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The role of accelerometer hardware limitations in focal caller identification from acoustic recording tags attached to mysticetes

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ABSTRACT:
Multi-sensor acoustic tags have revolutionized our understanding of the behavior of large whales. One limitation, however, is the inability to reliably distinguish calls produced by the tagged whale from those produced by other nearby whales. One proposed solution has been to detect calls using both hydrophone and accelerometer data to identify signals produced by the tagged animal. Some high-amplitude low-frequency calls can be detected with accelerometers, but the success in using this approach with all calls within and across species is variable. Here, we provide guidance on the role of the physics of sound propagation and the tag hardware's accelerometer capabilities for successful application of this method with examples from tag data collected from fin whales (*Balaenoptera physalus*), blue whales (*B. musculus*), and southern right whales (*Eubalaena australis*). Of 1190 high amplitude calls believed to likely be from the tagged animal, only 517 were also detected on the accelerometer. Reasons for lack of detection were primarily the frequency of the signal lying outside the usable frequency detection range of the accelerometer on the tag, indicating selection of appropriate hardware capabilities are critical for this approach.
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I. INTRODUCTION

Marine mammals, including cetaceans, use sound in many aspects of their lives, and these sounds can be used to gain insight into their ecology (Erbe and Thomas, 2022; Zimmer, 2011). Sounds produced by vocally active marine mammals can be monitored using passive acoustic sensors installed on different platforms to obtain information on their presence, distribution, and behavior (Van Parijs *et al.*, 2009; Davis *et al.*, 2020). Passive acoustic monitoring (PAM) allows for large-scale environmental and population monitoring; therefore, it has become a crucial tool for studying marine mammal populations (Mellinger *et al.*, 2007). Baseline information on individual sound production behavior is necessary to make ecological inferences from PAM data. Multisensor tags for the study of marine mammal vocal behavior were first developed in the 1990s (Burgess, 2009; Burgess *et al.*, 1998; Johnson and Tyack, 2003) and have become increasingly sophisticated with advances in miniaturized electronics and battery power. These tags synchronously collect acoustic, environmental, and animal movement data that can provide insight into the acoustic behavior of individual tagged animals [e.g., Burgess (2009) and Johnson *et al.* (2009)]. Tags that can record audio for several week have been developed, allowing for long-term data collection on individual's behavior and sound production (Mikkelsen *et al.*, 2019; Parks *et al.*, 2019). The potential to detect animal calls without audio, using the accelerometer on the tags, could further extend the duration of tag data collection when battery or memory are a limiting factor.

Multisensor acoustic tags have revolutionized our understanding of the acoustic ecology of free-ranging marine mammals, but challenges remain in unequivocally assigning recorded high amplitude calls to the whale carrying the tag. This challenge has limited the ability to calculate individual call rates in baleen whale species from these tags (Lewis *et al.*, 2018) which is a requirement for estimating animal density from PAM (Marques *et al.*, 2013). A range of methods have been employed to minimize the incorrect assignment of high amplitude calls to the tagged whale, including signal-to-noise (SNR) thresholds and visual confirmation of a whale being separated from conspecifics at the time of call production (Parks *et al.*, 2011; Lewis *et al.*, 2018). Both methods have limitations. Whales in close physical proximity with the tagged animal may produce signals that would be received with high SNR on a tag, and call rates from periods when a whale is alone bias data sampling to particular behavioral states and exclude data from periods of close social interactions limiting the

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applicability of findings. Another proposed solution to increase confidence in assigning calls to individuals has been to use the tag's inertial sensors to support focal caller assignment (Goldbogen *et al.*, 2014). Most multi-sensor acoustic tags have 3-axis accelerometers. These accelerometers measure motion and postural acceleration and detect vibrations transferred to the tag. When using the accelerometer method to assign calls to a tagged whale, previous studies have inferred that vibrations detected on the accelerometer come from vibrations generated by the acoustic signal production of the tagged whale.

