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METHODS FOR CHARACTERIZING FIN WHALE SONG NOTES FOR COMPARATIVE STUDIES OF GEOGRAPHIC VARIATION IN SONG

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METHODS FOR CHARACTERIZING FIN WHALE SONG NOTES FOR COMPARATIVE STUDIES OF GEOGRAPHIC VARIATION IN SONG

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ABSTRACT

The identification and delineation of “stocks” (management units of a species ranging from independent populations to subspecies) is important for understanding and mitigating potential sources of human-caused mortality. This is especially critical for endangered and protected species, such as the large whales. Stock identification for whales has typically been based on ecology, life history, morphology, and genetics. However, for many species, acoustic differences in whale call types may indicate the presence of unidentified populations or subspecies. The potential role of acoustics in identifying structure at various levels of divergence in cetaceans has been recognized in numerous publications; however, this potential has yet to be implemented for large whales. In an effort to include acoustic data in this process, we are contributing to current efforts to update the status of endangered fin whales (*Balaenoptera physalus*) in the North Pacific. An analysis of North Pacific fin whale populations based on identification of ‘song’ provides hypotheses that can be tested with other lines of evidence such as genetics. Standardized methods for processing recordings from autonomous recorders will be presented in detail with a summary of the data to be processed and published on peer-reviewed contributions.

INTRODUCTION

In 2010, National Marine Fisheries Service developed a recovery plan for fin whales (*Balaenoptera physalus*). The goal of this plan was to promote the recovery of fin whales to the point at which they can be downlisted from endangered to threatened status, and ultimately to remove them from the list of endangered species. An important component of this plan is to first clarify the global taxonomy of the species, which entails ensuring that subspecies are properly described, followed by examining stock structure in the North Pacific and North Atlantic.

Stock identification for cetaceans has typically been based on genetics, morphology, and geography. More recently, information obtained from a species' life history and ecology has been considered when defining stocks (Martien *et al.* 2015). There is strong evidence to support the notion that acoustic differences in call types may indicate population or subspecies structure, and that acoustics may provide plausible yet unsuspected hypotheses about stock structure (McDonald *et al*. 2006, Mellinger and Barlow 2003). In the case of fin whales, it has been suggested that the inter-note-interval (INI) and note bandwidth of fin whale song shows geographic variation (Castellote *et al*. 2012, Delarue *et al*. 2009, Hatch and Clark 2004), and that this measure may assist in identification of population and sub-population structure.

In an effort to explore the role that acoustics can play in identifying population structure, we have formed a collaborative effort between experts in fin whale acoustics and stock structure analysis to analyze fin whale song recorded on autonomous seafloor recorders and U.S. Navy Sound Surveillance System (SOSUS) in the North Pacific Ocean. In this report, we present a summary of the standardized methods used to process the data collected contributed by collaborators. A complete spatial and temporal analysis of this data will be published at a later date.

METHODS

Study Area, Data and Recorder Information

Recordings were examined from a variety of sources in locations across the Pacific Ocean (Table 1, Fig. 1). Most recordings were continuous; however, some recordings on a duty cycle were included (Table 2).

Recordings from U.S. Navy SOund SUrveillance System (SOSUS) and other hydrophones deployed in the Northwest Pacific Ocean (NWP), Central Pacific (CP), Aleutian Islands (ALE), and Gulf of Alaska (GOAs) were examined. SOSUS consists of a series of cabled seafloor hydrophones with shore-based recording facilities (Nishimura and Conlon 1994). As the actual location of these hydrophones is classified information, only general locations are provided (Table 1). The SOSUS recordings were continuous recordings sampled at 250 or 100 Hz and were low-pass filtered at 120 Hz and 40 Hz respectively (Fox *et al*. 1995).

Recordings from the Canadian coast include Cape St. James (CSJ), Brooks Peninsula (BRP), and Langara Island (LAN), provided by Fisheries and Oceans Canada; Caamano

Sound (CAS) and Prince Rupert (PRU) provided by Rob Williams (Oceans Initiative). The CSJ and BRP recording packages were located in 100 m of water, approximately 5 km from land, near the edge of the continental shelf. The packages were anchored so that the instruments were suspended at 10 m above the ocean floor. Recordings at CSJ and BRP were made using Autonomous Underwater Recorders for Acoustic Listening (AURAL, Multi-Electronique, Inc., Rimouski, Canada), which include an HTI-96-MIN hydrophone (High Tech, Inc., Long Beach, MS; sensitivity -165 dB re: 1 V/uPa; frequency response 2 Hz to 30,000 Hz). Recordings were made with a 16,384 Hz sample rate, and 16-bit resolution. The recording package at LAN consisted of a Sparton 57B hydrophone (sensitivity -154 dB re: 1 V/uPa, frequency response 5 Hz to 20,000 Hz) cabled to an onshore AURAL recorder. Recordings were made with a 16,384 Hz sample rate, and 16-bit resolution. The package at LAN was located in 40 m of water, 30 m from shore. Duty cycles for CSJ, BRP and LAN varied by location and deployment (Table 2). The CAS and PRU recording packages were located in 197 and 158 m of water respectively, suspended 1 m above the ocean floor (Williams et al. 2014). PRU datasets contained significant low-frequency electrical noise and were too noisy to identify useful segments for identifying fin whale notes. Recordings were made using a novel configuration of Marine Acoustic Recording Units (MARU) designed by the Cornell University Bioacoustics Research Program to extend battery life. This configuration caused electrical noise in the PRU deployment that could be corrected in ambient noise measurement, but confounded signal detection (this configuration has since been discontinued). The MARUs include the same HTI hydrophone as AURALs. Acoustic data was recorded continuously at 16,000 Hz sampling rate and 16-bit resolution.

Chukchi Sea (CHU) recordings were obtained using Autonomous Underwater Recorders for Acoustic Listening (AURAL, Multi-Electronique, Inc., Rimouski, Canada) in 2007 and Autonomous Multichannel Acoustic Recorder (AMAR, JASCO Applied Sciences, Halifax, Canada) in 2010. Recorders were deployed at depths between 15 m and 100 m. CHU recordings were provided by JASCO Applied Sciences. Aural data were sampled at a rate of 16,384 Hz with 16-bit resolution, which provided a usable bandwidth of 10 Hz to 7,700 Hz. The AMARs were equipped with GTI-M15B hydrophones with -160 dB re 1V/lPa sensitivity (GeoSpectrum Technologies, Inc., Dartmouth, Canada). Acoustic data were recorded continuously at a rate of 16,000 Hz with 24-bit resolution. The usable bandwidth was 10 Hz to 7,600 Hz (Delarue *et al*. 2012).

Recordings from the Gulf of Alaska (GOA) were made with HARU autonomous recorders (Fox *et al*. 2001). These instruments were composed of a logging system including an ITC-1032 hydrophone, a preamplifier designed to pre-whiten ambient noise spectra from 5 Hz to 970 Hz and s digital recorder that sampled at 2,000 Hz, 16-bit resolution (low-passed at 970 Hz). The data were recorded continuously.

