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Assessing Exposure and Response of Three Species of Odontocetes to Mid-Frequency Active Sonar During Submarine Commanders Courses at the Pacific Missile Range Facility:

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Short-finned pilot whale (*Globicephala macrorhynchus*) photographed north of Kaua‘i. Photograph taken by Robin W. Baird under National Marine Fisheries Service permit no. 15330 issued to Robin W. Baird.

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14. ABSTRACT

The U.S. Navy's marine species monitoring program addresses four general topics surrounding the impact of mid-frequency active sonar (MFAS) on protected species: occurrence, exposure, response, and consequences. Occurrence of odontocete cetaceans on and around the Pacific Missile Range Facility (PMRF) has been studied for several years using a combination of satellite tags and photo-identification, demonstrating the existence of resident populations of several species of odontocetes and resulting in considerable information on diving behavior and movement patterns of these species. In an effort to measure and evaluate both exposures and responses to MFAS during actual military training exercises, we used data from 20 satellite tags deployed on odontocetes prior to three Submarine Commanders Courses (SCC) held on PMRF between August 2013 and February 2015.

MFAS use during each SCC occurred under normal operating conditions north of the Kaulakahi Channel and spanned a three-day period. Sonar transmissions were not controlled according to the location of tagged individuals, but this orientation provided a spatial-temporal opportunity for individuals to avoid MFAS exposure by moving to the opposite sides of either Kauaʻi or Niʻihau. Eleven of the 20 tags had either stopped transmitting prior to the start of the SCC or the tagged individuals were far from MFAS and thus exposure levels could not be estimated. For the other nine individuals, we combined locations obtained from satellite tags with Navy-provided data on MFAS use and ship tracks to assess MFAS exposure and potential responses. Subjects included: false killer whales, Pseudorca crassidens (n=1), short-finned pilot whales, Globicephala macrorhynchus (n=5), and rough-toothed dolphins, Steno bredanensis (n=3). Individuals from all three species were known to be part of island-resident populations, with false killer whales from the Northwestern Hawaiian Islands population, and pilot whales and rough-toothed dolphins from populations that generally range from Ni‘ihau to O‘ahu, but whose core areas encompass the Kaulakahi Channel and southern portions of PMRF. Methods used were similar to earlier analyses but with several improvements. Received levels (RLs) were estimated using the Peregrine propagation model for each satellite tag location within 1 hour of an MFAS transmission, allowing for calculations of thousands of RL estimates relatively quickly. We explicitly accounted for known uncertainty associated with Argos location classes (LCs) by calculating 1,000 RL estimates along a radial through the tagged animal location, with the radial length reflecting the LC uncertainty. Both median and mean (with standard deviations [SDs]) RL levels of the 1,000 estimates were used to address variability associated with LCs. Consistency between mean and median RLs and small SDs suggest that resulting estimates are relatively robust. Estimated RLs were determined at tagged animal locations for both 10-meter depths (m) (+/- 5 m) and at depths representing typical dive depths for each of the three species (false killer whale – 50 m; rough-toothed dolphin – 50 m; short-finned pilot whale – 500 m). Estimated RLs at depth representing typical dives were generally lower than at 10-m depth for all species.

The false killer whale was estimated to have been intermittently exposed to MFAS at distances ranging from 6.5 to 75.4 kilometers (km) over a 1.6-day span. During the period of MFAS exposure the false killer whale transited away from an area of relatively low exposure (starting at an estimated RL of mean = 90.9 [7.68]; median = 89.4 decibels referenced to 1 microPascal root mean square (dB re: 1 µPa RMS; hereafter dB)) to the area of highest RL (mean (SD) = 160.2 (9.55); median = 156.6 dB). The individual then moved away from the area where MFAS was being used for several hours, then moved back through the area of exposure (to an estimated maximum mean RL = 150.8 [7.05]; median = 157.6 dB), and then to an area of lower RLs. The three rough-toothed dolphins were exposed to MFAS at ranges of 19.5 to 94.4 km, with maximum estimated mean (SD) RLs at 10 meters of 150.6 (0.96), 155.3 (3.5), and 157.1 (1.5) dB. The individual with highest estimated RLs (SbTag014) moved from an area farther from the MFAS source into an area with the maximum estimated RL before moving into an area with lower RLs (<140 dB). The five short-finned pilot whales represented three different groups. One of the three groups, which included three different tagged individuals, was exposed to MFAS at ranges of 3.2 to 48.1 km, while the others were exposed at distances of 14.9 to 39.5 km and 48.0 to 57.3 km. Two individuals (GmTag081 and GmTag083) exposed at relatively short distances had relatively high estimated RLs at 10 m (GmTag081 mean = 169 [1.41], median = 168.9 dB; GmTag083 mean = 168.3 [1.50], median = 167.9 dB). No large-scale movements of the individuals away from areas of relatively high RLs, for example to areas in the lee of Kaua‘i or Ni‘ihau, were observed. An almost complete dive record spanning the period from before to after the SCC (22, days with 1,363 dives) was obtained for only one individual, the short-finned pilot whale (GmTag081) with the highest estimated RLs.

Clear changes in diving behavior were documented during the SCC in comparison to pre- and post-SCC periods for the short-finned pilot whale GmTag081. Dive rates during the SCC were lower both during the day and night in comparison to the pre- and post-SCC periods. Day-time dive depths were significantly deeper during the SCC, while night-time dive depths were similar for all three periods. These exposure case studies indicated no large-scale avoidance of areas with moderately high (>150 dB) MFAS RLs where responses might be expected to be likely by nine individuals of three species spanning two years. However, clear behavioral changes during the SCC were observed for one individual for which detailed dive data were available. All individuals were from populations that are generally resident to the area. Given that MFAS has been used in Hawai‘i for many years, these individuals have likely been exposed to MFAS on multiple previous occasions.

15. SUBJECT TERMS

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Acronyms and Abbreviations

BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range Expansion
CPA	closest point of approach
CRC	Cascadia Research Collective
dB	decibel(s)
est.	estimate
Exp.	exposure
hr	hour(s)
km	kilometer(s)
LC	location class
LIMPET	Low-Impact Minimally Percutaneous External Electronics Tag
m	meter(s)
MFAS	mid-frequency active sonar
PAM	passive acoustic monitoring
PMRF	Pacific Missile Range Facility
RL	received level(s)
RMS	root mean square
SCC	Submarine Commanders Course
SD	standard deviation
SL	source level(s)
SPL	sound pressure level
SPOT	Smart Position or Temperature Transmitting Tag
TL	transmission loss
μPa	micropascal

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Section 1 Abstract

The United States Navy's marine species monitoring program addresses four general topics surrounding the impact of mid-frequency active sonar (MFAS) on protected species: occurrence, exposure, response, and consequences. Occurrence of odontocete cetaceans on and around the Pacific Missile Range Facility (PMRF) has been studied for several years using a combination of satellite tags and photo-identification, demonstrating the existence of resident populations of several species of odontocetes and resulting in considerable information on diving behavior and movement patterns of these species. In an effort to measure and evaluate both exposures and responses to MFAS during actual military training exercises, we used data from 20 satellite tags deployed on odontocetes prior to three Submarine Commanders Courses (SCC) held on PMRF between August 2013 and February 2015.

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Methods used were similar to earlier analyses but with several improvements. Received levels (RLs) were estimated using the Peregrine propagation model for each satellite tag location within 1 hour of an MFAS transmission, allowing for calculations of thousands of RL estimates relatively quickly. We explicitly accounted for known uncertainty associated with Argos location classes (LCs) by calculating 1,000 RL estimates along a radial through the tagged animal location, with the radial length reflecting the LC uncertainty. Both median and mean (with standard deviations [SDs]) RL levels of the 1,000 estimates were used to address variability associated with LCs. Consistency between mean and median RLs and small SDs suggest that resulting estimates are relatively robust. Estimated RLs were determined at tagged animal locations for both 10-meter depths (m) (+/- 5 m) and at depths representing typical dive depths for each of the three species (false killer whale – 50 m; rough-toothed dolphin – 50 m; short-finned pilot whale – 500 m). Estimated RLs at depth representing typical dives were generally lower than at 10-m depth for all species.

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Section 2 Introduction

The United States (U.S.) Navy’s marine species monitoring program addresses four general topics surrounding the question of potential adverse impacts of Navy activities, in particular the use of mid-frequency active sonar (MFAS) on protected species. These four topics are: *occurrence* – which species are in the areas where MFAS is used; *exposure* – what are the MFAS conditions to which animals are exposed; *response* – what are the reactions to MFAS exposure; and *consequences* – does exposure have individual or population-level consequences?

Off Kaua‘i, Cascadia Research Collective (CRC) has conducted extensive studies of odontocete cetaceans as part of the marine species monitoring program and with additional support by other (Navy and non-Navy) sources. This work has used a combination of small-vessel surveys, photo-identification of individuals to assess sighting histories, biopsy sampling to examine population structure (e.g., Albertson et al. 2017; Courbis et al. 2015), and satellite tagging to determine movements and diving behavior. Many of these efforts to date have primarily addressed *occurrence* (see Baird 2016; Baird et al. 2016, 2017a, 2017b) and have identified resident, island-associated populations of three species of odontocetes around Kaua‘i and Ni‘ihau: rough-toothed dolphins (*Steno bredanensis*), common bottlenose dolphins (*Tursiops truncatus),* and short-finned pilot whales (*Globicephala macrorhynchus*). Kernel density analyses of locations from satellite tags have shown that core areas of these three populations all partially overlap with the Pacific Missile Range Facility (PMRF) (Baird et al. 2017a). For short-finned pilot whales, there is also evidence of an overlapping population of pelagic or open-ocean individuals having a much larger range (Baird et al. 2017a). A fourth resident island-associated species, spinner dolphins (*Stenella longirostris*), had been previously documented based on genetics (Andrews et al. 2010). The islands are also an area of overlap between two island-associated populations of false killer whales (*Pseudorca crassidens*), the endangered Main Hawaiian Islands insular population that ranges from Ni‘ihau to Hawai‘i Island, and a Northwestern Hawaiian Islands population that ranges from western O‘ahu at least as far west as Gardner Pinnacles (Baird 2016). Evidence from encounter rates from surveys, photo-identification, satellite tagging, and/or genetics also suggests that numerous additional species do not have resident, island-associated populations off Kaua‘i and Ni‘ihau (Baird 2016; Baird et al. 2017b). These include pantropical spotted dolphins (*Stenella attenuata*), Cuvier’s (*Ziphius cavirostris*) and Blainville’s (*Mesoplodon densirostris*) beaked whales, dwarf sperm whales (*Kogia sima*), sperm whales (*Physeter macrocephalus*), melon-headed whales (*Peponocephala electra*), and pygmy killer whales (*Feresa attenuata*).

