Underwater Passive Acoustic Monitoring Around Kauai, Hawaii

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DEDICATION

For Avi.

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A dissertation is completed by one individual but it is the culmination of efforts and support of many. My tenure at the Marine Mammal Research Program was longer than anticipated, and for the contributions of others towards helping me complete my degree, I have tremendous gratitude.

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ABSTRACT

Passive acoustic monitoring is a powerful tool for non-invasive and unbiased data collection in remote locations. The ability to collect data over long durations in areas that are not easily accessible and during all weather conditions has become a common technique for surveying for marine mammals as well as assessing the soundscape that may impact their behavior or distribution. Very little is known about the occurrence of fin (*Balaenoptera physalus*), sei (*Balaenoptera borealis*), and Bryde’s (*Balaenoptera edeni*) whales that are very rarely observed in the coastal waters around the main Hawaiian Islands. This dissertation presents results obtained from underwater passive acoustic data collected at five sites around the island of Kauai, Hawaii, from February 2009 through October 2010. Acoustic files scanned manually to search for sounds produced by fin, sei, and Bryde’s whales. The results corroborate the extremely low sighting rates for these three species. Out of a total 31 acoustic encounters, 18 were from fin whales, 9 were from sei whales, and 4 were from Bryde’s whales. These detections were also compared to those produced by two automated techniques and unfortunately, neither performed well enough to be reliable alternatives to time consuming manual analyses. The broadband acoustic data collected for this study are very useful for determining contributions of natural and anthropogenic sources towards the overall soundscape around Kauai. While fin, sei, and Bryde’s whales were not frequently detected in the data, humpback whale song was ubiquitous during the winter months and was present in nearly each recording from December through March. When comparing the broadband noise levels around Kauai to sites off of Oahu and Nihoa (the closest of the Northwest Hawaiian Islands), it is evident that weather (mainly wind) and shipping noise have the greatest impact on the soundscape.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:
DISSERTATION INTRODUCTION

1.1 Introduction

The main Hawaiian Island chain is among the most remote archipelagos on the planet. Marine mammals are commonly encountered in the coastal waters of the Hawaiian Islands, and in the winter, no species occurs more frequently than humpback whales (*Megaptera novaengliae*). Humpbacks migrate to lower latitudes each winter for mating opportunities and to give birth. In recent years, particularly after the discovery that the mysterious “boing sound” was attributed to minke whales (*Balaenoptera acutorostrata*), it has been demonstrated that this species also winters in the tropics, presumably for the same reason as humpback whales (Thompson and Friedl 1982, Rankin and Barlow 2005, Oswald et al. 2011). This behavior has been well documented and provides a plausible model for the occurrence of other baleen whale species in Hawaiian waters.

The other baleen whale species of the Eastern North Pacific include blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*), sei whales (*Balaenoptera borealis*), Bryde’s whales (*Balaenoptera edeni*), gray whales (*Eschrichtius robustus*), and North Pacific right whales (*Eubalaena japonica*). Baleen whales, in general, are mostly solitary animals that have ephemeral interactions with conspecifics usually associated with breeding and foraging opportunities. The diet of a variety of filter feeding baleen whale species can be similar. For lunge feeding balaenopterid species (blue, fin, sei, and Bryde’s), small shoaling fish and krill (euphausiids) are the dominant prey. Copepods and other invertebrates are targeted near the surface for skimming balaenid whales (right whales). Gray whales are unique in that they gulp sediment to filter invertebrates. As such, these animals tend to be encountered in shallower more coastal habitats.

The most enigmatic North Pacific species is the right whale. They were hunted to near-extinction and most recently the only records of their occurrence have been made in the far North Pacific near Kodiak Island, Alaska, and in the Bering Sea. Interestingly, there were two sightings (likely of the same individual) in Hawaii in the winter of 1979 (Herman et al. 1980). No other records of right whales in Hawaii give reason to believe that this is no more than an isolated event.

Blue whales also occur in the North Pacific and in the tropics are most commonly observed along the coast between Baja, Mexico and Central America (in particular the region known as the Costa Rica Dome). The population was severely depleted from commercial whaling and, while they are still endangered, the populations are very slowly showing signs of recovery. Stafford (2003) reported blue whale sounds recorded in the Gulf of Alaska when, at that time, no post whaling surveys had sighted any individuals. More recently, blue whales have been sighted in Alaskan waters and, while not abundant, they are not as rare as a decade ago. Around Hawaii, however, there are no sightings reported nor are there whaling records that may indicate a historical range in these waters. Despite the lack of sightings, blue whales have been detected acoustically as early as 1965 (Northrop et al. 1968, Northrop et al. 1971) in the Main and Northwest Hawaiian Islands.

Fin, sei and Bryde’s whales have been sighted during surveys in the Main Hawaiian Islands as well as the Northwest Hawaiian Islands (Papahānaumokuākea Marine National Monument). While it is not unexpected to see these species, sightings are very infrequent. Most observations have been in deep water and not in areas where research effort and vessel traffic is most common. Sightings in windward and open ocean conditions, where the ability to see them is significantly reduced, may be indicative of a habitat preference that differs from the shallow areas exploited by humpback whales. Due to the infrequency of their respective sightings, very little is known about their distribution and occurrence in the Central Pacific.

The inherent value of passive acoustic monitoring (PAM) with autonomous devices is that they are able to detect marine mammal signals in challenging sea conditions and in areas that are not easily accessible by traditional, and very cost prohibitive, visual survey means; boats and aircraft. These devices can be deployed for long durations and can be used to determine seasonal occurrence, movement patterns, spatial distribution, and vocal activity of soniferous marine life, including cetaceans. The Hawaiian Islands are ideal for employing PAM techniques for marine mammal monitoring. While many species are commonly encountered in coastal areas and are abundant seasonally, occurrence and distribution studies are difficult due to rough sea states and inaccessibility around the islands and further from shore.

Fin, sei, and Bryde's whales all produce distinctive vocalizations that have been described in the literature. Like most balaenopterids, their calls are downswept with frequencies between 200 and 20 Hz. In Hawaii, the majority of fin whales signals reported are a stereotyped "20 Hz pulse" (Schevill et al. 1964, Watkins et al. 1987, Thompson et al. 1992). While fin whales do produce downsweeps with other frequency characteristics, the 20 Hz pulse is most commonly heard in lower latitudes and is seasonally common (Thompson and Friedl 1982, Watkins et al. 1987, McDonald and Fox 1989). Sei whale signals recorded near the main Hawaiian Islands produced two downsweep signals. Rankin and Barlow (2007) report a 39 – 21 Hz call that is similar to a "35 – 20 Hz irregular repetition" fin whale call. Even though the sei whale signal is longer than the fin calls, it may be hard to distinguish between them with certainty. Sei whales also produced a 100 – 44 Hz downsweep signal that has been confirmed in subsequent recordings among and between years (unpublished data analyzed during this study). These higher frequency calls are approximately 1.0s in duration and can be distinguished from published descriptions of Bryde's whale calls in the North Pacific (Cummings et al. 1986, Oleson et al. 2003, Heimlich et al. 2005).

1.2 Dissertation Objectives

For this study, autonomous Ecological Acoustic Recorders (EARs [Lammers et al., 2008]) were deployed around the island of Kauai, Hawaii. These instruments were deployed over a period of two years and provide both spatial and temporal data in order to compare acoustic detections among and between deployment sites.

The research questions I will be addressing in this dissertation are:

1. What is the occurrence of baleen whales around the island of Kauai?
    a. Which species are present?
    b. What is the seasonality of the species detected on the acoustic recorders?
    c. Are there any spatial differences in the distribution of whales detected on the recorders?
    d. Does acoustic data offer a distinct advantage over the traditional visual survey methodology for species occurrence?
2. Are automated acoustic detectors able to reliably locate and classify the sounds of non-humpback and non-minke baleen whales?
    a. What is the performance of the Baleen5 detection algorithm on a manually validated dataset?
    b. What is the performance of the Raven fin whale detection tool on a manually validated dataset?
3. What is the deep-water soundscape around the island of Kauai?
    a. What are the seasonal trends of ambient noise levels around Kauai?
    b. How do baleen whales affect the overall soundscape around Kauai?
    c. What is the anthropogenic contribution to the soundscape around Kauai?

These objectives are part of a comprehensive program to characterize the habitat and movement of cetaceans around Hawaii, in the hope of providing a stronger scientific foundation for the management and conservation of these species.

CHAPTER 2:
MANUAL ANALYSIS OF KAUAI EAR DATA FOR BALEEN WHALE OCCURRENCE

2.1 Introduction

Passive acoustic monitoring (PAM) is a very powerful tool for non-invasive and unbiased data collection in remote locations. The ability to collect data over long durations in areas that are not easily accessible and during inclement conditions has become a common technique for surveying for animal occurrence, distribution, and density. Underwater recordings at sites around the globe have been used to detect and classify marine mammals for many decades.

PAM systems are ideal for monitoring projects in the Hawaiian Islands. In the early 1950's Schreiber (1952) described sounds recorded off Oahu and attributed them to whales. These sounds were later identified as humpback whales (*Megaptera novaengliae*) by Schevill (1964). Northrup et al. (1971) described 20 Hz sounds, later attributed to blue whales (*Balaenoptera musculus*), recorded off of Midway Island. In the decades that followed, cabled hydrophones provided an abundance of data to continue describing sounds of whales in close proximity to the Main Hawaiian Islands (MHI). Thompson and Friedl's paper (1982) was one of the first to look at a single dataset and describe multiple species detection and seasonal occurrences off Hawaii. The data were collected on two bottom-mounted hydrophones located offshore north of Oahu. With over two years of data they identified the presence of humpback whales, fin whales (*Balaenoptera physalus*), blue whales, sperm whales (*Physeter macrocephalus*), pilot whales (*Globicephala macrorhynchus*), and boing sounds (identified to be produced by minke whales [*Balaenoptera acutorostrata*]).

Acoustical analyses conducted in Hawaii over the past 50 years reveal that baleen whale species are recorded seasonally. Visual survey effort increased in the 1990's and generally centered on the occurrence and distribution of humpback whales (Mobley et al. 2001). Aside from ubiquitous wintertime sightings of humpback whales, the documented encounters with other large baleen whale species have been extremely rare. Prior to dedicated vessel surveys (Barlow 2002, Bradford et al. 2017) of the Hawaii Exclusive Economic Zone (EEZ) only a handful of fin whale sightings had been made (Mobley et al. 1996) to go along with those reported for Bryde's whales (*Balaenoptera edeni*), sei whales (*Balaenoptera borealis*), minke whales (Rankin and Barlow 2005), and even North Pacific right whales (*Eubalaena japonica*; Herman et al. 1980). While blue whales were one of the first species to be acoustically identified, it was not until a 2010 research cruise assessing cetacean populations in the Hawaii EEZ that the first, and at present only time that blue whales (one sighting of two animals among fin whales) have been seen in Hawaiian waters (Bradford et al. 2017).

It is not a surprise that baleen whales are heard more easily than they are seen. Generally speaking, from insects to large vertebrates, the size of the animal is proportionate to the frequencies of sound that they produce; the larger the animal, the lower the frequency (Ketten 1992, Ketten 1997, Fitch and Hauser 1995, Bennet-Clark 1998, Fitch 2006, Cranford et al. 2008). The sounds that baleen whales produce range from approximately 20 Hz up to 1500 Hz (Figure 2.1, adapted from Mellinger et al. 2007). Sounds below 1000 Hz have significantly lower seawater absorption rates and are able to travel greater distances (Francois and Garrison 1982). Since nearly all baleen whale signals are very low frequencies and can be detected from great distances, the animals do not necessarily have to be close to the PAM devices in order to be detected. It has been estimated that blue and fin whale signals can be detected over hundreds of kilometers as sounds propagate along the deep sound channel axis (Payne and Webb 1971) and others have empirically localized animals at ranges of 56 km to 200 km (Sirovic et al. 2007).

The Hawaiian Islands rise from the seafloor in the middle of the North Pacific and are surrounded by deep water where baleen whale signals can travel relatively long distances. The majority of the large baleen whale sightings have been further offshore away from the coastal Main Hawaiian Islands (Barlow 2002, Bradford et al. 2017). While the majority of vessel traffic

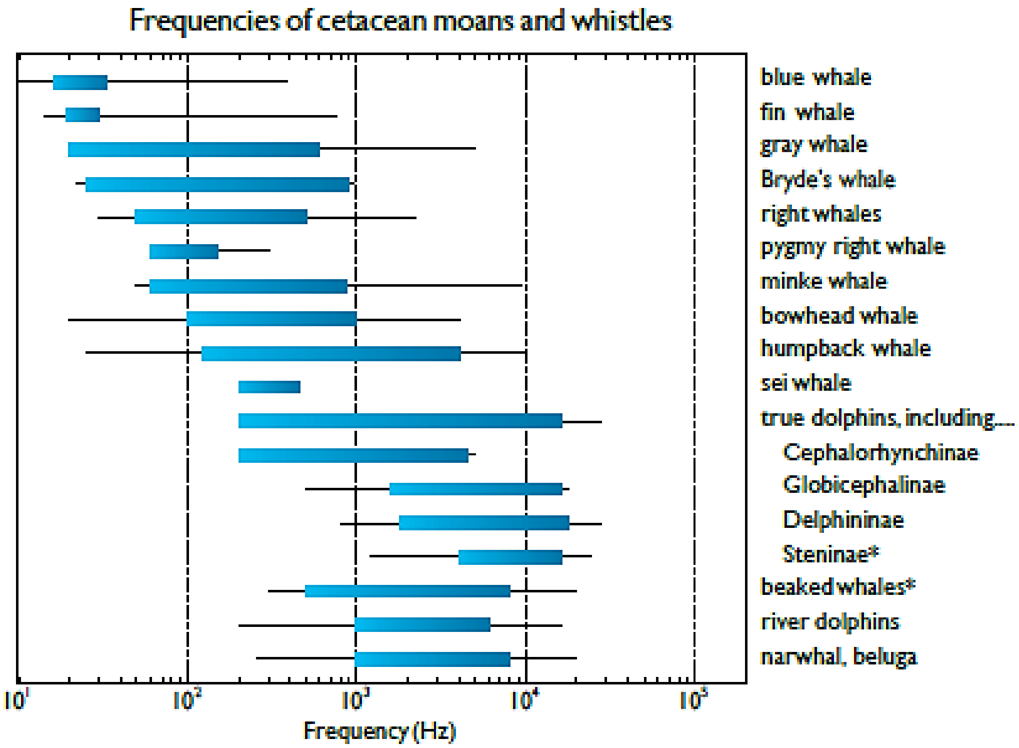


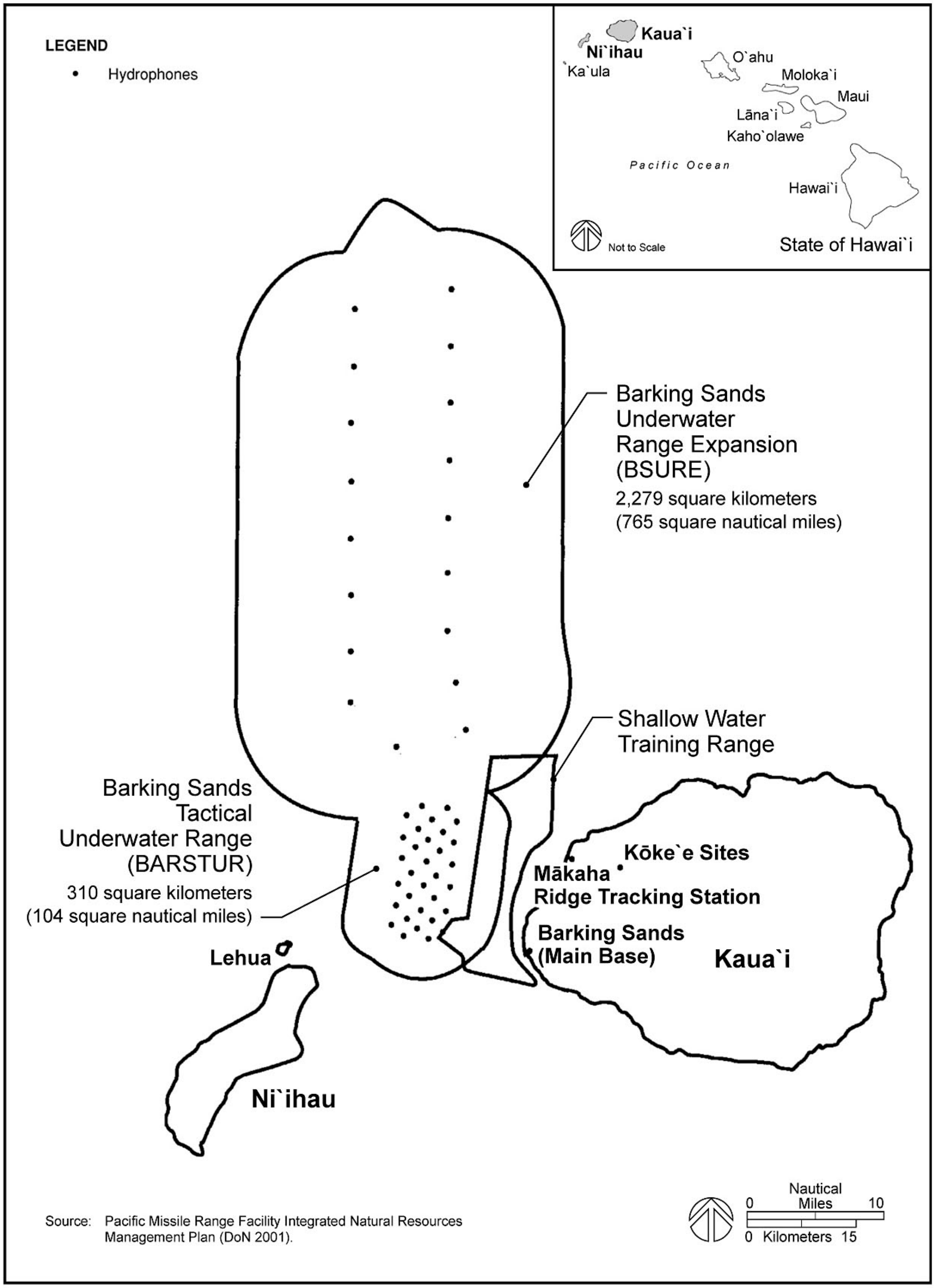
Figure 2.1: Known frequency ranges of cetacean sounds. Large whales are listed by species while toothed whales are grouped into families. The thick bar shows the range of the most common types of vocalizations, while the thinner line shows recorded extremes of frequencies. The asterisk (*) indicates that the upper frequency is unknown (adapted from Mellinger et al., 2007).

and watchful eyes are closer to shore, acoustic detections coastally are a valuable way of determining the presence of baleen whale species that are very rarely seen. However, with the ability for their sounds to travel great distances in deep water, uncertainty would still remain as to how close the animals travel near coastal areas.

Paired acoustic and visual surveys are perhaps the most comprehensive way to assess the occurrence of widely distributed cetacean species. Not all animals will be making noise all of the time and not all animals can be easily seen, particularly those that spend the majority of their lives below the surface. In addition to determining the detection function for visual and/or acoustic encounter rates, for poorly understood species validation of acoustic signals is imperative and can be very difficult to achieve. One of the most notable examples of this in the North Pacific is the boing sound first described by Wenz (1964) from U.S. Navy submarine recordings in the 1950's. The sounds were also recorded in other locations of the North Pacific but not verified as minke until visual sightings were made concurrently with localized positions of the sound (Rankin and Barlow 2005).

The U.S. Navy operates a network of underwater hydrophones (Figure 2.2) off the North and West coast of Kauai that are cabled to the Pacific Missile Range Facility (PMRF) at Barking Sands. The data collected from these hydrophones have been made available to scientists, and numerous studies been conducted to localize and track soniferous marine mammals that pass through the range (Marques et al. 2013, Martin et al. 2013, Helble et al. 2015, Martin and Matsuyama 2015). Many of these studies have been able to use visual sightings to confirm the species being tracked acoustically (Tiemann et al. 2006). In addition to echolocating and whistling odontocetes, many baleen whale species have been studied on the range including humpback and Bryde's whales. Until 2005, the mysterious boing sounds were also tracked on the range, but it was not until the origins were verified as minke whales that the seasonal occurrence and distribution made more sense.

The minke whale boing example underscores the need to understand the sounds that particular species or populations make, in order to begin addressing regionally specific questions of animal species distribution and/or occurrence. Without knowing the full acoustic repertoire of geographically associated populations or without the ability to conduct visual validations of acoustic detections, conservative approaches to acoustic call classification are required. While the signals of some species are very well known, e.g. fin whale 20 Hz pulses, other more generic signals (low-frequency downsweeps) could possibly belong to a number of species likely to occur in a particular area. Nonetheless, documenting ambiguous signals is not without merit. Like the boing, they might later be classified with higher levels of confidence after validation studies are completed. However, without the ability to "search" for highly stereotyped signals that occur very regularly, the most rigorous way to examine particular acoustic datasets



Source: Pacific Missile Range Facility Integrated Natural Resources Management Plan (DoN 2001).

Figure 2.2: The underwater hydrophone ranges located off of Kauai and Niihau. These cabled hydrophones are part of the Pacific Missile Range Facility (PMRF) located at Barking Sands.

is to comb over the recordings manually, which is perhaps the most labor intensive method possible.

For this study, data were collected from bottom-mounted underwater PAM systems deployed near the island of Kauai. The aim of this research was to examine the occurrence of baleen whales based on the detection of stereotyped signals in the acoustic data recorded near the Hawaiian Archipelago (at depths less than 1000 m). Upon cursory examination of files, many different and ambiguous signals were present in the very low frequencies (under 100 Hz). Manual analyses were deemed to be the most reliable way to identify and classify signals of fin, Bryde's, and sei whales and distinguish them from sounds produced by humpback whales and anthropogenic noise sources.

2.2 Methods

Acoustic recordings were made on bottom-moored Ecological Acoustic Recorders (EARs). The EAR is a self-contained microprocessor-based autonomous recorder that samples the ambient sound field on a programmable duty cycle (Lammers et al. 2008). The EARs were deployed at five different sites around the island of Kauai, Hawaii (Figure 2.3) at depths ranging from 395 m to 710 m. Each EAR was paired with an acoustic release and custom syntactic foam collar for recovery and refurbishment. The first deployment at all five sites was February 2009 and the refurbishment cycle was aimed to recover and redeploy each recorder every six months over the project span of two years (EAR locations, recording sampling rate, and recording durations are depicted in Table 2.1). Due to the remote nature of most of the deployment sites, and challenges associated with circumnavigating the island even during calm weather conditions, the EAR recording parameters were set with a 10 percent duty cycle (30s recordings every 5 min). The first two deployments recorded with a sampling rate of 64 kHz (effective bandwidth of 32 kHz) and the final two deployments had an increased sampling rate of 80 kHz (effective bandwidth of 40 kHz). The sampling rate settings would not impact the lower frequencies and the system limitations had a low-frequency limit for signals below 20 Hz.

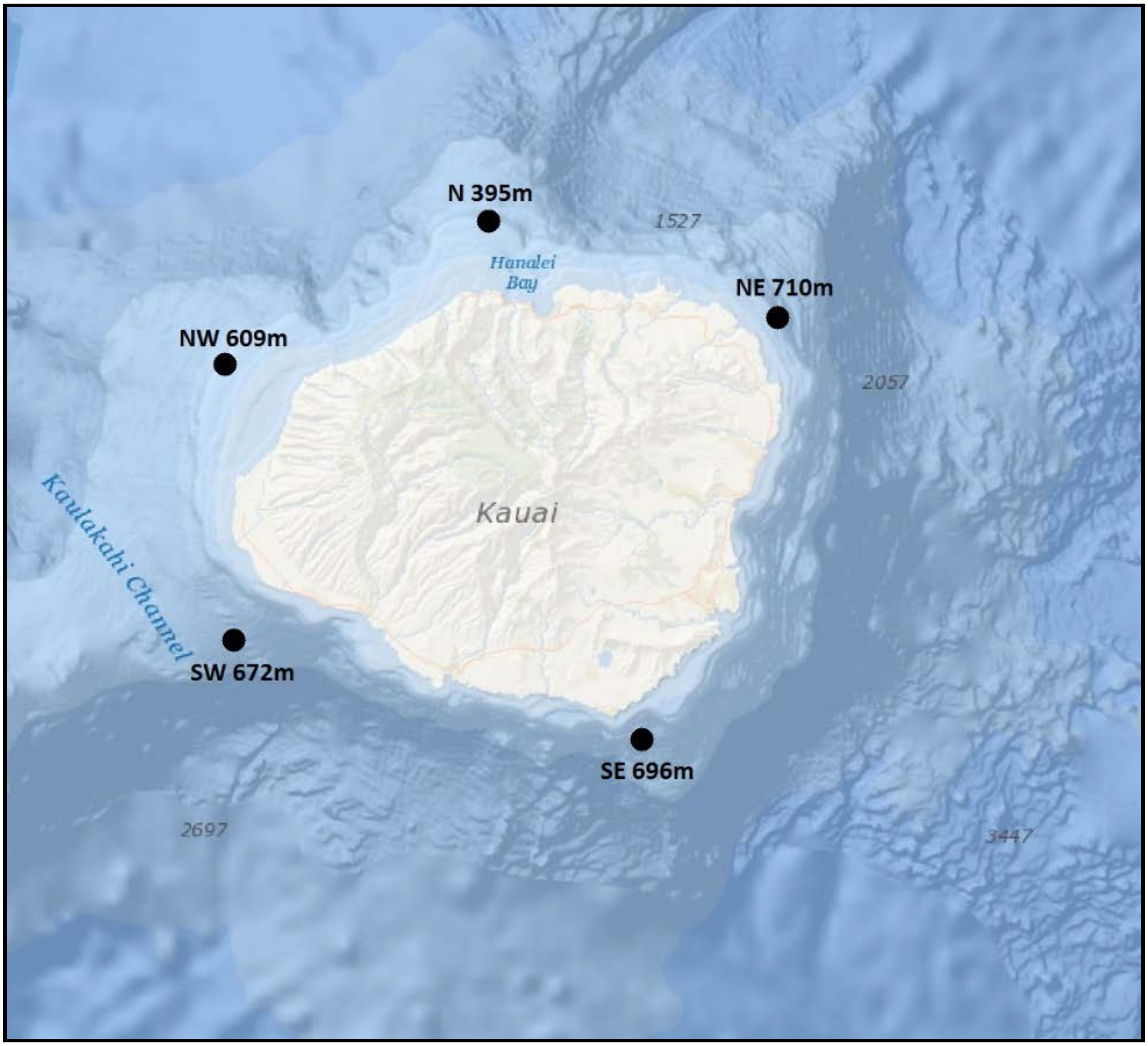


Figure 2.3: Map of Kauai and Niihau indicating the location for each of the EAR deployments. The depths for each deployment are indicated by the site name.

Table 2.1: EAR deployment information for the site location, deployment waypoint, unit depth, recording sampling rate (SR), and the recording durations for each unit on each deployment used for the analysis.

				Deployment 1			Deployment 2			Deployment 3			Deployment 4		
Site	**Latitude (N)**	**Longitude (W)**	**Depth (m)**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**
SE	21 51.577	159 21.542	696	64	10-Feb-2009	6-Mar-2009	64	10-Jun-2009	25-Sep-2009	80	26-Jan-2010	4-May-2010	80	13-Jun-2010	19-Sep-2010
NW	21 11.221	159 50.298	609	64	10-Feb-2009	24-May-2009	64	9-Jun-2009	22-Sep-2009	80	25-Jan-2010	5-May-2010	80	14-Jun-2010	20-Sep-2010
NE	22 08.954	159 14.702	710	64	10-Feb-2009	19-May-2009	64	9-Jun-2009	29-Sep-2009	80	25-Jan-2010	5-May-2010	80	13-Jun-2010	19-Sep-2010

Once the EARs were recovered, the raw acoustic data (.BIN files) were converted to .EWAV files, a variant of WAV files to be used within Triton, a MATLAB™ based analysis tool developed at Scripps Institute of Oceanography (Wiggins 2003). All data were decimated to 8 kHz for low frequency analysis of baleen whale calls. Long-term spectral averages (LTSA) were created for each EAR deployment. LTSAs allow a view longer durations of spectrographic data, to identify periods that may contain frequency bands of interest. After a cursory analysis, and determination that the low-frequency signals of interest (blue, fin, sei, and Bryde's whales) were not reliably and distinctly identifiable when viewing the LTSAs, all data were examined manually on a file by file basis. Trained analysts scrolled through each 30 second file and limited the frequency display to a range of 0 – 400 Hz to maximize their ability to identify low-frequency baleen whale signals. Individual calls were logged, as were the total encounter durations (defined as call bouts that had a minimum of two hours between two files containing logged calls). When calls were found, Triton was used to log the file location, duration, and frequency characteristics. In addition to exporting the call metrics to a spreadsheet, analysts also created sound and image files to be used for quality control. All calls annotated by each analyst were verified before the results were compiled and presented. For any calls that were questionable, other marine mammal acousticians were consulted to further ensure accuracy and consistency.

2.3 Results

Acoustic data were recorded at all five sites around the island of Kauai between February 2009 and January 2011. However, the EARs located at Kauai N (unrecoverable after the third deployment) and at Kauai SW (missing wintertime data from the second deployment) did not have concurrent recordings and these sites were omitted from analyses. Additionally, the EAR located at Kauai NW suffered from equipment failure on the fifth deployment and no data were obtainable. Thus, the 12 datasets collected from the first four deployments at Kauai SE, Kauai NW, and Kauai NE were used to scan for the occurrence of baleen whales (Figure 2.4).

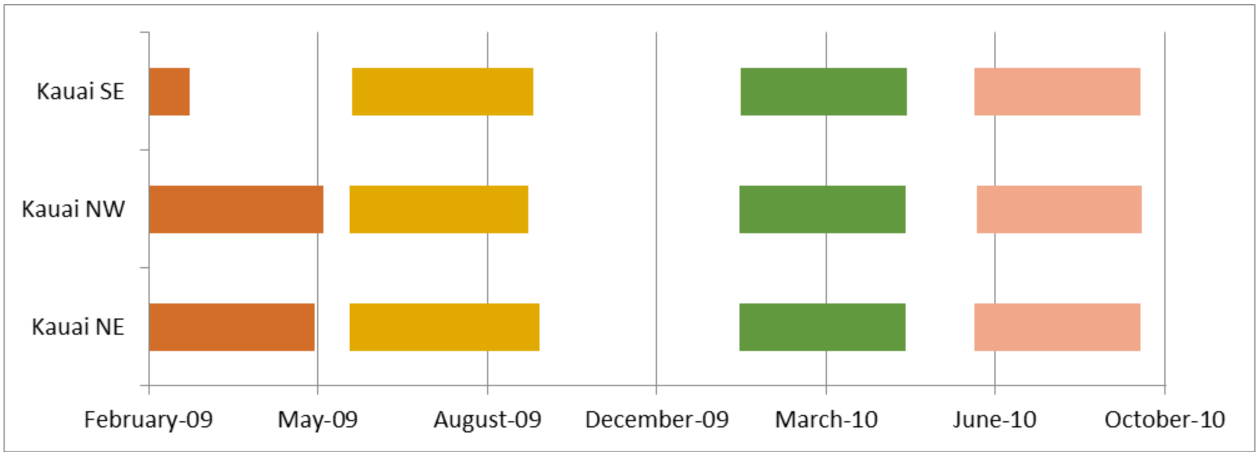


Figure 2.4: Deployment timeline of the EARs that recorded the data used to manually document baleen whale signals.

The 12 datasets had a cumulative number of 327,649 files of acoustic data (Table 2.2). Of these, only 110 files (0.034%) contained sounds produced by baleen whales of interest (fin, sei, and Bryde's whales). In the winter, humpback whales were ubiquitous at each site and for the purposes of this study, their calling behavior was not analyzed. Despite searching between 0 and 400 Hz, no blue whales signals were detected in this two year period.

Fin whales were the most commonly detected species with 18 encounters among all three sites. Their short duration 20 Hz pulsed signals (Figure 2.5) were noted 132 times. These calls were only detected during the winter months with the earliest detection being 25 January (2010). The latest fin whale call was 2 April (in 2009) but the majority of signals were recorded during the month of February.

Sei whale calls (Figure 2.6) were detected at all three sites. The downswept signals had a mean starting frequency of 100.1 Hz and a mean ending frequency of 40.1 Hz. The mean duration of each call was 1.2 seconds. The sei whale signals were recorded primarily in January and February; however, there was one encounter at Kauai NW on 29 June 2009. It is conceivable that this call is not actually produced by sei whales since they are expected to have a wintertime occurrence in Hawaii, but the calls look, and sound, most similar to sei whales.

Table 2.2: Results from manual analyses of the 12 EAR datasets collected around Kauai Island.

