Final Report

Cetacean Studies on the Kona Coast in March 2010: Passive Acoustic Monitoring of Marine Mammals Using Gliders - Results from an Engineering Test

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14. ABSTRACT
A passive-acoustic glider survey was conducted off the Kona, Hawaii, coast between 16 and 26 March 2010. This glider survey was conducted with funding from the U.S. Navy’s Office of Naval Research; awards # N00014-10-1-0515 and # N00014-08-1-1082. The survey was part of the development effort of the passive-acoustic Seaglider. The purpose of this field trial was primarily to test the general functionality of the passive-acoustic monitoring (PAM) board and a new onboard acoustic data-storage system (Revision A). Funding provided by U.S. Pacific Fleet enabled a thorough analysis of the previously collected data set, which is presented in this report. The results of this analysis will be used in an ongoing Office of Naval Research effort, “Cetacean density estimation using slow-moving underwater vehicles,” led by the University of St. Andrews, Scotland.

Odontocete acoustic encounters were dominated by small delphinids, which could not be classified to the species level. Beaked whales were detected on seven occasions (three Cuvier’s and four Blainville’s beaked whale encounters).
Only two species of baleen whales were recorded during this survey, most likely because we flew the glider during mid- to late-March, a time when many baleen whales have made their seasonal migration to more northern feeding grounds. Humpback whale song dominated the recordings and was present almost continuously throughout the survey. Minke

whale boing vocalizations were also fairly common. Thirty-eight minke whale encounters were recorded in total. The Seaglider worked well as an underwater vehicle and was able to navigate successfully on its programmed track. The vehicle did not experience any flight problems.

During the SG022's survey, various settings of the PAM system (Rev. A) were tested. The trial was essential for identifying various internal noise sources. Several modifications were subsequently made to the PAM system to further suppress vehicle-generated noise and to improve the quality of the audio recordings with the development of the next-generation Revision B PAM system. This newer PAM system was deployed in 2014-2015 for a marine mammal monitoring project funded by U.S. Pacific Fleet through Contract N62470-10D-3011, Task Orders KB23 and KB25, with Naval Facilities Engineering Command Pacific.

This survey exemplified how crucial long-duration field tests are to thoroughly evaluate the performance of newly developed ocean-going instruments and to identify potential issues with their operations.

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Executive Summary

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The Seaglider worked well as an underwater vehicle and was able to navigate successfully on its programmed track. The vehicle did not experience any flight problems.

During the SG022's survey, various settings of the PAM system (Rev. A) were tested. The trial was essential for identifying various internal noise sources. Several modifications were subsequently made to the PAM system to further suppress vehicle-generated noise and to improve the quality of the audio recordings with the development of the next-generation Revision B PAM system. This newer PAM system was deployed in 2014-2015 for a marine mammal monitoring project funded by U.S. Pacific Fleet through Contract N62470-10D-3011, Task Orders KB23 and KB25, with Naval Facilities Engineering Command Pacific.

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Acronyms and Abbreviations

APL-UW	Applied Physics Laboratory, University of Washington
dB	decibel(s)
Hz	Hertz
ICI	inter-click-interval
kHz	kilohertz
km	kilometer(s)
LTSA	long-term spectral average
m	meter(s)
ms	millisecond(s)
μs	microsecond(s)
ONR	Office of Naval Research
PAM	passive-acoustic monitoring
UTC	Coordinated Universal Time

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1. Background and Objectives

This glider survey was conducted in 2010 with funding from the U.S. Navy's Office of Naval Research (ONR); awards # N00014-10-1-0515 and # N00014-08-1-1082. The survey was part of the development effort of the passive-acoustic Seaglider, currently being used for a marine mammal monitoring project funded by U.S. Pacific Fleet through Contract N62470-10D-3011 Task Orders KB23 and KB25 with Naval Facilities Engineering Command Pacific.

This survey tested the functionality of the passive-acoustic monitoring board (Rev. A), including an onboard acoustic real-time detection system for beaked whales. Because this survey was predominantly an engineering test, the glider was flown in deep waters (>1,000 meters [m]) along the shelf break of the Kona, Hawaii, coast.

After recovery, the data were exclusively analyzed for beaked whales to comply with the goals of the original ONR project. Additional funding by U.S. Pacific Fleet enabled a thorough analysis in 2015-2016 of the collected data set, which is presented in this report. The results of this analysis will be used in an ongoing ONR effort "Cetacean density estimation using slow-moving underwater vehicles," led by the University of St. Andrews, Scotland (award # N00014-15-12142).

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2. Methods

2.1 General Glider Information

Underwater gliders use small changes in buoyancy to produce vertical motion, and wings to convert the vertical motion to horizontal movement, thereby propelling them forward with very low power consumption. This allows them to perform long-duration surveys autonomously (Rudnick et al. 2004). During a mission, a glider is piloted remotely, via Iridium™ satellite connection, from a control center onshore. This project used the Seaglider™, originally developed by Applied Physics Laboratory, University of Washington (APL-UW) (commercially available from Kongsberg Inc., Lynwood, Washington, USA), which is capable of repeatedly diving to 1,000-m depth and back at a typical horizontal speed of 25 centimeters per second (**Figure 1**). Dive durations are usually 4–6 hours for 1,000-m dives.

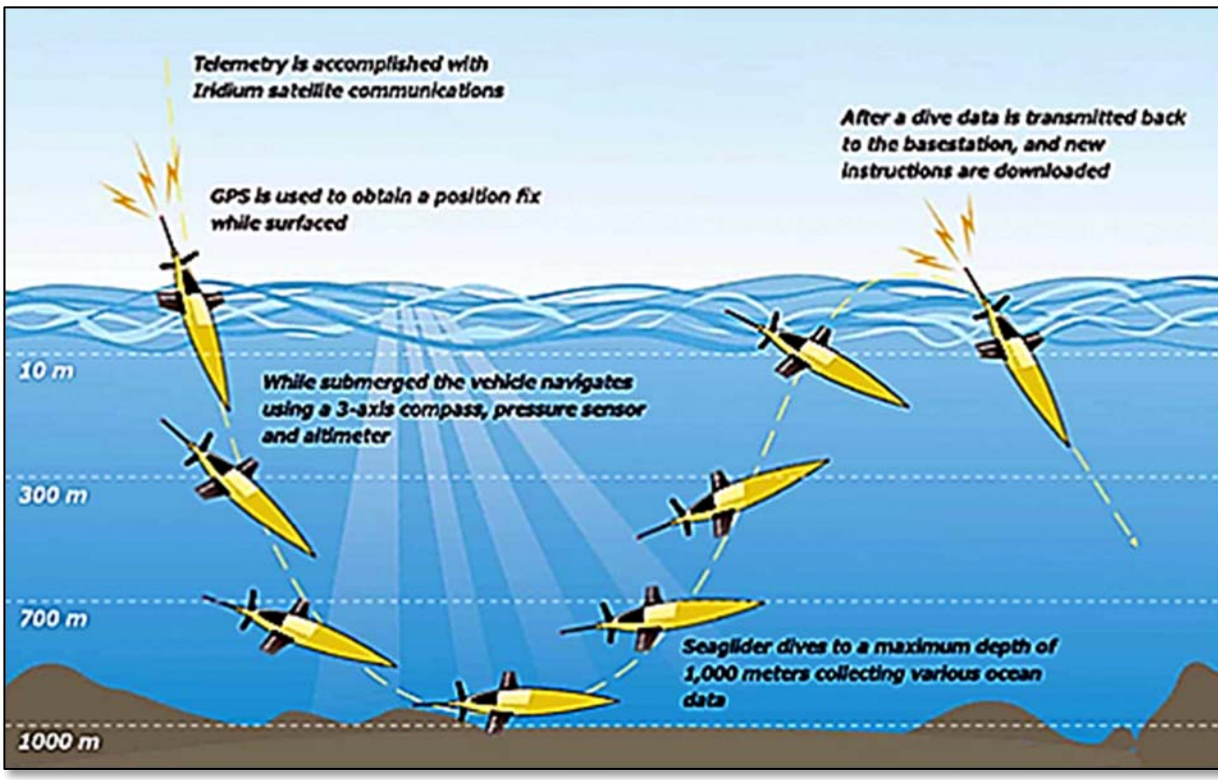

Figure 1: Mode of operation of the Seaglider™. Source: http://subseaworldnews.com.

The glider was equipped with a custom-designed and -built passive-acoustic recording system (APL-UW, Seattle, Washington, USA; Rev. A board). Acoustic signals were received by a single omni-directional hydrophone (type: HTI-99-HF, High Tech Inc, Gulfport, Mississippi, USA; sensitivity: −164 dB re. 1 V/μPa), amplified by 36 decibels, and recorded at a 194-kilohertz (kHz) sample rate with 16-bit resolution. Acoustic data were compressed using the Free Lossless Audio Codec and stored on flash memory drives. The PAM system was optimized for continuously collecting data in the frequency range of 15 Hertz (Hz) to 90 kHz, and thus was well suited for the recording of both baleen and toothed whales. However, the bandwidth of the system did not cover the frequency range (>100 kHz) of vocalizations produced by pygmy and dwarf sperm whales (*Kogia* spp.) or harbor (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*).

The system featured an automatic 'blanking mechanism' that mutes the PAM system during periods when the glider's noisy internal steering and buoyancy mechanisms were operated. During a typical 1,000-m dive, the associated data loss was between 5 and 10 percent. Because of high noise levels at the surface, recordings were made only at depths of 25 to 1,000 m.

These gliders are typically programmed to survey across diverse bathymetric features and cetacean habitats whenever possible. The instruments carried on-board digital bathymetric maps used for deciding how deep to dive in areas where the water depths are shallower than 1,000 m. The glider's depth-choice algorithm was designed to operate best when the instrument's course is orthogonal to the isobaths. Use of this map-reading method avoided the need to use active acoustics for altimetry, which would have hindered passive-acoustic recordings. The gliders transmit selected data packages via Iridium satellite link, including position and standard conductivity, temperature, and depth profiles, to shore when surfacing between dives. The instruments typically stayed at the surface for less than 10 minutes.

In 2007, the ONR Marine Mammals and Biology program started the Passive Acoustic Autonomous Monitoring of Marine Mammals program to develop near-real-time monitoring systems on autonomous underwater vehicles. The program focused on passive-acoustic systems for autonomous detection, classification, localization, and tracking of marine mammals on Navy exercise areas for periods in excess of 1 month. The passive-acoustic Seaglider used in this study is a result of this development effort. The system has been validated during several surveys, including week-long deployments at both Atlantic Undersea Test and Evaluation Center and the Southern California Offshore Range (Klinck et al. 2013). The passive-acoustic Seaglider is currently funded by U.S. Pacific Fleet to be used for marine mammal monitoring efforts exceeding 1 month in duration on various ranges in the North Pacific (Klinck et al. 2015a, 2015b). The PAM boards (Revision A used for the Kona, Hawaii trial and Revision B used in subsequent long-duration deployments) have been classified as a Demonstration and Validation (6.4) system. The 6.4 system encompasses integrated technologies ready to be evaluated in as realistic an operating environment as possible. The PAM board is a U.S. export-controlled item, both under the Department of State's International Traffic in Arms Regulation and the Department of Commerce's Export Administration Regulation programs.

2.2 Glider Survey

Seaglider SG022 (**Figure 2**) was operated for engineering tests along the Kona, Hawaii, coast between 16 and 26 March 2010.

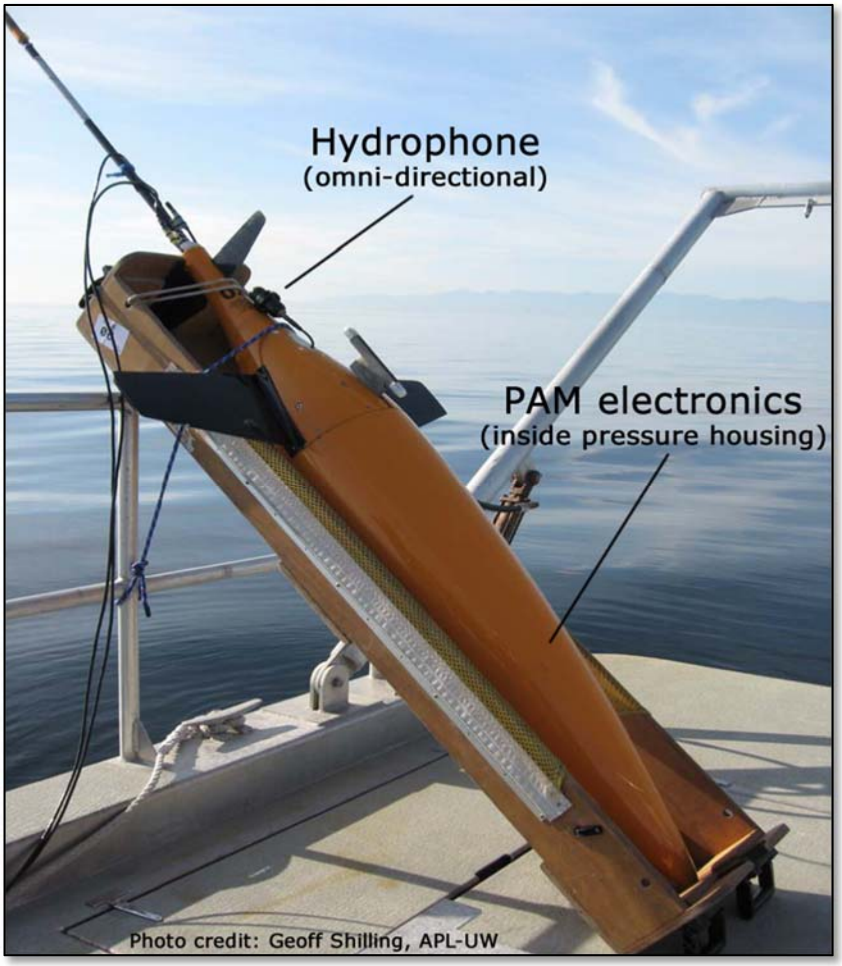

Figure 2: Passive-acoustic Seaglider. The Seaglider™ is a commercial off-the-shelf instrument sold by Kongsberg, Inc. (Lynwood, Washington, USA). The PAM system was developed and incorporated into the Seaglider by APL-UW (Seattle, Washington, USA).

The glider was deployed on 16 March 2010 at approximately 19:00 coordinated universal time (UTC) 10 kilometers (km) northwest of Kona, Hawaii (N19° 40.73', W156° 05.55'), and successfully recovered 10 km south of the deployment location (N19° 36.13', W156° 04.42') on 26 March 2010 at approximately 00:00 UTC.

Throughout the survey, various engineering tests were executed remotely:

- Turning the PAM system on/off
- Changing the amplification
- Changing the on/off depth
- Turning the detector on/off
- Changing detector settings
- Monitoring/evaluating power consumption of the PAM system
- Updating the firmware and control systems.

The sampling rate was not changed during the survey and remained fixed at 194 kHz.

2.3 Data Analysis

Because the dataset was only approximately 5 days total recorded duration, experienced analysts conducted the entire analysis manually. Detectors and classifiers were not used for the analysis. This approach, while more labor intensive, reduced the likelihood of missed marine mammal vocal encounters.

The Free Lossless Audio Codec files were decoded to standard waveform audio file format, and then low-pass filtered and decimated to produce three data sets with different sampling rates (194 kHz, 10 kHz, and 1 kHz) for specific analyses. Analysis was primarily done on a per-dive basis, where vocalizations were summarized for each dive and the percentage of time during a dive when analysts detected marine mammal sounds for each species was calculated. Analysts also tallied marine mammal sounds on an encounter basis. An encounter was defined as a period when target signals were present in the acoustic data sets, separated from other periods of signal detections by 30 or more minutes of 'silence.' See **Appendix A** for encounter data summarized in tabular format.

