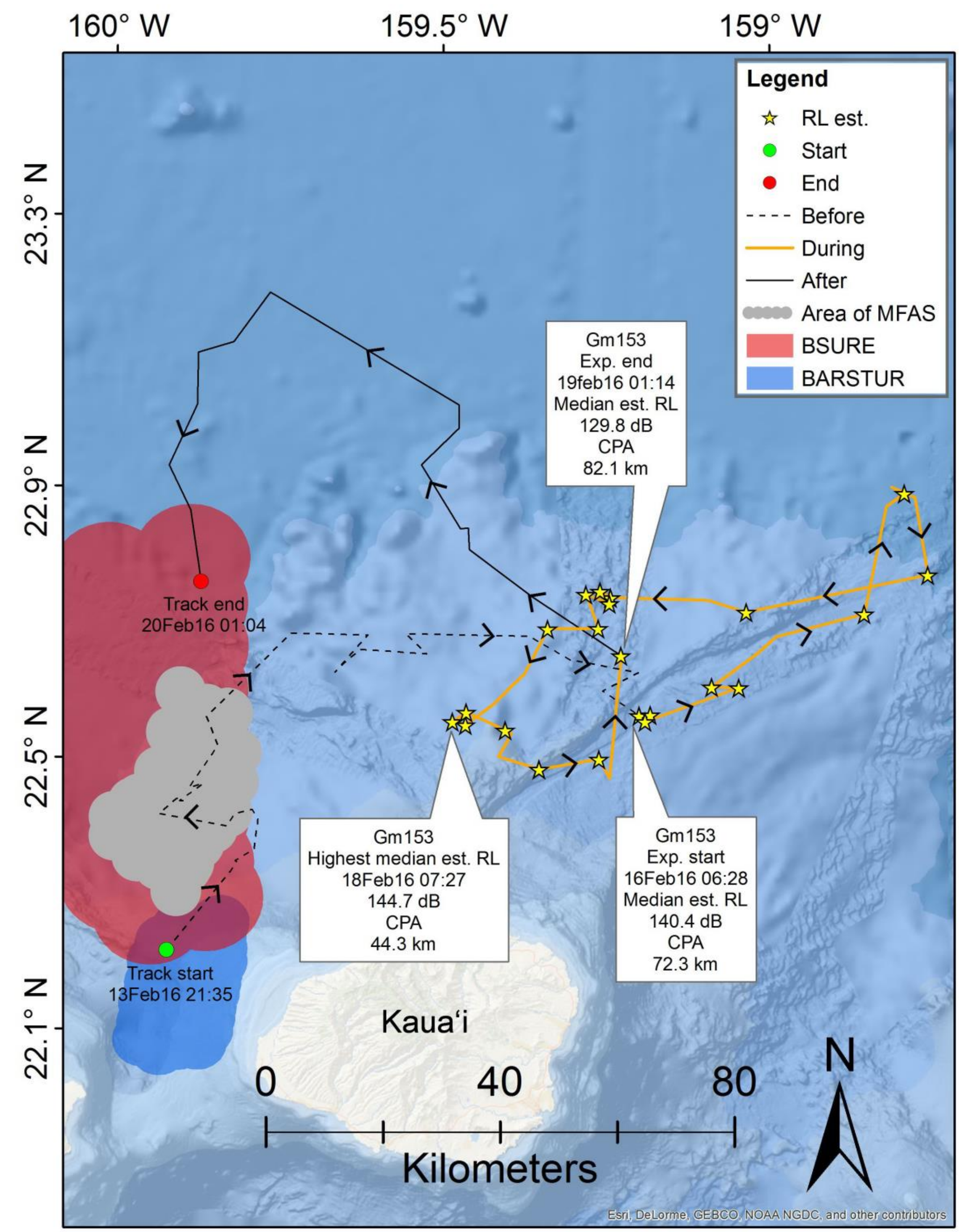

Figure 2. Filtered locations and interpolated track of short-finned pilot whale GmTag153 from 13 to 20 February 2016 prior to, during, and shortly after the end of a Submarine Command Course. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times are shown in GMT.

