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NOAA Technical Memorandum NMFS

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COMPARISON OF HARBOR PORPOISE *(Phocoena phocoena)* ECHOLOCATION CLICKS RECORDED SIMULTANEOUSLY ON TWO PASSIVE ACOUSTIC MONITORING INSTRUMENTS

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Eiren K. Jacobson[1], Karlina P.B. Merkens[2],
Karin A. Forney[3], and Jay Barlow[3]

[1]Scripps Institution of Oceanography, University of California, San Diego
[2]Lynker Technologies, under contract to Pacific Islands Fisheries Science Center
[3]Southwest Fisheries Science Center

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U.S. DEPARTMENT OF COMMERCE
Wilbur L. Ross, Secretary of Commerce

National Oceanic and Atmospheric Administration
Benjamin Friedman, Acting NOAA Administrator

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

Abstract

Passive acoustic surveys are a useful tool for long-term assessment of cetacean populations. However, the application of these methods requires that species of interest produce distinctive, well-characterized vocalizations. Several sympatric species of cetaceans produce narrow-band, high-frequency (NBHF) echolocation clicks which are difficult to distinguish. On the U.S. West Coast, Dall's porpoise *(Phocoenoides dalli)* and harbor porpoise *(Phocoena phocoena)* emit NBHF echolocation clicks and overlap in distribution. To determine whether different passive acoustic instruments could be used to monitor harbor porpoise, we recorded harbor porpoise echolocation clicks simultaneously on an autonomous hydrophone recording system (SoundTrap, Ocean Instruments New Zealand) and on a commonly used passive acoustic monitoring device (C-POD, Chelonia Ltd., UK) and investigated whether the number and peak frequency of recorded echolocation clicks were consistent between the two instruments. We found that the number of echolocation clicks recorded by the two instruments was highly correlated. However, the C-POD and SoundTrap measurements of the peak frequency of echolocation signals were not well-correlated. This suggests that while both instruments are capable of detecting harbor porpoise echolocation clicks, it may not be feasible to use C-PODs to discriminate harbor porpoise echolocation clicks in regions where multiple species with NBHF echolocation clicks are present. The use of calibrated hydrophones with full-bandwidth recording instruments may be required for this task.

Introduction

The use of narrow-band high-frequency (NBHF) echolocation signals (Au 1993, Au et al. 1999) has evolved independently in four odontocete lineages (Madsen et al. 2005, Kyhn et al. 2010, Miller and Wahlberg 2013). NBHF echolocation is relatively high-frequency (above 100 kHz), narrow-band (less than 15 kHz at -3 dB), long-duration (greater than 100 μsec), and weak (source levels less than 200 dB). This type of echolocation is used by at least four of the six species of porpoises (genera *Neophocaena*, *Phocoena* and *Phocoenoides*), dwarf and pygmy sperm whales (genus *Kogia*), at least four species of dolphins (genera *Lagenorhynchus* and *Cephalorhynchus*), and one species of river dolphin (genus *Pontoporia*). The convergent use of NBHF echolocation and the loss of whistles among this disparate group of small-bodied odontocetes has likely been driven by the need to avoid passive acoustic detection and predation by killer whales (*Orcinus orca*; Madsen et al. 2005, Morisaka and Connor 2007) which do not hear well above 100 kHz (Szymanski et al. 1999), as well as the need to maintain functional echolocation while avoiding increasing thermal noise and attenuation due to sound absorption at higher frequencies (Madsen et al. 2005, Kyhn et al. 2013). Though these highly stereotyped signals appear identical across species, it is possible that exploitation of different ecological niches or the need for intra-species communication have led to subtle differences in echolocation clicks between sympatric species (Kyhn et al. 2013).

Along the U.S. West Coast, Dall's porpoise (*Phocoenoides dalli*), harbor porpoise (*Phocoena phocoena*), and dwarf (*Kogia sima*) and pygmy (*Kogia breviceps*) sperm whales produce NBHF echolocation clicks (Table 1). Harbor porpoise are found along the continental shelf mostly in water less than 100 m deep (Barlow 1988, Carretta et al. 2001) while Dall's porpoise have a more pelagic distribution and are found in relatively cold water hundreds to thousands of meters deep (Forney 2000). The distribution of dwarf and pygmy sperm whales is poorly characterized but they are thought to be deep-diving and to inhabit waters thousands of meters deep (Baird 2005). Given these depth distributions, some habitat overlap occurs between harbor porpoise and Dall's porpoise and between Dall's porpoise and dwarf and pygmy sperm whales. Therefore, recordings of NBHF clicks in these regions of overlap cannot currently be definitively attributed to a single species.

Harbor porpoise along the U.S. West Coast are monitored using aerial surveys, which are expensive, weather-limited, and therefore, infrequent. If harbor porpoise echolocation signals could be distinguished from Dall's porpoise echolocation signals, harbor porpoise populations along the U.S. West Coast could be assessed using passive acoustic monitoring (PAM), which requires that species of interest produce distinctive, well-characterized vocalizations (Marques et al. 2009). The development of PAM methods is of interest for both long-term monitoring of harbor porpoise populations and short-term impact assessments associated with offshore marine renewable energy projects.