Recordings from Monterey Bay (MOB) and Sea of Cortez (SOC) were made using Marine Acoustic Recording Units (MARUs) and were provided by Bioacoustics Research Program, Cornell University. MARUs are fitted with HTI-96 hydrophones with -164 to -185 dB re 1 V/ uPa nominal sensitivity (High Tech, Inc., Long Beach, MS), with system flat frequency response (±3 dB) in the 10 – 585 Hz frequency range. Three MOB

MARUs were placed 1 m above the seafloor using gravel bags as anchors at three locations around Monterey Bay canyon, two units in the north side and one unit in the south side of the canyon. Acoustic data at both MOB and SOC were recorded continuously at 2,000 Hz sampling rate and 16-bit resolution.

Cabled recordings from central California were obtained from a shore-cabled vertical line array of four hydrophones deployed at 30 m spacing above the seafloor on Pioneer Seamount (PS) deployed at 37° 21.1 N, 123° 26.1'W. Only data from the hydrophone at 970 m were used as all hydrophones recorded the same signals. The recordings were continuous and sampled at 1,000 Hz, and low-pass filtered at 440 Hz (Matsumoto *et al*. 2004).

Recordings from the Aloha Cabled Observatory (ACO) were made using a cabled seafloor-mounted hydrophone 100 km north of Oahu at a depth of 4.7 km (Duennebier *et al*. 2008). The hydrophone had a flat frequency response from 10 Hz to 1,000 Hz (Optimum Applied System, Poughkeepsie, NY Model E-2PD). The hydrophone was continuously sampled up to 96,000 Hz with 24-bit resolution. Data from the ACO were transmitted to the AT&T Makaha Cable Station via an electro-optical cable providing power and broadband Ethernet communications capability; data were then sent to the University of Hawaii, where they were downsampled to 24,000 Hz and archived.

Processing Methods

In order to address possible seasonal changes in call and song structure, as suggested by recent studies elsewhere (Morano et al. 2012, Oleson et al. 2014, Weirathmueller et al. 2017), and minimize the presence of overlapping song (which affects measures of INI and are more likely during the peak singing months, i.e. November to January (Nieukirk *et al*. 2012), recordings from the months of October and February from each dataset were considered for this study. October 2009 and February 2010 were the preferred months based on the periods of recordings available from all study areas; however, these two specific months were not available in all cases. In those cases, both months were selected from the same singing season (October and following February) to reduce any potential bias introduced by inter-season song variability. The only exceptions to this were recordings in September in the Chukchi Sea (recordings ended on 15 September in 2007 but songs were detected two days prior retrieval and included in this analysis) and in March from the Sea of Cortez (recordings lasted from 19 Feb to 13 March. Songs recorded in the first week of March were included to increase sample size and avoid sampling too many songs in the last 10 days of February). Recordings were decimated to 512 Hz and standardized analysis methods were used for consistency.

Spectroplotter v. 5.0.8 (JASCO Applied Science) was used for monitoring and analyzing recordings. For consistency, we used frequency resolution = 0.1 Hz (providing a true resolution of 0.063 Hz), frame sizes = 0.1 s, time step = 0.025 s, and window type = Reisz. A ‘rainbow’ color scheme provided the best visual resolution of calls in the spectrogram. Spectrograms were restricted to a bandwidth of 0 – 50 Hz with a 5 s window length. In addition, the 100 – 200 Hz bandwidth of each recording was checked for the possible presence of high frequency notes.

A minimum of 500 notes from non-overlapping songs was targeted for a minimum of 10 different days in October. Where possible, the days were evenly distributed throughout the month to minimize the possibility of sampling only a few individuals. When possible, entire songs were annotated, i.e. all notes between a rest and the consecutive rest (see Watkins *et al*. 1987) were tagged. Annotations were drawn to encompass all the visible energy for each call (Fig. 2). Harmonics associated with extremely loud calls were excluded. Multipath arrival effect was avoided by choosing only the strongest signal of the cluster. These and other strategies for selecting calls were provided to all analysts in order provide a level of consistency. Examples of call selection strategies are given in Appendix 1.

Within Spectroplotter, the ‘Intensity Boundary’ (defining the dB scale represented by the color scheme in the spectrogram) was set to ‘manual’ so that the dB scale in the spectrogram display was fixed for all browsing windows of a same song sequence. To do so, the entire song was scanned to select a song note with an intensity that was mid-range for the notes of that song sequence and the Intensity Boundary was set to manual with the dB scale applied in that particular spectrogram window.

For each annotated note, measurements were made using Spectroplotter for subsets of the annotation contents that contain 90% of the energy and a user-determined (UD) energy % selection, which varied by recording (see Fig. 1). Suggested methods for determining the UD energy selection are given in Appendix 2 and provide a level of consistency across analysts. The UD energy selection strategy was adopted to account for differences in background noise levels and spectra within the fin whale song frequency range among all deployment locations. For each annotation, the minimum and maximum frequency based on 90% and the UD% of energy as well as the peak and centroid frequency and centroid time were measured.

The definitions for measurements made using Spectroplotter are included in Table 3. The note bandwidth was obtained by subtracting the maximum and minimum frequencies using the 90% and UD measures only in notes classified as high SNR (C* or B*) because this measurement is affected by the SNR. The inter-note-interval (INI) was measured for all note types using the difference in time between centroid times of consecutive notes from each song sequence (Fig. 3).

For each annotated sound file, a log was extracted and named according to the mooring site (2-3 letters), latitude (decimal degrees N/S), longitude (decimal degrees E/W), file date (MMDDYY), file time (HHMMSS), and author initials (e.g. "GOA_50N_134W_102009_153500_MC" is Gulf of Alaska mooring at 50N, 134W on Oct 20th 2009 at 15:35:00, analyzed by Manuel Castellote). For songs that were subjectively determined to be from different individuals by the analyst, an extension was added to the file name to identify the animal (e.g., _001 for the first individual and _002 for the second individual, etc.). Determination of individual singers was made only when the analyst felt confident that a single individual was likely responsible for a song sequence.

Fin whales are known to make several note types and for this study we used two different approaches to identify note type. The classic song note is a loud note decreasing in frequency from 25 to 18 Hz over about 1 s and is well described in the literature (Thompson *et al*. 1992, Watkins *et al*. 1987). The backbeat, fainter than the 20 Hz note and slightly lower in frequency, often occurs during song and normally precedes a 20 Hz note (Castellote *et al*. 2012, Clark *et al*. 2002, Hatch and Clark 2004) but songs have also been described to be composed exclusively of, or be completely devoid of, backbeats (Clark and Gagnon 2002, Hatch and Clark 2004). The high frequency note, or upsweep, is a short upsweep that has been recorded in the North Atlantic and several areas of the southern hemisphere. In the North Atlantic, it is centered around 130 Hz and normally occurs just before 20 Hz notes (Clark *et al*. 2002, Clark and Gagnon 2002), although it is sometimes produced on its own. In the southern hemisphere, high-frequency notes occur simultaneously with classic notes and exhibit geographic variation in frequency that may be representative of population structure (Gedamke 2009, Simon *et al*. 2010, Širović et al. 2009). To our knowledge, this high note has not been identified from fin whales in the North Pacific.

