

1 Introduction

Beaked whales (family Ziphiidae) are a group of deep-diving cetaceans that rely on sound to forage, navigate, and communicate [macleod_review_2006; johnson_beaked_2004; aguilar_de_soto_no_2012]. Multiple mass strandings of beaked whales have been associated with high-intensity anthropogenic sound sources. These acute events have motivated research into whether and how beaked whales respond to different types and intensities of anthropogenic noise [cox_understanding_2006].

Anthropogenic sound can disrupt the patterned dive cycles of beaked whales [falcone_diving_2017], potentially leading to death [jepson_gas-bubble_2003] or to cumulative sublethal impacts [new_using_2013]. For example, research on Blainville’s beaked whales *Mesoplodon densirostris* on a Navy range in the Bahamas has shown that animals may stop foraging and/or move away from Naval sonar sources [tyack_beaked_2011; joyce_behavioral_2019].

Naval sonar can be broadcast from various platforms, including vessels, helicopters, buoys, submarines, and torpedoes [harris_changes_2019; u.s._department_of_the_navy_final_2018]. Most research has focused on the impacts of mid-frequency active (MFA) sonar broadcast from US Naval vessels. Separately, researchers have shown that, in the absence of MFA sonar, beaked whales may alter their behavior in response to vessel noise [aguilar_soto_does_2006; pirotta_vessel_2012].

The US Navy is interested in quantifying the effects of sonar on beaked whales for the purpose of risk assessments and permitting associated with training activities. There are different experimental and analytical ways of quantifying responses to sonar. Here, we focus on analyses of data from cabled hydrophone arrays.

For example, [mccarthy_changes_2011] used data from the cabled hydrophone array at the US Navy’s Atlantic Undersea Test and Evaluation Center (AUTEK) in the Bahamas collected before, during, and after Naval training exercises involving MFA sonar. The authors used separate generalized additive models (GAMs) for each period, and modelled the acoustic detection of groups of Blainville’s beaked whales (group vocal periods; GVPs) as a function of location on the range and time. They found that the number of GVPs was lesser during the exercises than before, and also lesser during an exercise than after.

Building on this work, [moretti_risk_2014] used a GAM to model the presence or absence of acoustic detections of groups of Blainville’s beaked whales on the AUTEK range as a function of a smooth on MFA sonar received level. They then compared the expected probability of detecting animals when no sonar was present to the expected probability of detecting animals across sonar received levels to estimate the probability of disturbance. They found that the probability of detecting groups of Blainville’s beaked whales was reduced by 50% at 150 dB rms re $1\mu\text{Pa}$.

In the present study, our primary objective was to replicate the effort of Moretti et al. with the same species on a different US Navy training range in a different oceanic environment. Unlike AUTEK, which occurs in a deep isolated basin surrounded by steep slopes, the Pacific Missile Range Facility (PMRF) range in Hawaii occurs on the side of an ancient volcano, with a steep slope down to the deep ocean floor. Density at PMRF is lower and more variable than at AUTEK, so we wanted to explicitly account for differences in underlying beaked whale presence across the range.

An additional objective was to isolate the effect of general training activity from the effect of MFA sonar, so that beaked whale response to MFA sonar could be quantified relative to pre-training baseline periods and to periods when general training activities were present on the range.

To accomplish these objectives, we used a spatially referenced dataset of Blainville’s beaked whale foraging dives recorded at the PMRF off the island of Kauai, Hawaii (Fig. 1). Acoustic detections of Blainville’s beaked whales were collected via a cabled hydrophone array at PMRF before and during Naval training exercises involving MFA sonar. Previous work in this region has shown that Blainville’s beaked whales are present year-round at this site, that they prefer certain slope habitats, and that acoustic detections decrease during multi-day training events involving MFA sonar [henderson_occurrence_2016; manzanoroth_impacts_2016].

A series of three models were fit to data collected before the training exercises began, data collected when

training exercises were ongoing but no MFA sonar was present, and to data collected when training exercises including MFA sonar were present. The expected values from each model were used as an offset in the next model, and uncertainty was propagated through all models using posterior simulation. Using this set of model results, we quantified the expected decrease in detection of GVPs across increasing sonar received levels relative to both the pre-training baseline period and the period when training activities were ongoing but no hull-mounted MFA sonar was present.