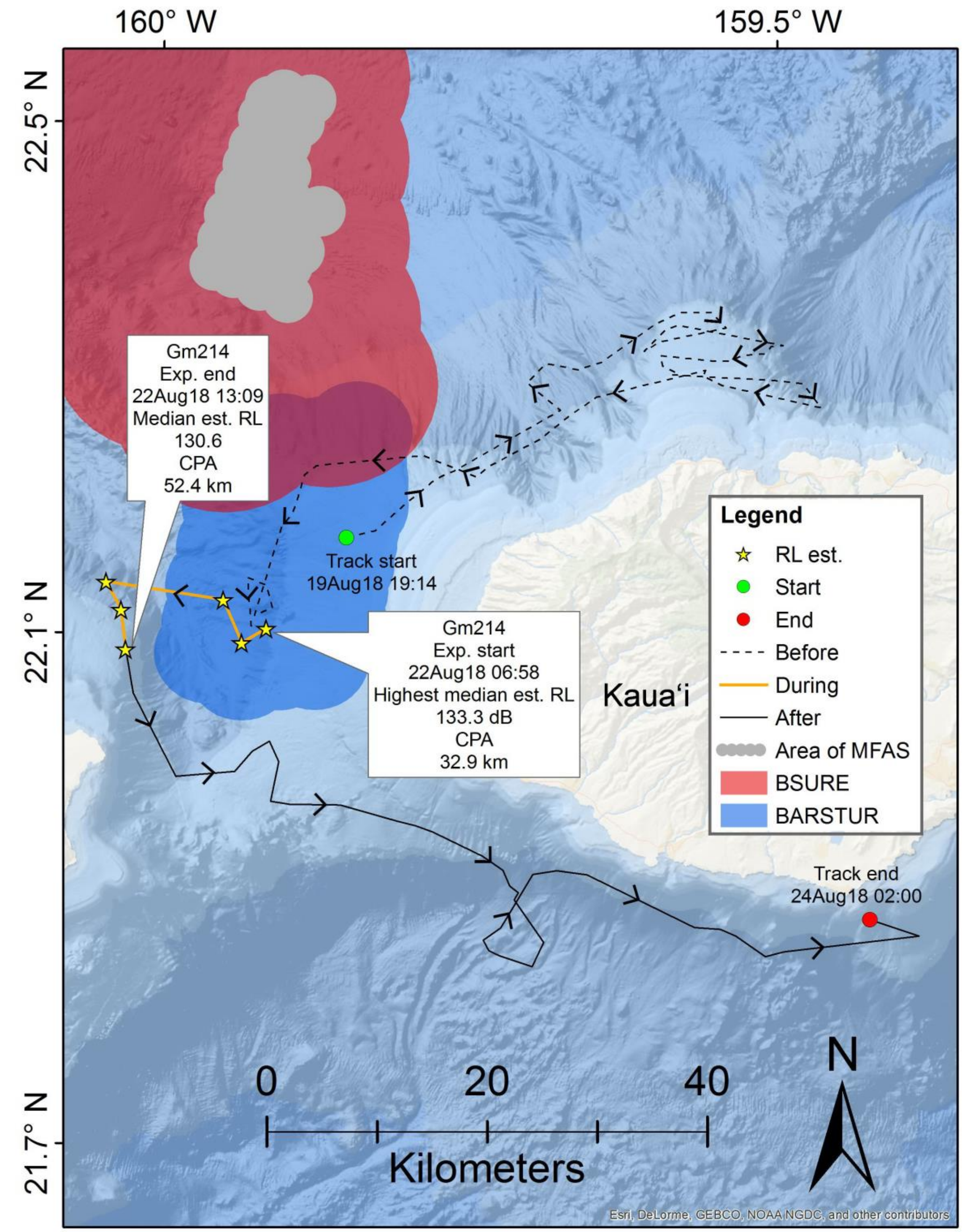

Figure 3. Filtered locations and interpolated track of short-finned pilot whale GmTag214 from 19 to 24 August 2018 prior to, during, and shortly after the end of a Submarine Command Course that was cut short due to the forecasted approach of Hurricane Lane. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times are shown in GMT.

A comparison of minimum, mean, median, and maximum RL estimates at 10 m depths suggest that all three measures are similar (Tables 3, 4). Estimated RLs at 500 m depth were approximately 13 to 15 dB lower than those at 10 m depth (Table 4). Variability of estimates at 500 m depth was greater than at 10 m depth, based on the range between minimum and maximum RLs (Table 4).

The two individuals tagged in February 2016 were outside of the range of the Kauaʻi Mote for all but the very beginning of the deployment periods, thus dive and surfacing data were obtained through the Argos system. The percent coverage of dive and surfacing data for each of the three sonar exposure periods (i.e., before, during, and after MFAS exposure) for these two individuals ranged from 54.2 percent (before exposure for GmTag153) to 100 percent (after exposure for GmTag152; Table 5). The two individuals showed generally similar behavior at night, in terms of dive rates, percentage of time in surface periods, and median dive depths and durations, although they differed considerably in terms of day-time diving behavior. These differences in day-time patterns were found in the before- and after-exposure periods as well as during the MFAS exposure period (Table 6), and thus did not appear to be related to MFAS exposure. During the day, GmTag152 had relatively low dive rates (0.78 to 1.53 dives/hour) and spent a large proportion of its time (69–82 percent) in surface periods, while GmTag153 had relatively high dive rates (1.57 to 7.34 dives/hour) and spent less time (29–77 percent) in surface periods. Day-time dives that were documented for GmTag152 were both long (13–15 minutes) and deep (425–570 m), while GmTag153's dives were shorter and shallower (Table 6). Although there were statistically significant differences in night-time dive depths and durations among the three sonar exposure periods (before, during, and after MFAS), these did not change in a consistent fashion for both GmTag152 and GmTag153 (Table 6). Moon-illuminated fraction varied significantly over the three periods (Kruskal-Wallis one-way ANOVA, $p < 0.001$), with a general increase over time. Given the increase in moon-illuminated fraction we would expect an increase in dive depths and durations over the three periods. Such increases were found for night-time dive depth and duration for GmTag152 but not for GmTag153.

Individual GmTag214 was tagged on PMRF on 19 August 2018 and moved east of the range for approximately 36 hours before returning onto PMRF prior to the start of the SCC. GmTag214 was on the south end of PMRF at the start of the SCC at a range of 32.9 km from the MFAS source with an estimated median RL of 133.3 dB. Over the next 6 hours, GmTag214 moved off the range to the west into an area with estimated median RLs of 124.4 to 127.3 dB. At the end of the SCC, this individual was 52.4 km from the MFAS source with an estimated median RL of 130.6 dB (Figure 3). This SCC was terminated early due to the forecasted approach of Hurricane Lane, although at the time of MFAS exposures Lane was several hundred kilometers distant. After the end of the SCC GmTag214 remained south and east of PMRF, remaining associated with the southern slope of Kauaʻi.

GmTag214 remained within range of the Motes for most of the deployment period, thus benefiting from increased throughput of dive and surfacing data. For this individual there was 100 percent coverage of dive and surfacing data for the before- and during-sonar exposure periods, and 98.9 percent for the period post-sonar exposure. Because of the shortened span of the August 2018 SCC, all of the dive data obtained during the sonar exposure period were during the night; thus, analyses were limited to night-time periods for all the before-, during-, and after-exposure periods. Dive depths did vary significantly over the three sonar exposure periods (Kruskal-Wallis one-way ANOVA, $p = 0.036$), but there was no significant difference in dive durations (Table 6). Moon-illuminated fraction varied significantly over the three periods (Kruskal-Wallis one-way ANOVA, $p < 0.001$), with a general increase over time. Given the increase in moon-illuminated fraction we would expect an increase in dive depth and durations over the three periods. Such an increase was found for night-time dive depth but not for dive duration.

Table 5. Summary of dive and surface data coverage for periods before, during and after MFAS exposure.

	Before MFAS use	During MFAS use	After MFAS use	Comments
GmTag152				
Duration overall (days)	2.35	2.85	4.07	
Days surfacing/dive data	2.00	2.75	4.07	
Percentage coverage	85.3	96.5	100.0	
GmTag153				
Duration overall (days)	2.03	2.62	4.05	
Days surfacing/dive data	1.10	1.93	3.80	
Percentage coverage	54.2	73.7	93.9	
GmTag214				
Duration overall (days)	2.51	0.25	5.6	Night-time only during MFAS
Days surfacing/dive data	2.51	0.25	5.54	
Percentage coverage	100.0	100.0	98.9	
PeTag026				
Duration overall (days)	1.04	2.74	1.32	
Days surfacing/dive data	0.11	0.57	0.58	
Percentage coverage	10.6	20.8	43.9	
SbTag017				
Duration overall (days)	1.40	2.97	4.45	
Days surfacing/dive data	1.35	2.61	2.96	
Percentage coverage	96.9	88.0	66.4	
SbTag018				
Duration overall (days)	1.38	2.43	11.59	
Days surfacing/dive data	1.25	2.14	7.88	
Percentage coverage	90.4	88.4	68.0	

Table 6. Comparison of short-finned pilot whale dive and surfacing parameters corresponding to periods before, during, and after MFAS exposure. For GmTag152 and GmTag153 dives were classified as periods where the animal dove to 30 m or more. For GmTag214 dives were classified as periods where the animal dove to 50 m or more.