			Fin Detections		**Sei Detections**		**Possible Bryde's**		
Site	**Deployment**	**Files Analyzed**	**Encounters**	**Calls**	**Encounters**	**Calls**	**Encounters**	**Calls**	**Total Files with Calls**
Kauai NE	1	28,159	2	3	0	0	0	0	2
Kauai NW	1	29,639	3	29	0	0	0	0	28
Kauai SE	1	6,938	1	18	1	3	0	0	11
Kauai NE	2	32,059	0	0	0	0	0	0	0
Kauai NW	2	30,179	0	0	1	6	1	1	4
Kauai SE	2	30,659	0	0	0	0	0	0	0
Kauai NE	3	28,330	4	13	1	1	0	0	10
Kauai NW	3	28,330	3	7	4	25	0	0	14
Kauai SE	3	28,329	5	62	2	10	0	0	32
Kauai NE	4	28,370	0	0	0	0	2	4	4
Kauai NW	4	28,330	1	2	0	0	1	8	7
Kauai SE	4	28,327	0	0	0	0	0	0	0
	Totals	**327,649**	**18**	**132**	**9**	**45**	**4**	**13**	**110**

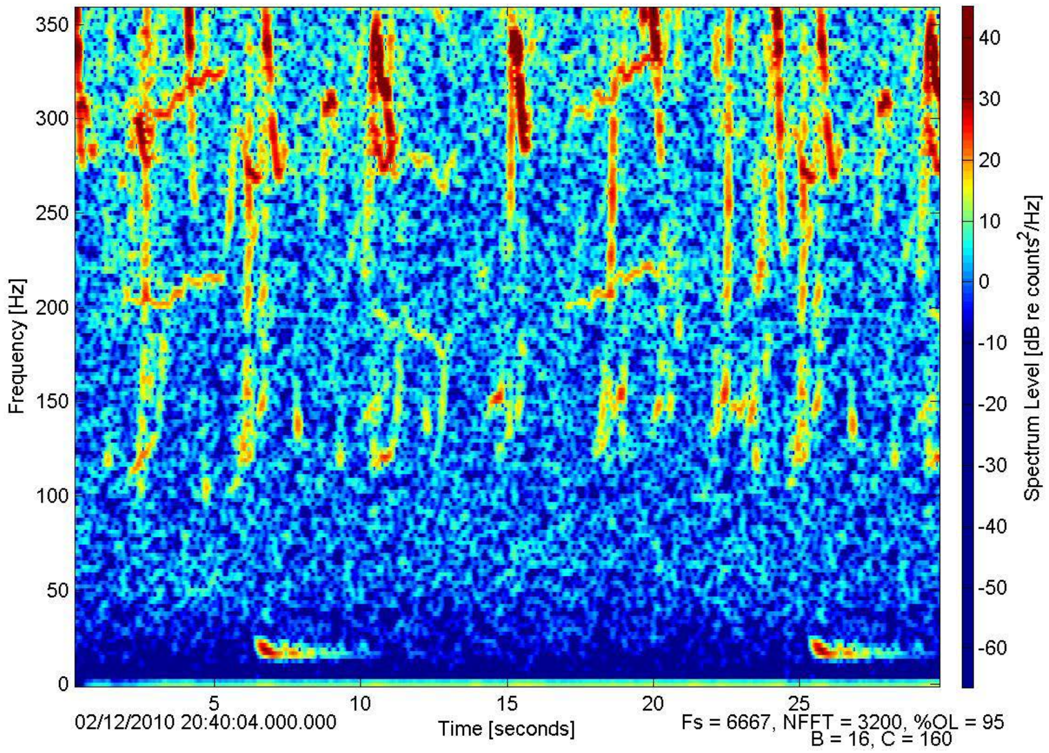


Figure 2.5: Example of fin whale 20 Hz pulse calls recorded on the Kauai EARs. Only the incident pulse was counted, not the reflected sounds that followed.

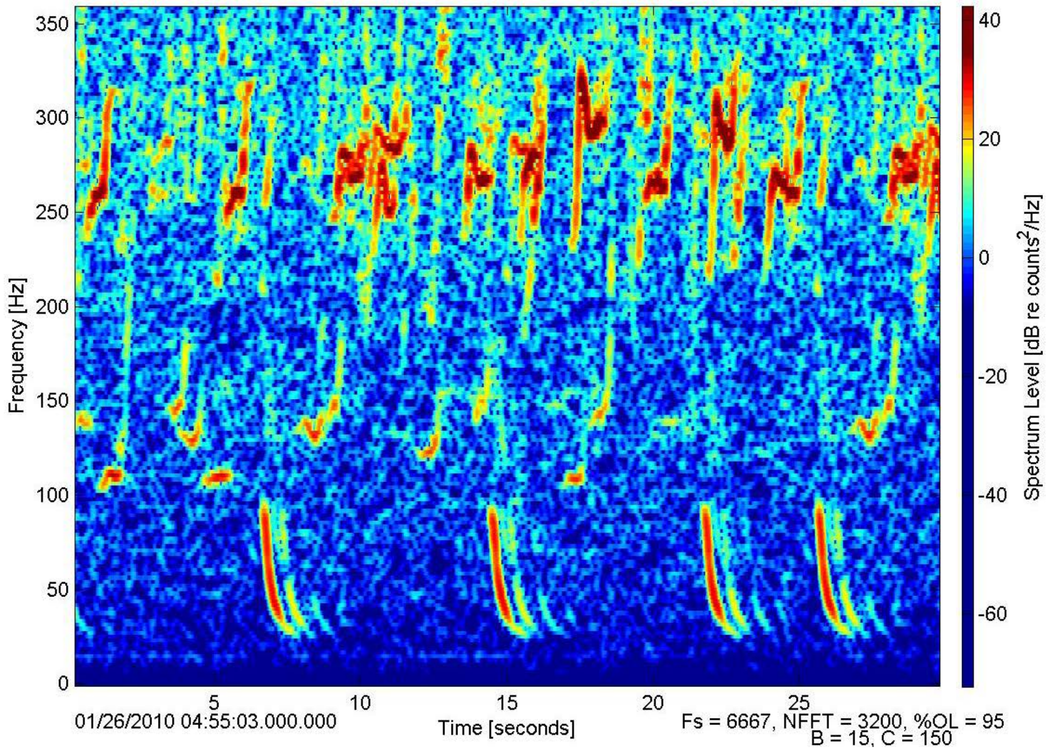


Figure 2.6: Example of sei whale calls recorded on the Kauai EARs. Only the incident signal was counted, not the reflected sounds that followed.

Possible Bryde’s whale signals were also observed (Figure 2.7); however, only for a total of 13 calls during four encounters. Oleson et al. (2003) described six call types recorded in the tropical and subtropical Pacific. The calls recorded on the EARs could be one of two different call types Be1 and Be3. All of these calls were detected on the NW and NE EARs and only in the summertime (June 2009 through August 2010).

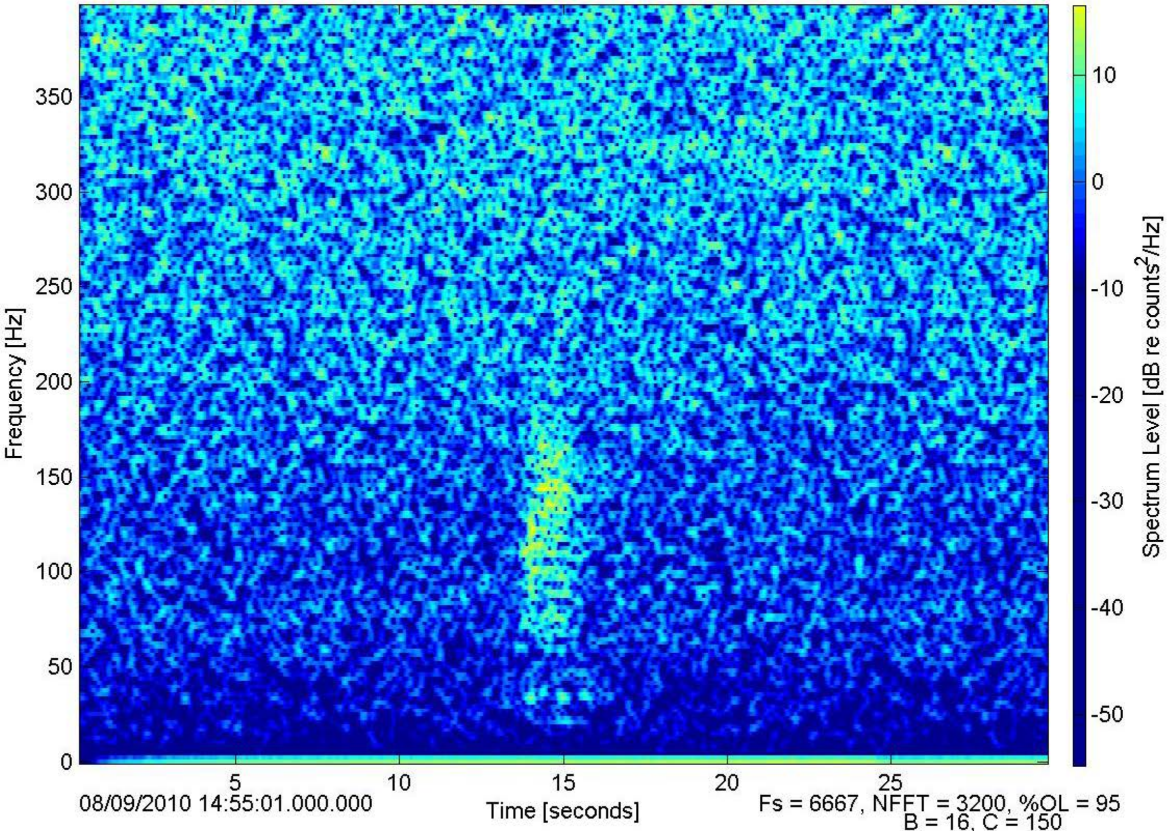


Figure 2.7: Example of possible Bryde’s whale calls recorded on the Kauai EARs.

An unknown sound was recorded on 13 July 2010 at the Kauai NE site (Figure 2.8). This call is most likely produced by a baleen whale and is similar to sounds produced by sei whales but the downsweep is higher frequency than the others observed. This signal was not tallied in the totals for fin, sei, and Bryde’s whales.

Three EAR sites recorded concurrent data for the first four deployments. The units deployed on the northwest and northeast corners, as well as another one on the southeast side

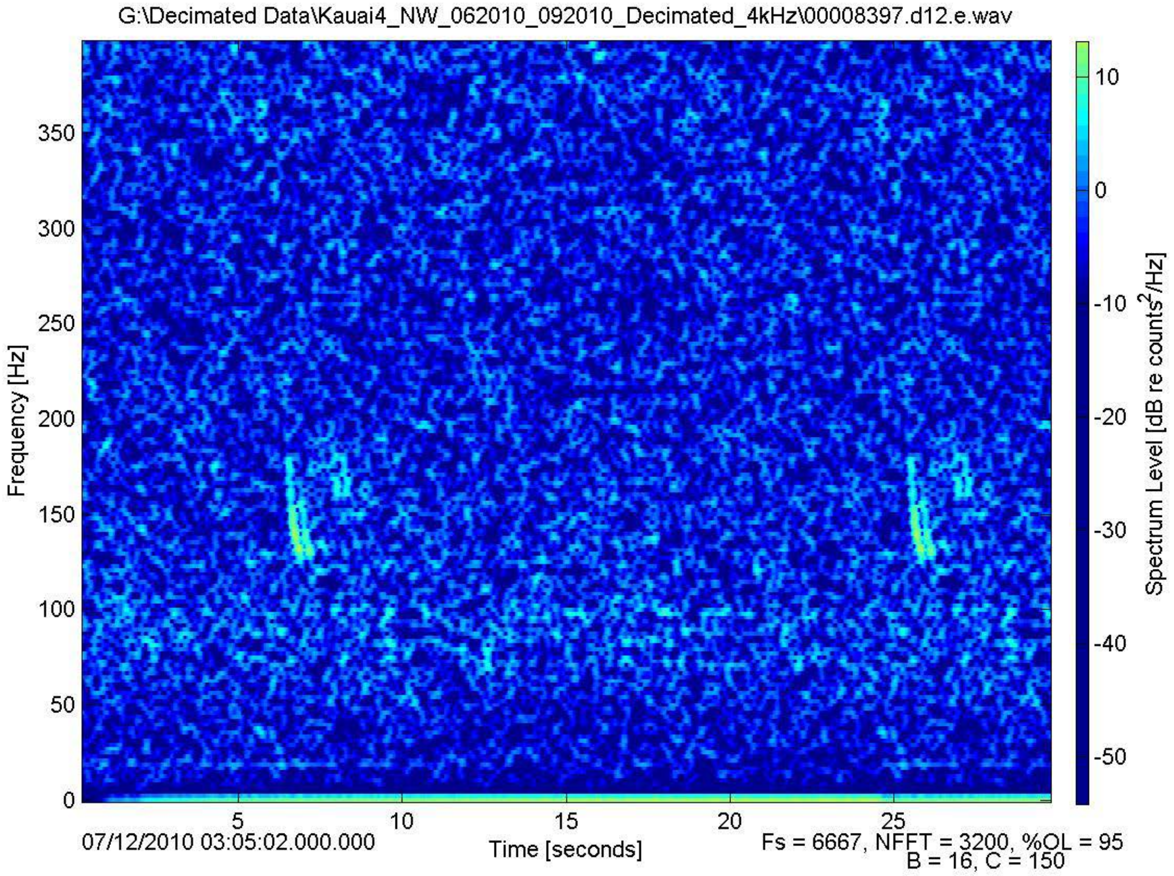


Figure 2.8: Example of unknown call likely produced by a baleen whale recorded on 13 July 2010 at the Kauai NE site.

were three areas that could hopefully provide some comparison of occurrence. All three sites recorded sounds from fin, sei, and Bryde’s whales (Table 2.3); however, the sample sizes were extremely low and no statistical comparisons of detection rates would yield significant results.

Table 2.3: Total number of encounters detected at each of the EAR deployment sites. The number in the parentheses indicate encounters in the summertime (June through August). All of the other encounters are during the winter months (January through April [one fin whale encounter in March and one fin whale encounter early April]).

	Fin	**Sei**	**Bryde’s**
Kauai NE	6	1	2 (2)
Kauai NW	6	5 (1)	2 (2)
Kauai SE	6	3	0

2.4 Discussion

Fin, sei, and Bryde’s whales have all been seen close to the MHI but very few records exist for waters near shore. The ability to acoustically monitor 24 hours per day in all seasons and weather conditions is a robust method for detecting species that are rarely seen. The initial objective of this study was to examine the occurrence of rarely seen whales around the island of Kauai using acoustic data recorded on bottom mounted PAM devices deployed relatively close to the shore.

Of the 327,649 files analyzed manually (each file individually), a surprisingly low number of files (110) detected fin, sei, or Bryde’s whales. This detection rate of 0.0003 per file was significantly lower than expected since all three species are known to occur near the MHI, and the acoustic propagation of signals in deep water would augment the detection rates of whales that were not in direct proximity to the instruments. The number of detections may have also been higher had the first wintertime deployment of the EAR at the Kauai SE site had not suffered a malfunction; however, the detection rates would still be much lower than anticipated at the outset of the study.

There was a total of 31 encounters for all three species. Each species was observed at all three sites with the exception of Bryde’s whales that were not detected on the Kauai SE EAR. Most of the encounters were very brief (5 to 40 minutes). The longest encounters were 290 minutes for a sei whale and 210 minutes for a fin whales. The short duration of the encounters likely indicates animals in transit. Localization was not possible with these data to confirm this; however, the calls appeared to have consistent signal to noise ratios indicating that only one individual was producing them while traveling. This is unlike the stationary singing behavior of humpback whales (Payne and McVay 1971) on the breeding grounds

Detections of blue and right whales were not made during this two year sampling period. Humpbacks were ubiquitous during all wintertime months and confounded the ability to detect other low-frequency whale signals, thus necessitating the manual analysis approach to validate detections. The signals of minke whales were also present during wintertime months although the frequency range used for the manual analyses (0 to 400 Hz) precluded logging those higher frequency signals. North Pacific right whales have been seen in Hawaii on very rare occasions and their calls would be detectable in the frequency band examined in this study. However, no signals similar to those described by McDonald and Moore (2002) were observed in the data. The only other baleen whale that occurs in Hawaiian waters is the blue whale. Their stereotyped AB calls (Stafford et al. 2001, Oswald et al. 2016) are longer duration (~20 seconds) and the window to capture the entirety of those calls in one 30 second EAR file is very slim. Their variable Type D calls (Oleson et al. 2007) have been recorded around Hawaii but in the coastal environment where humpback whales are extremely prevalent, making it difficult to distinguish the blue whale downsweeps produced in the same frequency range. Type D blue whale calls were targeted but none were verified in the datasets.

Visual data is concordant with the EAR data in confirming the presence and relative abundance of three baleen whale species. The most recent comprehensive survey of marine mammals within the Hawaii EEZ was in 2010, coincidentally during the same time that the EARs were deployed and recording off Kauai (Bradford et al. 2017). A single sighting of a blue whale approximately 460 kilometers to the northwest of Kauai was the first confirmation of their presence in Hawaiian waters, beyond the acoustic detections noted since the 1950's. Bryde's whales were the most abundant species observed, with a total of 32 sightings. There were also two sightings each for fin and sei whales. The Bryde's whales were the only species to be seen close to the MHI and even then, they occurred west of Kauai and Niihau (Figure 2.9).

The survey in 2010 was a follow up to a 2002 research cruise (Barlow 2004). Bryde's, fin, and sei whales were also seen during these efforts with the most common also being Bryde's (n=13) followed by sei (n=6) and fin whales (n=5). All of these sightings were also west of Kauai and this survey was the first to document sei whales in Hawaiian waters. The important thing to note about both of these EEZ surveys is that they occurred during the summer and fall

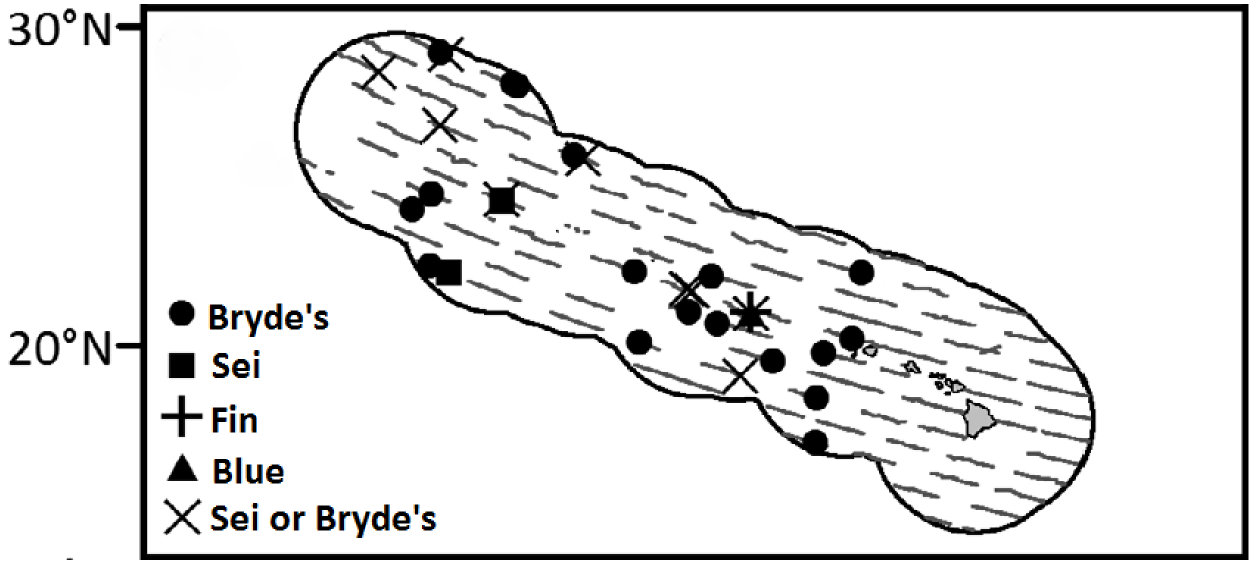


Figure 2.9: Visual sightings of baleen whales made during the 2010 survey of the Hawaii EEZ. The squiggly lines inside the outlined area indicate the effort trackline for the survey when observers were actively searching for animals. Adapted from Bradford et al., 2017.

months (August through November). Baleen whales are expected to be seasonal migrants to the lower latitude waters around Hawaii and if these projects were conducted during winter months, the detection rates for all baleen whales would likely differ.

The PMRF bottom-mounted hydrophone arrays have also been used to document the occurrence of baleen whales and their proximity to Kauai. Researchers have been able to track and localize individual singing humpback whales, minke whales, and Bryde’s whales (Marques et al. 2012, Martin et al. 2013, Helble et al. 2015, Martin et al. 2015). In addition to applying density estimation and abundance techniques, the ability to track the movements of individual whales has been helpful to document their occurrence and calling behavior. Helble et al. (2015) was able to depict the movement of individual humpback whales and noted that their behavior did not depart from what was already known about their movement and singing behavior. The follow on work was also able to track the calling of individual Bryde’s whales. In contrast to the EAR encounters, the animals on the PMRF range had long vocal bouts and multiple individuals were observed calling at the same time and moving parallel to one another, however, separated by many miles. The fact that the EAR was not able to detect the same number of Bryde’s whales may simply be due to deployment close to the island. The EARs have a depth limitation of 1000 meters and the PMRF range has hydrophones in much deeper water; where most of the Bryde's whales were detected.

While the initial aim of this study was to look at the seasonal distribution and spatial occurrence around Kauai Island, the low detection rates precluded applying meaningful metrics to examine this in detail. The conclusion after conducting thorough manual analyses on the data is simply that baleen whales that are infrequently seen close to the island are also very infrequently heard. The acoustic data from this study corroborates the visual data; we don't see nor hear the whales close to the island of Kauai. While the detection distances is likely significantly further for acoustic data, the scant number of encounters over two years of geographically spaced PAM data collection is an example of where the lack of positive results (detections) are meaningful. The paucity of acoustic encounters on the EARs further confirms what has been observed from dedicated shipboard surveys and from acoustic studies conducted on the PMRF range; (1) these species do occur in Hawaiian waters and (2) we should not expect to encounter them with any regularity at close proximities to the shore.

CHAPTER 3:
ASSESSMENT OF AUTOMATED ANALYSES FOR BALEEN WHALE CALLS RECORDED OFF OF KAUAI, HAWAII

3.1 Introduction

Animals (vertebrate and invertebrates alike) produce sound for a wide variety of social and survival needs. Intraspecific communication for reproductive displays, territoriality, group cohesion, migration, and a multitude of communicative purposes in addition to prey detection and localization are well documented across multiple taxa. The ability to correctly classify animals by the sounds they make has proven to be extremely useful for biological studies and species conservation and management. Passive acoustic studies in terrestrial ecosystems have been successfully used to monitor frog populations (Driscoll 1998, Bridges and Dorcas 2000, Bee et al. 2001, Rödel and Ernst 2004), but perhaps the most studied terrestrial animals are birds. Their songs and call production have been published in scientific literature for over a century. From species occurrence, to population surveys and from migratory routes through population structure, their acoustic behavior has been extremely well documented. In the first edition of *The Auk*, Bicknell (1884) described how bird song is not used for scientific purposes beyond descriptive purposes and does not have its own designated area of study. Today, it would be difficult to conduct a literature search on bioacoustics without examining, and acknowledging, the significant contributions of ornithologists. In 1935, Albert Brand used motion picture photography to record bird sound and study call characteristics. The ability to record sounds and examine it in detail has led to an incredibly diverse and technical scientific field.

Recording sound underwater is much more prohibitive, and less intuitive that terrestrial acoustics; however, remote recording stations have been used since the 1950’s (Nishimura and Conlon 1993). The U.S. Navy has been at the forefront of ocean acoustics since before World War II. While the initial efforts were primarily focused on military applications, eventually underwater assets were opened up to research and, after the cold war, included access to the

Sound Surveillance System (SOSUS) arrays. These cabled hydrophones were developed to passively track the sounds produced by submarines and, as such, were also ideal for tracking the low-frequency sounds of baleen whales in the Pacific and Atlantic (Clark 1995).

Acoustic research has always been integral to the study of marine mammals and has been very complimentary to traditional visual survey methodology. Hydrophones deployed from boats in the presence of wild animals were the first to tease out the sounds that different species make and, in certain circumstances, the context in which they were produced. Passive acoustic techniques to study and monitor for marine mammal occurrence and distribution are becoming more prevalent, particularly in remote areas of the world. The rate of technological development has allowed for recorders to be more compact, be deployed for longer durations with increased storage capacity, with improved bandwidth capabilities, and in some cases with on-board processing for signal detection. As the technology improves so do the analyses and acoustic data that are now being used to assess animal occurrence, behavioral responses, population trends, population density, and many other developing applications.

With the advancements of hardware technology and amassing of large datasets, a secondary need is established; efficient and reliable data analysis for signals of interest. Copious volumes of data are commonly archived and for passive monitoring without on-board filtering or signal processing, post-processing data is an arduous, extremely time consuming, and expensive effort. As is the point with the data collection, the need to find signals efficiently and accurately is paramount. There are many different approaches for detection and classification of sounds; however, in the case of marine mammal vocalizations, there is no panacea. Animal sounds, while often stereotyped, are highly variable and generally regionally specific within the same species (Thomas and Stirling 1983, Moore and Ridgeway 1995, Deecke et al. 2000, McDonald et al. 2006, Papale et al. 2013). So, while one technique or algorithm may be trained for a species in one region, it will likely not perform consistently or effectively for the same species in other regions. Other confounding issues for detecting signals in broadband acoustic data include masking noise sources (anthropogenic or environmental), interspecific vocal production, the transient nature of bioacoustic sounds, as well as the contextual use of sound production.

Despite the numerous challenges to developing reliable automated detectors, the sounds of many animals are very well suited their use. The first step in processing large datasets is to know what one is looking for. Recordings of wild populations and of animals in captivity have provided a catalogue of sounds that are not only unique for species and populations, but also demonstrative of the most instrumental component; stereotypy of sounds to provide a template for detection and classification. Baleen whales often produce very low frequency (predominantly under 150 Hz) and repetitive calls with very little structural variation. The most commonly used detectors are template-matching. Stafford et al. (1995) used a match filter to scan for blue whale (*Balaenoptera musculus*) calls recorded off the coast of central California. Templates were created from analyzed call components and the filter was convolved with the original time-series data to look for correlation peaks to indicate the presence of blue whales. Similarly, spectrogram correlation can be used to scan for template signals with high correlation peaks (Mellinger and Clark 1997, Mellinger and Clark 2000, Urazghildiiev and Clark 2007).

The use of detectors has become very prevalent in marine mammal monitoring and mitigation. Based on the matched-filtering techniques, near real-time detection of large whales is used for endangered North Atlantic right whale (*Eubalaena glacialis*) to avoid ship strikes in busy U.S. east coast waterways (Moscrop et al. 2001, Clark et al. 2005, Spaulding et al. 2009). Additional development of detectors using pitch tracking has been an effective tool as well. Pitch tracking, also called edge detectors or contour extractions, trace the fundamental frequency of all sounds in a spectrogram and correlate those characteristics with templates of known signals or compare them to known attributes of the desired call (Gillespie 2004, Urazghildiiev et al. 2009, Baumgartner and Mussoline 2011, Ou et al. 2013). This method is often much more computationally efficient and allows for smaller packets of data to be transferred to shore stations for near real-time monitoring. The ability to run detection and classification algorithms with on-board processors allows for the transmission of “results” rather than raw data needing post-processed analyses. While some of the detections may be falsely classified, the majority of effort has already been concluded by the time an experienced analyst reviews and confirms the presence of endangered right whales. Once an animal has been detected near the monitored shipping lanes of Boston Harbor, alerts are disseminated to commercial vessels and other operators in the area. The mitigation efforts to slow vessels in the area are much more successful with the use of automated signal detection and classification.

While the ability to detect whales near real-time is an emerging reality, the vast majority of acoustic data are archived and require analysts to find signals of interest. Detectors are incredibly useful and continue to be refined to reliably identify more species and in variable noise conditions. However, before any particular detector can be relied upon exclusively, it is necessary to first test its efficacy and ground-truth as much data in different recording environments as feasibly possible. Detector performance is subject to variations in the signal quality, changing ambient levels, masked signals due to other biologic or anthropogenic sources, geographic contours, seasonality and vocal behavior, and many other confounding circumstances. Ideally, automated detectors will be able to identify all the instances that a signal is found in a particular dataset. Realistically, even the most skilled and well trained human analyst will not be able to identify and locate each signal due to the many issues affecting the signal-to-noise as well as the aural and visual (most use spectrograms to visually scan acoustic data) degradation of signals in broadband data. Ultimately a balance will need to be achieved with regard to the allowable number of missed detections coupled with false detections. Fine-tuning detection thresholds for one dataset will likely need to be adjusted for another dataset recorded at a different time and location, but all automated techniques will need to be assessed for accuracy and consistency depending on the goals of the study. If occurrence trends are the aim, the thresholds can be lowered and false detection rates may be more allowable than missed detections (Mellinger 2004, Munger et al. 2005). However, if one is trying to conduct abundance estimation and/or other population level statistical analyses, the missed detections cannot be sacrificed. Regardless, using a detector should be done with a modicum of scrutiny as well as forgiveness.

Many studies have evaluated the effectiveness of automated detectors compared to skilled manual analyses. In addition to marine mammal studies, automated systems have been used for a diverse array of marine and terrestrial taxa (Mann and Lobel 1995, Bridges and Dorcas 2000, Rempel et al. 2005, Acevedo and Villanueva-Rivera 2006, Menhill et al. 2006, Tremain et al. 2008, Bardeli et al. 2010). Terrestrial surveys, or those in more confined ecosystems, are perhaps the better option for assessing automated techniques versus human analysts or other traditional survey methodology. Whereas remote underwater recordings for marine mammals requires an assumption that you are recording all animals that pass within an acoustically detectable range, terrestrial surveys can actually compare the number of known animals being soniferous to those detected using passive recorders. Despite the advantages and disadvantages of accurately measuring the correct classification rates relative to known animal occurrence, the outcome of the comparisons between automated and manual analyses are similar; the tradeoff between correct classification, missed detections, and incorrect/false positives will always need to be considered. Before publication, particularly for studies relying on passive acoustic monitoring to assess population abundance, risk, and exposure, validation is essential. While the entire dataset does not need to be screened using both techniques, a subset of automated results will need to be examined to test detector performance.

For this study, a large volume of underwater recordings had already been screened manually to identify low-frequency calls produced by large baleen whales around Kauai Island, Hawaii. Downswept signals of fin whale (*Balaenoptera physalus*) and sei whales (*Balaenoptera borealis*) were identified amongst three different deployment sites. Having a large validated dataset provides a unique opportunity to compare automated detectors and their ability to correctly locate and classify very infrequent baleen whale signals. Two different automated detectors were used to scan the data for fin and sei whale signals for comparison with labor-intensive manual analysis.