Passive acoustic monitoring (PAM) on the instrumented hydrophone range allows for location of MFAS on and around PMRF, as well as detection and localization of some vocalizing marine mammals species (e.g., Helble et al. 2013, 2016; Martin et al. 2015). The combination of data on MFAS use, vessel tracks, and vocalizing marine mammals has allowed for opportunistic studies of both *exposure* and *responses* to ongoing Navy training activity for several species (Martin et al. 2015; Manzano-Roth et al. 2016). These PAM methods also have been used to investigate baseline behavior of Blainville’s beaked whales over a three-year period (2011–2013) and to study species-typical MFAS response relative to longer-term behaviors (Henderson et al. 2016). The PAM data are particularly valuable given the low sighting rates of Blainville’s beaked whales in the area (Baird et al. 2017b).

Some of CRC’s tagging efforts off Kaua‘i have been strategically conducted immediately prior to Submarine Commanders Courses (SCCs) led by the U.S. Navy, which involve the use of MFAS. This has allowed for analyses using satellite tagging data, MFAS use data, and ship track information to examine both *exposure* and *response* as well (Baird et al. 2014a). These initial analyses used data from one common bottlenose dolphin, one short-finned pilot whale, and two rough-toothed dolphins tagged between February 2011 and February 2013 (Baird et al. 2014a). The purpose of the current assessment is to utilize additional satellite tag and MFAS data obtained between July 2013 and February 2015 to increase the sample size both of individuals and species examined to further evaluate *exposure* and *response* questions. Furthermore, we have developed and adapted more sophisticated and automated methods to estimate MFAS received levels (RLs) in a manner that more robustly integrates positional error from tag location quality.

Section 3 Methods

Satellite Tag Data

Vessel-based field efforts were undertaken between July 2013 and February 2015 on three occasions that immediately preceded SCCs. Details on field methods are available in Baird et al. (2016). Tags used were either location-only (Smart Position or Temperature Transmitting tag [SPOT]5, Wildlife Computers, Redmond, WA) or location-dive (Wildlife Computers Mk10A) tags in the Low-Impact Minimally Percutaneous External electronics Tag (LIMPET) configuration, attached with two titanium darts with backward-facing petals. Tags were programmed to transmit from 10 to 18 hours (hr) per day depending on species and tag type, with Mk10A tags transmitting for longer periods to maximize the likelihood of obtaining dive data. Location-dive tags transmitted dive statistics (start and end time, maximum depth, duration) for any dives greater than 30 meters (m) in depth, with depth readings of 3 m being used to determine the start and end of dives. In addition, they transmitted the duration of “surface” periods (i.e., any period for which the animal remained shallower than 30 m in depth). Prior to each field effort, satellite-pass predictions were carried out using available Argos schedules to determine optimal periods for transmission, given satellite overpasses for the approximately 60-day period following the start of tag deployments.

Tags were remotely deployed with a DAN-INJECT JM Special 25 pneumatic projector (DAN-INJECT ApS, Børkop, Denmark) from a 24-foot rigid-hulled inflatable boat. During each encounter tagged and companion individuals were photographed for individual identification. Photographs were compared to individual photo-identification catalogs (Baird et al. 2008a, 2008b; Mahaffy et al. 2015) to assess re-sighting histories and association patterns. Association patterns and re-sighting histories were used to determine population identity, in combination with previous genetic analysis of biopsy samples and movements of satellite tagged individuals from the same social network (Baird et al. 2013; Martien et al. 2014; Van Cise et al. 2015; Albertson et al. 2017).

Locations of tagged individuals were estimated using the Argos Data Collection and Location System with a least-squares method and assessed for plausibility using the Douglas Argos-Filter version 8.5 (Douglas et al. 2012) to remove unrealistic locations; this approach follows protocols applied previously (Schorr et al. 2009; Baird et al. 2016). This filter includes four user-defined variables:

1. Maximum redundant distance—consecutive points separated by less than a defined distance are kept by the filter because Argos location errors rarely occur in the same place, thus nearby temporally consecutive points are assumed to be self-confirming;
2. Standardized location classes (LCs, defined below) that are automatically retained;
3. Maximum sustainable rate of movement between consecutive locations that the animal is expected not to exceed; and
4. Rate coefficient for assessing the angle created by three consecutive points; the rate coefficient algorithm accounts for the fact that the farther an animal moves between

locations, the less likely it is to return to or near to the original location without any intervening positions, creating an acute angle characteristic of a typical Argos error.

We automatically retained locations separated from the next location by less than a maximum redundant distance of 3 kilometers (km), as well as LC2 and LC3 locations (i.e., estimated error of approximately 1 km and approximately 500 m, respectively; Costa et al. 2010). LC1 locations (i.e., with estimated error of approximately 1,200 m), as well as LC0, LCA, LCB, and LCZ locations, were only retained if they passed the Douglas Argos-Filter process. For maximum sustainable rate of movement, we used 20 km hr^{-1} for false killer whales and rough-toothed dolphins, and 15 km hr^{-1} for short-finned pilot whales, based on maximum travel speeds noted during observations of fast-traveling individuals in Hawaiʻi (R.W. Baird, pers. obs.). We used the default rate coefficient for marine mammals (Ratecoef = 25). Location data that passed the Douglas Argos-Filter were processed with ArcGIS to determine depth and distance from shore using 50-m resolution multibeam bathymetry data from http://www.soest.hawaii.edu/HMRG/multibeam/bathymetry.php.

In cases where more than one individual of the same species had temporally overlapping tag data, we assessed whether individuals were acting in concert during periods of overlap using a combination of association data from photo-identification and satellite-tag data. We measured straight-line distances between pairs of individuals when locations were obtained during the same satellite overpass. Individuals that had a mean distance between them of 5 km or less were considered associated. Association values from photo-identification data were used to confirm individuals were from the same social group (see Mahaffy et al. 2015).

For the single individual pilot whale tagged with a location-dive tag for which a nearly complete record of dive behavior was obtained before, during, and after the SCC, we calculated summary statistics for both day and night, given known diel patterns in pilot whale diving behavior (Baird 2016). The percentage of time in surface bouts during the day and night was calculated by summing the amount of time in each “surface” period (i.e., periods where the individual did not dive >30 m) from the behavior logs obtained. Surface periods longer than 1 hr that spanned sunrise or sunset were divided into appropriate day- and night-time categories based on the amount of time pre- or post-sunrise or sunset. Statistical tests comparing diving depths and durations pre-, during- and post-SCC were undertaken in Minitab 16.2.4 (Minitab, Inc., State College, PA) using Kruskall-Wallis one-way ANOVAs given the non-normal distribution of the data.

Acoustic and Ship Track Data

The methods for estimating MFAS RLs for satellite-tagged individuals near PMRF between February 2011 and February 2013 were previously described (Baird et al. 2014a). The methods utilized here were similar but with improvements in several areas, including more systematic accounting for positional uncertainty in the animal location and the utilization of a different propagation model that allowed batch-mode processing, outlined in detail below. Together these two factors allow a statistical representation of the estimated MFAS exposure levels for satellite-tagged individuals, which provided insight into the variability of each estimated RL.

The basic method for estimating RL for tagged individuals requires: 1) the locations of ships capable of transmitting MFAS (provided as standard data products from PMRF); 2) times and locations of sonar transmissions (obtained from PAM monitoring of PMRF range hydrophones); and 3) time and estimated location for each tagged animal (using locations that passed the Douglas Argos-Filter process). 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. Modeled sound pressure levels (SPL) in decibels (dB) referenced to 1 microPascal (µPa) root mean square (RMS), hereafter dB, were calculated as estimated RLs at two different depths, at the frequencies of the MFAS being used (see below). All species had estimated RLs near the surface (10 m +/- 5 m), as well as species-specific typical dive depths (also +/- 5 m), based on data collected for these species in Hawaiian waters (see Baird 2016). The deeper dive depths used in this analysis for each species were: rough-toothed dolphins – 50 m; false killer whales – 50 m; and short-finned pilot whales – 500 m.

Equation 1 below provides the simplistic form of the sonar equation, where the RL is defined as the source level (SL) of the MFAS transmission minus the transmission loss (TL) for the sound propagating from the MFAS transmitting ship to the animal location. The TL is complex and heavily affected by factors such as the bathymetry between the source and animal, environmental factors, sound-velocity profiles, and bottom characteristics. Mismatches in these factors from the actual conditions for which the model is run can result in different results of the propagation modeling. While *in situ* measurements with which to compare model results would be preferred, they were not available for this analysis given the offshore locations of animals and the scope of this project.

$$RL = SL - TL \qquad \text{(eq. 1)}$$

Several additional assumptions were necessarily made regarding SLs for MFAS sources. Given security concerns, sources were assumed to have no directionality in either azimuth or elevation angles for the analysis. The depth of the MFAS source was fixed as the nominal depth of the sonar dome of the MFAS ship. Source level values provided by the U.S. Navy (Department of Navy 2013) for the U.S. Navy AN/SQS-53C sonar system transmitting a one-second signal is 235 dB re 1µPa at 1m for a 3 kHz signal.

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, based upon a study of pinnipeds at-sea using Fastloc® GPS (Costa et al. 2010). Specific location code accuracies (from Costa et al. 2010) utilized were: LC3 – 0.49 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 at evenly distributed distances along a radial from the MFAS source location through the estimated location with the radial length on either side of the location equal to the location code accuracies noted above. For example, with LC3 locations, 1,000 estimated RLs were calculated along a radial extending from the tagged animal location 0.49 km towards and 0.49 km away from the vessel using MFAS. This allowed looking at the estimated RL in a manner which accounts for many possible animal positions in distance as well as the two depth regimes. 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 comparisons of RL estimates at the near-surface (10 m) and deep-dive depths, we used the estimate from the MFAS transmission closest in time to the tagged animal location. These estimates were then represented statistically (e.g., means, standard deviations, medians). Histograms were also generated, and for cases with low standard deviations (e.g., under a couple of dB), they appear to be reasonably represented by Gaussian-like distributions. In some cases the boxplots assume outliers as the minimum and maximum values in the estimate, and they do not fit expected values, although they are modeled as being present due to certain specific geometric conditions for the case. When the modeled minimum to maximum value spans are large (e.g., >30 dB) the histograms often show multi-modal character, which is present due to factors such as long ranges and geometric ducting, and results in two distributions of estimated RLs.

This analysis required hundreds of propagation model runs, each with 1,000 estimates, which was impracticable using the previous propagation model (Navy's PCIMAT standard propagation model that was used in the Baird et al. [2014a] analysis), as it did not have a batch-processing mode and required the analyst to input parameters for each model run. Heaney and Campbell (2016) with the company OASIS (Ocean Acoustical Services and Instrumentation, Inc., Lexington, MA) developed a parabolic equation propagation model called Peregrine which includes batch-processing capabilities. Thus, Peregrine was utilized in this analysis to generate transmission loss estimates for all model runs. Peregrine outputs were read using a MATLAB script and used to obtain a statistical representation of the estimated RLs.