Note ‘type’ was identified using a manual and automated method. Manual determination of call type was a qualitative decision made by the analyst and based on the comparison of the spectral characteristics to note types identified in the literature (see Hatch and Clark 2004). For each song sequence, all notes were manually annotated using the following codes: Classic note (C), Classic note with high SNR (C*), backbeat note (B), backbeat note with high SNR (B*), high-frequency (HF) and other (OT). All recordings were scanned to determine the presence of high frequency notes within a song. Automated determination of call type was based on the Density Clustering algorithm (Rodriguez and Laio 2014) only using notes characterized as “high quality” and the following spectral variables: centroid frequency, peak frequency, maximum frequency, bandwidth, and centroid peak difference (defined as the difference between the centroid frequency and the peak frequency).

DISCUSSION

Previous research has shown that acoustics may provide a valuable role in identifying population structure of cetaceans. Payne and Guinee (1983) first proposed using song characteristics as a means of identifying humpback stocks. The use of song characteristics to describe population affiliation over a broad geographical range has been extended to additional mysticete whale species including the minke whale (Rankin and Barlow 2005), blue whale (e.g., Ljungblad *et al*. 1998, McDonald *et al*. 2006) and fin whale (e.g., Castellote *et al*. 2012, Delarue *et al*. 2009, Hatch and Clark 2004, Thompson *et al*. 1992). However, realizing this potential requires consideration of large amounts of data over large geographic ranges (and possibly over large time scales). These data exist for much of the world's ocean basins; however, data analysis is either incomplete or has used inconsistent methods. This study is the first coordinated effort to examine ocean basin scale differences in cetacean acoustics for the explicit purpose of stock structure assessment. These recordings come from multiple types of autonomous seafloor recorders deployed throughout the North Pacific by a wide variety of institutions. Data were examined independently by many analysts (M. Castellote, J. Delarue, B. Koot, M. Richlen, K. Stafford, and J. Thompson). In order to provide consistent data processing among analysts, systematic methods, outlined in this report, were developed and extensive instruction was provided.

Classification of fin whale notes diverged between the manual and quantitative methods. Determination of call type using either method (manual or automated) relied on spectral measurements; however, analysts may have been influenced by additional features such as relative intensity and INI. The second quantitative approach to identifying call types based on clustering provided an arguably less subjective method to call type determination. This relatively new method for clustering based on identifying high density peaks provided an intuitive and informative means of identifying the number of call types (Rodriguez and Laio 2014). Our research suggests that quantitative approaches to call classification will provide more robust (and less biased) results.

Research has suggested that the INI of fin whale song may be informative for understanding population structure (Castellote *et al*. 2012, Delarue *et al*. 2009, Hatch and Clark 2004). Research also suggests that the INI may vary over the course of a season (Weirathmueller et al. 2017, Oleson *et al*. 2014, Morano *et al*. 2012, Watkins *et al*. 1987). To avoid complications due to seasonal variation, we selected two months for analysis. The months of October (early in the season) and February (late in the season), were selected as they showed relatively low levels of overlapping song from multiple whales in preliminary analyses. Only song with high SNR and considered to be from a single individual was selected for analysis for each day and time.

Fin whale song was detected on all recorders, but not necessarily during both months. Fin whale song was detected in October for all sites except for SOC (and PRU, Table 4); fin whale song was detected in February for NWP, CSJ, BRP, SOC, AOC, and GOA (Table 5). In addition, song was detected on three days in March in SOC and two days in September in CHU. Annotated notes from song sequences identified by the analyst as originating from a different whale are considered independent samples.

Detailed analysis of call measurements, including INI, will be analyzed and presented in a peer-reviewed journal. These publications will also include limitations and suggested improvements to these methods and should be referenced prior to consideration of these methods for future studies.

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Table 1. Recording characteristics and location of autonomous recorders used for this study.

Site	Full Site Name	Platform	Sampling Rate	Latitude	Longitude	Analyst
ALE	Aleutian Islands	SOSUS	250 Hz/ 100 Hz	50 N	180 W	Kate Stafford
GOAs	Gulf of Alaska	SOSUS	250 Hz/ 100 Hz	50 N	160 W	Kate Stafford
NWP	Northwest Pacific	SOSUS	250 Hz/ 100 Hz	45 N	160 E	Kate Stafford
CP	Central Pacific	SOSUS	250 Hz/ 100 Hz	35 N	140 W	Kate Stafford
PRU	Prince Rupert	MARU	16000 Hz	53 N	130 W	Manuel Castellote
CAS	Caamano Sound	MARU	16000 Hz	54 N	131 W	Manuel Castellote
LAN	Langara Island	AURAL	16.384 kHz	54 N	133 W	Barbara Koot
CSJ	Cape St. James	AURAL	16.384 kHz	52 N	131 W	Barbara Koot
BRP	Brooks Peninsula	AURAL	16.384 kHz	50 N	128 W	Barbara Koot
CHU	Chukchi Sea	AURAL/AMAR	16.384 kHz/16 kHz	70 N	166 W	Julien Delarue
MOB	Monterey Bay	MARU	2 kHz	36 N	122 W	Julien Delarue
SOC	Sea of Cortez	MARU	2 kHz	25 N	111 W	Julien Delarue
AOC	Hawaii	Cabled	24 kHz	22 N	158 W	Michael Richlen
BS	Bering Sea	AURAL	4 kHz	57 N	163 W	Jessica Thompson
GOA	Gulf of Alaska	HARU	2 kHz	52 N	157 W	Manuel Castellote
PS	Pioneer Seamount	Cabled	1 kHz	37 N	123 W	Kate Stafford

Table 2. Duty cycle information for sites that did not have continuous recording. Duty cycle consists of a period of time in which the unit is recording (Cycle On) per unit of time (Overall Cycle Time).

Site	**Date**	**Cycle On**	**Overall Cycle Time**
PRU	*NA*	13 min	60 min
CAS	Oct 2008, Feb 2008	13 min	60 min
LAN	Oct 2009, Feb 2010	10 min 7 s	30 min
LAN	Oct 2011, Feb 2012	4.5 min	15 min
CSJ	Oct 2009, Feb 2010	7 min	30 min
CSJ	Oct 2010, Feb 2011	9 min	30 min
BRP	Oct 2010, Feb 2011	4.5 min	15 min

Table 3. Definition of the measurements made by Spectroplotter v. 5.0.8.

Measurement	**Definition**
Maximum Frequency	Highest frequency within the note energy % independently of time.
Minimum Frequency	Lowest frequency within the note energy % independently of time.
Centroid Time	Time that bisects the note duration so that 50% of the energy lies before and 50% lies after that time value.
Peak Frequency	Frequency at peak energy; the center of the frequency bin in which the FFT generates the highest value; not limited to the band of the annotation
Center Frequency	Frequency that bisects the aggregate spectrum so that 50% of the total signal energy lies below median frequency and 50% lies above

Table 4. Dates in February with detection of fin whale songs from a single individual for each recording site. Detections occur in different years; multiple detections may occur on a given day for a given site. Additional SOC detections on 3/1, 3/3, and 3/7.