3.2 Methods

3.2.1 Field Recordings

Acoustic recordings were made on bottom-moored Ecological Acoustic Recorders (EARs). The EAR is a self-contained microprocessor-based autonomous recorder that samples the ambient sound field on a programmable duty cycle (Lammers et al. 2008). The EARs were initially deployed at five sites around the island of Kauai, Hawaii (Figure 3.1) at depths ranging from 395 m to 710 m. Each EAR was paired with an acoustic release and custom syntactic foam collar for recovery and refurbishment. The first deployment at all five sites was February 2009 and the refurbishment cycle was aimed to recover and redeploy each recorder every six months over the project span of two years (EAR locations, recording sampling rate, and recording durations are depicted in Table 3.1). Due to the remote nature of most of the deployment sites, and challenges associated with circumnavigating the island during calm weather conditions, the EAR recording parameters were set with a 10 percent duty cycle (30s recordings every 5 min). The first two deployments recorded with a sampling rate of 64 kHz (effective bandwidth of 32 kHz) and the final two deployments had an increased sampling rate of 80 kHz (effective bandwidth of 40 kHz). The sampling rate settings would not impact the lower frequencies and the system limitations had a low-frequency limit for signals below 20 Hz. Technical problems corrupted the data at two sites (see Chapter 2), so the final data set is based on the three sites described in Table 3.1

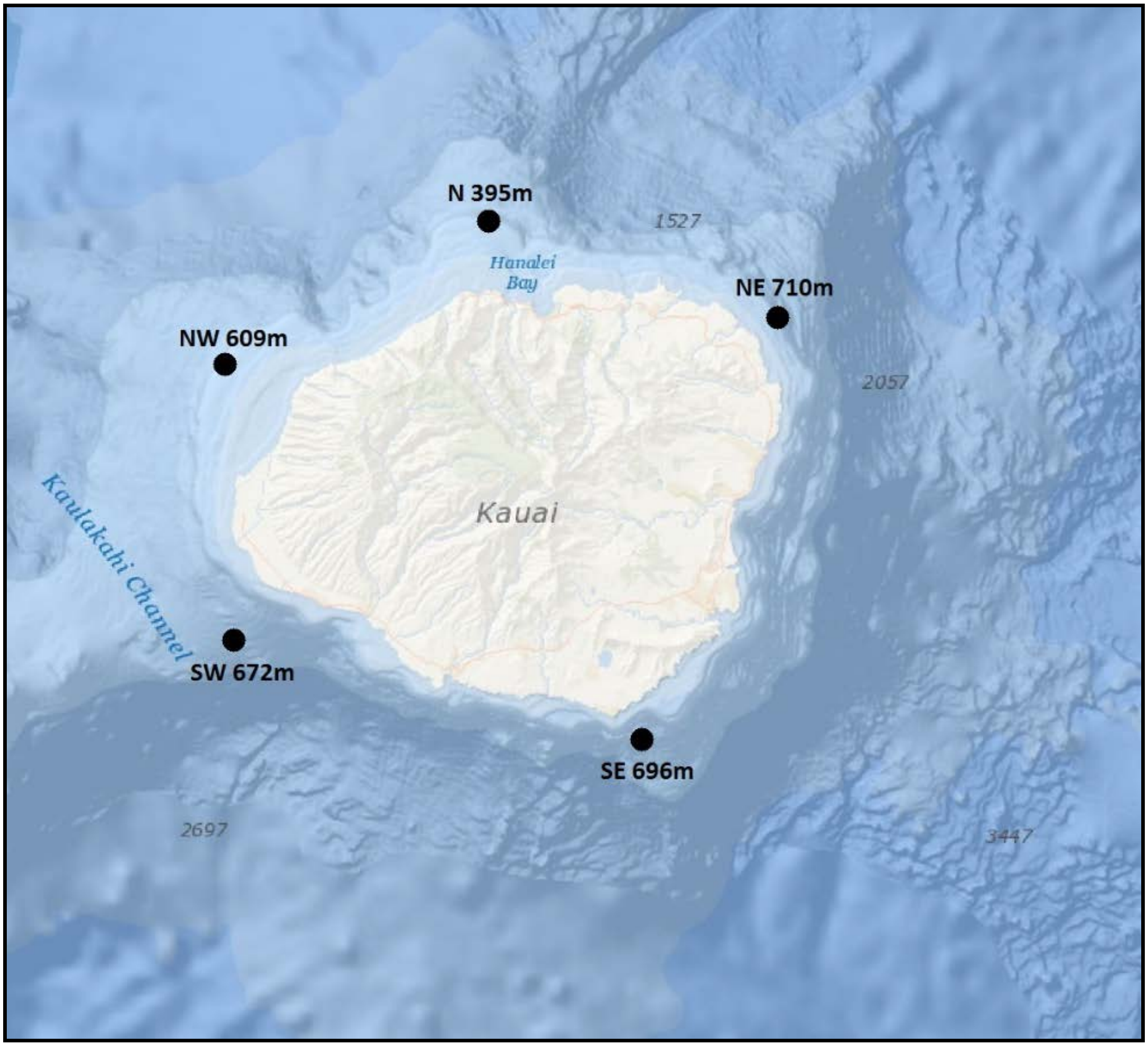


Figure 3.1: Map of Kauai indicating the location for each of the EAR deployments. The depths for each deployment are indicated by the site name.

Table 3.1: EAR deployment information for the site location, deployment waypoint, unit depth, recording sampling rate (SR), and the recording durations for each unit on each deployment used for the analysis.

				Deployment 1			Deployment 2			Deployment 3			Deployment 4		
Site	**Latitude (N)**	**Longitude (W)**	**Depth (m)**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**	**SR (kHz)**	**Start Recording**	**End Recording**
SE	21 51.577	159 21.542	696	64	10-Feb-2009	6-Mar-2009	64	10-Jun-2009	25-Sep-2009	80	26-Jan-2010	4-May-2010	80	13-Jun-2010	19-Sep-2010
NW	21 11.221	159 50.298	609	64	10-Feb-2009	24-May-2009	64	9-Jun-2009	22-Sep-2009	80	25-Jan-2010	5-May-2010	80	14-Jun-2010	20-Sep-2010
NE	22 08.954	159 14.702	710	64	10-Feb-2009	19-May-2009	64	9-Jun-2009	29-Sep-2009	80	25-Jan-2010	5-May-2010	80	13-Jun-2010	19-Sep-2010

3.2.2 Manual Data Analysis

Once the EARs were recovered, the raw acoustic data (.BIN files) were converted to .EWAV files, a variant of WAV files to be used within Triton, a MATLAB™ based analysis tool developed at Scripps Institute of Oceanography (Wiggins 2003). All data were decimated to 8 kHz for low frequency analysis of baleen whale calls. Long-term spectral averages (LTSA) were created for each EAR deployment. LTSAs allow for viewing longer durations of spectrographic data to more easily assess periods that may contain energy in the frequency bands of interest. After a cursory analysis, and determination that the low-frequency signals of interest (blue, fin, sei, and Bryde's whales) were not reliably and distinctly identifiable when viewing the LTSAs, all data were examined manually on a file by file basis. Trained analysts scrolled through each 30 second file and limited the frequency display to a range of 0 – 400 Hz to maximize their ability to identify low-frequency baleen whale signals. Individual calls were logged, as were the total encounter durations (defined as call bouts that had a minimum of two hours between two files containing logged calls). When calls were found, Triton was used to log the file location, duration, and frequency characteristics. In addition to export the call metrics to a spreadsheet, analysts also created sound and image files to be used for quality control.

3.2.3 Automated Data Analysis

Baleen 5 Detector

Baleen 5 is a MATLAB^{TM} algorithm developed by Dr. Helen Ou at the University of Hawaii. The detector scans datasets for five baleen whale species: humpback (*Megaptera novaengliae*), minke (*Balaenoptera acutorostrata*), blue (*B. musculus*), fin, and sei whales. The detector for each species functions by searching for spectral peaks within a defined frequency band and duration. The full bandwidth raw .BIN files are used as the data input and baleen 5 decimates the data to an effective sampling rate of 1 kHz. The next step was to analyze the data using bandpass filters to obtain the signals in the desired frequency ranges for each species (Table 3.2). Next, an envelope detector was applied to determine the mean ambient noise level in order to identify signals that had a higher intensity above the background levels (a minimum of 3 dB difference). Finally, a spectrogram template was used to calculate the beginning and ending frequencies as well as the slope of each identified signal. The output is a Microsoft Excel file identifying the file with each detection, the data, the detection type, the start time, end time, signal duration, the signal to noise value (in dB), the beginning and ending frequency, and the slope of the downswept signal (in Hz/s).

Table 3.2: The criteria used by Baleen 5 for fin and sei whale detections.

Species	Duration	Frequency
Fin Whale	0.5-1.0 sec	60-18 Hz Downsweep
Sei Whale	0.5-1.0 sec	100-40 Hz Downsweep

Since only fin and sei whales were identified in the manual analysis of the data, these were the only two species selected for the baleen 5 automated detection. The frequency and duration criteria used to define fin and sei whales is presented in Table 3.2. The results produced by baleen 5 were then validated against the manually scanned data to determine the number of correct classifications, the number of missed detections, and the number of false detections.

Raven Detector

Raven is a sound analysis software tool developed by the Bioacoustic Research Program at the Cornell Lab of Ornithology (Cornell University). The software package is a versatile suite of tools for recording, visualizing, and conducting detailed analyses of acoustic data. Large datasets can be imported into Raven and a number of customized detection algorithms can be applied to located signals of interest. For this analysis, I collaborated with researchers at Cornell University to run their pre-defined fin whale detector on the EAR data collected in Hawaii. The detector used a spectrogram template and correlation function to scan for fin whale pulses (20 Hz and 40 Hz downsweeps). The thresholds for detection were deliberately set low in order to minimize any missed detections. The default threshold for the fin detector is 0.2 on a 0-1 scale. Each detection is assigned a correlation “score” and this can be used to further assess the likelihood of correct classification when being reviewed manually. While the score is a somewhat subjective tool and does not empirically define correct vs. incorrect classifications, in generally the false positives (incorrect classification) increase substantially once the score is below 0.6.

Since the output annotates files in the original input dataset, all detections can be quickly recalled in the Raven software to allow for efficient manual validation of all signals. Once the detectors were run on all of the EAR datasets, I was able to review each fin whale call to determine the number of correct classifications, false positives, and missed detections.

Detector Performance

In order to assess the performance of automated detectors against manually verified data, one can use the metrics for precision, recall, and F-scores. Precision is a measure of exactness. For example, a value of .95 indicates that 95 percent of the detectors classifications are in fact actual and true detections. Recall is a measure of completeness where the higher the value indicates the ability for the detector to classify all of the possible calls. For example, a recall score of 0.75 means that the detector was able to classify 75 percent of the total possible calls for a given species. However, it is important to note that the recall metric does not reflect the number of false detections (incorrect classifications). Since neither the precision nor recall can accurately assess the overall performance of the detector, they do need to be evaluated together. The F-score takes into account the precision and recall performance and ranges from 0 to 1. The higher the F-score, the “better” the detector is performing.

Precision is calculated as:

Equation 1: $$P = \frac{\#\,True\ Positive}{\#True\ Positive + \#False\ Positive}$$

Recall is calculated as:

Equation 2: $$R = \frac{\#\,True\ Positive}{\#True\ Positive + \#Missed\ Detections}$$

F-score is calculated as:

Equation 3: $$F = 2 * \frac{P*R}{P+R}$$

3.3 Results

Due to the large volume of acoustic data collected at three sites over four deployments, the pragmatic approach to efficiently analyze the data might have been to employ automated detection algorithms to look for signals of interest. While automated detection algorithms were not expected to detect and classify every call, validation of signal subsets and/or the ability to locate instances where calls may have been present, would still be valuable and save a substantial amount of time and effort over manual analysis techniques. The Baleen 5 detector was initially run on a few datasets; however, after cursory examination, there was a significant amount of false positive (incorrect) detections and no ability to reliably locate low-frequency, non-humpback or minke, baleen whale signals in the data, or even narrow down instances in the data where it would be fruitful to focus manual searching. False positive detections and classifications were commonly triggered by low-frequency sounds extending below 150 Hz produced by humpback whales. These signals, often downswept, would occur in the same band needed to distinguish sei whales. Additionally, there was a tremendous amount of both broadband and tonal noise in the frequency bands where short duration signals would be found. The masking of signals below 50 Hz would obscure fin whale pulses with lower signal to noise ratios.

As a result of the inconsistent and unreliable results produced by automated detection algorithms, the method was abandoned and manual analyses was conducted on 12 of the datasets recorded around Kauai. Blue whale call classification is an option in Baleen 5; however, their A and B calls were not searched for in the EAR data due to the length of their signals (often in excess of 20 seconds) and the short duration of the recordings with the duty-cycled used (30 seconds). While variable Type D calls have been detected in Hawaiian waters at Station ALOHA, humpback production of abundant low-frequency downsweeps occurring below 250 Hz precluded the ability to identify the blue whale calls with any confidence, particularly since they were both variable in nature.

The exhaustive manual searching for fin and sei whale signals (previous chapter) amongst the 327,649 acoustic files yielded only 100 files contained signals of fin or sei whales (Table 3.3). The total number of manually annotated fin whale calls was 132 (18 total encounters) and 45 (9 total encounters) for sei whales.

Table 3.3: Results from manual analyses of the 12 EAR datasets collected around Kauai Island.

			Fin Detections		Sei Detections		
Site	**Deployment**	**Files Analyzed**	**Encounters**	**Calls**	**Encounters**	**Calls**	**Total Files with Calls**
Kauai NE	1	28,159	2	3	0	0	2
Kauai NW	1	29,639	3	29	0	0	28
Kauai SE	1	6,938	1	18	1	3	11
Kauai NE	2	32,059	0	0	0	0	0
Kauai NW	2	30,179	0	0	1	6	3
Kauai SE	2	30,659	0	0	0	0	0
Kauai NE	3	28,330	4	13	1	1	10
Kauai NW	3	28,330	3	7	4	25	14
Kauai SE	3	28,329	5	62	2	10	32
Kauai NE	4	28,370	0	0	0	0	0
Kauai NW	4	28,330	1	2	0	0	0
Kauai SE	4	28,327	0	0	0	0	0
	Totals	**327,649**	**18**	**132**	**9**	**45**	**100**

The Baleen 5 fin whale detector made a total of 2,253 fin whale detections compared to the 132 true positives that were found manually in the same files (Table 3.4). Surprisingly, only 5 of the detections were correct (example in Figure 3.2) and the 127 missed detections were of signals that met the criteria for fin whale 20 Hz pulses in the detector. The incorrect classifications were triggered by the unknown low-frequency noise around 20 Hz (Figure 3.3). The unidentified noise was often continuous and would mask low signal-to-noise calls produced by fin whales, particularly if the downswept portions were also masked. The precision, recall, and F-scores of the Baleen 5 detections of fin whales were very low and could not be calculated in the absence of true positives or false negatives. The overall performance across all datasets was low, with an F-Score of .0004.

The Baleen 5 sei whale detector classified a total of 74 calls (Table 3.5). Of the detections, 17 were true positives (example in Figure 3.4) and 57 were false positives. The false positives occurred when components of humpback signals were downswept below 150 Hz (Figure 3.5). These false detections were validated by examining the acoustic file with a larger bandwidth and reviewing both visually and aurally to confirm that the lower frequency components were in fact part of the higher frequency call components confirmed to be from humpback whales.

The performance metrics for sei whales were the highest for the three detectors used. For the dataset with the highest number of actual sei whale calls present (Kauai NW3), out of 25 manual detections, Baleen 5 had 12 true positives with only 4 false positives. This produced a precision value of 0.75 but due to the 13 missed calls, the recall value was only 0.48 and this lowered the F-Score to 0.585. However, for the Kauai NW2 dataset, there were 6 manually identified sei whale calls, none of which were logged by Baleen 5. The detector picked up 4 calls but each of those were false positives. The overall performance of the detector produced an F-Score of 0.286 which is very low if one were to rely on this detector for locating sei whales reliably.

Table 3.4. Results from the Baleen 5 fin whale detector. The number of true positives (correct), false positives (incorrect), and missed detections. The values represent the number of individual calls and not encounters nor number of files that contain fin whale signals. The blanks indicate where no detections were made as well as instances when the performance statistics could not be calculated.

		Baleen 5 - Fin Whales							
Site	**Deployment**	**Manual Detections**	**Automated Detections**	**True Positives**	**False Positives**	**Missed**	**Precision**	**Recall**	**F-Score**
Kauai NE	1	3	146	2	144	1	0.014	0.667	0.027
Kauai NW	1	29	291	0	291	29	0.000	0.000	0.000
Kauai SE	1	18	86	1	85	17	0.012	0.056	0.019
Kauai NE	2	0	0	-	-	-	-	-	-
Kauai NW	2	0	10	-	10	-	-	-	-
Kauai SE	2	0	2	-	2	-	-	-	-
Kauai NE	3	13	81	0	81	13	0.000	0.000	0.000
Kauai NW	3	7	351	0	351	7	0.000	0.000	0.000
Kauai SE	3	62	1,278	2	1,276	60	0.002	0.032	0.003
Kauai NE	4	0	3	-	3	-	-	-	-
Kauai NW	4	0	5	-	5	-	-	-	-
Kauai SE	4	0	0	-	-	-	-	-	-
	Totals	**132**	**2,253**	**5**	**2,248**	**127**	**0.002**	**0.038**	**0.004**

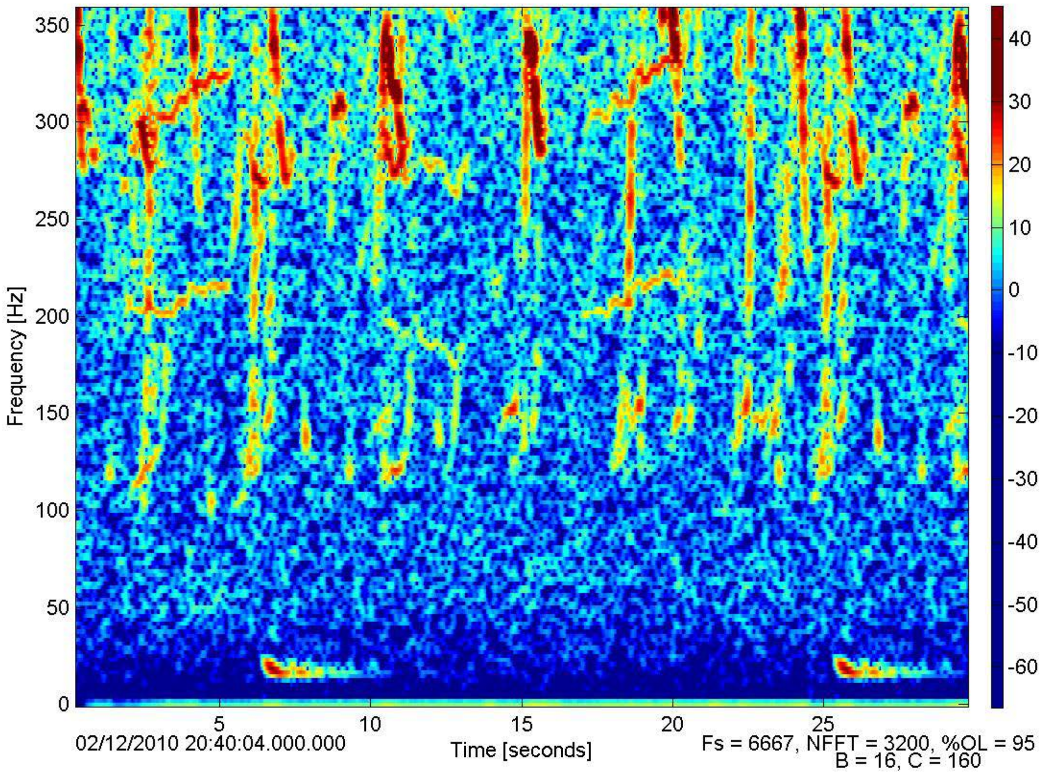


Figure 3.2: Example of fin whale 20 Hz pulse calls detected by Baleen 5.

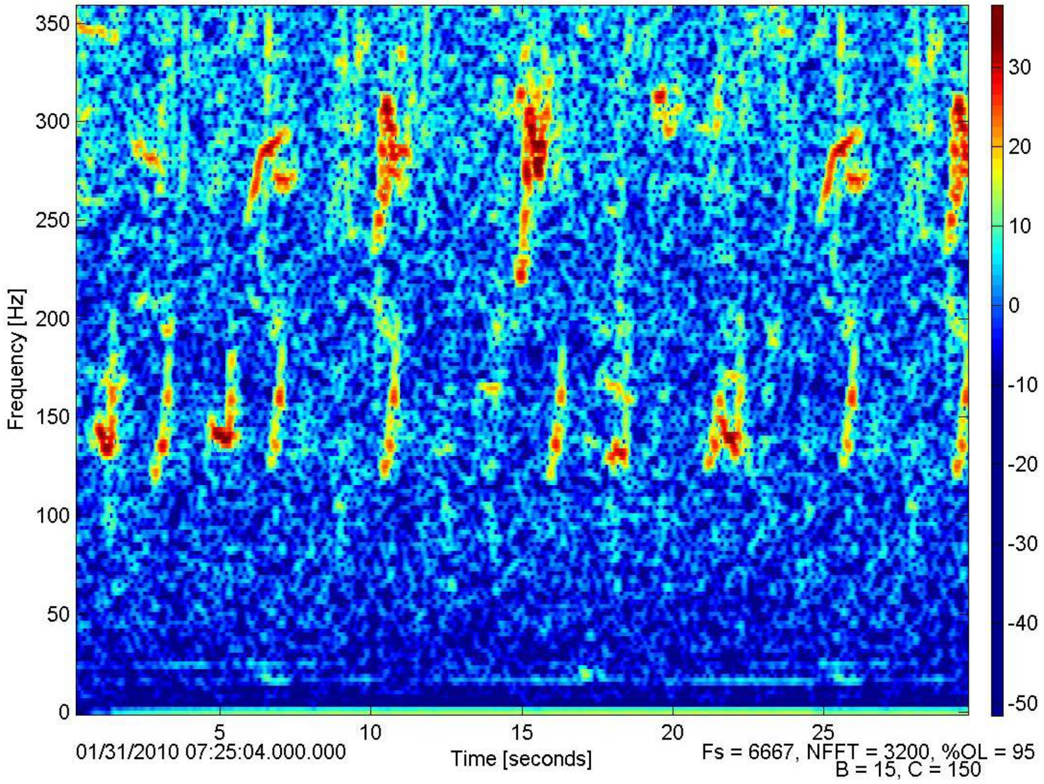


Figure 3.3: Example of low signal-to-noise ratio of fin whale calls masked by unknown low-frequency noise.

Table 3.5: Results from the Baleen 5 sei whale detector. The number of true positives (correct), false positives (incorrect), and missed detections. The values represent the number of individual calls and not encounters nor number of files that contain fin whale signals. The blanks indicate where no detections were made as well as instances when the performance statistics could not be calculated.

		Baleen 5 - Sei Whales							
Site	**Deployment**	**Manual Detections**	**Automated Detections**	**True Positives**	**False Positives**	**Missed**	**Precision**	**Recall**	**F-Score**
Kauai NE	1	0	0	-	-	-	-	-	-
Kauai NW	1	0	6	-	6	-	-	-	-
Kauai SE	1	3	1	0	1	3	0.000	0.000	0.000
Kauai NE	2	0	0	-	-	-	-	-	-
Kauai NW	2	6	4	0	4	6	0.000	0.000	0.000
Kauai SE	2	0	0	-	-	-	-	-	-
Kauai NE	3	1	0	0	0	1	0.000	0.000	0.000
Kauai NW	3	25	16	12	4	13	0.750	0.480	0.585
Kauai SE	3	10	47	5	42	5	0.106	0.500	0.175
Kauai NE	4	0	0	-	-	-	-	-	-
Kauai NW	4	0	0	-	-	-	-	-	-
Kauai SE	4	0	0	-	-	-	-	-	-
	Totals	**45**	**74**	**17**	**57**	**28**	**0.230**	**0.378**	**0.286**

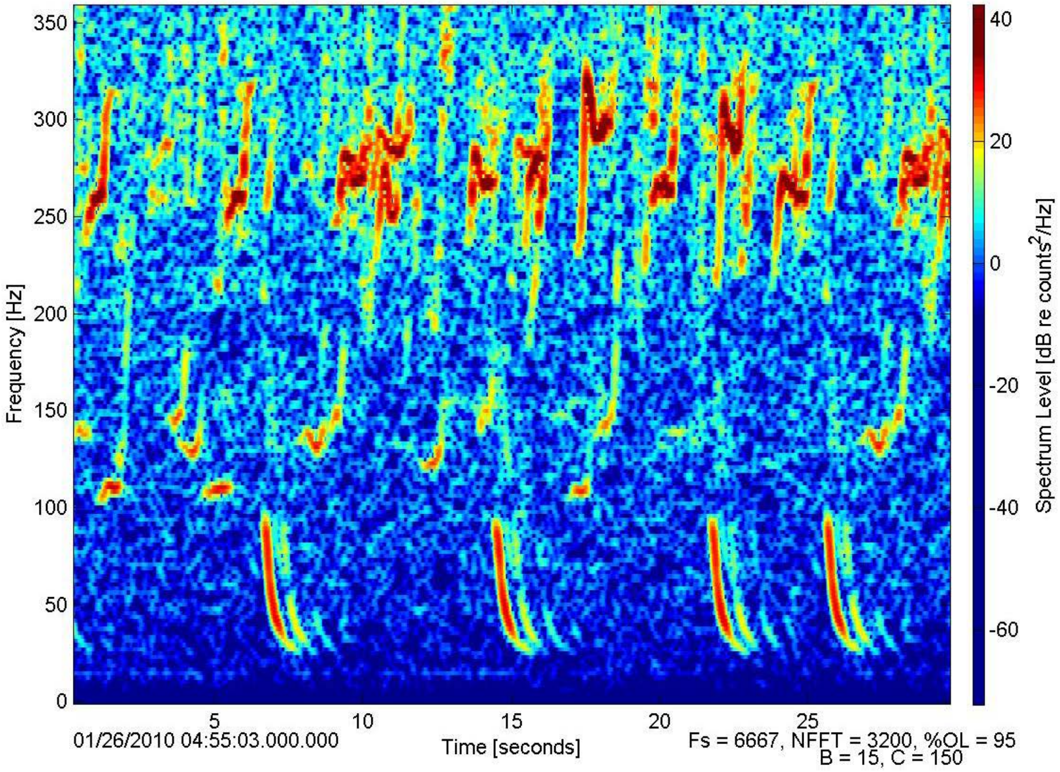


Figure 3.4: Example of sei whale downsweep calls detected by Baleen 5.

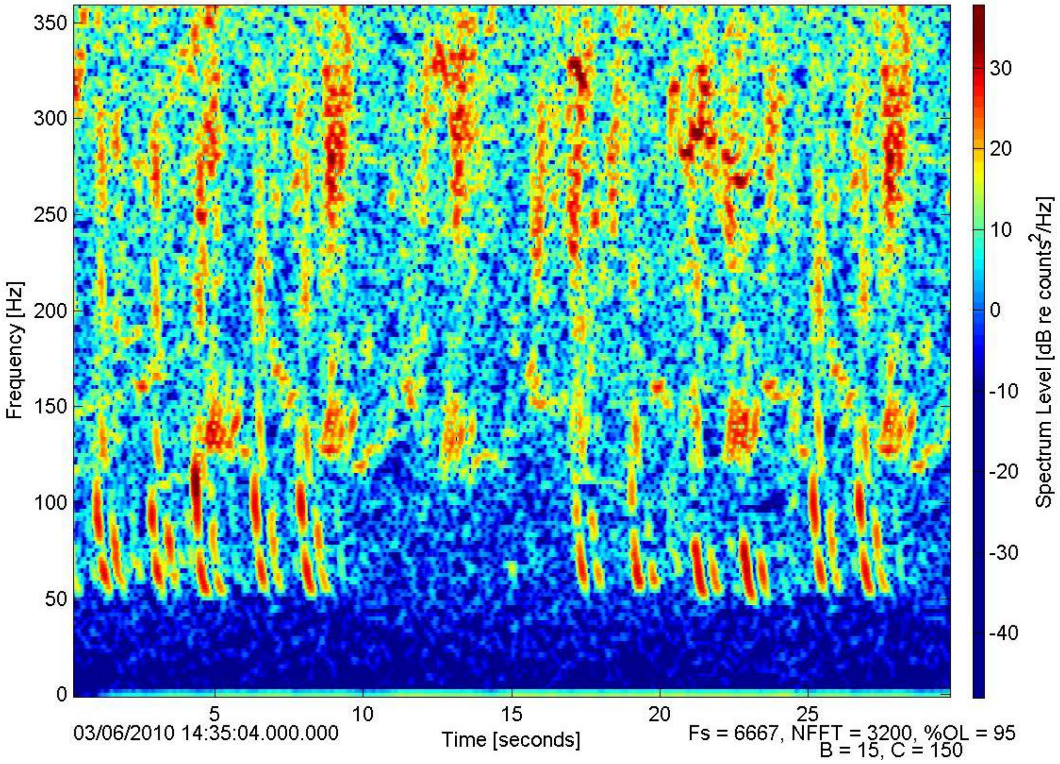


Figure 3.5: Example of false positive sei whale calls triggered by low-frequency components of humpback whale calls below 150 Hz.

The fin whale detector in Raven incorporated a very liberal threshold for detections and this was evident in the total number of detections made (24,883). The intent of the lowered threshold was to capture more possible fin whale signals and rule them out and not emphasize the accuracy of the detections as a performance measure. Of the actual 132 fin whale calls located manually, Raven was able to correctly classify 114 (Table 3.6). There were a total of 18 missed calls and 24,769 false positives. Many of the false positives from the Raven detector appeared to trigger from short duration broadband signals in addition to the unknown low-frequency noise.

Due to the high number of detections, the likelihood of classifying more calls increased while intentionally increasing the false positive rate as a result. This can be reflected in the precision and recall values of 0.005 and 0.864, respectively. The low value of precision indicates that only 0.5 percent of classified calls were in fact fin whales. The 0.864 value for recall shows that 86.4 percent of the true positives were detected by Raven. However, when examining the overall performance of the detector, the F-Score of 0.009 is very low, skewed by the poor precision.

A detailed examination of the types of signals and reasons for false detections was not conducted due to the extremely small sample size of true positive detections in the manual analyses. Due to the variability and overall poor performance of the automated detectors, the benefit of quantifying the false detections was not deemed practical or worthwhile. The cause of false detections was qualitative based on the familiarity with the acoustic data having examined all of the files manually and understanding what the confounding issues would be for each of the detectors.

Table 3.6. Results from the Raven fin whale detector. The number of true positives (correct), false positives (incorrect), and missed detections. The values represent the number of individual calls and not encounters nor number of files that contain fin whale signals. The blanks indicate where no detections were made as well as instances when the performance statistics could not be calculated.

		Raven - Fin Whales							
Site	**Deployment**	**Manual Detections**	**Automated Detections**	**True Positives**	**False Positives**	**Missed**	**Precision**	**Recall**	**F-Score**
Kauai NE	1	3	61	2	59	1	0.033	0.667	0.063
Kauai NE	1	29	954	29	925	0	0.030	1.000	0.059
Kauai NE	1	18	148	8	140	10	0.054	0.444	0.096
Kauai NE	2	0	16	-	16	-	-	-	-
Kauai NE	2	0	642	-	642	-	-	-	-
Kauai NE	2	0	138	-	138	-	-	-	-
Kauai NE	3	13	623	9	614	4	0.014	0.692	0.028
Kauai NE	3	7	4,443	7	4,436	0	0.002	1.000	0.003
Kauai NE	3	62	14,438	59	14,379	3	0.004	0.952	0.008
Kauai NE	4	0	1,607	-	1,607	-	-	-	-
Kauai NE	4	0	1,741	-	1,741	-	-	-	-
Kauai NE	4	0	72	-	72	-	-	-	-
	Totals	**132**	**24,883**	**114**	**24,769**	**18**	**0.005**	**0.864**	**0.009**

3.4 Discussion

The volume of passive acoustic monitoring data around the globe continues to grow. The advancement of technology to collect longer duration recordings in more remote locations necessitates the ability to productively and efficiently analyze the data for signals of interest. It is very difficult to justify the labor required to manually examine the data for target signals and it is not feasible for producing results in a timely manner.

Choosing the appropriate algorithms and methods for processing large acoustic datasets is essential to success. Even after employing different automated techniques, it is imperative to apply a modicum of scrutiny and not just take the results at face value. For the vast majority of datasets, for each algorithm used, there will need to be a balance for accepting a certain amount of false positive detections in combination with a number of missed detections. Ideally a balance can be struck such that caveats can be applied and researchers can reliably determine the occurrence of the target signals. Perhaps not all of the sounds recorded are identified in a given encounter, but the aim is to confidently detect the majority of signals in each encounter and not incorrectly identify an encounter that is false. For soniferous marine mammals, this becomes a difficult scenario when animals are not calling regularly within a given area (i.e., singing humpback whales), when animals are primarily transiting an area, for solitary animals that may not be calling at all, or for areas where particular species occurrence is rare or relatively unknown. Fin and sei whales have both been seen and recorded in Hawaiian waters; however, their residency patterns, movement among the islands, and group sizes are largely unknown in the tropical Pacific. They are very rarely observed and the EAR data recorded around Kauai Island was an ideal source to determine if acoustics can reveal a different pattern of occurrence than the historic visual data collected during large ship surveys in the Hawaiian Islands.

Two suites of detectors were run on 12 different deployments (3 sites with 4 deployments each) around the island of Kauai. Baleen 5 scanned for both fin and sei whales and Raven's built in fin detector was used for comparison with a different template matching technique. In order to assess the performance of these detectors, the Kauai data had previously been examined manually, file by file spectrogram scanning. Only 132 fin whale calls and 45 sei whale calls were found despite recording around two different winter seasons when these species would have been expected to occur in the region.