Section 4 Results

During the three field projects (totaling 27 days of field effort) between July 2013 and February 2015, 20 satellite tags were deployed on five species of odontocetes: one Blainville’s beaked whale, four bottlenose dolphins, six rough-toothed dolphins, one false killer whale, and eight short-finned pilot whales. Details on the deployments can be found in Baird et al. (2014b, 2015, 2016). Of the 20 deployments, nine individuals overlapped both spatially and temporally with MFAS from three discrete SCC events such that RLs could be estimated (**Table 1**). These nine individuals included one false killer whale from the Northwestern Hawaiian Islands population (see Baird et al. 2013; Carretta et al. 2016), five short-finned pilot whales (representing three different groups), and three rough-toothed dolphins. Eight of the nine individuals were classified as adult sized in the field, while the ninth (GmTag083) was considered a sub-adult in the field. All the short-finned pilot whales were from the western main Hawaiian Islands resident community and the rough-toothed dolphins were from the Kauaʻi and Niʻihau resident community. Of the remaining 11 tags for which it was not possible to estimate RLs, six stopped transmitting prior to the start of MFAS (three rough-toothed dolphins, and one each of bottlenose dolphin, short-finned pilot whale, and Blainville’s beaked whale), and five were either far enough away that RLs would have been below ambient noise levels or were in areas where paths to MFAS were blocked by land (two short-finned pilot whales and three bottlenose dolphin).

Table 1. Characteristics of MFAS use during Submarine Commanders Courses

Period	Span of hours from first to last ship 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
11–13 Aug 2013	40.2	18.7	17	0.98 (0.51)	1.64 (0.87)	SbTag010, PcTag037
18–21 Feb 2014	64.1	18.7	17	1.10 (0.73)	2.84 (3.28)	GmTag080, 081, 082, 083
16–19 Feb 2015	50.1	12.5	20	0.63 (0.42)	1.98 (1.58)	GmTag115, SbTag014, 015

MFAS use during the SCCs occurred during discrete blocks of time with multiple sonar pings (termed sonar blocks or MFAS blocks), with gaps between blocks of time with no pings (Table 1). For individuals across all three species, median values of the estimated maximum RLs ranged from 145.0 to 169.0 dB (**Table 2**). For seven of the nine individuals mean and median values for the maximum RLs were within 1 dB, and standard deviations (SDs) of these values were <2 for six of the seven, corresponding with Argos LCs of 1 and 2 (**Table 2**). For all cases RL estimates were lower, often substantially so, at typical deep dive depths than at the shallow (10-m) depths (**Table 3**). Measures of variability (SD, difference between mean and median) were predictably higher for LCA, LCB, and LC0 values. For the individual with the largest sample size, rough-toothed dolphin SbTag010, differences between the mean and median values were <1 dB for 17 of 24 (70.8 percent) estimates (**Table 4**). Examples of RL estimates with relatively high and low variability are shown in **Figure 1** (SbTag010, LC1, RL at 50-m depth: mean = 146.5, SD = 8.8) and **Figure 2** (GmTag081, LC2, RL at 10-m depth: mean = 152.8, SD = 0.17). Eight of the nine individuals across all three species, including two of the three pilot whale groups, were exposed to estimated median and mean RLs exceeding 150 dB; this received level has been identified as the 0.5 probability of disturbance in describing a risk function for Blainville’s beaked whales in response to Navy MFAS (Moretti et al. 2014).

Table 2. Summary of MFAS exposure modeling for satellite-tagged individuals.

Individual	Tag type	# locations with estimated RLs	Range of distance to MFAS (km)	Range of estimated mean RL at 10 m depth dB re: 1µPa RMS	Maximum estimated RL at 10 m depth dB re: 1µPa RMS mean/median/SD (associated tag LC code)
PcTag037	MK10A	9	6.5–75.4	77.5–160.2	160.2/156.6/9.6 (LCA)
GmTag080*	SPOT5	5	14.9–39.5	140.5–155.1	155.1/154.7/0.87 (LC2)
GmTag081**	MK10A	17	3.2–42.8	138.6–169.0	169.0/168.9/1.51 (LC2)
GmTag082**	MK10A	7	4.4–48.1	144.8–164.5	164.5/162.0/8.63 (LC0)
GmTag083**	SPOT5	14	3.5–36.7	138.2–168.3	168.3/167.9/1.5 (LC1)
GmTag115*	SPOT5	2	48.0–57.3	143.7–145.0	145.0/145.0/0.09 (LC2)
SbTag010	MK10A	24	19.5–86.2	70.5–150.6	150.6/150.8/0.96 (LC1)
SbTag014	SPOT5	12	22.3–68.1	125.7–157.1	157.1/156.8/1.5 (LC1)
SbTag015	MK10A	20	20.1–94.4	116.1–155.3	155.3/154.8/3.5 (LCB)

Key: *Tags for GmTag080 and GmTag115 stopped transmitting during the SCC, thus only a limited number of locations were available for modeling RLs. **Individuals GmTag081, GmTag082 and GmTag083 were together during this period, so values are not independent; # = number of; dB re: 1µPa = decibel referenced to a pressure of 1 microPascal; Gm = short-finned pilot whale (*Globicephala macrorhynchus*); km = kilometer(s); LC = location class; min = minute(s); Pc = false killer whale (*Pseudorca crassidens*); RL = received level; RMS = root mean square; Sb = rough-toothed dolphin (*Steno bredanensis*); SPOT = Smart Position or Temperature Transmitting Tag.

Table 3. Difference between estimated (est) RL values calculated from model results near the surface (10 m +/- 5 m) and at typical deep dive depths used for each species. Values shown are grand means (and SD of the means). Typical deep dive depths used were 50 m (+/- 5 m) for false killer whales and rough-toothed dolphins, and 500 m (+/- 5 m) for short-finned pilot whales.

Individual	Mean (SD) est RL at 10 m	Mean (SD) est RL at typical deep dive depth
PcTag037	117.6 (24.8)	116.5 (24.9)
GmTag080	147.8 (6.6)	135.0 (10.8)
GmTag081	148.4 (5.9)	134.6 (9.7)
GmTag082*	152.7 (7.6)	139.1 (15.3)
GmTag083*	150.5 (8.5)	139.4 (12.6)
GmTag115	144.8 (0.2)	122.8 (1.0)
SbTag010	122.6 (22.7)	122.7 (22.0)
SbTag014	145.1 (7.1)	138.0 (9.0)
SbTag015	143.0 (11.9)	135.5 (9.5)

Table 4. Comparison of RL estimates by Argos location class (LC) for rough-toothed dolphin SbTag010.

LC code	Range (km)	RL median	RL mean	Difference between median and mean	RL SD	CV
L3	38.3	121.0	120.9	0.1	1.40	1.16
L2	28.3	101.8	101.4	0.4	1.85	1.82
L2	46.3	118.6	118.6	0.1	0.91	0.77
L2	56.6	140.4	140.1	0.3	1.00	0.71
L2	86.3	70.8	70.6	0.2	0.93	1.32
L2	20.3	145.3	142.7	2.5	4.82	3.38
L2	32.3	121.4	122.4	1.0	3.62	2.96
L2	39.3	148.4	146.2	2.2	4.17	2.85
L2	33.8	146.5	145.4	1.1	2.84	1.95
L1	44.6	106.7	106.9	0.3	1.96	1.83
L1	31.7	118.8	118.7	0.1	1.54	1.30
L1	19.6	148.1	148.3	0.2	8.23	5.55
L1	55.6	103.4	103.0	0.4	2.15	2.09
L1	64.9	77.5	78.1	0.5	2.52	3.23
L1	23.0	128.7	133.1	4.4	9.17	6.89
L1	36.3	106.5	105.9	0.6	4.44	4.19
L1	21.8	146.1	145.6	0.5	4.27	2.93
L1	42.5	150.9	150.6	0.2	0.96	0.64
L1	66.2	134.1	133.8	0.3	1.69	1.26
L0	19.5	89.7	90.0	0.3	2.26	2.51
L0	43.6	149.0	147.0	2.1	4.84	3.29
L0	64.5	134.5	133.5	1.0	2.94	2.20
LB	36.9	119.1	120.7	1.6	8.16	6.76
LB	37.6	117.0	118.2	1.3	7.44	6.29

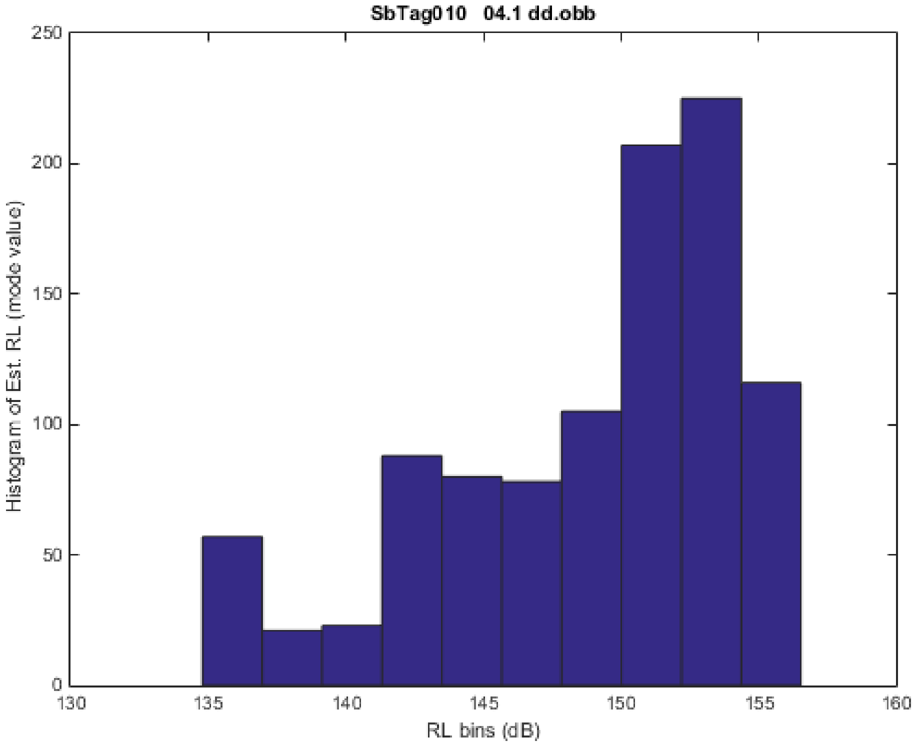

Figure 1. Distribution of RL estimates for SbTag010 for a LC1 location at 50-m depth. The mean RL was 146.4 dB (SD = 8.8), while the median was 147.2 dB.