The accelerometer method for detecting calls from the tagged animal faces three major challenges. First, due to the Nyquist sampling theorem, the sampling rate of the accelerometer must be a minimum of 2× the frequency of the signal of interest to successfully detect a sound. Acoustic sensors typically offer wide acoustic bandwidths, often reaching tens or even hundreds of kHz. In contrast, accelerometers in these tags, which are designed to detect body movement, have generally been sampled at low rates of 50 Hz yielding Nyquist frequencies <25 Hz. This explains why the accelerometer method has been used primarily with low frequency species such as blue (*Balaenoptera musculus*) and fin whales (*Balaenoptera. physalus*) that produce low frequency calls that are within the Nyquist frequency cut off for accelerometer sampling (Goldbogen *et al.*, 2014; Oestreich *et al.*, 2020). For higher frequency baleen whale species with calls > 100 Hz, such as the humpback whale (*Megaptera novaeangliae)*, accelerometers have detected calls produced at high amplitudes and within the Nyquist sampling frequency of the system as well as aliased calls in the Acousonde tag system with a built-in anti-alias analog filter for the accelerometer at 1.6 kHz (Stimpert *et al.*, 2020). Second, the lower sensitivity of accelerometers to acoustic vibrations and the received level and SNR of the calls affects the magnitude of the accelerometer signal and the ability of the signal to be separated from the background noise (Stimpert *et al.*, 2020). Further, when a whale in close physical proximity to a tagged whale produces a high-intensity call, the vibrations from the call may be transferred through the medium to another individual's body (Goldbogen *et al.*, 2014, Saddler *et al.*, 2017). Finally, the wavelengths of whale calls, particularly for blue and fin whales, are considerably greater than the animal's body size. Despite these challenges, the accelerometer method has been implemented to assign focal calls in baleen whales with variable success for distinct species, call types, and tag types (Goldbogen *et al.*, 2014; Saddler *et al.*, 2017; Stimpert *et al.*, 2020).

An aspect that has been previously overlooked in discussion of the use of the accelerometers to assign calls to tagged whales is the accelerometer's hardware limitations. To limit aliasing of higher frequency signals, to decrease noise, increase the storage speed, and decrease the memory space needed for acceleration data, accelerometers have built-in low-pass hardware filters that can further attenuate signals that are below the sensor's Nyquist sampling frequency. Different accelerometers have different filters, and different tags are equipped with accelerometers with distinct hardware capabilities. These hardware capabilities may explain the variable success in using the accelerometer method to assign calls to focal whales in different studies in the past [e.g., Saddler *et al.* (2017) and Stimpert *et al.* (2020)].

In this paper, we explore the theoretical challenges for acoustic vs accelerometer detection in tag data of low frequency signals produced by baleen whales. We predict that accelerometer detection of acoustic signals produced by whales will be limited by the hardware capabilities, with higher amplitude and lower frequency signals detected by a wider range of tag types than calls that are lower amplitude and higher in frequency. We explored the variability in the success of detecting acoustic signals with the accelerometers, based on predictions from different hardware's accelerometer capabilities for three baleen whale species: fin, blue, and right whales. The outcomes from this approach will aid in determining the appropriate hardware for using the coupled accelerometer/acoustic method for assignment of focal calls for future data collection to inform on individual cue rates needed for acoustic density estimation.

II. METHODS

A. Prediction of accelerometer signal level

The relationship between acoustic pressure and particle motion is described in the context of fish responses to sound in Gray *et al.* (2016). Acceleration of a fluid can be approximated to Eq (1):

$$a \sim -\frac{1}{\rho}\nabla p, \tag{1}$$

where **a** is acceleration (a vector quantity, having direction as well as magnitude), ρ is density, and p instantaneous pressure. ∇ is the gradient operator, i.e., the acceleration at any point in space is equal to the pressure gradient divided by the medium density.

Close to a spherically radiating source, the instantaneous pressure at distance r and time t is given by

$$p_{rt} = p_0 \frac{e^{irk}}{r} e^{-i\omega t}, \tag{2}$$

where p_0 is the peak pressure at unit distance from the source (i.e., $r = 1$ m), k is the wavenumber ($k \equiv 2\pi/\lambda = \omega/c$), ω is the angular frequency ($\omega = 2\pi f$), and c is the speed of sound.

Equations (1) and (2) can therefore be combined to determine an expression for acceleration, where

$$a = \frac{1}{\rho}\frac{\partial p(rt)}{\partial r} = \frac{p_0}{\rho}\left(\frac{1}{r} - ik\right)\frac{e^{ikr}}{r}e^{-i\omega t} = \frac{\omega}{\rho c}\left(\frac{1}{rk} - i\right)p_{rt}. \tag{3}$$

In the far field, where $r \gg \lambda$, the term $1/rk$ becomes trivially small, therefore Eq. (3) becomes the standard equation for particle acceleration in a free field (i.e., far from any sources or boundaries)

$$a = -i\frac{\omega}{\rho c}p_{rt}. \tag{4}$$

From Eq (3), we can see that close to a sound source (i.e., within ~1 wavelength), where the $1/rk$ term in Eq (3) is large, the acceleration close to a sound source is considerably higher than would be expected in the free field.