For fin whales, Raven identified 24,769 possible calls. Raven allowed for a higher false positive rate in order to maximize the likelihood that all calls will be located in the data, as evidenced by the extremely high number of detections. Neither of the detectors would be considered to have performed well; however, the overall recall statistic for Raven was 0.864, meaning that 86 percent of the actual fin whale calls were detected. The recall statistics for individual deployments ranged from 0.4 to 1.0 (for two datasets); however, the precision statistics never exceeded 0.05 (meaning that only 5 percent of detections were actually fin whale calls). The overall precision score for Raven was .005 and the F-Score, or the metric for detector performance taking into account both precision and recall, was .009. That F-Score is extremely low but that may not be the best indicator of the utility of Raven for automated scanning for fin whale calls. Raven is a sound analysis software package and when annotating calls, it provides streamlined and user friendly tools for reviewing each detection. Additionally, each detection is assigned a correlation score to help users locate calls with a higher likelihood of being true positives. Being an inclusive analysis tool, it is a practical strategy to lower the detection threshold knowing the many of them can be easily and quickly validated, with or without additional filtering based on the correlations score. This approach is why the number of total detections were so high, which in turn, increased the recall statistic. This tactic casts a wide net and sacrifices precision. After reviewing all of the detections, the false positives seemed to occur primarily with short duration broadband signals. This does makes some sense because the spectrogram template will identify the matched signal within a broadband sound and will not discard it due to failing to meet signal-to-noise criteria. Imagine as if you were to look through a keyhole in a street-facing door and search for vehicles passing by on the road. You would be much more likely to detect any vehicle from mopeds to tractor trailers since they will occupy the viewing space without having to discern a specific size or type. This is not a precise measure but you will likely be able to see the vast majority crossing your field of view.

The Baleen 5 algorithm applied a more conservative approach for identifying fin whale calls. By first applying a bandpass filter and using a signal-to-noise ratio threshold for template matched calls, some of the weaker signals will be missed. For fin whales, Baleen 5 identified 2,253 possible calls. Unlike Raven, the very troubling issue is that of the 132 possible fin whale calls, 127 were missed by Baleen 5. The recall statistics reflect this with a range from 0.0 to a high of 0.67. However, the recall of 0.67 is also a bit misleading as there were three total calls in the dataset for which only two were detected. The precision scores were also extremely low with a range of 0.0 to 0.014. The overall performance for Baleen 5 fin whale detections was very low with values of 0.002, 0.038, and 0.004 for precision, recall, and F-Score, respectively. The exact reason for the poor performance is unknown. The vast majority of the fin whale detections, all but 20, were during wintertime deployments when sympatric humpbacks were very common and calling continuously. It is possible that low-frequency humpback components triggered Baleen 5 and also, based on reviewing the data, there were a tremendous number of false positives due to the long-durations of unknown low-frequency tonal sounds around 20 Hz. These nearly flat signals were prevalent in the majority of the data; however, they also occurred during summer months and only 20 false positives were identified in these datasets.

The Baleen 5 sei whale detector performed much better than the two fin whale detectors, relatively speaking. Of the 45 possible calls, Baleen 5 had 17 true positive detections and 28 missed detections. Six of the possible nine sei whale encounters occurred during the third deployment. This wintertime deployment contained 36 of the 45 sei whale calls and the 27 correct classifications (true positives) were identified in the Kauai NW and Kauai SE datasets. As a result, these were the only two instances that performance statistics could be evaluated.

Kauai NW had a precision value of 0.75, a recall score of 0.48, and an F-Score of 0.59. The overall performance statistics were 0.23, 0.38, and 0.29 for precision, recall, and F-Score, respectively. In general, there were very few sei whales found in the data and, when assessing their occurrence during the manual analysis, the encounters were brief and very loud signals were recorded likely as the animal(s) transited the EAR deployment sites. Faint sei signals were discovered manually during the first summertime deployment from Kauai NW. There were four Baleen 5 detections however none of them were true positives. With the absence of humpbacks during the summer, automated detections without the masking of humpback signals in the same frequency band were expected; however, this was not the case. In general, the scarcity of sei whale signals around the island of Kauai is likely the reason for the improved performance of the detector. When detected, they were very loud and easily distinguished spectrographically from the humpback whale calls that also existed in the same frequencies. When comparing the sei calls and that false positive detections in Figures 3.2 and 3.3, perhaps one level of additional filtering could include the inter-call minimum threshold. However, since the detections are few and far between, and the fact that Baleen 5 did not have an overwhelming number of detections for verification, the current algorithms do not necessarily need to be modified. Still, the major concern is the high number of missed detections (28 of 45), in particular during the summer seasons when humpbacks are not present.

The EARs located around Kauai had a surprisingly low number of fin and sei whale detections. The visual sightings around the island are scant and irregular and the acoustic data corroborate this. Conversely, the Station ALOHA Cabled Observatory, located 100 kilometers north of Oahu, is a bottom-mounted oceanographic study site that records continuous acoustic data. Oswald et al. (2016), noted that fin whales were recorded year-round and that sei whales were seasonally present. The hydrophone at Station ALOHA is near the seafloor at a depth of approximately 4,700 meters. Unlike the coastally located EAR hydrophones around Kauai, Station ALOHA is in deep ocean water without land boundaries to hinder sound propagation.

While sound propagations properties near Station ALOHA may indicate that calling animals are within a convergence zone (±30 kilometers), longer distance signal propagation is more probable, particularly during certain times of the year when the Sound Fixing and Ranging (SOFAR) channel is present.

Oswald et al. (2016) also used automated detectors to determine the presence of baleen whales in continuous recordings at Station ALOHA. They were able to reliably detect blue, fin, sei, minke, and humpback whales in the data. Baleen 5 was used to for each of these species; however, it is important to note that the algorithms were trained using testing datasets from Station ALOHA recordings. Each detector was fine-tuned until it worked extremely well for each of the test datasets and ground-truth validation demonstrated correct classification rates of 98 percent and 97 percent for fin and sei whales, respectively.

The performance difference between Station ALOHA and the EARs in this study could be attributed to a number of differences. In addition to the signal propagation characteristics between the two habitats, humpback whales migrate to the Hawaiian Islands for breeding opportunities and males tend to sing primarily in shallow coastal habitats. While they produce song in deeper water while transiting between islands and during their migration (Matilla et al. 1987, McSweeney et al. 1989, Clapham and Matilla 1990, Clark and Clapham 2004), they are ubiquitous around Kauai throughout the winter and their sounds can impact not only the masking of specific calls but they also alter the ambient noise levels and possibly the detectability of signals. Detector performance varies significantly with different ambient noise conditions (Munger et al. 2005, Miksis-Old 2013, Clark et al. 2009) and, in contrast to Station ALOHA, the vessel activity and contribution of underwater noise from U.S. Navy training around the Pacific Missile Range Facility (PMRF) will impact the performance of detectors.

For this study, a total of 327,649 30-second audio files (2,730.41 total hours of data) were examined by two automated detectors and compared to a manual analysis of the same files. The results from this effort demonstrate that there is no easy solution to capably and reliably scan large volumes of acoustic data (especially in high noise environments) to detect species occurrence without further evaluation. Both detectors functioned similarly as matched filters but employed different approaches and thresholds. Their findings were not consistent with each other and as neither of them performed relatively well, my assessment is that the Raven spectrogram correlation performed better and would be recommended for fin whale detection. While the precision was very poor, the recall was acceptable with a correct classification rate of 86 percent. Coupled with the ability to review and validate calls easily and efficiently in the Raven software package, users are able to identify bouts of calling with a high level of confidence that the majority of the calls will be located within the dataset. However, a few caveats need to be recognized. There was only 132 manually identified fin whale calls in the entire dataset, an extremely low encounter rate. The raven results yielded 24,769 possible fin whale calls in the same dataset. If the Raven detector was run on recordings where fin whales are known to occur and produce calls regularly, the number of detections needing validation and review could easily become unwieldy and there could be diminishing returns with regards to the amount of effort needed to confidently generate meaningful results. Additionally, if the noise characteristics were different for the recordings, the results could vary wildly as well.

The performance of these detectors should not be evaluated simply from the results of this study. Adjusting the thresholds, settings, or detector parameters for either fin or sei whale detectors in Baleen 5 or Raven could improve the performance significantly.

This manually validated dataset could be a useful resource for tuning the detectors but with so few calls from either species, the lack of variability in the ambient conditions, unknown signal propagation characteristics, and unknown occurrence of the species are confounding concerns for improving detector performance. These duty-cycled EAR data may also not be ideal in that recordings made for 30 seconds every 5 minutes may be missing calls, particularly when the encounters appear to be short as animals are likely transiting past the recorders. The sampling rate, hydrophone sensitivity, other hardware configurations could also impact the ability to record low-frequency whale sounds in different ambient conditions. A subset of recordings from EARs or other instruments deployed in more densely populated regions would be preferable for testing the efficacy of these detector modifications.

Ideally any detector algorithms will produce results with relatively high levels of precision and recall. If not, high scores for either precision or recall may also be acceptable depending on the aims of the investigation. With all automated techniques, scrutiny of the results is essential. For each dataset, one algorithm may perform better than another; however, that may not be the case for another dataset or another target species. The refinement of automated techniques will no doubt continue and perhaps in the future, methods may become available that will be able to perform consistently well by striking a balance between the false detection rates and number of missed calls. In the meantime, the results produced by detection algorithms will need to be closely inspected and not be reported without validation metrics.

CHAPTER 4:
SOUNDSCAPE AND NOISE CHARACTERISTICS AROUND KAUAI, HAWAII

4.1 Introduction

Simply stated, the ocean is a noisy place and, notably quoted, one person's signal is another's noise. The previous chapters were aimed at detecting low-frequency baleen whale sounds from recordings around the island of Kauai. Knowing that humpback whales (*Megaptera novaengliae*) are seasonally abundant and other large baleen whales are detected acoustically at the Station ALOHA research site (100 kilometers north of Oahu, HI), it stands to reason that they would also inhabit areas closer to the Main Hawaiian Islands (MHI). However, after rigorous manual analysis and additional automated detection techniques applied to recordings around the island of Kauai, fin (*Balaenoptera physalus*), Bryde's (*Balaenoptera edeni*), and sei (*Balaenoptera borealis*) whales were very rarely detected near shore.

The results from the passive acoustic monitoring (PAM) efforts around Kauai indicate an extremely low density of non-humpback and non-minke whale (*Balaenoptera acutorostrata*) baleen whales in coastal MHI waters and corroborate the paucity of visual sightings. It is possible that background noise in the ocean from a combination of naturally occurring ambient sources as well as anthropogenic activities could obscure the ability to detect whale signals, particularly if they have a low signal-to-noise ratios (SNR). Noise was prevalent in the Kauai PAM data and if automated techniques were used exclusively to search for low-frequency whale sounds, further investigation on the impact of noise on signal detection would be necessary. In this case, the thorough manual analyses of the data (examining files individually) confirmed the scarcity of fin, sei, and Bryde's whales within a few miles of the Kauai coast. Their sounds, even in the presence of masking noise in the same frequency bands, could still be identified and annotated even with low SNR as the components could be detected visually in the spectrograms. This, however, does not mean that examining the soundscape and ambient levels around the MHI is not without tremendous value.

Noise in the ocean is ubiquitous and naturally occurring sources include weather events (particularly wind and rain), geophysical processes, and biological activity. The seminal work by Wenz (1962) summarized the contribution of different sources to ocean noise and resulted in one of the most cited publications and figures (the Wenz Curve; Figure 4.1), in ocean acoustics. In the lower frequencies (400 Hz and lower, as it pertains to the frequency bands examined for whale signals in the previous chapters) the noise is most significantly impacted by shipping, earthquakes, underwater detonations, heavy precipitation, and wind driven noise. All of them are naturally occurring with the exception of vessels, shipping traffic, and explosions. Since the naturally occurring noise sources have always been prevalent in ocean habitats whales have been able to evolve functionally such that these sounds do not impede their ability to navigate, locate food, and/or maintain interspecific communication for group cohesion, mating opportunities, or other behavioral needs (Boyd et al. 2011). Environmental noise is not constant. Steadier state noise like weather events are ephemeral and somewhat stochastic; thus would not be expected to impact localized whale distribution long term. Earthquakes are even more randomly occurring and shorter duration and these too would not likely deter baleen whale presence, particularly when they are inhabiting certain waters for either foraging or, in the case of lower latitude waters around Hawaii, breeding opportunities (as speculated following the model of humpback whale migration during the winter months).

Weather related noise impacts global and localized soundscapes substantially. Wind and rain are significant contributors to ambient noise levels. Wind driven noise is created when the surface waters get turned up and the crashing waves create bubble cavitation; the stronger the winds the louder the noise generated (Knudsen et al. 1948, Wenz 1962, Ma et al. 2005, Hildebrand 2009). The spectral characteristics of sounds generated by wind is also dependent on wind speed but generally loudest between 5 kHz and 8 kHz (Farmer and Lemon 1984,

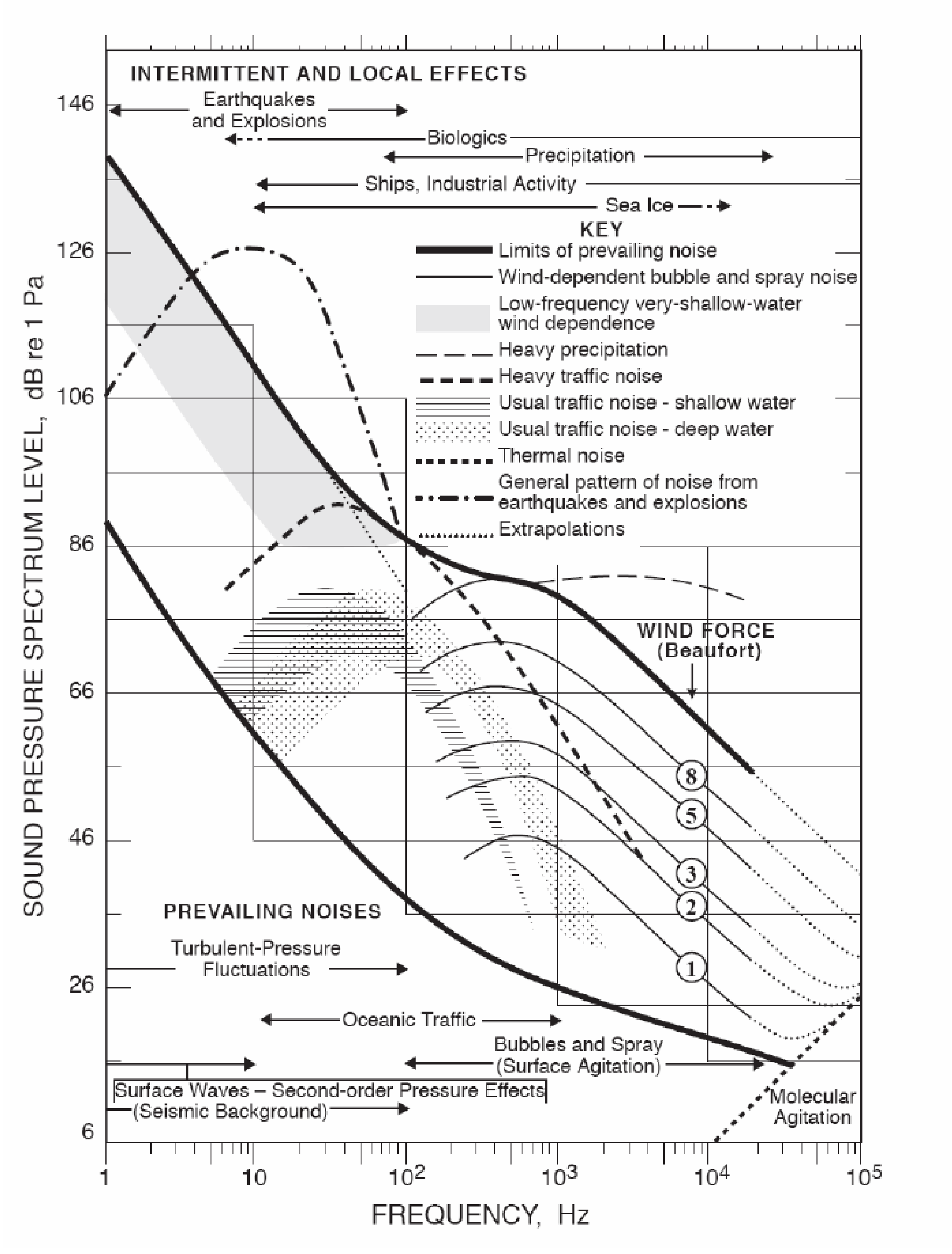


Figure 4.1: Wenz curves describing spectra levels of ambient noise sources from weather, geologic activity, and shipping (adapted from Wenz 1962).

Ma et al. 2005). While wind noise is a major constituent of ambient levels, underwater measurements are only possible when it is not raining. As rain drops get larger and rainfall increases, the sound characteristics change proportionately. When drops become large enough, bubbles form as they hit the ocean surface. Like wind, bubble cavitation is the major source of noise and can be very distinctive. The spectral characteristics differ from wind generated bubbles and rain produces a broad spectral peak around 15 kHz with varying amplitudes depending on the amount of rainfall (Nysteun 1986, Nystuen et al. 1993, Ma et al. 2005, Ma and Nystuen 2005). Fortunately the distinctive nature of weather events, particularly for wind and rain, are well studied and integral to any assessment of ambient levels.

Unlike naturally occurring environmental noise, anthropogenic sources are relatively recent, and have increased exponentially over the last century. Human introduced sounds are very diverse and in addition to those noted in the Wenz Curve, oil exploration, construction sounds, offshore energy activity, and underwater detonations, and commercial shipping are now prolific globally. When considering anthropogenic sounds, some are short duration and inconsistently produced regionally. For instance, construction noises (pile driving [vibratory or impact hammering]) are generally relegated to coastal areas with localized populations of coastal species. However, for activities like oil exploration and seismic exploration, surveys use large arrays (12 to 48) air guns to produce broadband sound pulses in order to penetrate the sea floor for return echo signatures that may indicate oil and gas deposits. It is estimated that there are over 90 seismic vessels available worldwide and 20 percent of them may be operational at any given time (Schmidt 2004). The sounds emitted from these vessels are very loud (source levels up to 260 dB rms re 1µPA at 1 meter) and while their impact may be more localized to animals occurring in proximity at a given time, the acoustic disturbance can span hundreds of kilometers and the detrimental effects could be injurious to nearby animals and cause significant behavioral disturbances at larger distances. Overall, the cumulative effects of these introduced sounds are a major component of increased ambient noise levels globally (Hildebrand 2009).

In recent decades, there has been more public concern over the impact of global shipping and how the constant din of vessels has increased ambient noise levels as much as 3 dB per decade (Andrew et al. 2002, McDonald et al. 2006). While a small portion of noise produced by ships is intentional, depth sounders for navigational purposes, the vast majority of radiated sounds are incidental from propulsion systems that are constantly running (Southall et al. 2017). While the acoustic signature of each vessel will vary based on many properties including size, speed, and propulsion type, the main concern is the overall cumulative contribution since shipping is an essential component of trade and the global economy (Lloyd’s Register 2013). With larger ships producing lower frequency sounds that propagate great distance, in many areas of the ocean there is a constant din and elevation of the ambient noise floor. Overall, the ambient levels of ocean noise has steadily increased (Andrew et al. 2002, Ross 2005, McDonald et al. 2006, Hildebrand 2009).

Honolulu is on the list of the 25 busiest ports in the United States (U.S.) and has over 4,000 cargo vessel calls to Honolulu Harbor annually (U.S. Department of Transportation Bureau of Transportation Statistics). Large cargo vessels predominantly port in Honolulu while the outer islands (Kauai, Maui, and Hawaii) are mainly supplied by tug and barge cargo. As such, the majority of the shipping traffic is centered on the southern side of Oahu (Figure 4.2). The shipping density maps are generated by tracking vessels that contain an Automatic Identification System (AIS), legally required for commercially operated ships over 300 gross tons and all passenger vessels. Since not all vessels have AIS (including the military, privately owned ships, and small watercraft) the overall assessment of vessel activity is not fully accounted for. Kauai Island has a lower population size and the marine traffic, recorded by vessels using AIS, is mainly in and out of the largest port located in Lihue, Nawiliwili Harbor. The predominant commercial activity is from inter-island tug companies as well as commercial

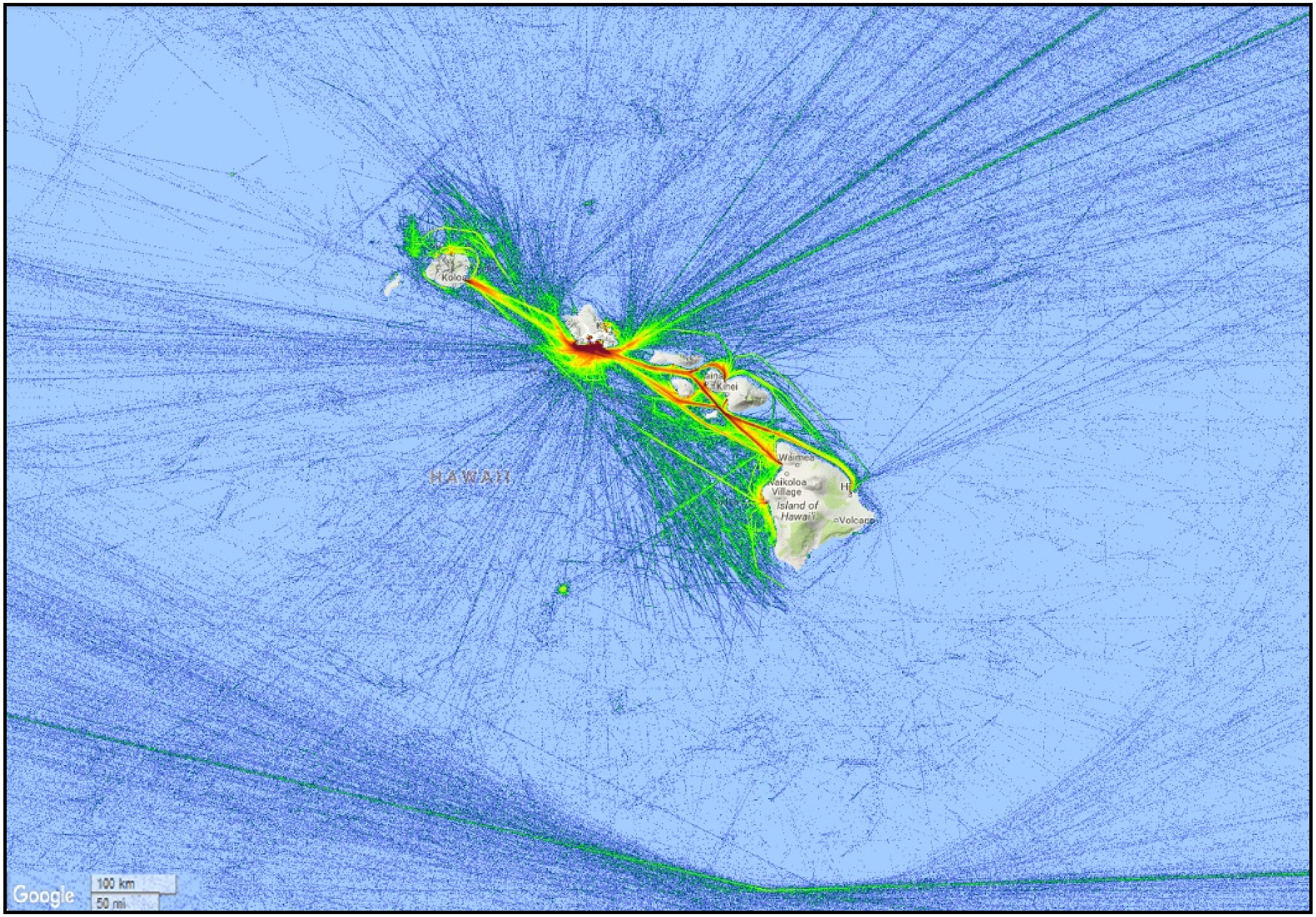


Figure 4.2: Annual shipping density around the Main Hawaiian Islands for 2016. The color intensity is based 155,453 vessels equipped with Automatic Identification Systems (AIS) and does not all include small pleasure craft or military vessels (marritimetraffic.com).

cruise lines and the majority of the vessels operating around the island are locally owned fishing charters and pleasure craft.

The U.S. Navy has active sites on the island, the biggest being the Pacific Missile Range Facility (PMRF). There are no large harbors or mooring areas for navy vessels and the base is primarily an airfield with various radar installations. PMRF is also an instrumented range with a large network of underwater hydrophones on the northwest side of the island towards Niihau and extending approximately 100 km to the north. Because of the network of hydrophones and its remote location relative to the major population centers in the state, PMRF is very suitable for a variety of Navy training and testing exercises. Some of these include submarine commander's training courses involving the use of multiple surface ships employing active sonar (primary tactical mid-frequency), multi-nation training operations (RIM of the Pacific RIMPAC]), and surface and underwater detonations. These events occur year-round; however, they are limited in duration and are not constant, generally lasting only a week or two at a time, with the exception of RIMPAC spanning over a month every second year.

In general, while there may be cumulative effects of increased noise around Kauai, the majority of the concern about marine mammals directed towards the risk of injury and mortality on and near the range. Navy activities are often blamed for detrimental activities, particularly after mass stranding events. While stranding events in Hawaii are not common, they do occur and this chapter will not delve into the potential causality associated with U.S. Navy activates. However, due to the location of this active training range, it is essential to discuss the possible impact that the military may have on the soundscape of the island.

This chapter will examine the noise characteristics around the Kauai at five different recording sites as well as an additional site each in the remote Northwest Hawaiian Islands and off of Oahu with a relatively close proximity to Honolulu Harbor, the primary commercial shipping port for the state. My hope is that this noise profile will contribute to better management of marine mammals and other marine resources in Hawaii.

4.2 Methods

4.2.1 Field Recordings

Acoustic recordings were made on bottom-moored Ecological Acoustic Recorders (EARs). The EAR is a self-contained microprocessor-based autonomous recorder that samples the ambient sound field on a programmable duty cycle (Lammers et al. 2008). The EARs were deployed at seven different sites around the islands of Kauai, Oahu, and Nihoa, Hawaii (Figure 4.3) at depths ranging from 395 m to 710 m. Each EAR was paired with an acoustic release and custom syntactic foam collar for recovery and refurbishment. The first deployment at all five sites was February 2009 and the refurbishment cycle was aimed to recover and redeploy each recorder every six months over the project span of two years (EAR locations, recording sampling rate, and recording durations are depicted in Table 4.1). Due to the remote nature of most of the deployment sites, and challenges associated with circumnavigating the island during calm weather conditions, the EAR recording parameters around Kauai and Oahu were set with a 10 percent duty cycle (30s recordings every 5 min). The first two Kauai deployments recorded with a sampling rate of 64 kHz (effective bandwidth of 32 kHz) and the final two deployments had an increased sampling rate of 80 kHz (effective bandwidth of 40 kHz). The Ohau EAR recorded at 64 kHz for all deployments and the Nihoa EAR sampled at 50 kHz with a 3 percent duty cycle (30 seconds on every 900 seconds). The sampling rate settings would not impact the lower frequencies and the system limitations had a low-frequency limit for signals below 20 Hz. The EAR uses a Sensor Technology SQ26-01 hydrophone with a sensitivity of -193.5 dB that is flat (±1.5 dB) from 1 Hz to 28 kHz.

The EARs were deployed with the intent of monitoring for marine mammal presence and other biological activity around the MHI. Noise measurements were not the primary driver for the research so no dedicated calibrations were made prior to, or after, each deployment. However,

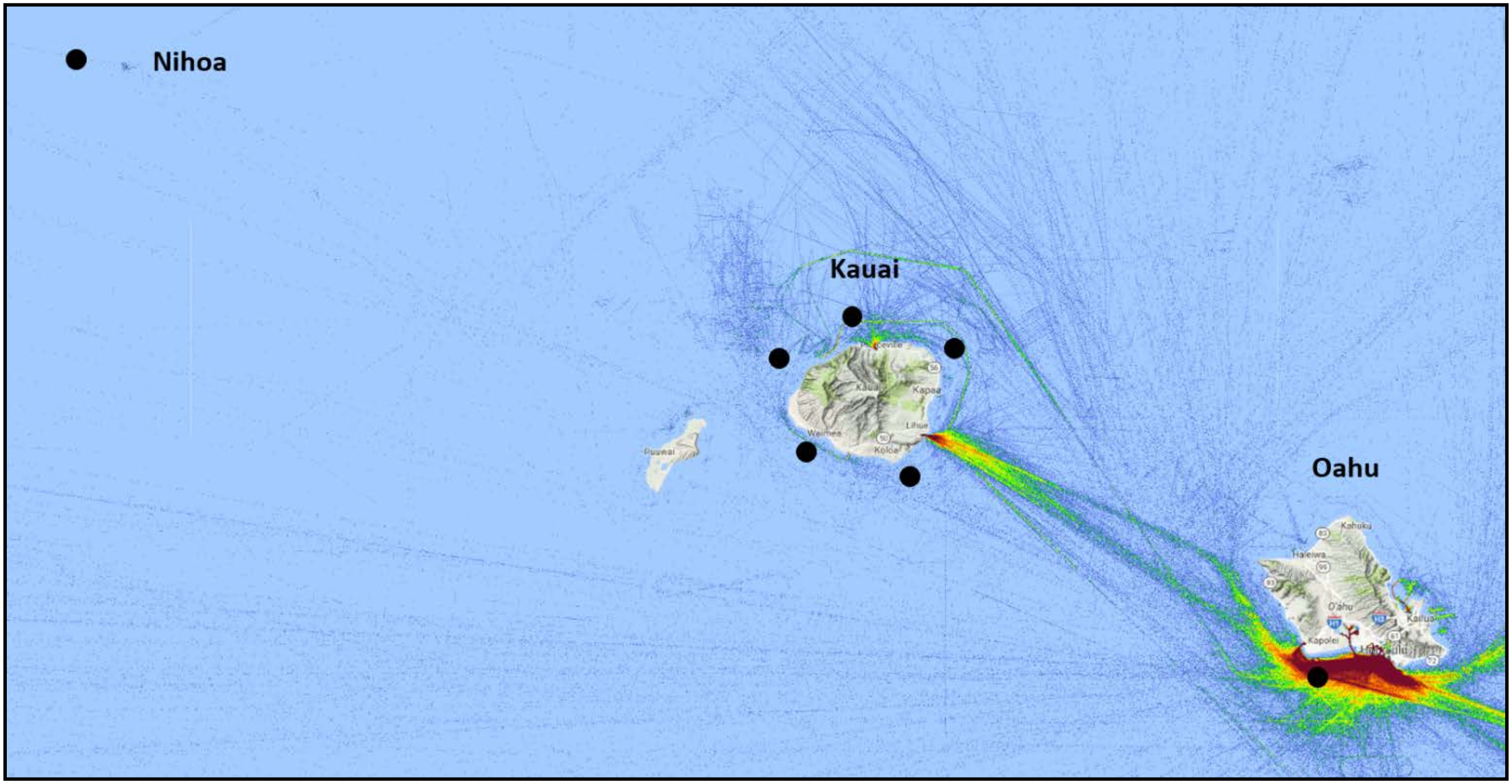


Figure 4.3: Annual shipping density around Oahu, Kauai, Niihau, and Nihoa for 2016. The color intensity is based on 155,541 vessels equipped with Automatic Identification Systems (AIS) and does not include all small pleasure craft or military vessels (marritimetraffic.com). The black dots indicate the locations of the EAR deployments.

Table 4.1: EAR deployment information for the site location, deployment waypoint, unit depth, recording sampling rate, and the recording durations for each unit on each deployment used for the noise analyses.

	Site	**Kauai SE**	**Kauai NW**	**Kauai NE**	**Kauai N**	**Kauai SW**	**Oahu**	**Nihoa**
	Latitude	**21 51.577 N**	**21 11.221 N**	**22 08.954 N**	**21 18.007 N**	**21 55.986 N**	**21 13.658 N**	**23 04.474 N**
	Longitude	**159 21.542 W**	**159 50.298 W**	**159 14.702 W**	**159 32.298 W**	**159 47.529 W**	**158 05.391 W**	**162 04.967 W**
	Depth	**696 m**	**609 m**	**710 m**	**394 m**	**675 m**	**576 m**	**405 m**
Deployment 1	Sampling Rate	64 kHz	64 kHz	64 kHz	64 kHz	64 kHz	64 kHz	-
	Start Recording	10-Feb-2009	10-Feb-2009	10-Feb-2009	10-Feb-2009	10-Feb-2009	7-Feb-2009	-
	End Recording	6-Mar-2009	24-May-2009	19-May-2009	6-Jun-2009	28-May-2009	15-Mar-2009	-
Deployment 2	Sampling Rate	64 kHz	64 kHz	64 kHz	64 kHz	-	64 kHz	-
	Start Recording	10-Jun-2009	9-Jun-2009	9-Jun-2009	9-Jun-2009	-	11-Jun-2009	-
	End Recording	25-Sep-2009	22-Sep-2009	29-Sep-2009	24-Sep-2009	-	12-Dec-2009	-
Deployment 3	Sampling Rate	80 kHz	80 kHz	80 kHz	-	80 kHz	64 kHz	-
	Start Recording	26-Jan-2010	25-Jan-2010	25-Jan-2010	-	26-Jan-2010	9-Feb-2010	-
	End Recording	4-May-2010	5-May-2010	5-May-2010	-	4-May-2010	2-Jun-2010	-
Deployment 4	Sampling Rate	80 kHz	80 kHz	80 kHz	-	80 kHz	64 kHz	50 kHz
	Start Recording	13-Jun-2010	14-Jun-2010	13-Jun-2010	-	14-Jun-2010	3-Sep-2010	3-Jun-2010
	End Recording	19-Sep-2010	20-Sep-2010	19-Sep-2010	-	20-Sep-2010	21-Dec-2010	1-Sep-2011
Deployment 5	Sampling Rate	80 kHz	-	80 kHz	-	80 kHz	64 kHz	-
	Start Recording	20-Oct-2010	-	20-Oct-2010	-	20-Oct-2010	2-Sep-2010	-
	End Recording	27-Jan-2011	-	26-Jan-2011	-	20-Jan-2011	21-Dec-2010	-

each instrument was built, programmed, and deployed with the same specifications and hardware settings for gain and/or any additional data conditioning or filtering (e.g., detection thresholds).

