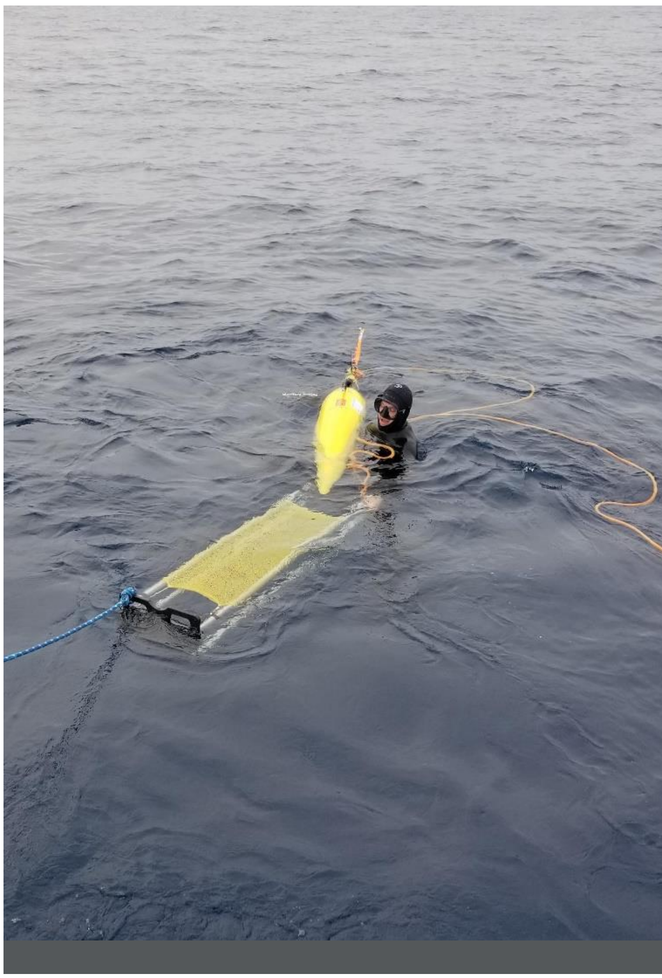
Final Report

for

Passive Acoustic Monitoring of Large Whales on and off the Continental Shelf of Southern California using Autonomous Underwater Vehicles

Contract No. N62470-15-D-8006
Task Order 18F0147



Prepared by:

Oregon State University, Hatfield Marine Science Center and HDR, Inc.

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Cover Photo: Recovery of glider SG607 by the crew of the *M/V Magician* off Southern California, 31 March 2020. Photograph taken by K. Ampela.

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Acronyms and Abbreviations

AUV	autonomous underwater vehicle(s)
CalCOFI	California Cooperative Oceanic Fisheries Investigation
CV	coefficient of variation
DoN	Department of the Navy
DPS	distinct population segment(s)
ESA	Endangered Species Act
FFT	Fast Fourier Transform
GPS	global positioning system
HARP	high-frequency acoustic recording package
HF	high-frequency
HSTT	Hawaii-Southern California Training and Testing
Hz	hertz
km	kilometer(s)
kHz	kilohertz
LF	low-frequency
LTSA	Long-Term Spectral Average
m	meter(s)
MF	mid-frequency
MMPA	Marine Mammal Protection Act
M/V	motor vessel
NMFS	National Marine Fisheries Service
PAM	passive acoustic monitoring
PMAR	Passive Miniature Acoustic Recorder
QA	quality assurance
SCB	Southern California Bight
SCORE	Southern California Offshore Range
SD	secure digital
SOAR	Southern California Anti-Submarine Warfare Range
SOCAL	Southern California
SSP	sound speed profile
U.S.	United States
UTC	Coordinated Universal Time
vdc	volts direct current

Executive Summary

A passive acoustic monitoring survey using mobile underwater gliders was conducted from 7 February to 31 March 2020 in the Southern California Bight, with the goal of characterizing the temporal and spatial distribution of odontocetes and mysticetes in the region. Initially, the focus of this Project was on beaked whales. However, upon recovery of the gliders post-deployment, it was discovered that neither glider recorded any useable data above 2.5 kilohertz, well below the frequency of beaked whale vocalizations. It was then decided to analyze the available data for baleen whale and sperm whale (*Physeter macrocephalus*) vocalizations, which was originally a focus of secondary importance for the Project.

Two Seagliders™ were deployed in the San Nicolas Basin on 7 February 2020. One, the “abyssal glider” (SG607), was piloted to survey over the abyssal plain offshore of the continental shelf break. The other, the “shelf glider” (SG639), was piloted to conduct several transects inshore of the shelf break in water depths shallower than 2,500 meters. Both gliders were programmed to survey in the vicinity of existing United States (U.S.) Navy-funded fixed acoustic sensors (high-frequency acoustic recording packages) with the goal of eventually comparing the acoustic datasets collected by both types of instruments. The abyssal glider completed its mission, recorded a total of 763 hours of acoustic data (4,721 sound files on a duty cycle recording 10-minute files every 15 minutes) and traveled 940 kilometers (km) (50 days) before being recovered on 31 March. The shelf glider malfunctioned and stopped recording well ahead of schedule on 10 February and was recovered on 14 February. The shelf glider surveyed successfully for 87 hours and traveled 95 km before failing. It recorded 55 hours of acoustic data in 351 files with the same duty cycle as the abyssal glider.

Blue (*Balaenoptera musculus*), fin (*B. physalus*), humpback (*Megaptera novaeangliae*), and sperm whale vocalizations were recorded by the abyssal glider, and fin and humpback vocalizations (no blue or sperm whales) by the shelf glider. Fin and humpback encounters were particularly abundant. No confirmed minke whale (*Balaenoptera acutorostrata*) vocalizations were recorded by either glider. The abyssal glider recorded blue whale B calls on three separate days, all while the glider was inshore of the shelf break west of Tanner Bank. Fin whales were detected on every day of both glider deployments, and on several days, they were present in 100% of the 10-minute recording periods. Humpback whales were detected on 48 of the 50 days of the abyssal glider’s deployment, both on and off the continental shelf, and on all five days of the shelf glider recordings (continental shelf only). The abyssal glider recorded sperm whales on 12 of the 50 recording days (n=165 confirmed detections), when the glider was located at the shelf break and over the abyssal plain.

The deep-water areas on the shelf slope and the abyssal plain are seldom surveyed for marine mammals, making the results of this study particularly valuable in improving our understanding of marine mammal occurrence and distribution in these areas, and in and around U.S. Navy training and testing areas in the region.

1. Project Overview and Objectives

1.1 Background

The purpose of this Project was to use autonomous underwater vehicles (AUVs) to conduct passive acoustic monitoring (PAM) in the Southern California Bight (SCB) and northern Baja California, Mexico, with the goal of characterizing the distribution of mysticete and odontocete species in these areas.

Study questions to be addressed:

- *What species of cetaceans other than beaked whales are present in the SCB?*
- *What is the spatial distribution of these cetacean species, particularly blue and fin whales, both inside and outside of the Navy's training ranges in the SCB, including on and off the continental shelf?*

This study was designed to complement ongoing marine mammal monitoring studies in the region, including small-vessel tagging and photo identification surveys for fin whales (*Balaenoptera physalus*) and Cuvier's beaked whales (*Ziphius cavirostris*) (e.g., Schorr et al. 2020); PAM of blue (*Balaenoptera musculus*), fin, and all species of beaked whales using high-frequency acoustic recording packages (HARPs) (e.g., Rice et al. 2020); and visual surveys for marine mammals on California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises (e.g., Trickey et al. 2020).

Previous United States (U.S.) Navy-funded AUV studies have been conducted in Hawaii, the Marianas, and the Pacific Northwest, with the goal of characterizing cetacean distribution in these areas. This work builds on those efforts and applies this new research technology to the Southern California (SOCAL) region.

1.1.1 The SOCAL Range Complex

The SOCAL Range Complex, a part of the Hawaii-Southern California Training and Testing (HSTT) Study Area, is composed of several marine- and land-based training areas primarily in and around San Diego, the southern Channel Islands of the SCB, and areas extending south to Isla de Guadalupe off Baja California, Mexico (**Figure 1**). This Range Complex includes training areas on the islands of San Nicolas and San Clemente and their surrounding waters (**Figure 1**). The Range Complex also notably contains the Southern California Offshore Range (SCORE) including an array of over 70 cabled, bottom-moored hydrophones capable of real-time acoustic monitoring. SCORE, a subset of complexes within SOCAL, is centered on San Clemente Island and managed via the Range Operation Center on North Island, Coronado, and includes the Southern California Anti-Submarine Warfare Range (SOAR), a focal area for U.S. Navy exercises involving mid-frequency active sonar systems in the San Nicolas Basin (**Figure 1**) (Schorr et al. 2020).

Training areas in and around the Channel Islands cover a range of diverse underwater habitats, including nearshore coastal waters along the mainland and island coasts, deep-water basins which lie between the islands and are marked by very steep and abrupt bathymetric changes, and the continental shelf edge and the subsequent abyssal plain with depths over 3,500 meters (m). Area currents are complex, change seasonally, and are dominated by the south-flowing California Current further offshore, and the north-flowing California Counter Current inshore. Wind-driven upwelling brings cold, highly productive waters into the area intermittently. This mix of complex bathymetry and circulation contribute to the biological diversity and richness of the SCB ecosystem, making it home to a variety of cetacean species (**Table 1**).

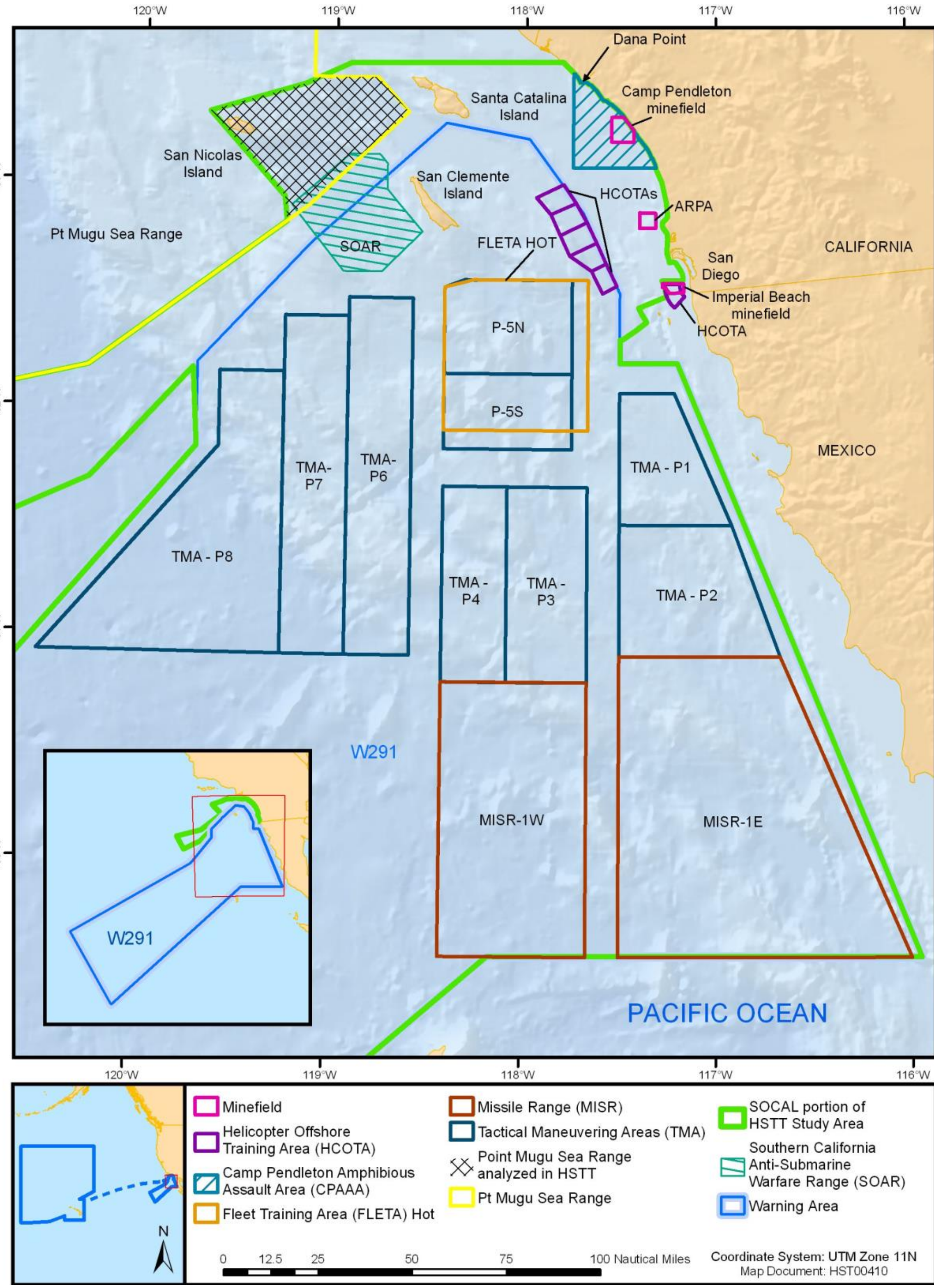

Figure 1. Map of the Southern California (SOCAL) Range Complex, a portion of the Hawaii-Southern California Testing and Training (HSTT) Study Area. SOAR, the region west of San Clemente Island, is part of SCORE and largely overlaps with it. Source: Department of the Navy (DoN) (2018).

Table 1. Cetaceans that could potentially occur in the offshore waters of the Southern California (SOCAL) Range Complex portion of the Hawaii-Southern California Training and Testing (HSTT) Study Area. Adapted from: Department of the Navy (DoN) 2018

Common Name (Scientific Name)	Stock[1]	ESA/MMPA Status[2]	Stock Abundance CV/ Minimum Population[3]	Occurrence in the Study Area[4]	Seasonal Occurrence within the Study Area**	Signal Type for Classification	Frequency Band***
Mysticeti (baleen whales)							
Family Eschrichtiidae (gray whale)							
Gray Whale (*Eschrichtius robustus*)	Eastern North Pacific	-	26,960 (0.05)/25,849	Coastal; Open Ocean	Regular - Winter and Spring	Tonal Calls	LF (<100 Hz)
Family Balaenopteridae (rorqual whales)							
Minke Whale (*Balaenoptera acutorostrata*)	California, Oregon, and Washington	-	636 (0.72)/369	Coastal; Open Ocean	Regular - Year-Round	Pulsed Signals	MF (1-10 kHz)
Sei Whale (*Balaenoptera borealis*)	Eastern North Pacific	Endangered/Depleted	519 (0.4)/374	Coastal; Open Ocean	Rare - Summer and Fall	Tonal Calls	LF (<150 Hz)
Bryde's Whale (*Balaenoptera edeni*)	Eastern Tropical Pacific	-	Unknown	Coastal; Open Ocean	Rare - Summer and Fall	Tonal Calls	
Blue Whale (*Balaenoptera musculus*)	Eastern North Pacific	Endangered/Depleted	1,496 (0.44)/1,050	Coastal; Open Ocean	Regular - Summer and Fall	Tonal Calls	
Fin Whale (*Balaenoptera physalus*)	California, Oregon, and Washington	Endangered/Depleted	9,029 (0.12)/8,127	Coastal; Open Ocean	Regular - Year-Round	Tonal Calls	
Humpback Whale (*Megaptera novaeangliae*)	California, Oregon, and Washington	Endangered/Depleted	2,900 0.05/2,784	Coastal; Open Ocean	Regular - Winter, Spring and Summer	Tonal Calls	MF (500 Hz-10 kHz)
Odontoceti (toothed whales, dolphins, porpoises)							
Family Physeteridae (Sperm whale)							
Sperm Whale (*Physeter macrocephalus*)	California, Oregon, and Washington	Endangered/Depleted	1,997 (0.57)/1,270	Coastal; Open Ocean	Regular - Year-Round	Echolocation Clicks	HF (>10 kHz)
Family Kogiidae							
Pygmy Sperm Whale (*Kogia breviceps*)	California, Oregon, and Washington	-	4,111 (1.12)/1,924	Coastal; Open Ocean	Rare	Echolocation Clicks	HF (>100 kHz)

Common Name (Scientific Name)	Stock[1]	ESA/MMPA Status[2]	Stock Abundance CV/ Minimum Population[3]	Occurrence in the Study Area[4]	Seasonal Occurrence within the Study Area**	Signal Type for Classification	Frequency Band***
Dwarf Sperm Whale (*Kogia sima*)	California, Oregon, and Washington	-	Unknown	Coastal; Open Ocean	Rare	Echolocation Clicks	
Family Ziphiidae (Beaked Whales)							
Baird's Beaked Whale (*Berardius bairdii*)	California, Oregon, and Washington	-	2,697 (0.60)/1,633	Open Ocean	Rare - Spring and Fall	Echolocation Clicks	HF (>10 kHz)
Hubbs' Beaked Whale (*Mesoplodon carlhubbsi*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Ginkgo-toothed Beaked Whale (*Mesoplodon ginkgodens*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Perrin's Beaked Whale (*Mesoplodon perrini*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Pygmy Beaked Whale (*Mesoplodon peruvianus*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Stejneger's Beaked Whale (*Mesoplodon stejnegeri*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Blainville's Beaked Whale (*Mesoplodon densirostris*)	California, Oregon, and Washington	-	3,044* (0.54)/1,967	Open Ocean	Rare	Echolocation Clicks	HF (>10 kHz)
Cuvier's Beaked Whale (*Ziphius cavirostris*)	California, Oregon, and Washington	-	3,274 (0.67)/2,059	Open Ocean	Regular - Year-Round	Echolocation Clicks	HF (>10 kHz)

Common Name (Scientific Name)	Stock[1]	ESA/MMPA Status[2]	Stock Abundance CV/ Minimum Population[3]	Occurrence in the Study Area[4]	Seasonal Occurrence within the Study Area**	Signal Type for Classification	Frequency Band***
Family Delphinidae (Dolphins)							
Killer Whale (*Orcinus orca*)	Eastern North Pacific Offshore	-	300 (0.1)/276	Coastal and Open Ocean	Regular - Year-Round	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Killer Whale (*Orcinus orca*)	Eastern North Pacific Transient/West Coast Transient[5]	-	243 unknown/243	Coastal and Open Ocean	Regular - Year-Round	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Short-finned Pilot Whale (*Globicephala macrorhynchus*)	California, Oregon, and Washington	-	836 (0.79)/466	Coastal; Open Ocean	Rare - Winter	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Long-Beaked Common Dolphin (*Delphinus capensis*)	California	-	101,305 (0.49)/68,432	Coastal; Open Ocean	Regular - Year-Round	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Short-Beaked Common Dolphin (*Delphinus delphis*)	California, Oregon, and Washington	-	969,861 (0.17)/839,325	Coastal; Open Ocean	Regular - Year-Round	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Risso's Dolphin (*Grampus griseus*)	California, Oregon, and Washington	-	6,336 (0.32)/4,817	Coastal; Open Ocean	Regular - Year-Round	Echolocation Clicks	MF and HF (1 Hz to 100 kHz)
Pacific White-Sided Dolphin (*Lagenorhynchus obliquidens*)	California, Oregon, and Washington	-	26,814 (0.28)/21,195	Coastal; Open Ocean	Regular - Winter and Spring	Echolocation Clicks and Burst Pulses	MF and HF (1 Hz to 100 kHz)
Northern Right Whale Dolphin (*Lissodelphis borealis*)	California, Oregon, and Washington	-	26,556 (0.44)/18,608	Coastal; Open Ocean	Regular - Year-Round	Echolocation Clicks and Burst Pulses	MF and HF (1 Hz to 100 kHz)
Striped Dolphin (*Stenella coeruleoalba*)	California, Oregon, and Washington	-	29,211 (0.20)/24,782	Coastal; Open Ocean	Rare - Summer and Fall	Whistles and Echolocation Clicks	MF and HF (1 Hz to 100 kHz)

Common Name (Scientific Name)	Stock[1]	ESA/MMPA Status[2]	Stock Abundance CV/ Minimum Population[3]	Occurrence in the Study Area[4]	Seasonal Occurrence within the Study Area**	Signal Type for Classification	Frequency Band***
Bottlenose Dolphin (*Tursiops truncatus*)	California Coastal		453 (0.06)/346	Coastal; Open Ocean; Bays and Harbors	Regular - Year-Round	Whistles and Echolocation Clicks	
	California, Oregon, and Washington Offshore		1,924 (0.54)/1,255	Coastal; Open Ocean			

[1] Stock designations for the U.S. Exclusive Economic Zones are from the Pacific (Carretta et al. 2017, 2018, 2019, 2020; Muto et al. 2020) Stock Assessment Reports prepared by National Marine Fisheries Service.