B. Tag sensitivity and noise floor

In this analysis, we considered tag data from Acousondes (Burgess, 2009) and three versions of Dtags (Johnson and Tyack, 2003) (Dtag 2, Dtag 3, and Dtag 4), the acoustic tags commonly used in studies of cetacean acoustic behaviour. These tag types vary in their acoustic and accelerometer sensitivities, sampling rates, and filtering of both the acoustic and accelerometer data. In all tags, the acoustic pressure data are sampled at 16-bit accuracy. Accelerometer data are sampled at 16-bits by Dtags and 10-bits by Acousonde. Using the sensitivity and sampling settings from the Dtag as an example, we can explore the theoretical relationship between acoustic pressure and accelerometer motion from whale calls. The acoustic channel on Dtags has a saturation level of around 175 dB re 1 μPa$_{0-\text{p}}$ and the three axis accelerometers have a peak value of $\pm$4 g.

Using these Dtag calibration values in Eq. (3), it becomes possible to calculate the relative strengths of signals detected on both the acceleration and acoustic pressure sensors of a Dtag. The calculations are performed for a signal of arbitrary amplitude, converted to ADC counts for each signal, and then to the relative signal strengths of the accelerometer and pressure signals in ADC count, since this gives a direct indication of the relative signal amplitudes for data collected using a tag [Fig. 1(a)], i.e., when looking at a pressure signal, it becomes possible to estimate the likely acceleration signal dependent on the frequency and range to the source.

The noise floor of the accelerometer in a dTag is 130 μg/$\sqrt{}$Hz, where g is the acceleration due to gravity, 9.8 m/s^2, though if all three acceleration channels are added, this will increase by a factor of $\sqrt{3}$ suggesting that a more realistic noise floor would be around 225 μg/$\sqrt{}$Hz. If we assume source levels for fin and right whales of 189 and 154 dB re 1 μPa, respectively, and analysis bandwidths for fin whale 20 Hz calls and right whale upsweeps of 20 and 100 Hz, respectively, then it also becomes possible to estimate an expected SNR for accelerometer signals for these two species.

Signal levels, in terms of recorded ADC values, on the accelerometer are always lower than those on the pressure sensor [Fig. 1(a)]. Due to the acceleration scaling with ω, acceleration signals are relatively higher for the higher frequency sounds. In the far field, the accelerometer signal amplitude is between 35 dB (at 300 Hz) and 58 dB (at 20 Hz) lower than the pressure signal. However, 1 m from the sound source, these differences reduce to between 33 and 37 dB (Fig. 1).

The expected signal to noise ratio for fin and right whale signals is shown in Fig. 1(b). Clearly, the fin whale accelerometer signal should be clearly detectable above the noise and may even be detectable from animals over 10 m away. However, the quieter right whale signal would likely have a very low SNR on the accelerometers and would only be detectable very close to the source.

The actual noise experienced on a tag is likely to be higher than the theoretical minimum used in these calculations due to flow induced vibration of the tag. Therefore, these differences in digitized amplitudes between the accelerometer and the pressure sensor can result in a situation where a low amplitude acoustic signal produced by a tagged whale would not register on the accelerometer, or even a possibly high amplitude signal may not register if the tag is deployed far enough on the body of a large whale from the sound production source.

These hardware and software constraints from distinct types of tags are important to consider in determining the feasibility of detecting whale calls from a tagged whale on the accelerometer sensors. Based on the equations and values outlined above, we predict the following:

1. **Hardware limitations**: Due to built-in hardware anti-aliasing low-pass filters on many accelerometers, it is important to determine whether the tag hardware is capable of detecting calls produced by the tagged whale based on the frequency of the signals of interest. Whales that do not produce calls with energy in the frequencies below the Nyquist value of sampling or the frequency of the built-in low-pass anti-alias filters are unlikely to be detectable.
2. **Signal parameter limitations**: Lower frequency signals have less acceleration, and higher frequency signals may be removed by anti-aliasing filters meaning that there is a limited frequency range over which acceleration signals might be detected. Despite this, acceleration signals from high amplitude, low frequency whales such as blue whales and fin whales should be detectable on tags out to distances of several 10s of meters. In contrast, acceleration signals from baleen whales with higher frequency (>100 Hz) and lower amplitude calls, such as right whales, while theoretically may have higher acceleration, are less likely to be detected due to their lower amplitude and hardware filtering.