2.3.1 Environmental Data

The glider collected conductivity/temperature/depth profiles as well as information on depth-averaged currents throughout the duration of the survey (including periods when the PAM system was deactivated). APL-UW processed the raw environmental data using custom software routines and provided temperature and sound speed profiles and depth-averaged current plots for this report.

2.3.2 Odontocetes

The full bandwidth data (194-kHz sampling rate) were used to calculate long-term spectral average (LTSA) plots with a temporal resolution (Δt) of 5 seconds and a frequency resolution (Δf) of 100 Hz using the Triton Software Package (Scripps Whale Acoustics Lab, La Jolla, California, USA). Data slices of 15 minutes in duration were visually and aurally inspected by experienced analysts for acoustic encounters with odontocetes. We expected to record sounds from the following odontocete species, known to inhabit Hawaiian waters, with known acoustic signal types (Baird et al. 2013): Cuvier's beaked whales (*Ziphius cavirostris*), Blainville's beaked whales (*Mesoplodon densirostris*), Longman's beaked whales (*Indopacetus pacificus*), killer whales (*Orcinus orca*), Risso's dolphins (*Grampus griseus*), sperm whales (*Physeter macrocephalus*), short-finned pilot whales (*Globicephala macrorhynchus*), false killer whales (*Pseudorca crassidens*), bottlenose dolphins (*Tursiops truncatus*), rough-toothed dolphins (*Steno bredanensis*), melon-headed whales (*Peponocephala electra*), Fraser's dolphins (*Lagenodelphis hosei*), spinner dolphins (*Stenella longirostris*), striped dolphins (*Stenella coeruleoalba*), and pantropical spotted dolphins (*Stenella attenuata*). Pygmy killer whales (*Feresa attenuata)* are a potential species the glider could encounter in the Hawaiian Islands; however, very little is known about this species' life history and acoustic behavior (Madsen et al. 2004, McSweeney et al. 2007), and we did not feel confident assigning them to any of the odontocete annotation classes listed below.

Vocalizations of odontocetes are typically placed into three categories: echolocation clicks, burst pulse sounds, and whistles. Echolocation clicks are broadband, impulsive sounds with peak frequencies from 5 to over 150 kHz to aid in foraging and navigation. Burst pulse signals are click trains, or rapidly repeated clicks with a very short inter-click interval, that sound like a buzz or creak. Burst pulse signals are thought to have social implications and echolocation functions. Whistles are frequency modulated signals and cover (depending on species) a wide frequency range from a few hundred Hz to many kHz, have a significantly longer duration and are thought to be used in social contexts.

The analysts logged species information whenever possible. The first six species listed above have species-specific call features that allow acoustic encounters to be identified to the species level, and were classified using the following call characteristics:

- **Beaked whales (BW):** Cuvier's beaked whale clicks are uniquely identified by a frequency-modulated click with a peak frequency of 40 kHz and an inter-click-interval (ICI) of over 300 milliseconds (ms) (Baumann-Pickering et al. 2013). Echolocation clicks recorded from Blainville's beaked whales have the characteristic beaked-whale frequency modulated pulse, a long click duration, and a long inter-pulse interval (Baumann-Pickering et al. 2013). Such upsweeping clicks with peak frequencies near 35 kHz and ICIs of approximately 200 ms were identified as Blainville's beaked whales. Longman's beaked whale clicks are not as well documented as Cuvier's and Blainville's, but from the known recorded examples, the clicks exhibit the same frequency modulation and long click duration. The peak frequency for Longman's beaked whale echolocation clicks is lower than the other two species at 22 kHz (Baumann-Pickering et al. 2013). Little is known about their ICIs, thus the click shape and peak frequency were used as the discriminating characteristics for this report. An additional distinct type of frequency-modulated signal has been described from passive-acoustic recordings made at Cross Seamount (McDonald et al. 2009). These clicks are marked by a long duration (over 700 μs), short ICI (approximately 130 ms) and a peak frequency near 47 kHz (Baumann-Pickering et al. 2013). These echolocation clicks have a very obvious frequency modulated upsweep, as seen in other beaked whale echolocation clicks, and so are thought to be made by a beaked whale. Three additional BW call types have been recorded in the Eastern Tropical Pacific, referred to as BW50, UBW, and BWP by Baumann-Pickering et al. (2012). These signals also exhibit the frequency-modulated upsweep, long duration and ICI found in other beaked whale clicks, and analysts scanned for these signals, as well as any other beaked whale-like signals.
- **Sperm whale:** Echolocation clicks produced by sperm whales contain energy from 2 to 20 kHz with peak energy from 10 to 15 kHz (Møhl et al. 2003). These clicks are observed during foraging dives and are characterized by a metronomic ICI of about one second (Møhl et al. 2003). Sperm whale click trains can be readily identified in the LTSA plots, and echolocation clicks were the focus of analysis as they are the easiest to differentiate from other species.
- **Killer whale:** Killer whale pulsed calls are the best described and well documented of their call types, and serve well to differentiate them from other species. Pulsed calls have energy between 1 and 6 kHz, with high-frequency components occasionally reaching over 30 kHz. Duration is typically 0.5 to 1.5 seconds (Ford 1987). Aural and visual detection of pulsed calls were used for killer whale encounter identification.

- **Risso's dolphin:** Risso's dolphin echolocation clicks have a unique band pattern observable in bouts of click on an LTSA. Peak energy bands are located at 22, 26, 30, and 39 kHz, with distinct notches at 27 and 36 kHz (Soldevilla et al. 2008) This notch and peak pattern is not as apparent when looking at individual clicks, but the LTSA shows the characteristic appearance of many hundreds of clicks that was used to identify Risso's dolphins in this report.

The remaining nine delphinid species are very difficult to classify to the species level acoustically. Thus, these species were grouped by similarity of the acoustic features of their whistles, when possible, which overlap across species and thus cannot definitively be assigned to species without concurrent visual observations. As described by Frankel and Yin (2010) whistle acoustic characteristics in delphinids often vary geographically and as ground-truth data for the Kona, Hawaii, coast are sparse, the following groups were used for classification (similar to Munger et al. 2014).

- **Low-frequency whistles:** This group included whistles produced by the false killer whale, short-finned pilot whale, melon-headed whale, and rough-toothed dolphin. The defining whistle characteristics for this group were whistles that were relatively low-frequency (predominantly below 10 kHz). Numbers of inflection points/steps and frequency ranges of the whistles are variable and species dependent (Frankel and Yin 2010, Ketten 2004, Lima et al. 2012, Oswald et al. 2003, Richardson et al. 1995, Watkins et al. 1997)**.**
- **High-frequency whistles:** This group included whistles produced by the bottlenose dolphin, pantropical spotted dolphin, spinner dolphin, striped dolphin, and Fraser's dolphin. The defining whistle characteristics for this group were whistles that were higher in frequency (predominantly above 10 kHz). Numbers of inflection points/steps and frequency ranges of the whistles are variable and species dependent (Frankel and Yin 2010, Ketten 2004, Lammers et al. 2003, Oswald et al. 2003, Richardson et al. 1995)
- **Low- and high-frequency whistles:** This group included encounters characterized by [a] whistles with significant energy below and above 10 kHz or [b] various whistle types which covered a wide frequency range in one encounter.
- **Echolocation clicks and/or burst pulses:** This group included encounters which only contained echolocation clicks and/or burst pulses. The recorded clicks and pulsed calls did not contain any characteristic acoustic features enabling species identification. Many of the identified whistle encounters did include echolocation clicks and burst pulses, but because of the added information contained in the whistles, we were able to classify them more specifically. Click and burst pulse encounters could potentially be associated with any of the above-mentioned nine delphinid species.

2.3.3 Mysticetes

The Hawaii Range Complex study area provides habitat for numerous species of baleen whales that produce low-frequency vocalizations. During the winter months, we could potentially record the low-frequency sounds of blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), sei whales (*B. borealis*), Bryde's whales (*B. edeni/brydei*), minke whales (*B. acutorostrata*), and humpback whales (*Megaptera novaeangliae*), as these species typically migrate to low latitudes in winter.

To analyze the collected data efficiently for these species, the broadband data were down-sampled and divided into two datasets: one with a sampling rate of 1,000 Hz (15–500 Hz effective band) and the other 10 kHz (5 kHz effective bandwidth). From these data we calculated LTSA plots with a Δt of 1 second and Δf of 1 Hz (1 kHz data) and a Δt of 2 seconds and Δf of 10 Hz (10 kHz data) using the Triton Software Package. Both LTSAs were coarsely screened visually and aurally by analysts for bioacoustic activity and general quality assurance. The actual logging of acoustic encounters was done in Raven Pro (Bioacoustics Research Program, Cornell University, Ithaca, New York, USA). Based on experience with the Mariana Islands Range Complex dataset (Klinck et al. 2015a), it is most efficient to import the two datasets into Raven Pro, time align them, and examine them simultaneously for the species of interest (**Figure 3**). This provided sufficient detail in all frequency bands, but also enabled us to clearly identify sounds that had both very low-frequency components (i.e., 50 Hz) and higher components (> 1,000 Hz) such as minke whale boings.

Experienced analysts examined the low-frequency data for down-sweeping calls from the sei whale (Baumgartner et al. 2008, Rankin and Barlow 2007), the short and variable calls from Bryde's whale (Heimlich et al. 2005, Oleson et al. 2003), western and central pacific blue whale calls (Stafford et al. 2011, 1999), blue whale D calls (McDonald et al. 2001) and 20-Hz and 40-Hz fin whale calls (Thompson et al. 1992, Watkins 1981). We also screened the data for North Pacific right whale "up calls" (90 to 150 Hz upsweeping 7-second calls; McDonald and Moore 2002), but detecting these calls in a dataset with singing humpback whales is extremely difficult (Mellinger et al. 2007, Waite et al. 2003). The mid-frequency data were primarily analyzed for humpback whale song and social sounds (Payne and McVay 1971, Stimpert and Au 2008), and the complex minke whale calls (Gedamke et al. 2001, Rankin and Barlow 2005). Because the recorded data set was short (10 days), and because the 1- and 10-kHz data were time aligned and analyzed simultaneously, we did not use automatic detection algorithms. Instead, we visually and aurally identified target vocalizations and manually marked identified sequences in Raven Pro.

2.3.4 Navy Sonar and Seismic Airgun Signals

The LTSA plots were also screened visually and aurally for occurrences of low- and mid-frequency active sonar and seismic airgun signals.

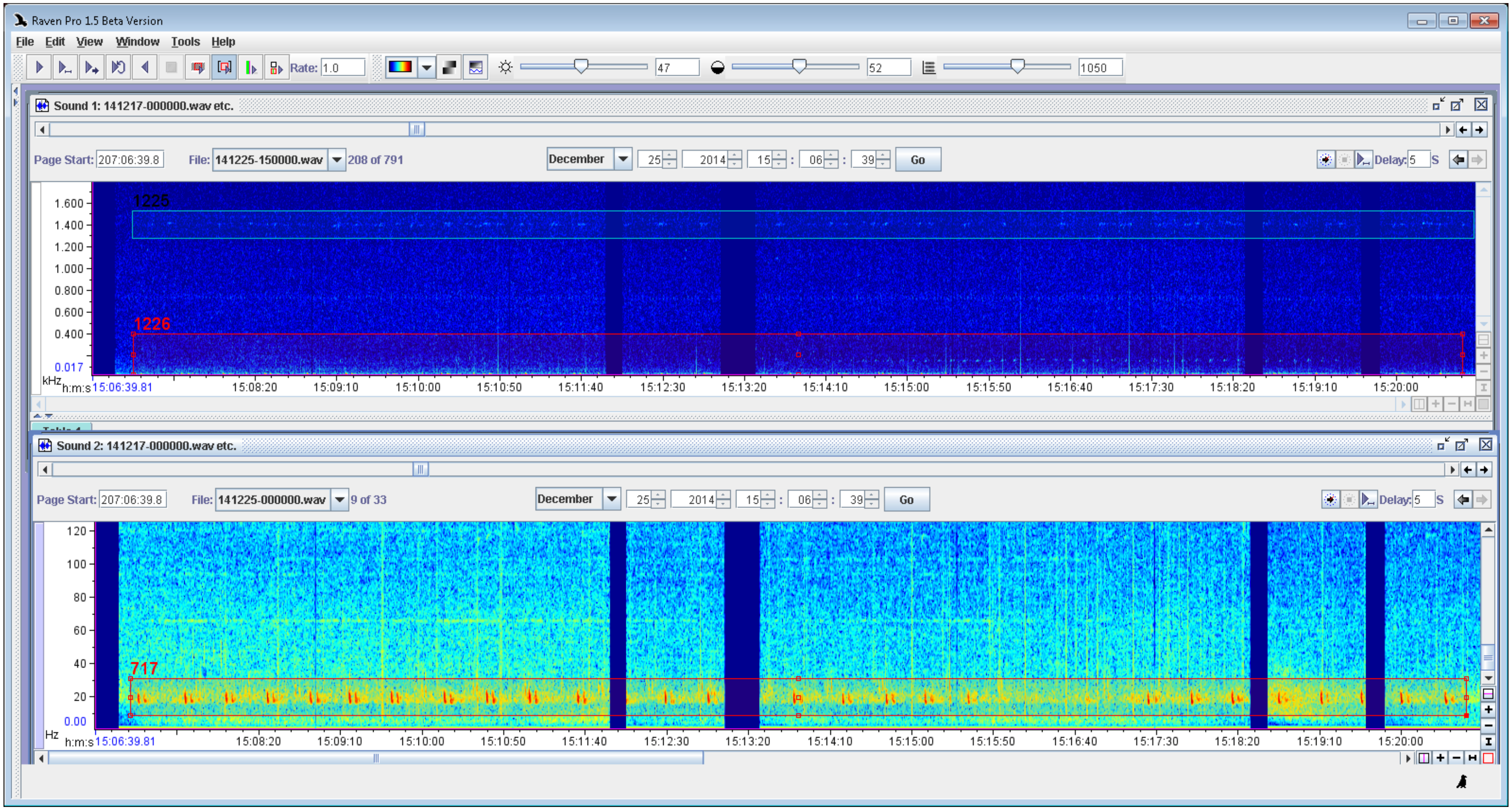

Figure 3: Example of time-aligned spectra displayed in the software Raven Pro. The upper spectrogram is the 10-kHz down-sampled data and was used to identify mid-frequency vocalizations from minke whales (blue box) and humpback whales (red box). The lower spectrogram is the 1-kHz data and was used to identify calls from fin whales (red box) and blue whales, and also provided context when identifying the mid-frequency calls.

3. Results

The glider conducted a total of 61 dives during the survey. Because this was intended primarily as an engineering test, the PAM system was active for only 53 of the dives, intermittently between 16 and 26 March 2010 (**Figure 4**).