Dive parameter Individual	Before MFAS Use	During MFAS Use	After MFAS Use	Significance
Night-time dive rate (dives/hour)				
GmTag152	3.95	3.25	3.04	
GmTag153	3.99	4.48	3.36	
GmTag214	3.39	2.67	2.69	
Percentage time in surface periods at night				
GmTag152	33.42	36.66	39.00	
GmTag153	29.23	33.00	41.76	
GmTag214	36.84	53.67	51.45	
Day time dive rate				
GmTag152	1.53	0.78	0.94	
GmTag153	5.94	7.34	1.57	
Percentage time in surface periods during day				
GmTag152	69.02	82.20	76.06	
GmTag153	29.40	39.59	77.53	
Median dive depth night (m)				
GmTag152	228.7	293.5	322.0	P < 0.001*
GmTag153	310.5	235.5	351.5	P = 0.114*
GmTag214	331.3	487.5	511.5	P = 0.036
Median dive duration night (min)				
GmTag152	10.11	11.71	12.04	P < 0.001*
GmTag153	10.66	9.27	10.82	P = 0.005*
GmTag214	11.19	12.01	11.67	P = 0.541*
Median dive depth day (m)				
GmTag152	425.5	519.6	570.9	
GmTag153	48.0	40.0	55.5	
Median dive duration day (min)				
GmTag152	13.37	13.75	15.24	
GmTag153	6.13	3.97	6.53	

*Kruskal-Wallis one-way ANOVA

4.2 Rough-toothed dolphins

Two rough-toothed dolphins were included in the analyses. While these individuals were tagged in the same group on 14 February 2016 and appeared to remain associated for several hours after tagging, the overall distance between pairs of locations received during the same satellite overpass (median=11.8 km, maximum=52.4 km) suggest they were acting independently. The individuals were tagged on PMRF, and moved south off the range prior to the start of the SCC. SbTag017 was approximately 60 km from the MFAS source at the start of the SCC with an estimated median RL of 143.4 dB for the first exposure (Figure 4). This individual remained in an area where RLs could be estimated for approximately 12 hours after the start of the SCC, and then moved into an area off southwest Kauaʻi where it was not possible to estimate RLs for approximately 12 hours. The individual then moved back to the southwest and then north, and at the time of the last RL estimate had moved to the north in the direction of PMRF, moving into an area with slightly higher RLs (median estimated RL of 146.3 dB), at a distance of 46.5 km from the MFAS source. The maximum estimated RL for this individual at 10 m depth was 148.3 dB (standard deviation [SD] = 0.5 dB).

SbTag018 was approximately 50 km from the MFAS source at the start of the SCC, with an estimated median RL of 147.3 dB. This individual moved to an area west of PMRF (southwest of the area where the SSC was being undertaken) where it remained for approximately 40 hours, in an area with estimated median RLs ranging from 136.4 to 149.5 dB. After that time SbTag018 moved back onto PMRF and to the north in the direction of the MFAS source, with a closest point of approach of 21.2 km and an estimated median RL of 151.4 dB (Table 3). The maximum estimated RL for this individual was 155.9 dB (SD=1.1 dB) at 10-m depth and 147.2 dB at 50 m depth. For both SbTag018 and SbTag017 the mean and median estimated RLs were similar and both had low RL standard deviations, suggesting a Gaussian distribution.

Both individuals remained within range of the Kauaʻi Mote for much of the deployment period, and dive data were obtained for both individuals. The percentage coverage of dive and surfacing data obtained for SbTag017 for each of the three periods ranged from 66.4 percent to 96.9 percent (after- and before-sonar use, respectively; Table 5). The percent coverage of dive and surfacing data obtained for SbTag018 for each of the three periods ranged from 68.0 percent to 90.4 percent (after- and before-sonar use, respectively). No dives were documented during the day for either the before- or after-MFAS exposure periods for SbTag017, and only a single dive was documented during the day in the before- and during-sonar periods for SbTag018, thus comparisons were restricted to night-time periods (Table 7). Night-time dive depths and durations did differ significantly among the three sonar exposure periods for both individuals, but not in a consistent way (Table 7). For SbTag017, dive depths and durations increased during MFAS exposure, but showed an additional increase in the period after MFAS use. For SbTag018, dive depth and duration decreased during MFAS exposure, and then dive depth increased after MFAS use, while dive duration decreased further (Table 7). Dive rates and the percentage of time at the surface at night also varied for both individuals but not in a consistent way.