C. Tag data collection

Tag data used for this section of the study were collected opportunistically, during multiple studies of large baleen whales that targeted data collection with several types of commonly used acoustic recording tags with a range of accelerometer sampling frequencies (Table I). We

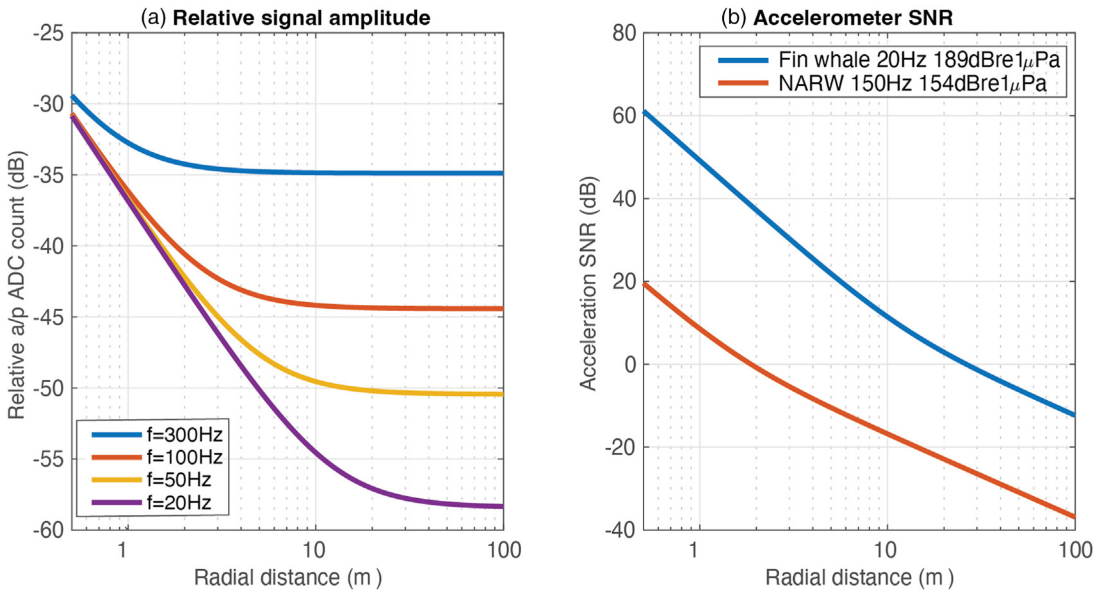

FIG. 1. (a) Theoretical relative amplitudes of digitized signals in a dTag from the accelerometer channels compared to the pressure sensor for a point source. (b) Theoretical SNR for fin and right whale calls on a dTag.

selected tags for analysis that recorded whale calls and were collected from individuals or mother-calf pairs that appeared to be alone and not closely associated with other whales during the time of tag deployment (though other whales may have been in the area and potentially joined the tagged whale) to try to limit detected high amplitude calls to those produced by the tagged whale. Therefore, for the purposes of this manuscript all detected high amplitude calls are presumed to be produced by the tagged whale.

Blue and fin whale tag data were collected in the Southern California Bight between 2006 and 2012. Data collection is described in Lewis *et al.* (2018), Southall *et al.* (2012), and McKenna *et al.* (2015). Data included three blue whale tag deployments (one Dtag 2, one Dtag 3, and one Acousonde) and seven fin whale tag deployments (two Dtag 2, one Dtag 3, and four Acousonde) on whales that were solitary at the time of tag attachment. Southern right whale data were collected on the calving ground off southern Brazil in 2022 and included two Dtag 3 and two Dtag 4 tag deployments on females in mother-calf pairs. Data collection methods were previously described by Dombroski *et al.* (2020). Detailed metadata on the tag deployments can be found in the supplementary material.

D. Tag hardware capabilities

A total of seven different tag hardware and sampling configurations were tested in this study. The configurations that varied across the tags included the accelerometer sampling and Nyquist frequencies, the built-in hardware filtering characteristics for the accelerometer, resulting in the variation of the maximum possible accelerometer frequency the tag was able to detect (Table I).

E. Data analysis

Acoustic recordings were audited for presence of the most common calls by species: A, B, and D calls for blue whales (Širović and Oleson, 2022) and 20 and 40 Hz pulses for fin whales (Širović *et al.*, 2013) and upcalls and tonal calls for southern right whales (Dombroski *et al.*, 2020) (Table II for call characteristics). All calls occurring within the first two hours of the deployments were extracted from

TABLE I. Accelerometer hardware characteristics of tags tested in this study. 1: Acousonde parameters provided by Burgess (2022); 2: Dtag parameters provided by Johnson (2022).