Noise levels were calculated using custom written MATLAB^{TM} algorithms. For each 30 second acoustic data file an average power spectrum density level (dB re 1 µPa^2/Hz) was calculated using the following equation:

Equation 1: $$I(i) = k\, FFT(p^2(i))$$

where k is a conversion constant, Δf = 1/(N Δt), Δt being the same size of the digitalization process, or 1/sample rate of the EARs. In addition, band levels (dB re 1 µPa) were calculated for the frequency range 20 Hz and 25 kHz to maintain consistency among and between deployments (Nihoa had the lowest sampling rate at 50 kHz). The band level calculations were done using the following equation:

Equation 2: $$p_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} p^2(i)}$$

where i = 1 to N and N is equal to the number of points per file (p(i) is the instantaneous pressure, in µPa, at each sample that has been processed through a bandpass filter with a lower cutoff frequency of 20 Hz and a high cutoff frequency of 25 kHz).

The mean band levels were calculated as follows, where x = median levels for each deployment and n is the number of deployments per site:

Equation 3: $$mean = 20\, Log10\, \frac{1}{n}\sum_{i=1}^{n}\left(10^{\left(\frac{x}{20}\right)}\right)$$

Spectral probability density plots were created following the methods described by Merchant et al. 2013.

4.3 Results

Broadband ambient noise levels varied at each site (Table 4.2 and Figure 4.4). The band level measurements all exceeded 96 dB (*re* 1μPa throughout unless otherwise specified). The deployment with the highest band level measurements was Oahu 3 at 140.28 dB. The loudest overall site was Kauai SE with a mean band level of 104.1 dB. The quietest site was Kauai SW with a mean level of 100.2 dB.

Broadband measurements are useful for noticing trends in the data, if they exist, but examining the data in different frequency bands is useful for determining the potential contribution of different natural and anthropogenic sources. Figures 4.5 through 4.11 show the frequency plots for spectrum levels measured at 500 Hz, 5 kHz, and 15 kHz. Multiple deployments for the same site are included in each plot and the areas with no measurements indicate when the EARS were not recording either due to malfunction or when refurbishments were not able to be conducted due to weather and/or logistical issues.

Spectral probability density plots do not take into account the temporal nature of the recordings and is a statistical representation of the probability of the spectrum levels in each 1 Hz bin for the entire deployment. The spectral probability density (SPD) plot for the Nihoa dataset does not contain too many distinguishable peaks (Figures 4.12). This deployment spanned a period over a year and there is a lack of prominent peaks in any specific frequency bands. The Oahu sites (Figures 4.13 and 4.14) show a clear presence of low-frequency noise in both winter and summer months. The plots in Figures 4.15 through 4.24 are for alternate seasons at each Kauai EAR site. The increased spectral levels below 1 kHz in the winter months are the due to the present of humpback whales. The summer deployments do not show the same spectral peaks in the frequency bands of chorusing humpback whales.

Table 4.2: The 10th percentile, 90th percentile, median, and quarter percentile values for the band level measurements from each deployment. The band level measurements are between 20 Hz and 25 kHz averaged for each day. All data are dB re 1µPa.

Deployment Site	Start Recording	End Recording	10th Percentile	25th Percentile	Median	75th Percentile	90th Percentile	Mean of Band Level Medians
Nihoa	Jun-10	Sep-11	90.07	101.27	103.36	105.02	106.96	103.36
Oahu 1	Feb-09	Mar-09	99.37	101.01	102.56	104.00	106.46	101.90
Oahu 2	Jun-09	Sep-09	99.82	100.88	101.90	103.31	106.12	
Oahu 3	Sep-09	Dec-09	98.44	99.71	101.22	102.99	105.68	
Oahu 4	Feb-10	Jun-10	99.46	100.84	102.19	103.75	106.26	
Oahu 5	Sep-10	Dec-10	98.75	99.94	101.58	103.27	105.84	
Kauai N 1	Feb-09	Jun-09	97.76	100.03	103.70	106.10	108.06	102.78
Kauai N 2	Jun-09	Sep-09	99.13	100.65	101.74	102.61	103.44	
Kauai NE 1	Feb-09	May-09	101.97	103.00	104.61	105.72	107.34	102.96
Kauai NE 2	Jun-09	Sep-09	102.03	102.75	103.35	103.93	104.63	
Kauai NE 3	Jan-10	May-10	102.22	103.15	104.24	105.24	106.08	
Kauai NE 4	Jun-10	Sep-10	99.43	100.24	101.11	101.98	102.89	
Kauai NE 5	Oct-10	Jan-11	97.74	98.84	100.79	102.29	103.47	
Kauai NW 1	Feb-09	May-09	97.27	99.78	103.21	105.26	106.66	102.69
Kauai NW 2	Jun-09	Sep-09	97.17	99.63	101.60	102.82	103.82	
Kauai NW 3	Jan-10	May-10	99.96	102.06	103.86	105.42	106.74	
Kauai NW 4	Jun-10	Sep-10	98.55	100.59	101.87	102.98	105.54	
Kauai SE 1	Feb-09	Mar-09	103.07	104.25	105.48	106.66	108.10	104.13
Kauai SE 2	Jun-09	Sep-09	100.80	101.82	102.75	103.52	104.31	
Kauai SE 3	Jan-10	May-10	100.36	102.10	103.90	105.61	107.12	
Kauai SE 4	Jun-10	Sep-10	103.30	103.80	104.40	104.96	105.54	
Kauai SE 5	Oct-10	Jan-11	102.13	102.85	103.91	105.00	105.93	
Kauai SW 1	Feb-09	May-09	97.20	98.67	100.88	102.90	104.92	100.17
Kauai SW 3	Jan-10	May-10	98.06	99.16	100.92	102.90	104.75	
Kauai SW 4	Jun-10	Sep-10	97.05	97.83	99.13	100.48	101.80	
Kauai SW 5	Oct-10	Jan-11	96.79	97.82	99.60	101.42	103.39	

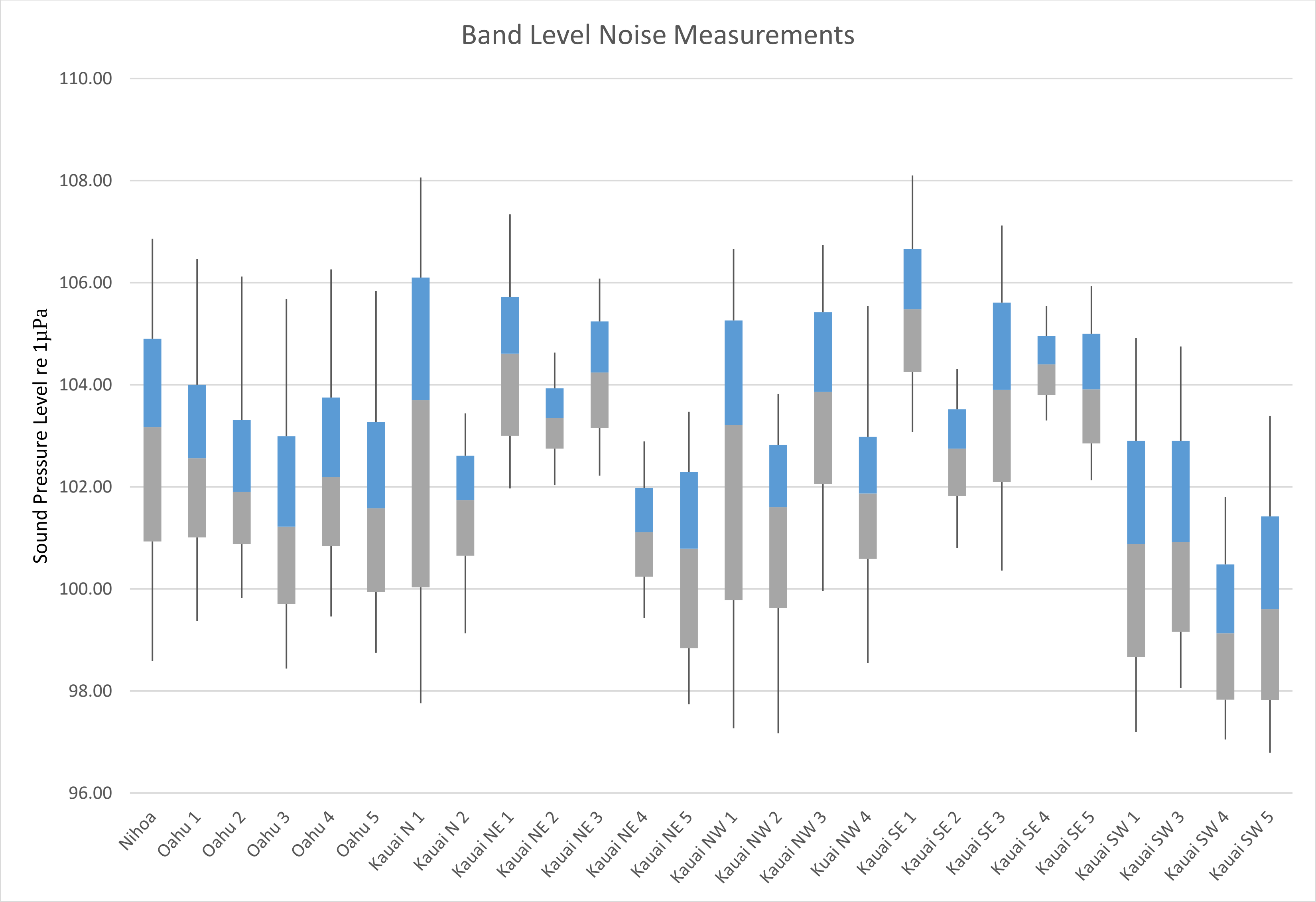


Figure 4.4: Box plots of band level noise measurements from 20 Hz to 25 kHz for each EAR deployment. The shaded areas indicate the quartile (Q1 and Q3) levels around the median and the vertical lines extend to the 10th and 90th percentile, respectively.

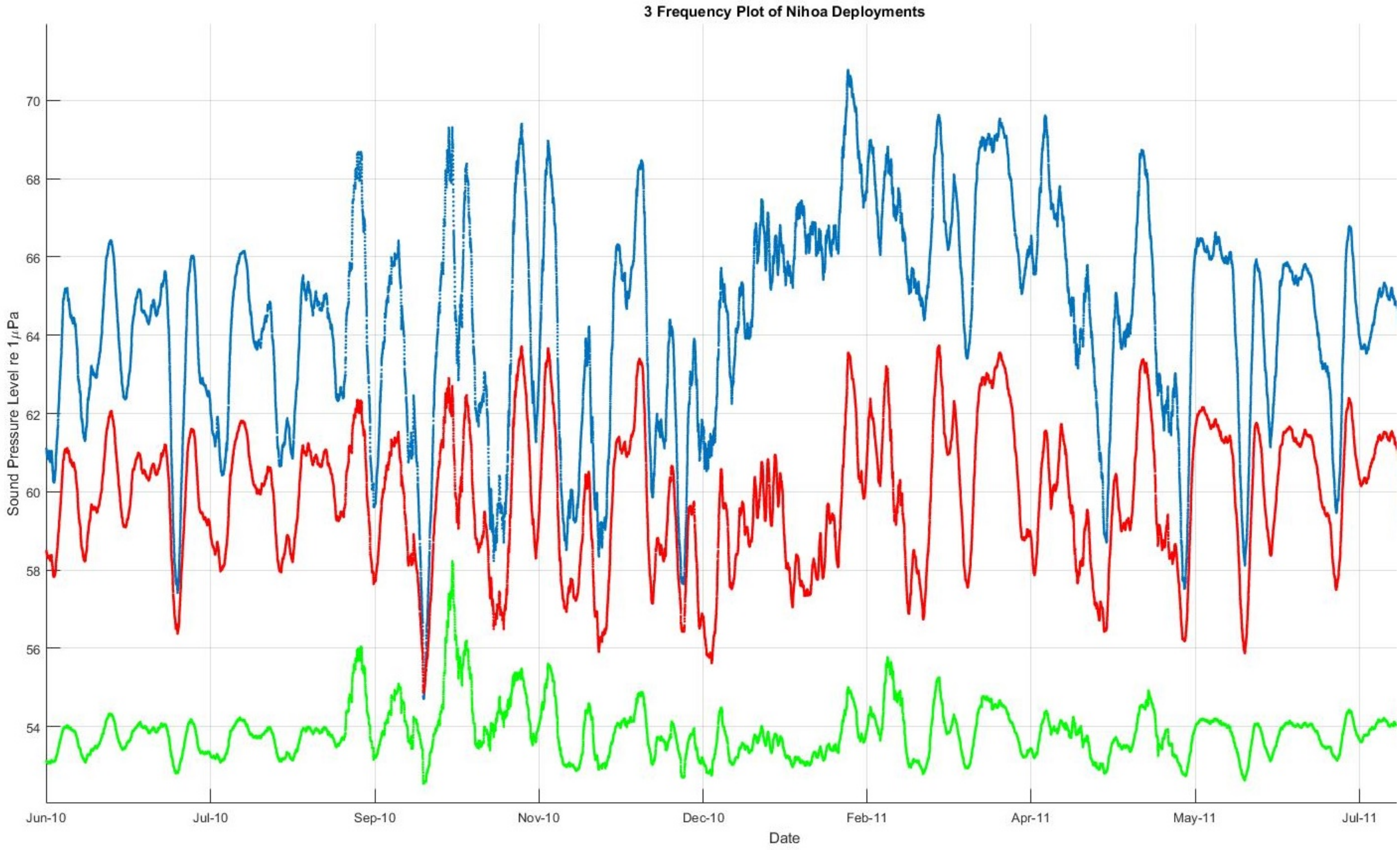


Figure 4.5: Spectrum level measurements for recordings made at the Nihoa site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz.

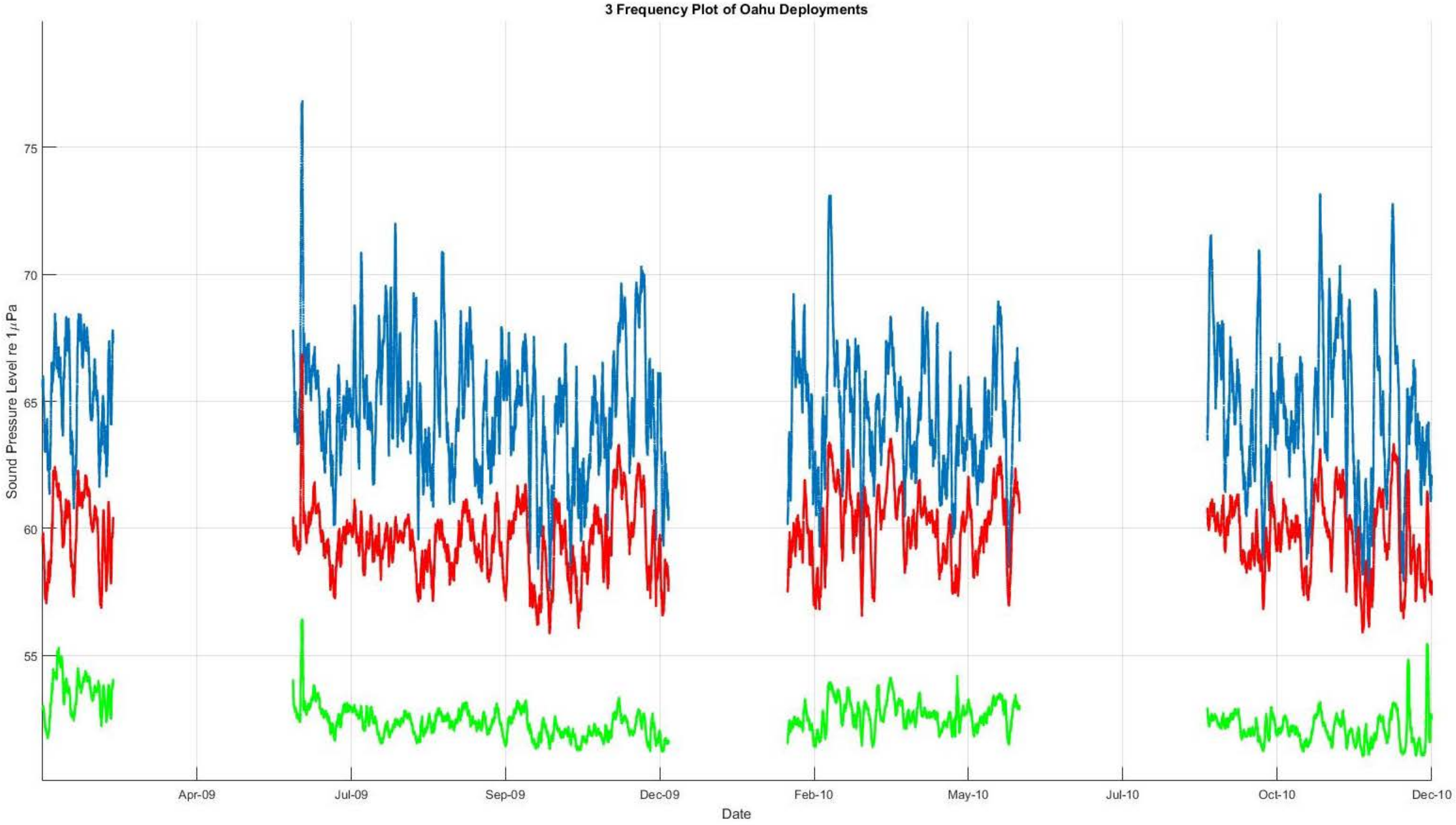


Figure 4.6: Spectrum level measurements for recordings made at the Oahu site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz.

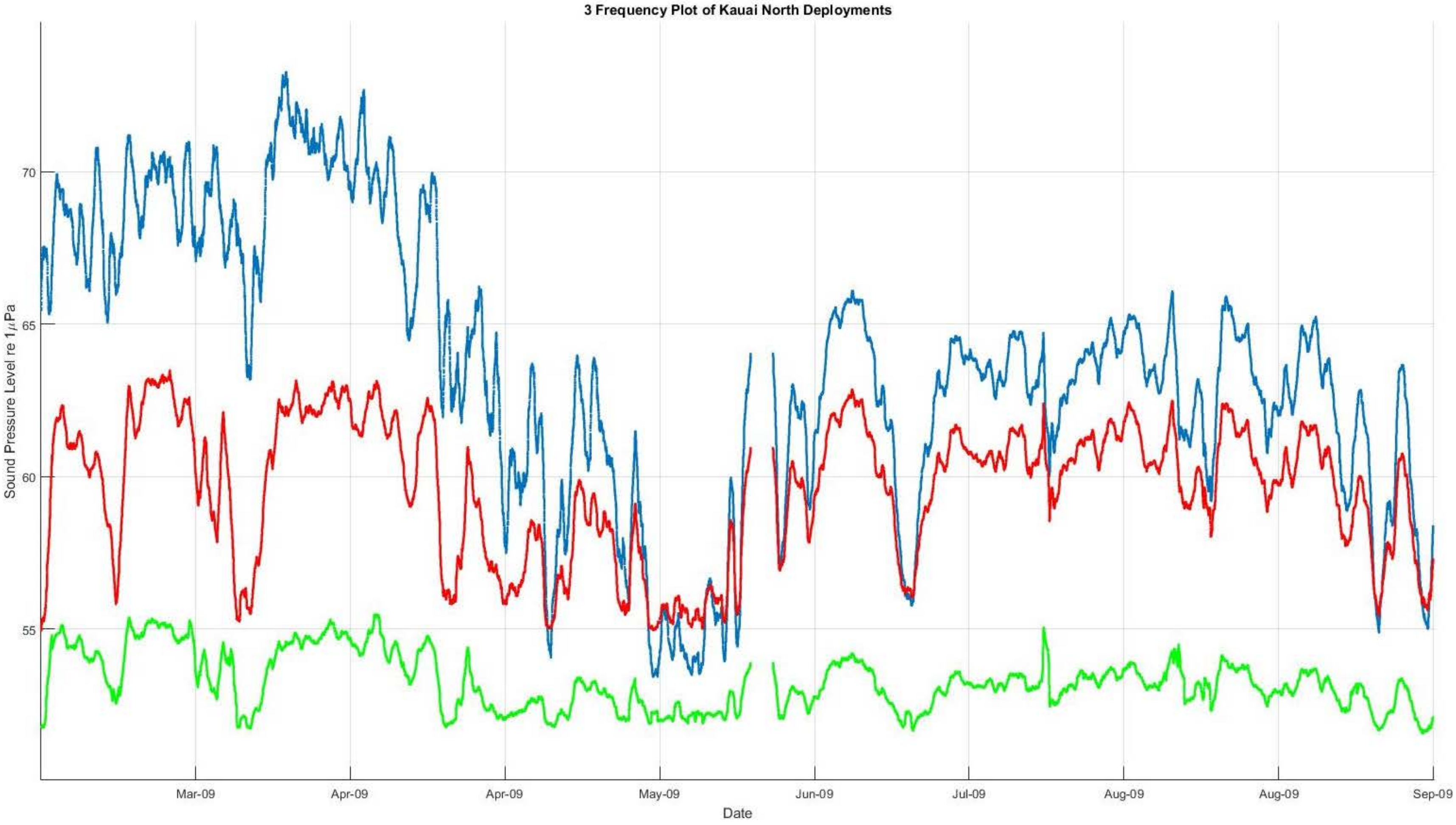


Figure 4.7: Spectrum level measurements for recordings made at the Kauai N site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz.

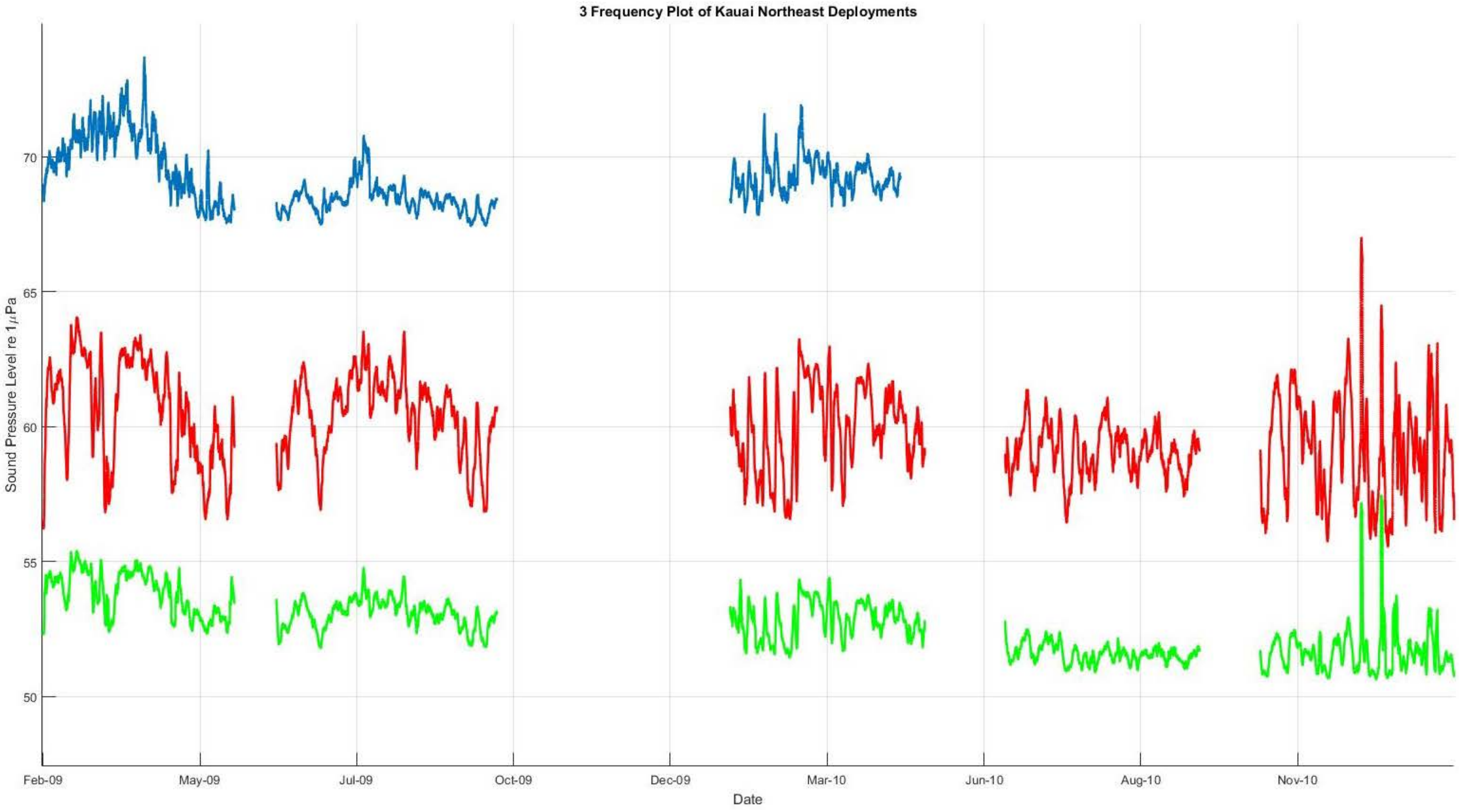


Figure 4.8: Spectrum level measurements for recordings made at the Kauai NE site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz. The EARs on the final two deployments had equipment issues and the 500 Hz measurements were not able to be calculated.

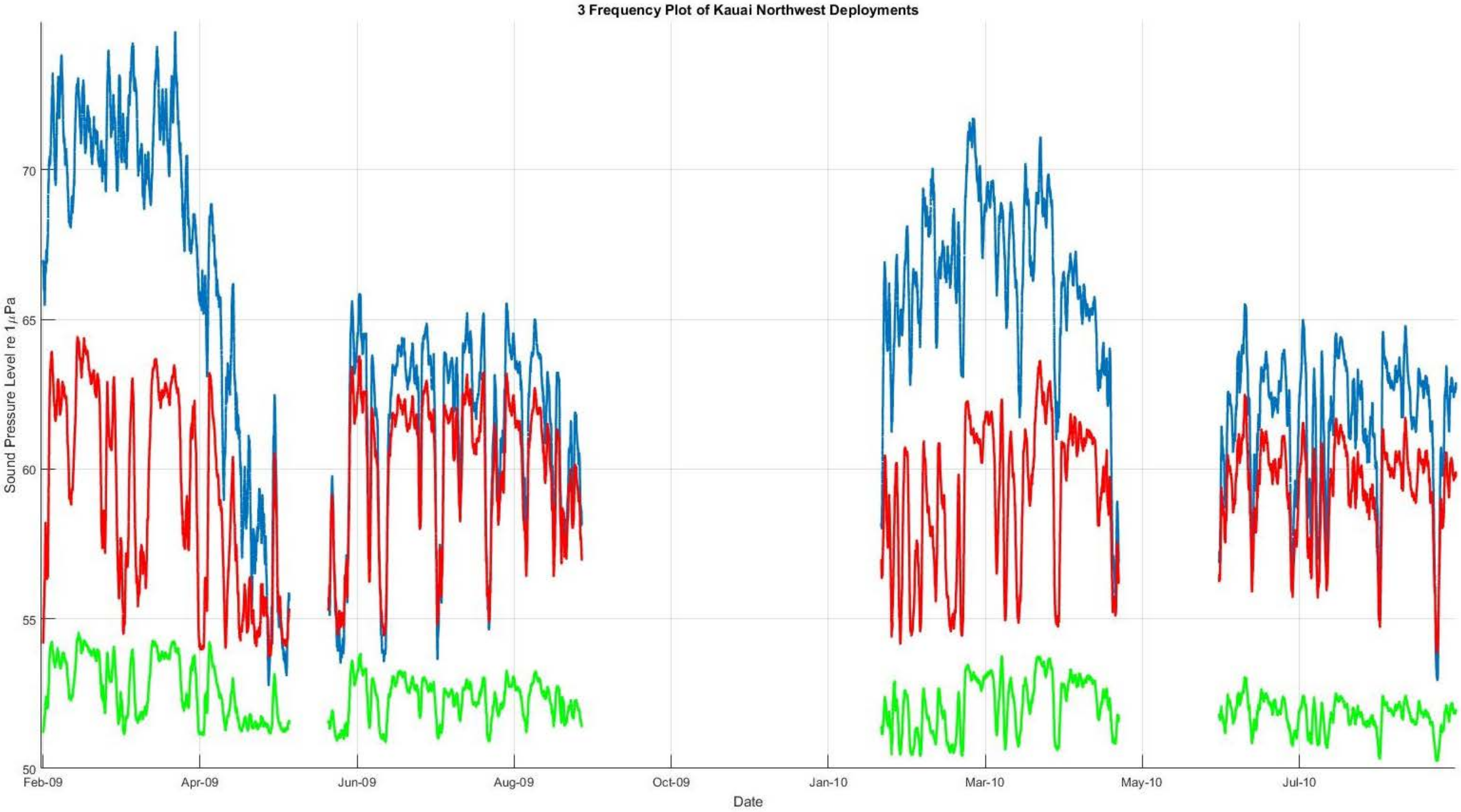


Figure 4.9: Spectrum level measurements for recordings made at the Kauai NW site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz.

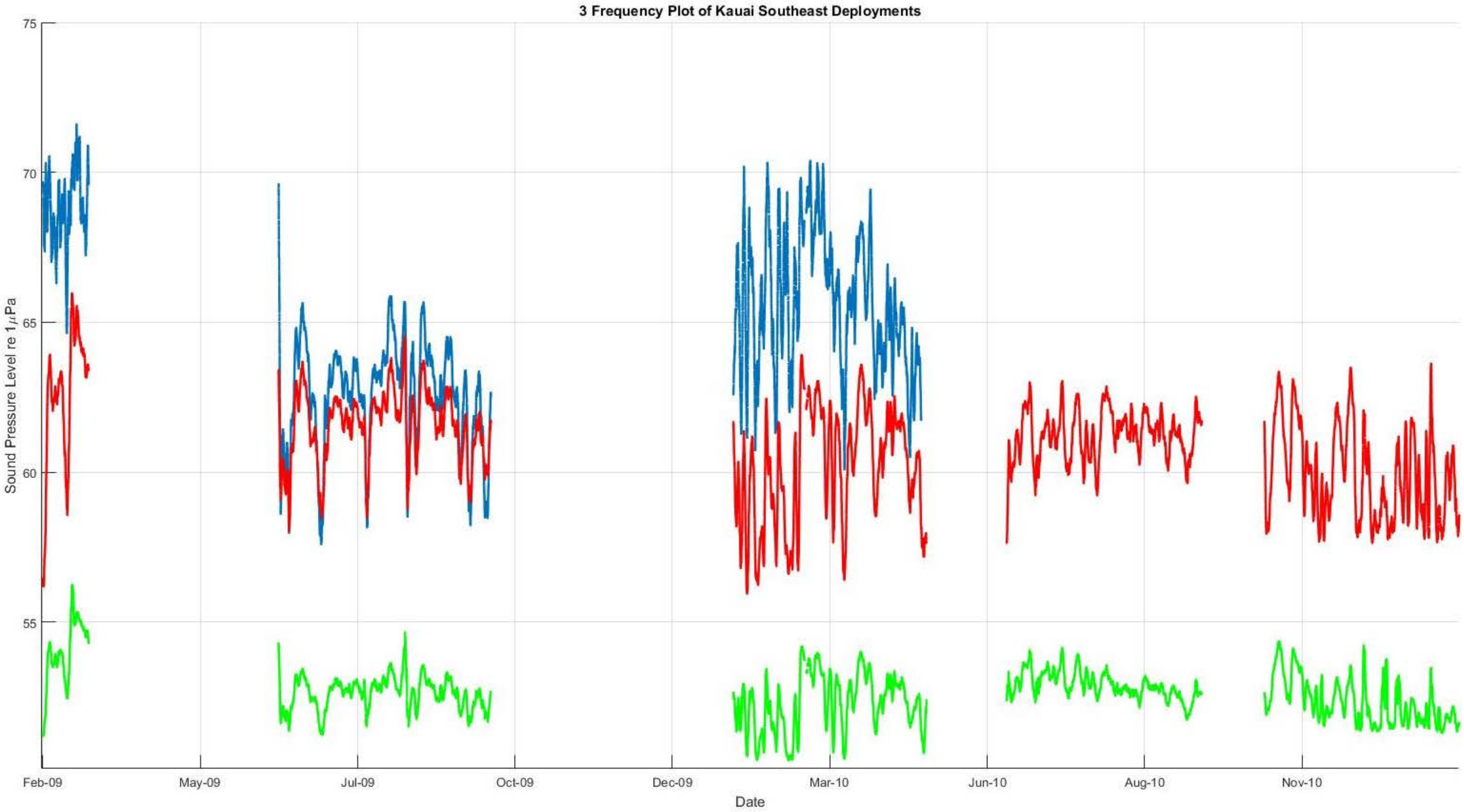


Figure 4.10: Spectrum level measurements for recordings made at the Kauai SE site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz. The EARs on the final two deployments had equipment issues and the 500 Hz measurements were not able to be calculated.