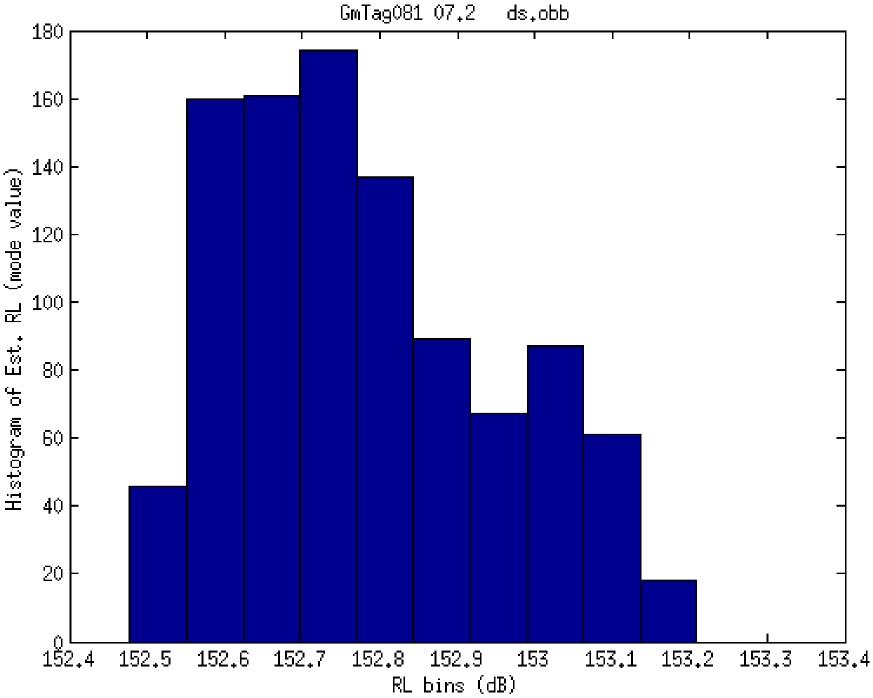

Figure 2. Distribution of RL estimates for GmTag081 for a LC2 location at 10-m depth. The mean (152.8 dB, SD = 0.17) and median (152.7 dB) RL estimates are similar.

Physical ranges from Navy ship sources for the false killer whale (PcTag037) during MFAS exposures were estimated using tag and ship locations as ranging from 6.5 to 75.4 km over a 1.7-day span. Maximum RLs at 10-m depth were: mean (SD) = 160.2 dB (9.55); median = 156.6 dB (**Table 2**). During the MFAS period the false killer whale transited in a direction that took it away from an area of relatively low exposure (starting at an estimated RL of mean = 90.9 dB (7.68), median = 89.4 dB) to the area of highest RL (**Figure 3**). Figures 3 to 11 provide plan views of the PMRF area showing: the islands of Kaua‘i and Ni‘ihau; blue areas indicating the southern portion of the PMRF underwater instrumented range (BARSTUR); red areas indicating the northern portion of the PMRF underwater instrumented range (BSURE); gray areas indicating areas of shipboard MFAS during the time period; black dots indicate tagged whale positions, typically connected with dashed lines; orange whale track overlay indicate periods of MFAS exposures; yellow stars indicate periods of estimating RLs; the callout boxes provide details for some exposures in terms of distances between the animal and MFAS sources along with estimated RLs. The whale then moved away from the exposure, moving away from PMRF to the southwest around the island of Ni‘ihau, before heading back towards PMRF. The whale then moved back through the area of relatively high exposure (to an estimated maximum mean RL = 150.8 dB [7.05]; median = 157.6 dB), then to an area of lower RLs (**Figure 3**). While the tag deployed on PcTag0037 was a depth-transmitting tag, no dive data were obtained during or after MFAS exposure.

Three tagged rough-toothed dolphins were exposed to MFAS at ranges of 19.5 to 94.4 km, with maximum estimated mean (SD) RLs at 10 m of 150.6 dB (0.96), 155.3 dB (3.5), and 157.1 dB (1.5) (**Table 2**). Analysis of distance between two of the tagged rough-toothed dolphins with overlapping tag data indicated they were acting independently (see Baird et al. 2016 for details). During some MFAS periods all three individuals moved from areas with lower RLs to higher RLs (**Figures 4, 5, 6**), although there were also periods when tagged individuals moved away from areas with higher RLs. The individual with highest estimated RLs (SbTag014) moved from an area farther from the MFAS source into an area with the maximum estimated RL before moving into an area with lower RLs (<140 dB) to the east of PMRF (**Figure 4**). Dive and surfacing data including before (28.6 hr), during (5.8 hr), and after (57.2 hr) the SCC were obtained from one (SbTag015) of the two location-dive tags. Dive depths varied significantly among the three periods (Kruskall-Wallis one-way ANOVA, p = 0.003), with median dive depths (of dives >30 m) during the SCC (71.5 m) being deeper than the pre- (47.0 m) or post-SCC (61.5 m) periods. However, this difference is due to significantly shallower dive depths in the pre-SCC period in comparison to the post-SCC period (Mann-Whitney U-test, p = 0.0007).

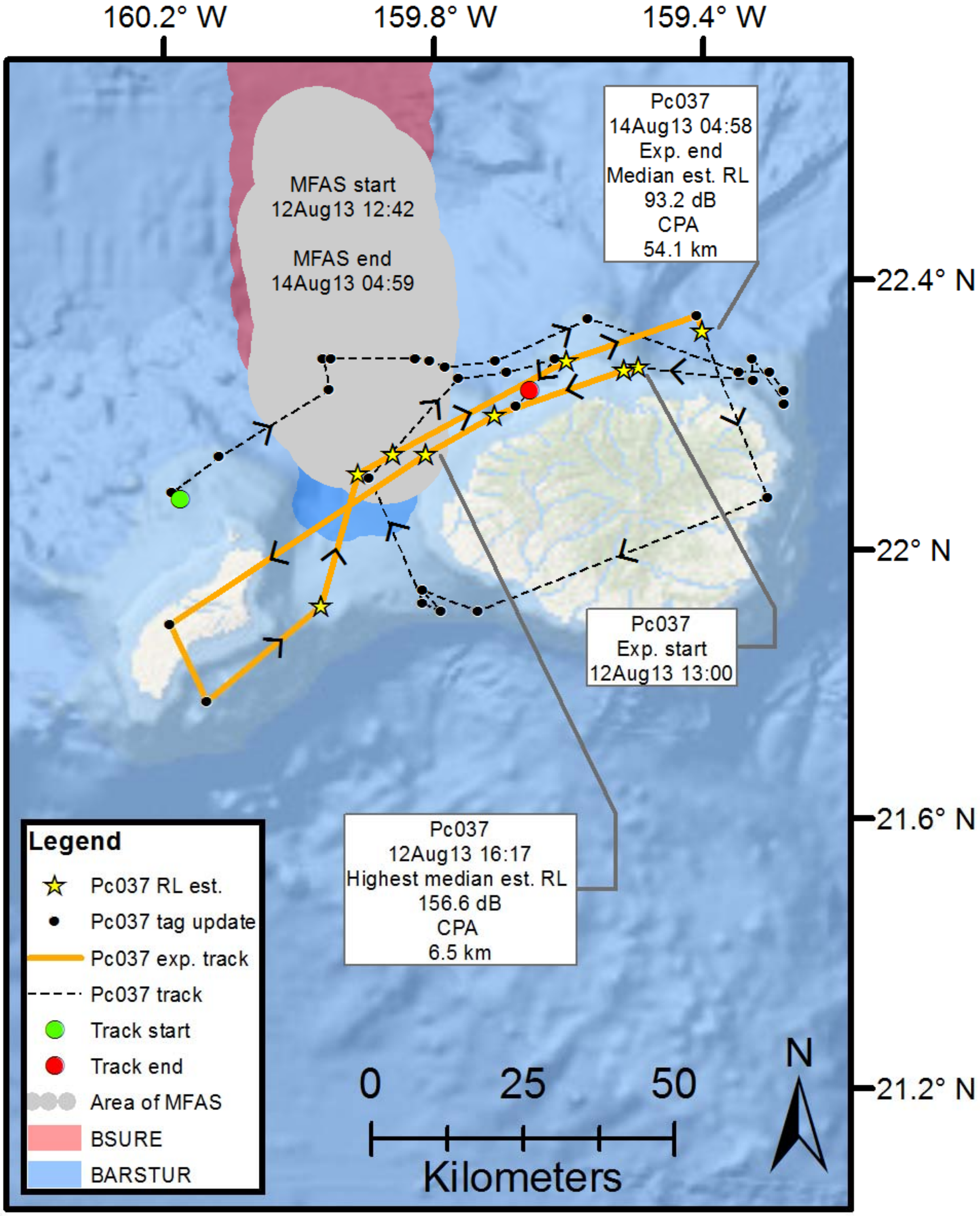

Figure 3. Filtered locations and interpolated track of false killer whale PcTag037 from 11 to 15 August 2013 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the whale's track during the SCC is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Exp = exposure. See text for other abbreviations. Dates and times shown are in GMT.