Site	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
ALE																															
GOAs																															
NWP		■	■	■	■		■																								
CP																															
PRU																															
CAS																															
LAN																															
CSJ			■	■												■															
BRP	■	■	■				■	■		■	■	■	■				■	■	■	■	■	■		■	■	■	■	■			
CHU																															
MOB																															
SOC																			■	■	■			■		■		■			
HAW	■				■						■						■	■					■	■	■						
BS																															
GOA	■					■	■			■																					
PS																															

Table 5. Dates in October with detection of fin whale songs from a single individual for each recording site. Detections occur in different years; multiple detections may occur on a given day for a given site. Additional CHU detections on 9/14 and 9/15.

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
ALE							■			■																					
GOAs				■					■			■		■		■		■	■					■							
NWP		■	■	■		■		■	■	■	■	■	■	■		■	■					■									
CAS				■	■	■	■	■	■			■	■	■					■												
CP					■										■	■		■			■										
LAN									■											■										■	■
CSJ					■	■		■			■	■							■			■			■				■		
BRP	■				■	■	■	■			■	■	■	■			■	■			■	■	■					■		■	■
CHU			■																												
MOB		■	■					■																							
SOC																															
HAW																								■							
BS					■	■	■	■		■				■	■																
GOA							■	■	■		■																				■
PS	■	■			■																										

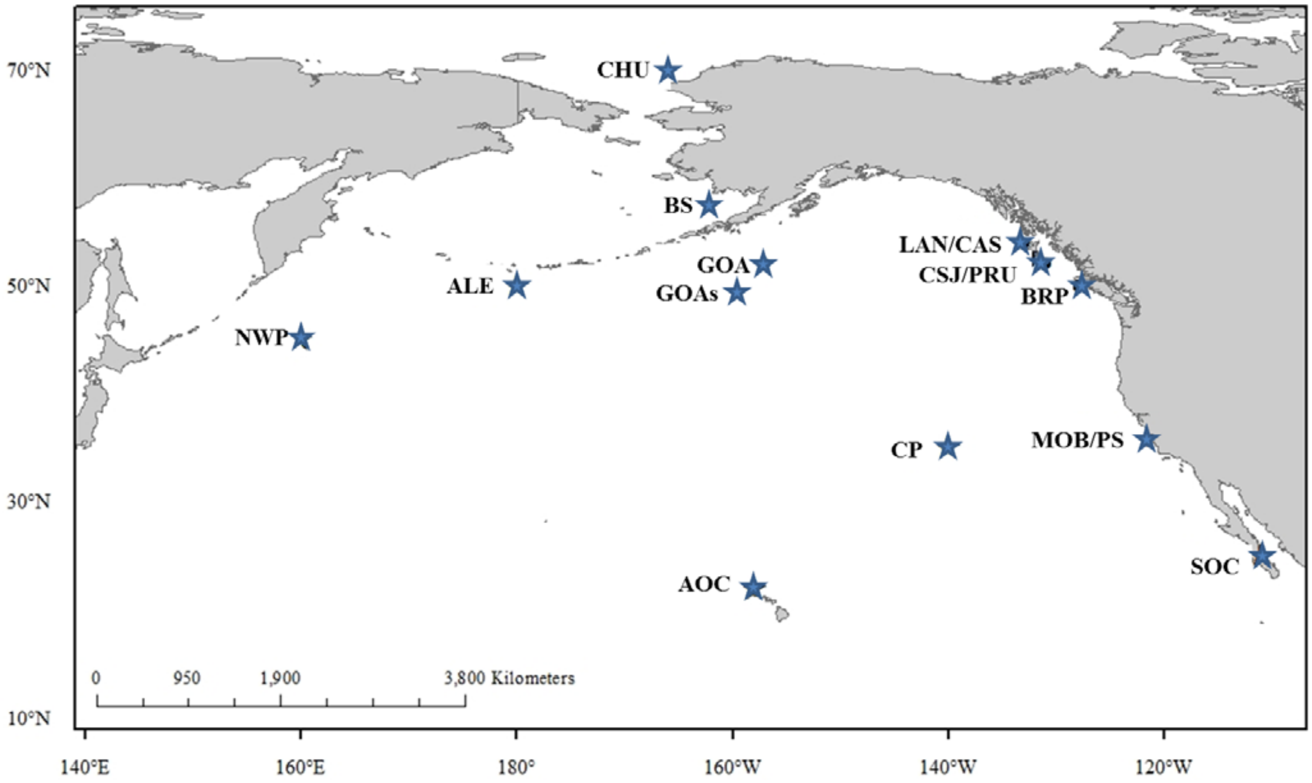
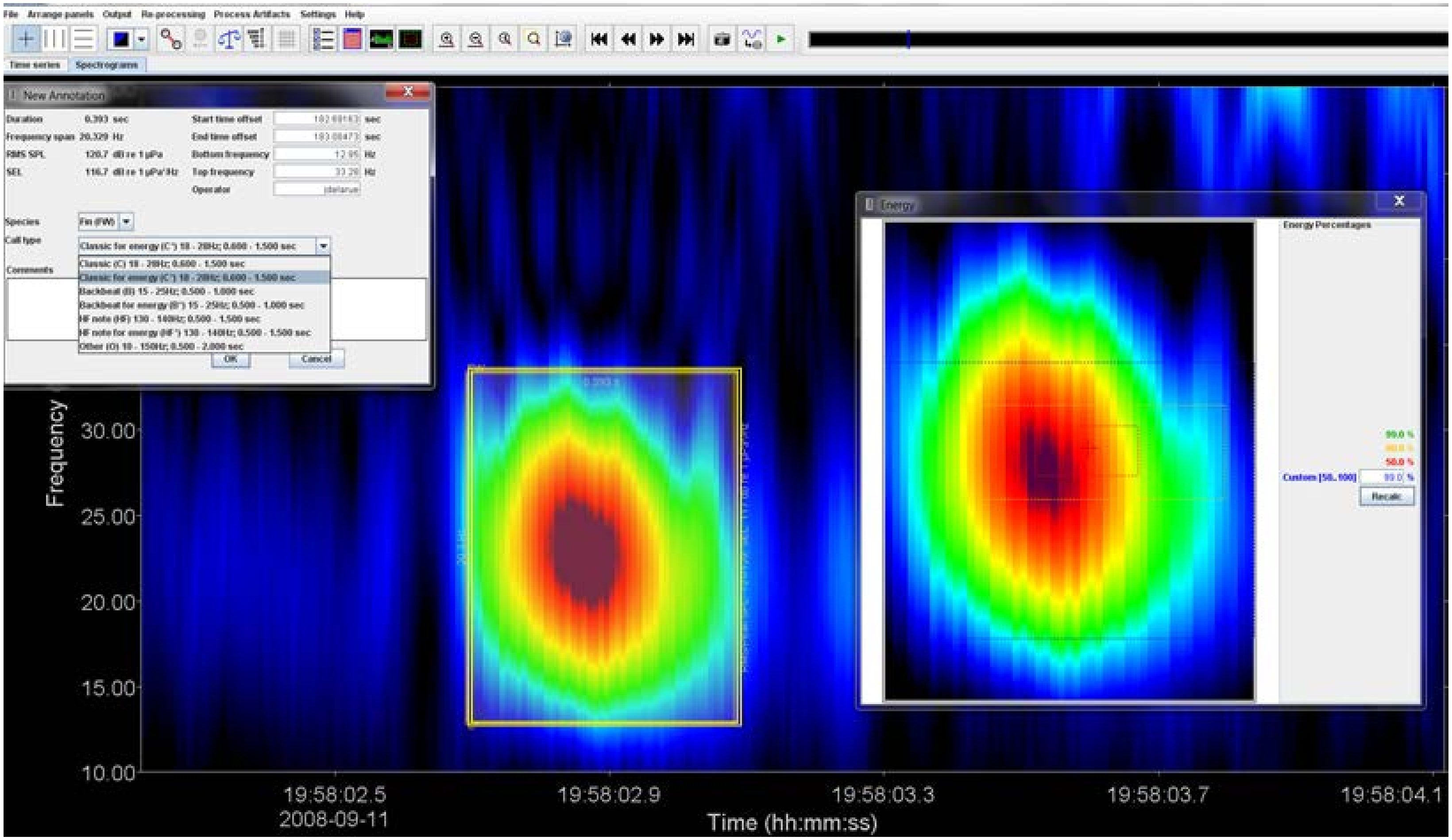


