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This report presents the results of marine and freshwater scientific work carried out for Marine Scotland under external commission.

Report to Marine Scotland

Acoustic assessment of SIMRAD EK60 high frequency echo sounder signals (120 & 200 kHz) in the context of marine mammal monitoring

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Key Findings

- The full frequency spectra of the SIMRAD EK60 120 and 200 kHz echo sounders were measured.
- Both echo sounders produce sound at frequencies below the centre frequency and within the hearing range of harbour porpoises (*Phocoena phocoena*) and harbour seals (*Phoca vitulina*).
- Generated frequencies range from 70-100 kHz and 90-150 kHz for the 120 and 200 kHz signals, respectively.
- Both signal types have the potential to elicit behavioural responses.

1. Summary

The use of active high frequency echo sounders for commercial activities and marine research has been increasing in recent years. Compared to other anthropogenic noise sources, high frequency echo sounders have received little attention in terms of their potential impacts on marine life. However, while these devices typically operate at centre frequencies outside the hearing range of most marine species, recent work has demonstrated that they may produce unintended energy at lower frequencies. These lower frequencies may extend into the audible range for several species of marine mammals and have the potential to affect their behaviour (Deng et al., 2014).

This study measured the full frequency spectrum of the SIMRAD EK60 echo sounder operating at target frequencies of 120 and 200 kHz. This echo sounder is widely used in the marine science and fish stock assessment communities. Results showed that the generation of both signal types produced broadband energy at frequencies below the system’s target frequencies of 120 kHz and 200 kHz, in the range of 70-100 kHz and 90-150 kHz for the 120 and 200 kHz signals, respectively. For harbour porpoises (*Phocoena phocoena*), the target frequency of the 120 kHz signal and subcomponents of the 200 kHz signal fall within the region of highest

hearing sensitivity and are thus potentially detectable. While less sensitive at higher frequencies, measured signal levels indicate that harbour seals (*Phoca vitulina*) will likely also be able to detect the lower frequencies (70-100 kHz) generated by both signal types. Detection of these signals will be dependent on source power, signal duration, repetition rate, signal directionality and the animal's proximity to the beam centre. In addition, detection will be dependent on water depth, local ambient noise and seabed and surface scattering, all affecting signal propagation characteristics.

Given the theoretical detectability of these lower frequencies by marine mammals, both signal types have the potential to elicit behavioural responses towards them. This should be considered in environmental impact assessments of activities using these devices and when planning marine mammal monitoring studies alongside ecosystem studies using active acoustic sonar systems.

2. Introduction

Echo sounders are used for navigation and species detection in recreational and commercial fisheries, as well as in many areas of marine science, such as hydrography or seafloor and benthic habitat mapping (Calvert et al., 2015, Howe et al., 2015). Most devices operate within the range of 12-400 kHz (Lurton & DeRuiter, 2011). Although these higher frequencies attenuate relatively fast in sea water and the often narrow beam widths further limit the potential for auditory injury and impact ranges (Lurton & DeRuiter, 2011; Lurton, 2016), many of the devices fall within the hearing range of marine mammals.

High frequency scientific echo sounders are increasingly being used to measure top predator habitat and predator-prey relationships (Hazen et al., 2011; McInnes et al., 2015; Benoit-Bird & Lawson, 2016; Lawrence et al., 2016). Visual and acoustic marine mammal abundance surveys also often employ scientific echo sounders in order to collect concurrent prey and habitat data. In addition, active echo sounders have been proposed as potential tools for tracking behaviour of fish, sea birds and cetaceans around tidal turbines to assess collision risk (Williamson & Blondel, 2016; Williamson et al., 2017). Although few studies have been conducted so far, recent studies have shown behavioural responses of some marine mammal species towards scientific echo sounders (Southall et al., 2013; Quick et al., 2016). Importantly, such responses have been documented towards signals with peak frequencies outside the documented hearing range of the species under study (200 kHz; Hastie et al., 2014). Cholewiak et al. (in prep.) recently showed that some species of beaked whales may change their behaviour in the presence of these devices, with implications to species detection and hence abundance estimates when echo sounders are used during population monitoring surveys. Thus, detection and behavioural response towards high frequency echo sounders might impact the validity and interpretation of research results in contexts where marine mammal monitoring and environmental studies using active acoustics are carried out simultaneously.

The mechanisms behind the described behavioural responses towards echo sounders are poorly understood. However, it has been shown that high frequency (200 kHz) commercial echo sounders may also produce energy at frequencies below their intended target frequency and within the hearing range of several species of marine mammals (Deng et al., 2014). These lower signal components are a by-product of the signal generation process, necessary to achieve the sharp rise and fall times of the short, rectangular shaped echo sounder pulses (Deng et al., 2014). In order to increase detection range, maximum source levels of these devices are high, typically ranging from 210 to 240 dB re 1µPa at 1m (Lurton & DeRuiter, 2011), which also raises sound pressure levels of the lower frequencies and increases their potential detection range for some marine mammals.

One of the most commonly used scientific echo sounders is the SIMRAD EK60, which includes high frequency split-beam transducers operating at 120 kHz and 200 kHz (Andersen, 2001; Cotte & Simard, 2005; Benoit-Bird et al., 2016). However, despite their wide use full bandwidth analyses of signals produced by these transducers within the hearing range of marine mammals have not been conducted. This study will evaluate signal levels of the EK60 with 120 kHz (ES120-7C) and 200 kHz (ES200-7C) transducers at different pulse durations and power settings, with the aim to assess the potential of their audibility for harbour porpoises and harbour seals.

3. Methods

3.1. Acoustic signal measurements

This study evaluated high frequency acoustic signals transmitted by a SIMRAD EK60 scientific echo sounder (Andersen, 2001) with split-beam transducers centred at 120 kHz (ES120-7C) and 200 kHz (ES200-7C), respectively. Beam width for both transducers was seven degrees. Acoustic signals were recorded in a 9 m long x 2 m wide x 3 m deep laboratory tank. Both transducers were situated at a depth of 1.5 m and horizontally and vertically aligned with the hydrophone at a distance of 6.1 m for the 120 kHz and 5.8 m for the 200 kHz transducer. Sound speed within the tank was 1.447 m/s (10 degree Celsius and 0 ppt salinity).