Configuration	Tag type	Acc. Sampling frequency	Acc. Nyquist cut-off frequency	Acc. hardware filtering	Acc. Detection Cutoff Freq. (Hz)
1a	Acousonde B[1]	10	5	1.6 kHz single-pole low-pass	5
1b	Acousonde B	20	10	1.6 kHz single-pole low-pass	10
2	Dtag 2[2]	50	25	50 Hz single-pole low-pass	25
3	Dtag 3	200	100	50 Hz single-pole low-pass	50
4	Dtag 3	250	125	50 Hz single-pole low-pass	50
5	Acousonde B	200	100	1.6 kHz single-pole low-pass	100
6	Dtag 4	1000	500	180 Hz low-pass + digital filtering 0.4*sf (400 Hz)	180
7	Acousonde B	400	200	1.6 kHz single-pole low-pass	200

TABLE II. Characteristics of call types invested as part of this study, including the frequency range and peak frequency of the calls in Hz, the minimum accelerometer Nyquist rate estimated for potential detection and estimated source levels. Source levels for blue whale A and D calls are estimated from Thode *et al.* (2000), who provided spectral density measurements, and calculated assuming 70 Hz and 40 Hz bandwidth, respectively. Source levels for right whales are from North Atlantic right whales, as no published RLs are available for southern right whales.

Species	Call type	Frequency range (Hz) Min – Max	Peak Frequency (Hz)	Minimum acc Nyquist rate for detection (Hz)	Estimated source level (dB rms re: 1 μPa)	References for call type parameters
B. musculus	NE Pacific A	17–90	∼85	100	∼180′	McDonald *et al.*, 1995; McDonald *et al.*, 2001; Stafford *et al.*, 1998; Oleson *et al.* 2007a, b; Thode *et al.*, 2000
	NE Pacific B	15–56	∼45	50	186	
	D	30–80	variable	100	∼180′	
B. physalus	20 Hz	13–35	16-23	40	181–189	Širović *et al.*, 2013; Varga *et al.*, 2018; Wiggins and Hildebrand, 2020; Weirathmueller *et al.*, 2013
	40 Hz	42–65	N/A	100	188	
E. australis	Upcall	65–150	101	150	147–154	Matthews and Parks, 2021; Dombroski *et al.*, 2016; Dombroski *et al.*, 2020
	Other	60–240	117	150	137–169	

the full dataset using a custom MATLAB script that extracted the acoustic waveform occurring 60 s before and 60 s after the logged start of the call and saved it as a separate .wav file. The raw accelerometer data covering the same period were also extracted and saved into a separate file. For each tag, nominal sensor calibration was performed, and the accelerometer data were analyzed in tag frame for all datasets. We limited our data to the first two hours after the deployment because that was the time with more visual coverage to make our best attempt to avoid periods of time with additional whales in close proximity, although without focal follows we cannot ascertain these animals were alone during this entire period. SNR measurements were made using the build-in RAVEN Pro 1.6 software (Cornell University) rapid SNR measurement and only calls with an acoustic SNR > 15 dB were included in the analysis.

To determine whether calls could be detected on the accelerometer, acoustic and accelerometer data files were visualized using a custom-made MATLAB script [Focal Call Visualization tool (FOCA)—see supplemental material]. FOCA allows the user to plot spectrograms of the audio and each of the concurrent three accelerometer axes (x, y, z) to visually search for an accelerometer signal that relates to a focal call. Accelerometer spectrograms were obtained through short-time Fourier transformation of accelerometer data that were filtered with a 5th-order, 1 Hz high-pass filter and normalized for each axis by subtracting the mean acceleration in each axis and dividing by its standard deviation (Saddler *et al.*, 2017). The time and frequency resolution of the Fourier transform was dependent on the accelerometer sample rate and varied from 64 to 256 samples. A visible contour in the accelerometer spectrogram was scored as a detectable signal if it occurred on at least one accelerometer channel within the start and end time of the call and had a similar shape to the fundamental frequency or harmonics of the call in the audio spectrograms. Partial shapes in the accelerometer spectrogram were considered sufficient evidence to classify a call as detectable. When looking for calls on the accelerometer spectrograms, the analyst was blind to call type and to the focal or non-focal nature of the calls.

To compare the effects of the hardware filtering characteristics on the detectability of high-quality calls on the accelerometer, we decimated higher frequency accelerometer data with a lowpass filter to lower sampling rates in MATLAB using the *resample* function to assess the impact on the detection of signals.

III. RESULTS

A. Signal parameters

We provide a summary of the frequency ranges and estimated source levels for each of the call types examined based on published values in the literature (Table II). Based on these values, we predicted the minimum hardware capabilities required for the accelerometer to detect each call (Fig. 2).