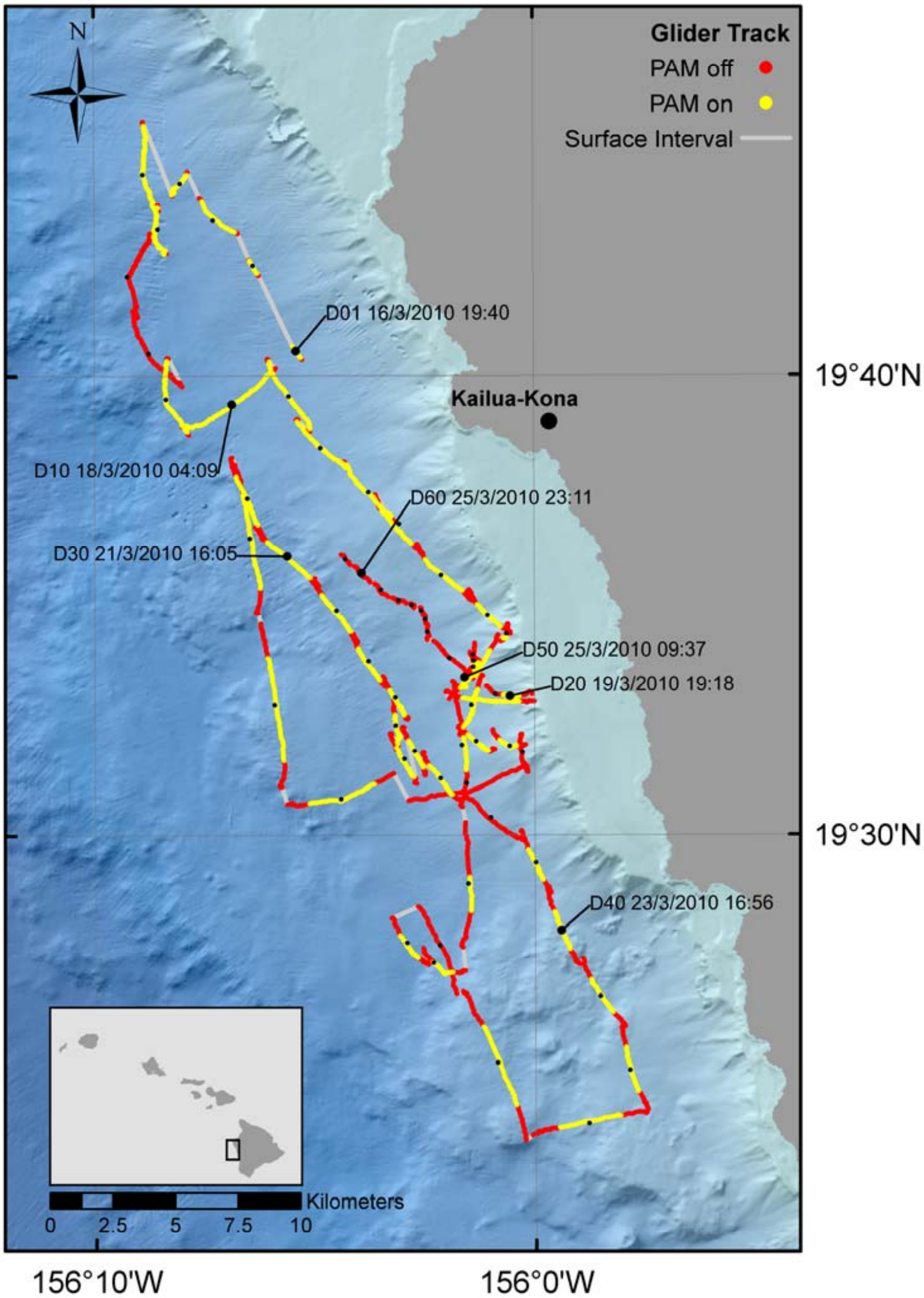

Figure 4: SG022 track line for the period 16 to 26 March 2010. Each black dot on the track line indicates the midpoint location of a glider dive; every 10th dive is represented by a larger dot. Labels indicate dive number (e.g., D01 for dive no. 1) and date/time (format: dd/m/yyyy hh:mm UTC). Red sections indicate that the PAM system was OFF. The yellow marks indicate that the PAM system was active. Gray lines indicate surface intervals between dives (PAM system inactive).

The system recorded a total of 112 hours (approximately 4.6 days) of acoustic data, amounting to 131 gigabytes. An additional 22.4 megabytes of engineering/environmental data were collected.

3.1 Environmental Data

The results of the environmental data analysis are summarized in **Figures 5 through 7**. The sea-surface temperature (**Figure 5**) varied little geographically and temporally and was around 24 degrees Celsius.

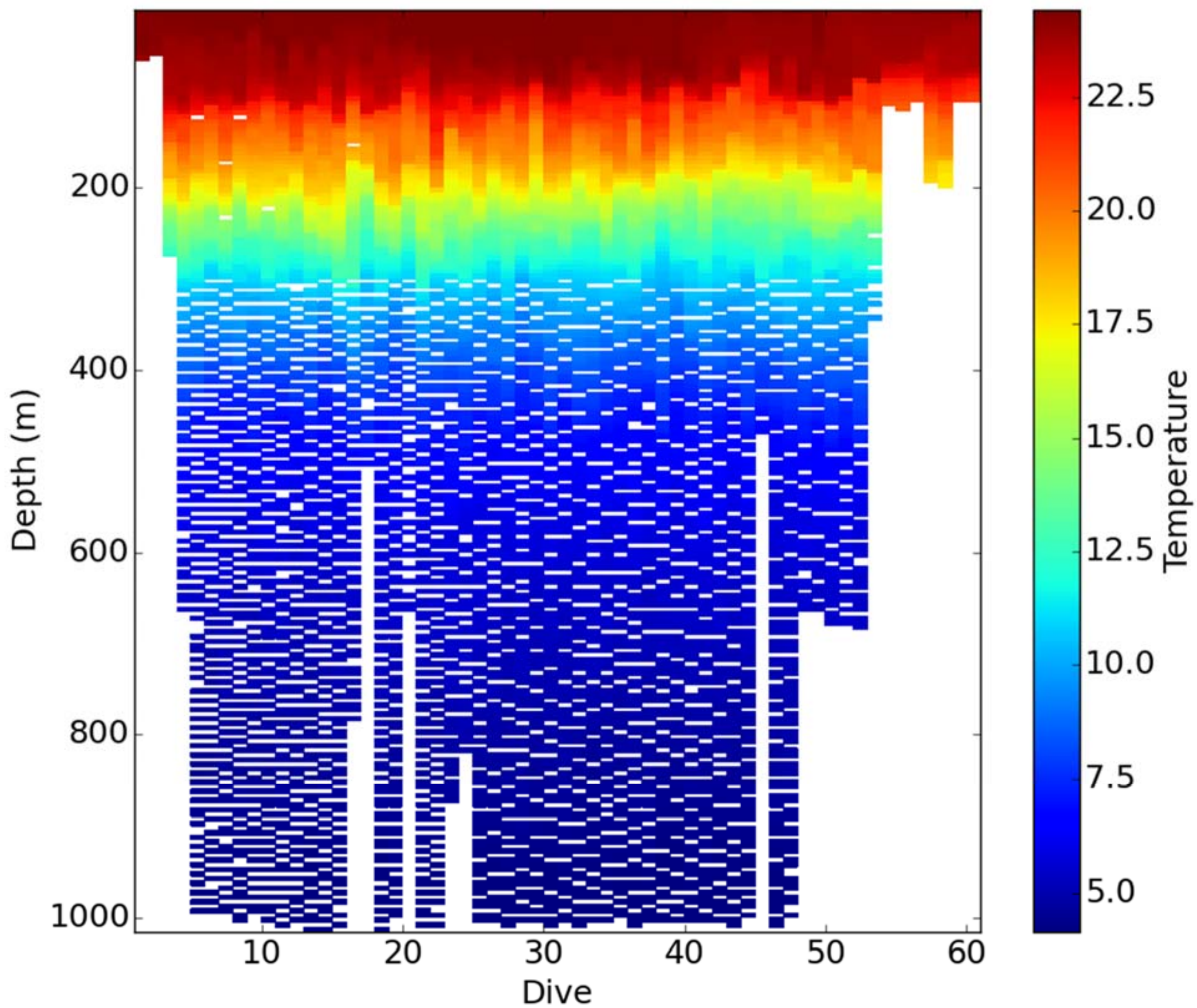

Figure 5: Temperature [°C] profiles recorded with SG022. White areas at the bottom of some dives indicate no data, resulting from dives shallower than 1,000 m (e.g., bathymetry-limited dives).

The sound-speed profiles (**Figure 6**) showed downward refracting sound propagation conditions and no significant surface duct. There were no significant changes observed in time and space. Furthermore, the glider did not reach the sound fixing and ranging channel axis, which in the deployment area is located below the instrument's maximum operation depth of 1,000 m.

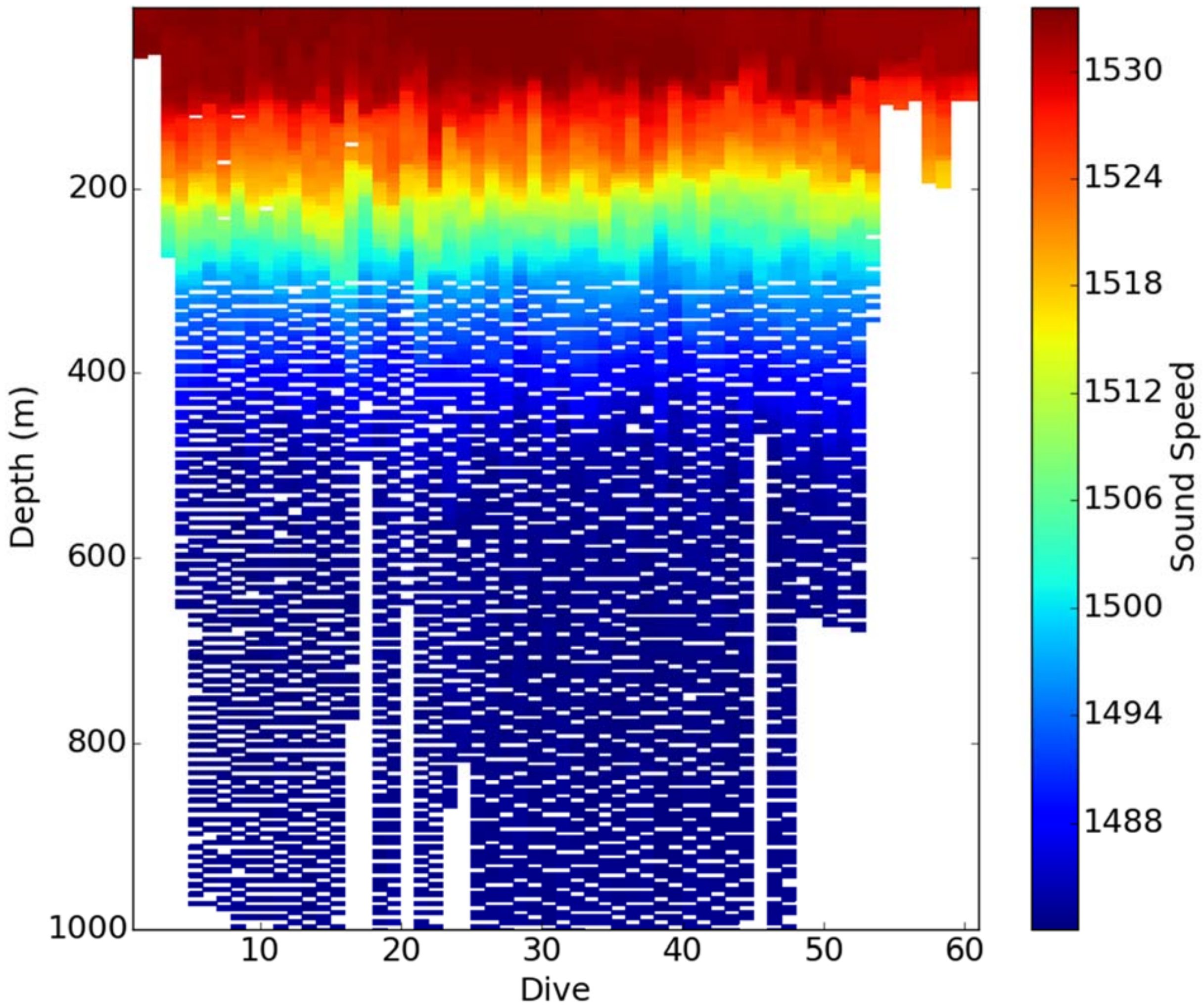

Figure 6: Sound-speed profiles [meters per second] recorded with SG022. White areas at the bottom of some dives indicate no data, resulting from dives shallower than 1,000 m (e.g., bathymetry-limited dives).

SG022 reported a median depth-averaged current velocity of 15.8 centimeters per second. The direction of the current flow was very consistent in north-northwesterly direction (median: 333 degrees; **Figure 7**).

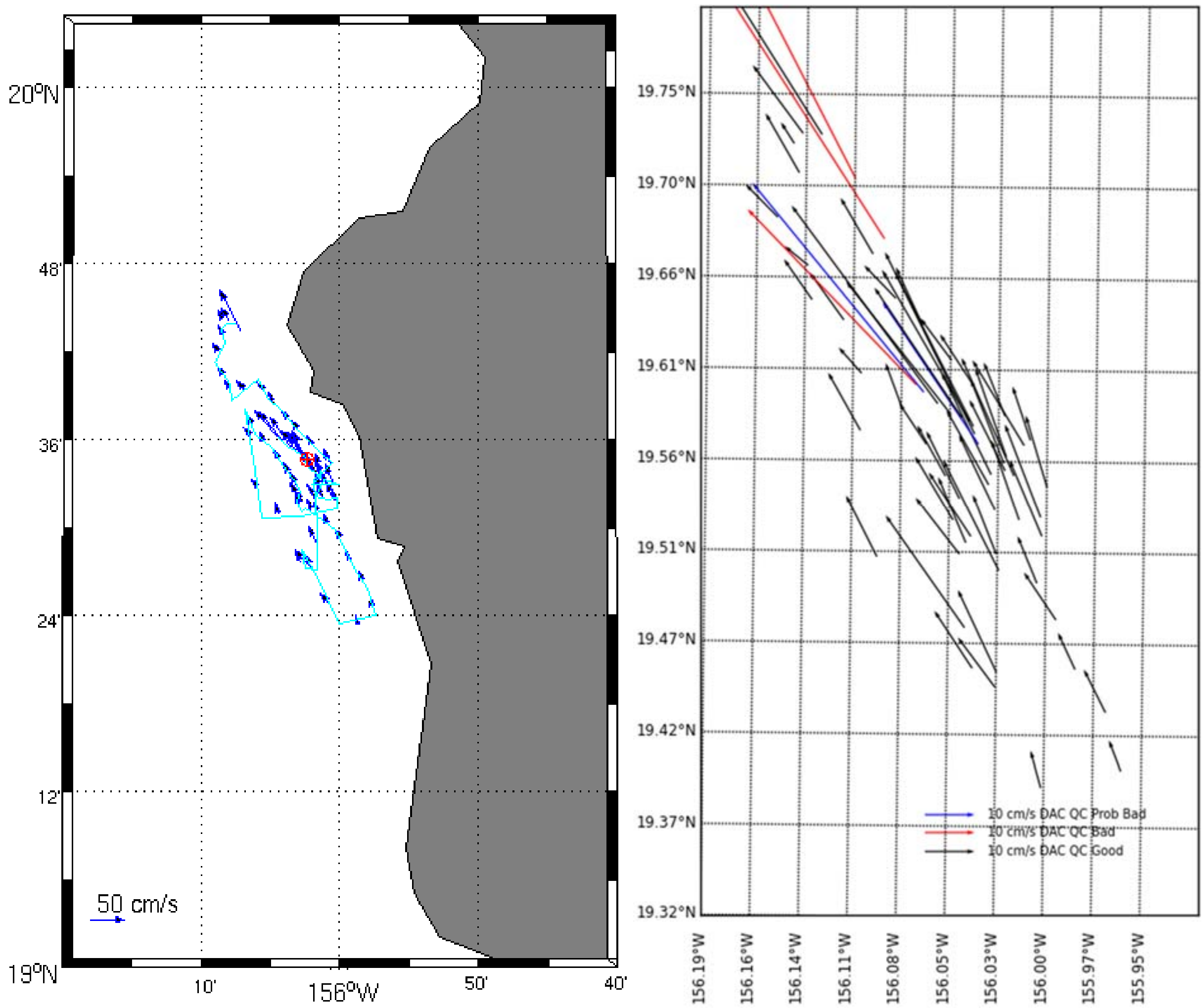

Figure 7: Depth-averaged currents [centimeters per second] measured with SG022.