At present, collecting full-bandwidth recordings of NBHF clicks is typically impractical in the context of long-term monitoring due to the prohibitive cost and limited storage capacity of available instruments. The C-POD (Chelonia Ltd.) is an alternative, inexpensive, commonly used echolocation click detector that has been successfully used to monitor the population decline of the critically endangered vaquita *(Phocoena sinus)* in the Gulf of California (Jaramillo-Legorreta et al. 2017) and to estimate the abundance of the critically endangered Baltic Sea harbor porpoise (Gallus et al. 2012). C-PODs detect individual echolocation clicks and store digital summary information about each click. No waveform data are collected, and therefore data storage demands are low and long-term deployment (3-6 mo.) is possible. In post-processing, clicks are classified as belonging to NBHF echolocation trains using characteristics including the peak frequency and duration of clicks along with the inter-click interval (ICI).

If C-PODs are to be used to monitor harbor porpoise populations along the U.S. West Coast, they must be shown to predictably record information about NBHF signals that could be used to discriminate harbor porpoise and Dall's porpoise echolocation clicks. The goal of the present study is to determine whether a C-POD can accurately or consistently record the number and peak frequency of echolocation clicks compared to a simultaneous full-bandwidth recording analyzed using a custom-written MATLAB (v. 2015a; The MathWorks Inc., 2015) click detection and spectra-based click measurement routine.

Table 1: Previously reported measurements (± standard deviation, when available) of echolocation clicks produced by Dall's porpoise, harbor porpoise, and dwarf and pygmy sperm whales. Region indicates whether the measured clicks were recorded from individuals in the Atlantic (A) or Pacific (P). Some measurements were not included in all publications and are reported as NA in those instances.

Species	**Region**	**Peak Frequency (kHz)**	**Source Level (dB *re.* 1 μPa)**	**Duration (μsec)**	**-3dB Bandwidth (kHz)**	**Source**
K. breviceps	A	130±0.7	175	119±19	8±2.3	Madsen et al. 2005
K. sima	A	129±2	NA	222±53	10±2	K.P.B.M unpublished data
K. sima	P	117±3	NA	241±70	11±4	K.P.B.M unpublished data
P. dalli	P	137±4	183±7	104±3	11±5	Kyhn et al. 2013
P. phocoena	A	127.5±7	157.2±6.9	NA	16.4±4.3	Au et al. 1999
P. phocoena	A	135	170	125	7	Madsen et al. 2005
P. phocoena	A	129-145	178-205	44-113	6-26	Villadsgaard et al. 2007
P. phocoena	P	140±1	178±4	88±29	8±3	Kyhn et al. 2013
P. phocoena	A	137±6	178±5	54±8	17± 5	Kyhn et al. 2013

Methods

Data Collection

We deployed a passive acoustic mooring including a SoundTrap 202HF autonomous hydrophone recording system[1] and a C-POD echolocation click detector[2] in Monterey Bay, California, USA on 24 August 2015. We selected a nearshore location in northern Monterey Bay for the mooring deployment (Fig. 1) in an area where harbor porpoise are known to be common (Jacobson et al. 2014, Forney et al. 2014). At this location, the only regularly observed cetacean species are harbor porpoise and bottlenose dolphins (*Tursiops truncatus*). The mooring location was approximately 10-m deep, and the instruments were suspended approximately 5-m below the sea surface. The instruments were attached to each other so that the respective hydrophones were as close as possible to one another (Fig. 2). The SoundTrap recorded continuously with a sampling rate of 576 kHz. The C-POD continuously monitored frequencies from 20 kHz to 160 kHz and recorded parameters associated with click events. The instruments were retrieved on 27 August 2015.

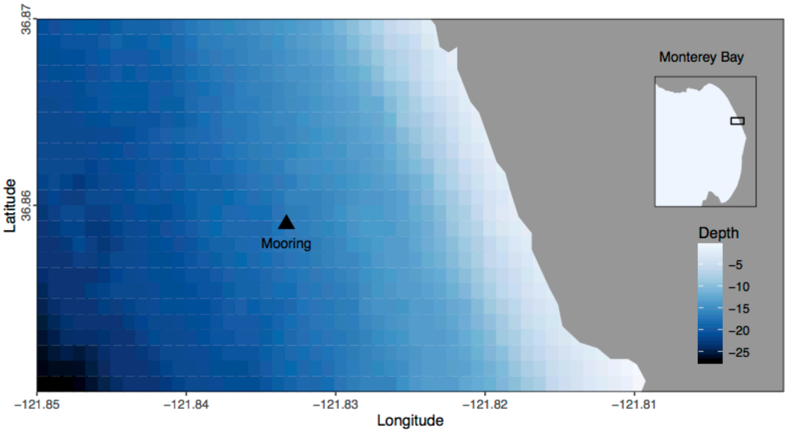

Figure 1: Map of SoundTrap/C-POD mooring location (black triangle) in northern Monterey Bay, CA.