However, complexity in the sound production of different species makes this process more complicated than simply converting minimum or peak frequency of a call into required Nyquist frequency for detection. For example, while the blue whale A call is a pulsed call with a peak frequency around 85 Hz (Oleson *et al.*, 2007a), these calls have substantial energy down to 17 Hz (McDonald *et al.*, 1995). Combined with a high source level, blue whale A calls could potentially be detected on the accelerometer of tags configured with a cutoff frequency as low as 50 Hz (see tag configurations 3–7 from Table I). However, if only the peak frequency of this call was detectable on the accelerometers due to the greater call amplitude at this frequency, a higher cutoff frequency of up to 100 Hz (tag configurations 5–7 from Table I) would be necessary to reliably detect this signal. Blue whale D calls also can range in frequency from 30 to 80 Hz (Oleson *et al.*, 2007a). However, the lower amplitudes and frequency modulated nature of these D calls, suggest that an accelerometer frequency cutoff of 50 Hz may not be sufficient for detecting presence of this call on the accelerometer (tag configurations 3–5 from Table I). In the

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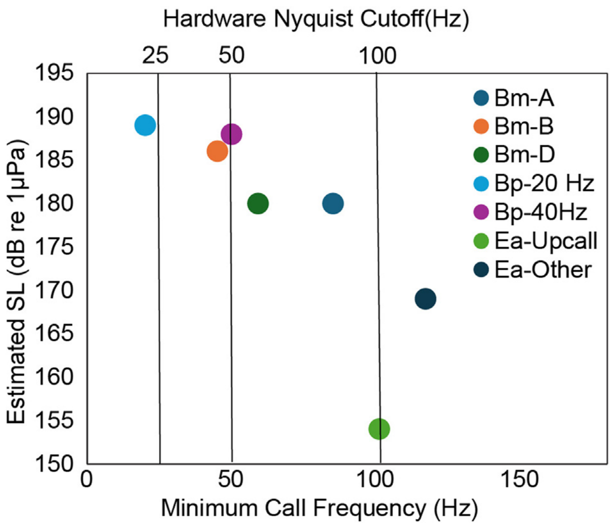

FIG. 2. The estimated peak frequency of each call type (Bm represents blue whale calls types, Bp are fin whale call types, and Ea are right whale calls) analyzed in the study and what minimum hardware Nyquist frequency is necessary to detect the signal in the accelerometer record. For example, tags with hardware capabilities with Nyquist cutoff frequency > 50 Hz would be needed to be capable of detecting blue whale A calls on the accelerometer.

case of these calls, substantially higher sample rates of 150 Hz and higher (tag configurations 6 and 7) are necessary to capture the signal well enough for identification. In general, use of an accelerometer capable of detecting the full bandwidth of the call of interest would improve detection of calling behavior by tagged whales.

B. Testing of accelerometer limitations

We tested the detectability of high amplitude examples of each of the call types from Table II across all hardware tag configurations that were available to us for each species. For each call type, the total number of calls with SNR > 10 dB were identified, and the percentage of those calls with successful detection in the accelerometer were calculated (Table III). Overall, accelerometer detection of calls was most successful with the highest percentage of calls detected in the accelerometers for signals that were lower than the maximum accelerometer detection frequency (e.g., fin whale 20 Hz calls across most tag types tested) and the lowest for calls that either exceeded or were at maximum accelerometer detection frequency for the tags (e.g., fin whale 40 Hz calls).

To compare the effects of the hardware filtering characteristics on the detectability of high-quality calls on the accelerometer, we decimated higher frequency accelerometer data to lower sampling rates using the MATLAB *resample* function to look at the impact on the detection of signals. A southern right whale accelerometer dataset originally sampled at 1000 Hz (Dtag4) was filtered to match the sample rate of Dtag3 sampling rates of 250 Hz. Dtag4 data were resampled using a decimation factor 4 (resulting in sampling frequencies 1\4 of the original sampling rate, fs = 250, Fig. 3).

IV. DISCUSSION

Our analyses demonstrate that there can be variable success in detecting baleen whale calls on the accelerometers of biologging tags. The ability to detect an acoustic signal on an accelerometer is determined by the hardware capabilities and the characteristics of the signal of interest. The accelerometer must first be capable of sampling rates at least 2× the frequency of the call being produced. Additionally, built in low-pass filtering in the hardware must be considered when determining whether accelerometers can be used to detect acoustic signals from a particular species. Our findings have implications for planning which hardware will be used in future studies on baleen whale cue rates. This includes potential explanation for results from previous studies that had variable success using the accelerometer method to detect baleen whale calls [i.e., Saddler *et al.* (2017) and Stimpert *et al.* (2020)]; and for planning for future use of accelerometers in movement biologging tags not equipped with acoustic sensors to potentially investigate acoustic output of low frequency baleen whale species.