3.2 Odontocetes

SG022 recorded two known species of odontocetes and several sounds attributed to small odontocete species during this engineering test (See **Appendix A** for detail on all encounters). No sperm whales, killer whales, or Risso's dolphins were detected during this survey.

Beaked whales

Both Cuvier's (**Figure 8**, left panel) and Blainville's (**Figure 8**, right panel) beaked whale signals were recorded by SG022. Cuvier's beaked whale clicks were recorded on three separate dives, and Blainville's clicks were detected on four separate dives. Both click types were recorded relatively close in time during dive 22.

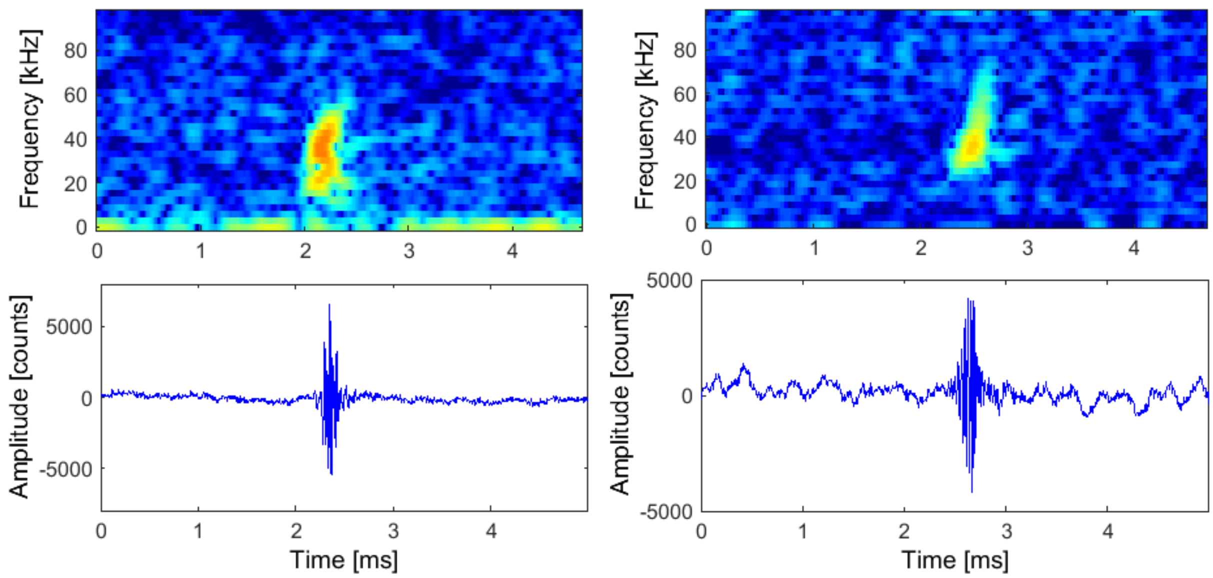

Figure 8: Cuvier's beaked whale echolocation click (left) and Blainville's beaked whale echolocation click (right) recorded with SG022. Both examples are high-pass filtered at 10 kHz. Amplitude range of waveform is ±32,768 digital counts (16 bits).

The Cuvier's beaked whale detections occurred in the northern two-thirds of the survey area, with the longest encounter occurring near the edge of the widest part of the shelf south of Kailua-Kona (**Figure 9**). Conversely, the Blainville's beaked whale detections occurred in the southern two-thirds of the survey area, but also had the most detections near the edge of the widest part of the shelf south of Kailua-Kona (**Figure 10**).

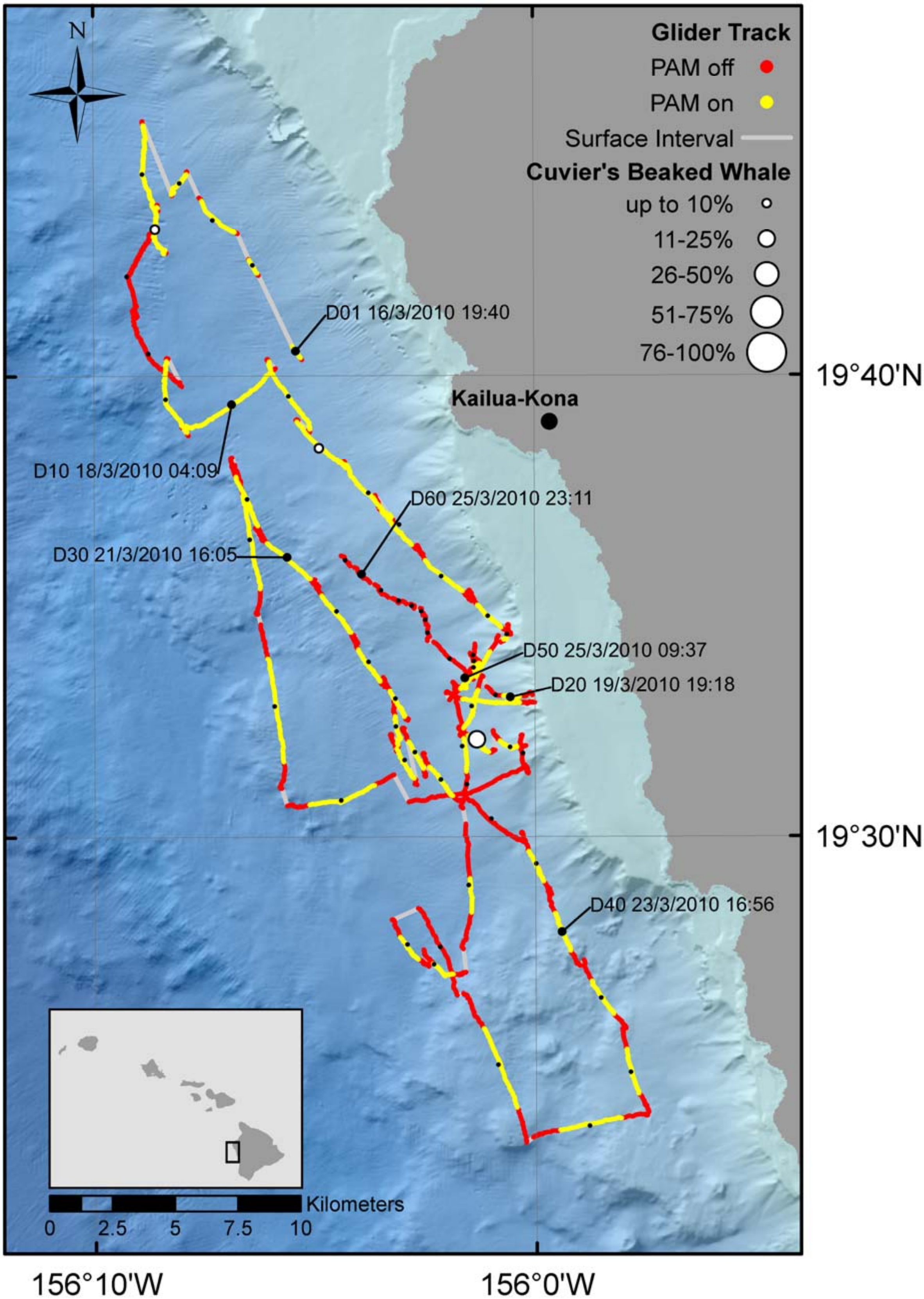

Figure 9: SG022 Cuvier's beaked whale detections. The circle size indicates percentage of recording time per dive with target signals.

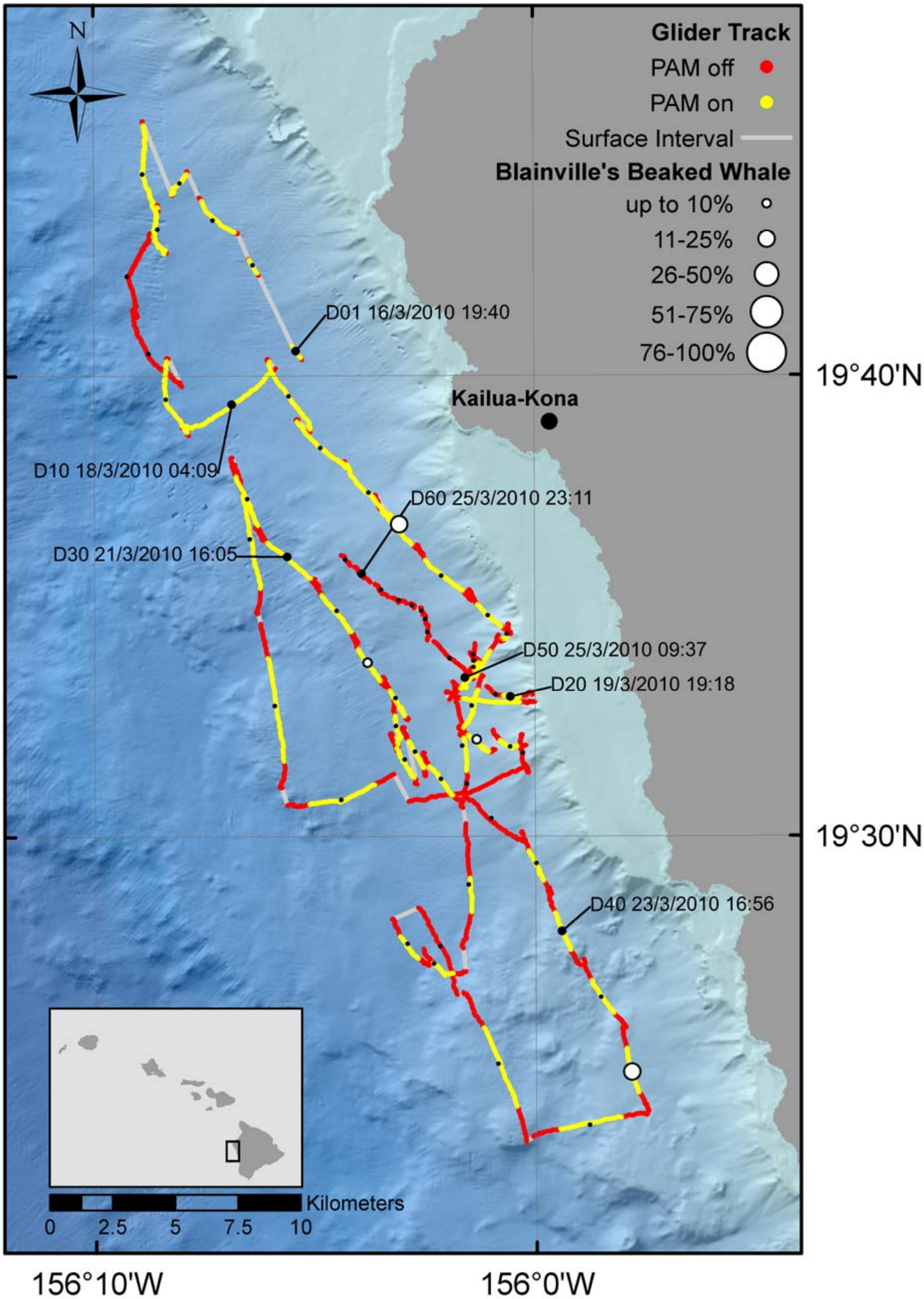

Figure 10: SG022 Blainville's beaked whale detections. The circle size indicates percentage of recording time per dive with target signals.

Whistles

Recordings of odontocetes that contained whistles were classified according to the maximum frequency of the whistles, but often also included echolocation clicks and sometimes pulsed calls or buzzes.

Low-frequency whistles

Acoustic encounters that contained whistles with maximum frequencies below 10 kHz (**Figure 11**) were recorded on 12 dives (**Figure 12**), with the longest recordings occurring near the northernmost extent of the survey area, but the most encounters occurring south-southwest of Kailua-Kona on the slope. Due to low-frequency noise on the glider, these whistles were best observed in the data downsampled to a 10-kHz sampling rate. Based on maximum frequency and range of frequencies within a whistle, these detections were likely produced by short-finned pilot whales, false killer whales, melon-headed whales, or rough-toothed dolphins.

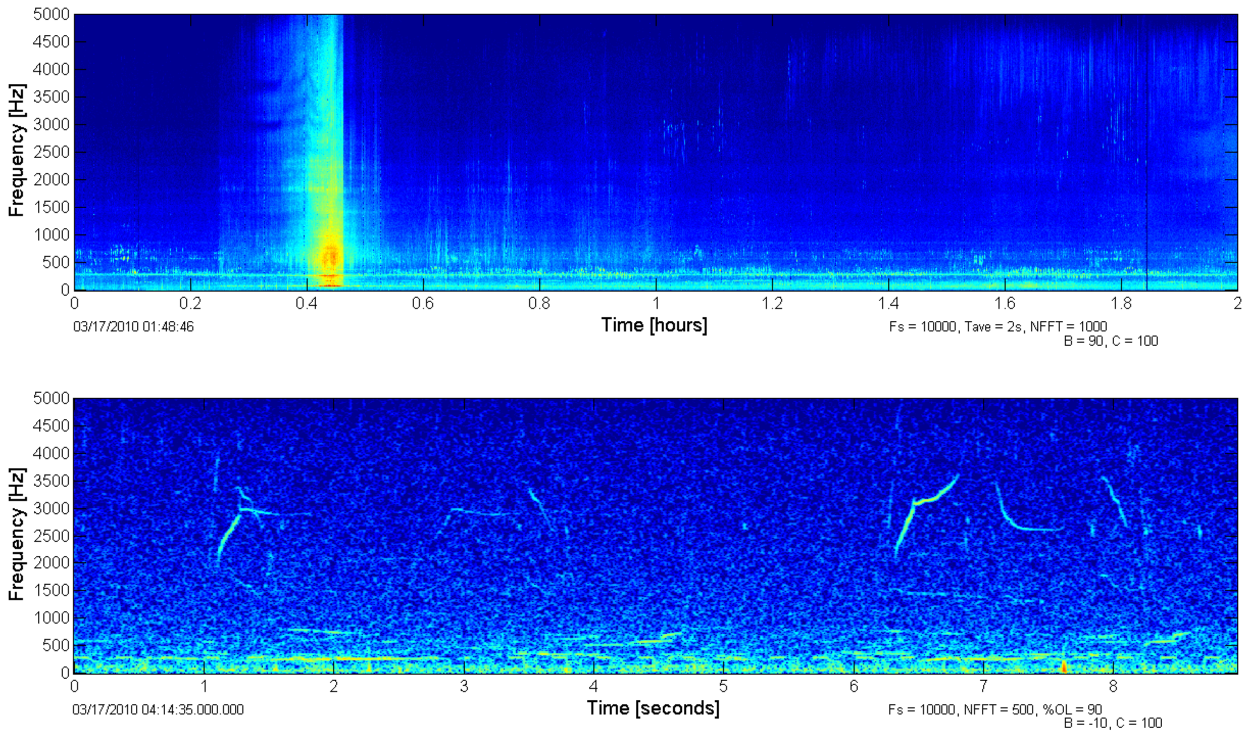

Figure 11: Low-frequency whistles recorded with SG022 on 17 March 2010.