Data Analysis

C-POD data were processed using the KERNO algorithm in the program CPOD.exe (Tregenza 2012) to detect and classify echolocation clicks. The exact algorithm used by the C-POD is proprietary, but in principle it uses a real-time energy detector to detect possible echolocation clicks and stores summary information about those clicks. In post-processing, the KERNO algorithm determines if those clicks are part of cetacean-like series or “trains” of clicks. Click trains are then assigned to a species class based on click characteristics including peak frequency, duration, and ICI, and are assigned a confidence rating based on the consistency of the click train and ambient noise conditions. We considered all narrow-band, high-frequency (NBHF) click trains as belonging to harbor porpoise, and included only clicks from high- and

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[1] Ocean Instruments New Zealand, www.oceaninstruments.co.nz.

[2] Chelonia Ltd., www.chelonia.co.uk

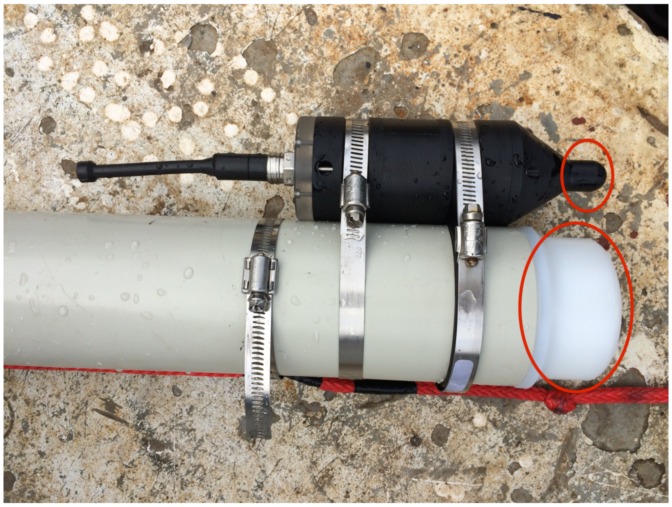

Figure 2: SoundTrap (black, top) and C-POD (white, bottom) attached for deployment. Red ovals indicate approximate hydrophone locations on each instrument. The instruments were attached to a nylon line with a surface float and 50-lb anchor weight for deployment.

moderate-quality click trains in our analyses. EKJ manually validated these click trains in the program CPOD.exe. Because no waveform data are collected by the C-POD, the program CPOD.exe uses a zero-crossings approach to calculate peak frequency. This technique uses the time between successive zero-crossings of the incoming waveform to calculate the frequency of the signal and ignores the amplitude envelope of the original signal (Parsons et al. 2000). Based on previously published peak frequency values for harbor porpoise echolocation clicks (Table 1) and for consistency with the analysis of SoundTrap data, we eliminated echolocation click detections with peak frequencies less than 120 kHz and greater than 150 kHz. Click details were exported from CPOD.exe to a text file for further analysis in R[3].

Sound files collected using the SoundTrap were processed using a custom-written MATLAB click detection and measurement routine[4] modified from Soldevilla et al. (2008) and Roch et al. (2011). SoundTrap data were not corrected for frequency-specific sensitivity; however, we calibrated the SoundTrap relative to a Reson TC4014 reference hydrophone and found the response to be flat ($\pm$ 1 dB re. 1 μPa/V) from 75 to 150 kHz. In summary, the MATLAB detection and measurement routine uses an energy detector to detect possible echolocation clicks and generates spectra from which click parameters are calculated. Candidate clicks are pruned according to user-specified parameter ranges for the species of interest including minimum and maximum peak frequency; we pruned candidate clicks with peak frequencies below 120 kHz and above 150 kHz. Concatenated spectrograms of resulting click detections were visually validated (see Fig. 3 for example). Data were exported from MATLAB for further analysis in R.

We calculated the total number of harbor porpoise echolocation clicks recorded by the C-POD and by the SoundTrap/MATLAB routine as well as the average peak frequency of recorded echolocation clicks. We also plotted the distribution of peak frequencies recorded by each instrument. For each hour during which the instruments were deployed, we calculated the number of echolocation clicks recorded by each instrument and the corresponding proportion of seconds during which harbor porpoise were detected (porpoise-positive seconds; PPS) per

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[3] version 3.2.2, www.r-project.org

[4] An archived version of the code used can be found at http://doi.org/10.5281/zenodo.164881.

hour.