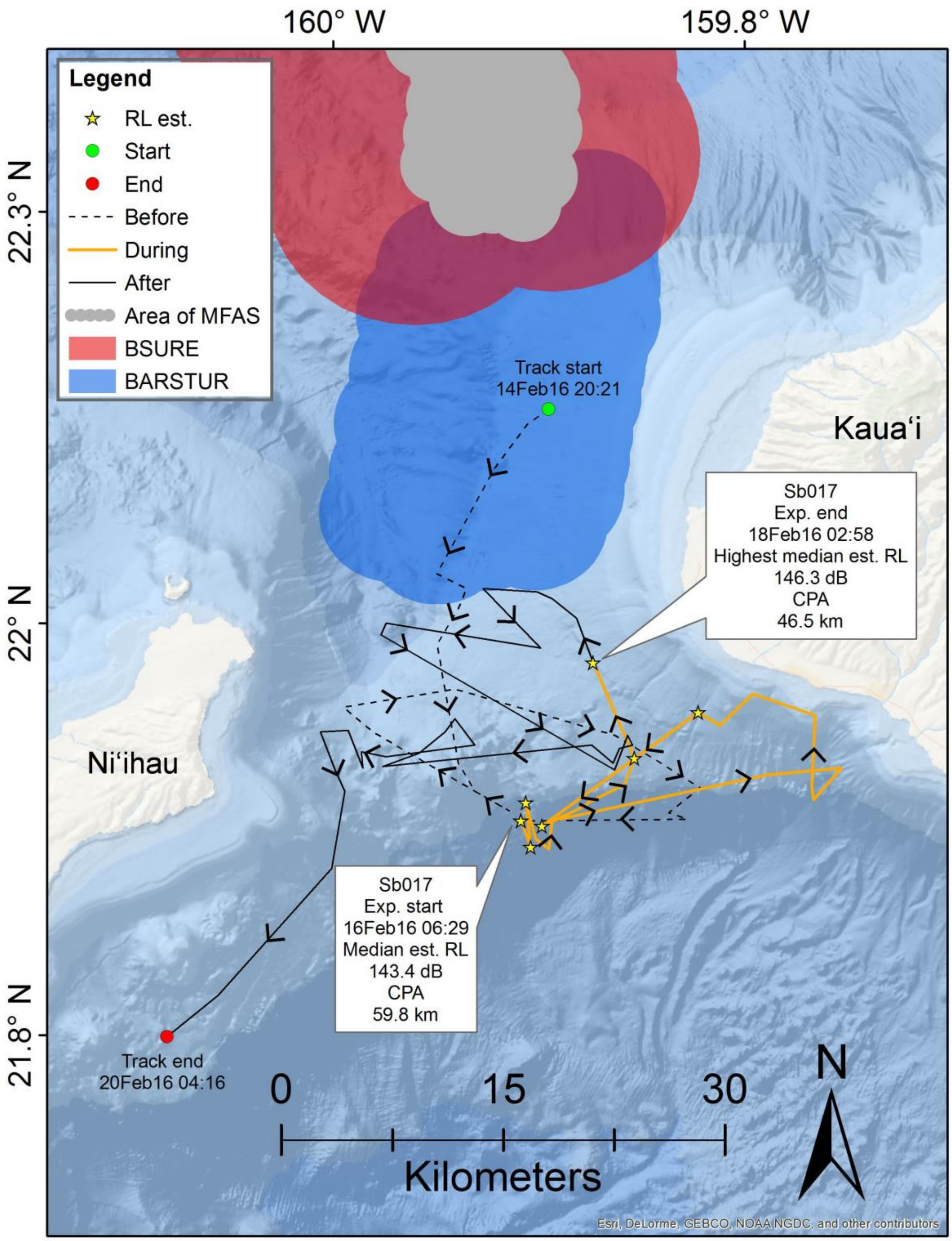

Figure 4. Filtered locations and interpolated track of rough-toothed dolphin SbTag017 from 14 to 20 February 2016 prior to, during, and shortly after the end of a Submarine Command Course. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times are shown in GMT.

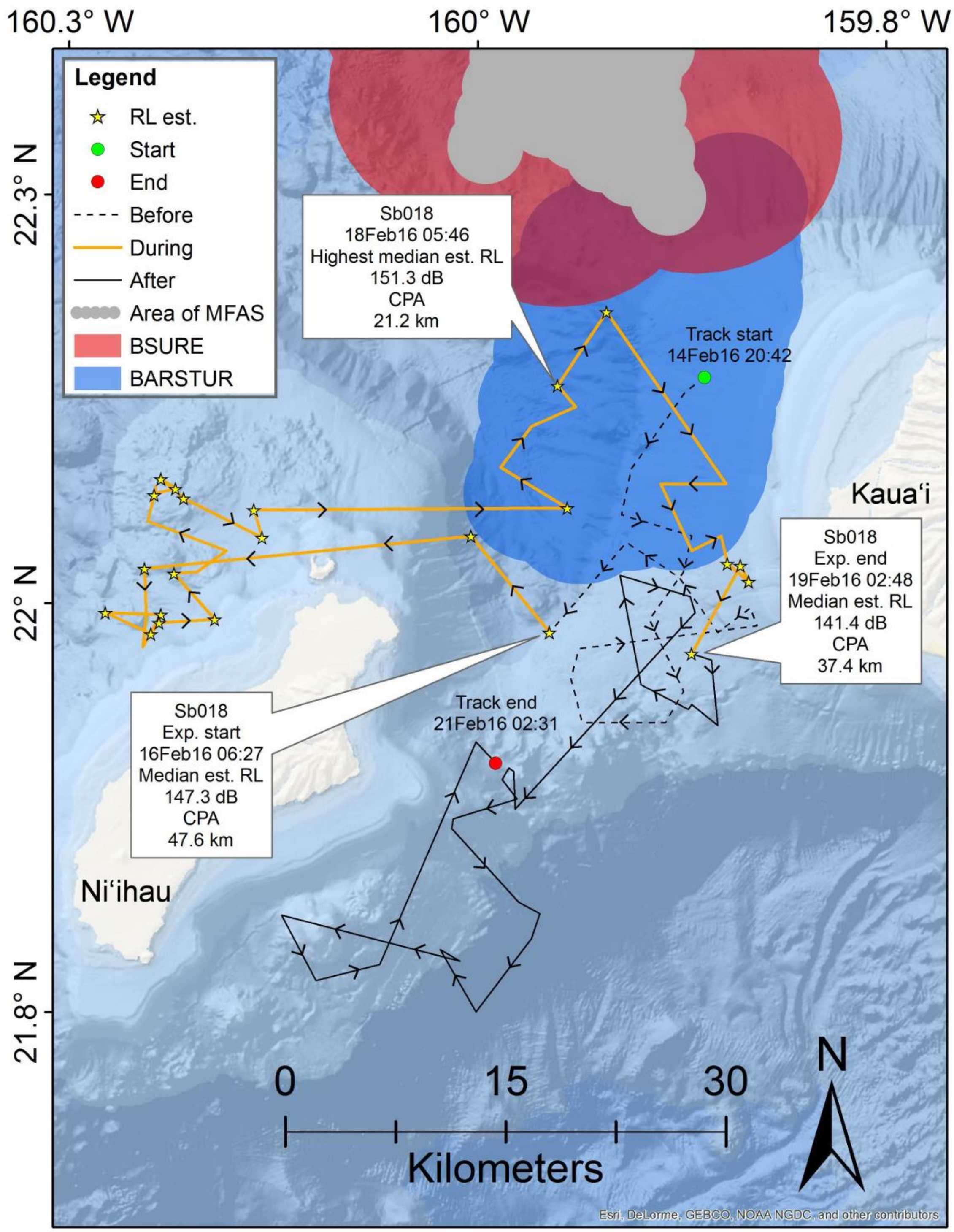

Figure 5. Filtered locations and interpolated track of rough-toothed dolphin SbTag018 from 14 to 20 February 2016 prior to, during, and shortly after the end of a Submarine Command Course. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times are shown in GMT.

Table 7. Comparison of rough-toothed dolphin dive and surface parameters corresponding to periods before, during and after MFAS exposure. Dives were defined as any periods where the individual went to or below 30 m in depth.