[2] Populations or stocks defined by the Marine Mammal Protection Act (MMPA) as "strategic" for one of the following reasons: (1) the level of direct human-caused mortality exceeds the potential biological removal level; (2) based on the best available scientific information, numbers are declining and species are likely to be listed as threatened species under the Endangered Species Act (ESA) within the foreseeable future; (3) species are listed as threatened or endangered under the ESA; and (4) species are designated as depleted under the MMPA.

[3] Stock Abundance, Coefficient of variation (CV), and minimum population are numbers provided by the Stock Assessment Reports (Carretta et al. 2017, 2018, 2019, 2020). The stock abundance is an estimate of the number of animals within the stock. The CV is a statistical metric used as an indicator of the uncertainty in the abundance estimate. The minimum population estimate is either a direct count or the lower 20th percentile of a statistical abundance estimate.

[4] Occurrence in the Study Area is defined as Coastal (<200 m depth) and Open Ocean (>200 m depth).

[5] This stock is mentioned briefly in the Pacific Stock Assessment Report (Carretta et al. 2017, 2018) and referred to as the "Eastern North Pacific Transient" stock; however, the Alaska Stock Assessment Report contains assessments of all transient killer whale stocks in the Pacific and the Alaska Stock Assessment Report refers to this same stock as the "West Coast Transient" stock (Muto et al. 2020).

* The stock abundance for the six Mesoplodont beaked whale species that occur in Southern California are clumped as one stock.

** Regular = A species that occurs as a regular or normal part of the fauna of the area, regardless of how abundant or common it is; Rare = A species that only occurs in the area sporadically.

*** HF = high-frequency; LF = low-frequency; MF = mid-frequency: Hz = hertz; kHz = kilohertz.

1.1.2 Priority Species

The following sections describe the known occurrence and seasonal distribution of the cetacean species that were the focus of this study and occur within the offshore waters of the SOCAL Range Complex portion of the HSTT Study Area.

1.1.2.1 MYSTICETES

1.1.2.1.1 Blue whale (*Balaenoptera musculus*)

Blue whales in SOCAL belong to the Eastern North Pacific stock ranging from Alaska to the Costa Rica Dome (**Table 1**). The blue whale is listed as endangered under the U.S. Endangered Species Act (ESA) and as depleted under the U.S. Marine Mammal Protection Act (MMPA) throughout its range, but there is no designated critical habitat for this species (Carretta et al. 2018, 2020). Southern and central California coastal waters are important feeding areas for this population in the summer and fall where their numbers appear to have increased from 1979-1996 (Carretta et al. 2010). Since 1996, blue whale numbers have fluctuated and declined off California, attributed to changes in the portion of the population feeding there in summer and fall (Calambokidis et al. 2009). In winter and spring, these blue whales migrate to biologically productive waters off Baja California, the Gulf of California, and the Costa Rica Dome, where at least small numbers are seen year-round (Carretta et al. 2018, 2020).

1.1.2.1.2 Fin whale (*Balaenoptera physalus*)

Fin whales, one of the most common large whales in the SOCAL portion of the HSTT Study Area (Jefferson et al. 2015b), belong to the California/Oregon/Washington stock within the eastern North Pacific population that ranges from Alaska to Mexico (Carretta et al. 2017, 2020). The fin whale is listed as depleted under the MMPA and endangered under the ESA throughout its range, but there is no designated critical habitat for this species (Carretta et al. 2018, 2020). Historical surveys indicate that these whales occur year-round in southern/central California, with peak feeding numbers in summer and fall (Forney et al. 1995). However, based on visual observations, fin whale numbers appear to decline in winter/spring off California (Forney et al. 1995; Smultea and Bacon 2012, 2013; Campbell et al. 2015; Jefferson et al. 2015b).

Fin whales are typically associated with continental shelf waters (Jefferson et al. 2015a). Within SOCAL, recent studies indicate that fin whales concentrate primarily in waters west of San Clemente Island within the U.S. Navy's SOAR (see **Figure 1**), particularly along steep underwater ridges (Schorr et al. 2010; Smultea and Bacon 2012). In particular, during June, fin whales have been commonly observed across San Nicolas Basin/SOAR between San Clemente Islands and Tanner Bank (Smultea and Bacon 2012). However, they are also commonly found feeding within 10 kilometers (km) of San Diego, oftentimes with blue whales (Smultea and Bacon 2012). Seasonal habitat-use models based on data from 67 tagged fin whales indicated year-round residency of fin whales in the SCB (Scales et al. 2017). Tracked fin whales used nearshore habitats along the mainland coast and in the northern Catalina Basin in fall and winter, then traveled to the offshore waters of the SCB and further north in spring and summer months (Scales et al. 2017).

1.1.2.1.3 Humpback Whale (*Megaptera novaeangliae*)

Along the U.S. west coast, one humpback whale stock is currently recognized, including two separate feeding groups: 1) a California and Oregon feeding group of humpback whales that belong to the Central American and Mexican distinct population segments (DPSs) defined under the ESA (81 FR 62259), and 2) a northern Washington and southern British Columbia feeding group that primarily includes whales from the Mexican DPS but also includes a small number of whales from the Hawaii and Central American DPSs (Wade et al. 2016). The National Marine Fisheries Service (NMFS) defines the California/Oregon/Washington stock as humpback whales that feed off the U.S. West Coast (**Table 1**; Carretta et al. 2018, 2020). The California/Oregon/Washington stock primarily includes whales from the endangered Central American DPS and the threatened Mexico DPS, plus a small number of whales from the non-listed Hawaii DPS. The California/Oregon/Washington stock is considered endangered and depleted for MMPA management purposes.

Humpback whales occur year-round off the California coast (Munger et al. 2009; Hildebrand et al. 2011; Campbell et al. 2015), with peak densities occurring in spring (Becker et al. 2017). One hypothesis is that both the California feeding population, and migrants traveling through California waters, are present in spring (Forney et al. 1995; Calambokidis et al. 1996; Becker et al. 2017). Humpbacks occur near the coast in summer, but further offshore in winter (Forney and Barlow 1998; Campbell et al. 2015).

1.1.2.2 ODONTOCETES

1.1.2.2.1 Sperm whale (*Physeter macrocephalus*)

The sperm whale is listed as endangered and depleted under the MMPA throughout its range, but there is no designated critical habitat for this species in the North Pacific (Carretta et al. 2018, 2020). Sperm whales that occur in SOCAL are from the California/Oregon/Washington stock (Carretta et al. 2018, 2020) and their range extends throughout the entire SOCAL area. Although sperm whales are found in the temperate and tropical waters of the Pacific (Rice 1989), their secondary range includes areas of higher latitudes in the northern part of the SOCAL area (Jefferson et al. 2015a). Sperm whales are found year-round off California and appear to have a preference for offshore deeper waters (Smultea and Jefferson 2014; Jefferson et al. 2015a) and, typically, concentrations correlate with areas of high productivity; however, these areas are generally near drop offs and areas with strong currents and steep topography (Jefferson et al. 2015a).

2. Methods

2.1 Glider Specifications

The Seaglider™ (cover photo) is a low-power, battery-operated AUV commercially available from Huntington Ingalls Industries (Lynnwood, Washington). It is buoyancy-driven and remotely operated. Small changes in the volume of an oil-filled bladder control the glider's buoyancy, while small movements in the internal battery mass alter the glider's pitch and roll, allowing forward propulsion and flight control. On-board sensors allow the glider to adjust its orientation mid-dive to move towards a programmed geographic coordinate (specified as latitude and longitude) waypoint or heading direction. The glider communicates with a shore-based pilot via Iridium™ satellite when it is at the surface, allowing the pilot to remotely control the glider's programmed path, dive depth, and speed. The glider collects basic oceanographic data – temperature and salinity – during each dive at a specified sample interval, typically every 5-10 seconds.

2.2 Acoustic System

The Passive Miniature Acoustic Recorder XL system (PMAR-XL, available from Huntington Ingalls Industries, the Seaglider manufacturer, Lynnwood, Washington) was integrated into two Seagliders (the abyssal [SG607] and the shelf glider [SG639]) and used to record acoustic data. Signals were received through a single HTI-92WB hydrophone that captured frequencies from 10 Hertz (Hz) to 90 kilohertz (kHz). The data acquisition system sampled 16-bit data at 180 kHz, allowing sound recording of frequencies up to approximately 85 kHz. System sensitivity of the PMAR-XL system was not available, but since spectrograms had a pre-whitening filter applied as a step of laboratory analysis, the overall system sensitivity was not critical. A low-pass anti-aliasing filter is applied by the PMAR-XL system and the filter cutoff value can be set by the user. The 512 GB storage capacity allowed for up to 776[1] hours of recordings. Both gliders were programmed to use a duty cycle of recording a single 10-minute file every 15 minutes, to ensure acoustic recordings could be made throughout the survey area. When the glider entered apogee (end of descending portion of a dive cycle when glider reached programmed target depth) or surface maneuver (end of ascending portion of a dive cycle at water surface) recording was stopped automatically, sometimes resulting in file durations less than 10 minutes. Recordings were programmed to be made at all possible glider depths, as testing by the manufacturer showed the programmable feature to limit recordings to certain glider depths was not reliable at the time of deployment.

[1] The storage capacity of the PMAR-XL system was originally estimated to be 388 hours, but during the glider testing phase larger memory cards were installed which doubled this capacity.

2.3 Field Operations

The abyssal and shelf gliders were planned to be deployed in the San Nicolas Basin just north of SCORE during early February 2020, dependent on weather conditions, from the motor vessel (*M/V) Magician*. The captain of the *Magician*, Carl Mayhugh, had final call on acceptable weather conditions. The abyssal glider was designated as the “offshore” glider and was programmed to survey over the abyssal plain offshore of the continental shelf break (**Figure 2 –** yellow track). The shelf glider was designated as the “inshore” glider and was programmed to conduct several transects inshore of shelf break in water depths shallower than 2,500 m (**Figure 2 –** orange track). Both planned tracks were approximately 800 km in length and planned for 6 weeks of survey time. For the first two days of the survey both gliders were planned to remain relatively close to one another and survey in the vicinity of two HARPs deployed within SCORE and just west of SCORE’s northern edge (**Figure 2** - black circles H and E; **Figure 3 –** WPo2 and WPo3; **Figure 4 –** WPi01 and WPi02).

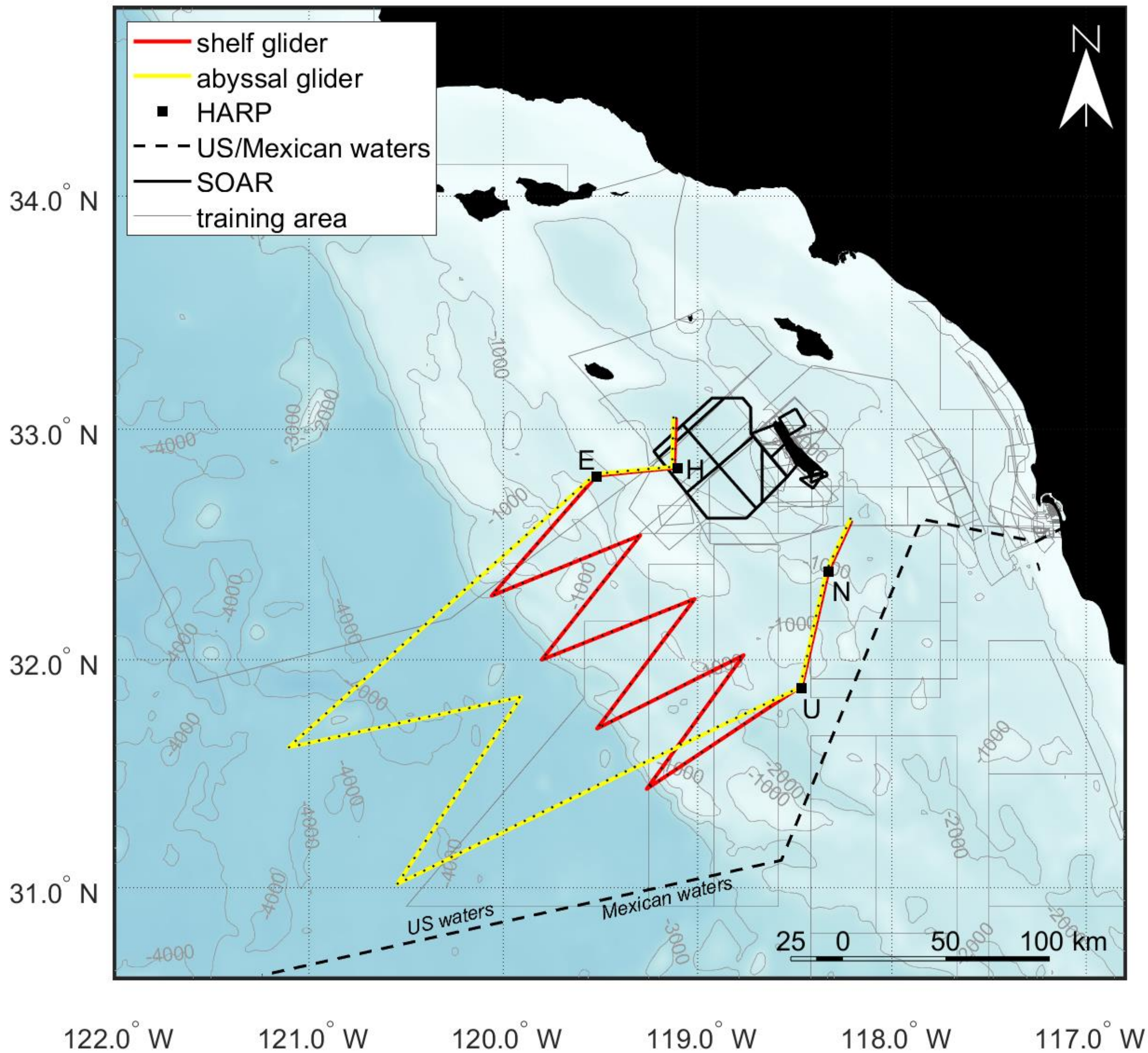

Figure 2. Proposed glider tracks for the abyssal glider (yellow line) and shelf glider (red line) for the winter 2020 deployment. Small black dots along trackline are 5 km apart. HARPs are shown as black squares and are labeled by a letter identifier. The black lines around HARP H delineate the U.S. Navy's Southern California Offshore Range (SCORE).

Note: Each track is ~800 km and covers the survey area in about 6 weeks. Border between U.S. and Mexican waters is approximate. Bathymetry data is from Amante and Eakins (2009).

After reaching the HARP E (**Figure 2**) early on 11 February 2020, the abyssal glider continued west-southwest offshore for approximately 200 km, then traveled east towards the shelf break for 110 km, navigated west-southwest back offshore for 110 km, and then transited back to the northeast towards the shelf break and inshore waters (**Figure 3**). After reaching the shelf edge, we assessed the remaining recording space and battery available and added an additional two turns to the planned track to survey more of the shelf edge waters (**Figure 3** – WPx1 and WPx2). The abyssal glider navigated in the vicinity HARPs U and N south of SCORE (**Figure 3** – WPo7 and WPHN) before available recording storage was filled on 27 March 2020. Following communications with researchers at the Scripps Institution of Oceanography, we discovered that HARP N had been recovered and redeployed in a different location (moved to the west, see **Figures 3** and **4** compared to **Figure 2**). We then updated its position in our maps and adjusted the path of the glider to fly directly over the new location (WPHN). The abyssal glider then was flown towards Santa Catalina Island for recovery on 31 March 2020.

The shelf glider reached WPi03 and the area of HARP E late on 10 February 2020 (**Figure 4**). Shortly after, it stopped recording acoustic files. We worked with the manufacturer to troubleshoot the PMAR-XL system remotely, but we were not able to get the system recording properly. The manufacturer suspected there might be a seawater leak and suggested recovering the shelf glider to avoid total loss of the glider. The shelf glider was put into recovery mode on 12 February 2020 at 23:58 Coordinated Universal Time (UTC) and held at the surface west of WPi03 while an emergency recovery was planned. The shelf glider was recovered in the morning on 14 February 2020 and sent to the manufacturer for diagnostics and repair. The reason was later discovered to be a failed filtering capacitor for one of the hydrophones. The capacitors are rated to a maximum of 10 volts direct current (vdc), and the PMAR was integrated into a 15vdc glider without voltage regulation in place.

2.4 Data Analysis

After recovery of the data, an initial Long-Term Spectral Average (LTSA) was calculated in Triton[2] (Wiggins et al. 2010) for the full-bandwidth data using a time average of 5 seconds and a frequency resolution of 100 Hz. The LTSAs were coarsely screened visually by an analyst for quality assurance (QA) and the data were downsampled into two low-frequency datasets sampled at 1 kHz (with frequencies below 0.5 kHz) and 5 kHz (with frequencies below 2.5 kHz) for further analyses. Automated detectors were run on the downsampled datasets to detect calls from several baleen whale species and sperm whales as outlined below.

Blue whale. Blue whale B calls (Thompson and Freidl 1982) were detected in Ishmael 3.0 (Mellinger et al. 2018) using a spectrogram correlation detector (Mellinger and Clark 2000) applied to the 1 kHz downsampled data. B calls were chosen because they are the most numerous type of call, with A calls always succeeded by B calls but not vice versa, and D calls associated with foraging but not other contexts (Oleson et al. 2007). The detection kernel was made by measuring a number of example calls and averaging the durations and upper and lower frequencies. The contour width was 2 Hz, a value that has been found effective for blue whale calls in the past (Mellinger et al. 2004a). The specifications for the kernel are shown in **Appendix A**. All detections were manually checked by an experienced analyst to ensure there were no false positives. Checking was done using the “CheckDetections” system in MATLAB (Mellinger et al. 2010), which shows each detection with identical time and frequency scaling and allows the user to indicate whether the detection was correct or not.

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[2] http://cetus.ucsd.edu/technologies_Software.html

Fin whale. Fin whale 20-Hz pulses (Watkins et al. 1987) were detected in Ishmael 3.0 using a spectrogram correlation detector applied to the 1 kHz downsampled data. The detection kernel was made slightly differently from the blue whale detector using the "average-slope, max-frequency-span" method: first the start-frequency, end-frequency, and duration of a number of example pulses were measured in time-frequency space. This allowed us to compute the average *slope* of a fin whale pulse. The kernel was then constructed to start at the highest frequency measured and end at the lowest, and to have the same slope as the average. This method was used because fin whale pulses in a given geographic area (like SOCAL) in a given year can have different frequency spans – they appear at different vertical positions in a spectrogram – but tend to have similar slopes, and a given pulse anywhere in the frequency range of the kernel will intersect the kernel over at least part of the kernel's span and thus trigger a detection. The specifications for the kernel, which has a contour width of 4 Hz, is shown in **Appendix B**; also, in that appendix is the MATLAB code used to construct the kernel as well as the details of the detector configuration. Detections were manually checked by an experienced analyst using CheckDetections. Because fin whale pulses were so numerous, not all detections were checked. Instead, detections were checked in 10-minute bins, such that the quantity measured was whether or not fin whale(s) were present in each 10-minute bin. This meant that as soon as a fin whale pulse was found in a given 10-minute bin, that bin was marked as detection-positive and the analyst could proceed to the following 10-minute bin instead of having to check all the remaining detections in that bin. The 10-minute bins were time-aligned to the start on the hour.