In addition to comparing average click characteristics recorded by the two instruments, we were also interested in examining whether and how individual echolocation clicks were simultaneously recorded by both instruments. Directly matching timestamps between clicks detected on the two instruments is not possible because of clock drift in both instruments. To align the data sets, we divided the first 24 h of data into 5-min bins. Within each bin, we tested clock offsets between the instruments of -2 sec to +2 sec in increments of 1 ms. We used the number of clicks matched between instruments with each offset as an indicator of the offset accuracy. To be considered a match, click timestamps on the two instruments had to be within 0.5 ms of each other after offset correction. These parameters are stringent in the context of harbor porpoise echolocation clicks; reported ICIs are on the order of 50 ms (Villadsgaard et al. 2007) and click durations on the order of tens of μsecs (Table 1). An optimal offset (defined as the offset producing the highest number of matched clicks) was selected for each 5 min bin. After offset, at least 5 clicks within each 5-min bin had to match between instruments to be considered valid. Data from bins which did not meet this criterion were discarded. We used the optimal offsets to correct timestamps within each 5-min bin, then matched individual clicks between instruments, and finally, compared the peak frequency recorded by each instrument for each matched click. Because of the computer-intensive nature of this procedure, only the first 24 h of data were analyzed.

Results and Discussion

The C-POD and SoundTrap were co-deployed for 75 h in northern Monterey Bay, California, USA. At the time of deployment, tens of harbor porpoise were present and appeared to be foraging near the mooring site. Over the 75-h deployment period, the MATLAB routine detected 229,376 harbor porpoise echolocation clicks in the SoundTrap recording (Fig. 3). The C-POD detected 202,390 echolocation clicks during the same time period. Qualitatively, patterns of harbor porpoise echolocation activity were similar between instruments (Fig. 4) and correlations between the number of echolocation clicks or the PPS recorded by each instrument per hour were high ($R^2 = 0.95$ for both; Fig. 5). The mean peak frequency of clicks recorded by the SoundTrap/MATLAB routine was 139.13 kHz (SD = 6.08) while the mean peak frequency of clicks recorded by the C-POD within the range of 120–150 kHz was 135.93 (SD = 5.62). The distribution of peak frequencies recorded by the C-POD appears to be unimodal around the mean, while the distribution of peak frequencies recorded by the SoundTrap/MATLAB may be bimodal, with peaks at 136 kHz and 141 kHz (Fig. 6). A Kolmogorov-Smirnov test rejected the null hypothesis that these distributions could have been drawn from a single overlying distribution (p-value < 0.001). The only published estimate of Pacific harbor porpoise echolocation click peak frequency (Tab. 1; Kyhn et al. 2013) is 140 kHz, which is closer to the average peak frequency calculated by the SoundTrap/MATLAB than to the average peak frequency calculated by the C-POD. Kyhn et al. (2013) used only on-axis echolocation clicks to calculate peak frequency, resulting in a much more precise estimate (mean = 140 kHz, SD = 1 kHz) than our SoundTrap measurements (mean = 139.13 kHz, SD = 6.08 kHz).

Previous studies (e.g., Kyhn et al. 2013) have recorded thousands and analyzed tens or hundreds of clicks; we recorded and analyzed more than 200,000 echolocation clicks. The C-POD and SoundTrap/MATLAB did not record the same number of echolocation clicks, probably due to different sensitivities of the hydrophones and of the echolocation click detection algorithms (e.g., threshold amplitudes for click detection were not identical). The two instruments reported similar patterns in echolocation click activity over the 3-day period (Fig. 4) and the number of echolocation clicks recorded was highly correlated between instruments (Fig. 5),

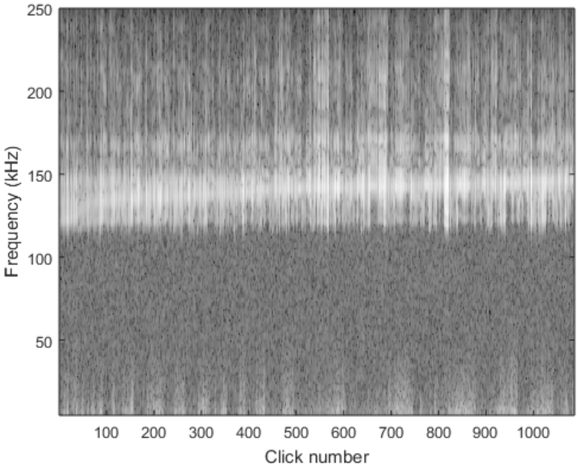

Figure 3: Representative concatenated spectrogram of 1086 harbor porpoise clicks detected by the MATLAB routine in a 30 min SoundTrap recording and sorted by peak frequency.

indicating that the instruments are probably similarly reliable for the purpose of monitoring harbor porpoise presence. Visual examination of detected echolocation clicks indicated no false positives in either dataset, though the instruments may have detected multipath arrival of single echolocation clicks in some instances.

Within each 5-min bin used to test instrument timestamp offsets (Fig. 7) the range of optimal offsets was between -0.56 and +1.9 sec (Fig. 8). The consistency of optimal offsets from one time bin to the next gives us confidence that this matching technique was successful. Drift in the clocks of both instruments are apparent and non-linear over time, with periods of stability or gradual drift followed by large shifts in the clock alignment (e.g., the approx. 1-sec jump in alignment at 00:00 on 25 August). Due to the nonlinearity of the observed instrument clock drift, simply correcting instruments relative to synchronization at the start and end of a deployment would not be sufficient to match individual echolocation clicks recorded on two instruments. Regular synchronization of the two instruments during the deployment period (e.g., with a pinger programmed to ping every minute) would allow for a better and echolocation-independent alignment of the two datasets.