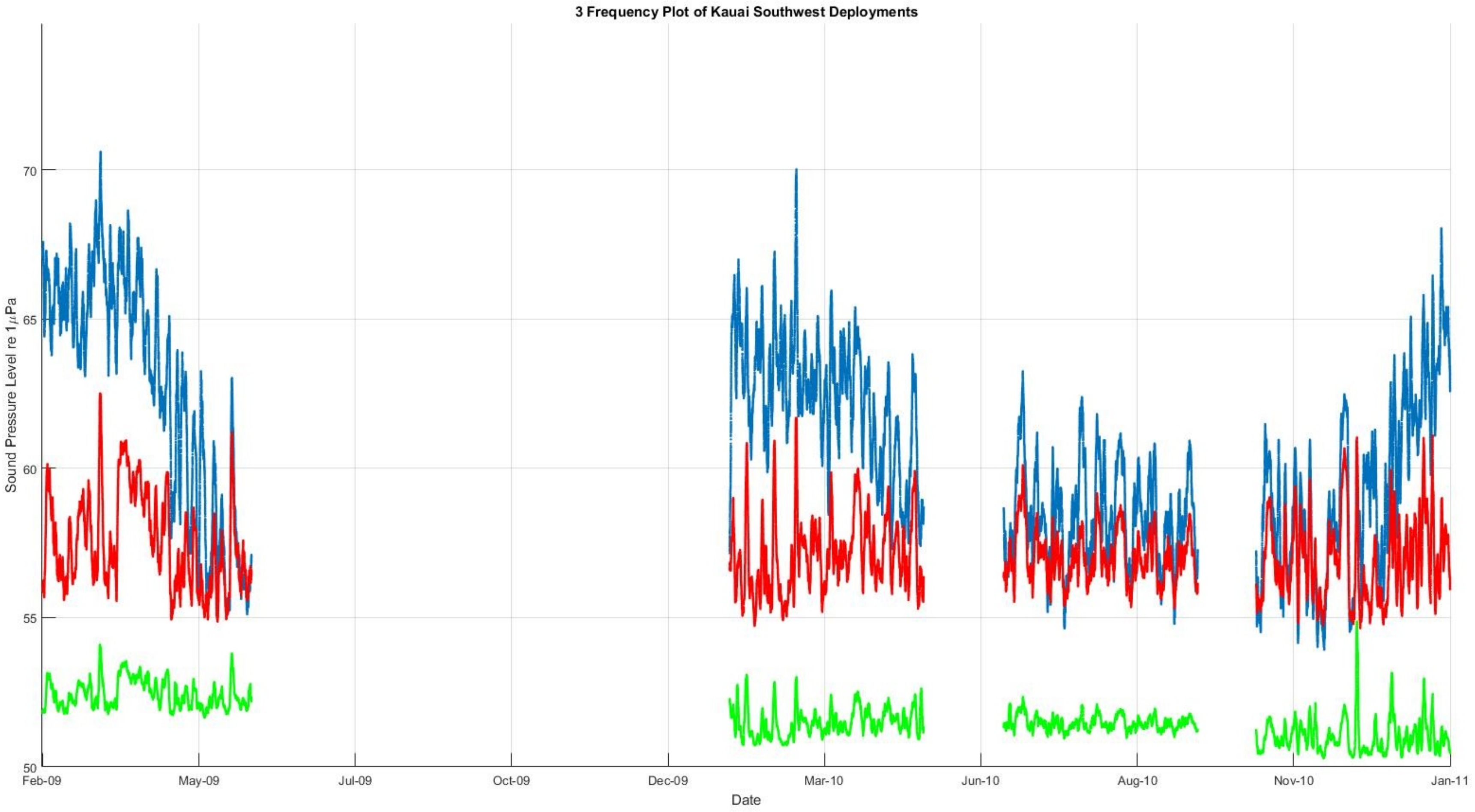


Figure 4.11: Spectrum level measurements for recordings made at the Kauai SW site. The blue levels are band levels at 500 Hz, the red levels are for measurements of 5 kHz, and the green levels are for 15 kHz.

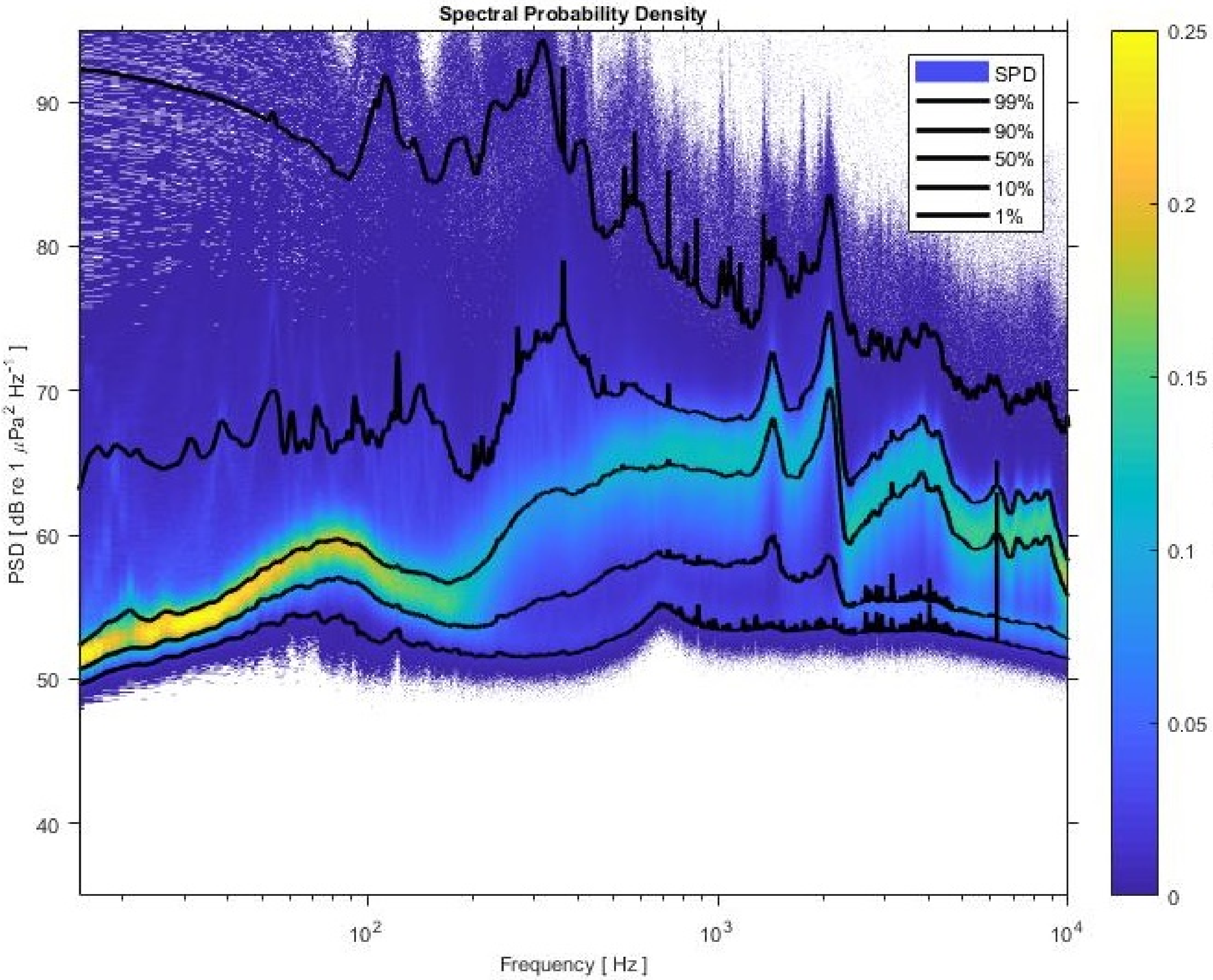


Figure 4.12: Spectral probability density plot for the Nihoa EAR deployment from June 2010 through September 2011. The color bar indicates the empirical probability density.

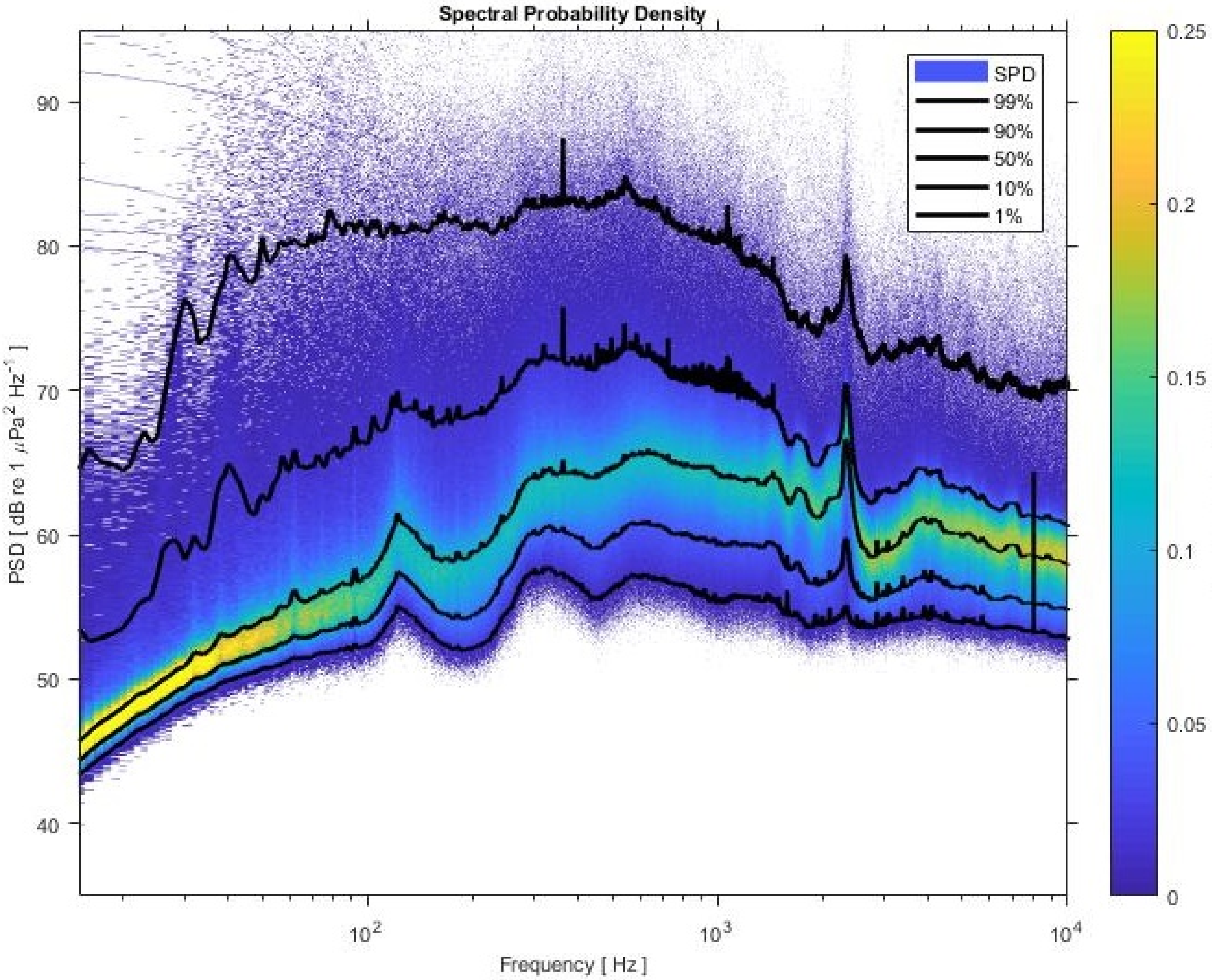


Figure 4.13: Spectral probability density plot for the Oahu 1 EAR deployment from February through March 2009. The color bar indicates the empirical probability density.

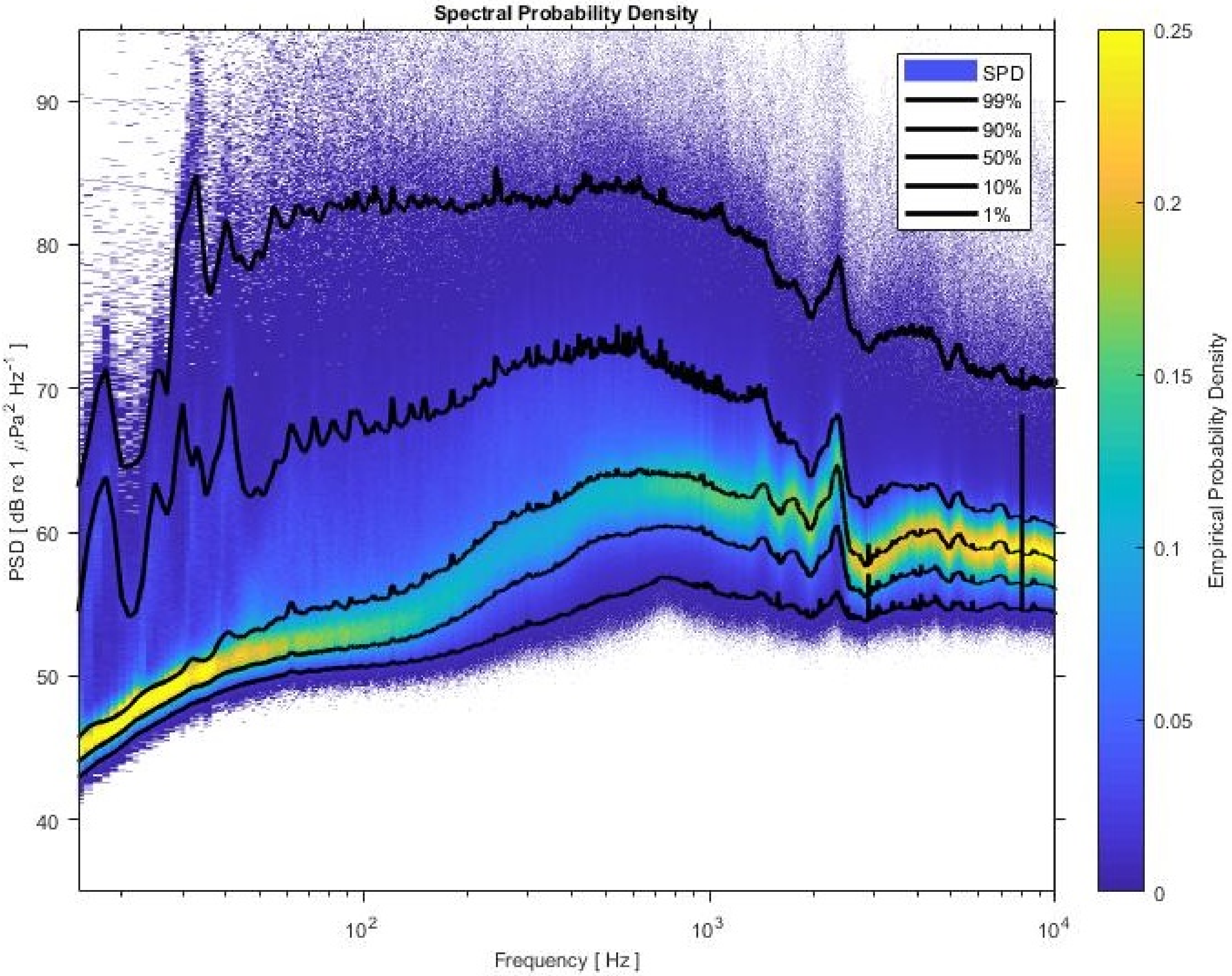


Figure 4.14: Spectral probability density plot for the Oahu 2 EAR deployment from June through September 2009. The color bar indicates the empirical probability density.

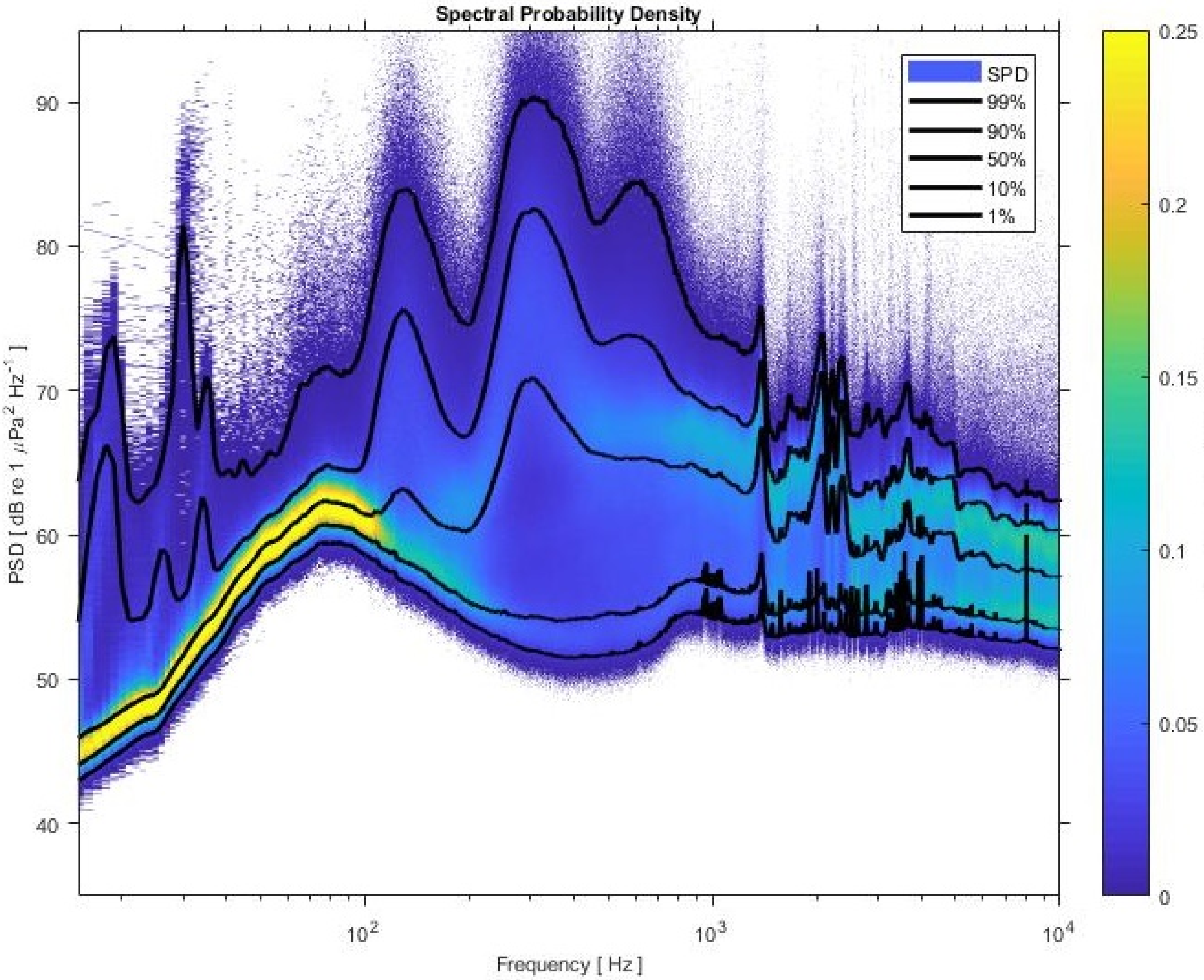


Figure 4.15: Spectral probability density plot for the Kauai N 1 EAR deployment from February through June 2009. The color bar indicates the empirical probability density.

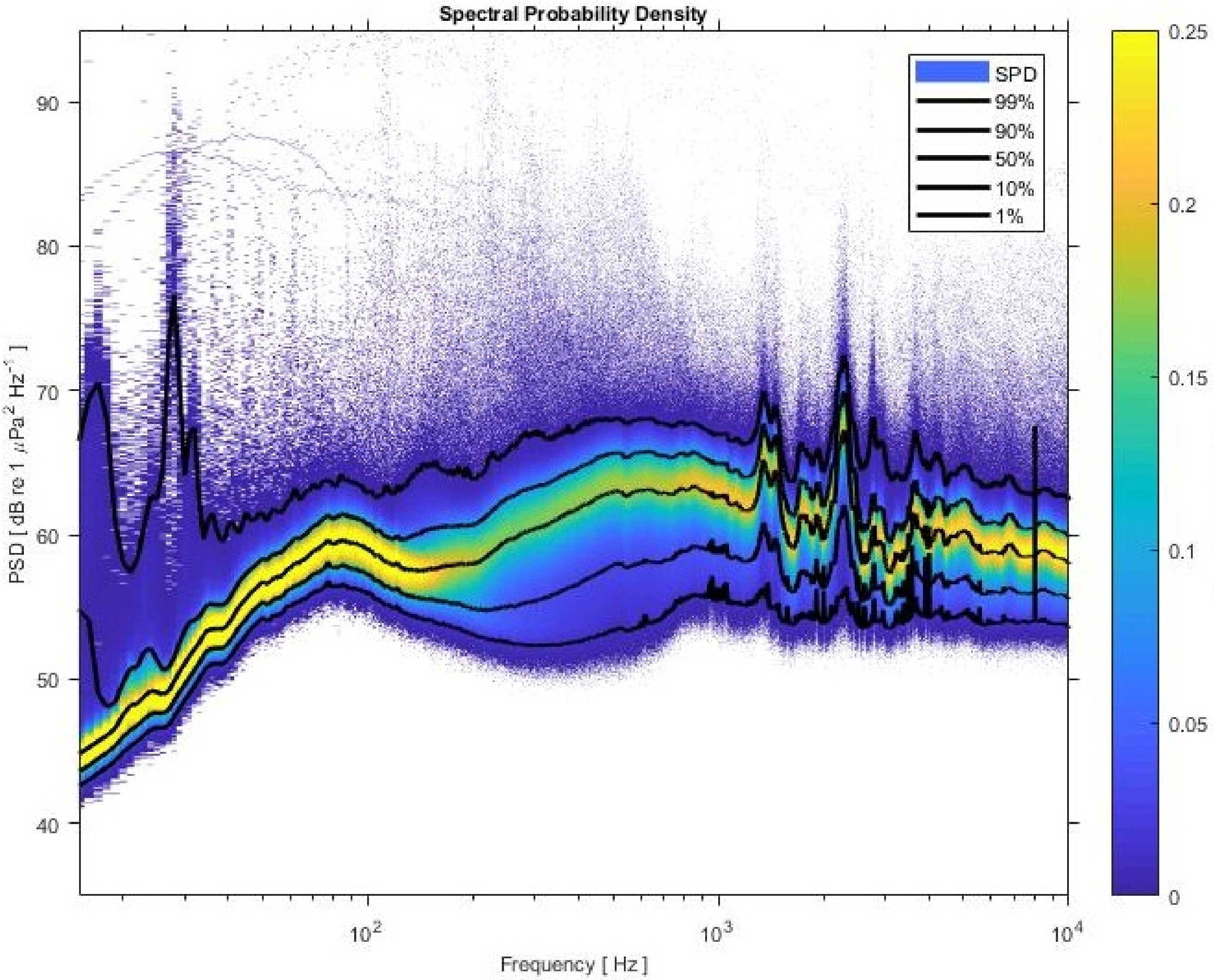


Figure 4.16: Spectral probability density plot for the Kauai N 2 EAR deployment from June through September 2009. The color bar indicates the empirical probability density.

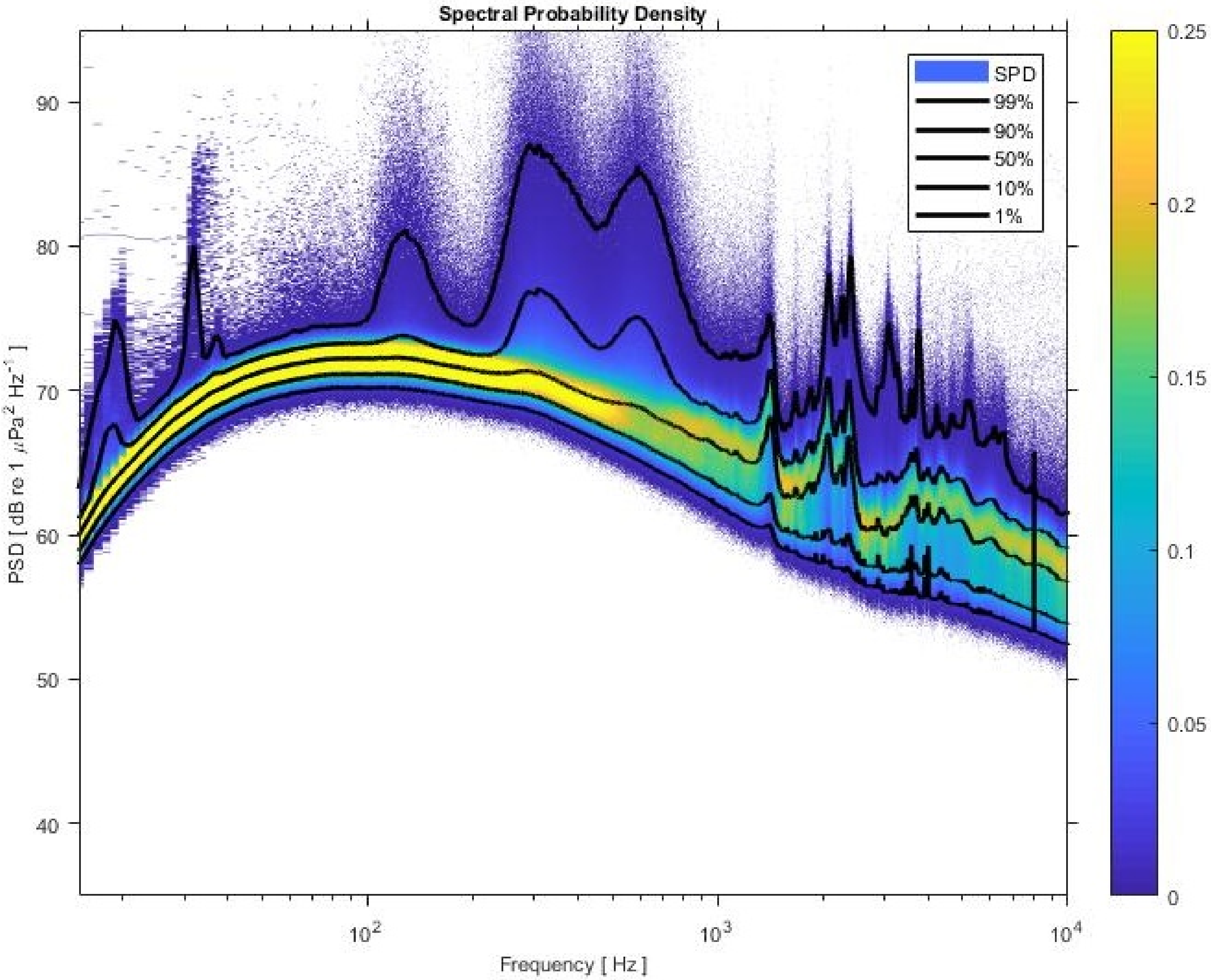


Figure 4.17: Spectral probability density plot for the Kauai NE 1 EAR deployment from February through May 2009. The color bar indicates the empirical probability density.

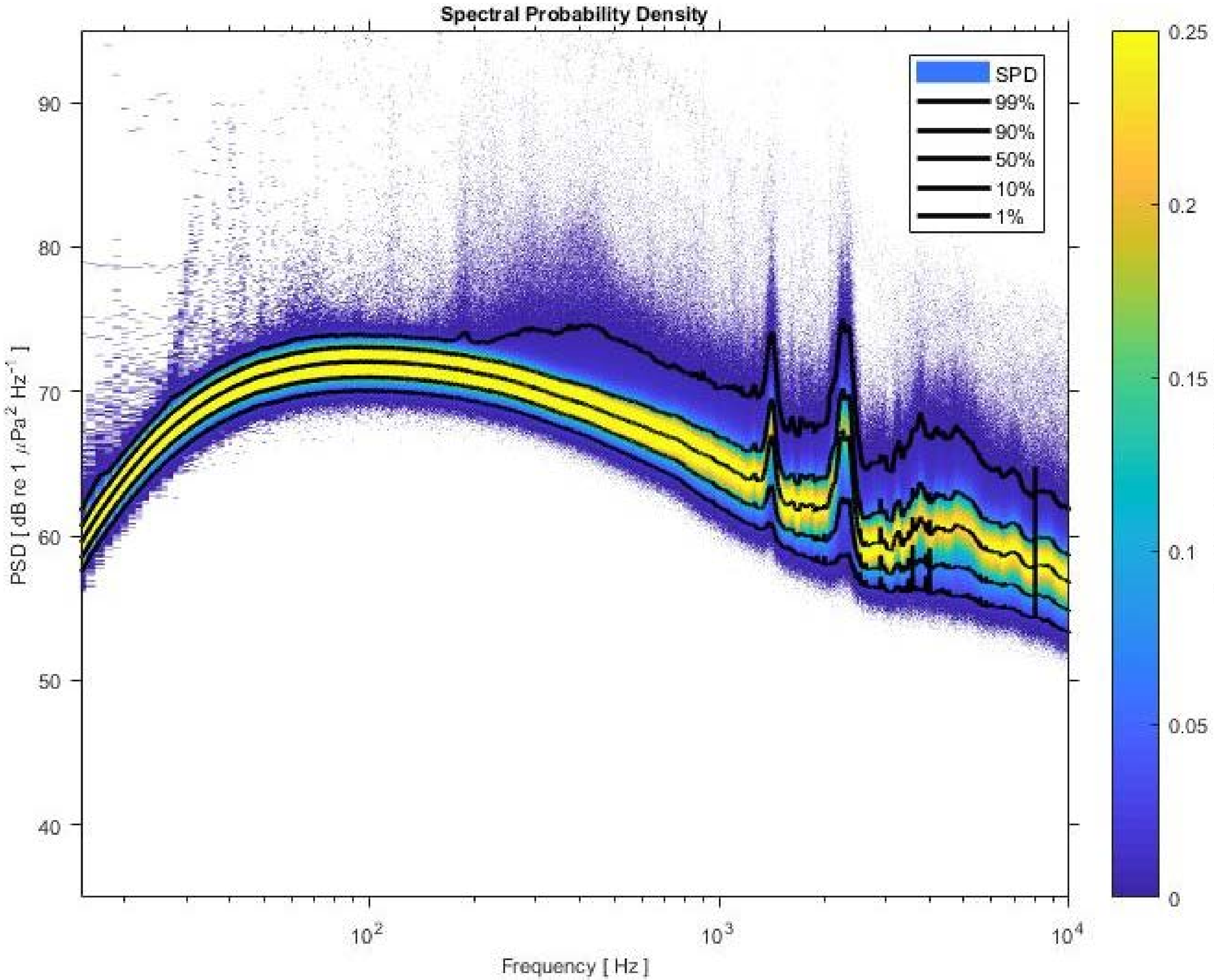


Figure 4.18: Spectral probability density plot for the Kauai NE 2 EAR deployment from June through September 2009. The color bar indicates the empirical probability density.