The data acquisition system consisted of a calibrated hydrophone (B&K 8105), a band-pass filter (100 Hz - 360 kHz), a NI data acquisition card (National Instruments, Austin, Texas), a laptop computer and custom written LabVIEW^{TM} software. Signals were digitized at 16 bit and using a 1.2 MHz sample rate. Received sound levels were measured for a variety of different signal pulse durations (64, 128, 256, 512, 1024 µs) and power settings (120 kHz: 50, 150, 200, 250, 300, 350, 400, 450, 500 Watt; 200 kHz: 30, 60, 90, 120, 180, 210, 240, 270, 300 Watt).

Recorded signals were processed using custom-written MATLAB (The MathWorks, Inc., Natick, MA, USA) scripts. Individual pulses were isolated and processed using the fast Fourier transform (FFT) with the Hann window function, a FFT length of 1024 (1024 µs), 512 (512 µs) or 256 (64-256 µs) points, and a 50% overlap for in-pulse measurements of root-mean-square (RMS) sound pressure levels (SPL_{rms}; dB re 1 µPa) and power spectral density levels (PSD; dB re 1 µPa^2/Hz), resulting in a frequency resolution of 1.2, 2.3 kHz and 4.7 kHz, respectively.

In order to take marine mammal auditory integration times into account (see Appendix), signal levels (SPL, PSD, TOL) were also calculated over a fixed time window of 30 ms, using a FFT length of 1024 points and a 50% overlap, resulting in a frequency resolution of 1.2 kHz. In addition, for these analyses signal levels were calculated as 1/3-octave band levels (TOL_{rms}) in dB re 1 µPa, spanning 24 1/3-octave bands with centre frequencies from 1-200 kHz.

Finally, peak-to-peak ($SPL_{pk\text{-}pk}$; dB re 1 µPa) and maximum RMS sound pressure levels (SPL_{rms}; dB re 1 µPa) of the full signal were calculated for both signal types and temporal integration times.

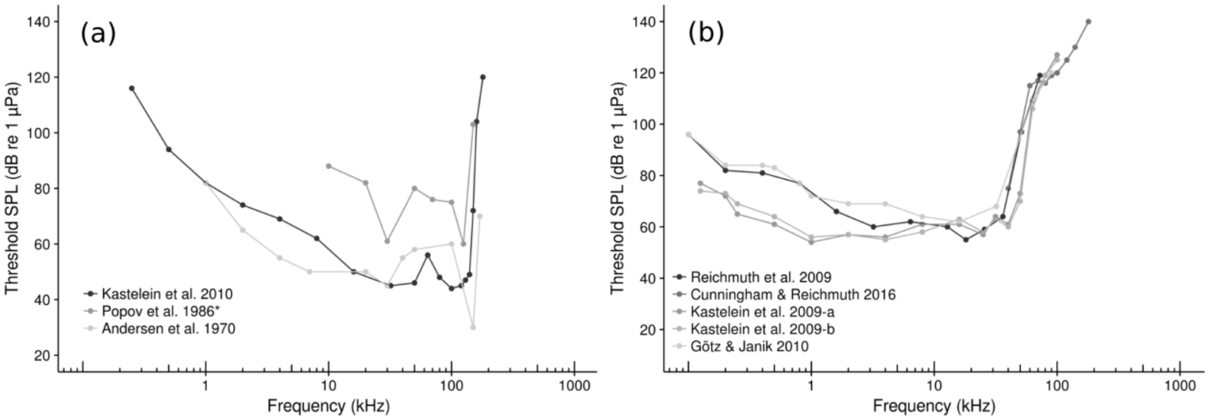


Figure 1: Audiograms measured by different investigators for (a) harbour porpoises and (b) harbour seals; *Popov et al. 1986 used the auditory evoked potential (AEP) method, while all other studies used behavioural methods.

3.2. Analysis Metrics Presented in this Report

3.2.1. Spectral Analysis

When comparing signal levels of tonal and narrowband sounds, metrics need to be carefully chosen, because signal levels need to be adjusted, taking analysis bandwidth into account, when power spectrum density levels (PSD; dB re 1 µPa^2/Hz) rather than spectrum levels (SPL; dB re 1 µPa) are reported. In general, for strong narrowband tonal sounds, such as the EK60 pulses investigated in this study, SPLs are more appropriate to use, whereas PSD levels should be used for more continuously distributed sound sources (see Richardson et al., 1995).

Marine mammal hearing is frequency-dependent and sounds are being processed in auditory filters or critical bands, the size and shape of which will affect the hearing thresholds measured in hearing studies (see Appendix). When directly comparing signal levels, especially of more complex signals, to hearing thresholds, signals should, therefore, ideally be analyzed as critical bandwidth (CB) levels (Erbe 2002). However, few direct measurements of critical ratios (CR), from which critical bands can be derived or critical bands themselves are available for marine mammals. This is especially true for the lower and higher frequencies (see Erbe et al., 2016 for a review). While, for harbour porpoises, critical ratio measurements are available up to 150 kHz (Kastelein et al., 2009), the highest frequency for which critical ratio and critical bandwidth measurements are available for harbour seals is 32 kHz (Turnbull & Terhune, 1990). In the absence of direct measurements, and based on research on humans and other terrestrial vertebrate species, 1/3-octave band levels (TOL; dB re 1 µPa) are commonly used as an approximation of critical bandwidth when comparing signal levels against marine mammal audiogram data (Erbe, 2002; Madsen et al., 2006; Tougaard et al., 2009; Erbe et al., 2016).

Given that the range of lower frequencies produced by the measured EK60 echo sounder signals are mostly above available CB measurements for harbour seals, this approach was adopted in this report as well. For comparison, SPL as well as PSD power spectra, were computed and presented as well. However, given the discussion above, comparisons of signal levels with available audiogram data for harbour seals and harbour porpoises, as well as assessments of the influence of pulse duration and signal power on signal levels, were based on TOLs.

Finally, peak-to-peak ($SPL_{pk\text{-}pk}$; dB re 1 µPa) and maximum RMS sound pressure levels (SPL_{rms}; dB re 1 µPa) of the full signal for both signal types were compared for different pulse durations and power settings (see 3.1).

3.2.2. Temporal Analysis

In order to directly compare signal levels to audiograms, signal analysis should use time windows that approximate the integration time of the study species, rather than focus only on the short duration signal of interest (Erbe et al., 2016; see Appendix for further explanation).