Within the first 24-h period, 19% of individual echolocation clicks were successfully matched between the two instruments (N = 17,825). This relatively low match rate could be due to the extremely high directionality of harbor porpoise echolocation clicks resulting in few simultaneous arrivals at the two instruments, or to overly stringent matching criteria that excluded “true” matches from the data set. It is also possible that the instruments shadowed one another so that some clicks arrived at only one instrument.

The mean peak frequency of echolocation clicks recorded by the C-POD was lower than that of those recorded by the SoundTrap/MATLAB when averaged over the entire deployment period (C-POD mean = 135.93, SoundTrap/MATLAB mean = 139.13 kHz) but very similar when individual echolocation clicks were matched between instruments (C-POD mean = 137.10 kHz, SoundTrap/MATLAB mean = 137.74 kHz). However, the peak frequencies of individual matched clicks were not well-correlated ($R^2 = 0.27$; Fig. 9).

Our MATLAB routine used an FFT-based method to calculate peak frequency of echolocation clicks, while the C-POD used a zero-crossings approach. The FFT-based method calculates the peak frequency by weighting the different frequencies present in a signal by their

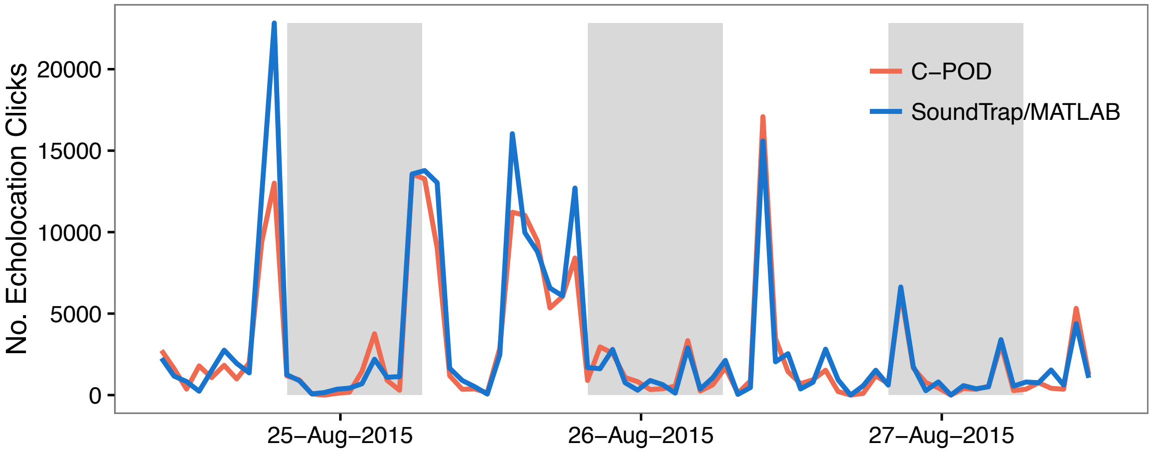

Figure 4: Number of harbor porpoise echolocation clicks recorded per hour by the C-POD (orange line) and the SoundTrap/MATLAB detector (blue line) over the 3 d deployment period. Gray shading indicates local nighttime (time between sunset and sunrise).

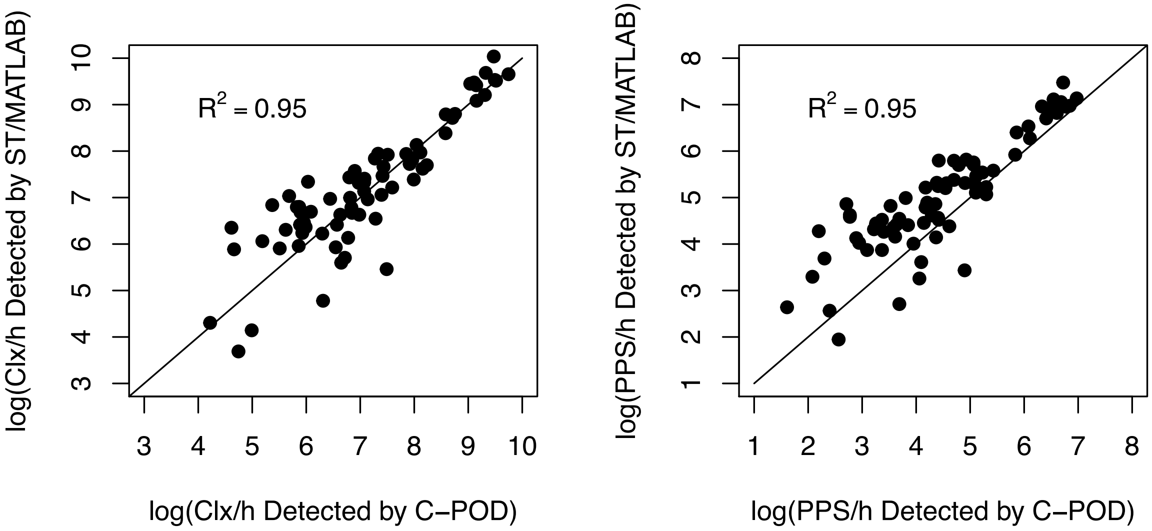

Figure 5: Log-transformed comparison of the number of echolocation clicks detected by each instrument per hour (left panel) and the number of porpoise positive seconds (PPS) detected by each instrument per hour (right panel) with correlations for each comparison and a one-to-one line (black) indicating perfect agreement.