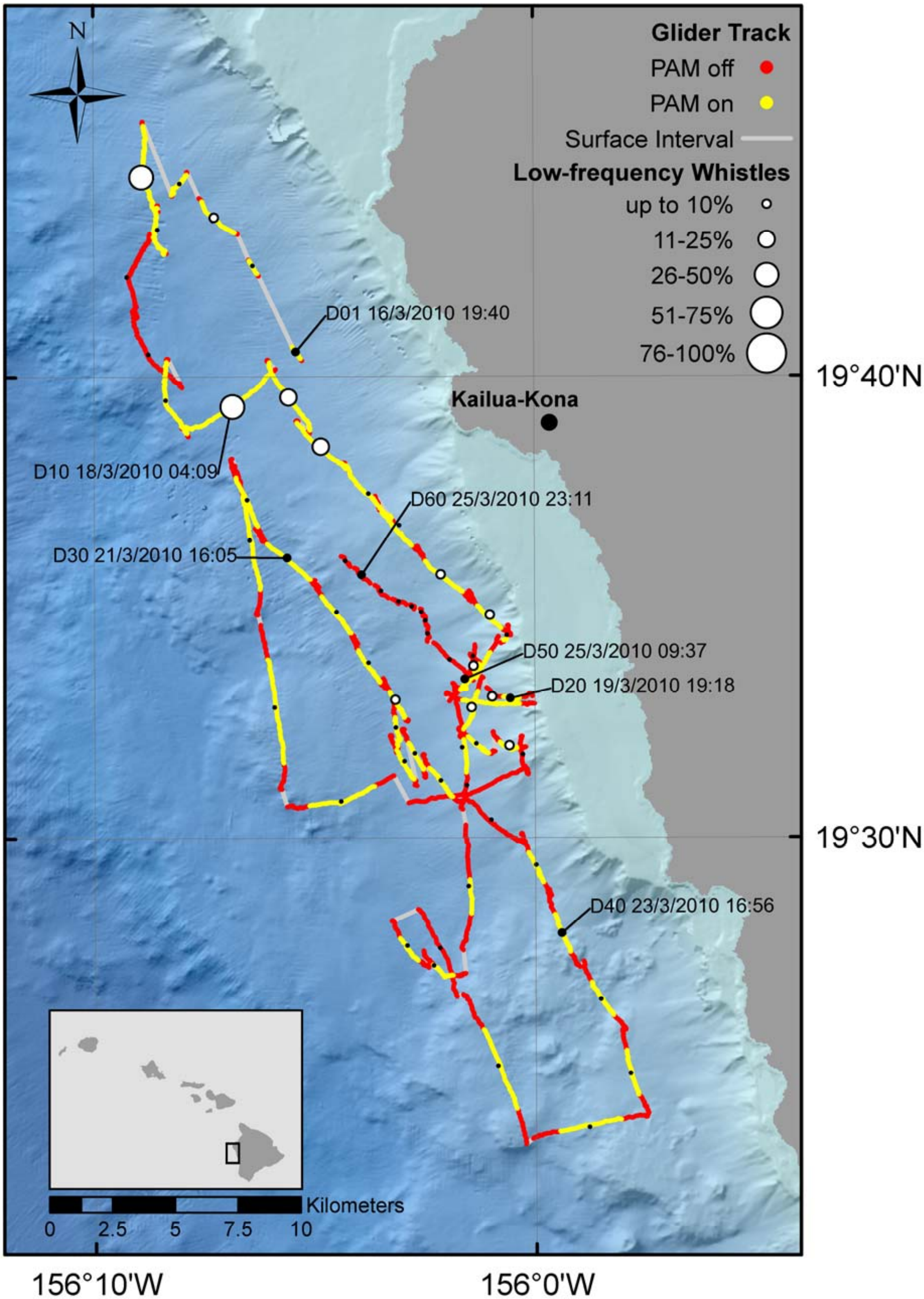

Figure 12: SG022 low-frequency whistle detections. The circle size indicates percentage of recording time per dive with target signals.

High-frequency whistles

Acoustic recordings containing whistles with energy predominantly above 10 kHz (**Figure 13**) were recorded on 10 glider dives.

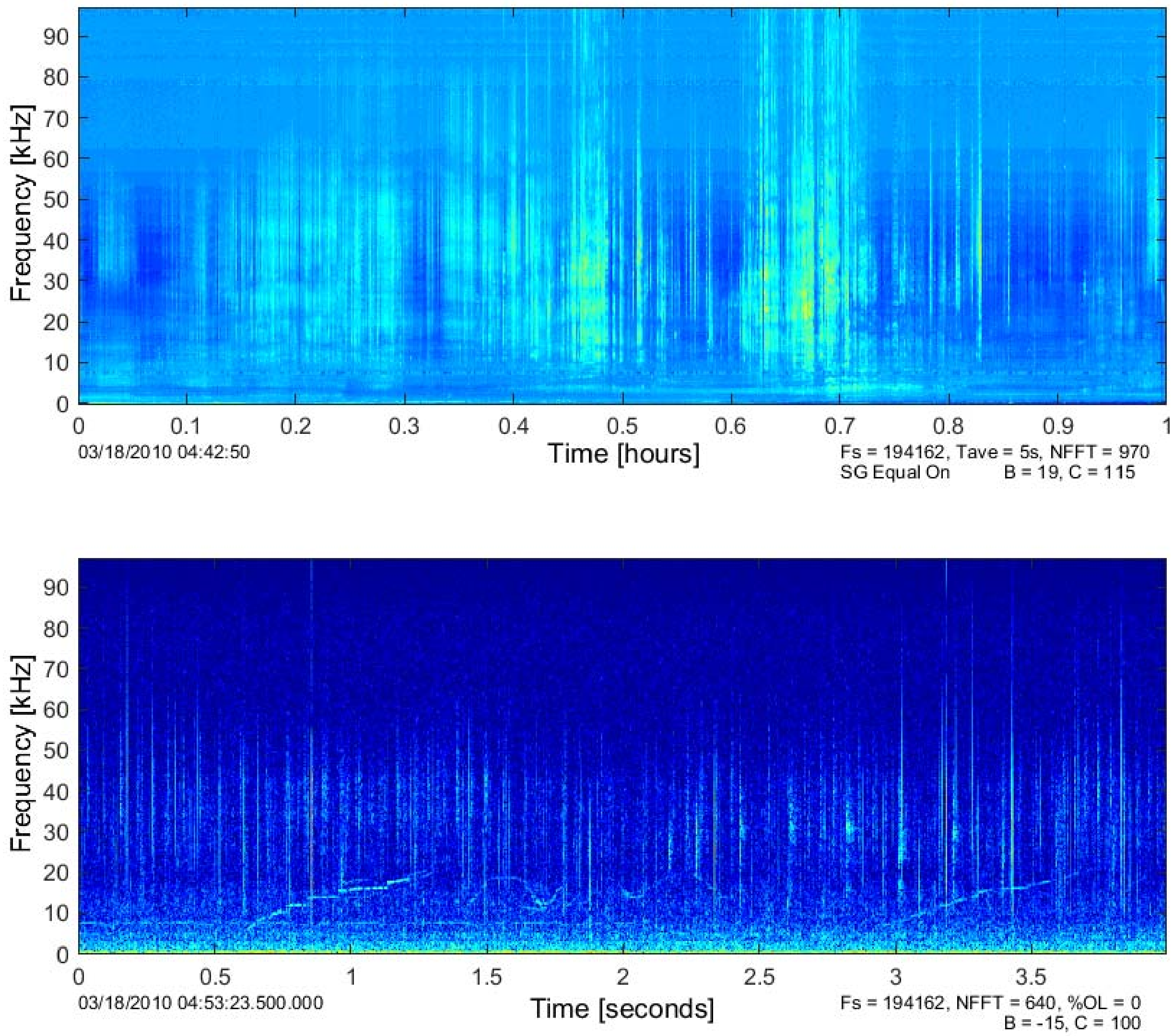

Figure 13: High-frequency whistles recorded with SG022 on 18 March 2010.

Recordings of high-frequency whistles occurred throughout the survey area, with the most detections occurring near the shelf break at the wide part of the shelf, south of Kailua-Kona (**Figure 14**). These whistles are likely associated with one of the following species, based on maximum frequency and range of frequencies within a whistle: bottlenose dolphin, pantropical spotted dolphin, spinner dolphin, striped dolphin, and Fraser's dolphin.

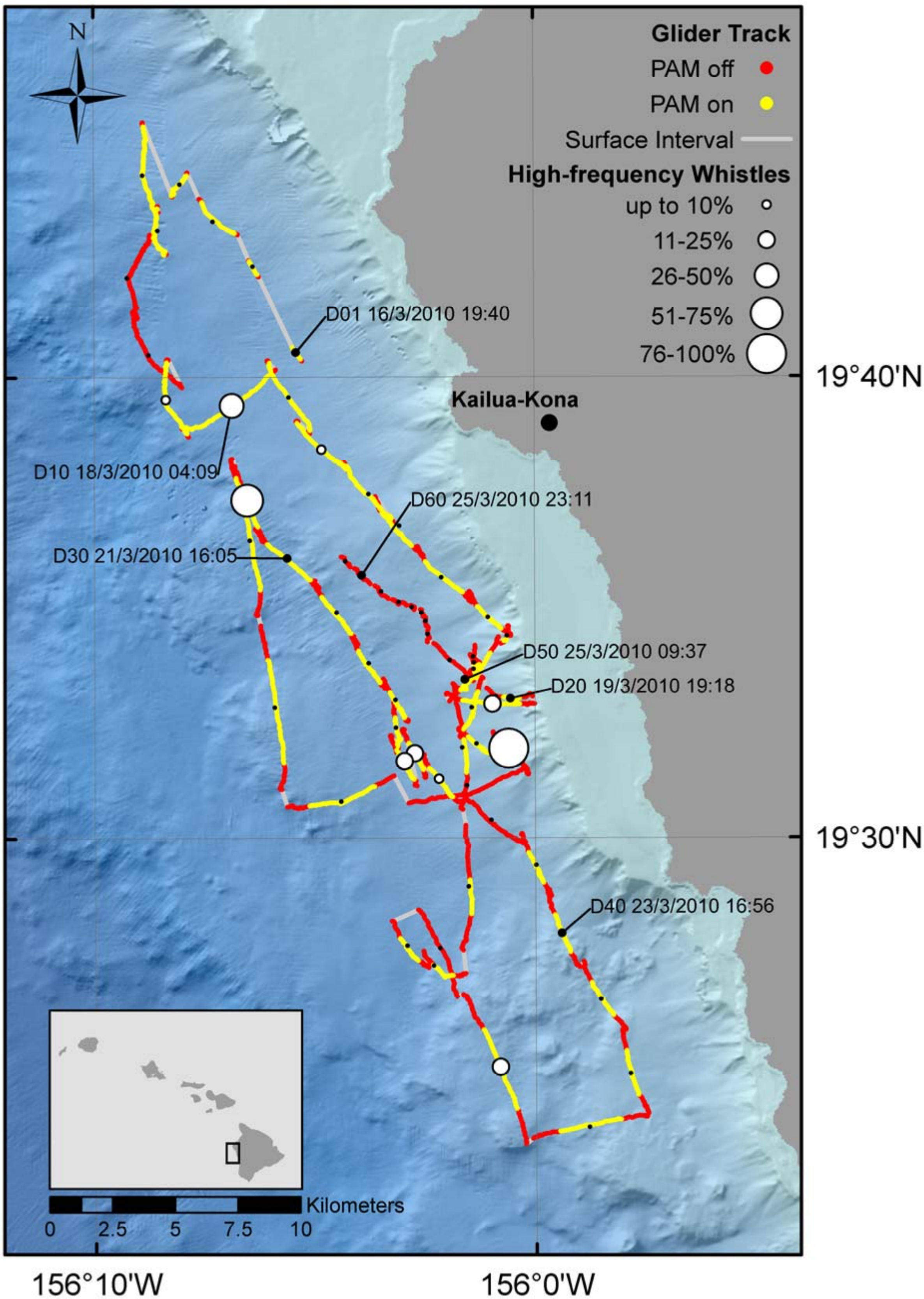

Figure 14: SG203 high-frequency whistle detections. The circle size indicates percentage of recording time per dive with target signals.

Low- and High-frequency whistles

Fourteen dives contained recordings of both low- and high-frequency whistles, classified as such because either both types of whistles or whistles that spanned a frequency range above and below 10 kHz were present (**Figure 15**).

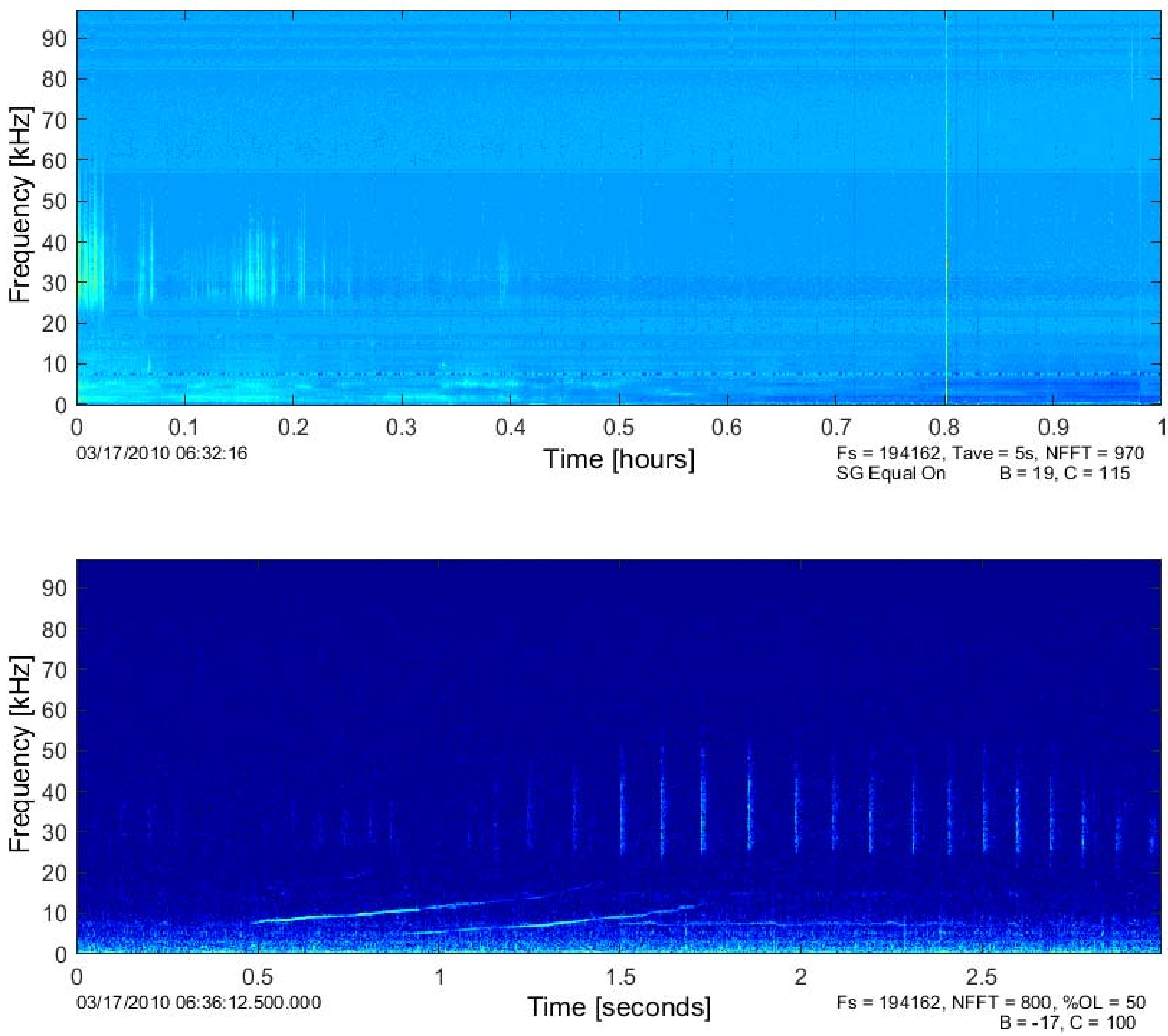

Figure 15: Low- and high-frequency whistles recorded with SG022 on 17 March 2010.