In this report, signal levels of in-signal measurements were initially compared with signal levels measured over a fixed time window of 30 ms. The 30 ms window was used to approximate known auditory integration times for harbour seals (Kastelein, Hoek, Wensveen, et al., 2010). The positioning of the 30 ms analysis time windows was selected to minimise a majority of the high multipath levels typically observed in a tank, providing level estimates more indicative of an open water environment. Signal measurements (TOL) using the fixed 30 ms time window were then used to assess the influence of pulse duration and signal power on received signal levels.

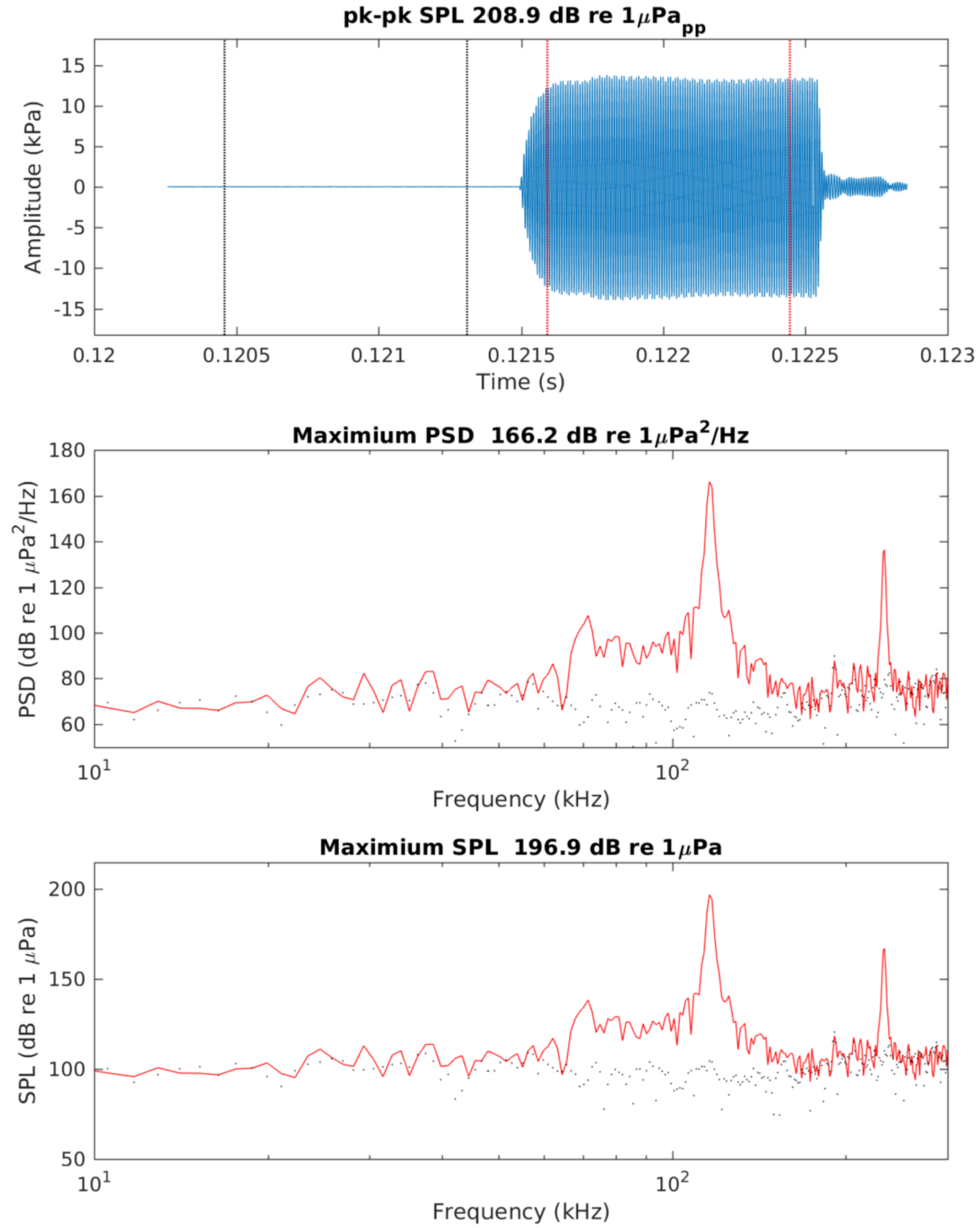
Although not further considered here, it is important to note that the rate of pulse repetition may also play a role in signal perception and higher repetition rates may increase the probability of signal detection (see Appendix).

4. Results

The highest recommended power settings to reduce non-linear acoustic interactions for the EK60 120 kHz and 200 kHz signals are 250 Watt and 120 Watt, respectively (Korneliussen et al., 2008). Thus, Figures 2-5 show signal measurements for both types of transducers operated at these power levels and the longest pulse duration of 1024 µs, in order to present highest signal levels for the typical operation of these echo sounders. At a range of 6.1 m, the peak-to-peak sound pressure level (SPL_{pk-pk}) of ES120-7C 120 kHz sonar signals were measured at 208.9 dB re 1 µPa (Figures 2,3,6). Signals showed broadband energy at frequencies below the target frequency of 120 kHz and within the range of 70-100 kHz (Figures 2,3). These lower frequency components were apparent even when signal duration and power were varied (Figure 8). Frequencies from 70-100 kHz showed average sound pressure levels (SPL_{rms}) of 136 dB re 1 µPa for in-signal (Figure 2), and 132 dB re 1 µPa for measurements using a 30 ms integration period (Figure 3). The relevant 1/3-octave levels (TOL) with centre frequencies of 80 and 100 kHz showed SPL_{rms} levels of 155 and 178 dB re 1 µPa, respectively, when measured over 30 ms (Figure 3). For the 200 kHz transducer, SPL_{pk-pk} levels were 208.8 dB re 1 µPa (Figures 4,5,7) at a range of 5.8 m from the transducer. There were lower frequency components in the range of 90-150 kHz with average SPL_{rms} levels of 136 dB re 1 µPa for in-signal (Figure 4), and 129 dB re 1 µPa for signals integrated over 30 ms (Figure 5). TOLs for bands with centre frequencies of 100, 125 and 160 kHz were 155, 158 and 175 dB re 1 µPa, respectively, when measured over 30 ms (Figure 5). Similarly to the 120 kHz signal, lower frequency components were apparent independent of variations in signal duration and power (Figure 9).