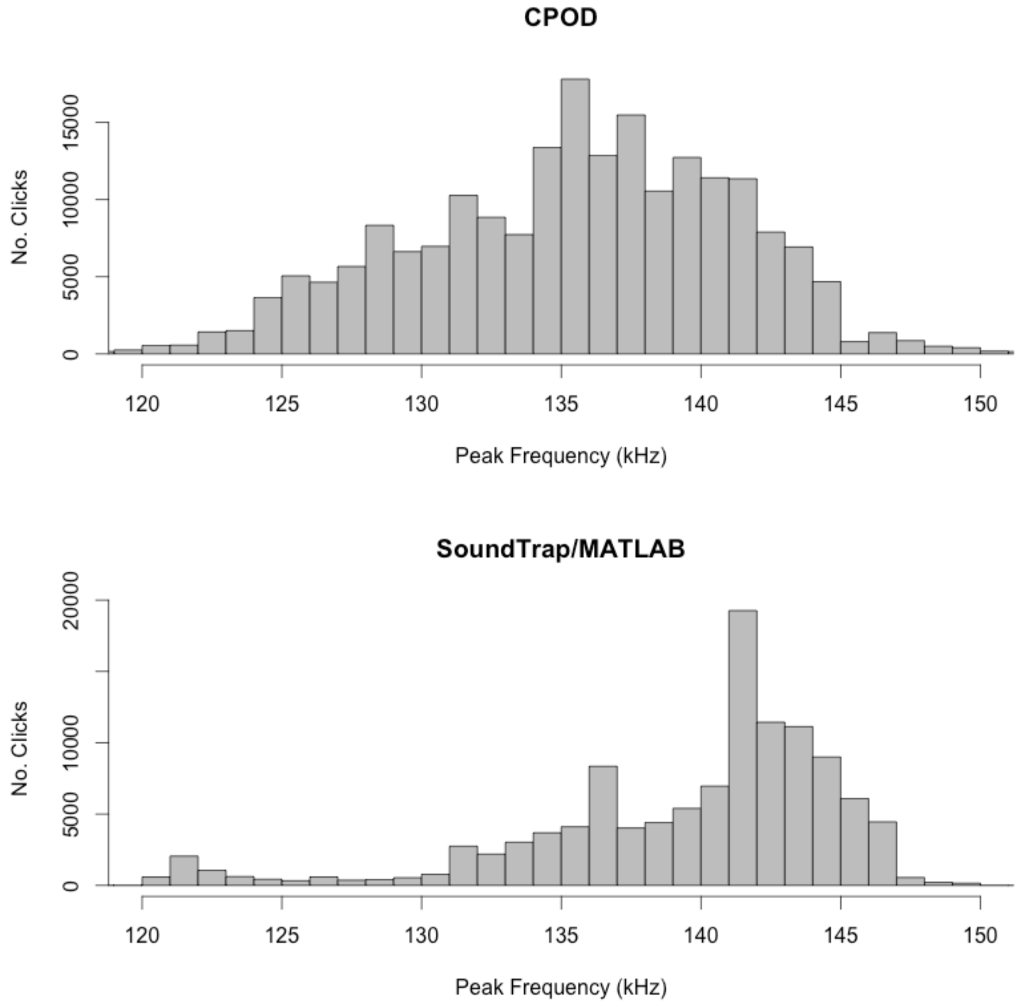

Figure 6: Histograms illustrating the distribution of click peak frequencies recorded by the C-POD (top panel) and the SoundTrap/MATLAB (bottom panel) within the range of 120-150 kHz.