These whistles were the most commonly recorded odontocete whistle type and were spatially and temporally distributed throughout the survey area (**Figure 16**).

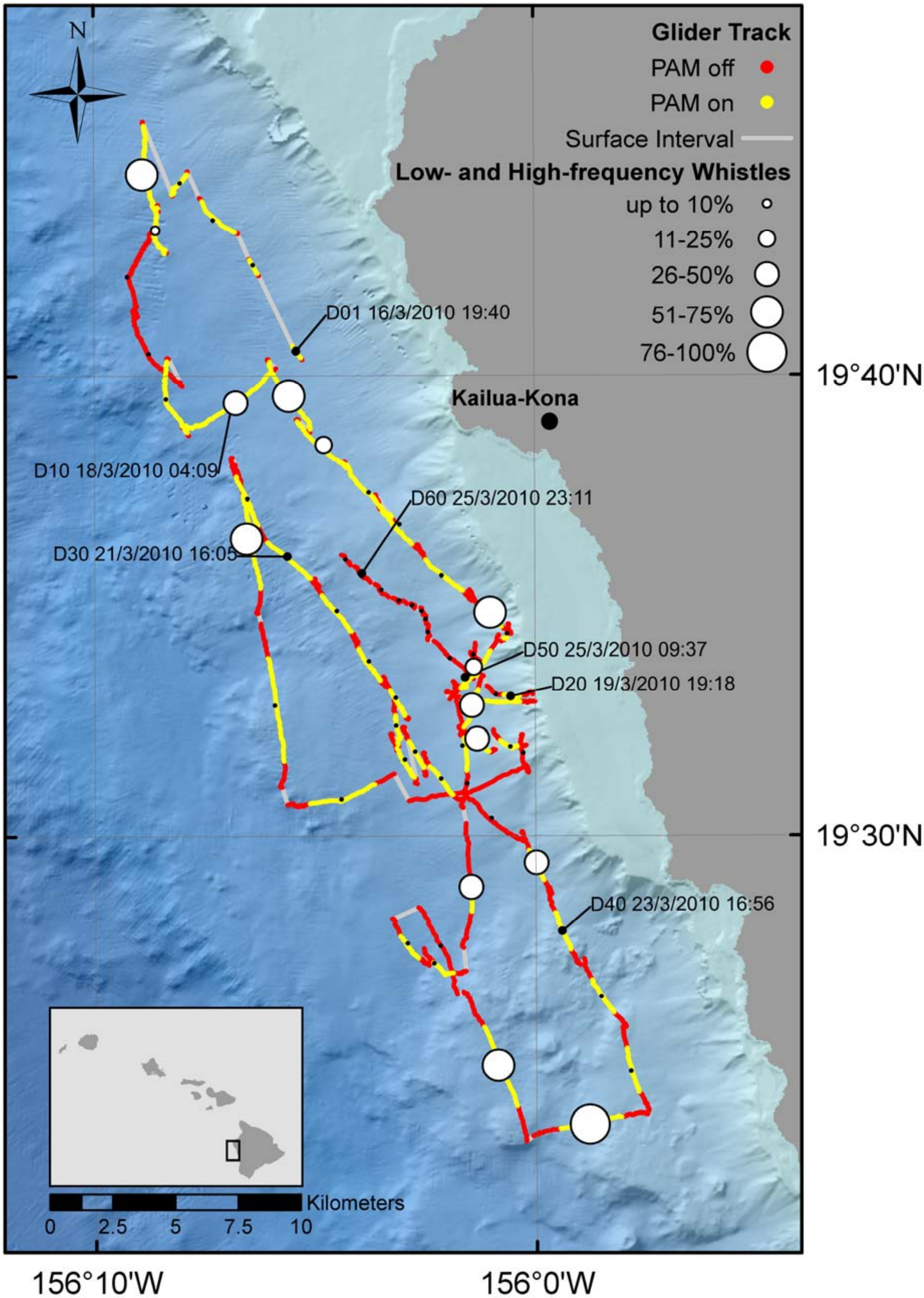

Figure 16: SG022 low- and high-frequency whistle detections. The circle size indicates percentage of recording time per dive with target signals.

Echolocation clicks and burst pulses

Acoustic encounters that did not contain whistles, or signals that could not be identified to species level, were classified as echolocation clicks and burst pulses (**Figure 17**). Such encounters occurred on 11 individual glider dives.

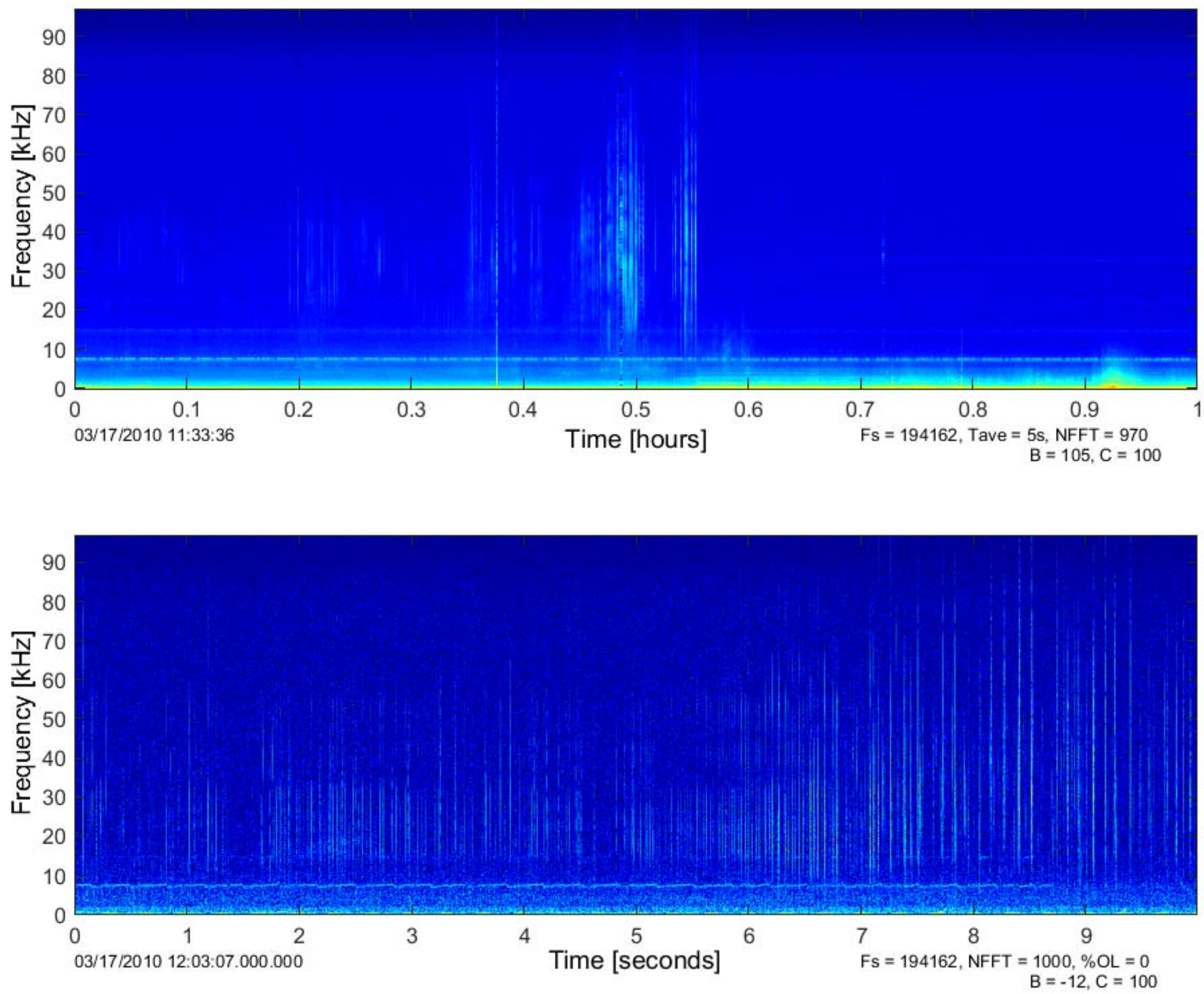

Figure 17: Echolocation clicks recorded with SG022 on 17 March 2010.

These recordings also occurred near the edge of the widest part of the shelf in the middle of the survey (**Figure 18**), with a few encounters northwest of Kailua-Kona, when the glider was over deeper water.

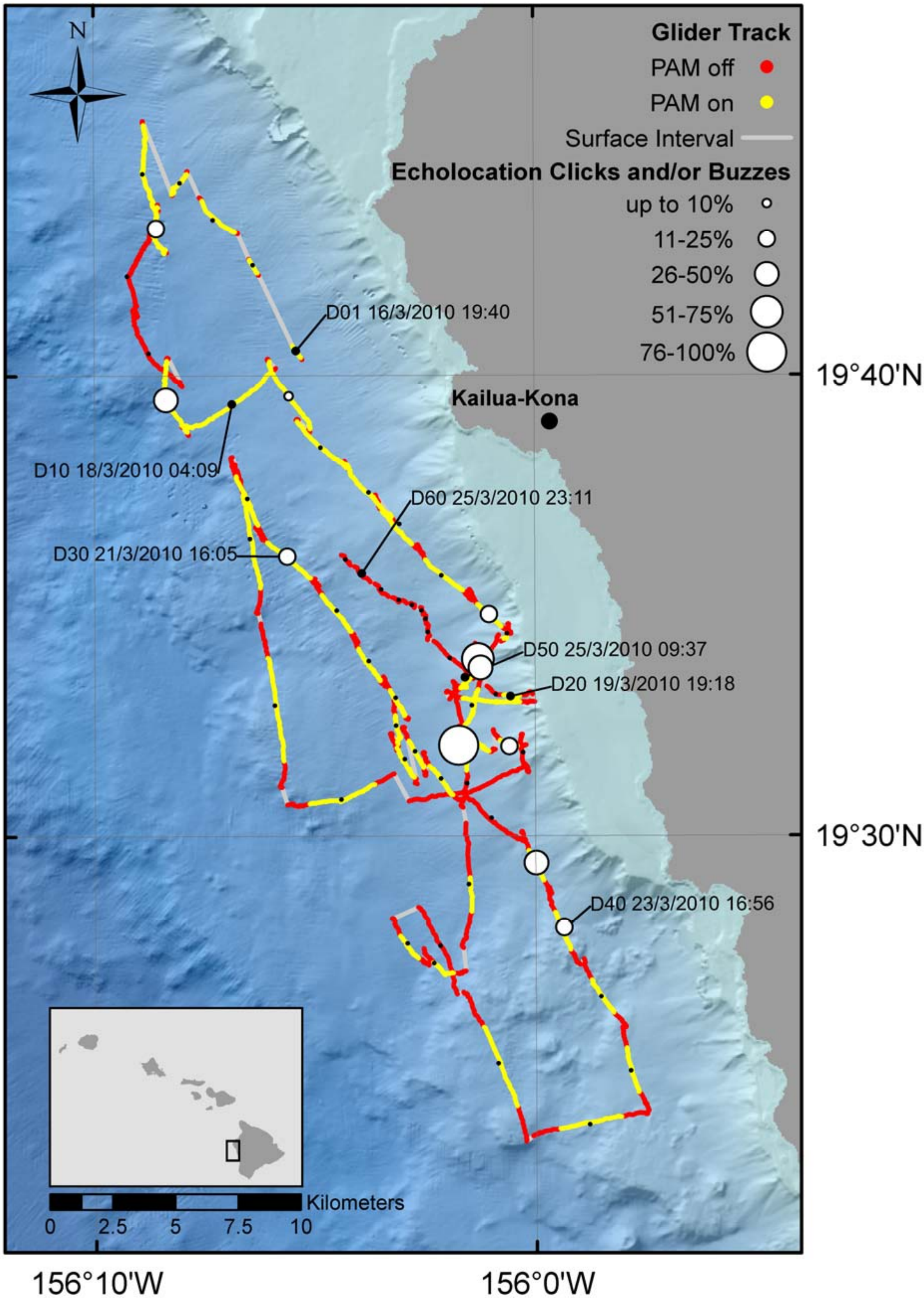

Figure 18: SG203 echolocation clicks and burst pulses encounters. The circle size indicates percentage of recording time per dive with target signals.

3.3 Mysticetes

Details on all mysticete detections can be found in **Appendix A**. Signals produced by blue, fin, sei, Bryde's and right whales were not identified in this dataset.

Humpback whale

As expected, the songs of humpback whales (**Figure 19**) were recorded in nearly all glider dives (**Figure 20**). Sounds were complex and variable and ranged in frequency from approximately 30 Hz to more than 5 kHz. Often there was more than one whale singing at a time.