Dive parameter Individual	Before MFAS Use	During MFAS Use	After MFAS Use	Significance
Night-time dive rate (dives/hour)				
SbTag017	10.47	3.44	5.10	
SbTag018	7.87	9.27	4.13	
Percentage time in surface periods at night				
SbTag017	49.69	83.12	73.55	
SbTag018	49.34	44.14	77.11	
Median dive depth night (m)				
SbTag017	79.5	92.5	97.5	P < 0.001*
SbTag018	85.5	77.5	91.5	P < 0.001*
Median dive duration night (min)				
SbTag017	2.87	2.97	3.17	P = 0.005*
SbTag018	3.93	3.67	3.47	P < 0.001*

*Kruskal-Wallis one-way ANOVA

4.3 Melon-headed whales

Two melon-headed whales tagged in August 2017 were south of PMRF when surface-ship MFAS use began as part of the SCC. Distances between the two individuals when locations were received during the same satellite overpass for the period from tagging through the end of the SCC (median=1.7 km) suggest the two individuals were acting in concert. Ranges from the tagged individuals to the MFAS source were greater than 95 km and the individuals continued to move away from the MFAS source during the period of exposure. The propagation conditions for these two individuals was such that the source ships were on the north side of the Kaulakahi Channel with the whales approximately 100 km to 200 km distant on the south side of the channel. This geometry resulted in very challenging conditions for sound propagation modelling. PeTag025 had only a single Argos location available within 1 hour of MFAS transmissions while PeTag026 had nine Argos locations available, although only four of those had a path from the ship to the whale due to the island of Kaua‘i shadowing the whale from five of the ship transmissions. Further, only two of those four had mean estimated RLs above the cutoff value of 70 dB. PeTag025’s single Argos location had estimated RLs from 73.6 to 88 dB (Tables 3, 4) which is near the cutoff value of 70 dB. On the other hand, PeTag026 was located even farther away from MFAS transmissions with the grand means of all estimated RLs below the cutoff value of 70 dB at shallow depth (two were just below that threshold at 68.75 and 66.23 dB median and mean values), with the 200 m dive depth levels in the range of 72 to 78 dB (Tables 3 and 4).

Given the limited sample sizes, we used a switching state-space model to generate locations at 1-hour intervals during the period when MFAS was being used (Figure 6, Figure 7). Utilizing the continuous movement model resulted in PeTag025 having 10 estimated RLs at 10m depth over the 70 dB cutoff threshold, while PeTag026 had three estimated RLs. Table 8 provides summary details of the grand means of the estimated exposure metrics. Figures 6 & 7 provide spatial relationship of nominal SSSM track relative to estimated RLs in a similar manner to results shown in Figures 1 through 5. The quantitative results should be treated with caution as this was a preliminary utilization of one realization of a continuous time movement model with overly optimistic errors, and historical sound velocity profiles utilized in a difficult acoustic modeling scenario. One full depth estimated RL plot is shown in Figure 8 for the radial from the MFAS source to a distance of 140 km on the bearing towards the PeTag025 modeled location on 16 August 2017 at 0014GMT. Using the modeled location data, maximum estimated RLs at 10 m depth were 109.6 dB for PeTag025 and 81.0 dB for PeTag026 (Table 8). Estimated RLs were generally greater at 200 m depth than at 10 m depth (Table 8), likely due to the complex propagation characteristics in this situation (Figure 8).

The melon-headed whales were outside of the range of the Motes except at the very start of the tag attachment period. For PeTag026, there were some dive data obtained (Table 5) although over the 5.1-day span covering the three MFAS exposure periods there were only 1.27 days of dive and surface data. Of that, 64 percent was during day-time periods, although there were no day-time data for the before-MFAS exposure period. Given the known diel patterns in diving behavior for this species (West et al. 2018) analyses would have to be carried out separately for day- and night-time periods. We did not attempt to assess potential changes in diving behavior given the limited coverage during the three exposure periods.

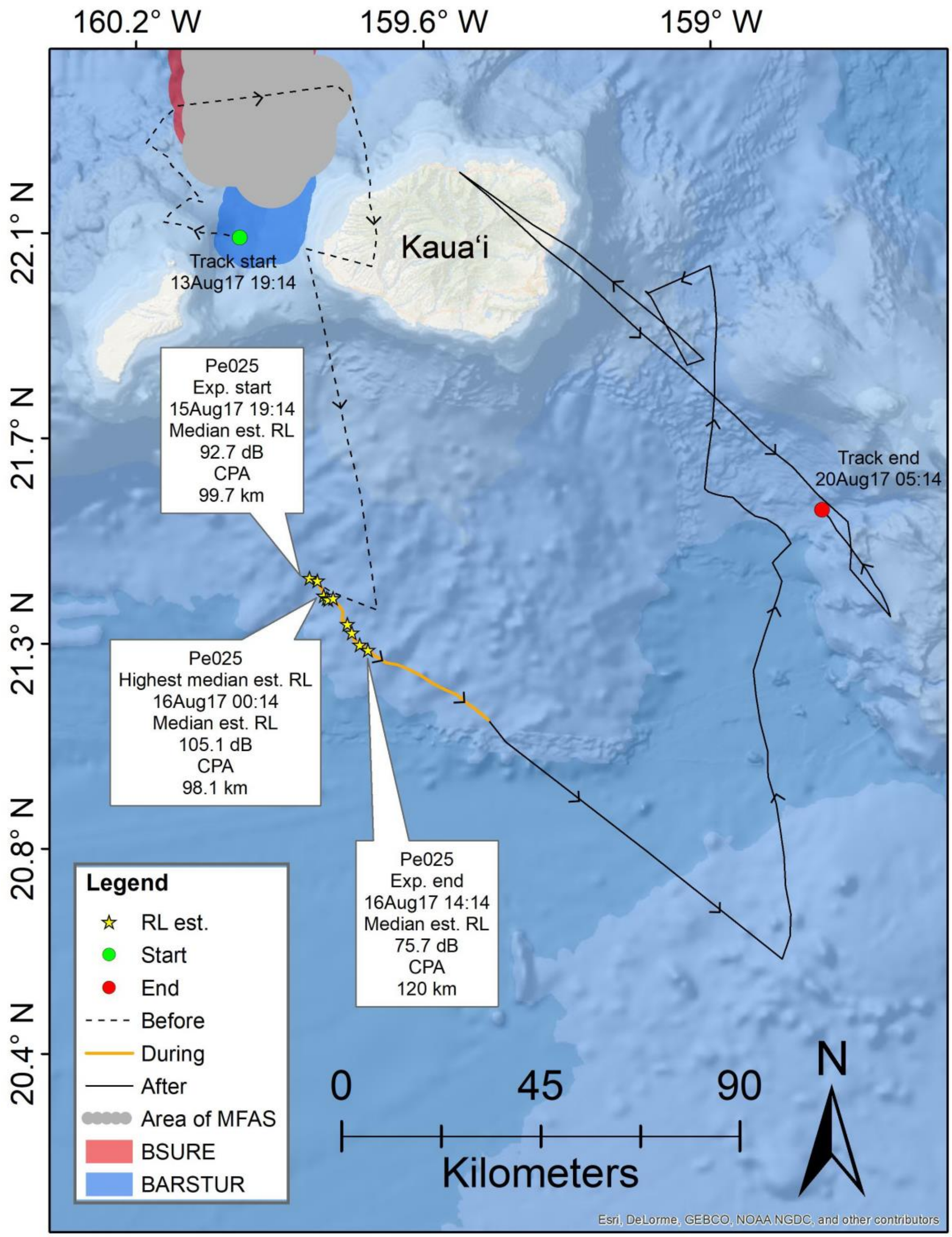

Figure 6. Filtered locations and interpolated track of melon-headed whale PeTag025 from 13 to 20 February 2017 prior to, during, and shortly after the end of a Submarine Command Course. Update positions shown are from a switching state space model producing locations every hour.