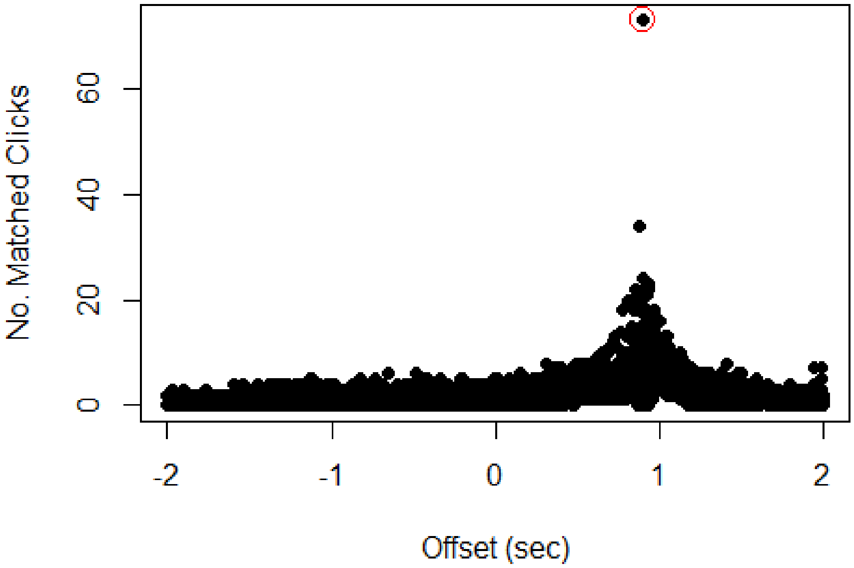

Figure 7: Example of tested offsets between the SoundTrap and C-POD (*x*-axis) and the number of matched clicks resulting from that offset (*y*-axis) within a single 5-min bin. The offset which produced the highest number of matches within this bin is indicated by a red circle.

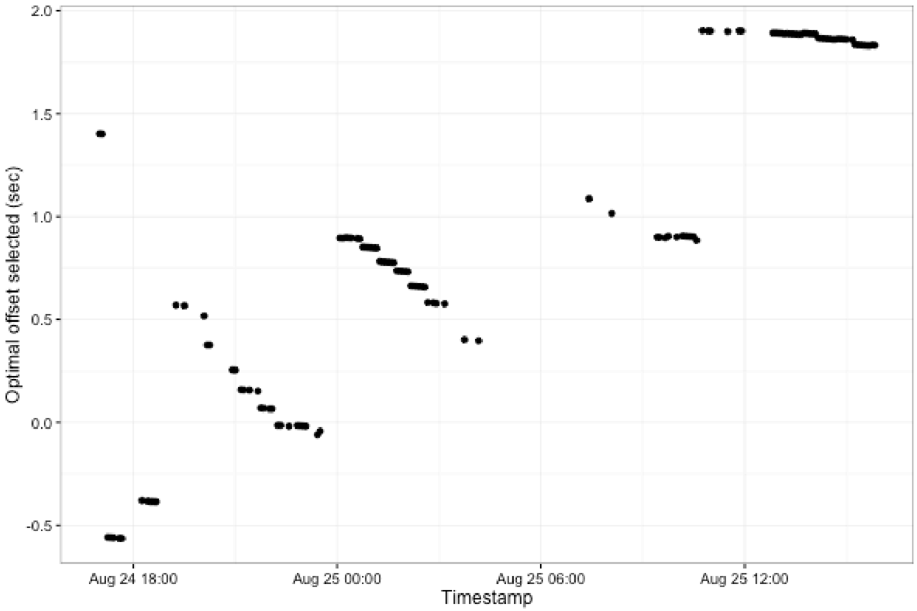

Figure 8: Time series of optimal offsets (*y*-axis) calculated within each 5 min bin over a 24-h period (*x*-axis).