Humpback whale. Humpback whales were detected manually in LTSA (Wiggins and Hildebrand 2007) plots using Triton. Detection was initially performed using a generalized power law detector (Helble et al. 2012), but it was found to detect too many glider self-noise signals – hundreds of thousands of them – and it was impractical to check them. An LTSA was created from the 5 kHz downsampled data with a time average of 5 seconds and frequency resolution of 2 Hz. The LTSA was manually browsed using a 30-minute window size. Start and end times of bouts of humpback sounds were logged using the Triton Logger Remora and were graded from 1 (faint, sparse humpback vocalizations) to 5 (clear and numerous humpback vocalizations); **Appendix F** shows examples of some of the grades for reference. Logged bouts of calls were then converted to presence or absence per 1-hour bin for temporal and spatial assessment.

Minke whale. Minke whale boing sounds (Wenz 1964; Thompson and Freidl 1982) were detected in the data sampled at 5 kHz using Ishmael 3.0 with a spectrogram correlation detector. The kernel for this detector was designed using example minke "boing" sounds recorded in the same geographic region (specifically, Catalina Basin) in 2016. This detector, which is detailed in **Appendix D**, was designed to detect the long, constant-frequency tail of a boing sound since this part of the call has a lot of sound energy; this meant it could also detect other constant-frequency sounds in the same frequency range, such as vessel propeller noise. Checking was done using Ishmael, which was configured to display each detected call and allow the user to quickly specify whether the detection was correct or not. Ishmael was used here instead of CheckDetections because of the large number of detections; Ishmael allows less flexibility for the user in examining the time surrounding a given detection, but it's faster in moving from one detection to the next.

Sperm whale. Sperm whale regular clicks (Backus and Schevill 1966) were detected in the data sampled at 5 kHz in Ishmael 3.0 using an energy ratio followed by a sequence detector. The energy ratio was calculated, at each time step in a spectrogram, using the average spectrogram value from 1,600-2,200 Hz divided by the average value from 40-80 Hz. Using this ratio prevents loud noises (thumps, glider noises, etc.) that span the entire range of recording (approx. 10 Hz-2.5 kHz) from triggering detections; the 40-80 Hz “guard band” is below nearly all sperm whale click energy. This energy ratio calculation results in a number for each spectrogram time step, and the resulting time series is input into a system for finding *click sequences*: regularly-repeating sounds with a specified repetition rate (Mellinger et al. 2004b). Here, a time-windowed (with a 10-s window) autocorrelation was used to detect sequences with repetition rates in the range 0.3-1.5 seconds. Details of this detector are in **Appendix E**. This method has been very effective at detecting odontocete clicks in noise, even at noise levels that make it difficult for humans to detect the clicks. Detections were checked using Ishmael because of the large number of detections.

3. Results

3.1 Mission Summary

The abyssal and shelf gliders were deployed in the San Nicolas Basin just north of SCORE on 7 February 2020 at approximately 15:00 UTC. For the first two days of the survey both gliders remained close to one another, as planned, near the two HARPs in and near SCORE (**Figure 3** – WPo2 and WPo3; **Figure 4** – WPi01 and WPi02).

The abyssal glider surveyed for the entire planned deployment. It followed the programmed track successfully and travelled 940 km (**Figure 3**). The initial flight plan was followed closely, but was adjusted slightly to steer around shallow areas (i.e., fly between Cherry Bank and Tanner Bank, Figure 3 WPTB and avoid Sixtymile Bank east of WPx3). The abyssal glider recorded 763 hours of acoustic data as 4,721 sound files on a duty cycle recording 10-minute files every 15 minutes. A total of 314 files shorter than 10 minutes were recorded because of the automatic shut-off of the recording system at apogee or the surface. On 27 February 2020, at 1848 UTC, a single large file (87 minutes duration) was recorded. The reason why this single larger file occurred is not known. On 3 March 2020, recording stopped for approximately 4 hours when the first of two secure digital (SD) cards filled up halfway through Dive 116. Recording resumed on the second SD card at the start of Dive 117.

The shelf glider surveyed successfully for 87 hours and traveled 95 km (**Figure 4**) before experiencing an issue with the PMAR-XL system. It recorded 55 hours of acoustic data in 351 files with the same duty cycle as the abyssal glider. A total of 32 of the files were shorter than 10 minutes. We worked with the manufacturer’s staff to troubleshoot the PMAR-XL system remotely, but we were not able to get the system recording properly. The manufacturer suspected there might be a seawater leak and suggested recovering the shelf glider to avoid total loss of the glider. The shelf glider was put into recovery mode on 12 February 2020 at 23:58 UTC and held at the surface while an emergency recovery was planned. The shelf glider was recovered (D. Mellinger and the captain and crew of the *Magician*) on the morning on 14 February 2020 and sent to the manufacturer for diagnostics and repair (Mellinger et al. 2021). The SD cards containing the data were removed and sent to the OSU laboratory in Newport, Oregon.

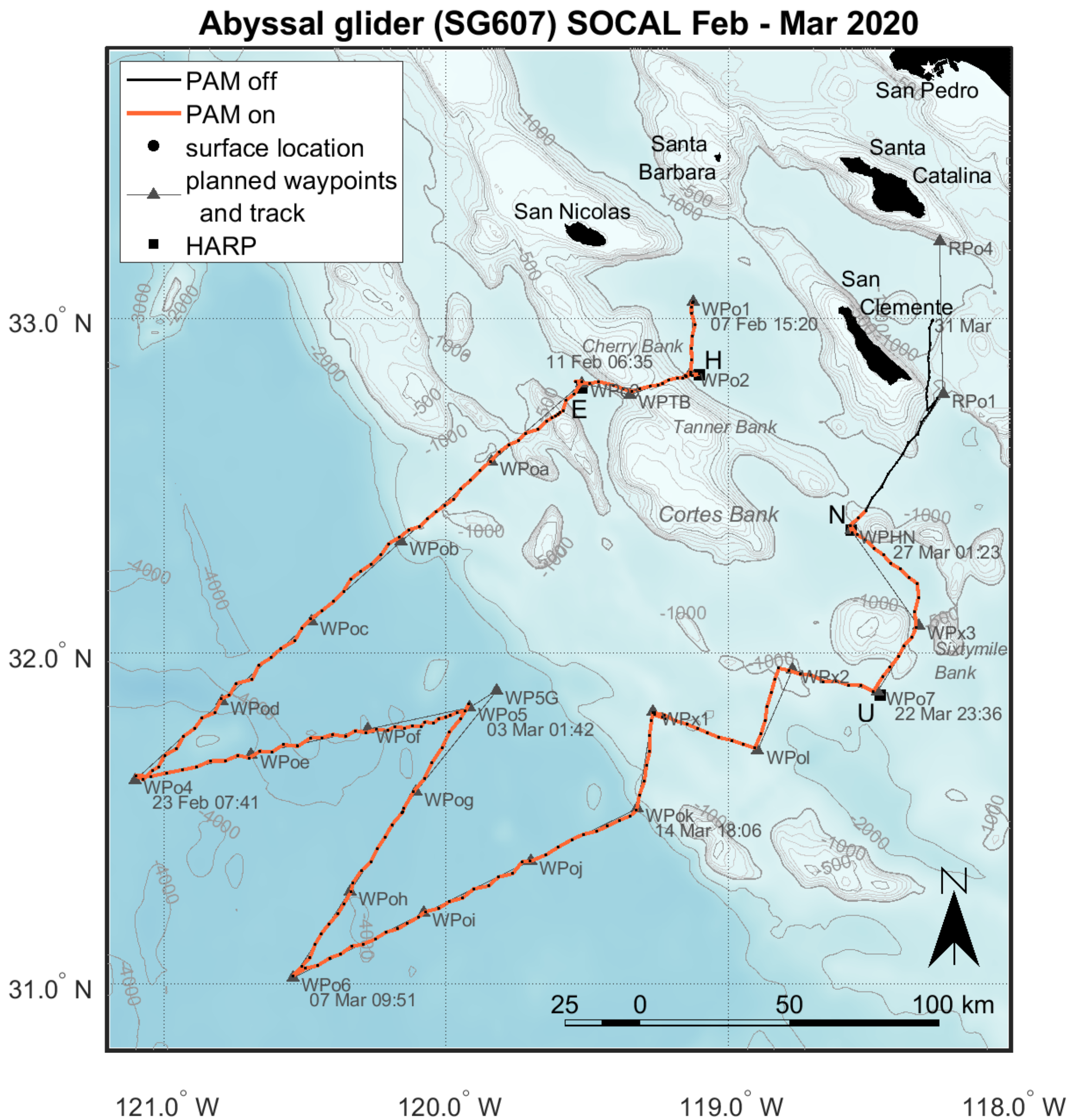

Figure 3. Map of abyssal glider (SG607) survey trackline. Orange line is glider position, using straight line interpolation between global positioning system (GPS) surface positions (black dots). HARPs are shown as black squares and are labeled with a letter identifier.

Note: The planned track is shown as a thin gray line, often hidden by the orange glider track, and specified waypoints are marked as gray triangles and labeled (e.g., WPo1, RPo4). A selection of waypoints is labeled with the date and time the glider reached that waypoint. Bathymetry data is from Amante and Eakins (2009).

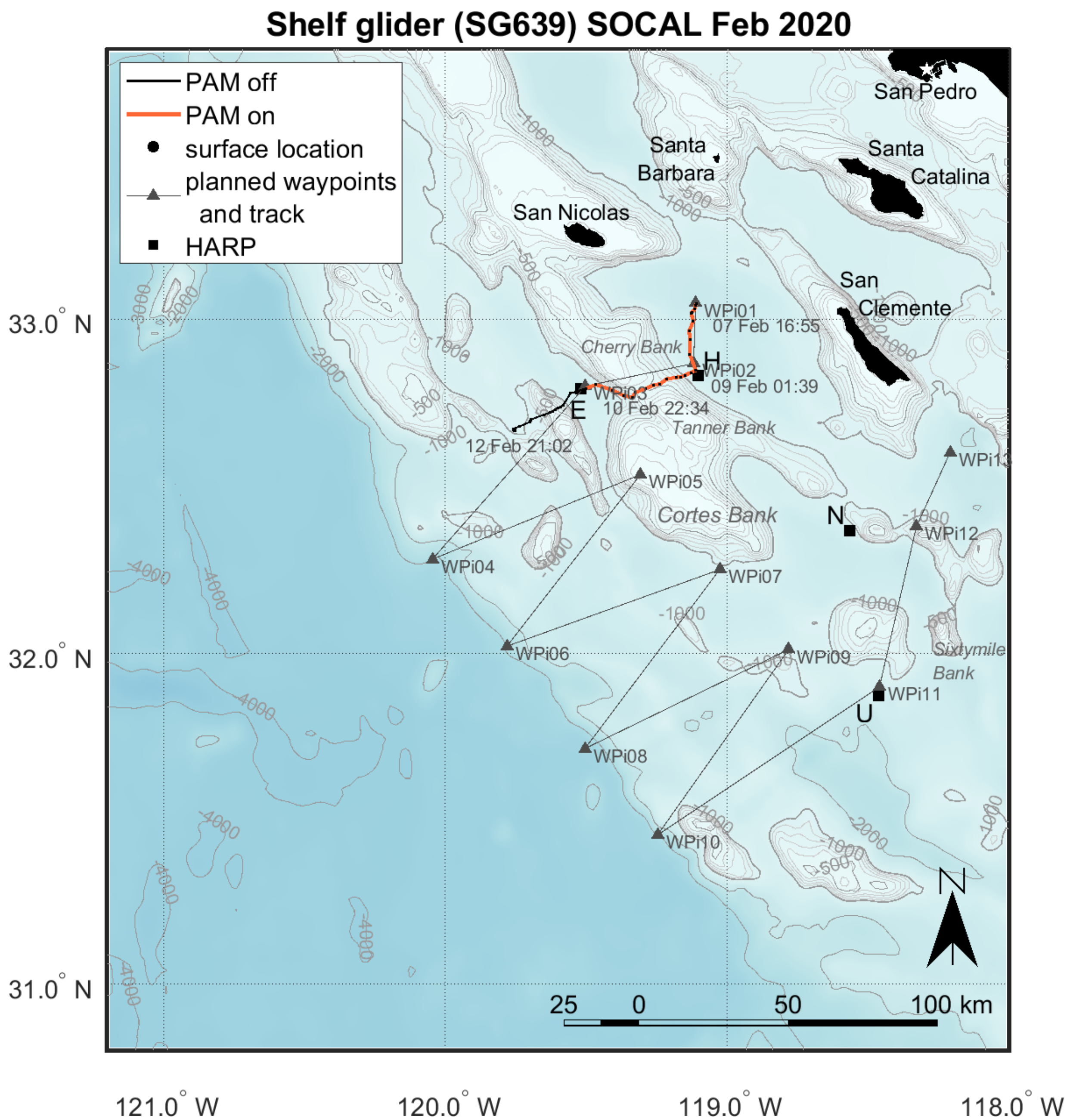

Figure 4. Map of shelf glider (SG639) survey trackline. Orange line is glider position, using straight line interpolation between global positioning system (GPS) surface positions (black dots). HARPs are shown as black squares and are labeled with a letter identifier.

Note: The planned track is shown as a thin gray line and specified waypoints are marked as gray triangles and labeled (e.g., WPi01). A selection of waypoints is labeled with the date and time the glider reached that waypoint. Bathymetry data is from Amante and Eakins (2009).

Oceanographic data was collected by both gliders every 5 seconds at depths from 0 to 50 m and every 10 seconds at depths below 50 m. Resulting plots can be found in **Appendix G** (sound speed) and **Appendix H** (temperature, salinity, and density).

After offshore glider recovery (by K. Ampela and the captain and crew of the *Magician*) and shipment to the OSU lab in Newport, Oregon, the glider was opened and the SD cards containing the data were extracted and the data converted to WAVE (.wav) files.

Shortly afterward a problem with the PMAR-XL anti-aliasing filter was observed: there was no usable energy available above about 2.5 kHz. The acoustic systems' low-pass filter corner frequency was set to 80 kHz, but after recovery it was discovered that this is an invalid input setting, and therefore the PMAR-XL defaulted to a cutoff of 2 kHz. This limited the useable data to 2.5 kHz and below. (Note that the filter starts to attenuate sound above this frequency, but because of gradual filter roll-off some sound energy still comes through at nearby frequencies above the cutoff.) The maximum valid cutoff frequency setting is 60 kHz, which results in data capture up to approximately 90 kHz. The 60 kHz filter setting will be used in any future deployments so as to capture sounds of beaked whales.

The data were then downsampled as described above and analyzed for sounds of baleen whales and sperm whales.

3.2 Blue Whales

A total of 84 automated detections of blue whale B calls (**Figure 5**) were made from the abyssal glider's recordings on three separate days (**Figure 6**). Upon checking, 83 (99%) were found to be correct. These were recorded by the abyssal glider on three separate days (9 one-hour bins containing calls, 83 total detections). See **Figure 7** for locations of the abyssal glider when blue whales were detected. Most of the detections occurred on 11 February 2020 from to 08:55 to 17:32 UTC. Additional calls were detected on 15 February 2020 at 08:51 UTC and 26 March 2020 at 18:26 UTC. Automatic detection on the shelf glider's recordings found 60 candidate detections, of which none (0) were blue whale calls. A type of glider noise on the shelf glider triggered most of the false detections[3].

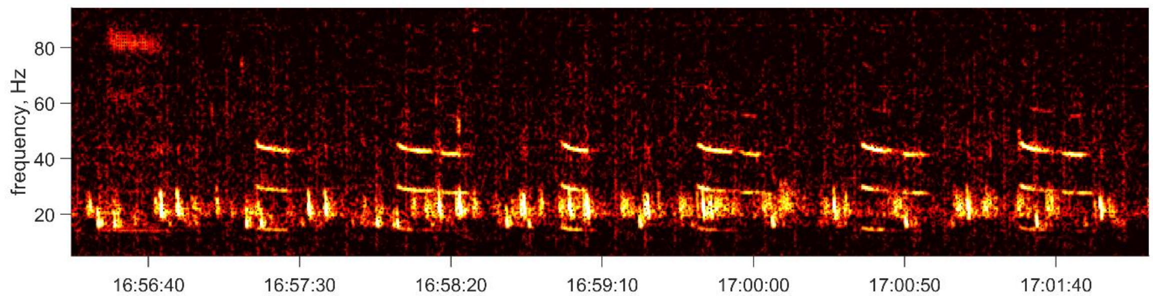

Figure 5. Example blue whale A call (~80 Hz at 16:56:40) followed by six B calls (16-to-14 Hz contours, with evenly-spaced harmonics at 2-4 times the frequency) detected on the abyssal glider on 11 February 2020 around 17:00 UTC. Fin whale calls are also apparent in the 15-30 Hz band. (Spectrogram parameters: frame and Fast Fourier Transform (FFT) size 1.64 s, 75% overlap, Hamming window).

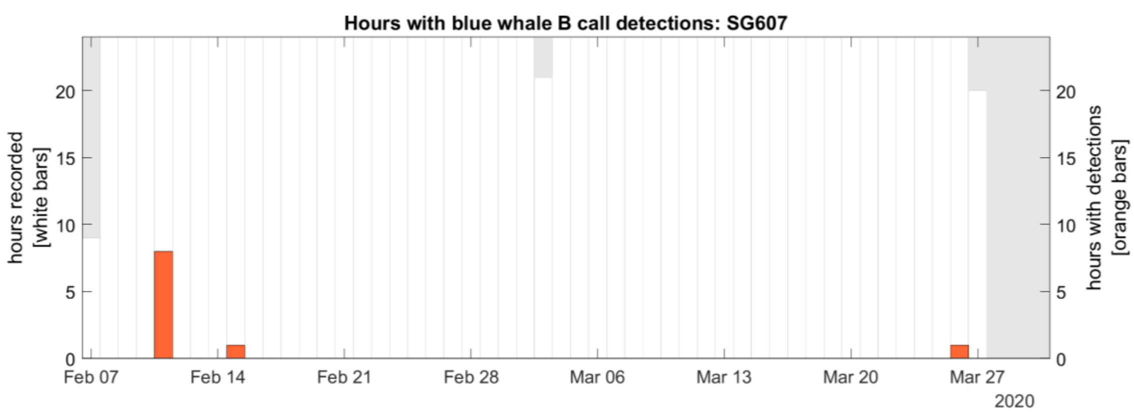

Figure 6. Number of hours per day containing detections of blue whale B calls on the abyssal glider. Gray background indicates a period of no data.

[3] This noise was related to the glider malfunction and therefore should not recur on future deployments.