Figure 1. Map of study area and recorder locations. NWP = Northwest Pacific, ALE = Aleutian Islands, CHU = Chukchi Sea, BS = Bering Sea, GOA = Gulf of Alaska, GOAs = Gulf of Alaska (SOSUS), LAN = Langara Island, CAS = Caamano Sound, CSJ = Cape St. James, PRU = Prince Rupert, BRP = Brooks Peninsula, CP = Central Pacific, MOB = Monterey Bay, PS = Pioneer Seamount, SOC = Sea of Cortez, and AOC= Hawaii. The locations of some buoys are paired due to the relatively close proximity of the buoys (given the map scale).



Duration 0.393 sec

Frequency span 20.329 Hz

RMS SPL 120.7 dB re 1 µPa

SEL 116.7 dB re 1 µPa²Hz

Start time offset 182.69163 sec

End time offset 183.08473 sec

Bottom frequency 12.95 Hz

Top frequency 33.28 Hz

Operator jdelarue

Species Fin (FW)

Call type Classic for energy (C') 18 - 28Hz; 0.600 - 1.500 sec

Comments

Custom [50..100] 99.0 %

Figure 2. Fin whale classic note shown in Spectroplotter's spectrogram (surrounded by the yellow rectangle); the annotation pop-up window with the drop-down menu to select note types (left), and the energy percentage window (right) showing the location of the centroid time and frequency (cross), various default energy percentages (dashed rectangles) and the field to enter the user-define energy percentage for measuring bandwidth.

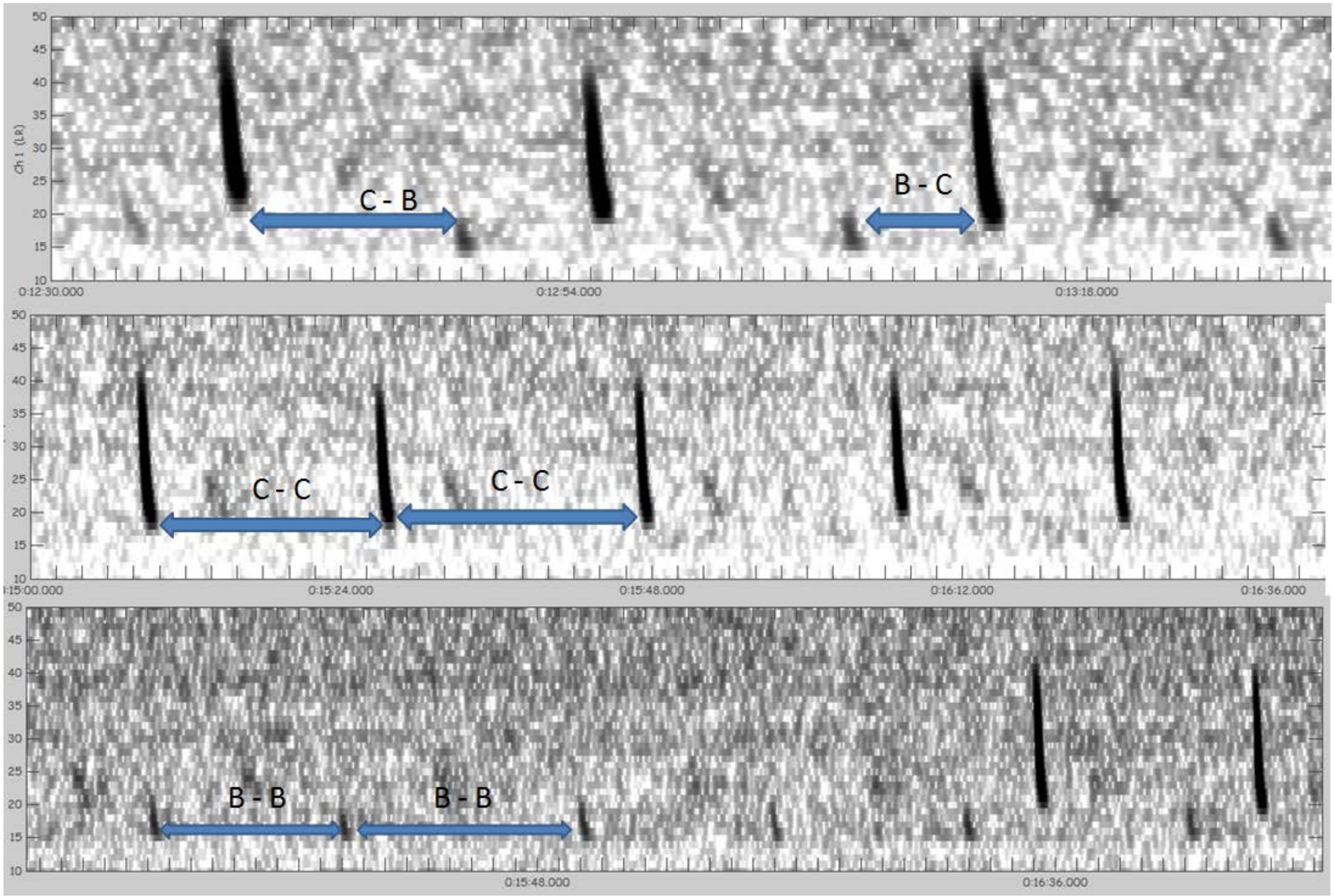
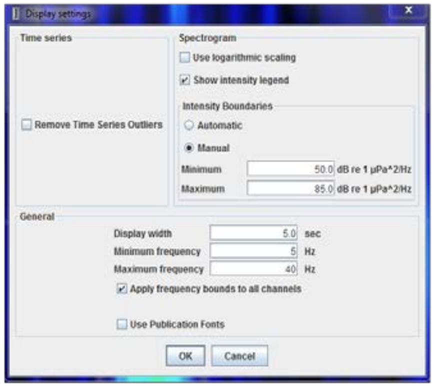


Figure 3. Example of fin whale song showing inter-note-intervals for (a) C-B and B-C, (b) C-C, and (c) B-B, where C is a ‘classic’ fin whale note and B is a ‘backbeat’.

Appendix 1

Example of spectrogram parameters and suggested boxing strategies for fin whale calls of variable quality. This example serves to minimize variation in measurement values due to variations in user-defined boxing of notes.