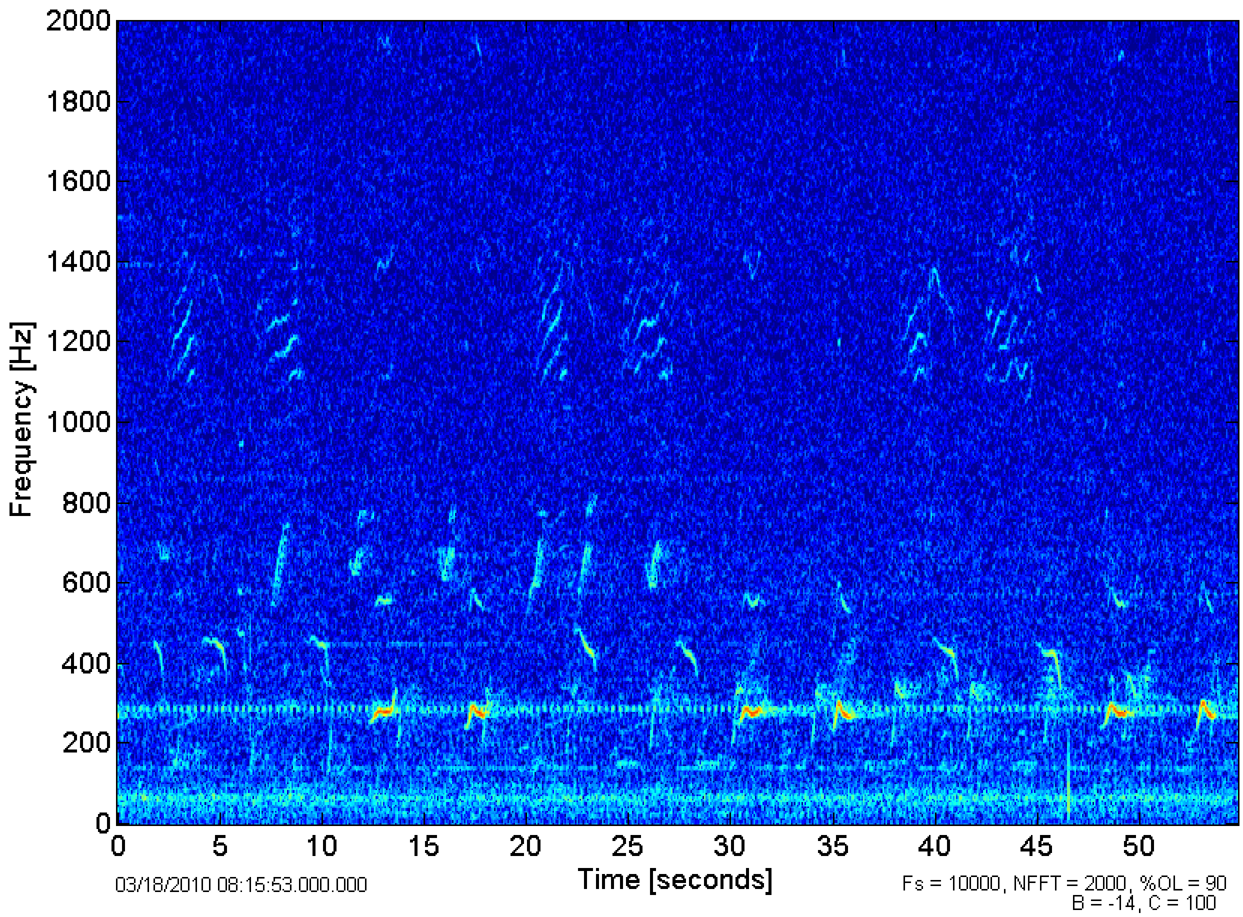

Figure 19: Humpback whale song recorded with SG022 recorded on 18 March 2010.

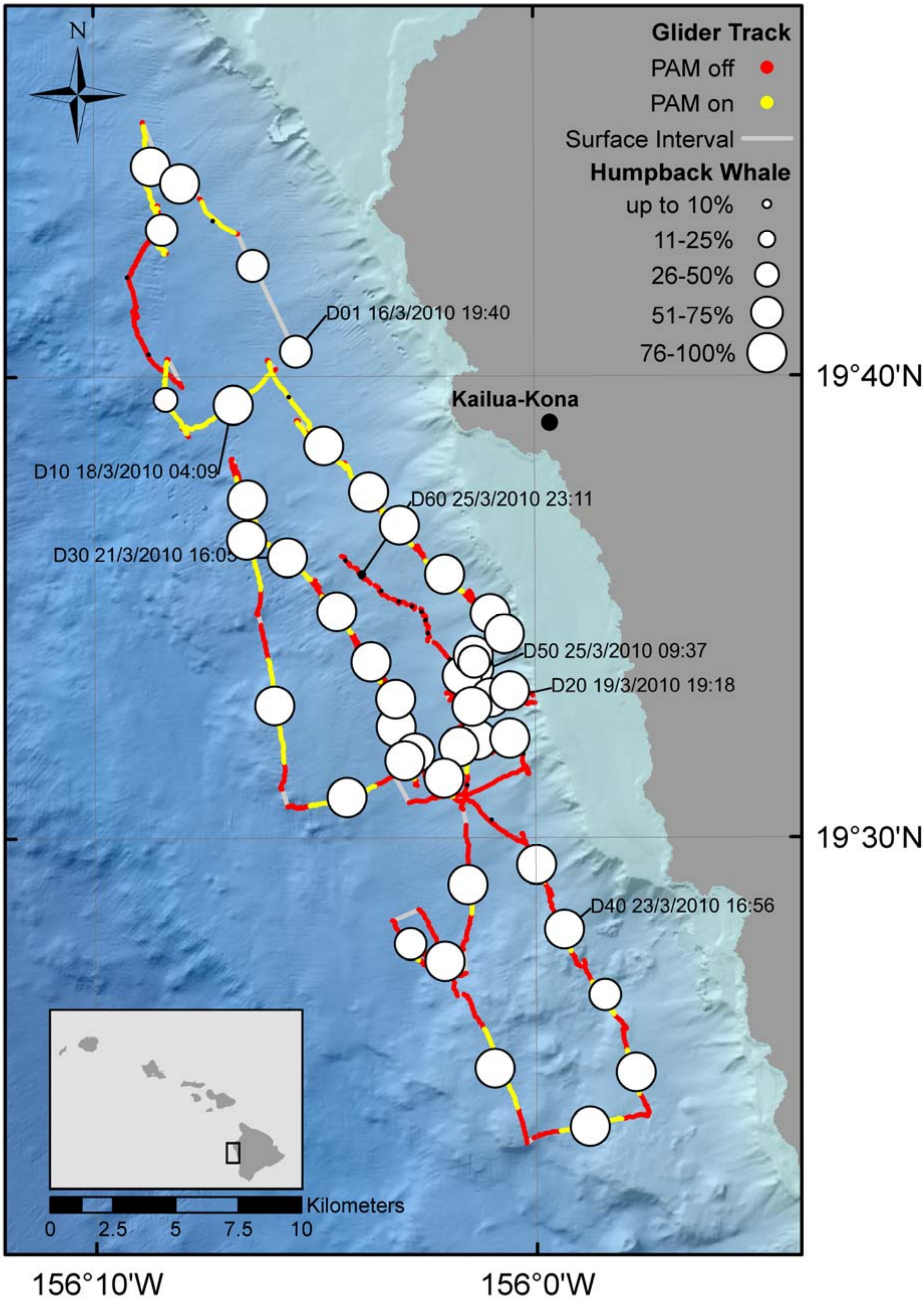

Figure 20: SG022 humpback whale encounters. The circle size indicates percentage of recording time per dive with target signals.

Minke whale

Minke whale boings (**Figure 21**) were also recorded in many of the glider dives during which there was passive-acoustic monitoring (**Figure 22**). Individual boings with the best signal-to-noise ratio were recorded during the first 2 days of the survey.

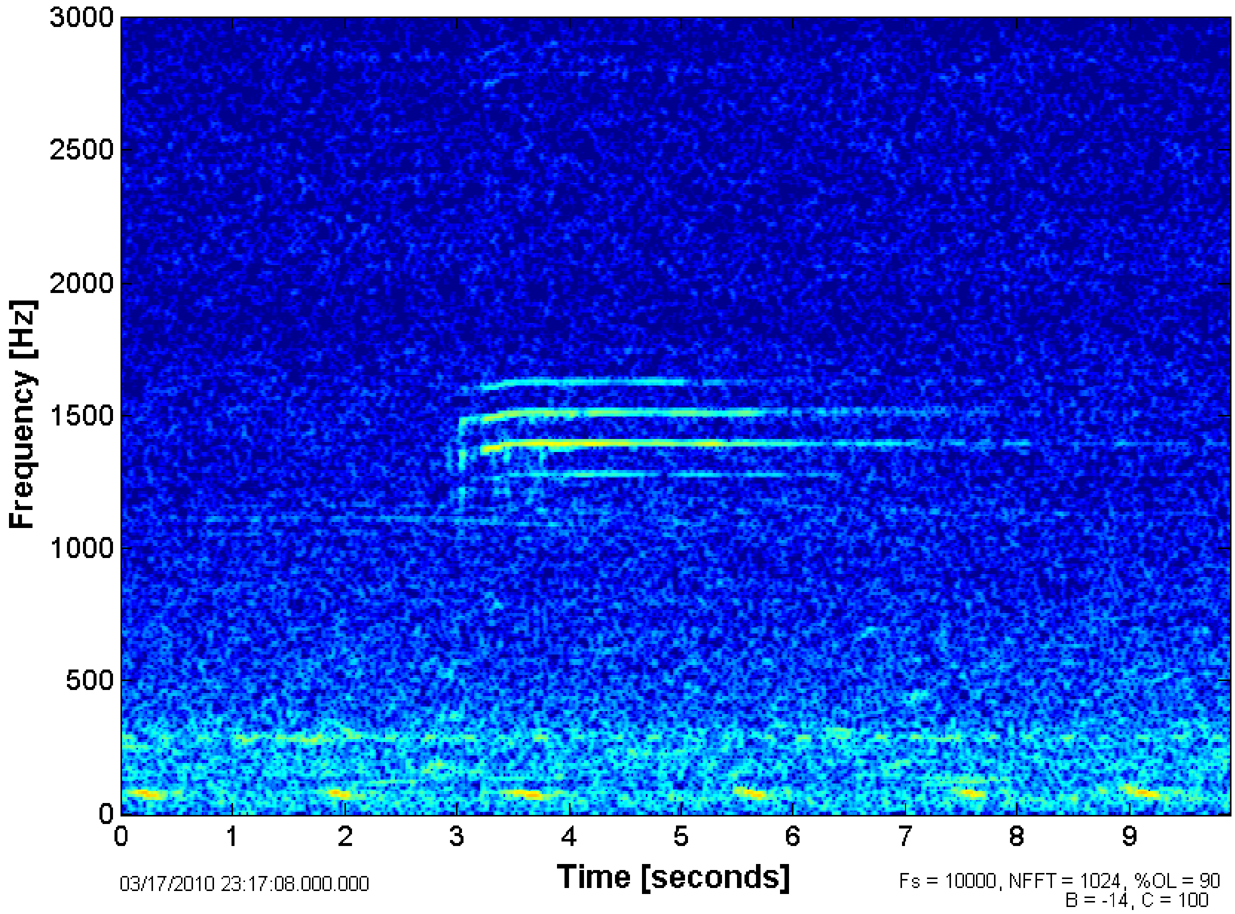

Figure 21: Minke whale boing call recorded with SG022 on 17 March 2010.

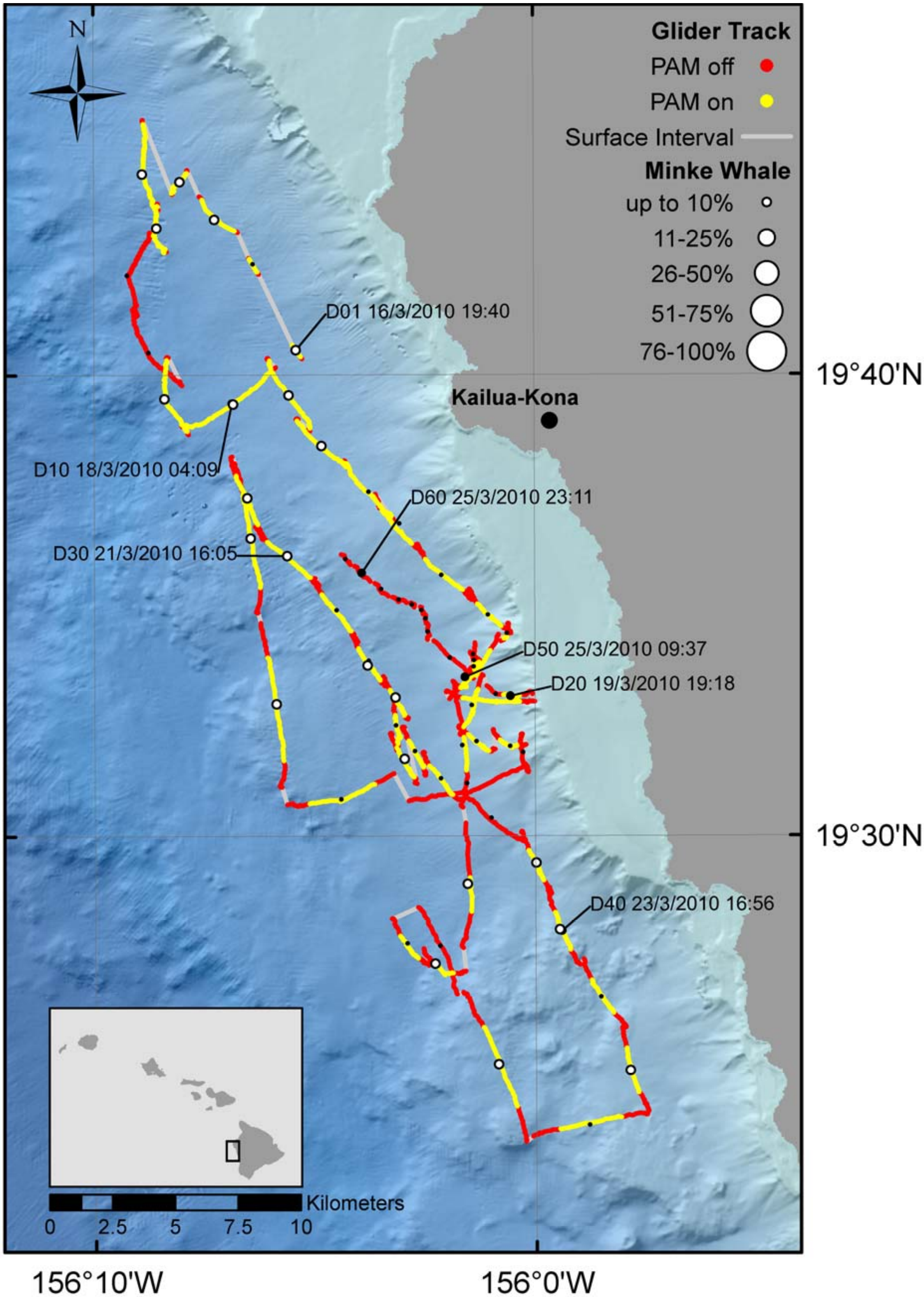

Figure 22: SG022 minke whale encounters. The circle size indicates percentage of recording time per dive with target signals.

3.4 Navy Sonar and Seismic Airgun Signals

No sonar or airgun signals were detected during this survey.

4. Discussion

Glider Performance

The Seaglider worked well as an underwater vehicle and was able to navigate successfully on its programmed track. The vehicle did not experience any flight problems.

During the SG022's survey, various setting of the PAM system (Rev. A) were tested. The trial was essential for identifying various internal noise sources. Several modifications were subsequently made to the PAM system to further suppress vehicle-generated noise and to improve the quality of the audio recordings, and were implemented as part of the development of the next-generation Revision B PAM system.

Environmental Data

An additional benefit of using gliders for marine mammal surveys is the collection of environmental data. The measured depth-averaged currents indicated that the glider can be safely operated off the Kona, Hawaii, coast. The current information as well as the temperature profiles are useful for additional future analysis efforts on occurrence patterns of cetacean species in the study area. The in-situ measured sound-speed profiles (derived from the CTD data) can be used to describe the sound propagation conditions in the study area in detail. These data will be used in an ongoing project funded by ONR to develop and evaluate a framework for density estimation of cetacean species using slow-moving underwater vehicles including gliders and floats.

The Seaglider can be equipped with a suite of additional environmental sensors. For example, active acoustic sensors would provide information on prey fields, which would be helpful for more comprehensive ecosystem studies (e.g., how the occurrence of cetaceans relates to the availability of prey and oceanographic conditions).