4.1. Influence of Power and Pulse Duration

When comparing TOLs for the 120 kHz signal, measured over a fixed window size of 30 ms, signal levels varied by 7-8 dB when increasing the power from 50 to 250 Watt and 7-15 dB when increasing pulse duration from 64 to 1024 µs (Figure 8). For the 200 kHz signal, an increase in power from 30 to 120 W raised signal levels by 7-8 dB. When increasing pulse duration from 64 to 1024 µs, signal levels of the 200 kHz signal were raised by 1-9 dB (Figure 9).



pk-pk SPL 208.9 dB re 1μPa$_{pp}$

Maximum PSD 166.2 dB re 1μPa^2/Hz

Maximum SPL 196.9 dB re 1μPa

Figure 2: Raw waveform (upper panel); power spectral density (PSD) spectrum and 1/3-octave band levels (TOL) (middle panel); root-mean-square (RMS) sound pressure level (SPL$_{rms}$) spectrum and TOL (lower panel) for in-signal measurement of an EK60 120 kHz signal (duration: 1024 µs, power: 250 W, FFT: 1024 pt). Spectrum levels (red line); background noise levels (black dotted line). Maximum SPL$_{pk\text{-}pk}$, PSD and SPL$_{rms}$ indicated above plots.

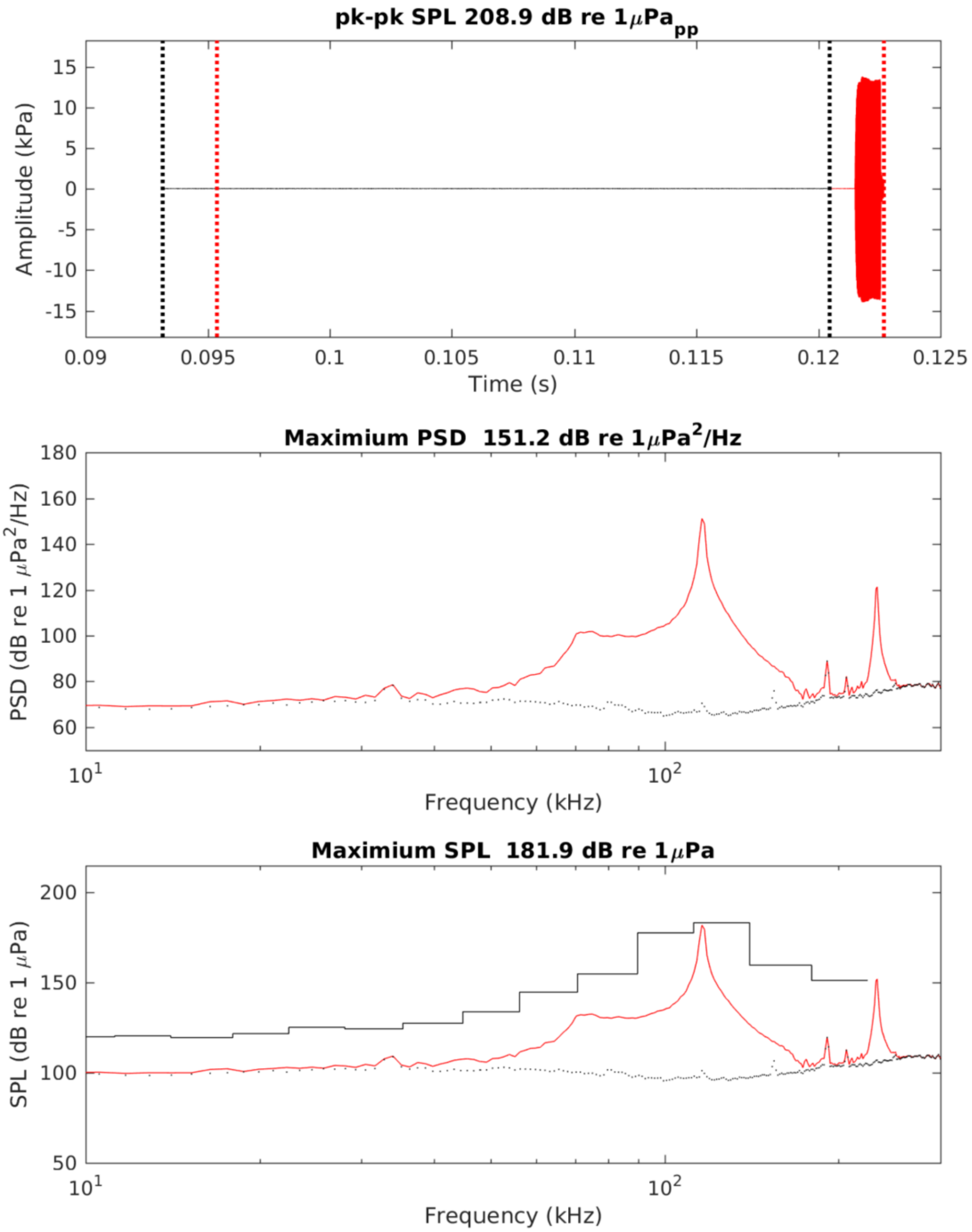


Figure 3: Raw waveform (upper panel); power spectral density (PSD) spectrum and 1/3-octave levels (TOL) (middle panel); root-mean-square (RMS) sound pressure level (SPL_{rms}) spectrum and TOL (lower panel) for 30 ms integration time measurement of an EK60 120 kHz signal (duration: 1024 µs, power: 250 W, FFT: 1024 pt). Spectrum levels (red line); TOL (black solid line); background noise levels (black dotted line). Maximum SPL_{pk-pk}, PSD and SPL_{rms} indicated above plots.