Time series

☐ Remove Time Series Outliers

Spectrogram

☐ Use logarithmic scaling

☑ Show intensity legend

Intensity Boundaries

○ Automatic

● Manual

Minimum 50.0 dB re 1 μPa^2/Hz

Maximum 85.0 dB re 1 μPa^2/Hz

General

Display width 5.0 sec

Minimum frequency 5 Hz

Maximum frequency 40 Hz

☑ Apply frequency bounds to all channels

☐ Use Publication Fonts

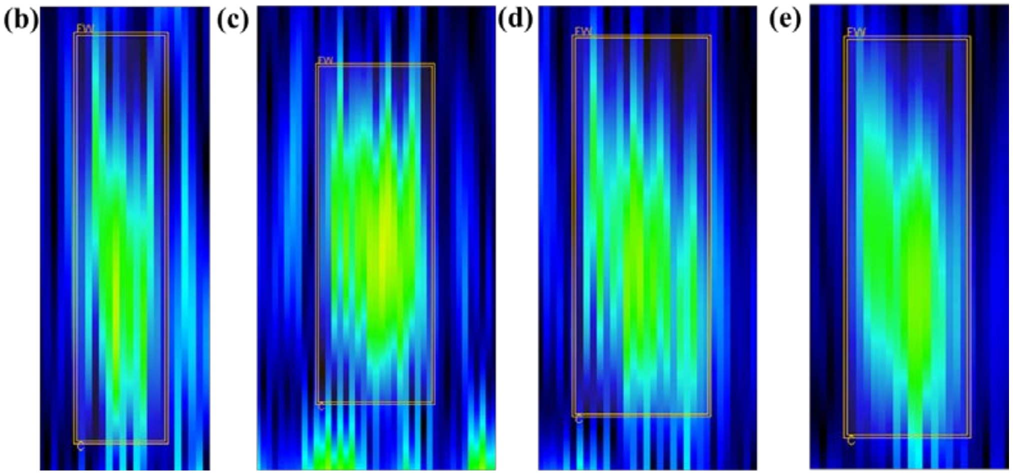
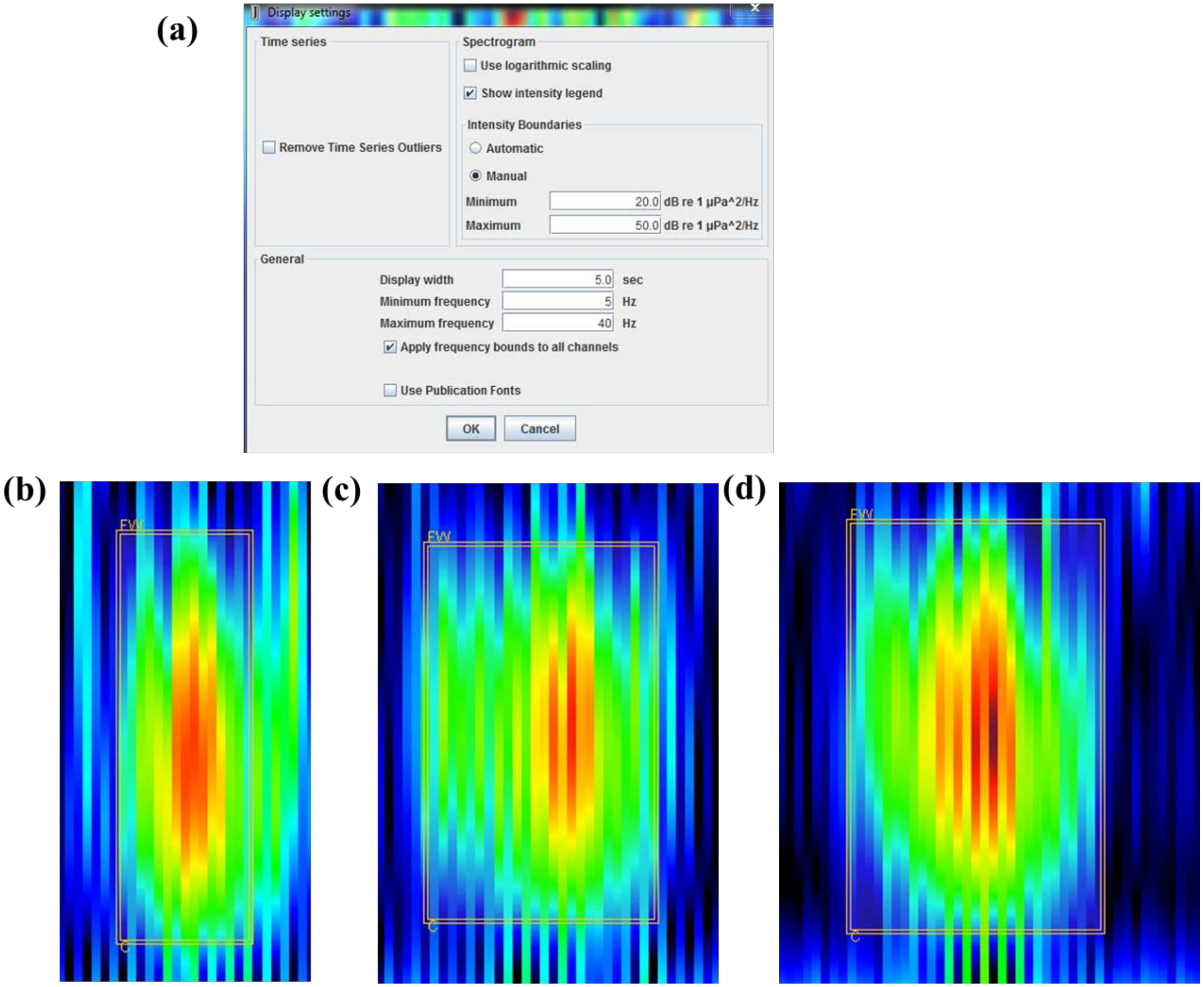


Figure 1. Example of an (a) event box and (b-e) four note selections for low-SNR notes.