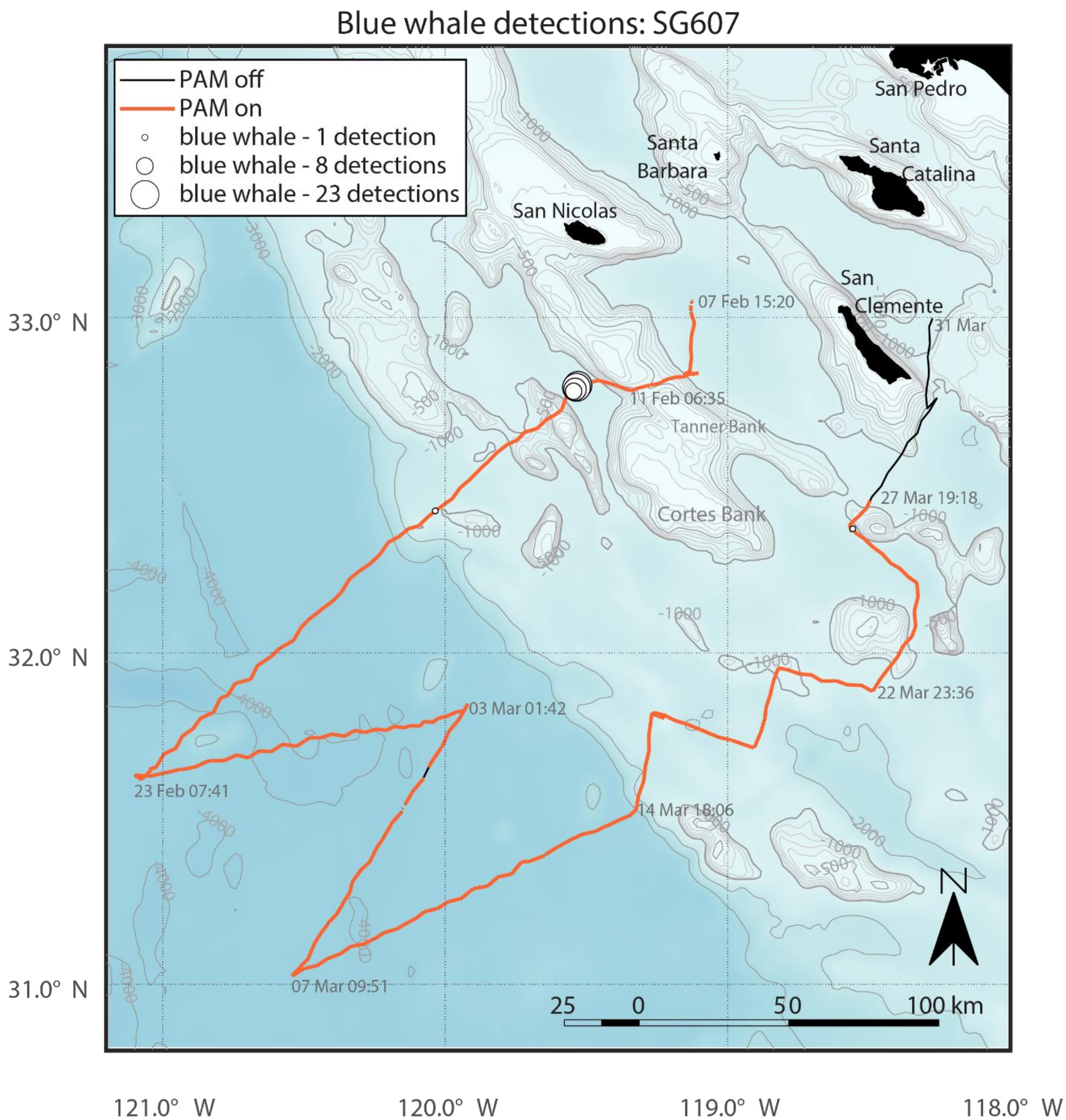

Figure 7. Track of abyssal glider (SG607) (orange when recording system was on) and locations of blue whale detections (white circles), with circle size scaled to the number of detections.

3.3 Fin Whales

At total of 40,314 fin whale pulse vocalizations (**Figure 8**) were automatically detected on the abyssal glider and 5,847 on the shelf glider. As explained in the Methods section (**Section 2**), not all detections were checked, only those in each 10-minute bin up to the first true-positive detection. Fin whale vocalizations occurred in 952 hours (across 50 days) of the abyssal glider's deployment and 87 hours (across 5 days) of the shelf glider's deployment. Fin whales were found on every day of both glider deployments, and on several days they were present 100% of the time periods (**Figure 9, Figure 10**). **Figure 11** shows the locations of the abyssal glider when fin whale calls were detected and **Figure 12** shows the locations of the shelf glider when fin whale calls were detected.

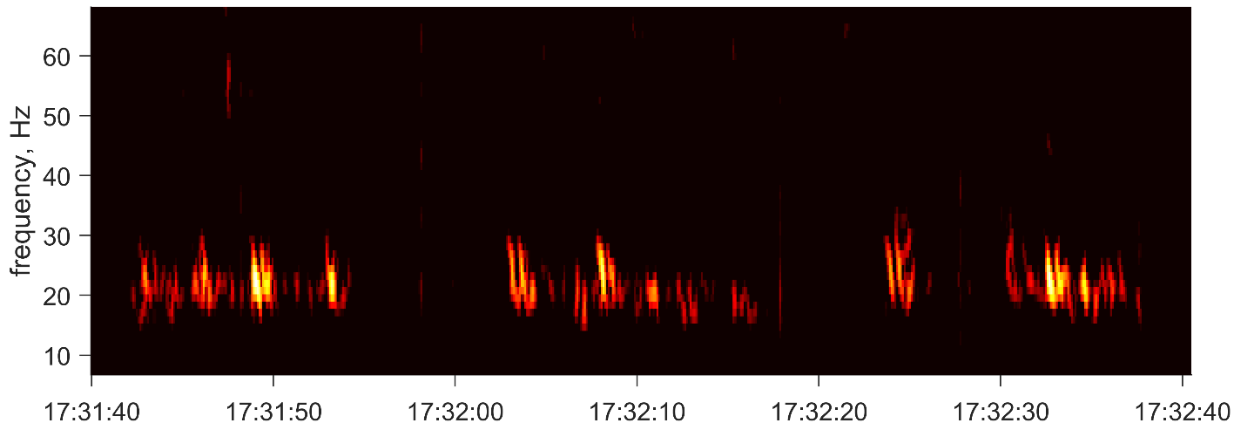

Figure 8. Example pulses from several fin whales recorded on 8 February 2020 on the abyssal glider. (Spectrogram parameters: frame length 0.41 s, FFT size 0.82 s, overlap 75%, Hamming window)

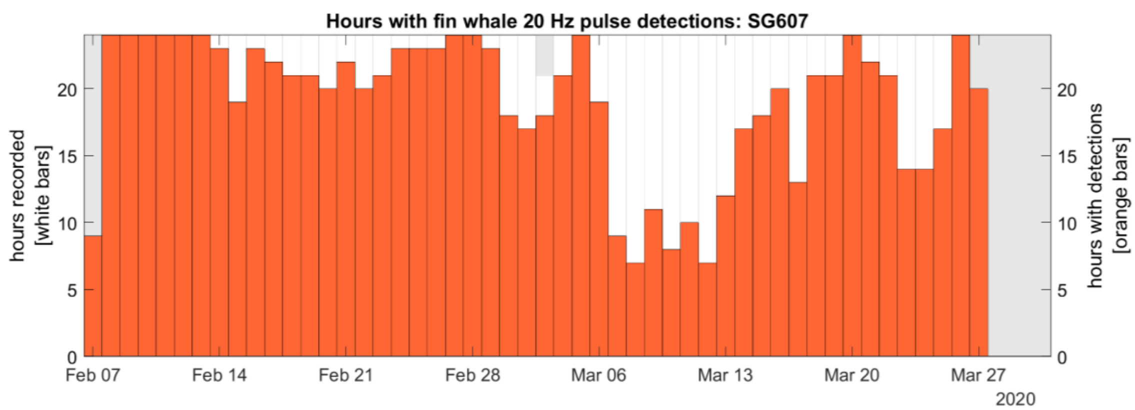

Figure 9. Number of hours per day containing detections of fin whales on the abyssal glider (SG607). Gray background indicates a period of no data.

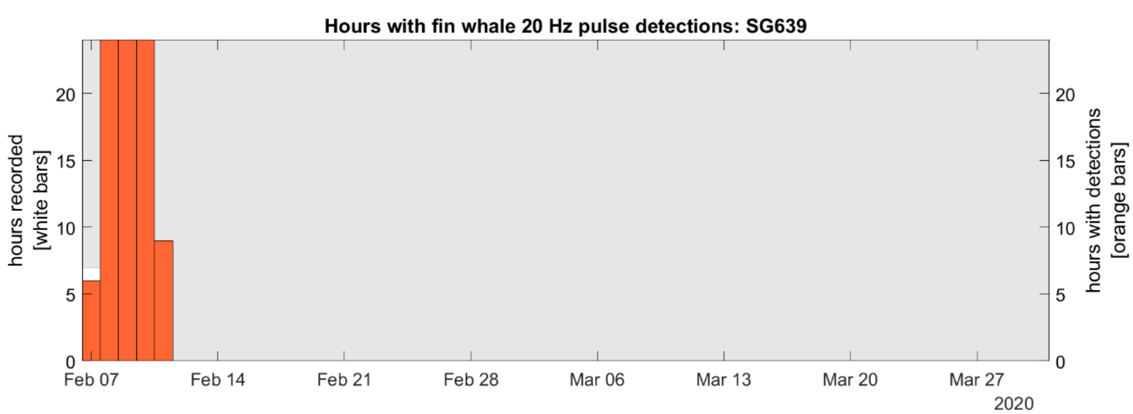

Figure 10. Number of hours per day containing detections of fin whales on the shelf glider (SG639). Gray background indicates a period of no data.

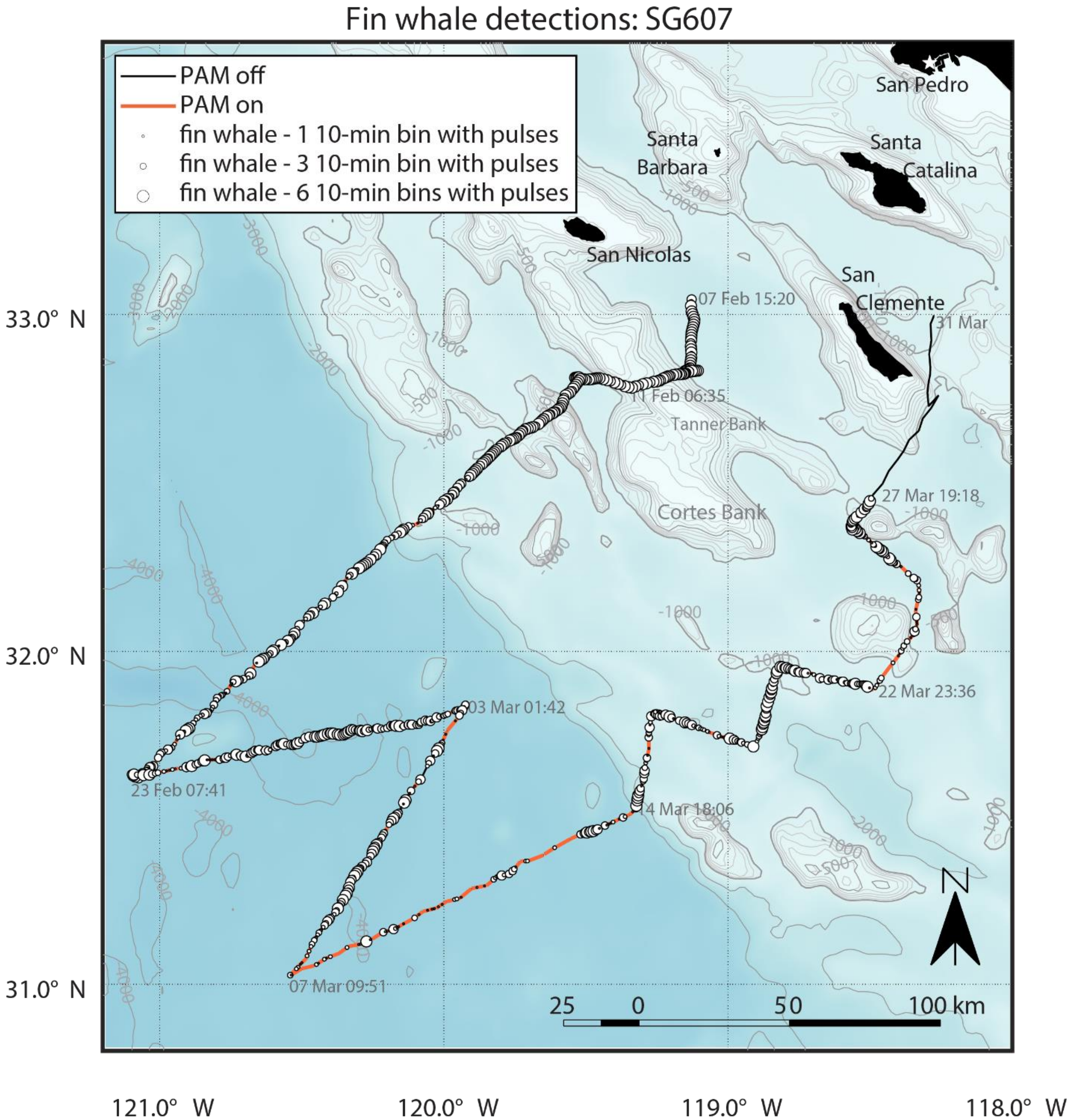

Figure 11. Abyssal glider (SG607) track (orange when recording system was on) and locations of the glider when fin whale detections were present (white circles). Circle size is scaled to the number of 10-minute (min) periods per hour with detections.

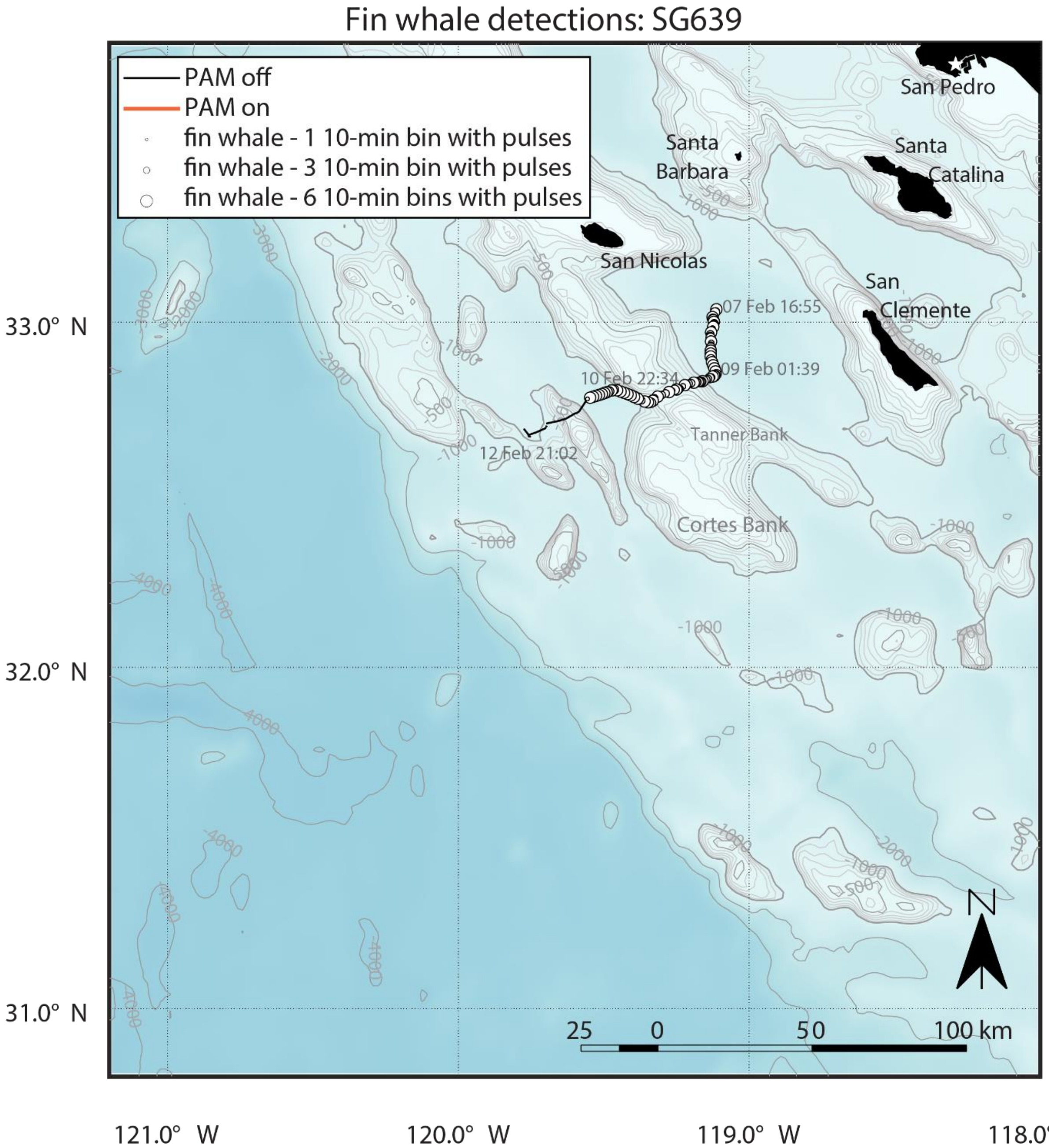

Figure 12. Shelf glider (SG639) track (orange when recording system was on) and locations of the glider when fin whale detections were present (white circles). Circle size is scaled to the number of 10-minute (min) periods per hour with detections.

3.4 Humpback Whales

Humpback whale sounds (**Figure 13**) were manually detected in LTSAs on 48 of the 50 days of the abyssal glider's deployment, a total of 625 hours with vocalizations, and on some days in nearly all hours (**Figure 14** and **Figure 16**). Locations of humpback whale detections as recorded by the abyssal glider are shown in **Figure 16**. For the shelf glider, humpback whales were found on all five days of recording, in 38 hours (**Figure 15** and **Figure 17**).

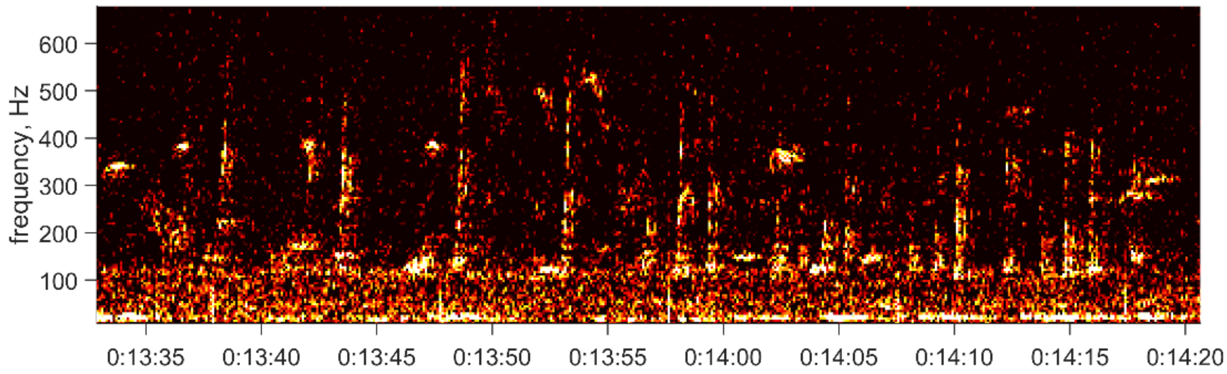

Figure 13. Humpback whale song recorded on 14 February 2020 by the abyssal glider. (Spectrogram parameters: frame and FFT size 0.20 s, 50% overlap, Hamming window)

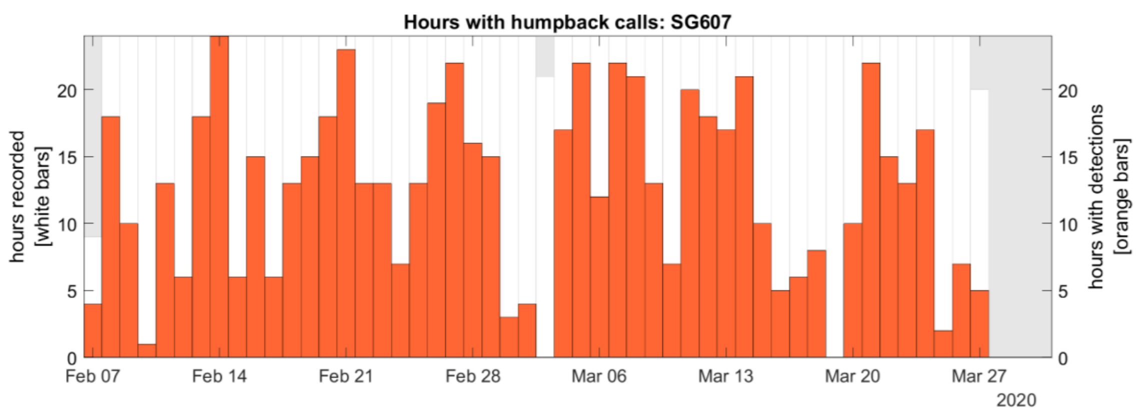

Figure 14. Number of hours per day with detections of humpback whales on the abyssal glider (SG607). Gray background indicates a period of no data.