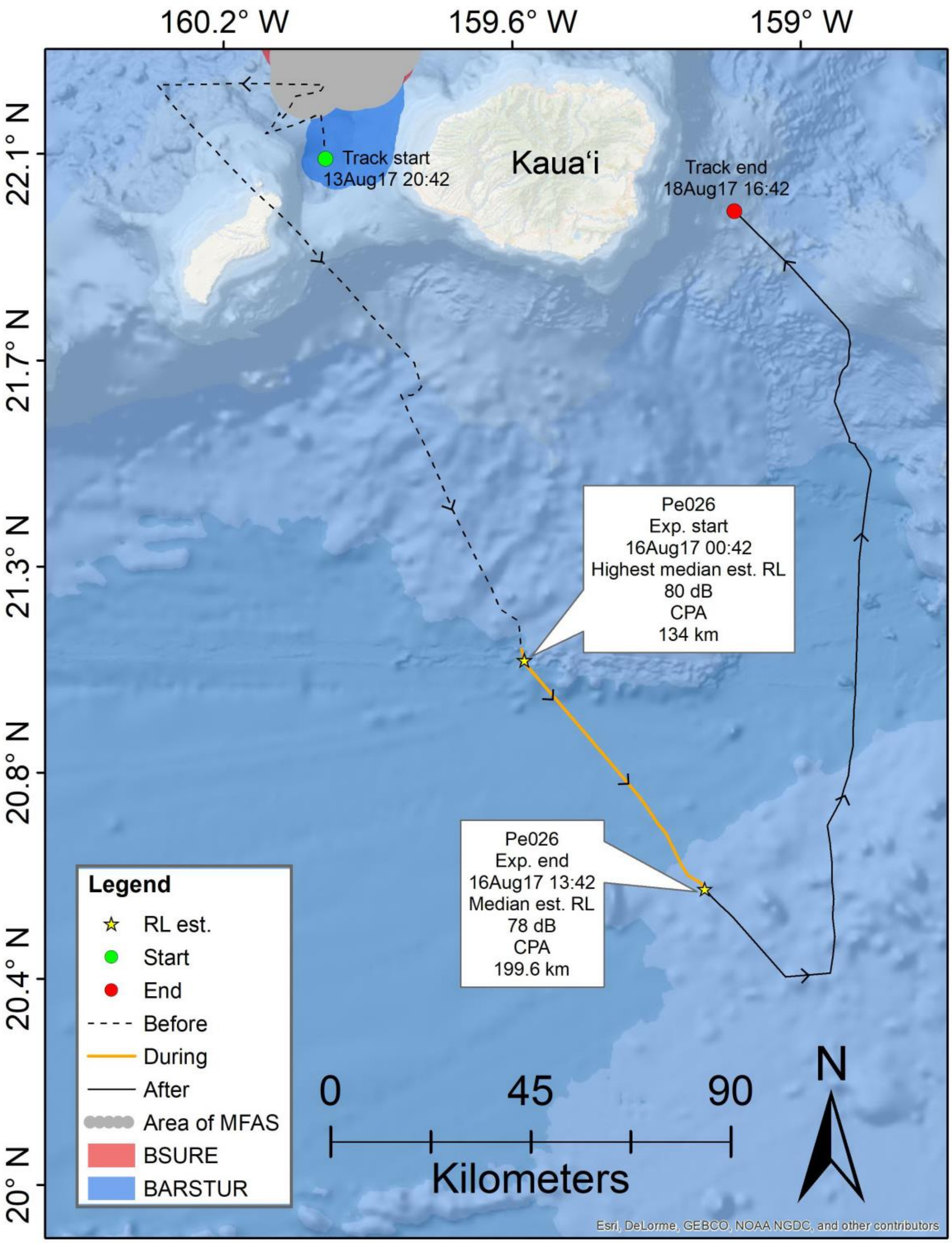

Figure 7. Filtered locations and SSSM whale locations during the period of MFAS exposure for melon-headed whale PeTag026 from 13 to 18 February 2017 prior to, during and shortly after the end of a Submarine Command Course. Estimated RLs (n=3, first two on top of one another) utilizing one (50% locations) realization of a SSSM producing locations every hour. Overly optimistic errors were utilized so RLs should be treated accordingly.

Table 8. Summary of MFAS modeling and comparison of metrics of MFAS RL estimates at 10 m and at 200 m for the switching-state space modeled positions of melon-headed whales.

Tag ID	Range of distance to MFAS (km)	Minimum estimated RL at 10-m (depth dB re 1µPa RMS)	Maximum estimated RL at 10-m depth (dB re 1µPa RMS)	Grand means of estimated RLs at 10-m depth (dB re 1µPa RMS)				Grand means of estimated RLs at 200-m depth (dB re 1µPa RMS)			
		Min/SD	Max/SD	Min RL	Mean RL	Median RL	Max RL	Min RL	Mean RL	Median RL	Max RL
PeTag025	95.1 – 142.2	59.8 / 4.3	109.6 / 3.0	75.7	88.2	86.8	92.4	82.4	95.3	94.3	98.8
PeTag026	133.9 – 199.6	65.1 / 2.2	83.4 / 1.8	70.4	76.5	76.1	77.7	77.7	84.9	84.3	86.1