Display settings

Time series

☐ Remove Time Series Outliers

Spectrogram

☐ Use logarithmic scaling

☑ Show intensity legend

Intensity Boundaries

○ Automatic

● Manual

Minimum 20.0 dB re 1 µPa^2/Hz

Maximum 50.0 dB re 1 µPa^2/Hz

General

Display width 5.0 sec

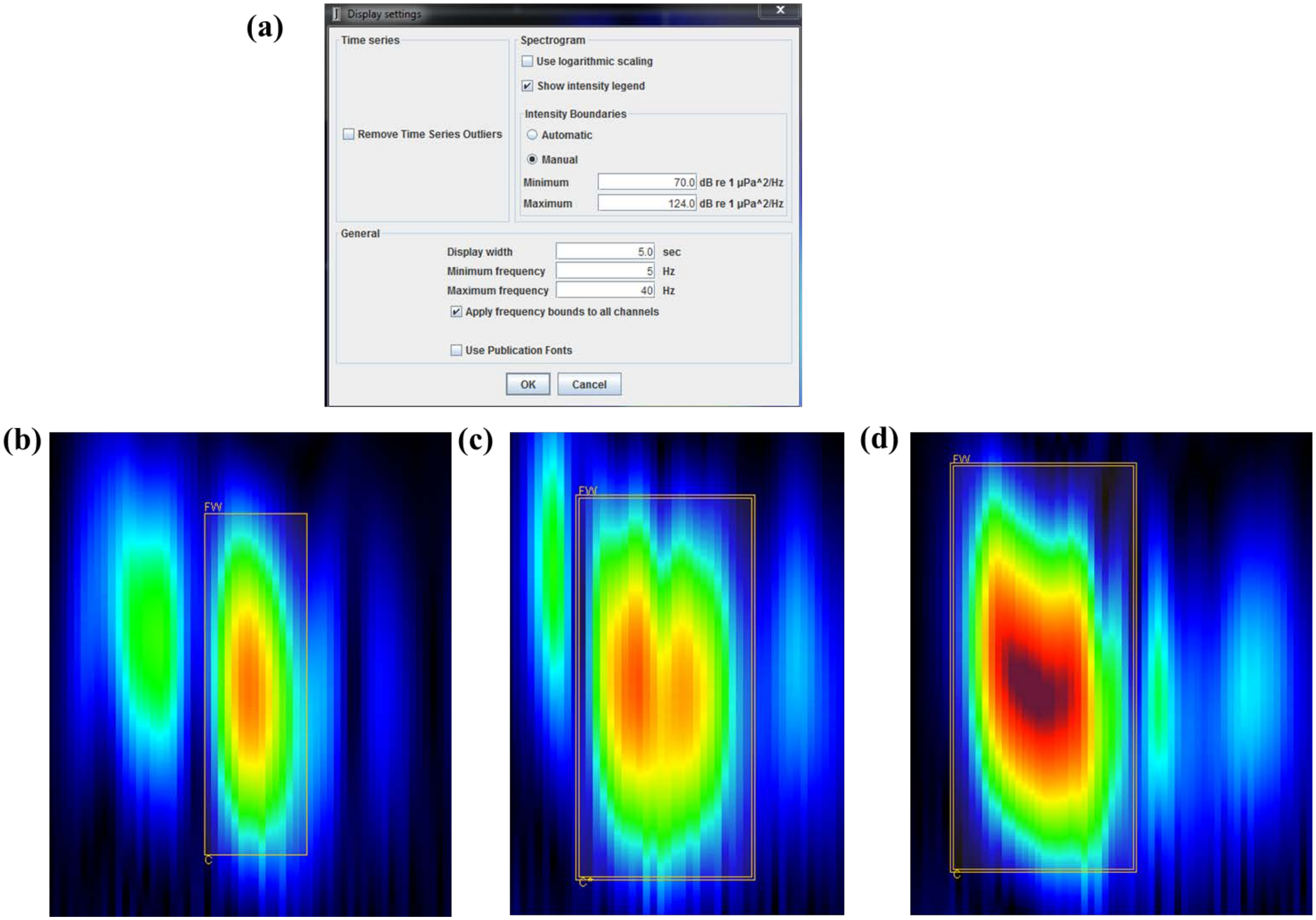
Minimum frequency 5 Hz

Maximum frequency 40 Hz

☑ Apply frequency bounds to all channels

☐ Use Publication Fonts

Figure 2. Example of an (a) event box and (b-d) three note selections for low-quality notes.



Display settings

Time series

☐ Remove Time Series Outliers

Spectrogram

☐ Use logarithmic scaling

☑ Show intensity legend

Intensity Boundaries

○ Automatic

● Manual

Minimum 70.0 dB re 1 μPa^2/Hz

Maximum 124.0 dB re 1 μPa^2/Hz

General

Display width 5.0 sec

Minimum frequency 5 Hz

Maximum frequency 40 Hz

☑ Apply frequency bounds to all channels

☐ Use Publication Fonts

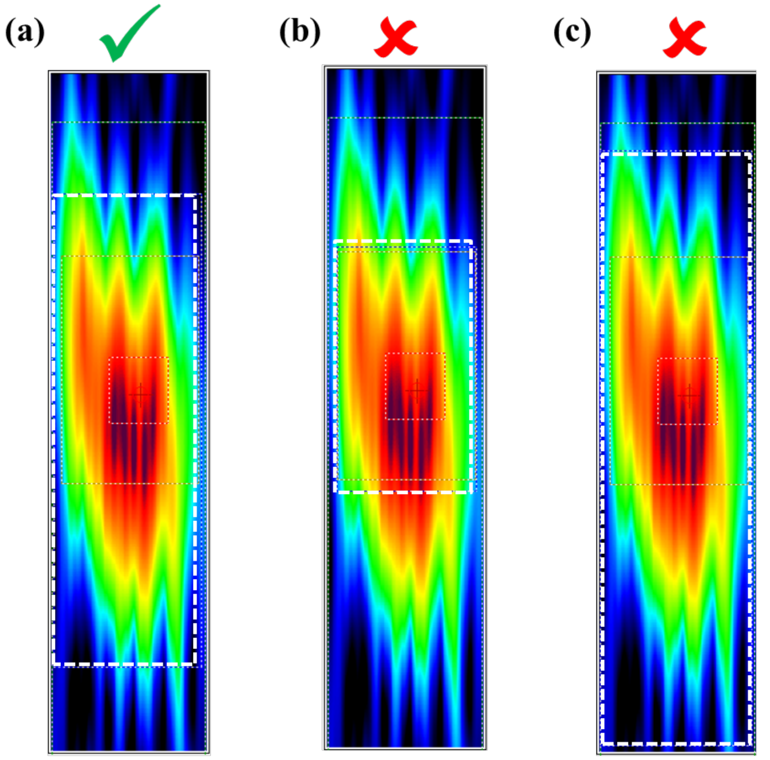
Figure 3. Example of (a) event box and selection of (b-d) three low-quality notes with multi-path, where only the loudest signal is annotated.

Appendix 2

The following examples will serve as a guide for selecting the user-defined (UD) % energy boxes within Spectroplotter.

Maximize the UD % energy window in your screen to improve visibility. Examples of ideal selection (left) and incorrect selection (middle, right) are given for several examples. Specifically, users should consider the following:

1. Do not include multipath, select only the highest SNR signal
2. Try to exclude the same amount of energy above the upper and lower limits of the box (keep the selection symmetrical around the signal).
3. Minimize the amount of background noise in the selection
4. Be sure to include ALL of the signal energy (do not exclude initial or final signal energy).