Odontocetes

During this comparatively short engineering test, many encounters with odontocetes (primarily small delphinids) were registered. This included six dives with beaked whale detections (both Cuvier's and Blainville's beaked whales). Due to the intermittent PAM on/off time and the short duration of this trial, it is difficult to make conclusions about the spatial and temporal distribution of odontocetes in this region. However, the species recorded in this region were not surprising. Recently Abecassis et al. (2015) identified the Kona Coast as a hot spot for Blainville's beaked whales, and previous acoustic surveys detected both Blainville's and Cuvier's beaked whales in this region (Oleson and Hildebrand 2012). The low-frequency whistles (whistle frequency <10 kHz) are likely produced by blackfish (short-finned pilot whales or false killer whales) that are known to be common in this area (Abecassis et al. 2015, Baird et al. 2013, Oleson and Hildebrand 2012).

Mysticetes

Only two species of baleen whales were recorded during this survey, most likely because we flew the glider during mid- to late-March, a time when many baleen whales have made their seasonal migration to more northern feeding grounds. As expected, the most common baleen whale vocalization recorded was humpback whale song. Humpback songs last 5–30 minutes and consist of complex, repetitive sounds that range from 25 Hz to 5 kHz (Payne and McVay 1971, Winn and Winn 1978). In most of the data, two or more singers were recorded simultaneously, likely because individuals will often sing for hours at a time. The function of singing is still unknown, but given that it is the males that sing and singing is most common during the winter breeding season it is likely related to breeding behavior. In addition to humpback song, the very distinct minke whale boing vocalization (Rankin and Barlow 2005) was occasionally recorded throughout the survey. In Hawaiian waters, minke whale boing sounds have been detected near the Hawaiian Islands for decades, with detections by the U.S. Navy during February and March (Thompson and Friedl 1982) and at the ALOHA Cabled Observatory 100 km north of Oahu from October to May (Oswald et al. 2011). It is suspected that only sexually active males make boing calls for breeding purposes, similar to the humpback whale. Based on preliminary analysis of the recorded boing call duration, frequency and pulse repetition rate, it appears that the glider recorded “central” or “Hawaiian” boings.

4.1 Conclusions

This survey was part of the original ONR-funded (awards # N00014-10-1-0515 and # N00014-08-1-1082) development effort of the passive-acoustic Seaglider. However, even though this was primarily an engineering test, the glider collected valuable acoustic data to document the presence of cetaceans in this area. The results of this data analysis (funded by the U.S. Pacific Fleet) will especially be useful for the ongoing ONR effort “Cetacean density estimation using slow-moving underwater vehicles,” led by the University of St. Andrews, Scotland.

The Kona, Hawaii, trial focused on testing the proper functionality and robustness of the PAM system Rev. A). The trial helped to identify internal noise sources and based on the results of this survey modifications were conducted which further improved the quality of the audio recordings.

This survey exemplified how crucial long-duration field tests are for thoroughly evaluating the performance of newly developed ocean-going instruments and for identifying potential issues with their operations.

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A

Details of All Acoustic Encounters Recorded by Glider SG022

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Appendix A: Details of All Acoustic Encounters Recorded by Glider SG022

This section includes a series of tables where encounter information is listed for each species acoustically identified in the glider data collected during the Hawaii Range Complex survey. An encounter was defined as a period when target signals were present in the acoustic data and separated from other periods of signal detections by 30 or more minutes of ‘silence.’ Note, however, that in other parts of this report we have summarized the acoustic data by glider dives, not encounters. Encounter data have been provided to enable direct comparison with line-transect studies conducted in the area.

A.1 Odontocetes

Beaked whale encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	6	17/03/2010 08:51:08	17/03/2010 08:57:56	Zc	19.7198	156.1409
2	12	18/03/2010 12:27:45	18/03/2010 12:27:56	Zc	19.6417	156.0798
3	22	20/03/2010 01:17:45	20/03/2010 01:44:40	Zc	19.5352	156.0220
4	14	18/03/2010 21:53:00	18/03/2010 22:13:00	Md	19.6129	156.0512
5	22	20/03/2010 01:48:00	20/03/2010 02:00:17	Md	19.5352	156.0220
6	32	22/03/2010 02:11:58	22/03/2010 02:13:24	Md	19.5636	156.0622
7	42	24/03/2010 01:05:38	24/03/2010 01:36:55	Md	19.4151	155.9623

*Zc = Ziphius cavirostris (Cuvier’s beaked whale); Md = *Mesoplodon densirostris* (Blainville’s beaked whale)

Low-frequency whistle encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	3	16/03/2010 22:26:31	16/03/2010 22:28:58	LFW	19.7252	156.1197
2	5	17/03/2010 03:24:40	17/03/2010 05:18:43	LFW	19.7427	156.1451
3	5	17/03/2010 06:12:25	17/03/2010 06:13:09	LFW	19.7427	156.1451
4	10	18/03/2010 02:36:00	18/03/2010 03:39:51	LFW	19.6588	156.1156
5	10	18/03/2010 05:02:40	18/03/2010 05:19:45	LFW	19.6588	156.1156

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
6	11	18/03/2010 08:48:26	18/03/2010 09:44:00	LFW	19.6594	156.0930
7	12	18/03/2010 12:55:00	18/03/2010 13:17:55	LFW	19.6417	156.0798
8	15	19/03/2010 03:03:34	19/03/2010 03:05:35	LFW	19.5951	156.0342
9	16	19/03/2010 04:59:47	19/03/2010 05:03:09	LFW	19.5809	156.0170
10	18	19/03/2010 12:46:11	19/03/2010 12:47:33	LFW	19.5612	156.0232
11	19	19/03/2010 16:06:00	19/03/2010 16:08:46	LFW	19.5504	156.0169
12	21	19/03/2010 21:43:05	19/03/2010 21:45:39	LFW	19.5473	156.0240
13	23	20/03/2010 07:07:35	20/03/2010 07:09:25	LFW	19.5358	156.0097
14	33	22/03/2010 07:09:24	22/03/2010 07:22:51	LFW	19.5500	156.0528

*LFW = Low-frequency whistle

High-frequency whistle encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	9	18/03/2010 01:36:49	18/03/2010 01:38:30	HFW	19.6592	156.1348
2	10	18/03/2010 04:33:02	18/03/2010 05:52:54	HFW	19.6588	156.1156
3	12	18/03/2010 11:31:26	18/03/2010 11:31:51	HFW	19.6417	156.0798
4	19	19/03/2010 14:29:00	19/03/2010 14:50:05	HFW	19.5504	156.0169
5	19	19/03/2010 15:54:11	19/03/2010 15:58:00	HFW	19.5504	156.0169
6	23	20/03/2010 05:13:38	20/03/2010 07:18:33	HFW	19.5358	156.0097
7	29	21/03/2010 09:30:26	21/03/2010 11:29:46	HFW	19.6222	156.1087
8	35	22/03/2010 16:26:43	22/03/2010 16:50:19	HFW	19.5278	156.0495
9	36	22/03/2010 21:08:56	22/03/2010 21:49:28	HFW	19.5307	156.0455
10	37	23/03/2010 02:42:59	23/03/2010 03:39:18	HFW	19.5215	156.0346
11	44	24/03/2010 10:07:13	24/03/2010 10:39:51	HFW	19.4166	156.0157

*HFW = High-frequency whistle

Low- and high-frequency whistle encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	5	17/03/2010 04:09:06	17/03/2010 06:55:26	LHFW	19.7427	156.1451
2	6	17/03/2010 10:07:49	17/03/2010 10:14:59	LHFW	19.7198	156.1409
3	10	18/03/2010 02:12:50	18/03/2010 03:22:37	LHFW	19.6588	156.1156
4	11	18/03/2010 06:32:11	18/03/2010 07:56:45	LHFW	19.6594	156.0930
5	11	18/03/2010 08:44:47	18/03/2010 10:03:15	LHFW	19.6594	156.0930
6	12	18/03/2010 12:46:18	18/03/2010 13:09:12	LHFW	19.6417	156.0798
7	16	19/03/2010 04:46:36	19/03/2010 06:00:12	LHFW	19.5809	156.0170
8	18	19/03/2010 10:33:07	19/03/2010 10:56:56	LHFW	19.5612	156.0232
9	21	19/03/2010 21:14:29	19/03/2010 22:11:41	LHFW	19.5473	156.0240
10	22	20/03/2010 02:30:16	20/03/2010 03:18:21	LHFW	19.5352	156.0220
11	28	21/03/2010 05:21:29	21/03/2010 07:29:47	LHFW	19.6077	156.1091
12	39	23/03/2010 10:44:25	23/03/2010 11:43:18	LHFW	19.4902	155.9997
13	43	24/03/2010 05:29:37	24/03/2010 07:48:42	LHFW	19.3955	155.9798
14	44	24/03/2010 11:18:54	24/03/2010 12:32:10	LHFW	19.4166	156.0157
15	48	25/03/2010 02:56:27	25/03/2010 03:20:30	LHFW	19.4823	156.0270

*LHFW = Low- and high-frequency whistle

Echolocation clicks and/or burst pulses encounters *

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	6	17/03/2010 11:13:01	17/03/2010 12:06:16	ECBP	19.7198	156.1409
2	9	18/03/2010 00:29:49	18/03/2010 01:26:00	ECBP	19.6592	156.1348
3	11	18/03/2010 08:05:40	18/03/2010 08:11:52	ECBP	19.6594	156.0930
4	16	19/03/2010 06:08:34	19/03/2010 06:20:05	ECBP	19.5809	156.0170
5	18	19/03/2010 11:14:07	19/03/2010 12:53:02	ECBP	19.5612	156.0232

Encounter [no.]	**Dive [no.]**	**Start date [UTC] [dd/mm/yyyy hh:mm:ss]**	**End date [UTC] [dd/mm/yyyy hh:mm:ss]**	**Species ID/Label**	**Latitude [degrees N]**	**Longitude [degrees W]**
6	23	20/03/2010 06:48:00	20/03/2010 07:05:00	ECBP	19.5358	156.0097
7	30	21/03/2010 15:15:12	21/03/2010 15:44:30	ECBP	19.6013	156.0937
8	39	23/03/2010 12:03:39	23/03/2010 13:07:47	ECBP	19.4902	155.9997
9	40	23/03/2010 15:25:21	23/03/2010 15:32:41	ECBP	19.4668	155.9893
10	40	23/03/2010 16:54:32	23/03/2010 17:22:19	ECBP	19.4668	155.9893
11	49	25/03/2010 06:08:05	25/03/2010 06:48:08	ECBP	19.5327	156.0290
12	51	25/03/2010 11:44:41	25/03/2010 12:07:34	ECBP	19.5657	156.0235

*ECBP = Echolocation clicks and/or burst pulses

A.2 Mysticetes

Humpback whale encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	3	16/03/2010 19:38:27	17/03/2010 01:55:25	Mn	19.7252	156.1197
2	5	17/03/2010 03:15:41	17/03/2010 10:56:59	Mn	19.7427	156.1451
3	10	17/03/2010 23:49:08	18/03/2010 05:52:58	Mn	19.6588	156.1156
4	19	18/03/2010 06:32:08	21/03/2010 02:44:06	Mn	19.5504	156.0169
5	30	21/03/2010 04:40:10	22/03/2010 03:17:39	Mn	19.6013	156.0937
6	34	22/03/2010 05:08:15	22/03/2010 17:34:34	Mn	19.5399	156.0527
7	38	22/03/2010 20:22:10	23/03/2010 22:16:16	Mn	19.5073	156.0156
8	43	24/03/2010 00:38:18	24/03/2010 12:30:54	Mn	19.3955	155.9798
9	48	24/03/2010 17:26:23	25/03/2010 15:33:05	Mn	19.4823	156.0270

*Mn = *Megaptera novaeangliae* (humpback whale)

Minke whale encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	9	16/03/2010 19:41:55	16/03/2010 19:45:05	Ba	19.6757	156.0902
2	10	16/03/2010 21:32:49	16/03/2010 22:23:25	Ba	19.7252	156.1197
3	10	16/03/2010 23:13:46	17/03/2010 01:46:45	Ba	19.7365	156.1341
4	10	17/03/2010 03:17:07	17/03/2010 03:19:07	Ba	19.7427	156.1451
5	11	17/03/2010 04:25:04	17/03/2010 04:25:13	Ba	19.7427	156.1451
6	11	17/03/2010 07:21:02	17/03/2010 07:30:10	Ba	19.7427	156.1451
7	12	17/03/2010 08:22:55	17/03/2010 08:35:17	Ba	19.7198	156.1409
8	12	17/03/2010 09:08:37	17/03/2010 09:08:45	Ba	19.7198	156.1409
9	12	17/03/2010 10:35:25	17/03/2010 11:24:42	Ba	19.7198	156.1409
10	27	17/03/2010 11:58:22	17/03/2010 12:03:58	Ba	19.7198	156.1409

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
11	27	17/03/2010 22:02:43	18/03/2010 01:34:26	Ba	19.6592	156.1348
12	28	18/03/2010 02:18:26	18/03/2010 02:35:27	Ba	19.6588	156.1156
13	29	18/03/2010 03:14:44	18/03/2010 04:20:48	Ba	19.6588	156.1156
14	29	18/03/2010 05:02:47	18/03/2010 05:24:15	Ba	19.6588	156.1156
15	30	18/03/2010 06:54:35	18/03/2010 07:44:36	Ba	19.6594	156.0930
16	32	18/03/2010 09:42:33	18/03/2010 10:01:13	Ba	19.6594	156.0930
17	33	18/03/2010 11:12:26	18/03/2010 11:45:38	Ba	19.6417	156.0798
18	35	18/03/2010 12:25:43	18/03/2010 12:25:52	Ba	19.6417	156.0798
19	39	18/03/2010 13:19:16	18/03/2010 13:24:54	Ba	19.6417	156.0798
20	40	20/03/2010 23:41:18	21/03/2010 01:00:55	Ba	19.5474	156.0999
21	42	21/03/2010 01:40:59	21/03/2010 02:37:35	Ba	19.5474	156.0999
22	42	21/03/2010 04:35:04	21/03/2010 06:50:49	Ba	19.6077	156.1091
23	44	21/03/2010 09:31:28	21/03/2010 11:09:23	Ba	19.6222	156.1087
24	44	21/03/2010 12:21:00	21/03/2010 12:21:11	Ba	19.6222	156.1087
25	44	21/03/2010 14:20:33	21/03/2010 16:44:12	Ba	19.6013	156.0937
26	47	22/03/2010 02:23:03	22/03/2010 02:31:53	Ba	19.5636	156.0622
27	47	22/03/2010 05:13:48	22/03/2010 05:20:28	Ba	19.5500	156.0528
28	48	22/03/2010 15:35:35	22/03/2010 16:33:20	Ba	19.5278	156.0495
29	9	23/03/2010 12:08:00	23/03/2010 12:12:41	Ba	19.4902	155.9997
30	10	23/03/2010 17:14:36	23/03/2010 17:14:45	Ba	19.4668	155.9893
31	10	24/03/2010 02:16:45	24/03/2010 02:17:54	Ba	19.4151	155.9623
32	10	24/03/2010 02:53:34	24/03/2010 03:01:42	Ba	19.4151	155.9623
33	11	24/03/2010 10:22:44	24/03/2010 10:22:50	Ba	19.4166	156.0157
34	11	24/03/2010 11:01:38	24/03/2010 11:08:27	Ba	19.4166	156.0157

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
35	12	24/03/2010 11:39:04	24/03/2010 11:39:09	Ba	19.4166	156.0157
36	12	24/03/2010 22:52:52	24/03/2010 23:13:55	Ba	19.4553	156.0345
37	12	24/03/2010 23:44:56	24/03/2010 23:47:23	Ba	19.4553	156.0345
38	27	25/03/2010 03:18:57	25/03/2010 03:28:54	Ba	19.4823	156.0270

*Ba = *Balaenoptera acutorostrata* (minke whale)

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