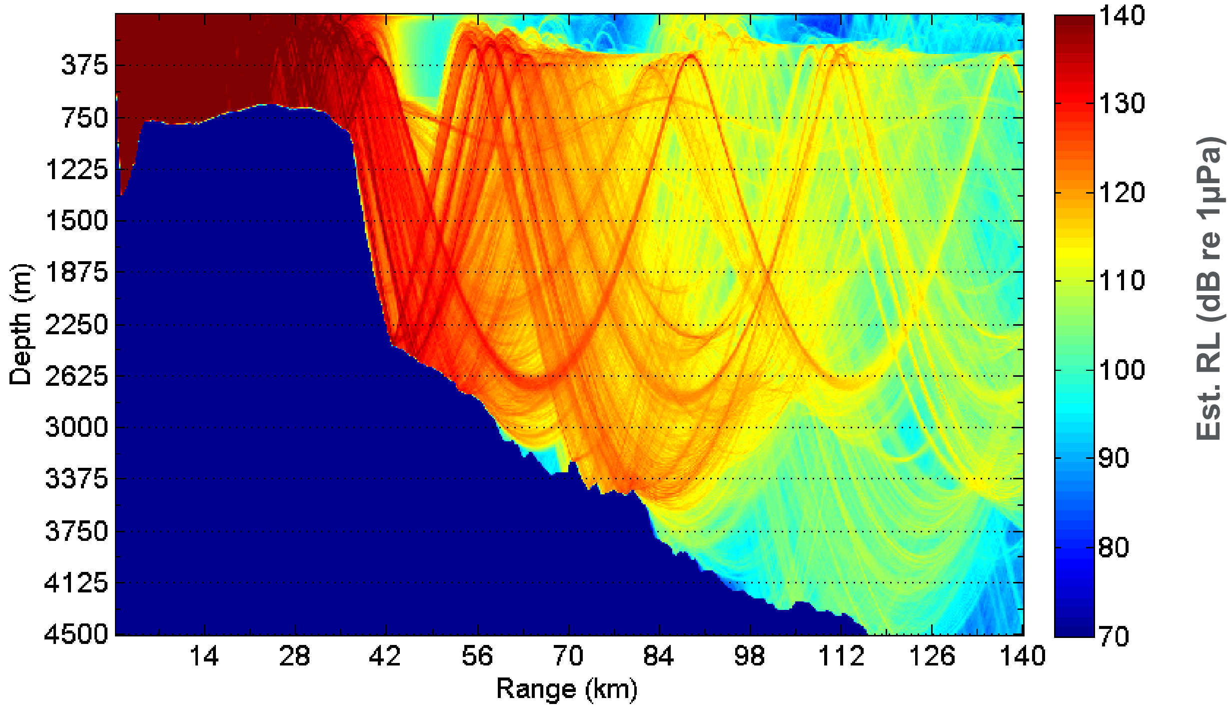

Figure 8. Peregrine propagation model estimated RL in the direction of one modeled SSSM location for PeTag025 on 08/16/2017 at 0014 GMT. This corresponds to the data shown in Figure 6 for the highest estimated median RL this whale received at the beginning of exposure, at a median distance to the whale of 98.1 km. The estimated RL is shown out to a distance of 140 km over the full depth of the ocean. The dark blue areas in the lower portion of the figure corresponds to the seafloor with the Kaulakahi Channel in the upper left at distances of approximately 6 to 40km from the MFAS source, with depths of under 1 km. The path from the source to the whale includes going over the shallower channel between the two islands which makes results much more sensitive to whale locations and actual vs modeled sound velocity profiles over the area.

5. Discussion and Conclusion

Previous studies examining behavioral reactions of odontocetes to MFAS have revealed responses at varying SPLs dependent on species, as well as considerable within-species variability, emphasizing the role of exposure context (Harris et al. 2018). The onset of avoidance responses by killer whales (*Orcinus orca*) varied between 94 and 164 dB for four different killer whale groups, with the mean response threshold of 142 dB (Miller et al. 2014). For Blainville's beaked whales (*Mesoplodon densirostris*) from a population that is regularly exposed to MFAS, 50 percent of individuals were predicted to respond at RLs of 150 dB, based on group estimates of vocal behavior during operations (Moretti et al. 2014). For long-finned pilot whales (*G. melas*), the estimated SPL with 50 percent of individuals predicted to respond was 178.6 dB (Antunes et al. 2014). Other case studies conducted at PMRF have also looked for behavioral responses from acoustically-tracked cetaceans resulting from MFAS exposures. Both Blainville's beaked whales and minke whales (*Balaenoptera acutorostrata*) occur in reduced numbers on PMRF during SCCs (Manzano-Roth et al. 2016; Martin et al. 2015), and maximum estimated RLs for minke whales ranged between 129.2 and 152.3 dB (Martin et al. 2017). Humpback whales (*Megaptera novaeangliae*) satellite tagged near the range were exposed to mean estimated RLs between 99.9 and 146.3 dB, with a change in dive behavior occurring in one animal at maximum levels of up to 158 dB (Henderson et al. 2019). The most recent Behavioral Risk Function developed by the U.S. Navy combined all odontocete behavioral response data (other than beaked whales and harbor porpoises), with an estimated SPL for 50 percent of individuals predicted to respond at 157 dB (U.S. Department of the Navy 2017). Our analyses provide additional case studies with both short-finned pilot whales and rough-toothed dolphins, as well as with melon-headed whales. The latter two species have not been subject to controlled exposure experiments, and the former species includes individuals from two different populations (resident and non-resident), providing an opportunity to examine potential reactions from individuals that likely have very different exposure histories. Our methods integrate movement data from satellite-tagged individuals with information on hull-mounted MFAS use to estimate exposure levels and assess whether individuals show large-scale avoidance of areas when exposed to MFAS (Baird et al. 2014, 2017a). Of the seven individuals for which we were able to estimate received levels, four had maximum RLs ranging from 133 to 148.3 dB. Only a single individual in our study, a rough-toothed dolphin (SbTag018), had a maximum RL exceeding 150 dB (155.9 dB, SD=1.1 dB). Thus individuals in our study were generally exposed at SPLs in the lower end of those known to result in behavioral responses in some other odontocetes.

One of our groups with two tagged short-finned pilot whales was exposed to estimated maximum received levels from MFAS of 147 and 148 dB, levels that in a closely related species, long-finned pilot whales, were unlikely to result in avoidance (Antunes et al. 2014). It is possible that the initial movement of these short-finned pilot whales away from the MFAS source to an area with lower estimated RLs was a large-scale avoidance response. However, more than 24 hours after surface-ship MFAS began the tagged individuals moved from an area with relatively low RLs (approximately 127 dB) to an area with RLs of approximately 145 dB (Figures 1, 2). This suggests that after this initial period of possible avoidance the individuals may have shown increased tolerance to the MFAS exposure. Alternatively, the movements away from the MFAS source could have been in response to prey availability. Unlike previous groups of pilot whales where we were able to estimate RLs and examine movements (Baird et al. 2014, 2017a), this group is not from the resident western main Hawaiian Islands community of pilot whales but instead is thought to be either a pelagic group or part of the eastern main Hawaiian Islands community. Prior exposure history is likely to influence animal response to MFAS (Harris and Thomas 2015), and this group is likely to have a substantially different history of exposure to MFAS.