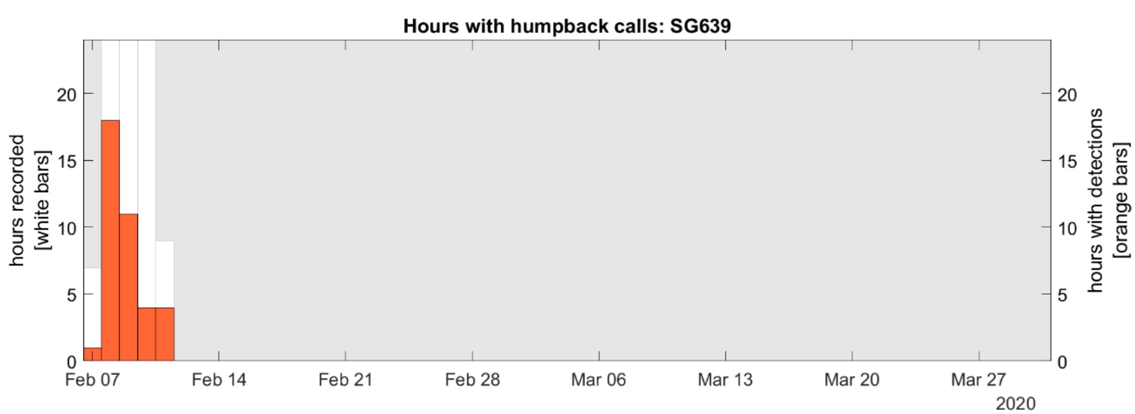

Figure 15. Number of hours per day with detections of humpback whales on the shelf glider (SG639). Gray background indicates a period of no data.

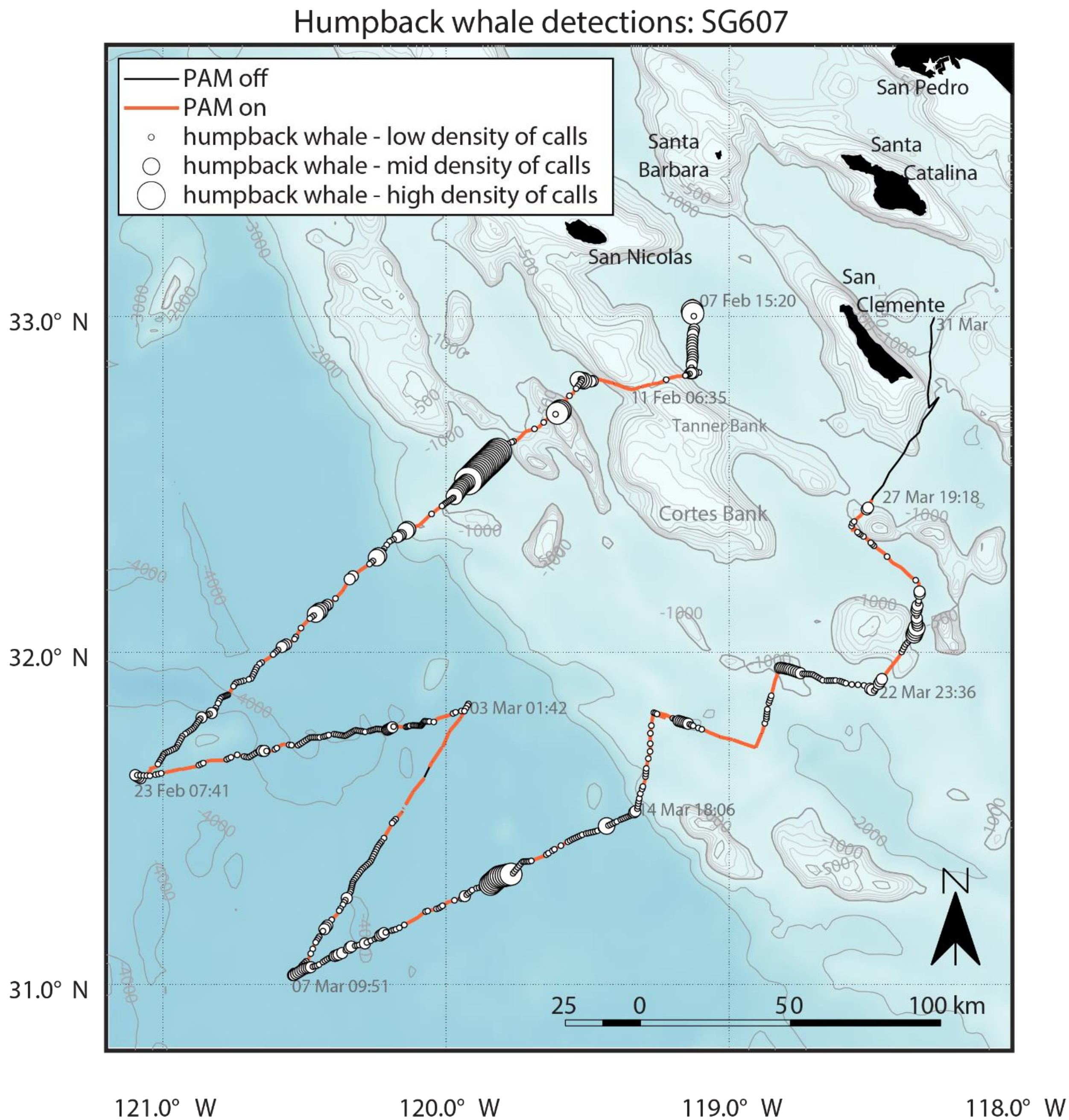

Figure 16. Abyssal glider (SG607) track (orange when recording system was on) and locations of the glider when humpback whale sounds were present (white circles). Circle size is scaled to the estimated density of detections (qualitative score from 1 to 5; see Section 2.4 and Appendix F).

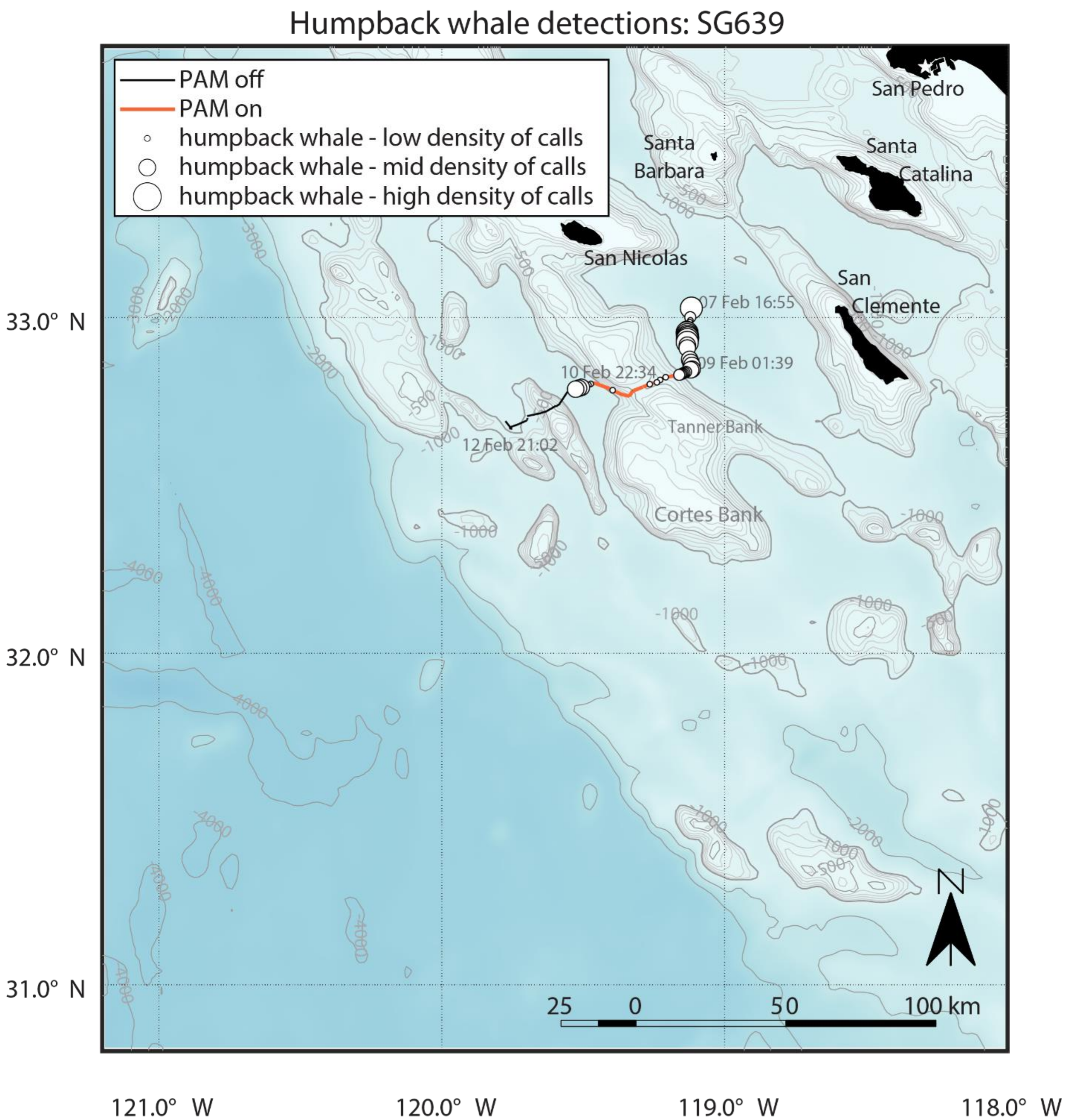

Figure 17. Shelf glider (SG639) track (orange when recording system was on) and locations of the glider when humpback whale sounds were present (white circles). Circle size is scaled to the estimated density of detections (qualitative score from 1 to 5; see Section 2.4 and Appendix F).

3.5 Minke Whales

The detector found a total of 7,426 candidate minke whale boings on the abyssal glider's recordings and 743 candidate boings on the shelf glider's recordings. The detection threshold was set deliberately low so as to not miss any minke whale boings. These were manually checked by an experienced analyst, and all of them were false detections – i.e., none were minke whale vocalizations. An example of an incorrect minke “boing” sounds detection is shown in **Figure 18.** An example of an incorrect minke ‘boing’ sound detection from 27 March 2020; this appears to be a glider steering motor sound. (Spectrogram parameters: frame and FFT size 0.10 s, 50% overlap, Hamming window). Glider self-noise was responsible for nearly all of the false detections, which occurred at a rate of 10.0 per hour; although Seagliders are very quiet platforms in general, they occasionally require operating motors for steering.

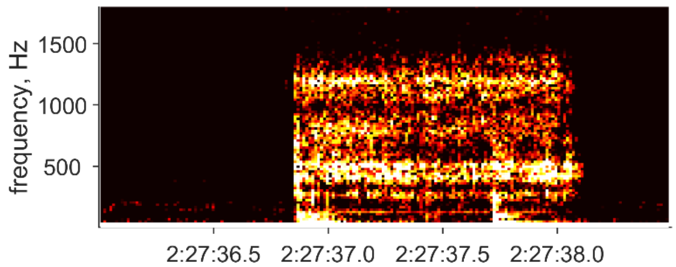

Figure 18. An example of an incorrect minke ‘boing’ sound detection from 27 March 2020; this appears to be a glider steering motor sound. (Spectrogram parameters: frame and FFT size 0.10 s, 50% overlap, Hamming window)

3.6 Sperm Whales

In the abyssal glider’s recordings, candidate detections of sperm whale click sequences (**Figure 19**) were made on 1,432 occasions; manual checking revealed that 165 of them (12%), in 31 hours on 12 days (**Figure 20**), were true sperm whale sounds.

On the shelf glider, sperm whales were detected on 539 occasions, of which none (0) were actual sperm whale sounds. The primary cause of false detections was glider self-noise. **Figure 21** shows the locations of sperm whale detections.

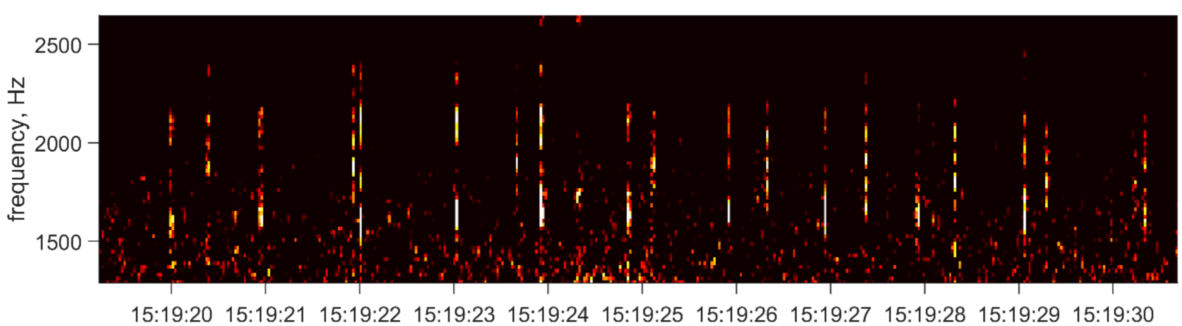

Figure 19. Sperm whale clicks from at least two whales recorded on 26 February 2020. (Spectrogram parameters: frame and FFT size 0.051 s, 50% overlap, Hamming window)

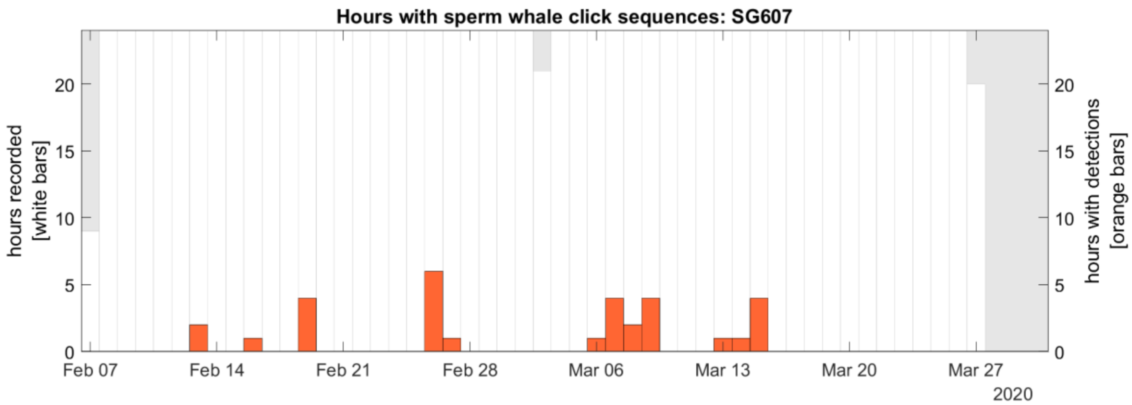

Figure 20. Number of hours per day with detections of sperm whale click sequences on the abyssal glider (SG607). Gray background indicates a period of no data.

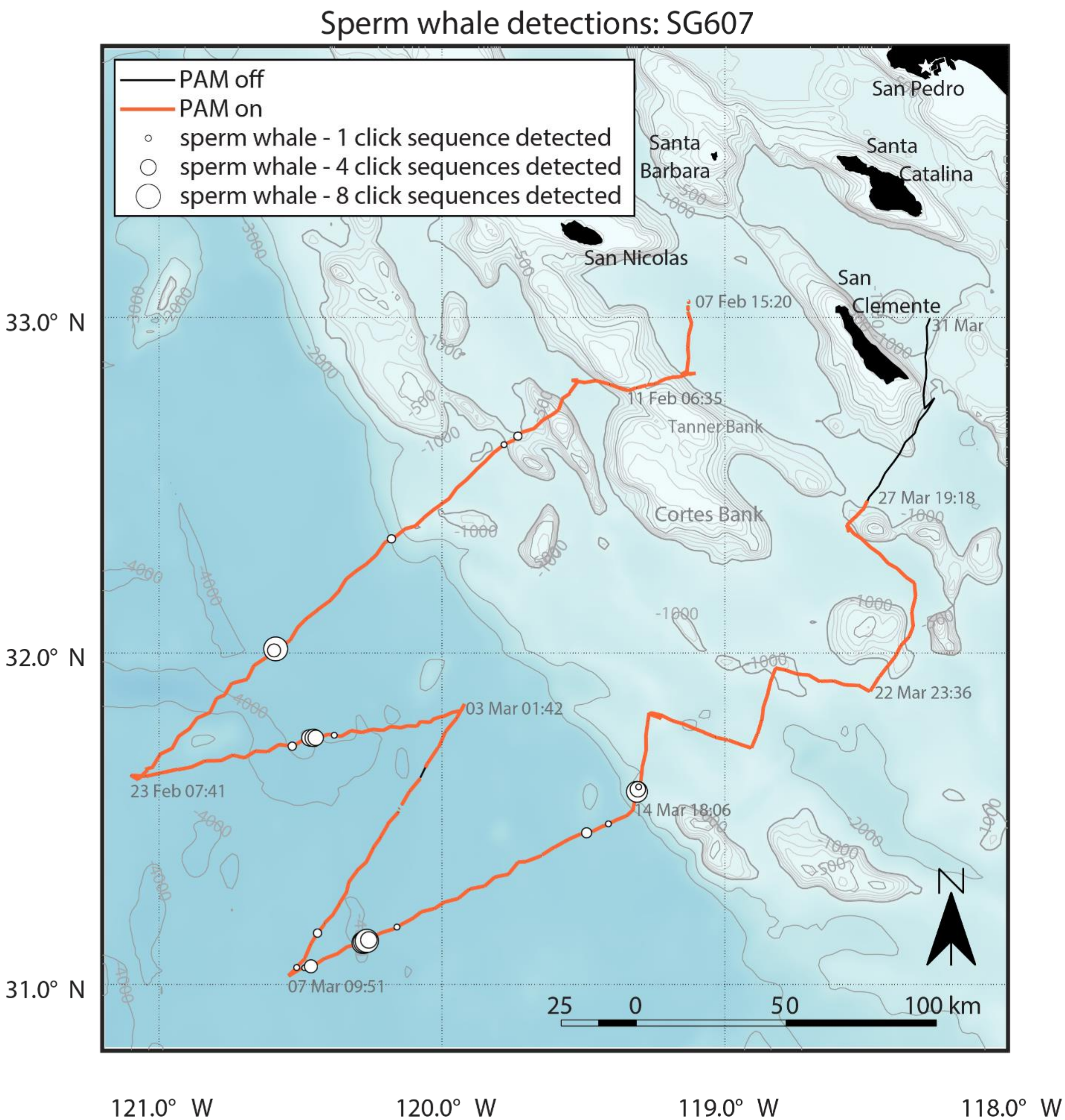

Figure 21. Abyssal glider (SG607) track (orange when recording system was on) and locations of the glider when sperm whale click sequences were present (white circles; see Section 2.4 Data Analysis for what was defined as a sequence). Circle size is scaled to the number of click sequences detected per hour bin.