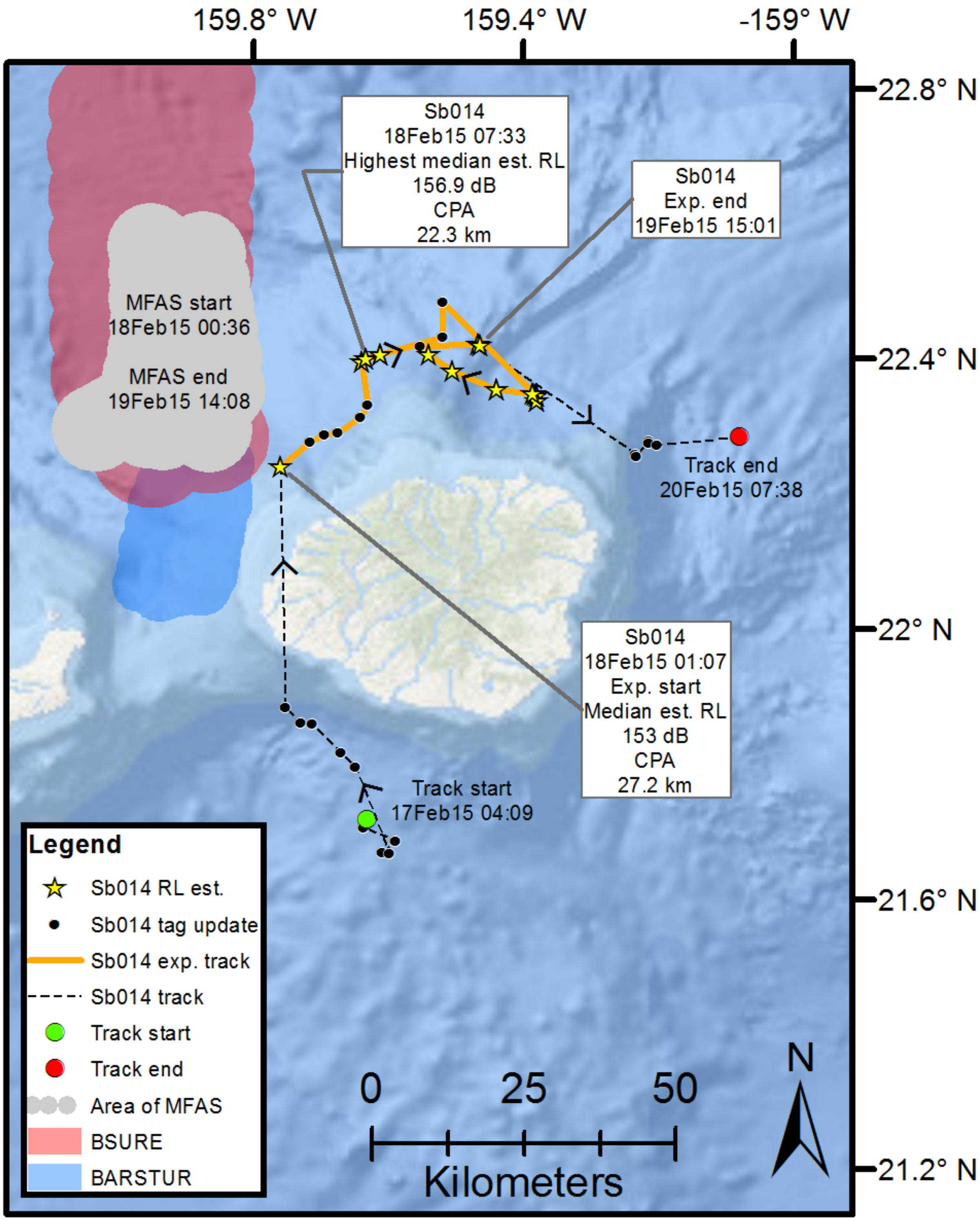

Figure 4. Filtered locations and interpolated track of rough-toothed dolphin SbTag014 from 17 to 19 February 2015 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the dolphin's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

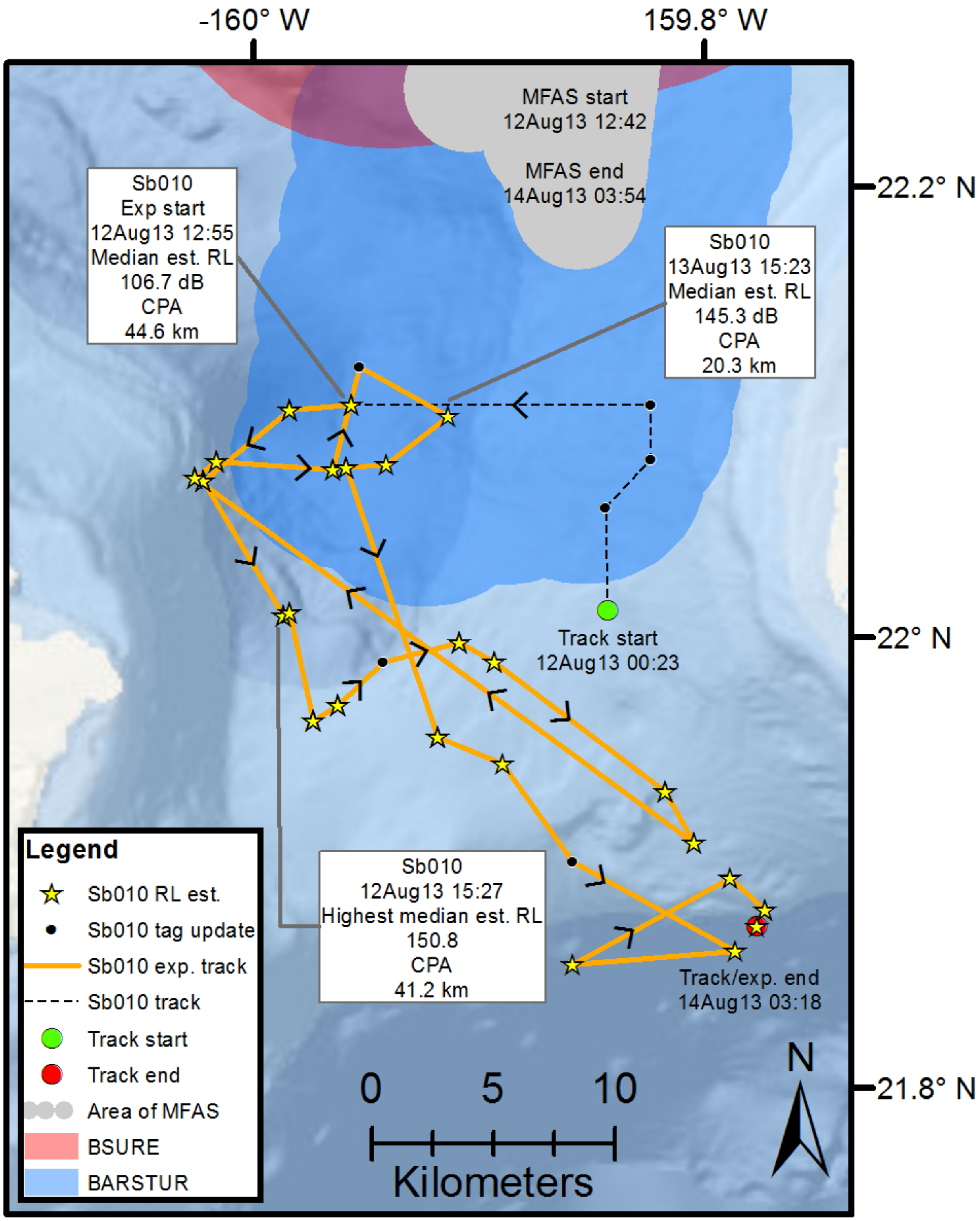

Figure 5. Filtered locations and interpolated track of rough-toothed dolphin SbTag010 from 12 to 14 August 2013 prior to and during a Submarine Commanders Course. The tag stopped transmitting shortly prior to the end of the SCC. The general area of MFAS use is shown in gray shading, while the dolphin's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

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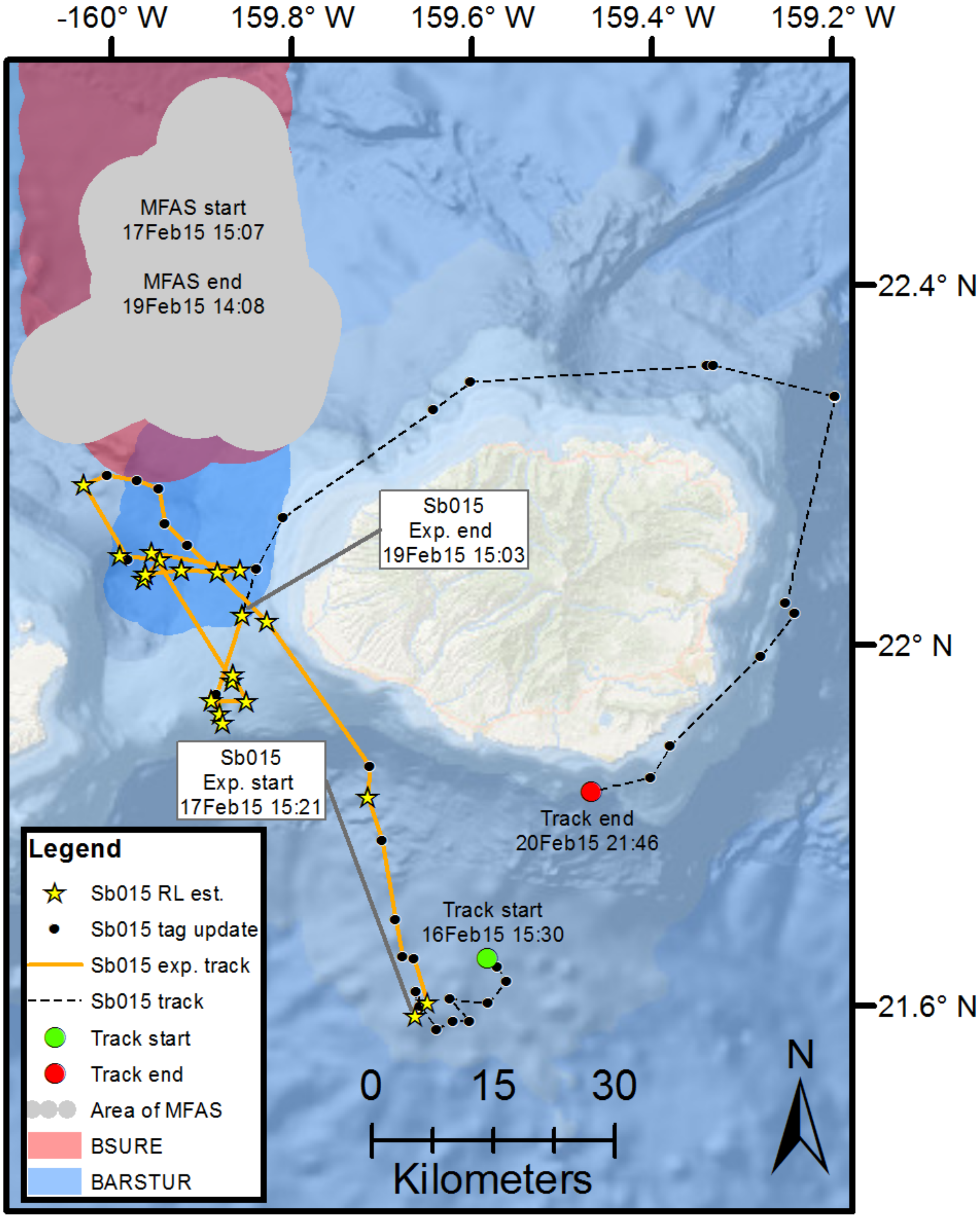

Figure 6. Filtered locations and interpolated track of rough-toothed dolphin SbTag015 from 16 to 20 February 2015 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the dolphin's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

Analysis of distances between individuals and association patterns for the four individual short-finned pilot whales tagged in February 2014 indicated they were from two different groups (see Baird et al. 2015 for details). Thus, combined with the one individual tagged in 2015, the five short-finned pilot whales represented three different groups. Three individuals in one group (GmTags 081, 082 and 083) were exposed to MFAS at ranges of 3.2 to 48.1 km (**Table 2**). A single individual was tagged in each of the other two groups, but in both cases the tags stopped transmitting early in the SCCs, with distances of the tagged individuals to the MFAS transmitting ships of 14.9 to 39.5 km (GmTag080) and 48.0 to 57.3 km (GmTag115). The individuals (GmTag081, GmTag082, GmTag083) exposed at relatively short distances had high maximum estimated RLs at 10 m (GmTag081 mean = 169 dB (1.41), median = 168.9 dB; GmTag082 mean = 164.5 dB [8.63], median = 162.0 dB; GmTag083 mean = 168.3 dB [1.50], median = 167.9 dB). Consistency between mean and median RLs and small SDs suggest that these estimates are relatively robust. No large-scale movements of the individuals away from areas of relatively high RLs, for example to areas in the lee of Kaua‘i or Ni‘ihau, were observed, and all five individuals moved into areas with higher RLs at some point during the period of overlap with the SCCs (**Figures 7** through **11**).