As predicted, we could not detect calls on the accelerometer on the Acousonde B (tag configuration 1a and 1b) deployed on a blue whale due to the low sampling rate (10–20 Hz sampling with Nyquist of 5 or 10 Hz) that does not overlap with the fundamental frequency of the whale call type being investigated. Our next lowest sample rate datasets were Dtag2 deployments sampled at 50 Hz with a Nyquist frequency of 25 Hz. According to our predictions and the acoustic descriptions of the calls, we expected to detect the lower frequencies of blue whales' D calls, as well as fin whale 20 Hz pulses. Our analysis showed that a considerable proportion of high SNR calls for the D calls were not detected in the accelerometer and likely reflect the energy distribution of these calls with peak frequencies that exceed the Nyquist sampling frequency for this tag configuration. In contrast, the 20 Hz fin whale calls were well detected, with 99% of the calls visible on the accelerometer record.

The increase in the Dtag3's accelerometer maximum sampling frequency (250 Hz) resulted in a theoretical increase in the frequency bandwidth available to detect calls (from 0 to 25 Hz to 0 to 125 Hz). This increase in sampling frequency should increase the potential of using the accelerometer of the Dtag3 to investigate calls in species with repertoires with higher frequency ranges than blue and fin whales, such as right whales. However, we found that the hardware's built-in anti-alias filtering settings impose a loss of 6 dB for every octave above 50 Hz in the accelerometer. Our analysis of the Dtag3 datasets confirms the limiting effect of the additional filtering on the accelerometer signals, with only 9% of the blue whale D calls detected on this tag type with none of the right whale call types being detected from any Dtag3 deployments.

The Dtag4 deployments were collected at higher frequency accelerometer sampling rates (1000 Hz) and had hardware filtering at 180 Hz. Compared to previous tags

TABLE III. Table summarizing the total number of each high SNR example of each call type across each tested tag configuration. Data provided include the tag configuration (1–7 see Table I), maximum accelerometer detection frequency either due to sample rate or hardware filtering, species (Bm-blue whale; Bp-fin whale; Ea-right whale), call type (see Table II for characteristics), total high SNR calls detected in the audio record on each tag configuration, total calls detected on the accelerometer sensor, percentage of high SNR acoustic signals detected in the accelerometer for each call type.

Tag configuration (Tag type and acc sample rate)	Maximum acc detection frequency (Hz)	Species	Call type	Total high SNR calls	Total calls detected on acc	Percent detected
1 (Acousonde B, 10 Hz)	5	Bm	A	32	0	0
		Bm	B	31	0	0
2 (Dtag 2, 50 Hz)	25	Bm	D	124	43	35
		Bp	20 Hz	47	45	96
		Bp	40 Hz	2	0	0
3 (Dtag 3, 200 Hz)	50	Bm	D	33	3	9
4 (Dtag 3, 250 Hz)	50	Bp	40 Hz	63	25	40
		Ea	Upcall	91	0	0
		Ea	Other	26	0	0
5 (Acousonde B, 200 Hz)	100	Bp	20 Hz	3	3	100
		Bp	40 Hz	6	1	17
6 (Dtag 4, 1000 Hz)	180	Ea	Upcall	169	155	92
		Ea	Other	44	31	71
7 (Acousonde B, 400 Hz)	200	Bp	40 Hz	519	211	41
Totals				1190	517	44

tested, this allowed for greater bandwidth to detect higher-frequency acoustic signals. We successfully detected a high percentage of high-amplitude right whale calls in the accelerometers on Dtags, with 92% of the low frequency upcalls, and 70% of variable frequency tonal calls detected. When we decimated the 1000 Hz Dtag4 datasets to match the maximum sampling frequency of Dtag3s (250 Hz), we detected the same high-quality calls on the acc, suggesting that the hardware built in anti-aliasing filter was likely the primary limiting factor when detecting right whale acoustic signals in the accelerometer record of Dtag3s. This finding is important for future studies with southern and North Atlantic right whales as it demonstrates that the accelerometer can detect calls for these species with adequate accelerometer sampling rate and hardware features.

Acousonde B is capable of higher sampling rates of the accelerometer and, to our knowledge, has a relatively high frequency (1.6 kHz) built-in hardware filter in the accelerometer. However, we had poor success in detection of fin whale 40 Hz calls at both 200 and 400 Hz accelerometer sampling rates (17% and 41%, respectively). This result was interesting, as Stimpert *et al*. (2020) successfully detected humpback whale song units, higher in frequency than the fin whale 40 Hz calls, on the Acousonde 3B tag type. More