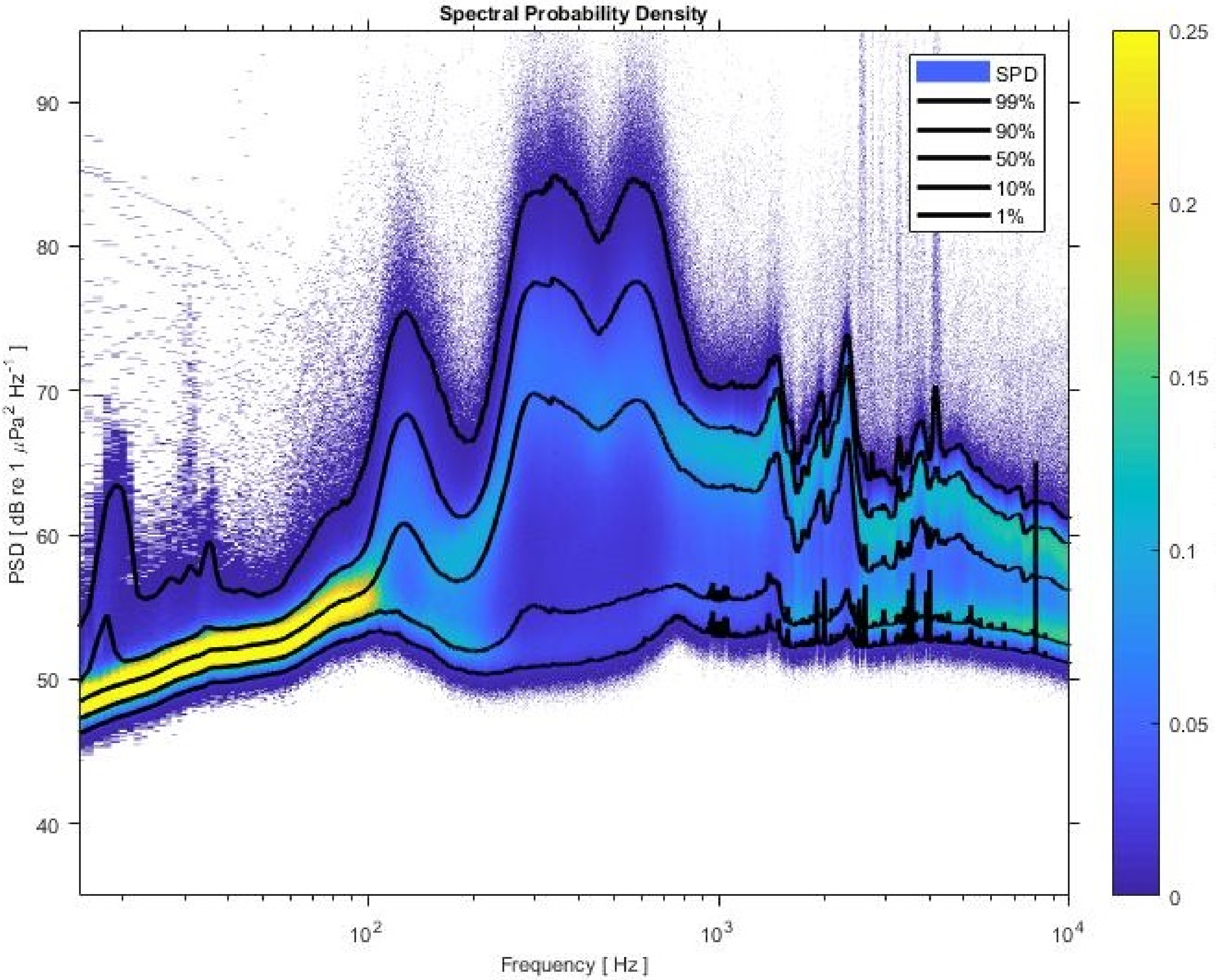


Figure 4.19: Spectral probability density plot for the Kauai NW 1 EAR deployment from February through May 2009. The color bar indicates the empirical probability density.

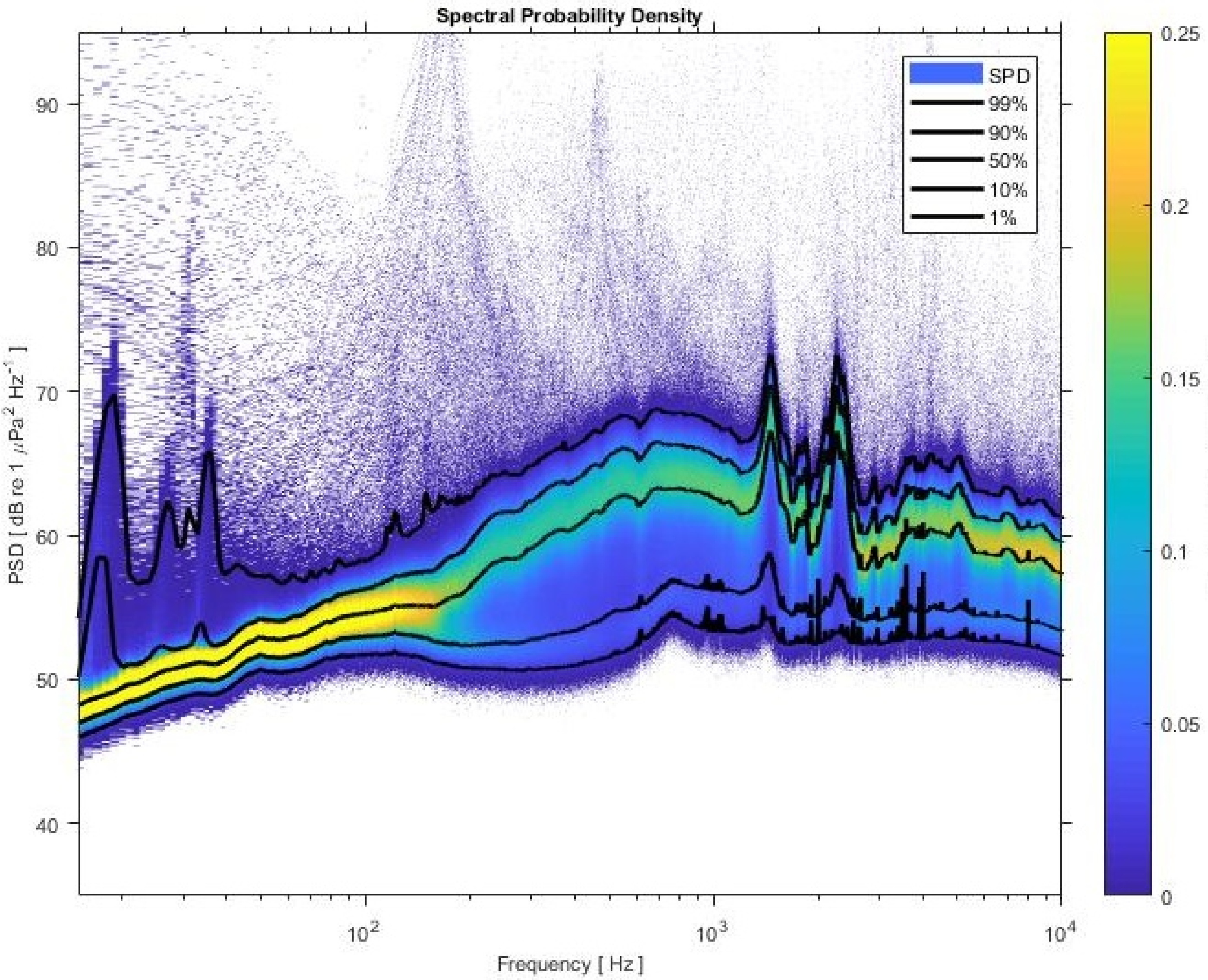


Figure 4.20: Spectral probability density plot for the Kauai NW 2 EAR deployment from June through September 2009. The color bar indicates the empirical probability density.

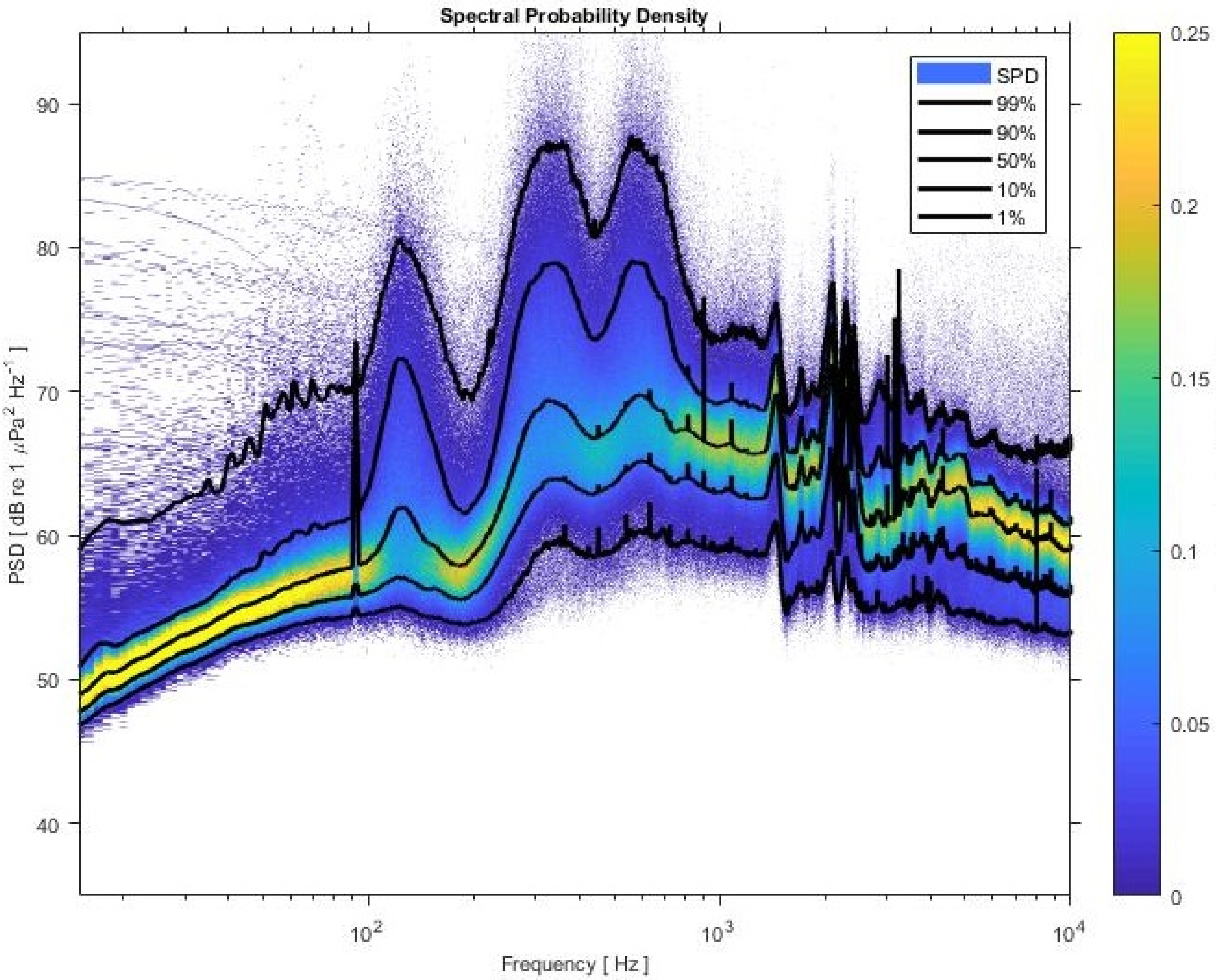


Figure 4.21: Spectral probability density plot for the Kauai SE 1 EAR deployment from February through March 2009. The color bar indicates the empirical probability density.

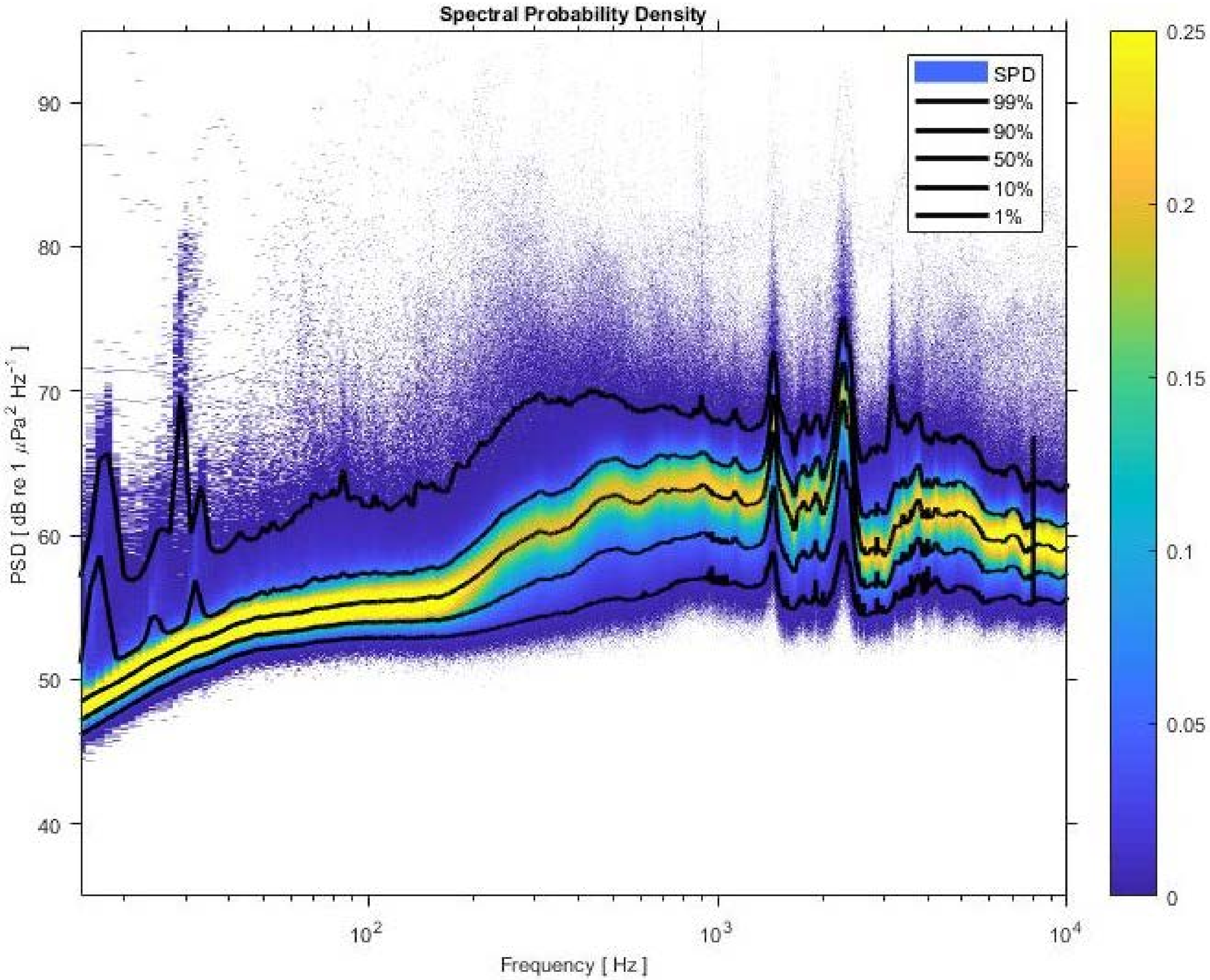


Figure 4.22: Spectral probability density plot for the Kauai SE 2 EAR deployment from June through September 2009. The color bar indicates the empirical probability density.

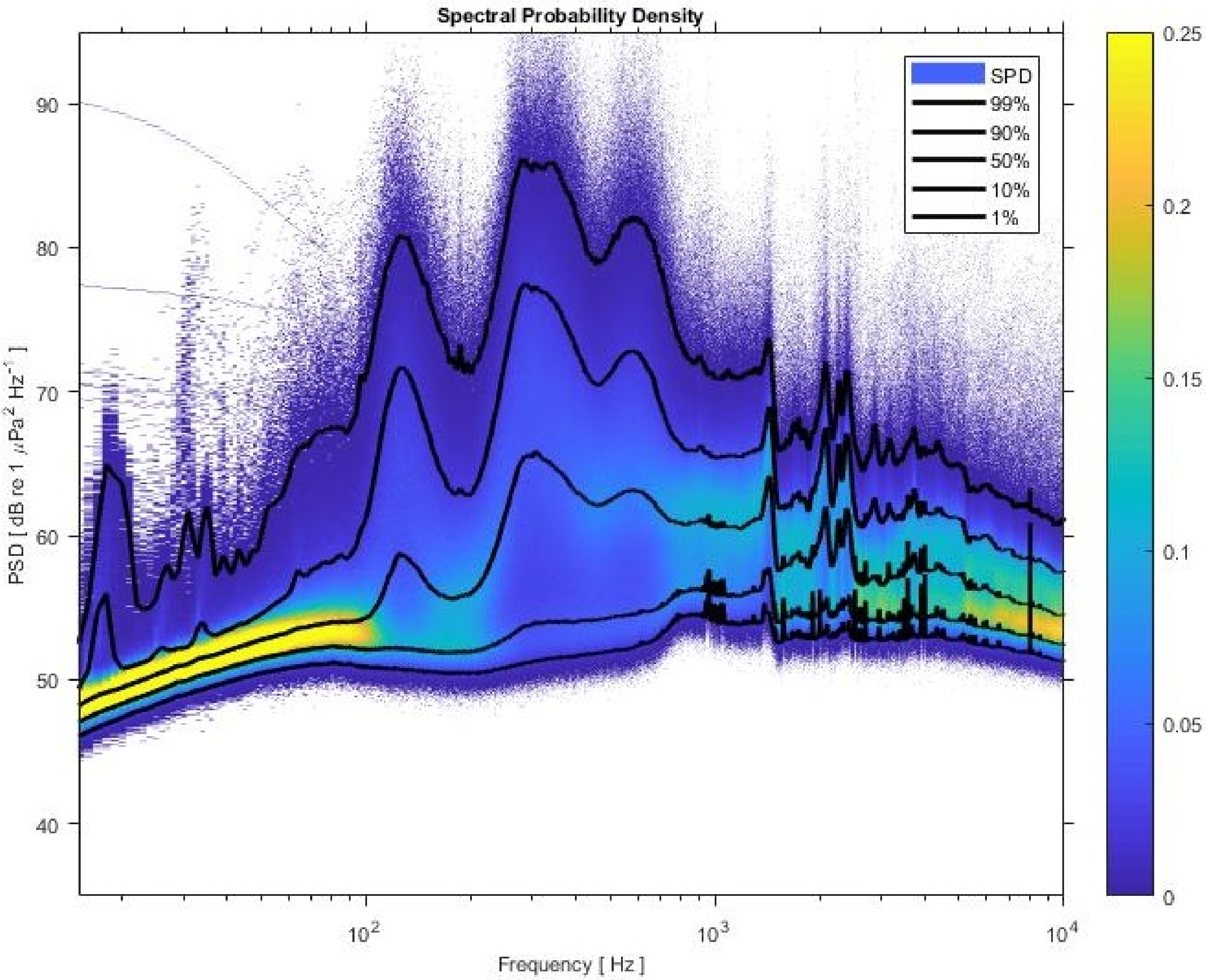


Figure 4.23: Spectral probability density plot for the Kauai SW 1 EAR deployment from February through May 2009. The color bar indicates the empirical probability density.

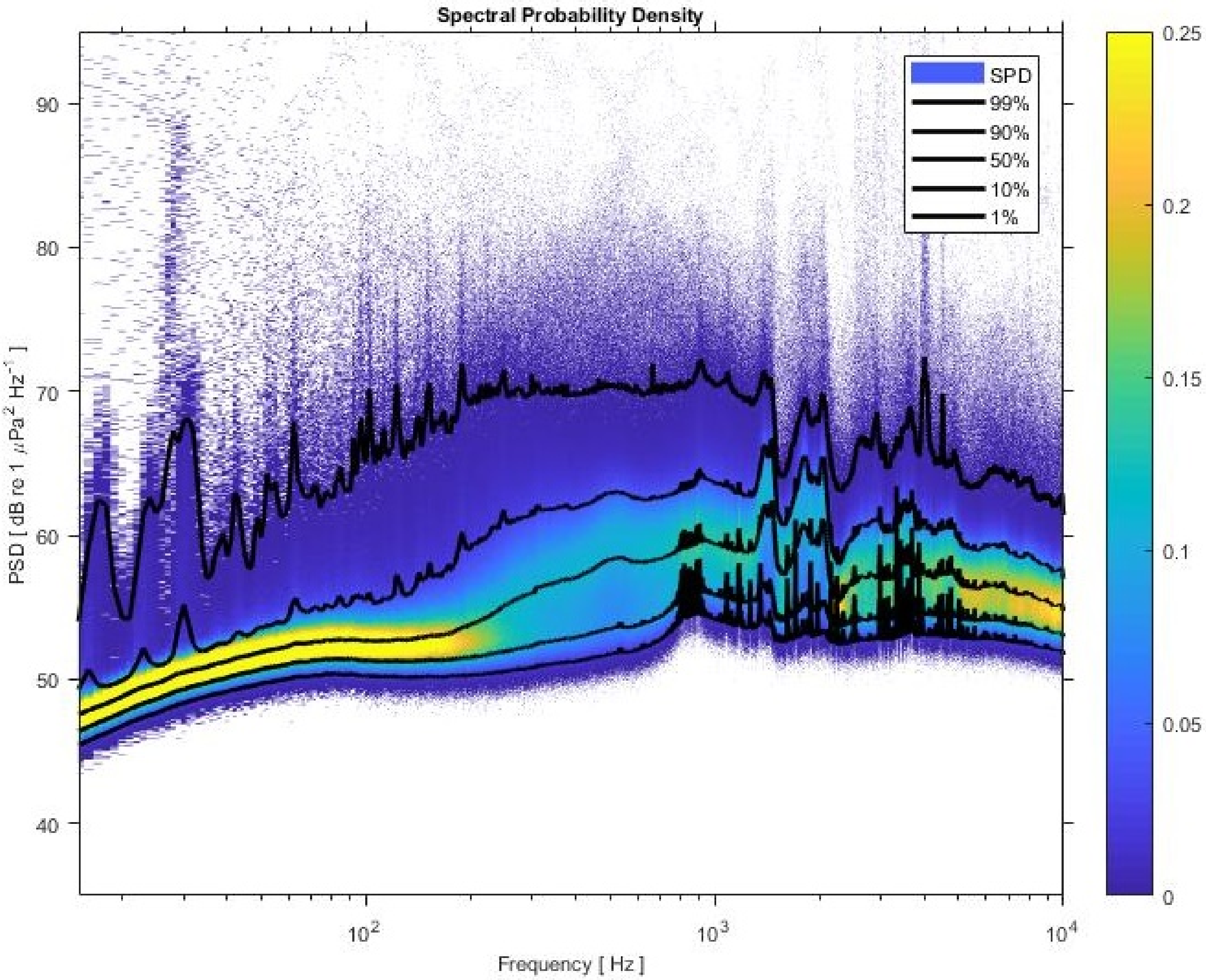


Figure 4.24: Spectral probability density plot for the Kauai SW 4 EAR deployment from June through September 2010. The color bar indicates the empirical probability density.

4.4 Discussion

The sound levels recorded at each of the EAR sites are consistent with recently published data from sites around the MHI as well as around the Pacific Ocean. Širović et al. (2013) conducted low-frequency noise analyses recorded at seven locations including Kauai (near the EAR NW site) and Kona (Hawaii Island). The aim of the study was to look at the impact of shipping and other noise sources below 1 kHz. The spectra level measurements that they made ranged between 55 and 67 dB re 1μPa^2/Hz at 500 Hz. The levels obtained from the EAR data in this study ranged from 51 to 76 dB re 1μPa^2/Hz. These measurements have lower levels than those recorded from other study sites in the Pacific (Andrew et al. 2002, McDonald et al. 2006) which had ranges between 66 and 68 dB re 1μPa^2/Hz. There are many things that could account for the differences in the reported noise measurements including deployment depth, bathymetric characteristics at each site, and instrument recording characteristics. The EARs were more shallow and located closer to the sea floor as well as the coast of Kauai and Oahu. While sound propagation studies were out of scope for this project, it can be assumed that the EAR placement will impact the received characteristics of low-frequency sound. If this project was intended to monitor for low-frequency noise, the deployment sites would have been selected with different criteria.

The general processes and influences on the soundscapes of the MHI are pretty well understood and the data analyzed in this study produced results that were more or less expected. The data recorded at Nihoa were used as a reference location outside of the MHI that is not subjected to the same volume of vessel traffic and is not known to be a significant breeding ground for wintering humpback whales. The band level noise from Nihoa were comparable to the EAR deployment sites around Kauai and Oahu. The island of Nihoa is only 63 acres and much smaller than both Kauai and Oahu. Without a predominant lee, it is not expected that the noise levels recorded on the EAR would differ had the deployment been located on the eastern side of the island. Plotting the three frequencies in Figure 4.5 shows that the levels at 5 kHz are higher than those at 15 kHz. This is to be expected since the wind generated noise is expected to be more persistent than more ephemeral rain events. While rain events may be louder at any given time, the band level measurements are averaged over a 24-hour period and the rain signals are more likely to be washed out, no pun intended. When looking at the broadband levels around Nihoa, there are no strong seasonal trends evident in the data and the noise levels are varied. Figure 4.25 shows band noise levels (20 Hz to 25 kHz) for the entire Nihoa deployment. The top figures are archived wind data from Weather Underground (wunderground.com) from the Lihue Airport weather station (the closest available to Nihoa). The majority of the wind is easterly, as would be expected with the predominant trade winds in the Eastern Tropical Pacific. It is interesting to note, however, that when the winds shift to the north, the band level noise is lower. It is unclear why this is the case at this particular location. From this figure, even without statistical correlation, it is clear that the noise levels are very much influenced by the predominant wind conditions more than any other factor.

With regards to biological contributions to the soundscape, Figure 4.5 shows that during the winter there is an increase in the 500 Hz noise, indicating the presence of humpback whales. The whales are definitely present in the winter but do not appear to use the waters around Nihoa as a primary habitat for song chorusing and are likely transiting through the area during the winter months. The spectral level noise (Figure 4.12) shows that there is a distribution of noise throughout the recorded frequency range. There are no discernable spectral peaks that would correlate to particular noise sources in specific frequency bands and the majority of the noise at the Nihoa EAR site is broadband in nature. If the humpback whales had a strong seasonal preference for this site, one would expect peaks similar to those observed with the Kauai EARs.

The Oahu EAR was located near the primary shipping lanes for Hawaii (Figure 4.3). As expected, vessel noise was pervasive in the lower frequencies of the recordings. While humpback whales occur in high densities around Oahu, they are primarily found in waters less

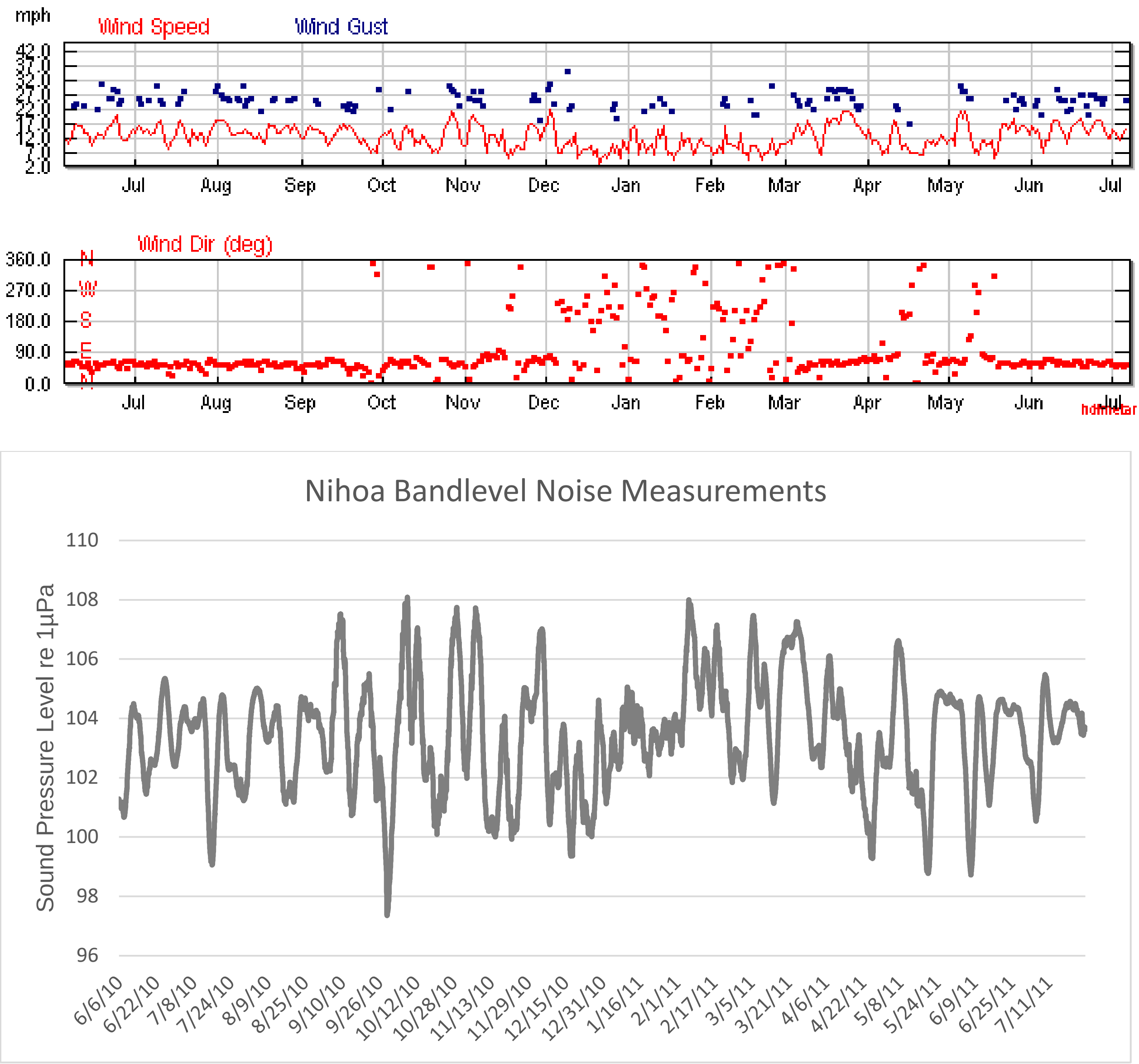


Figure 4.25: Band level noise (20 Hz to 25 kHz) at the Nihoa EAR site. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

than 100 fathoms, where the majority of song chorusing occurs (Herman and Antinoja 1977). Despite this habitat preference, the whales move around the islands and continue to produce songs even in deeper water (Mate et al. 1998, Clapham and Mattila 1990). However, the near constant presence of vessels in the data make it difficult to discern humpback song. The 500 Hz bands plotted in Figure 4.6 do not show any seasonal difference between deployments. Additionally, the SPD plots (Figures 4.13 and 4.14) have no spectral peaks between 500 Hz and

1 kHz as would be expected if humpback sounds were detected above the increased background levels caused by the present of low-frequency vessel noise. For this study, the occurrence of humpbacks in the data were not analyzed either manually or using automated algorithms. However, while scanning the data humpbacks can be detected amongst the vessel noise during the winter months. The constant din of vessels would be problematic for automated techniques and any results produced by these methods would need additional levels of scrutiny to test for underrepresentation of occurrence when the signal to noise ratios are low enough for masking to occur. It is uncertain if humpback whales would avoid this noisy habitat due to an impact on their effective communication range. Future investigations could examine the detectability of humpback whales in this area and perhaps telemetry data could demonstrate if the whales avoid spending time near the shipping lanes and prefer more suitable acoustic habitat for their acoustic displays.

The mean broadband noise levels (101.90 dB) at the Oahu EAR site are surprisingly not much louder than other sites without as much nearby shipping. Figure 4.6 shows that the noise is consistently variable among the three different frequencies plotted. Figure 4.26 further shows that the broadband levels do not vary much between different deployments. The high peak observed in the Oahu 2 deployment is the result of a very loud boat that was present over the course of 1.5 days, resulting in the maximum band level measurement of 111.70 dB. Similar to the Nihoa site, the broadband levels are greatly influenced by the prevailing wind conditions.

Similar to the Nihoa site, the broadband levels are greatly influenced by the prevailing wind conditions. The top two panels in Figure 4.27 show the wind data recorded at the Honolulu Airport. The EAR and the airport are both located on the leeward side of the island and the prevailing wind conditions are from the easterly trade winds. The broadband levels are variable but the loudest periods observed during this deployment (early March and early April) correspond somewhat to increased wind speeds.