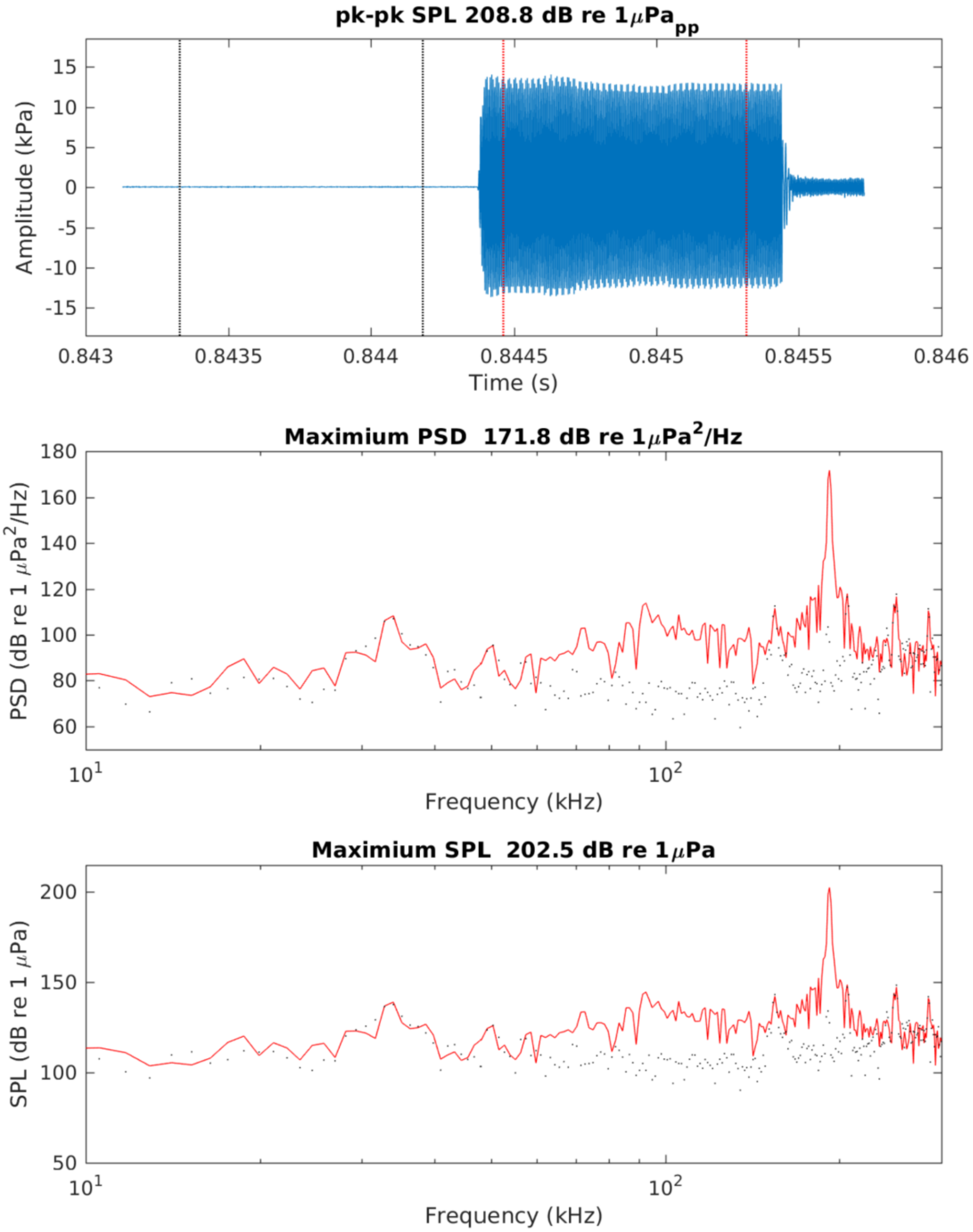


Figure 4: Raw waveform (upper panel); power spectral density (PSD) spectrum and 1/3-octave levels (TOL) (middle panel); root-mean-square (RMS) sound pressure level (SPL_{rms}) spectrum and TOL (lower panel) for in-signal measurement of an EK60 200 kHz sonar signal (duration: 1024 µs, power: 120 W, FFT: 1024 pt). Spectrum levels (red line); background noise levels (black dotted line). Maximum SPL_{pk-pk}, PSD and SPL_{rms} indicated above plots**.**