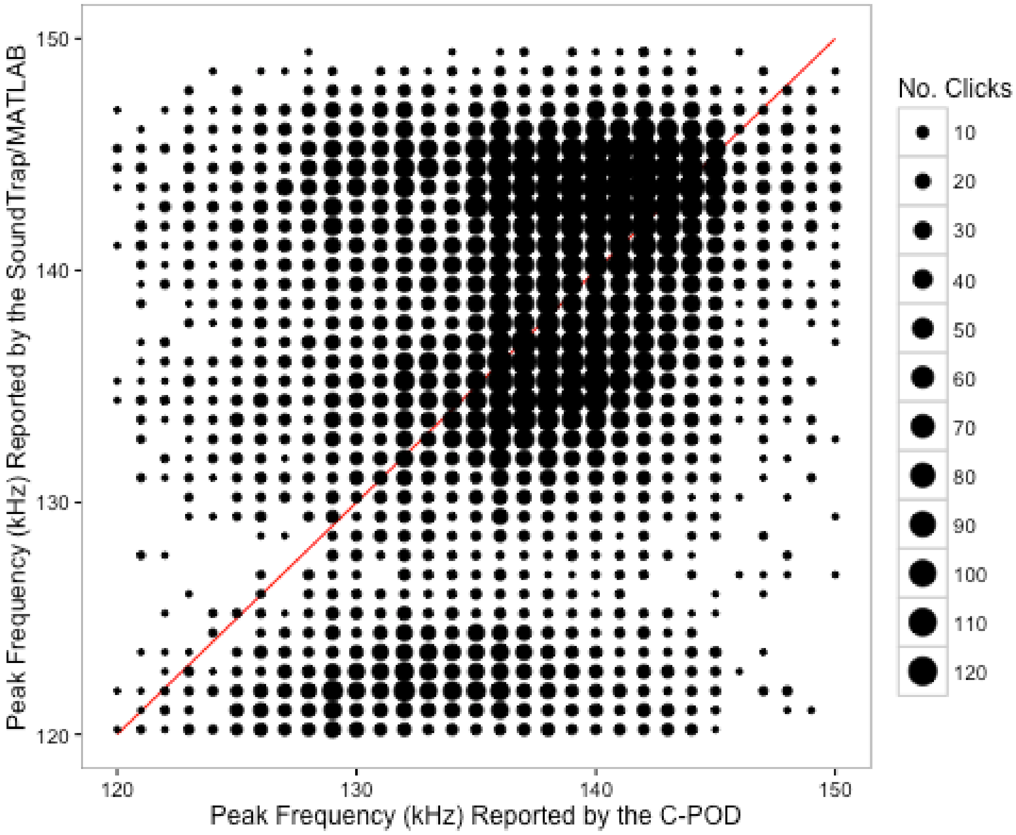

Figure 9: Comparison of measured peak frequencies of matched harbor porpoise echolocation clicks recorded by the C-POD (*x*-axis) and the SoundTrap/MATLAB routine (*y*-axis) over a 24-h period. The size of the point indicates the number of matched clicks, and the red line indicates perfect agreement between the measurements.

amplitudes, so that higher amplitude components of the signal are more influential to the measurement of peak frequency than lower amplitude components. The zero-crossings approach ignores the amplitude variation in the signal and only analyzes the most energetic part of the signal. Because the zero-crossings approach does not capture the frequency-time information of the original signal, it produces less accurate estimates of the peak frequency of the signal (Parsons et al. 2000). For very narrow-band clicks, zero-crossings and spectral methods should produce similar estimates of peak frequency, but as clicks become more broadband the zero-crossings approach to calculating peak frequency becomes more of an approximation.

In our data set, the difference in mean peak frequency recorded by the C-POD versus the SoundTrap/MATLAB of all echolocation clicks was 3.2 kHz. This is a small difference, but similar in magnitude to the difference in peak frequency between Dall's porpoise and harbor porpoise echolocation clicks (3 kHz; Tab. 1; Kyhn et al. 2013). Additionally, it does not appear that the C-POD is reporting consistently lower peak frequencies than the SoundTrap/MATLAB. If this were the case, we would expect to see the same distribution in the histograms of peak frequency shown in Fig. 6, but with the histogram of peak frequencies recorded by the C-POD shifted to have a lower mean. Furthermore, as shown in Fig. 9, there is low correlation (R^2 = 0.27) between the peak frequencies of individually matched echolocation clicks, although this may be partly due to the difficulty in simultaneously detecting echolocation clicks on both instruments or to inaccurate synchronization between instruments.

Summary and Conclusions

Harbor porpoise echolocation clicks were simultaneously recorded on a hydrophone (SoundTrap 202HF) and a passive acoustic monitoring device (C-POD) in Monterey Bay, California, USA over a 3-day period. SoundTrap data were processed using a custom-written MATLAB click detection and measurement routine while C-POD data were processed using the KERNO classifier within the proprietary software CPOD.exe. The time series of echolocation activity reported by the co-deployed instruments were highly correlated ($R^2 = 0.95$), although the absolute number of echolocation clicks detected by the SoundTrap/MATLAB was 13% greater than that detected by the C-POD/KERNO classifier. The average peak frequency of echolocation clicks reported by the C-POD was 3.2 kHz lower than that reported by the SoundTrap/MATLAB. However, this difference was not consistent at the level of individually matched echolocation clicks; correlation in peak frequencies of individually matched clicks was poor ($R^2 = 0.27$). The C-POD uses a more computationally efficient method to detect echolocation clicks and to calculate peak frequencies, but this efficiency comes at the expense of detailed information about the echolocation signals, making it difficult to accurately measure species-identifying features of echolocation clicks. Based on these findings, we do not think it will be feasible to monitor harbor porpoise using C-PODs in areas with multiple NBHF species; however, we recommend further data collection and analysis to support or refute this preliminary conclusion.

Future Directions

Regional variation has been observed in echolocation signals of NBHF species (Tab. 1). The extent and magnitude of this variation is not well-resolved. A collaborative effort to collect and analyze recordings from different NBHF species and regions using a variety of instruments, particularly when multiple instruments can be deployed simultaneously, would be useful to researchers hoping to use PAM for long-term monitoring of NBHF species. In the present study, we focused on peak frequency as a possible metric for distinguishing harbor porpoise from Dall's porpoise echolocation clicks; however, other metrics (e.g., bandwidth, duration, and ICI; see Kyhn et al. 2013) might prove more useful in distinguishing NBHF echolocation clicks produced by different species. Further, two new technologies may replace C-PODs as the default instrument for PAM of harbor porpoise. The F-POD (Chelonia Ltd., UK) is an extension of the C-POD which records full waveform data when echolocation clicks are detected. This instrument is currently under development and might be a good option in areas where it is necessary to distinguish multiple species with similar echolocation signals. Additionally, firmware for click detection-triggered recording has been developed for the SoundTrap (Ocean Instruments New Zealand), which would extend the deployment duration and could make it possible to use this instrument for long-term PAM.

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