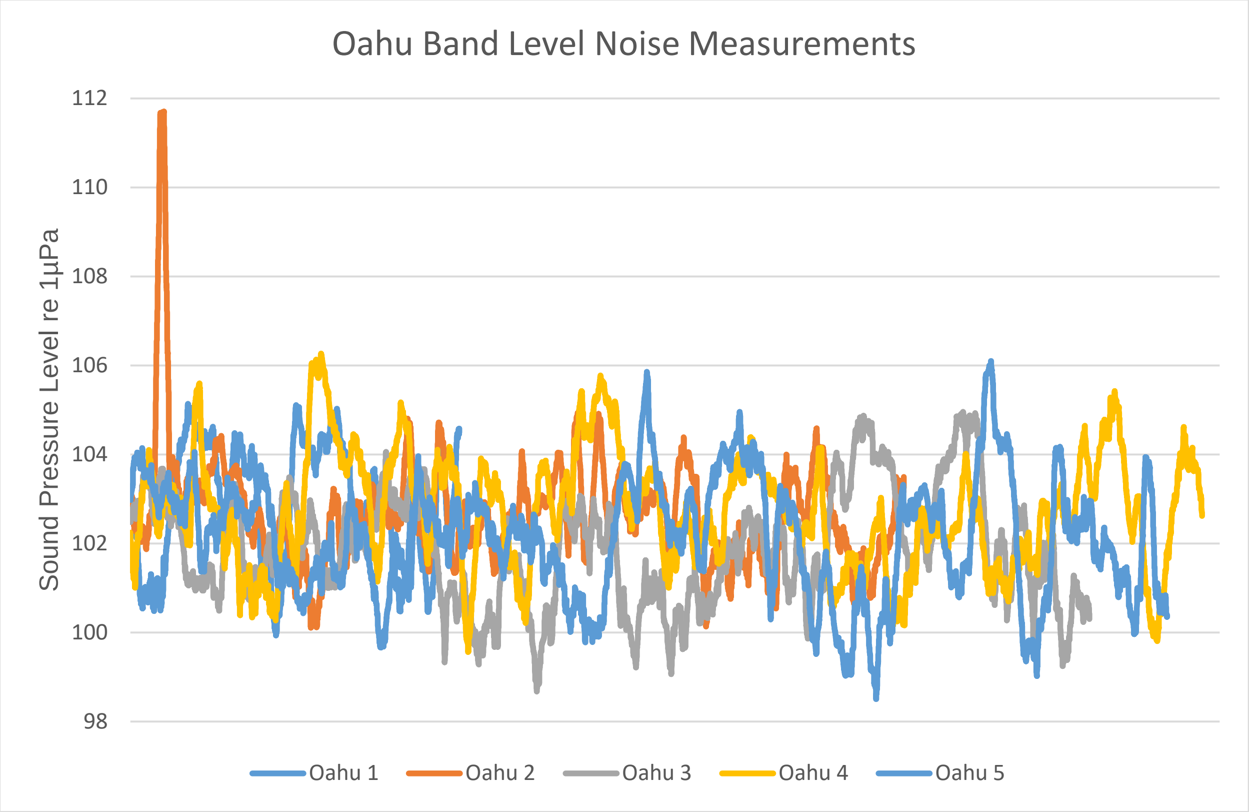


Figure 4.26: Band level noise (20 Hz to 25 kHz) at the Oahu EAR site for all deployments. The x-axis is time and not all deployments were the same duration so date ranges have been omitted.

The EAR deployments around Kauai are likely to show more noise variation depending on seasonality as well as site location. Sounds from shipping activities are prevalent and the occurrence of humpback whales is well documented in winter months, despite lower overall densities compared to other island breeding habitats (Mobley et al. 1999).

The Kauai N site was the shallowest EAR deployment around the island (394 m). Unfortunately on the third deployment the instrument remained stuck on the seafloor and data were only obtained for the first two. The near continuous recordings show that the humpbacks were present during the winter months and in the summer the noise levels at 500 Hz decreased (Figure 4.7). Their presence in the two datasets is also evident in the SPD plots (Figures 4.15 and 4.16). The spectral humps seen below 1 kHz are due to the presence of humpback song in the data. There are also spectral peaks the very low frequencies of the SPD plots but the low

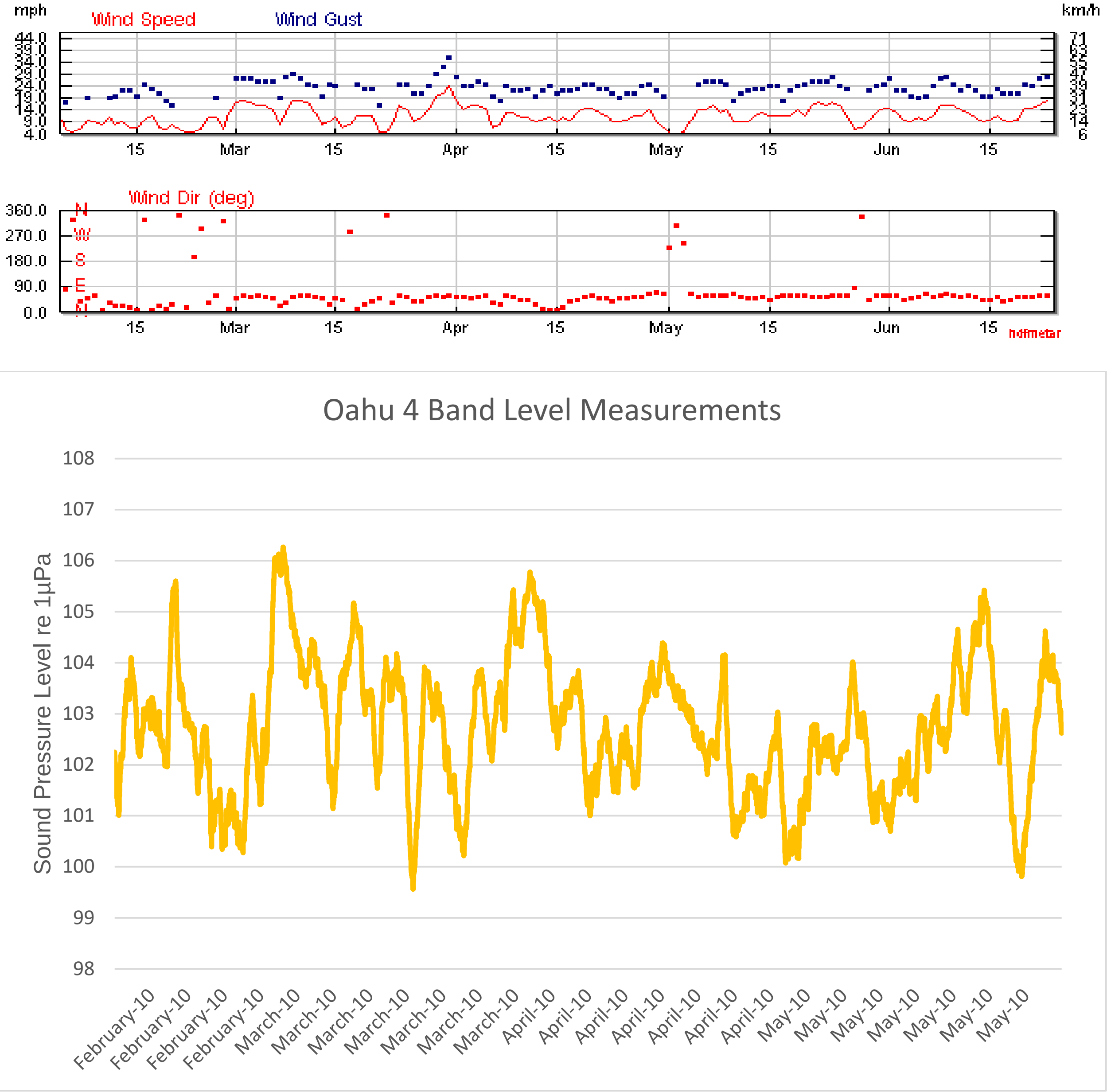


Figure 4.27: Band level noise (20 Hz to 25 kHz) at the Oahu EAR site (deployment 4). The top two panels are weather data observed at the Honolulu Airport weather station for the corresponding deployment time period.

end cutoff for EAR recordings is 20 Hz and those peaks are the result of system generated noise.

Aside from the Kauai NE site, the same overall patterns of humpback occurrence, based on the relative levels of noise at 500 Hz, is evident at each of the other Kauai locations. The Kauai NE EAR is located on the windward side of the island and similar to Oahu, and a lesser extent Nihoa, humpback whales are not easily detected when looking only at the 500 Hz frequency band (Figure 4.8). There is a slight decrease in the band level noise during the second deployment but the presence of whales is really only detectable when examining the SPD plots (Figures 4.17 and 4.18). The mean broadband noise level at the Kauai NE site is second loudest to those recorded at the Kauai SE site, 102.96 dB and 104.13 dB, respectively. The windward sides of the islands will experience stronger and more persistent wind conditions and the overall noise levels correspond accordingly. Figures 4.28 through 4.32 show the broadband noise levels and corresponding wind data for each of the deployment periods. In Figure 4.29, the Kauai NW site had periods that were much quieter than the other locations. This site was leeward these periods follow the same wind trends but are more exacerbated due to the reduced wind speeds based on the easterly winds that prevailed during this summertime deployment period.

The ambient noise levels around Kauai are correlated to their exposure to the easterly trade winds. The loudest sites are Kauai SE, Kauai NE, and Kauai N. The quietest site is Kauai SW (mean broadband level of 100.17 dB) is in the lee of the island as well as located closer to the shoreline. It is evident in Figures 4.28, 4.30, 4.31, and 4.32 that the broadband noise at the Kauai SW site do not follow the wind trends nor the patterns of noise observed at the other four sites. For each of the deployments, the wind is the predominant cause of ambient levels and the contribution from humpback whales and rain do not impact the overall soundscape as dramatically.

The Kauai NW site is located closely to the Navy's PMRF training area. If the Navy used this site consistently and extensively, we would expect to see noticeable differences in the broadband levels as well as in the 500 Hz low-frequency band. Vessel activity was recorded on the Kauai NW EARs but it was not consistent. Additionally, very loud detonations, presumably from U.S. Navy testing, were also infrequently observed (Figure 4.33). Unfortunately, the amplitude of the detonation could not be determined due to clipping of the recording system but

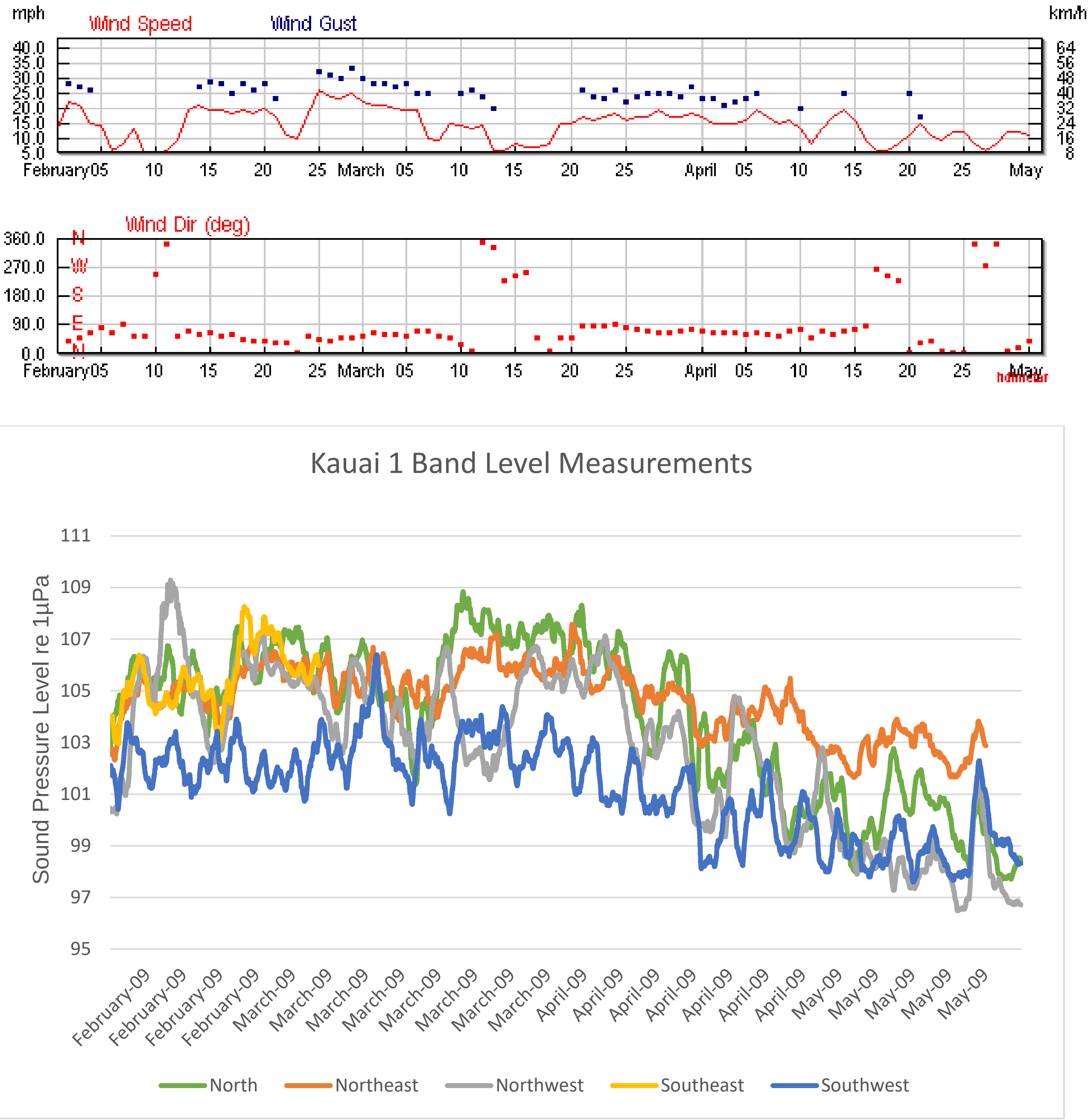


Figure 4.28: Band level noise (20 Hz to 25 kHz) for the Kauai 1 deployments. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

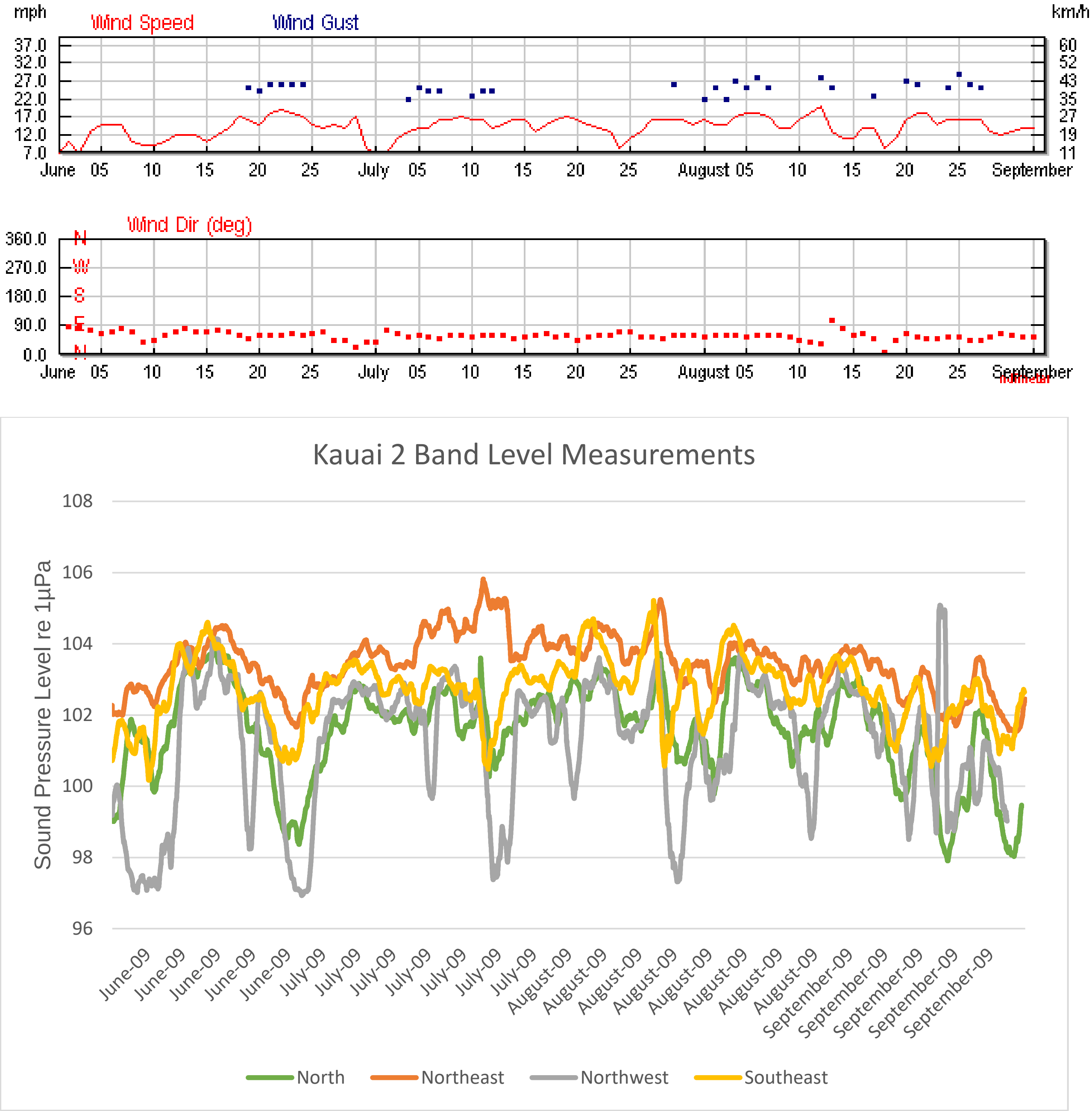


Figure 4.29: Band level noise (20 Hz to 25 kHz) for the Kauai 2 deployments. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

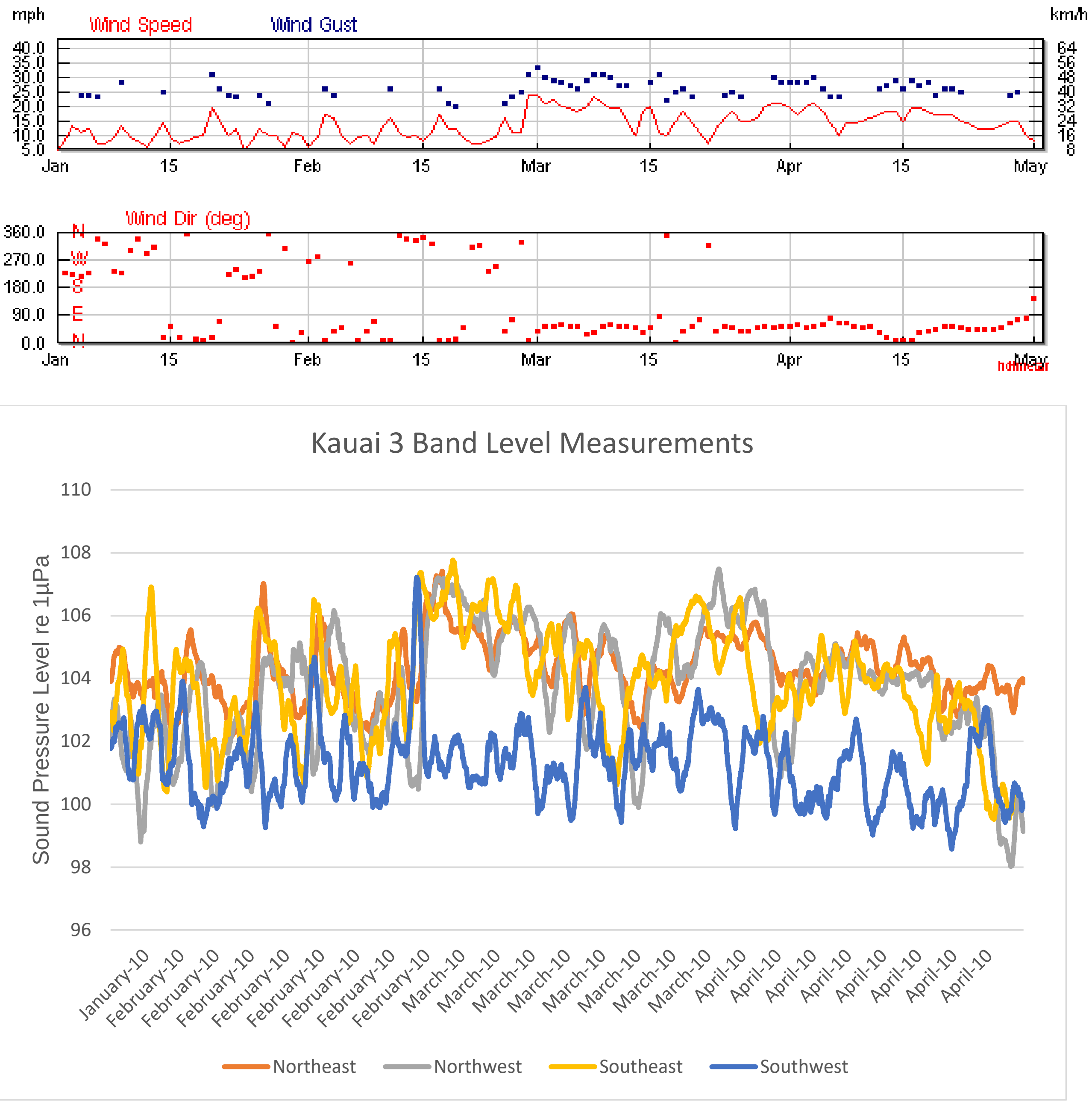


Figure 4.30: Band level noise (20 Hz to 25 kHz) for the Kauai 3 deployments. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

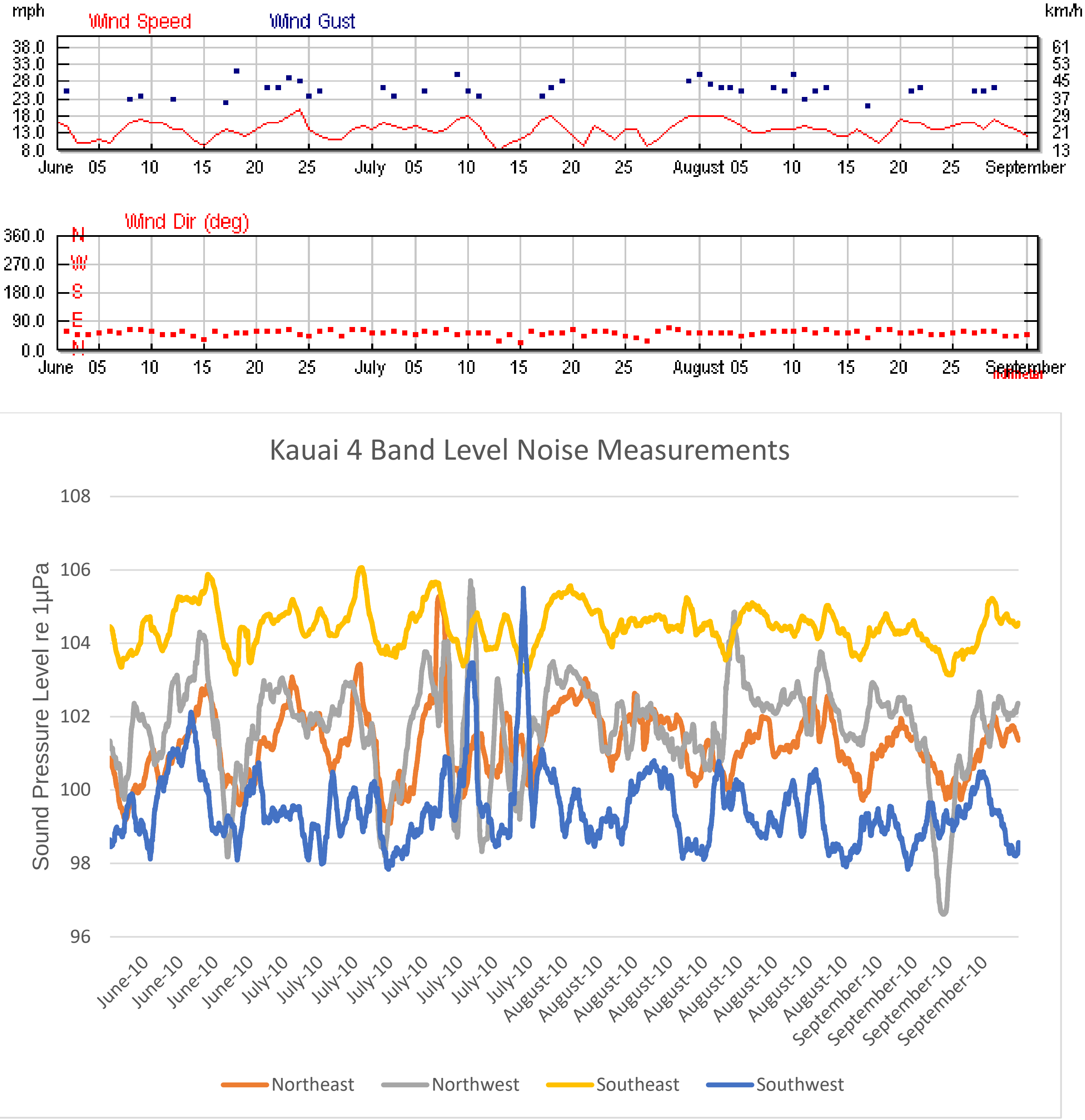


Figure 4.31: Band level noise (20 Hz to 25 kHz) for the Kauai 4 deployments. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

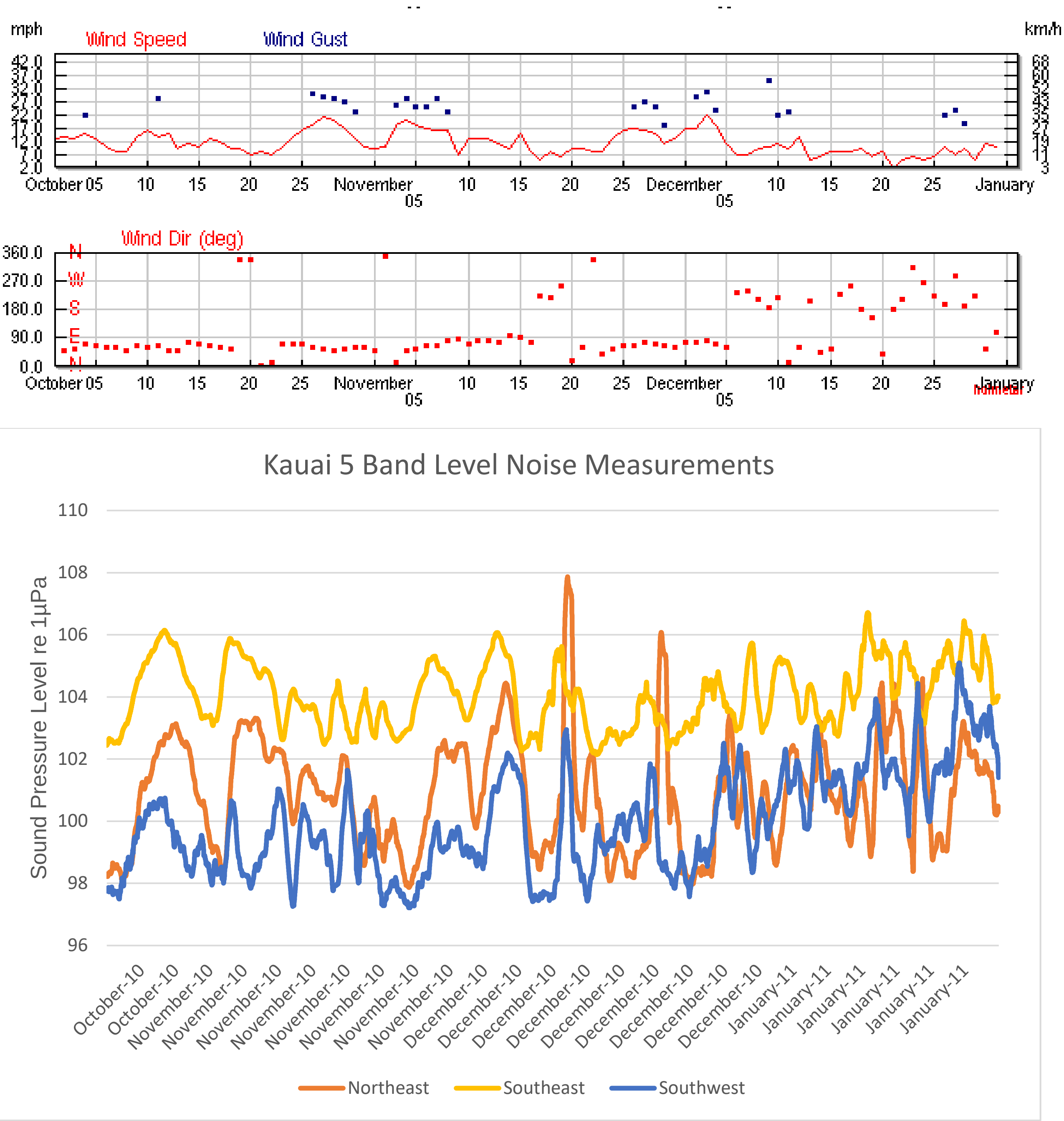


Figure 4.32: Band level noise (20 Hz to 25 kHz) for the Kauai 5 deployments. The top two panels are weather data observed at the Lihue Airport weather station for the corresponding deployment time period.

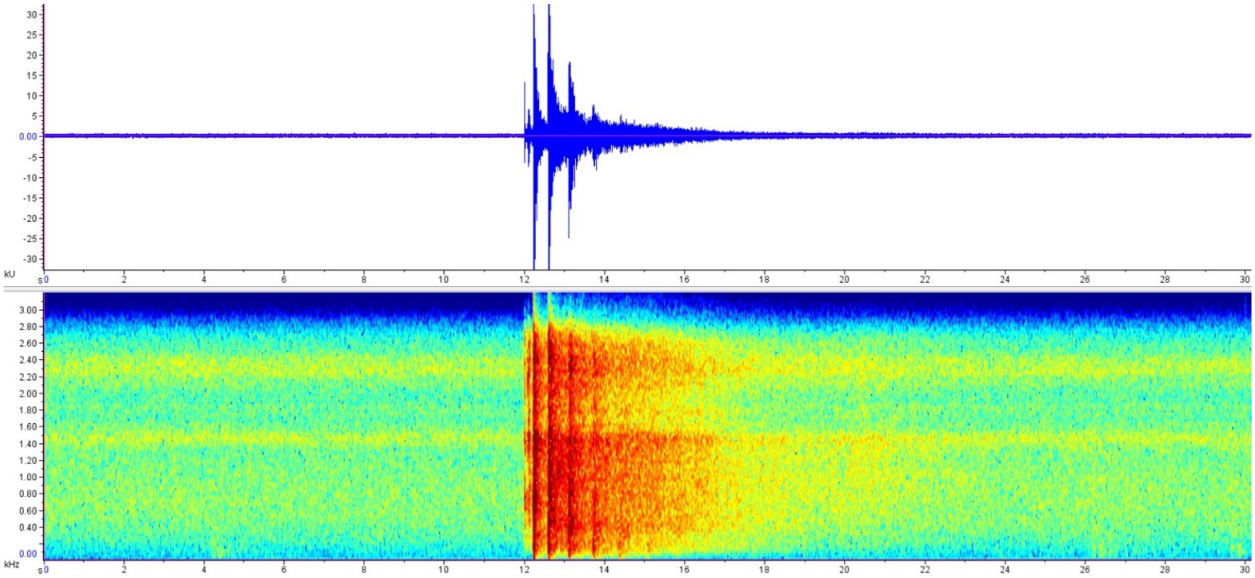


Figure 4.33: Example of an underwater detonation recorded on the Kauai NW EAR, presumably from a U.S. Navy training exercise.

if the detonations were more regular and consistent, it would be reasonable to expect that the broadband levels would reflect the noise contribution of these very loud events.

Overall, the ambient levels and recorded sounds around each of the EAR sites were consistent with what was expected by comparing these sites to one another. Nihoa was selected due to its remoteness compared with the busier MHI and demonstrated that it is not a primary chorusing site for humpback whales nor subject to a heavy shipping activities. The variability in the noise, and the lack of seasonality reveals that the influences on the soundscape are weather related, particularly the wind.

The noise levels around the island of Kauai show that weather, particularly wind, has the greatest impact on the soundscape. There is some commercial shipping (tug and barge) out of Nawilili Harbor but if the impact was significant, the low-frequency noise would be evident in the 500 Hz plot as well as the spectral probability densities. Seasonal humpback whales are easily identifiable in the three frequency and SPD plots and easily detectable in deeper water despite their habitat preference for singing in shallower waters less than 100 fathoms. From these data it could not be determined if they were singing while transiting between shallow coastal areas or if they also seek mating opportunities in deep water off of Kauai. As the population increases, and more whales occur farther from shore during breeding months, future studies could determine the signing behavior of individuals in deep water is a product of their moving between sites or possibly using this habitat for additional breeding opportunities.

Oahu was not the loudest overall site, although it did have the loudest deployment, but it was drastically impacted by vessel activities near Honolulu Harbor, the major commercial port for the entire state. The low-frequency noise did affect the detection of seasonal humpback whale song within each dataset but when exploring the data during winter periods, their sounds could be identified spectrographically. The MHI are very isolated relative to the expansive North Pacific and humpback migratory behavior is very well documented. Future investigations could be useful to determine if masking from the shipping activity impacts the detectability of humpback whales to conspecifics or if the whales actively avoid spending time in habitats surrounding this busy port.

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