4. Discussion

The area of the shelf slope and abyssal plain is monitored for marine mammals relatively infrequently, so the results from this study are particularly pertinent. Inshore of the shelf edge, long-term acoustic monitoring has been conducted at a few sites around SCORE (e.g., Baumann-Pickering et al. 2018).

The detection distances of the whale species here are affected by sound propagation, which in turn is heavily dependent on the sound speed profile (SSP). **Appendix G** shows a typical SSP during February made using measurements by the abyssal glider. This SSP reveals that the conjugate depth is approximately 3,300 m, implying that anytime the glider was in water deeper than 3,300 m, sound propagation from a whale to the glider was relatively unimpeded. Although detection distances are not known with any exactitude, they are likely at least several tens of km for baleen whales and possibly 10 km for sperm whales. This was observed in other work with acoustic Seagliders using a different recording system (Fregosi 2020, Fregosi et al. 2020).

In this study, blue whales were recorded in February and March, and only when the glider was on the continental shelf, among the basins and banks found off SOCAL. This is consistent with recent tagging studies where blue whales were tracked off SOCAL during the winter months (December through February) (Mate et al. 2018a). Blue whale calls have been detected on HARPs summer through winter, with a peak in November, and only a few detections in early winter (Baumann-Pickering et al. 2018). Most of these detections were at Sites N and H (north of Tanner Bank and south of San Clemente). HARPS have recorded very few blue whale detections from February to May (Rice et al. 2019). Sightings of blue whales in winter are similarly rare, with only two sightings during CalCOFI cruises from 2012 to 2019 (Debich et al. 2017; Trickey et al. 2020), and the lowest estimated density of this species is during winter and spring (Campbell et al. 2015).

Fin whales were detected throughout the paths of both gliders, on every survey day. This is in contrast to results from visual surveys. The majority of fin whale sightings on recent CalCOFI cruises (2016-2019) occurred in summer, with only a single winter sighting (Hildebrand et al. 2018; Trickey et al. 2020). Density estimates from CalCOFI surveys estimate lowest fin whale densities in the winter months (Campbell et al. 2015). The low number of visual sightings in winter is not necessarily surprising because weather conditions are often poor and make visual surveys more difficult. On the other hand, fin whale 20-Hz pulses are produced most commonly during the breeding season in the winter months (Watkins et al. 1987). These differences make it challenging to compare visual and acoustic data. It would be valuable to perform an acoustic survey in summer and compare the results to CalCOFI data from this period when more visual observations are recorded. This would help put the winter/spring acoustic results from this study in better historical context.

Although acoustic propagation affects how often whales are heard, the disparity between the quantity of fin whale detections in this study (heard every day, and on most days for the majority of the day) and blue whale detections (heard on three days, with two of those days having just a single call) implies that fin whales were significantly more common in the study area than blue whales in the February-March 2020 timeframe.

Humpback whale sounds were recorded throughout both glider deployments, both on and off the continental shelf. Humpbacks are observed year-round on CalCOFI cruises (Hildebrand et al. 2018; Trickey et al. 2020), but predominantly on the shelf (<200 m depth), concentrated near Point Conception and the Channel Islands (Munger et al. 2009). Humpbacks have been also tracked in winter months during recent tagging studies off SOCAL (Mate et al. 2018b).

No confirmed minke whale detections were recorded by either glider in this study. In terms of seasonal distribution, this is consistent with visual observations during CalCOFI cruises, when minke whale sightings were recorded in the spring (April) and summer (July) only (Debich et al. 2017; Trickey et al. 2020).

Most sperm whale detections occurred beyond the shelf slope in water deeper than 3,000 m (**Figure 19**). Sperm whales were also detected both times the glider crossed the shelf slope, first in the outbound direction on February 19 and then in the inbound direction on March 15. The most numerous sperm whale click detections occurred far offshore, 50-120 km beyond the shelf slope. Sperm whales are observed year-round during CalCOFI cruises, both on and off the continental shelf (Debich et al. 2017; Hildebrand et al. 2018; Trickey et al. 2020).

There were multiple delays and technical failures on this project. A summary of these issues, actions taken, lessons learned, implemented solutions, and future recommendations are detailed in a separate interim report for this project (Mellinger et al. 2021). Seagliders have been used previously on over 25 PAM missions, 15 of these using previous iterations of the PMAR-XL system (e.g., Klinck et al. 2012, 2015) and the technical issues encountered on this mission are rare. Notwithstanding the technical challenges encountered, the survey results presented here demonstrate that gliders can be effective platforms for monitoring areas of U.S. Navy interest for cetaceans. The gliders did quite well at staying on the planned survey tracks (**Figure 3**), generally staying within 2 km of the trackline. (Deviations near WPx2 and WPx3 were planned, the former to make the area surveyed slightly larger and the latter as a result of HARP N redeployment at a different position as mentioned above.) In addition, the ability to change glider survey tracks was useful, as it allowed us to respond to a newly-discovered change in HARP position while the mission was ongoing. This work demonstrated a successful survey track and approach and would be useful to repeat with beaked whales as the target species group. This is especially true for areas far offshore and in times of year with inclement weather, when visual surveys are both more difficult to conduct and less effective because of large waves, whitecaps, and spray. Although HARP records are valuable, all HARP deployments to date have been on the continental shelf, and they would not record sounds of beaked whales from off the shelf as the maximum detection range is likely less than 4 km (Hildebrand et al. 2015).

5. Acknowledgements

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A.

Appendix A –
Blue Whale Detector

Blue whale detector

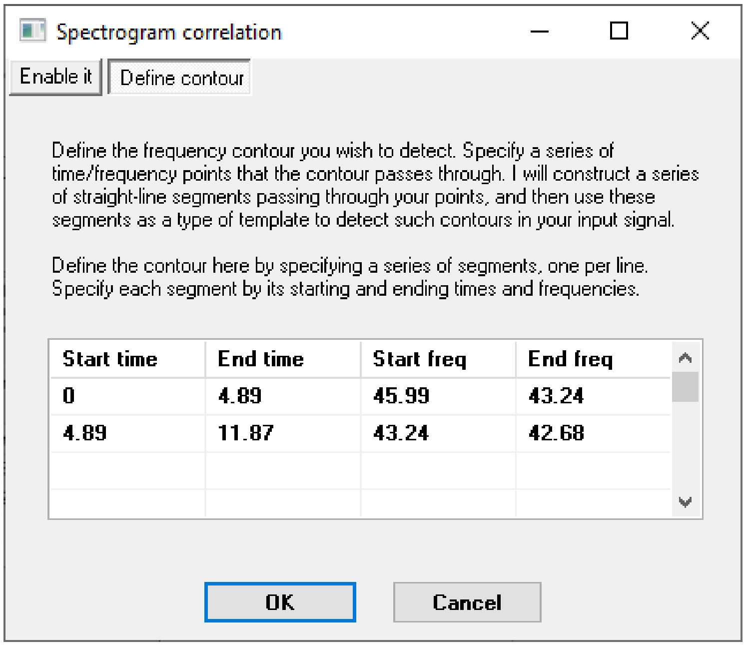

Figure A-1. Spectrogram correlation kernel parameters in Ishmael for the blue whale detector. The contour width was 2 Hz.

The Ishmael settings file (.ipf) for the blue whale kernel:

```
# This is an Ishmael settings file.  It is okay to edit it with a text
# editor or word processor, provided you save it as TEXT ONLY.  It's
# generally safe to change the values here in ways that seem reasonable,
# though you could undoubtedly make Ishmael fail with some really poor
# choices of values.
#
# Also:
#    * Keep each line in its original section (Unit) or it will be ignored.
#
#    * A line beginning with '#', like this one, is a comment.
#
#    * Spaces and capitalization in parameter names ARE significant.
#
#    * If you delete a line containing a certain parameter, then loading
#      this settings file will not affect Ishmael's current value of that
#      parameter.  So you can create a settings file with only a handful of
#      lines for your favorite values, and when you load that file, it will
#      set those parameters and leave everything else alone.
#
#    * Ishmael's default settings file -- the one it loads at startup -- is
#      called IshDefault.ipf .


Unit: Spectrogram calculation, prefs version 1
    frame size, samples  = 4096
    frame size, sec      = 4.0960002
    zero pad             = 4096
```

```
    hop size              = 1024
    window type           = Hann
    keep same duration    = true
    quadratic scaling     = false

Unit: Equalization, prefs version 1
    equalization enabled = true
    equalization time    = 1
    floor enabled        = true
    floor is automatic   = false
    gram floor value     = 3.4879999
    ceiling enabled      = true
    ceiling is automatic = false
    gram ceiling value   = 5.1789207

Unit: Spectrogram correlator, prefs version 1
    enabled              = true
    kernel               = 0 4.89 45.99 43.24^015^0124.89 11.87 43.24
42.68^015^012
    kernel bandwidth     = 2

Unit: Sequence recognition, prefs version 1
    sumautocorr enabled  = false
    sac window length    = 200
    sac hop size fraction = 0.25
    sac min period       = 9
    sac max period       = 25
    use old method       = false

Unit: Detector, prefs version 1
    time averaging enabled = true
    time averaging constant = 3
    detection threshold  = 8
    min call duration    = 3
    max call duration    = 10
    detection neighborhood = 0
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
    save all channels    = false
    time before call     = 1
    time after call      = 9
    retrigger            = false
    display amplitude min = 0
    display amplitude max = 21.722321
    old nbd method       = false
    use system clock     = true
    which time stamp     = 1
    Teager-Kaiser enabled = false
    detector name        =
    det display channels =
1000000000000000000000000000000000000000000000000000000000000000

Unit: Spectrogram display, prefs version 1
    brightness           = 0.23999999
    contrast             = 2.2428312

Unit: Time-domain beamforming, prefs version 1
```

```
    beamforming enabled  = false
    0 degrees is Y-axis  = true
    beam angles          = 0:45:180
    plot beam angles     = 70
    plot beam freqs      = 500
    weighting enabled    = true

Unit: DCLInterface, prefs version 1
    enabled              = false
    dcl function search dir =
    dcl function path to json =
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
```

B.

Appendix B – Fin Whale Detector

Fin whale detector

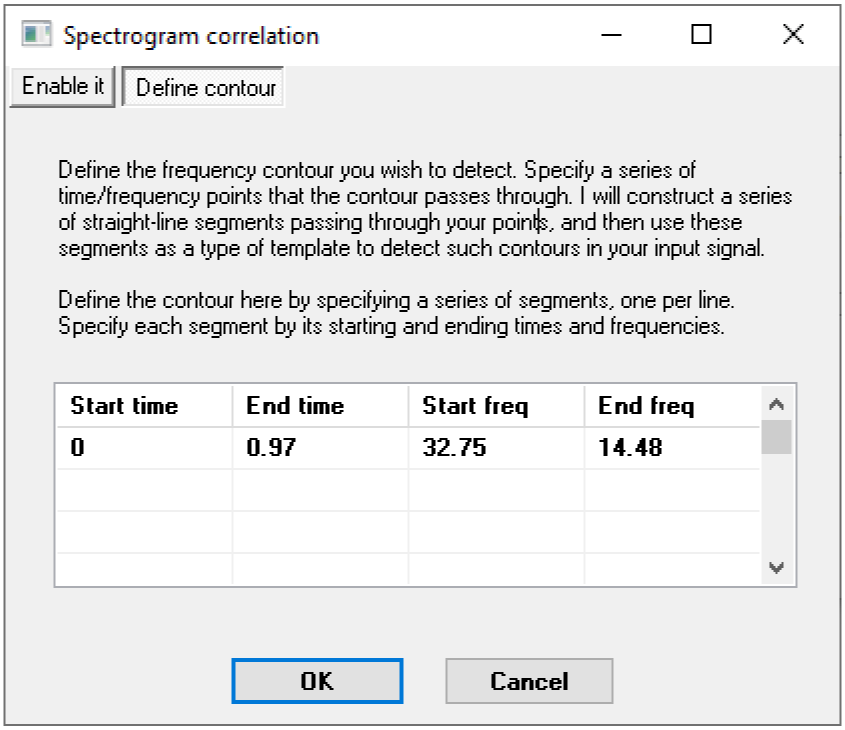

Figure B-1. Spectrogram correlation kernel settings for the fin whale detector.

Note: The contour width of the kernel was 4 Hz; this is wider than the blue whale kernel because a wider kernel allows for more variation in the detected calls, and fin whale pulses are more variable (less stereotyped) than blue whale calls.

<u>MATLAB code used for the average-slope, max-frequency-span method (see text) used to construct the fin whale kernel:</u>

```
% Make a spectrogram correlation kernel for fin whales. This is done by
% finding the average slope of fin calls, and making a kernel with that slope
% that spans the full frequency range.

% The log has columns of startTime, endTime, lowFreq, highFreq.
x = load('finMeasurements.log');

% Find mean slope and freq span.
slope = mean(diff(x(:,3:4),1,2) ./ diff(x(:,1:2),1,2));
freqs = minmax([x(:,3); x(:,4)]);

% Kernel params as startTime, endTime, startFreq, endFreq.
kernelParams = [0 diff(freqs)/slope freqs(2) freqs(1)]
```

The Ishmael settings file (.ipf) for the fin whale kernel:

```
# This is an Ishmael settings file.  It is okay to edit it with a text
# editor or word processor, provided you save it as TEXT ONLY.  It's
```

```
# generally safe to change the values here in ways that seem reasonable,
# though you could undoubtedly make Ishmael fail with some really poor
# choices of values.
#
# Also:
#    * Keep each line in its original section (Unit) or it will be ignored.
#
#    * A line beginning with '#', like this one, is a comment.
#
#    * Spaces and capitalization in parameter names ARE significant.
#
#    * If you delete a line containing a certain parameter, then loading
#      this settings file will not affect Ishmael's current value of that
#      parameter.  So you can create a settings file with only a handful of
#      lines for your favorite values, and when you load that file, it will
#      set those parameters and leave everything else alone.
#
#    * Ishmael's default settings file -- the one it loads at startup -- is
#      called IshDefault.ipf .


Unit: Spectrogram calculation, prefs version 1
    frame size, samples  = 512
    frame size, sec      = 0.51200002
    zero pad             = 512
    hop size             = 128
    window type          = Hann
    keep same duration   = true
    quadratic scaling    = false

Unit: Equalization, prefs version 1
    equalization enabled = true
    equalization time    = 1
    floor enabled        = true
    floor is automatic   = false
    gram floor value     = 0.23999999
    ceiling enabled      = true
    ceiling is automatic = false
    gram ceiling value   = 0.68586504

Unit: Spectrogram correlator, prefs version 1
    enabled              = true
    kernel               = 0 0.97 32.75 14.48^015^012
    kernel bandwidth     = 4

Unit: Sequence recognition, prefs version 1
    sumautocorr enabled  = false
    sac window length    = 200
    sac hop size fraction = 0.25
    sac min period       = 9
    sac max period       = 25
    use old method       = false

Unit: Detector, prefs version 1
    time averaging enabled = true
    time averaging constant = 0.5
    detection threshold  = 1.2
```

```
    min call duration    = 0
    max call duration    = 5
    detection neighborhood = 0
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
    save all channels    = false
    time before call     = 1
    time after call      = 2
    retrigger            = false
    display amplitude min = 0
    display amplitude max = 1.9200001
    old nbd method       = false
    use system clock     = true
    which time stamp     = 1
    Teager-Kaiser enabled = false
    detector name        =
    det display channels =
1000000000000000000000000000000000000000000000000000000000000000

Unit: Spectrogram display, prefs version 1
    brightness           = 0.176
    contrast             = 2.2428312

Unit: Time-domain beamforming, prefs version 1
    beamforming enabled  = false
    0 degrees is Y-axis  = true
    beam angles          = 0:45:180
    plot beam angles     = 70
    plot beam freqs      = 500
    weighting enabled    = true

Unit: DCLInterface, prefs version 1
    enabled              = false
    dcl function search dir =
    dcl function path to json =
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
```

C.

Appendix C – Humpback Whale Detector

Humpback whale detector

Parameters for the Generalized Power Law (GPL) detector used for detecting humpback whale vocalizations for PMAR-XL recordings. These constitute the ‘parm’ structure used by the MATLAB GPL code:

```
      sample_freq: 5000
             nrec: 300000
              xp1: 1
              xp2: 2
          freq_lo: 150
          freq_hi: 1000
      sum_freq_lo: 150
      sum_freq_hi: 1000
           whiten: 1
          white_x: 1
         min_call: 0.3500
         max_call: 5
             loop: 5
            merge: 2
          overlap: 2
             nbin: 582
             fftl: 2048
             skip: 512
           bin_lo: 61
           bin_hi: 410
            nfreq: 350
       sum_bin_lo: 61
       sum_bin_hi: 410
    noise_ceiling: 20
           thresh: 200
         template: 1
     measurements: 0
           filter: 0
```

D.

Appendix D – Minke Whale Detector

Minke whale detector

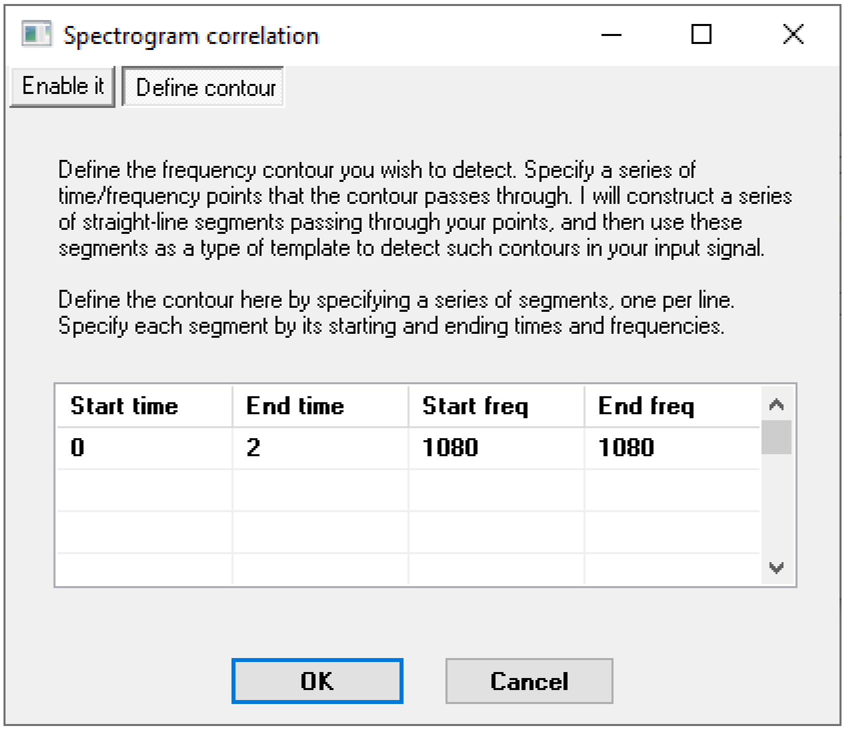

Figure D-1. Spectrogram correlation kernel settings for the minke whale detector. The contour width of the kernel was 50 Hz, wide enough to detect boings from 1030 to 1130 Hz.