For five of the seven individuals tagged, all of the short-finned pilot whales and rough-toothed dolphins, the coverage of dive data for the three sonar exposure periods ranged from 54 percent to 100 percent of the time (Table 5), allowing for an assessment of diving behavior in relation to sonar exposure (Table 6, Table 7). Individuals which remained within range of one or both of the Motes (the short-finned pilot whale in 2018 and the two rough-toothed dolphins in 2016) had reduced gaps in diving and surfacing data. In our earlier analyses, one short-finned pilot whale tagged in February 2014 and exposed to relatively high RLs (estimated median RL of 168.9 dB) showed clear changes in diving behavior associated with the SCC. That individual had lower dive rates both during the day and at night, and had deeper day-time dives during the SCC (Baird et al. 2017a). The two pilot whales tagged in the same group in February 2016 demonstrated differential diving patterns, both from the 2014 individual and from each other, despite the fact that our modeling estimates suggest that they were exposed to much lower RLs. In terms of dive rates, GmTag152 showed a progressive decrease in night-time dive rates over the three successive periods (i.e., highest rates in the before-exposure and lowest in the after-exposure period), while GmTag153 increased dive rates between the before- and during-sonar exposure periods, followed by a decrease in the after-exposure period (Table 6). Day-time dive rates for the two individuals also differed, with one decreasing then increasing (GmTag152), and the other increasing and then decreasing (GmTag153), over the three successive periods (Table 6). Dive depths and durations both during the day and at night also varied in different ways for the two individuals. Combined, these different patterns for two individuals within the same group exposed to similar levels of MFAS suggest that the individuals were either responding to different small-scale environmental factors, or that individual differences (e.g., in body size, condition, or reproductive state) were driving their diving behavior. While both individuals appeared to be in good body condition, one was a known adult male, while the other was a smaller individual (i.e., the size of either an adult female or a sub-adult male).

Short-finned pilot whales in Hawaiian waters do exhibit changes in diving patterns in relation to lunar and seasonal cycles that appear to reflect changes in the depth distribution of their prey in response to light levels (Owen et al. 2019). During a full moon and during periods with longer day-length, pilot whales are generally farther offshore and diving deeper than during the new moon or periods with shorter days (Owen et al. 2019). We used moon-illuminated fraction (i.e., the fraction of the lunar disk that is illuminated at local midnight) as a proxy for lunar cycle and found that there was a general increase in moon-illuminated fraction over the three MFAS exposure periods (before-SCC, during-SCC, and after-SCC) for all of the tagged groups. Such an increase in light levels should generally result in an increase in dive depths and durations over the three periods, although this was only documented for two of the three short-finned pilot whales (Table 6), suggesting that other factors were likely influencing diving patterns.

Both of the tagged rough-toothed dolphins were exposed to slightly higher estimated RLs than the short-finned pilot whales, although one of the two (SbTag017) spent part of the SCC period in the acoustic shadow of Kaua‘i (Figure 4); thus, there were fewer exposures overall (Table 3). In both cases, the tagged rough-toothed dolphins moved into areas with higher estimated RLs, rather than being exposed to high estimated RLs at the start of the SCC and moving into areas with lower RLs (Figure 4, Figure 5). This suggests no large-scale avoidance response at RLs of up to about 155 dB. While there were changes in diving patterns at night (dive rates, depths and durations) over the three sonar exposure periods, as was the case with the short-finned pilot whales, the two individuals did not show a consistent pattern. For example, while SbTag018, with a maximum estimated RL of 155.9 dB, showed a decrease in dive depths at night during the SCC, SbTag017, with a maximum estimated RL of 148.3 dB, showed an increase in dive depths over the three exposure periods. Interpreting such patterns is hindered by a relatively poor understanding of the normal diving and foraging patterns of this species (Baird 2016).

Although estimated RLs for hull-mounted MFAS for the two melon-headed whales were low, analyses for these individuals were still useful to assess the magnitude of their exposure. While using locations at regular time intervals estimated from the SSSM was useful for increasing the sample size of exposure estimates (n increased from 3 to 13), the higher uncertainty associated with SSSM locations generally resulted in greater variability in RL estimates, and uncertainty in the SSSM locations was highly dependent on the resolution and variability in the Argos locations used to generate them. For example, in the case of PeTag025 there was a gap in Argos locations of approximately 32 hours in the middle of the SCC, and the locations prior to the first MFAS exposure were all Argos LCB, i.e., locations with high uncertainty. By contrast, the longest gap in the Argos data for PeTag026 was approximately 12 hours, and the locations immediately prior to the start of MFAS exposure were Argos LC2, i.e., locations with low uncertainty. While we are confident in the general magnitude of the estimates (i.e., that they were exposed to relatively low levels), the complex sound propagation characteristics (Figure 8) and the high uncertainty indicated that the precise values of our mean and median estimates should be viewed with caution.

The extremely wide range in SPLs at which different groups of killer whales responded to controlled exposure experiments (Miller et al. 2014) and the extremely variable response of blue whales (*Balaenoptera musculus*) to MFAS in different behavior states to comparable received levels (Southall et al. 2019) illustrate that natural or contextual variability in behavioral responses will require relatively large sample sizes of exposures to fully understand and characterize how different species of odontocetes react to MFAS. Results presented here build on earlier work (Baird et al. 2014, 2017b), increasing the species-specific sample sizes and range in exposure levels of both short-finned pilot whales and rough-toothed dolphins to hull-mounted MFAS use in SCCs. It is important to recognize, however, that there are other sound sources associated with SCCs, including helicopter-dipping sonars, sonobuoy MFAS, torpedoes, torpedo-recovery helicopters, and high-speed boat maneuvers. Individuals exposed to hull-mounted MFAS in this study may have been exposed to one or more of these other sound sources, prior to or during their exposure to hull-mounted sources. While RLs may have been lower from such exposures, depending on distance, the unpredictable spatial nature of aircraft-deployed sources (see e.g., Falcone et al. 2017) may have already resulted in a response by the animals and thus masked their responses to subsequent exposure to hull-mounted sources.

There are a number of limitations to our approach taken here, and additional modeling of all satellite tag data obtained in association with SCCs (i.e., this study and case studies reported in Baird et al. 2014, 2017a) is warranted. Analyses to date have used location data that was filtered by Argos using the least-squares method, but re-processing data with Kalman filtering (Silva et al. 2014) would provide better temporal resolution as well as better representation of errors associated with locations. Future analytical efforts could also incorporate three-dimensional modelling of RLs, incorporate the depth of tagged animals when depth is available, and include more complex animal movement modelling (e.g., Jonsen et al. 2005; Johnson et al. 2008; Schick et al. 2019) to generate locations at even time steps and improve estimates of uncertainty associated with locations. In addition, incorporation of other MFAS sources (e.g., aircraft-deployed MFAS) will allow for a more robust assessment of animal responses to MFAS.

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