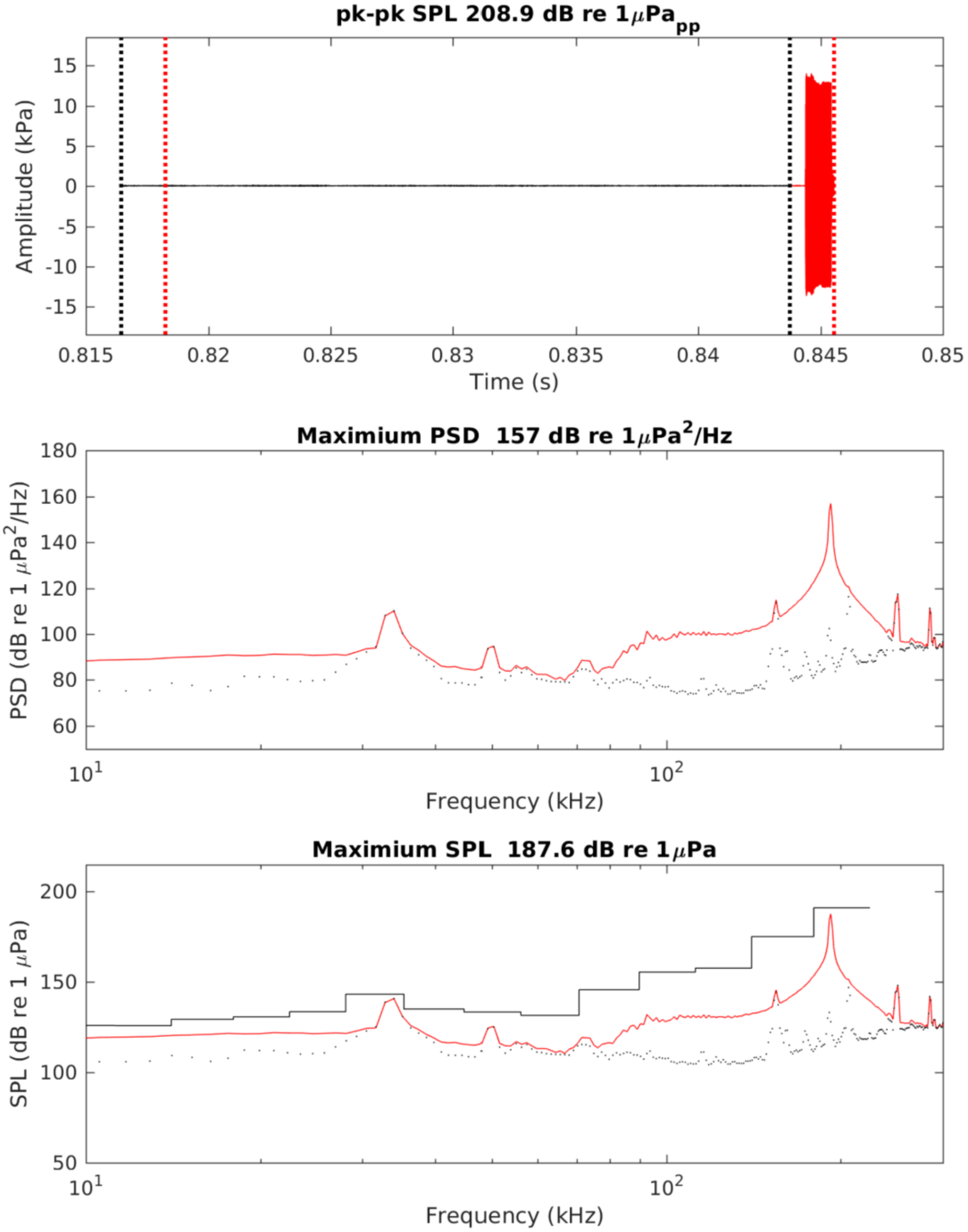


Figure 5: Raw waveform (upper panel); power spectral density (PSD) spectrum and 1/3-octave levels (TOL) (middle panel); root-mean-square (RMS) sound pressure level (SPL_{rms}) spectrum and TOL (lower panel) for 30 ms integration time measurement of an EK60 200 kHz sonar signal (duration: 1024 µs, power: 120 W, FFT: 1024 pt). Spectrum levels (red line); TOL (black solid line); background noise levels (black dotted line). Maximum $SPL_{pk\text{-}pk}$, PSD and SPL_{rms} indicated above plots.

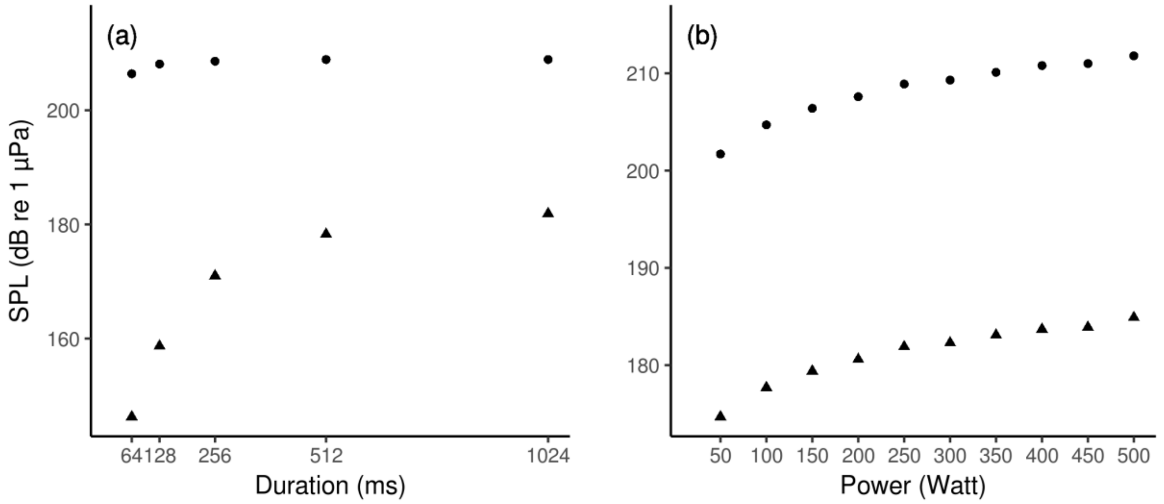


Figure 6: Peak-to-Peak (dots) and root-mean-square (RMS) (triangles) sound pressure levels (SPL) for EK60 120 kHz signals by (a) signal duration (power: 250 W) and (b) signal power (duration: 1024 µs).

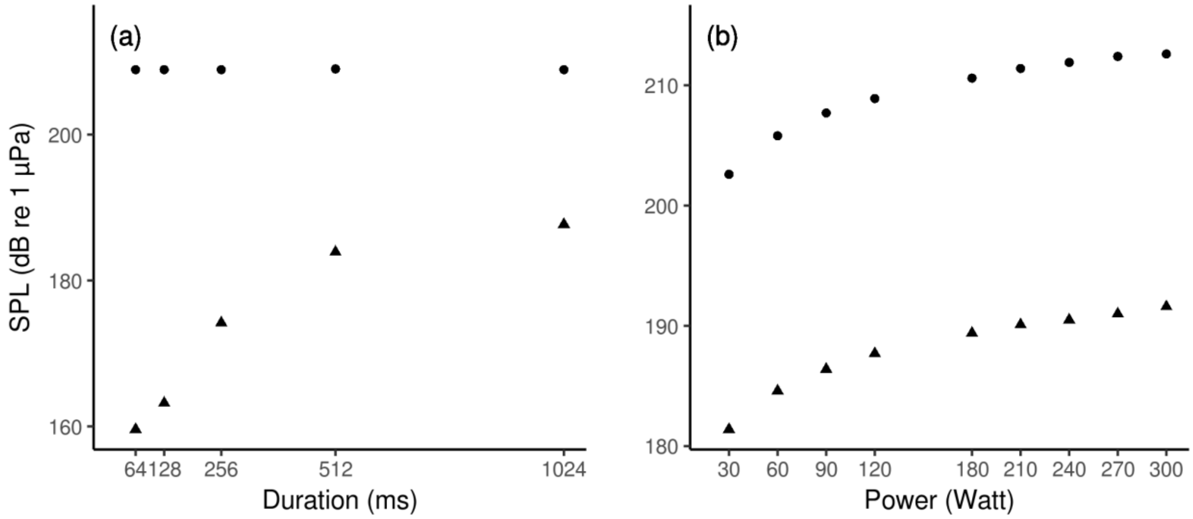


Figure 7: Peak-to-Peak (dots) and root-mean-square (RMS) (triangles) sound pressure levels (SPL) for EK60 200 kHz signals by (a) signal duration (power: 120 W) and (b) signal power (duration: 1024 µs).