The Ishmael settings file (.ipf) for the minke whale kernel:

```
# This is an Ishmael settings file.  It is okay to edit it with a text
# editor or word processor, provided you save it as TEXT ONLY.  It's
# generally safe to change the values here in ways that seem reasonable,
# though you could undoubtedly make Ishmael fail with some really poor
# choices of values.
#
# Also:
#    * Keep each line in its original section (Unit) or it will be ignored.
#
#    * A line beginning with '#', like this one, is a comment.
#
#    * Spaces and capitalization in parameter names ARE significant.
#
#    * If you delete a line containing a certain parameter, then loading
#      this settings file will not affect Ishmael's current value of that
#      parameter.  So you can create a settings file with only a handful of
#      lines for your favorite values, and when you load that file, it will
#      set those parameters and leave everything else alone.
#
#    * Ishmael's default settings file -- the one it loads at startup -- is
#      called IshDefault.ipf .


Unit: Spectrogram calculation, prefs version 1
```

```
    frame size, samples  = 2048
    frame size, sec      = 0.20479999
    zero pad             = 2048
    hop size             = 512
    window type          = Hann
    keep same duration   = true
    quadratic scaling    = false

Unit: Equalization, prefs version 1
    equalization enabled = true
    equalization time    = 1
    floor enabled        = true
    floor is automatic   = false
    gram floor value     = 0.208
    ceiling enabled      = true
    ceiling is automatic = false
    gram ceiling value   = 0.65386504

Unit: Spectrogram correlator, prefs version 1
    enabled              = true
    kernel               = 0 2 1080 1080^015^012
    kernel bandwidth     = 50

Unit: Sequence recognition, prefs version 1
    sumautocorr enabled  = false
    sac window length    = 200
    sac hop size fraction = 0.25
    sac min period       = 9
    sac max period       = 25
    use old method       = false

Unit: Detector, prefs version 1
    time averaging enabled = true
    time averaging constant = 0.5
    detection threshold  = 8
    min call duration    = 1
    max call duration    = 8
    detection neighborhood = 0
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
    save all channels    = false
    time before call     = 1
    time after call      = 2
    retrigger            = false
    display amplitude min = 0
    display amplitude max = 21.722321
    old nbd method       = false
    use system clock     = true
    which time stamp     = 1
    Teager-Kaiser enabled = false
    detector name        =
    det display channels =
1000000000000000000000000000000000000000000000000000000000000000

Unit: Spectrogram display, prefs version 1
    brightness           = 0.208
    contrast             = 2.2428312
```

```
Unit: Time-domain beamforming, prefs version 1
    beamforming enabled  = false
    0 degrees is Y-axis  = true
    beam angles          = 0:45:180
    plot beam angles     = 70
    plot beam freqs      = 500
    weighting enabled    = true

Unit: DCLInterface, prefs version 1
    enabled              = false
    dcl function search dir =
    dcl function path to json =
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
```

E.

Appendix E – Sperm Whale Detector

Sperm whale detector

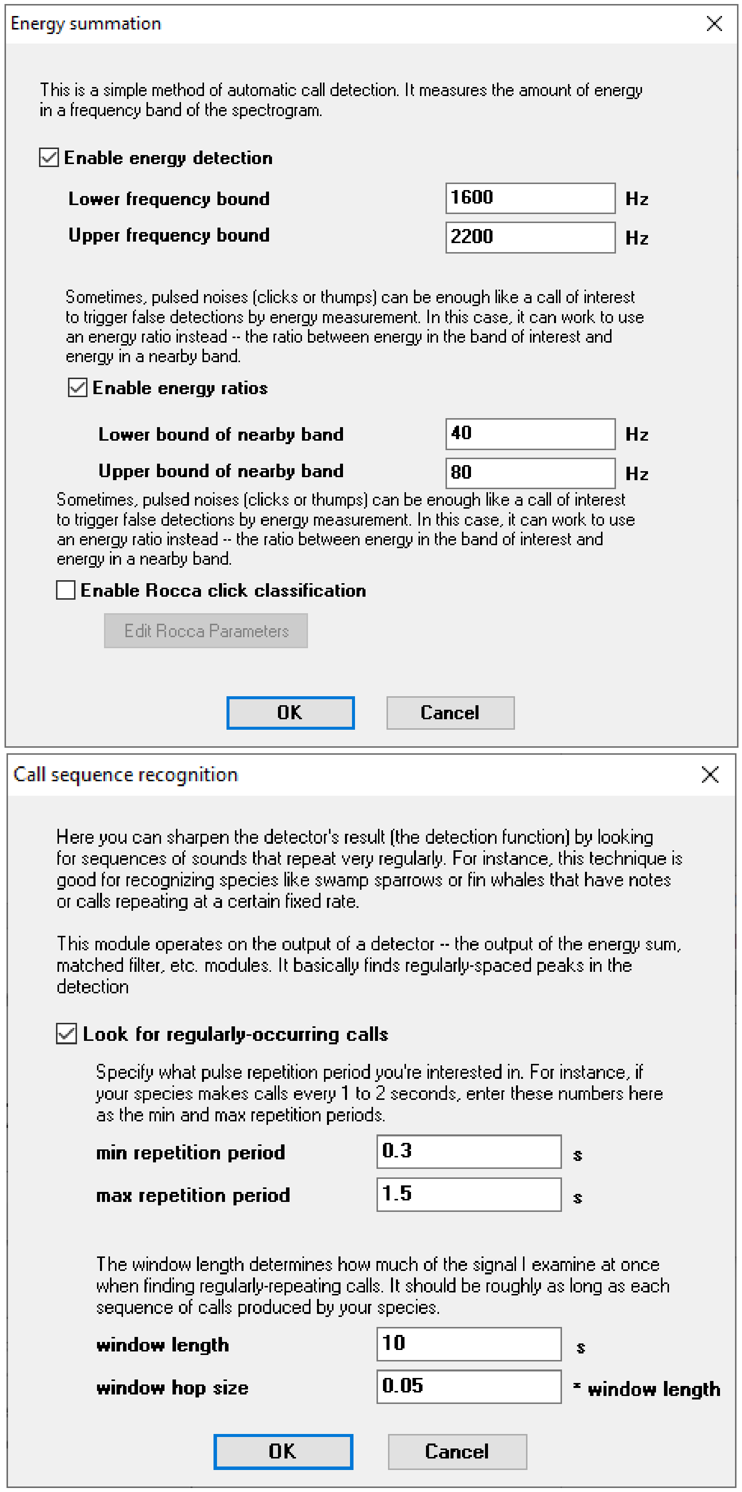

Figure E-1. Settings for the sperm whale detector, including the energy sum settings (top) and sequence recognition settings (bottom). The detector operated on the conditioned spectrogram.

The Ishmael settings file (.ipf) for the sperm whale detector:

```
# This is an Ishmael settings file.  It is okay to edit it with a text
# editor or word processor, provided you save it as TEXT ONLY.  It's
# generally safe to change the values here in ways that seem reasonable,
# though you could undoubtedly make Ishmael fail with some really poor
# choices of values.
#
# Also:
#    * Keep each line in its original section (Unit) or it will be ignored.
#
#    * A line beginning with '#', like this one, is a comment.
#
#    * Spaces and capitalization in parameter names ARE significant.
#
#    * If you delete a line containing a certain parameter, then loading
#      this settings file will not affect Ishmael's current value of that
#      parameter.  So you can create a settings file with only a handful of
#      lines for your favorite values, and when you load that file, it will
#      set those parameters and leave everything else alone.
#
#    * Ishmael's default settings file -- the one it loads at startup -- is
#      called IshDefault.ipf .


Unit: Spectrogram calculation, prefs version 1
    frame size, samples  = 1024
    frame size, sec      = 0.20479999
    zero pad             = 0
    hop size             = 128
    window type          = Hamming
    keep same duration   = true
    quadratic scaling    = false

Unit: Equalization, prefs version 1
    equalization enabled = true
    equalization time    = 0.5
    floor enabled        = true
    floor is automatic   = false
    gram floor value     = 0.16
    ceiling enabled      = true
    ceiling is automatic = false
    gram ceiling value   = 0.31517485

Unit: Energy sum, prefs version 1
    enabled              = true
    lower frequency bound = 1600
    upper frequency bound = 2200
    ratio enabled        = true
    ratio lower freq bound = 40
    ratio upper freq bound = 80

Unit: Sequence recognition, prefs version 1
    sumautocorr enabled  = true
    sac window length    = 10
    sac hop size fraction = 0.050000001
    sac min period       = 0.30000001
```

```
    sac max period       = 1.5
    use old method       = false

Unit: Detector, prefs version 1
    time averaging enabled = false
    time averaging constant = 0.30000001
    detection threshold  = 0.40000001
    min call duration    = 6
    max call duration    = 9999
    detection neighborhood = 0
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
    save all channels    = true
    time before call     = 60
    time after call      = 60
    retrigger            = true
    display amplitude min = 0
    display amplitude max = 2.4000001
    old nbd method       = false
    use system clock     = false
    which time stamp     = 2
    Teager-Kaiser enabled = false
    detector name        =
    det display channels =
1000000000000000000000000000000000000000000000000000000000000000

Unit: Spectrogram display, prefs version 1
    brightness           = 0.16
    contrast             = 6.4443426

Unit: Time-domain beamforming, prefs version 1
    beamforming enabled  = false
    0 degrees is Y-axis  = true
    beam angles          = 0:45:180
    plot beam angles     = 70
    plot beam freqs      = 500
    weighting enabled    = true

Unit: DCLInterface, prefs version 1
    enabled              = false
    dcl function search dir =
    dcl function path to json =
    detection channels   =
1000000000000000000000000000000000000000000000000000000000000000
```

F.

Appendix F – Humpback Manual Detection Quality

Humpback manual detection quality

To provide a measure of how much humpback vocal activity was present, humpback vocalizations found in LTSAs were graded from 0 (no humpback vocalizations) to 5 (clear and numerous humpback vocalizations). Figures F-1 to F-3 show examples of LTSAs graded as 1, 3, and 5, respectively.

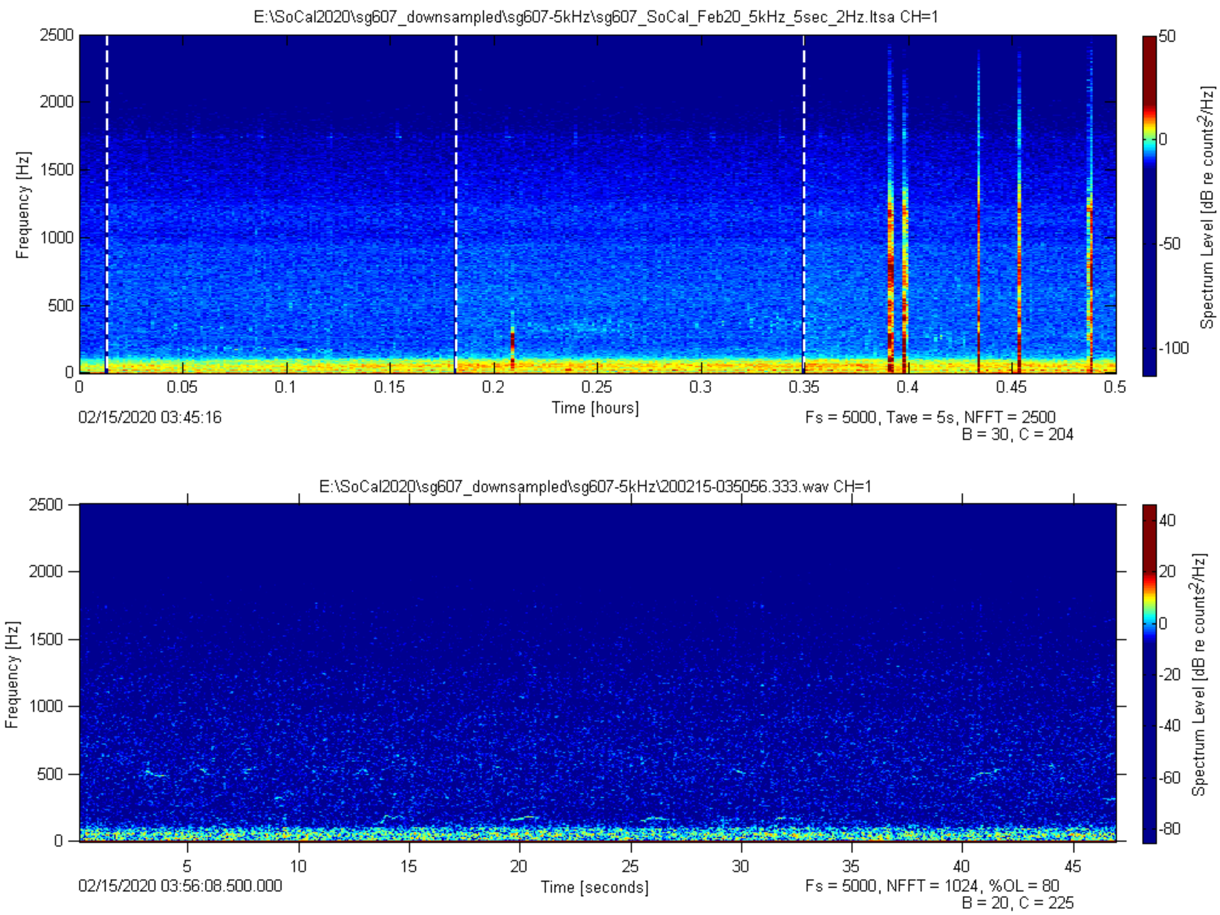

Figure F-1. Example of an LTSA of humpback vocalizations graded as a "1", on a scale of 1-5.

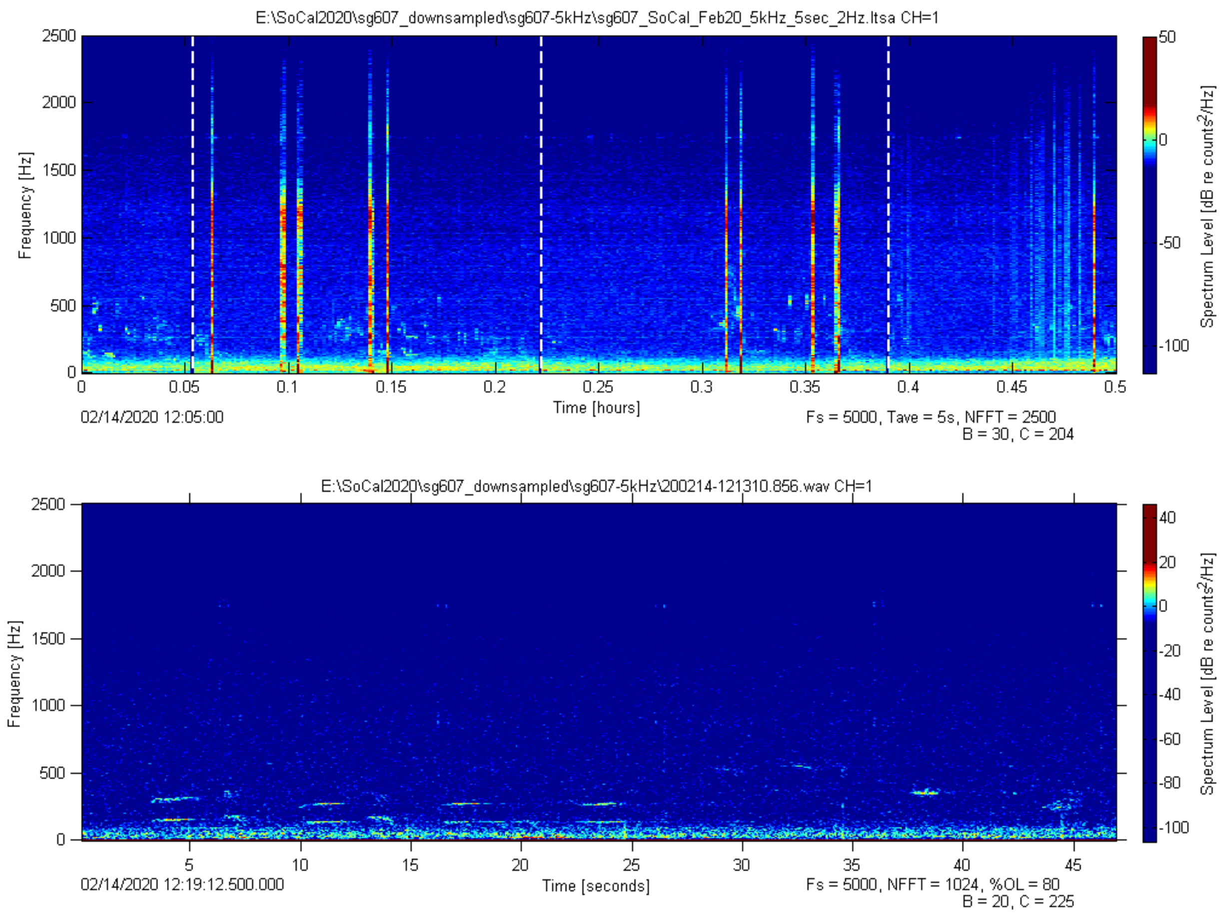

Figure F-2. Example of an LTSA of humpback vocalizations graded as a "3", on a scale of 1-5.

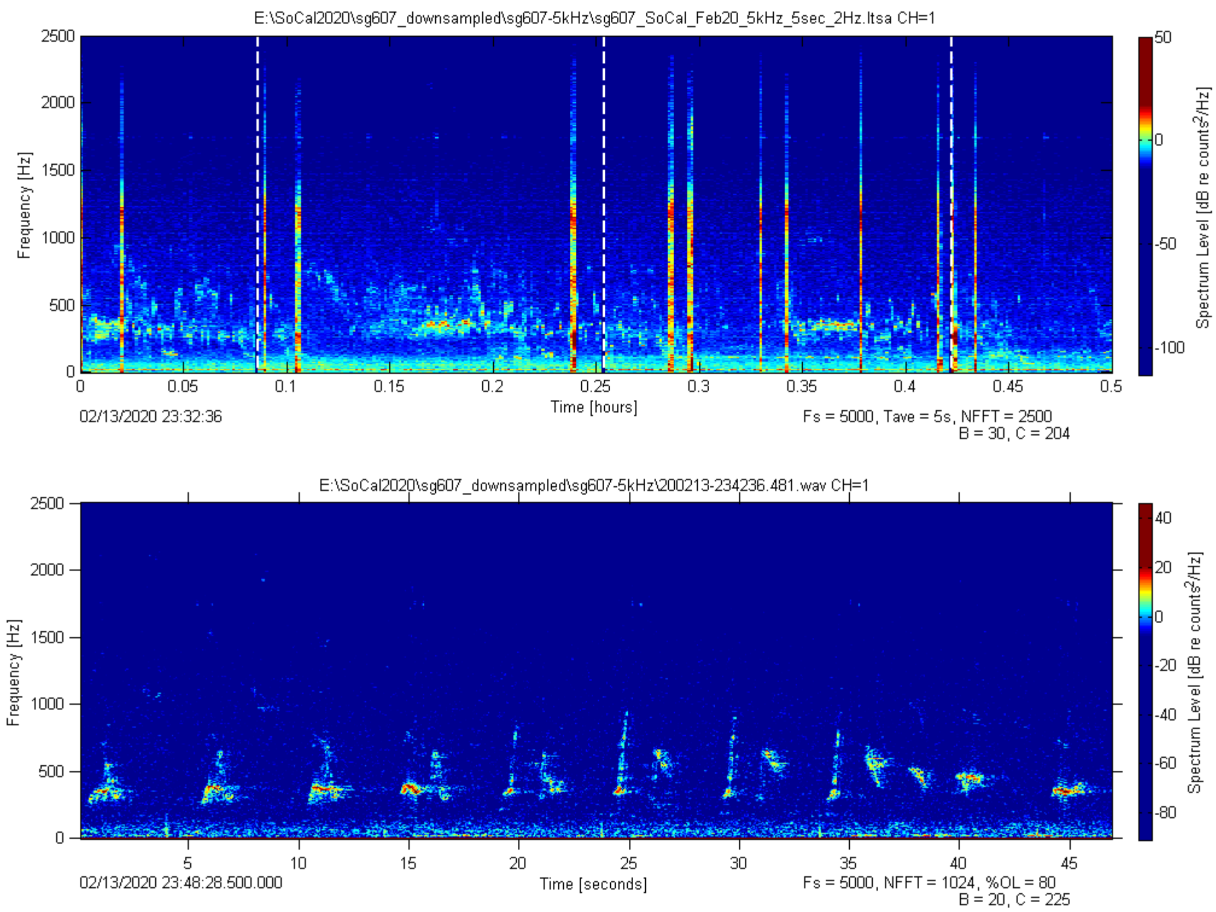

Figure F-3. Example of an LTSA of humpback vocalizations graded as a "5", on a scale of 1-5.