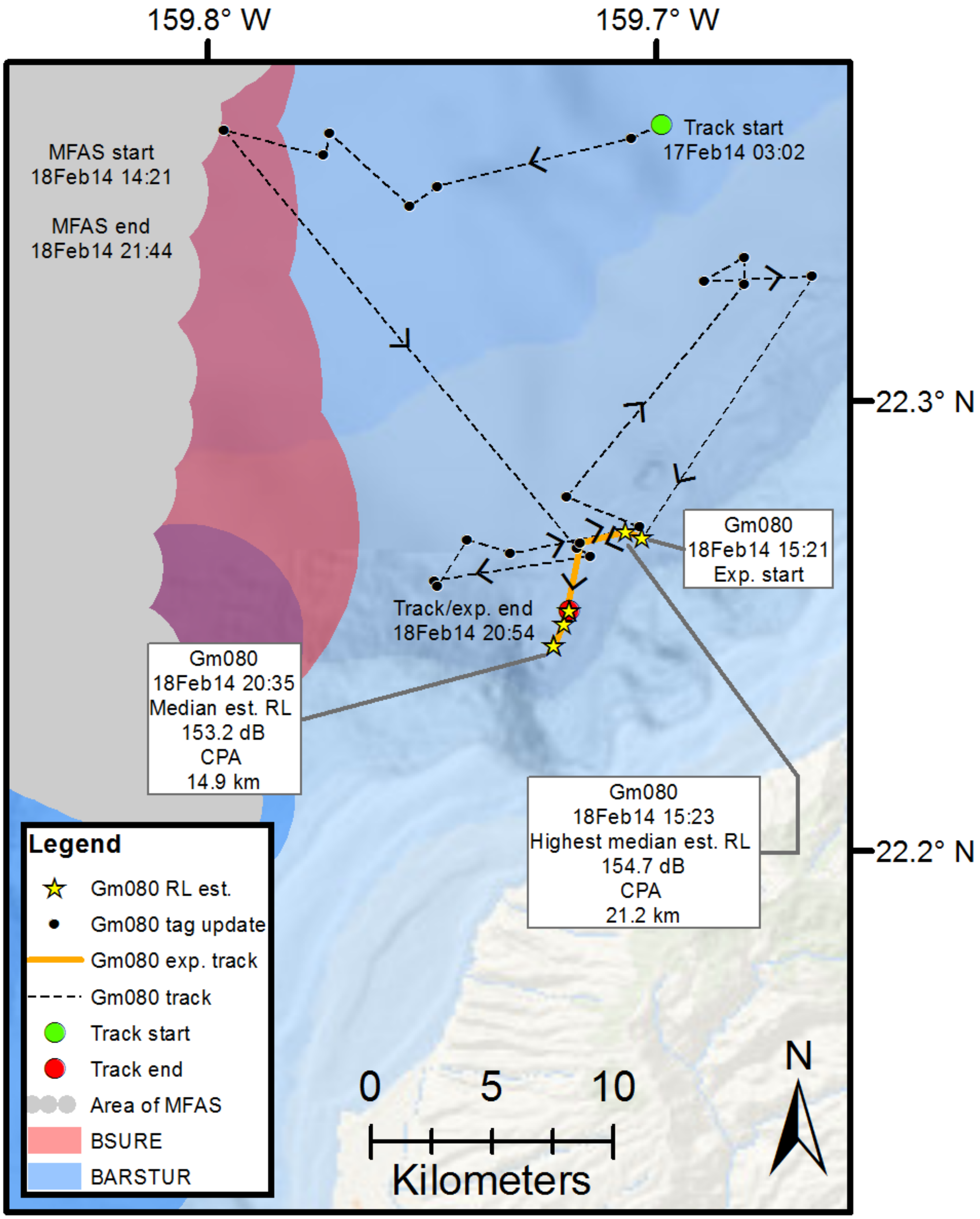

Figure 7. Filtered locations and interpolated track of short-finned pilot whale GmTag080 from 17 to 22 February 2014 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the whale's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

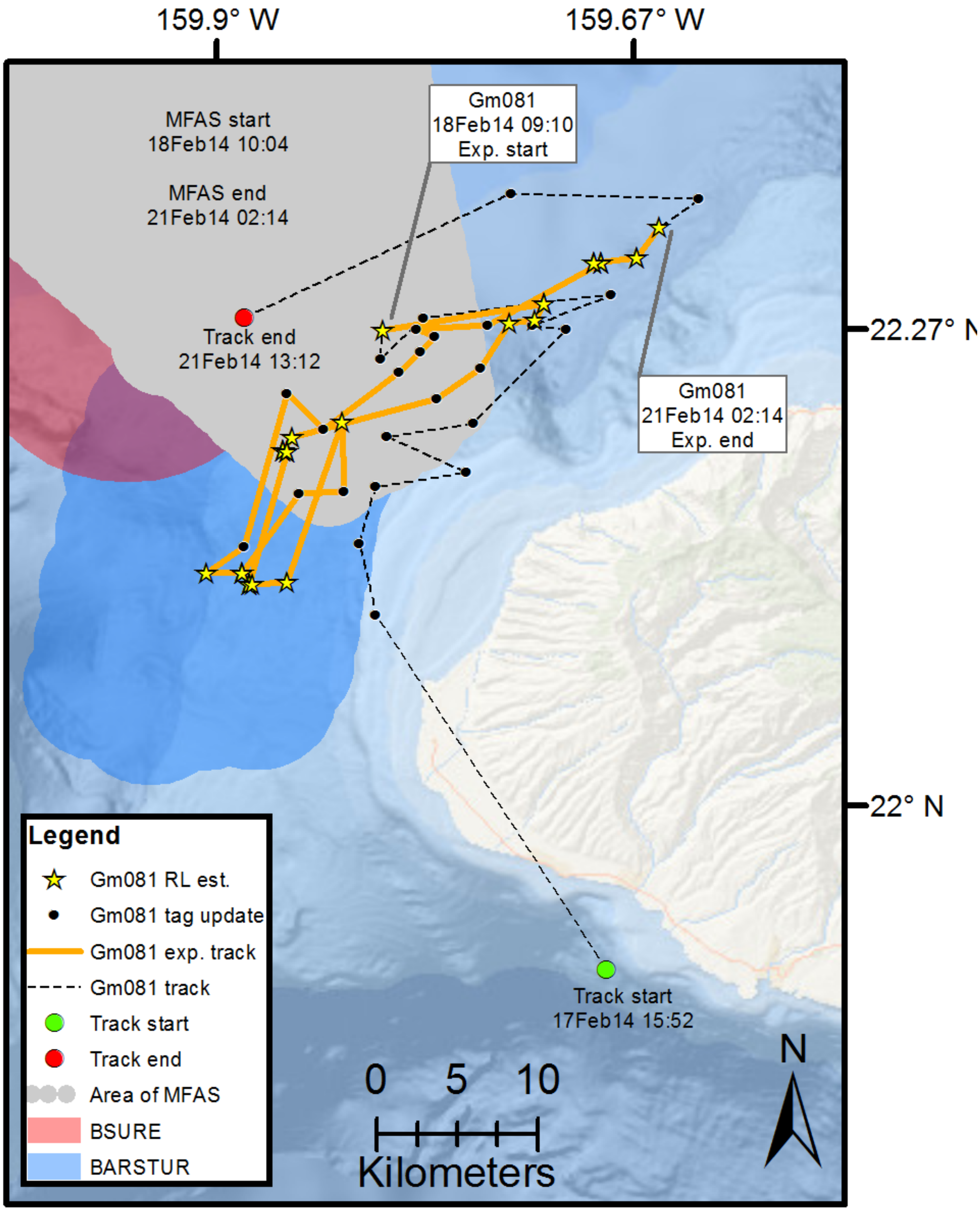

Figure 8. Filtered locations and interpolated track of short-finned pilot whale GmTag081 from 17 to 21 February 2014 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the whale's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