5. Discussion

5.1. Signal Analysis

As with the findings for other commercial high frequency sonar systems (Deng et al., 2014), both of the high frequency (120 and 200 kHz) EK60 signal transducers produced energy below their intended target frequencies. This energy was in the range of 70-100 kHz (target frequency: 120 kHz) and 90-150 kHz (target frequency: 200 kHz) and so has potential to be audible to marine mammals. Specifically, the secondary peak for the 120 kHz signal was observed at about 70 kHz. At a distance of 6.1 m, the received RMS signal level for the 1/3-octave band encompassing this peak was 155 dB re 1 µPa (1024 µs and 250 Watt). For the 200 kHz signal (1024 µs and 120 Watt), the secondary energy was distributed over a wider band, with signal levels of 155 and 158 dB re 1 µPa in the 1/3-octave bands centred at 100 and 125 kHz, respectively (range: 5.8 m).

These frequency components and signal levels are comparable to those found by Deng et al. (2014), for a Kongsberg 200 kHz sonar signal, which showed a secondary peak of about 90-120 dB SPL_{rms} at 90 kHz, and at a distance of 7-150 m from the source (signal duration: 625 µs; source level: 195 dB re 1 µPa at 1m).

Although these received levels are about 55 dB below peak received levels of the target frequencies (Figures 2-5), these lower frequency components will be above background noise levels in many marine habitats. Precise signal detection ranges will depend on ambient noise levels, bathymetry and propagation characteristics of the receiving environment, including surface and bottom scattering and reflection, as well as the directionality of signal energy (Deng et al., 2014; Lurton, 2016).

Measured TOLs for both signals varied by about 7-8 dB from highest to lowest power settings (120kHz: 50-250 W; 200 kHz: 30-120 W), and 1-15 dB from shortest to longest pulse durations (64-1024 µs). Thus, adjustment of power and/or pulse duration would alter the detection range of these signals and their lower frequency components but not necessarily affect their general audibility at close ranges (see 5.2).

5.2. Audibility of Lower Frequency Components to Harbour Porpoises and Harbour Seals

Estimating the range and probability of acoustic detection and recognition of underwater signals by marine mammals is complex and dependent on a variety of factors, including spectral characteristics, directionality and source level of the signal in question, environmental parameters affecting signal propagation and background noise, as well as species-specific and individual hearing capabilities of the receiver (see Appendix). These factors and their interactions need to be kept in mind when interpreting the results of this study, which measured spectral characteristics and received levels of the EK60 120 and 200 kHz sonar signals at varying pulse lengths and power settings in a laboratory tank.

For the worst case (i.e. longest pulse duration and highest recommended (Korneliussen et al., 2008) source power (120 kHz: 1024 µs and 250 W; 200 kHz: 1024 µs and 120 W), measured signal characteristics (Figures 2-5) and known hearing capabilities (Figure 1) indicate that harbour porpoises should be capable of hearing the full 120 kHz sonar signal, including lower frequency components. The lower frequencies of the 200 kHz signal between 90 and 150 kHz are also at levels well within the hearing threshold for this high-frequency species. While harbour seals are less sensitive at higher frequencies, with measured auditory thresholds between 116 and 125 dB re 1 µPa in the range of 70-120 kHz (Figure 1 b), they should also be able to hear the sub-components produced by both 120 and 200 kHz signals as well as the main frequency peak of the 120 kHz signal. This is true for in-signal as well as fixed 30 ms time window measurements, and independent of whether SPLs or TOLs are compared to audiograms (Figures 2-5). Adjusting pulse durations and power levels will reduce signals levels by 1-15 dB. However, even at shortest pulse durations and lowest power levels, lower frequency sound pressure levels for both signal types are above hearing thresholds in both species (Figures 1,8-9).

5.3. Potential for Behavioural Responses

Despite its wide use to investigate the underwater behaviour of marine mammals and prey fields (Doksaeter et al., 2009; Benoit-Bird et al., 2009), few studies overall have investigated potential behavioural responses of marine mammals to SIMRAD EK60 echo sounder signals. However, some recent studies have observed behavioural responses by marine mammals to the lower frequencies or a mixture of low and high frequency signals of the EK60. While long-finned pilot whales showed increased vigilance in the presence of EK60 38 kHz signals (Quick et al., 2016), acoustic detections of beaked whales were significantly reduced in the presence of 18-200 kHz EK60 signals compared to periods when the echo sounder was off (Cholewiak et al., in prep.). Fewer studies still have investigated behavioural responses of marine mammals towards high frequency signals of echo sounders, with the exception of one study showing, that grey seals respond to high frequency sonar, with target frequencies (200 and 375 kHz) that are beyond their known hearing range (Hastie et al., 2014).

Given the described behavioural responses to echo sounder signals in other species and the fact that results from this study show signal levels are high enough that harbour porpoises and harbour seals are potentially able to detect the lower frequency signal components of the high frequency pulses, it is plausible that behavioural responses towards these signals might occur, particularly at close ranges from the active device.