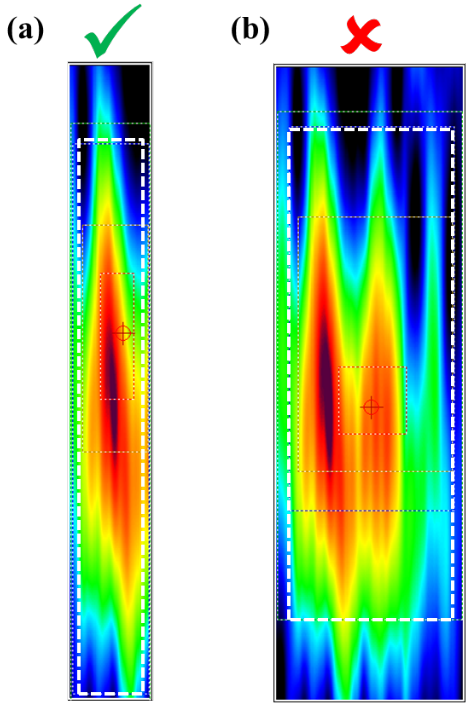


Correct Selection

Too Narrow (Frequency Range)

Too Wide (Frequency Range)

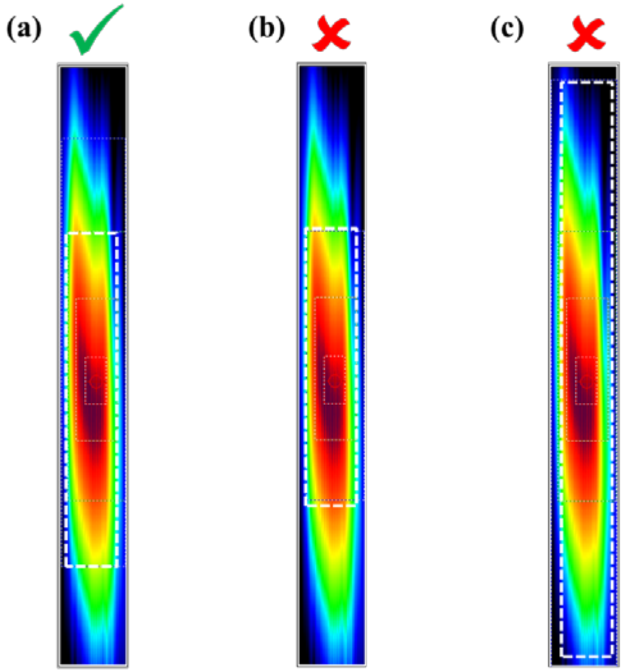
Figure 1. Example of Spectroplotter spectrogram of a high quality classic note. The outer edges of each box correspond to the analyst defined annotation box. The white dashed lines show what this annotation box would look like if only n % of the call energy, as defined by the user, was included. (a) the correct user-defined (UD) % energy encompasses all call energy; (b) the UD % energy misses the upper and lower end of the call bandwith and should be increased, and (c) the UD % energy encompasses more than the signal itself and should be decreased.



Correct Selection

Too Wide
(Includes multipath)

Figure 2. Selection of a note containing a multipath. The white dashed lines show what this annotation box (outer edge) would look like if only n % of the call energy, as defined by the user (UD), was included. The correct UD % energy (a) only include the higher SNR signal arrival. If the UD % eneryg is too high (b) the box will include energy from the multipath arrivals.

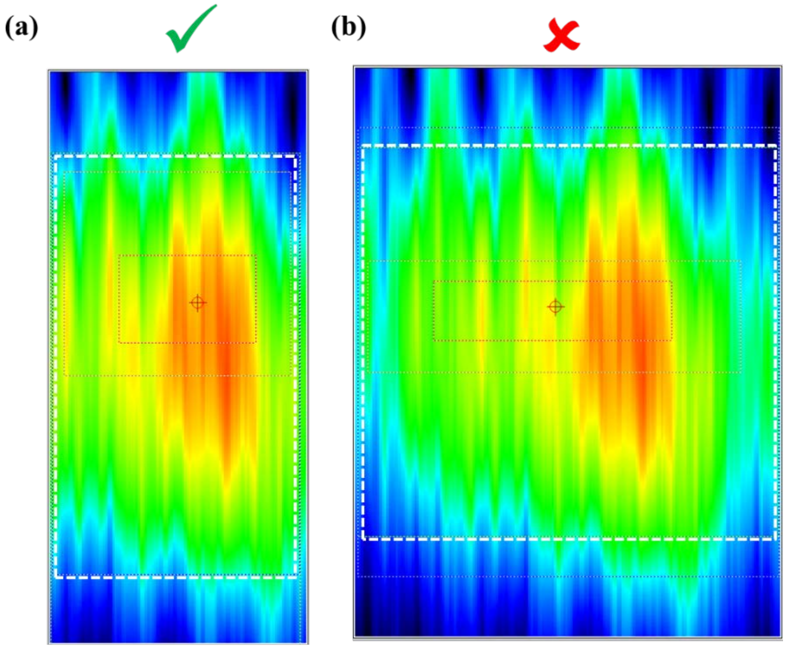


Correct Selection
(SNR ~ 99.9%)

Too Narrow
(Frequency Range, SNR ~ 99%)

Too Wide
(Frequency Range, SNR ~ 100%)

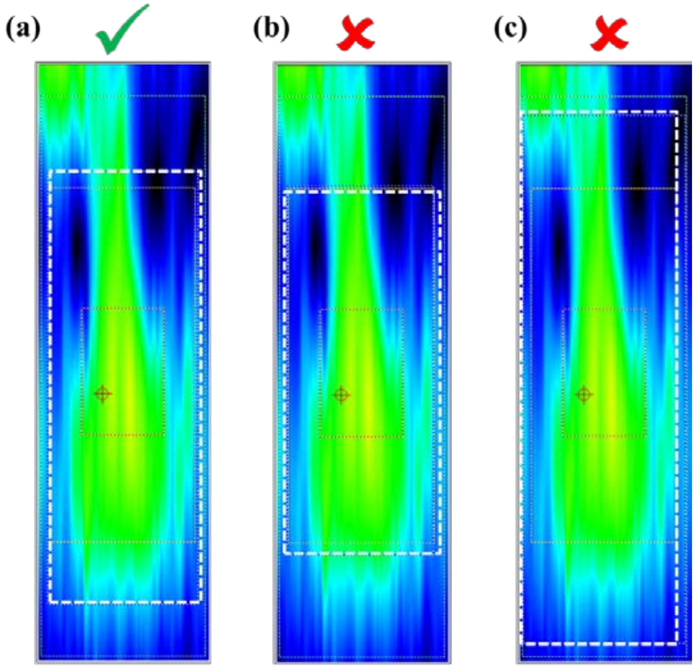
Figure 3. Selection of a high SNR note with (a) correct selection of approximately 99.9% of the energy. If the selection is too narrow (b) it may result in a smaller energy selection (≤ 99%); if the selection is too wide it may result in a larger energy selection (100%). Annotation box is shown as a white dashed line.



Correct
Selection

Too Wide
(Time Domain)

Figure 4. Selection of a low SNR note where (a) the correct UD % energy should result in a narrowed time domain. Selection of a wide time domain (low UD % energy) (b) is not advised for a low SNR note. The white dashed lines show what this annotation box (outer edge) would look like if only n % of the call energy, as defined by the user (UD), was included.



Correct
Selection

Too Narrow
(Frequency Range)

Too Wide
(Frequency Range)

Figure 5. This example shows a low SNR note with noise in upper frequencies. The white dashed lines show what this annotation box (outer edge) would look like if only n % of the call energy, as defined by the user (UD), was included. A correct UD % energy (a) should include as much of the energy from the note as possible, while minimizing energy from background noise. If the UD % energy is too low (b), it excludes too much of the signal energy. If it is too high (c), it will include energy from background noise and noise in upper frequencies.