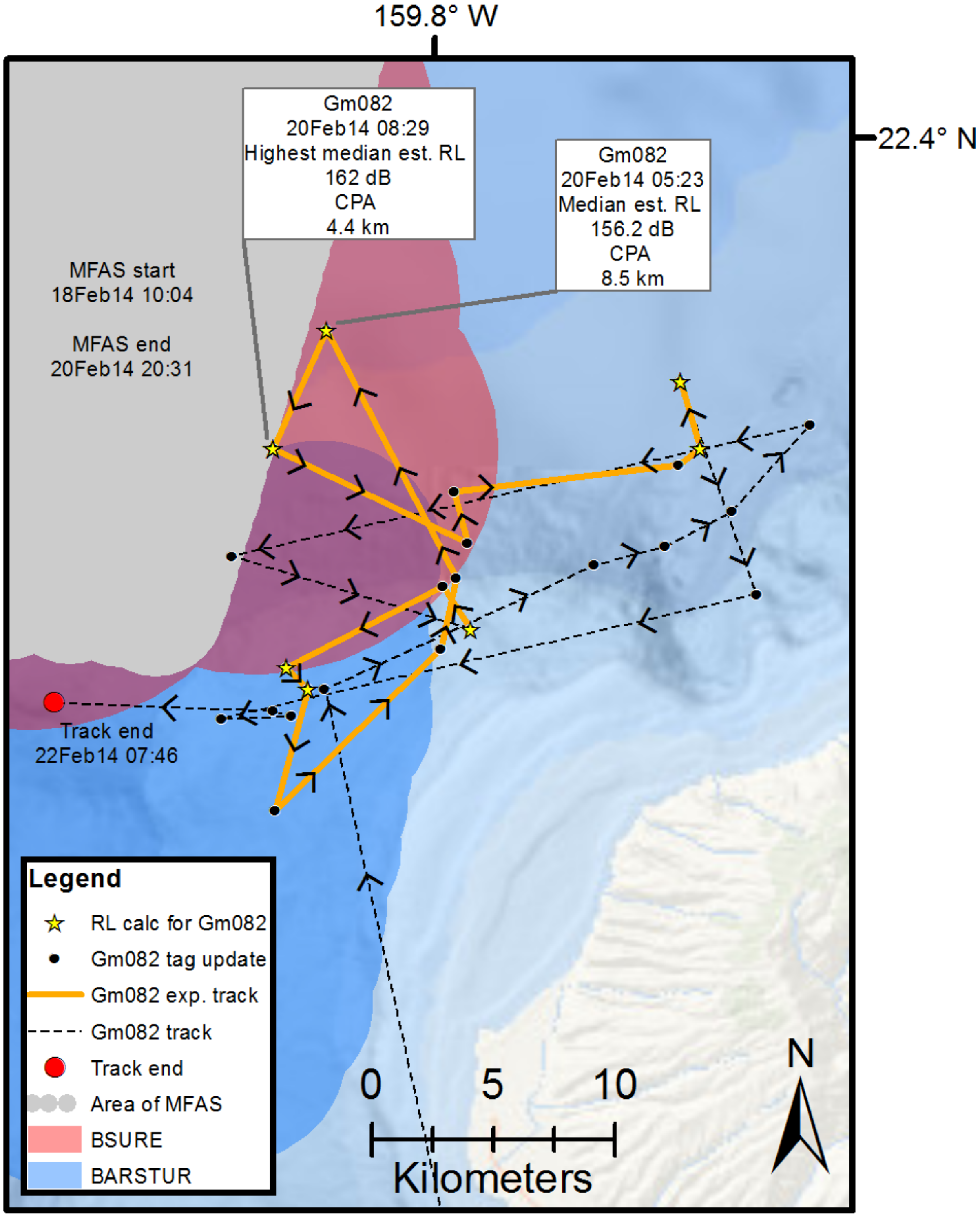

Figure 9. Filtered locations and interpolated track of short-finned pilot whale GmTag082 from 17 to 22 February 2014 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the whale's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT. The track start location is to the south, off the range of the map.

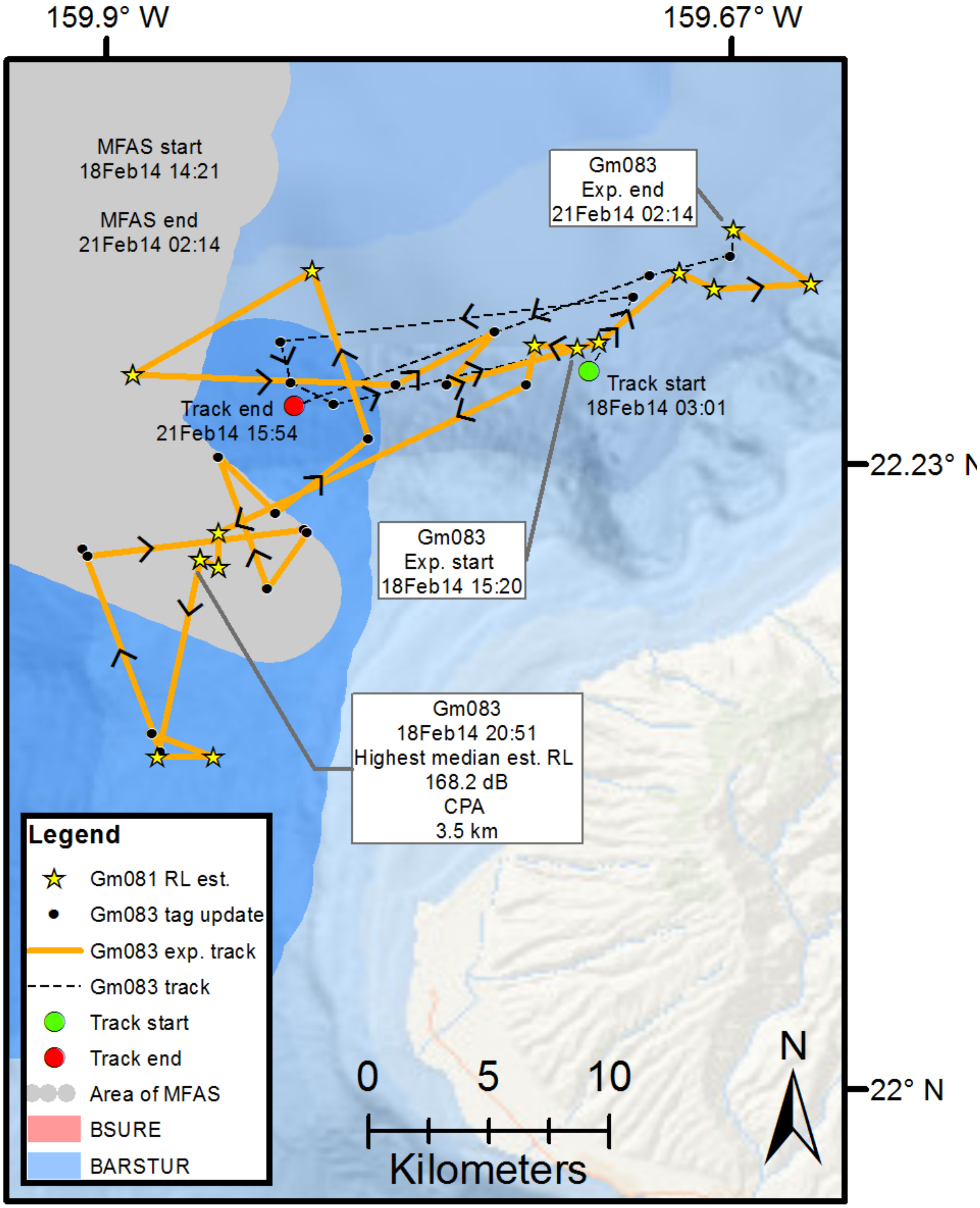

Figure 10. Filtered locations and interpolated track of short-finned pilot whale GmTag083 from 17 to 22 February 2014 prior to, during and shortly after the end of a Submarine Commanders Course. The general area of MFAS use is shown in gray shading, while the whale's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

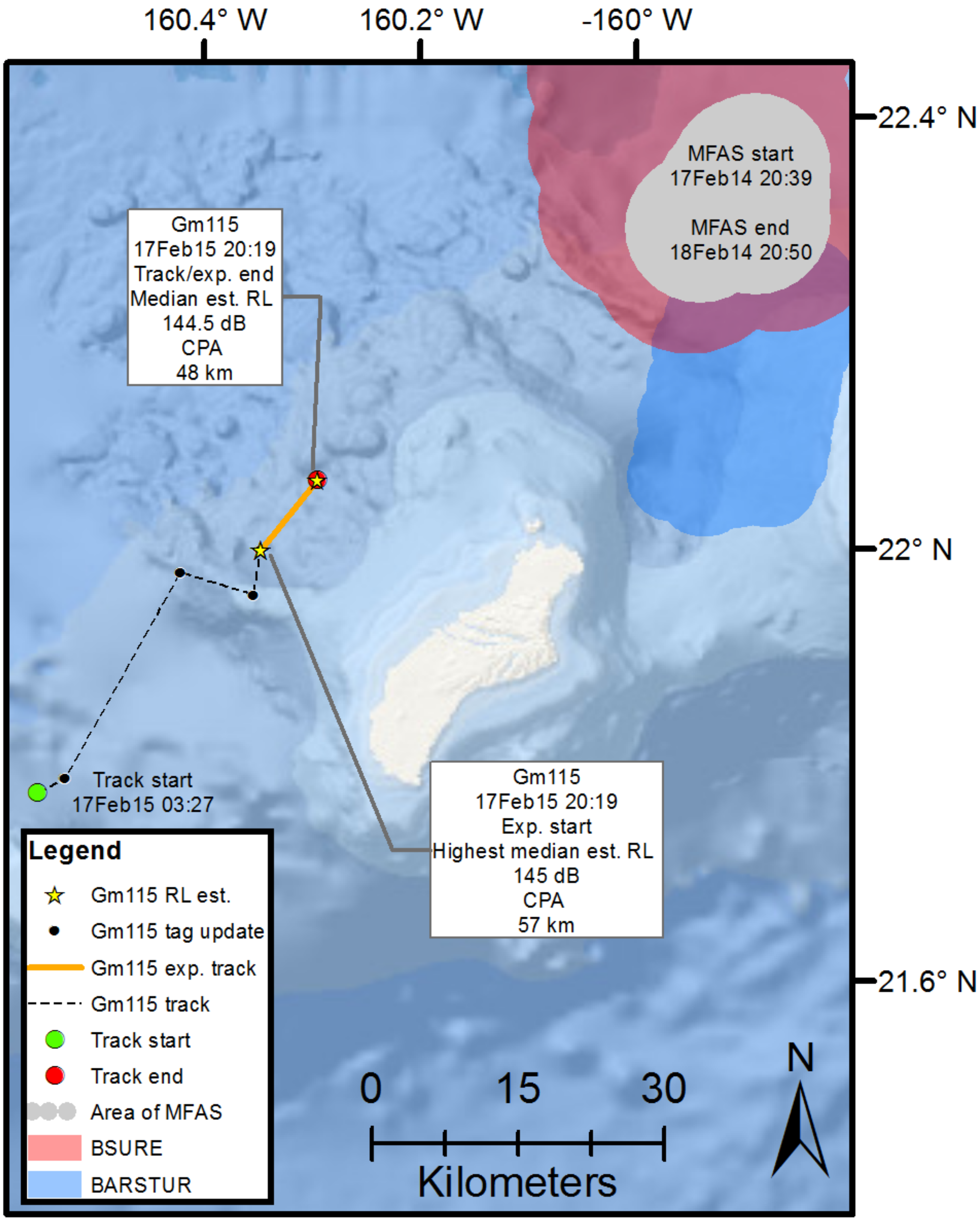

Figure 11. Filtered locations and interpolated track of short-finned pilot whale GmTag115 from 17 to 18 February 2014 prior to and during the beginning of a Submarine Commanders Course. The tag stopped transmitting after the last location shown. The general area of MFAS use is shown in gray shading, while the whale's track during MFAS sonar exposure is shown in orange. Locations where RLs were estimated (est) are indicated by stars. CPA = closest point of approach. Dates and times shown are in GMT.

Of the two individual pilot whales with location-dive tags, a detailed record of dive and surfacing data was obtained before (345.2 hr), during (60.8 hr), and after (129.1 hr) the SCC for one individual (GmTag081). Diving rates (# dives/hr >30 meters) were lower during the SCC than either before or after the SCC both during the day and at night (**Table 5**). Dive depths during the day varied significantly among the three periods (Kruskall-Wallis one-way ANOVA p <0.001; **Figure 12**), and the depths during the SCC were significantly deeper than the period with the most similar dive depths (the post-SCC period; Mann-Whitney U-test p = 0.0007). Dive durations during the day also varied significantly among the three periods (**Table 5**), as dive duration is correlated with dive depth. However, this was due to a difference between the pre-SCC period and the other two periods, rather than a difference between the during- and post-SCC periods (Mann-Whitney U-test p = 0.8386). At night, dive depths were not significantly different among the three periods, while dive durations were (**Table 5**). This difference in duration resulted from significantly longer dive durations during the pre-SCC period in comparison to the period with the most similar durations (post-SCC, Mann-Whitney U-test p = 0.0003). The proportion of time spent in surface bouts (i.e., periods where there were no dives >30 meters) were similar between the three periods during the day, but the individual spent considerably more time (approximately 73 percent versus approximately 45 percent) in surface bouts at night during the SCC (**Table 5**). Geospatial analysis of location data from this individual indicated that it was in slightly shallower water depths during the SCC than during the pre- or post-SCC periods (**Table 6**).