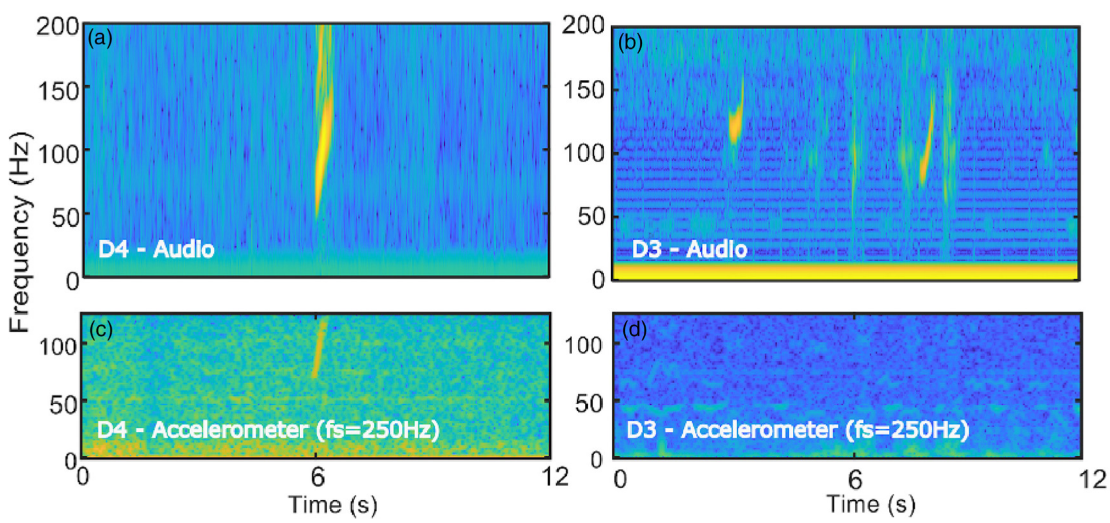

FIG. 3. The spectrogram of audio [(a) and (b)—Hamming window size 3062, 50% overlap] and the y axis accelerometer data [(c) and (d)—Hamming window size 128, 50% overlap] captured the right whale calls off the coast of Brazil. The data in panels a and c were acquired using Dtag4, which originally had an accelerometer sampling rate of 1000 Hz, a low-pass filter set at 180 Hz, and additional digital low-pass filtering at 400 Hz. These data were subsequently decimated by a factor of 4, resulting in a final sampling rate of 250 Hz. Data in panels (b) and (d) were collected using a Dtag3, which had an accelerometer sampling rate of 250 Hz and a low-pass filter of 50 Hz. Despite having a similar sampling rate, the Dtag3 accelerometer did not detect the whale calls, underscoring the potential impact of filtering on call detection.

investigation of the accelerometer capabilities and limitations on the Acousonde B are needed.

Our modeling approach suggests that the intensity of the calls picked up by the accelerometer can be a proxy for the caller's proximity to the tag. However, calls from a nearby conspecific could result in a detectable acceleration signal on the tag as calls from the whale the tag is attached to and additional tagging of pairs of animals would be useful to test this. When sufficiently high accelerometer sample rate and filtering characteristics are available, a device not equipped with acoustic sensors may be used to investigate acoustic cue rates. Theoretically, the phase of the signals detected in the accelerometer could hint at signal directionality and, therefore, aid in distinguishing if the signal is coming from the tagged or a nearby individual. Unfortunately, however, the Dtag's and the Acousonde's accelerometers and triggering systems are not built to detect phase differences; therefore, applications of this concept are limited at this point but are worth exploring for future tag deployments.

In this study, we aimed to demonstrate the importance of considering hardware filtering characteristics and signal parameters when using accelerometers to detect calls and identify the focal caller in recordings from multisensory acoustic tags attached to baleen whales. Our theoretical modeling approach, supported by analysis of opportunistically collected tag data, shows that the characteristics of the accelerometer hardware and the sample rates used are two important factors to consider when assessing the potential for calls can be detected by the accelerometer on a particular tag configuration. Future studies should conduct controlled tests with acoustic recording tags to test the predictions of the models under more controlled settings and consider additional variables such as the role of tag position on the body. This will allow for future exploration of the relationship between the phase of the accelerometer and pressure sensors, as well as confirm whether the hardware capabilities of a particular tag can detect the signals of species of interest prior to any data collection.

SUPPLEMENTARY MATERIAL

See the supplementary material and https://github.com/DombroskiJulia/Tag-accelerometer-caller-id for access to the Focal Call Visualization tool (FOCA).

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

Ethics Approval

All data used for this study were collected under the appropriate national permits and approval by internal animal care and use committees. For the blue and fin whale data, all tagging was conducted under the NOAA/NMFS Authorizations and Permits for Protected Species permit #14534-2 and Cascadia Research Collective's IACUC AUP-6 and for the southern right whale data: SISBIO permit #60324-7 and Syracuse University IACUC 23-002.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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