G.

Appendix G – Sound Speed Profiles

Sound speed profiles

Figure G-1 shows a typical sound speed profile encountered during the glider flight. The profile was constructed as follows:

1) From 0-987 m, temperature and salinity data were measured by the abyssal glider and used to calculate the sound speed. This calculation is done by the glider software, apparently using the formula of Mackenzie, K.V. (1981) “Nine-term equation for sound speed in the oceans,” J. Acoust. Soc. Am. 70:807.

2) From 1000-1950 m, ocean-climate temperature and salinity data for February (averaged 2012-2017) from the World Ocean Atlas 2018 were used to calculate the sound speed. At the transition from measured data to climatic data there was a slight offset in sound speed; this offset was subtracted from the climatic sound speed to make the curve continuous.

3) From 1950 m to the bottom, the sound speed was extrapolated from the 1500-1950 m sound speed curve.

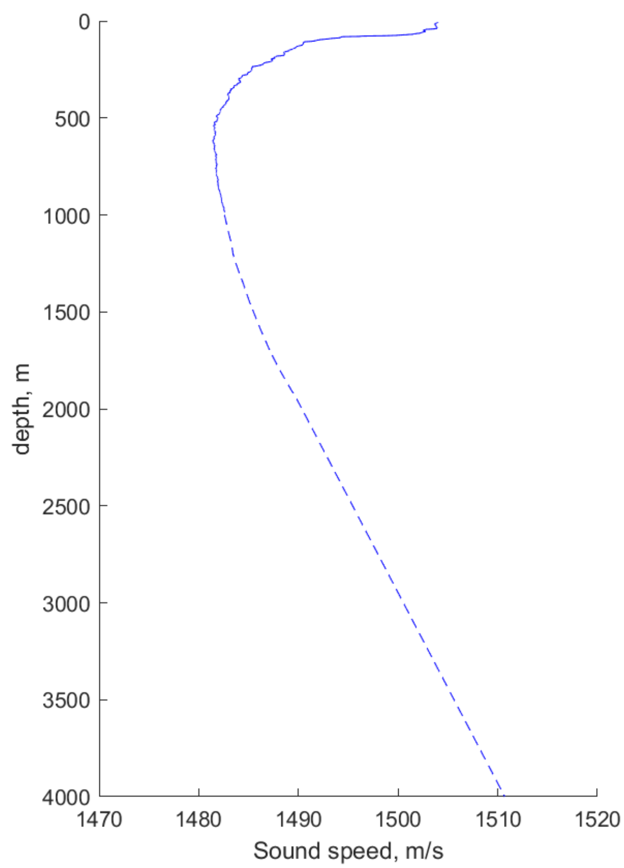

Figure G-1. Sound speed on Feb. 19, 2020. Data from 0-1000 m (solid line) are calculated from glider measurements to temperature, salinity and depth, and data from 1000 m to the bottom are calculated from climatic sources and extrapolation.

Figure G-2 shows all the sound speed profiles from 0-1000 m collected by the glider, along with the mean and median SSPs.

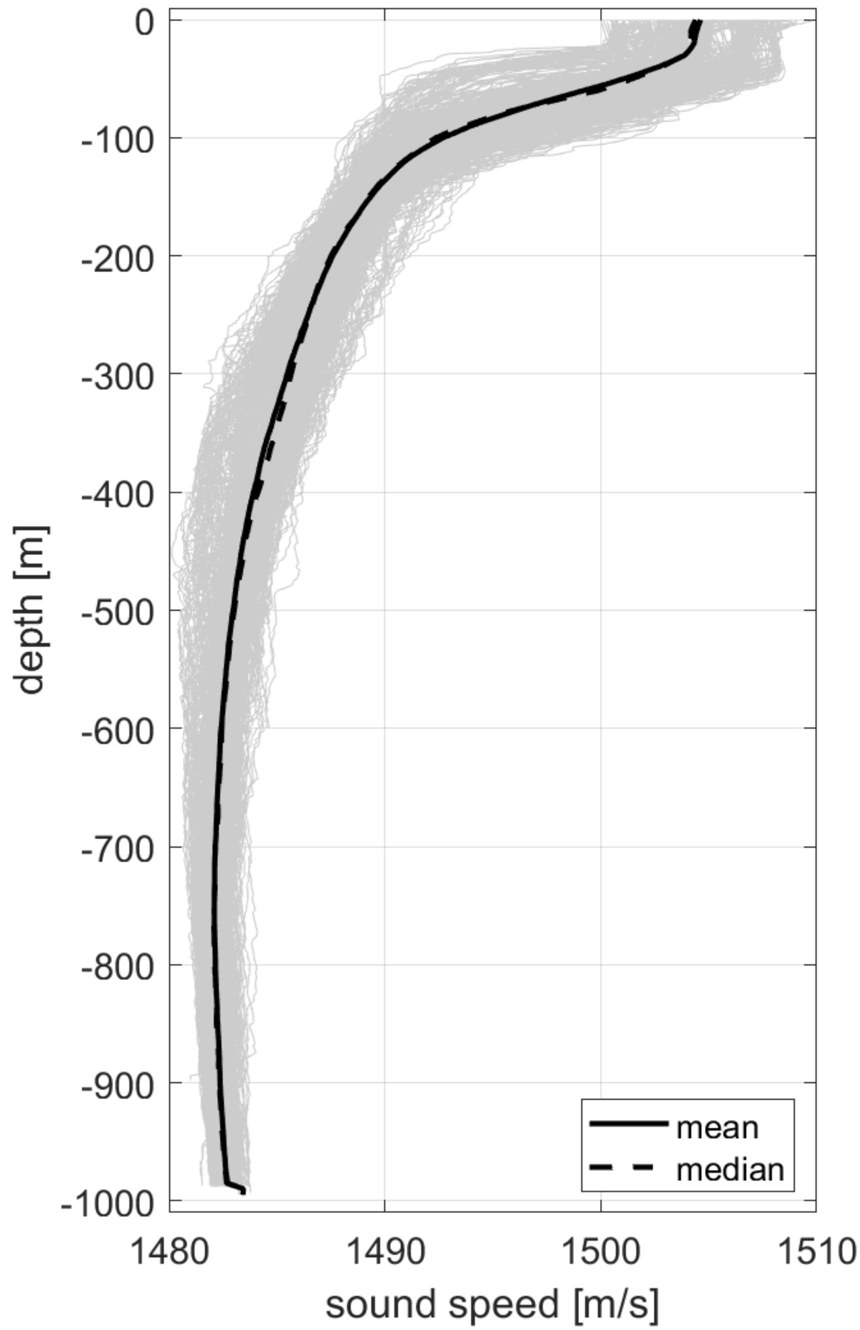

Figure G-2. All sound speed profiles collected by abyssal glider (gray curves) and the median and mean profiles (black curves). The abrupt change between 980 and 1000 m is an artifact due to the fact that there were very few dives that went deeper than ~980 m, and the ones that did happened to have slightly higher sound speeds.

H.

Appendix H – Oceanographic Data Transects

Oceanographic data transects recorded by the gliders.

Abyssal Glider (SG607)

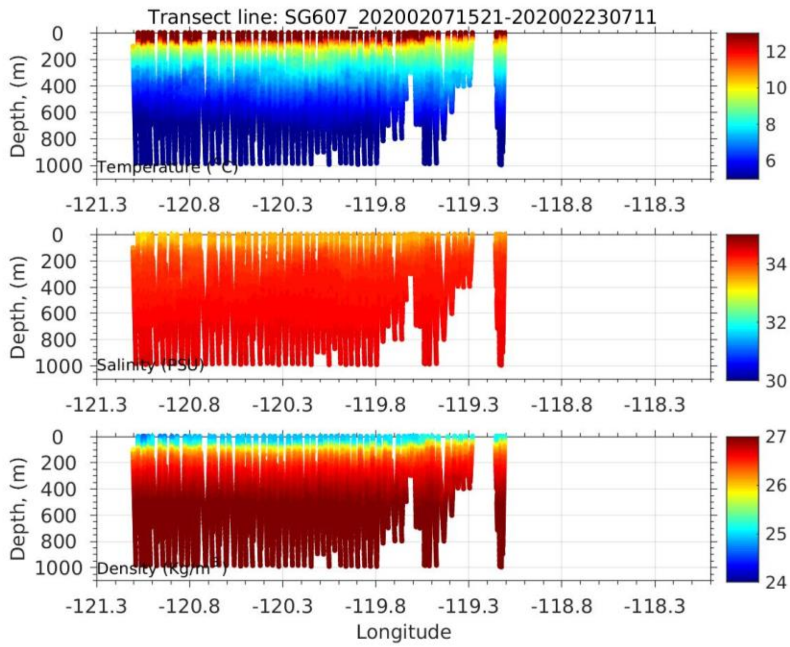

Figure H-1. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPo1 and WPo4 (traveling generally east to west).

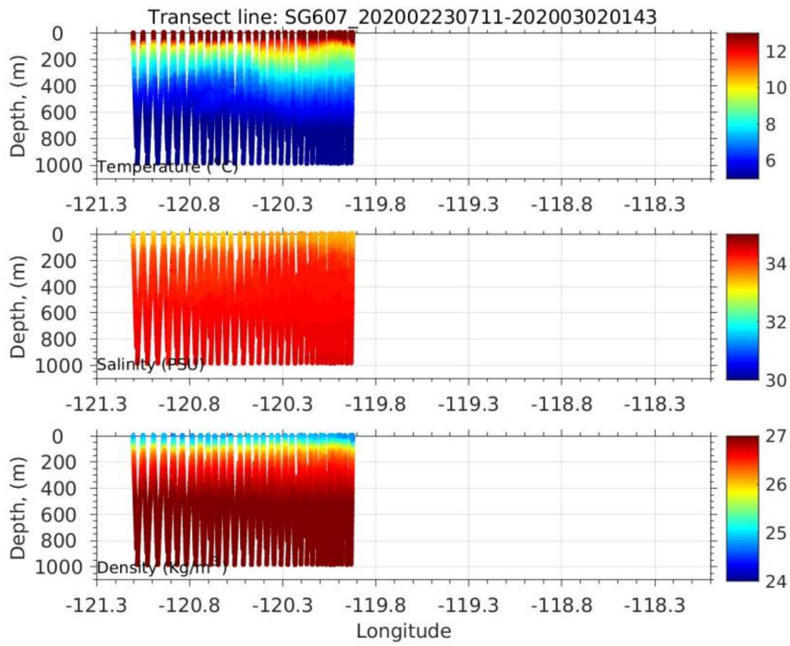

Figure H-2. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPo4 and WPo5 (traveling generally west to east).

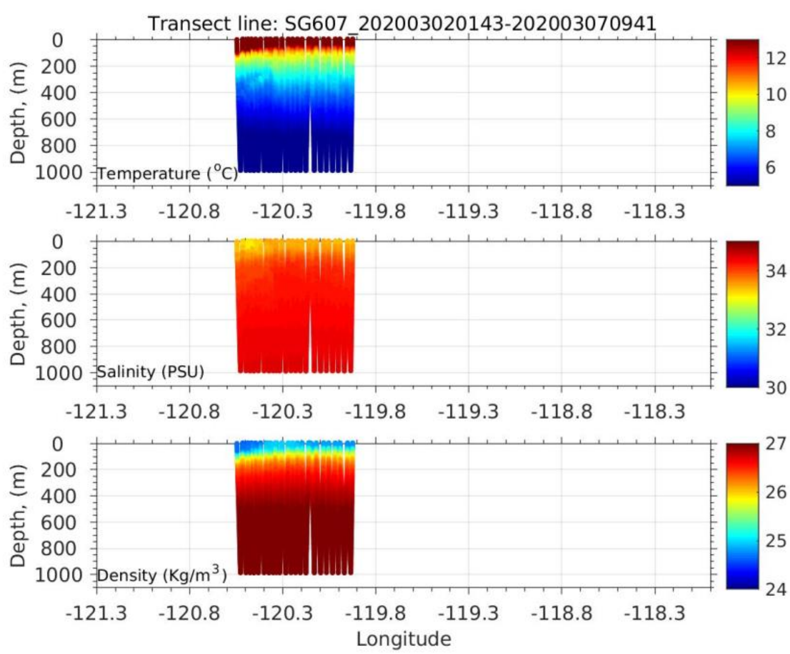

Figure H-3. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPo5 and WPo6 (traveling generally east to west).

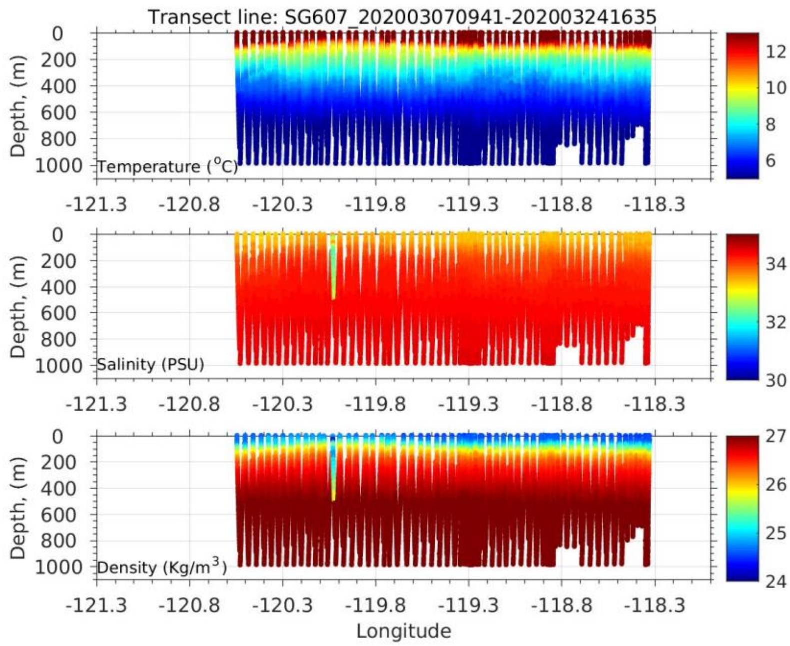

Figure H-4. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPo6 and WPx3 (traveling generally west to east). The very low salinity and density data around -120° is a series of anomalous readings during the first half of the descent of Dive 149.

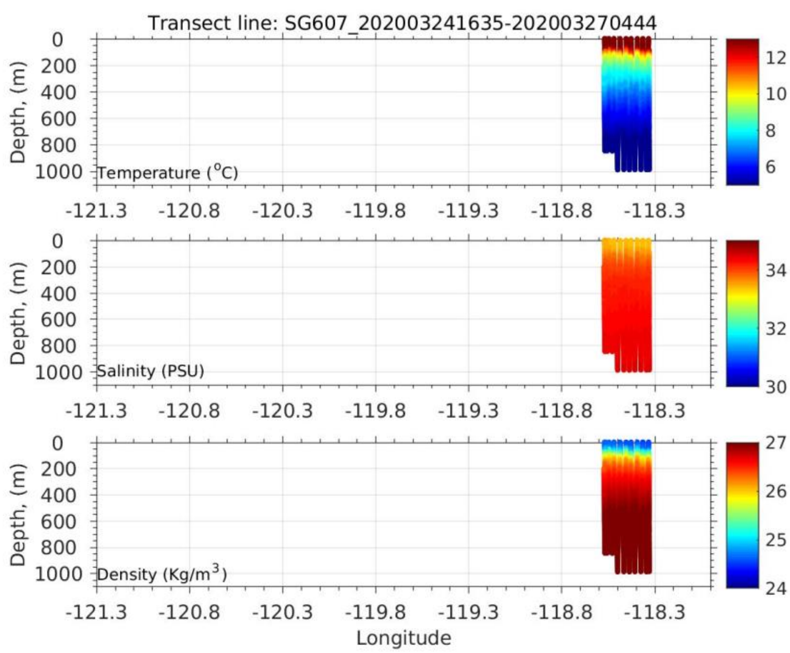

Figure H-5. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPx3 and WPHN (traveling north, but slightly from east to west).

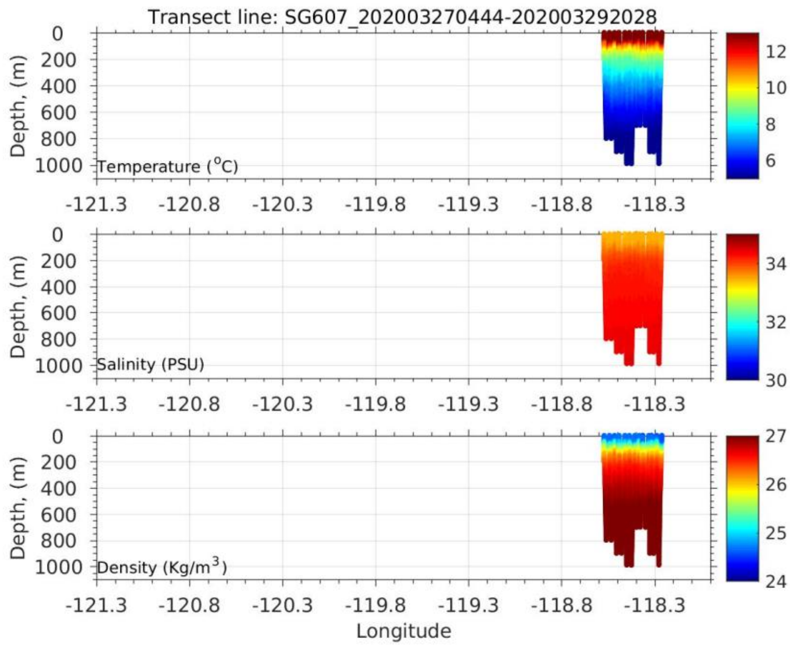

Figure H-6. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the abyssal glider between waypoints WPNH to RPo1 (traveling generally west to east).

Shelf Glider (SG639)

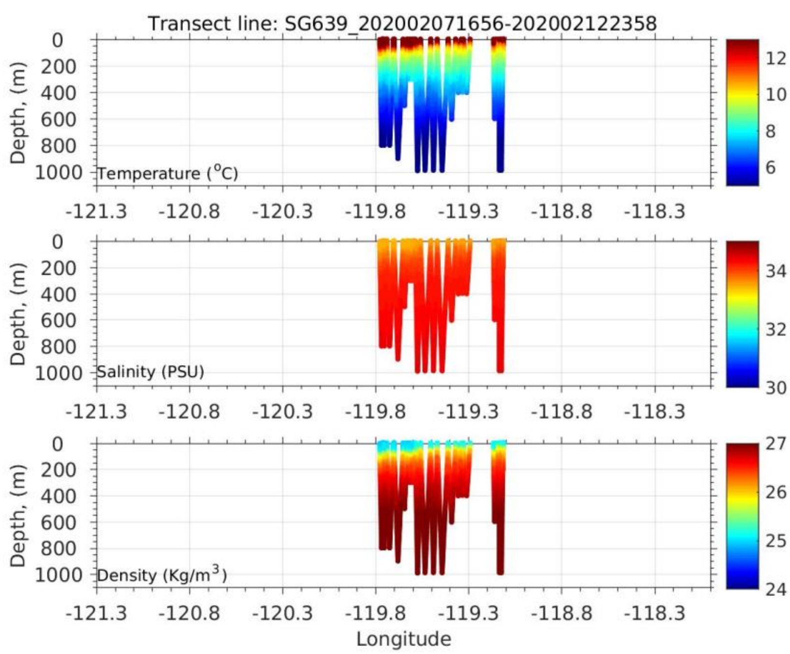

Figure H-7. Temperature (top panel), salinity (middle panel), and density (bottom panel) data collected by the CTD sensor for the shelf glider between waypoints WPi01 to recovery (traveling generally east to west).