Table 5. Comparison of diving parameters pre-SCC, during the SCC, and post-SCC, for short-finned pilot whale GmTag081.

Parameter	**Pre-**	**During**	**Post-**	**P[1]**
# hours day	148	30	65	-
# hours night	200	31	65	-
# dives day	304	32	90	-
# dives night	595	68	274	-
Dives/hr day	2.05	1.07	1.38	-
Dives/hr night	2.97	2.19	4.21	-
Day median dive depth (m)	79.5	735.5	535.5	<0.001
Day median dive duration (min)	9.0	13.7	13.1	<0.001
Night median dive depth (m)	123.5	123.5	115.5	0.115
Night median dive duration (min)	9.1	7.9	8.5	0.001
Day % time in surface bouts	75.8	73.5	68.9	-
Night % time in surface bouts	45.8	72.9	44.9	-

[1] Significance values are from Kruskall-Wallis one-way ANOVAs.

Table 6. Comparison of location data from short-finned pilot whale GmTag081 pre-SCC, during-SCC, and post-SCC.

	Pre-SCC	**During-SCC**	**Post-SCC**
# locations	203	27	103
# days	14.4	2.4	4.3
Depth, m – mean (SD)	1,509 (789)	1,295 (651)	1,770 (648)
Distance from shore, km – mean (SD)	13.3 (4.9)	13.1 (1.5)	18.5 (4.5)
Slope, degrees – mean (SD)	9.5 (8.4)	8.9 (7.9)	11.7 (9.4)

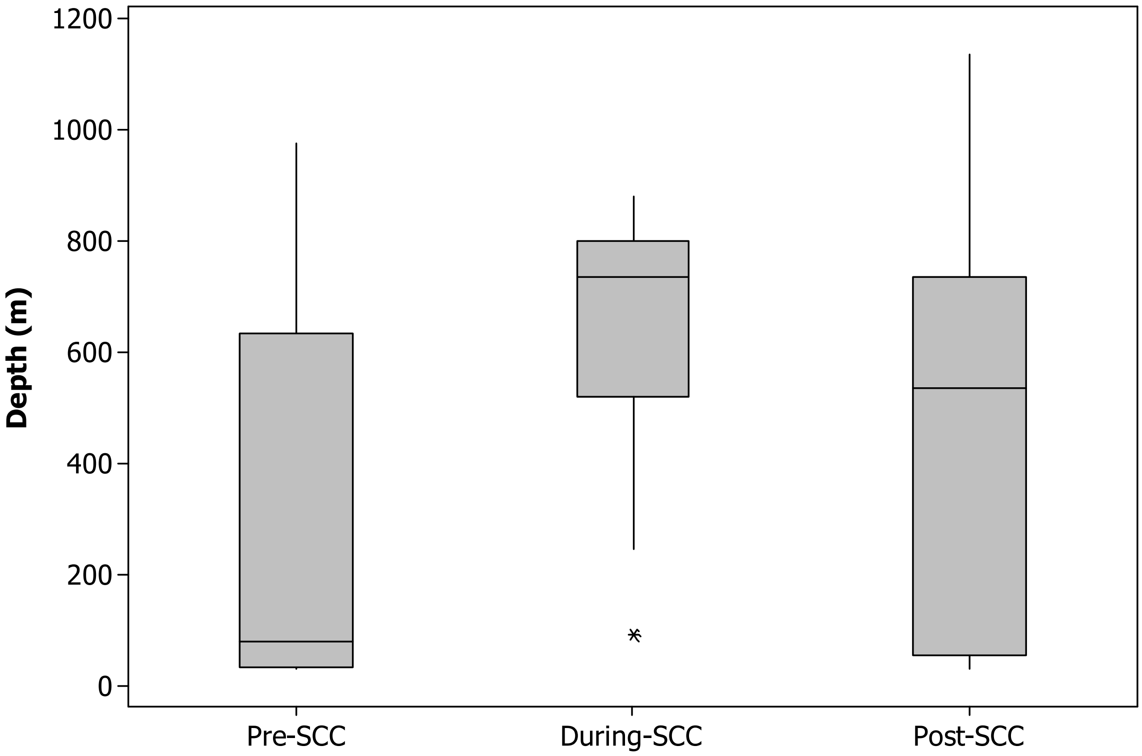

Figure 12. Box plot of day-time dive depths from short-finned pilot whale GmTag081 prior to, during, and after the Submarine Commanders Course. Middle lines within boxes represent the median values, while the top and bottom of the boxes represent the third (Q3) and first (Q1) quartiles. The upper vertical line represents the upper limit, defined as Q3 + 1.5 (Q3-Q1). The lower vertical line represents the lower limit, defined as Q1 – 1.5 (Q3-Q1). The * represents a value that is smaller than the lower limit.

Section 5 Discussion

These case studies integrating satellite-tagged cetacean movement data with available information on MFAS temporal and spatial use with which to reasonably estimate exposure indicated that individuals of three species of odontocetes did not demonstrate large-scale avoidance of areas with moderately high (>150 dB) MFAS use, levels at which another odontocete, Blainville's beaked whale, has shown a 0.5 probability of response to MFAS received levels (Moretti et al. 2014).These results substantially expand upon our earlier analyses (Baird et al. 2014a), more than doubling the number of individuals for which RLs were estimated for both rough-toothed dolphins and short-finned pilot whales, as well as adding an additional species, false killer whales. Furthermore, our current methods advance and improve upon earlier approaches. Specifically, we can now explicitly account for some known uncertainty associated with Argos-satellite derived locations (Costa et al. 2010) by integrating measures of associated RL variability and also utilize the batch-processing capabilities of the Peregrine propagation model to allow for calculations of thousands of RL estimates relatively quickly. The congruence between mean and median values and relatively low SDs of the RL estimates

(**Table 3**) suggest that the estimates are relatively robust. However it should be noted that with low quality tagged animal locations at relatively close distances to an MFAS source the error associated with estimates is likely to be greater. Regardless, the substantial improvements in analytical methods here will serve as useful examples in evaluating (uncontrolled) exposure scenarios that may be applied to other individuals and species in other MFAS use areas and contexts where similar evaluations may be conducted.

As with the earlier analyses, both short-finned pilot whales and rough-toothed dolphins were known to be from populations that are resident to the area (e.g., Baird et al. 2017a, 2017b). Similarly, the false killer whale was from the Northwestern Hawaiian Islands population, which is known to at least occasionally visit the area around PMRF (Baird 2016). Like the individuals in the earlier analyses, no large-scale avoidance of areas with relatively high MFAS exposure was observed. Given that MFAS has been used off PMRF for more than 30 years, these individuals have likely been exposed to MFAS on multiple previous occasions. As has been discussed in relation to the occurrence data available from PMRF (Baird et al. 2017), numerous authors have suggested that prior exposure history likely influences individual responses to MFAS exposures (Falcone et al. 2008; DeRuiter et al. 2013; Harris and Thomas 2015; Southall et al. 2016). Thus, we suggest that our results not be extrapolated to these species in general, particularly in areas where sonar is used less regularly than at PMRF. Individuals from more naïve populations may be more likely to exhibit avoidance responses where MFAS exposure is less frequent or occurs at lower levels, including those from pelagic populations or from island-associated populations elsewhere in Hawai‘i.

Despite the lack of any apparent broad horizontal avoidance response, an almost complete record of dive data obtained from a short-finned pilot whale with the highest estimated MFAS RLs (GmTag081; **Figure 8**) revealed numerous changes in diving behavior during the SCC relative to pre- and post-SCC periods (**Table 5; Figure 12**). Similarity in habitats used over the pre-, during-, and post-SCC periods (**Table 6**) suggest that these changes in diving behavior were likely not due to the individual using substantially different types of habitat. During the SCC this individual spent less time diving and more time in near-surface (<30-m) waters, with the greatest change occurring at night (**Table 5**). However, when diving, dive depths were statistically significantly deeper during the SCC than pre- or post-SCC periods (Figure 12). There was statistically significant variation in dive duration both during the day and night (**Table 5**), but these differences were driven by the pre-SCC dive durations, rather than a difference between the during-SCC period and the pre- and post-SCC periods. Pilot whales in Hawai‘i typically feed throughout the night, while during the day they intersperse deep feeding with periods of rest and socialization near the surface (Baird 2016). Given the fact that they span several diurnal periods, overall reduced diving rates and increased amount of time spent in surface bouts may reflect decreased foraging rates during the SCC. Such differences demonstrate that even with a lack of obvious broad-scale avoidance of important habitat areas during MFAS exposure, some animals that remain may exhibit changes in biologically-meaningful behavior. The ability to investigate both potential longer-term, broader-scale spatial avoidance as well as finer-scale individual behavior before, during, and after known sonar events illustrates the utility of these kinds of tag sensors and analytical methods.

While we have considerably expanded and improved the modeling and analytical methods from earlier analyses (Baird et al., 2014), there are a number of identified caveats and limitations to the current approach. Here, we have modeled received RMS RL values across exposure events. However, since MFAS use during SCCs in Hawaiʻi typically occurs multiple times over several days, calculating cumulative sound exposure levels in addition to mean and median RLs from individual events would be additionally informative, given that such cumulative sound exposure levels are typically one of several metrics used in exposure-risk probability functions from behavioral-response studies (Southall et al. 2016). Further, current methods use a single radial crossing the tagged animal position to account for known uncertainty in the Argos satellite-derived locations. While this provides a measure of variability associated with potentially closer or more distant actual locations, it does not incorporate uncertainty associated with the azimuth, thus not fully representing the ellipses of Argos error (Costa et al. 2010). We also estimated RLs for a single frequency, whereas estimates over a range of frequencies would both better reflect actual MFAS and help reduce artificially low RL estimates that occur due to destructive interference and have been incorporated for future analyses. Finally, it is acknowledged that current tagging methods involve positional errors that may be relatively large and challenging to fully quantify. Incorporating LIMPET tags with Fastloc® GPS capabilities would largely eliminate the uncertainty associated with Argos-derived locations and could generate locations at specified time intervals, improving upon the types of RL estimates undertaken or envisioned here.

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