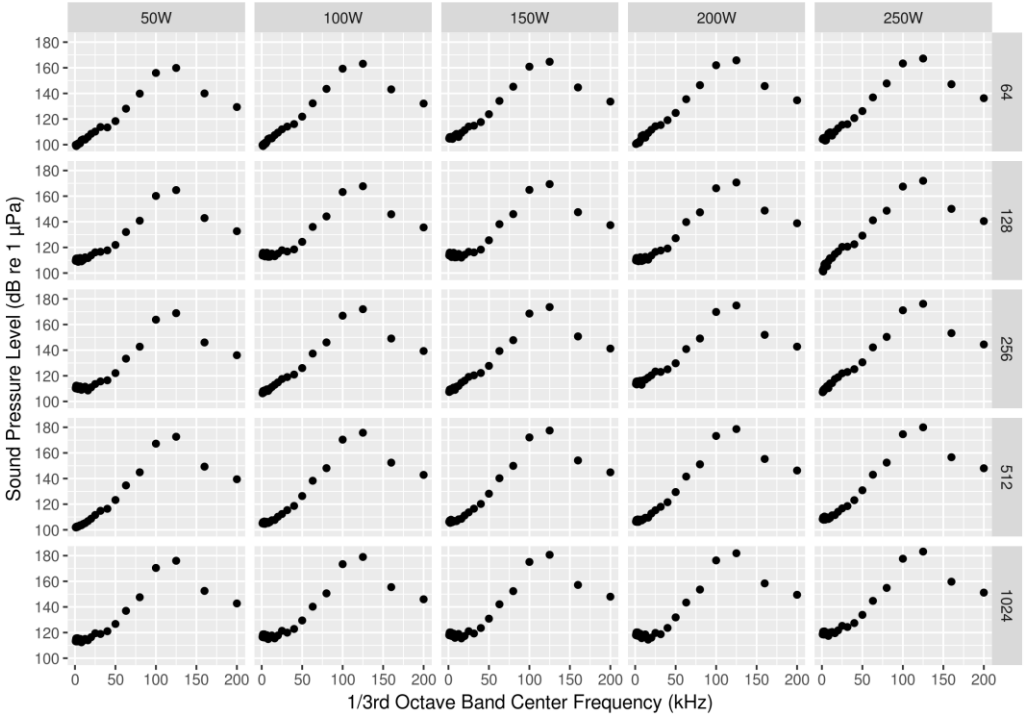


Figure 8: 1/3-octave sound pressure level (TOL) of EK60 120 kHz signals by power in Watt (vertical panels) and duration in µs (horizontal panels). Integration time: 30 ms; FFT size: 1024 pt.

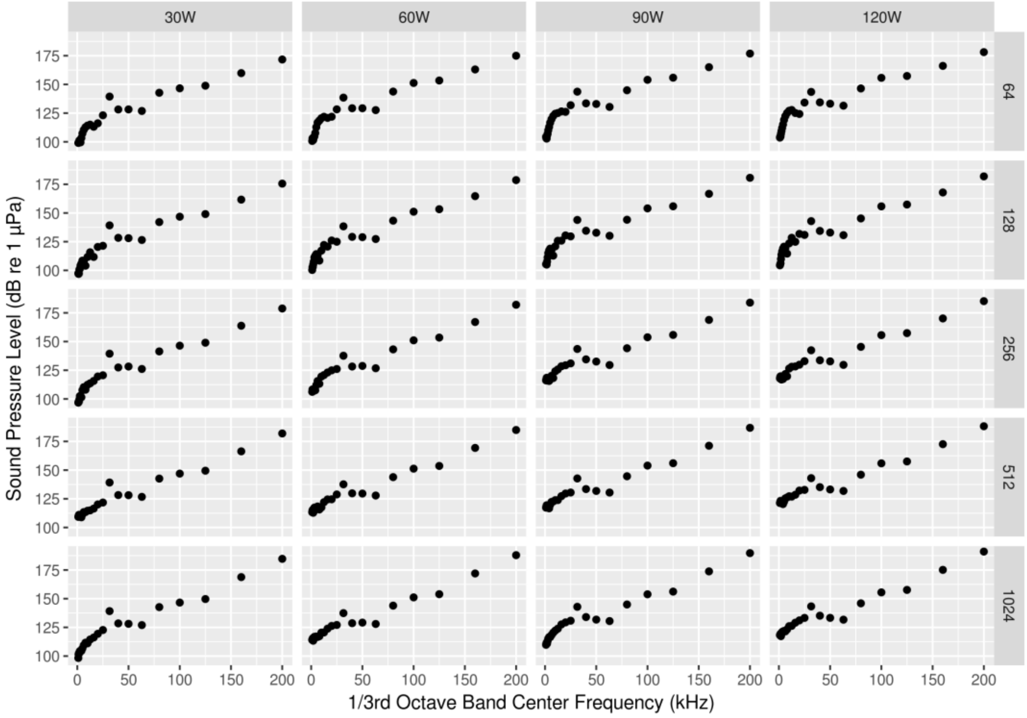


Figure 9: 1/3-octave sound pressure levels (TOLs) of EK60 200 kHz signals by power in Watt vertical panels) and duration in µs (horizontal panels). Integration time: 30 ms; FFT size: 1024 pt.

5.4. Study Limitations and Future Research Recommendations

Assessing the potential for audibility of a given signal is complex and is dependent on a variety of factors, relating to signal generation, as well as receiver and transmission medium characteristics, some of which are difficult to measure and need to be estimated (see Appendix). In addition, there are several limitations which should be taken into account when interpreting the results of the current study.

Firstly, due to the measurements being carried out in a freshwater tank rather than *in-situ*, background noise levels in the tank, reverberation and some multipath effects especially for the longer pulse durations could not be avoided and might have affected reported signal levels. Relative differences in absorption from fresh water to salt water in these measurements was considered relatively minor although consideration of non-linear effects may become more relevant at higher power levels in salt water environments (Korneliussen et al., 2008). However, signal levels in the region of interest (70-120 kHz) were at least 10 dB above background levels and, therefore, should have been generally less affected by background noise in the tank.

The measured lower frequency components, especially of the 200 kHz signal, were distributed relatively broadband. In order to compare broadband noise to audiogram data, signal levels need to be analyzed as critical band levels (Erbe, 2002; see Appendix). Thus, assumptions about the width of critical bands will affect estimates of audibility. Little is known about critical bandwidths for harbour porpoises and harbour seals, especially in the lower and higher frequencies. Although it is common to use 1/3-octave band levels as an approximation of critical bands, there is some indication that in the higher frequencies (above 20 kHz), critical bandwidths are better approximated by 1/12-octave bands in several marine mammal species (Erbe et al., 2016). The use of 1/3-octave band levels to compare signal levels to audiogram data may thus introduce uncertainty. However, next to 1/3-octave band levels, signal levels were calculated as sound pressure levels (SPL_{rms}) with a filter bandwidth of 1.2 kHz (which is below 1/12 octave bandwidths above 20 kHz). Since, independent of these filter bandwidths, all signal levels in the range of 70-120 kHz were above reported hearing thresholds for harbour porpoises and harbour seals, it is concluded that the unintended lower frequencies generated by both high frequency echo sounders are potentially audible to both species.

Audibility is also dependent on signal duration. In order to account for raised hearing thresholds for shorter signals and to approximate reported harbour seal integration time (Kastelein, Hoek, de Jong, et al., 2010), received levels for in-signal measurements were compared to measurements over a fixed 30 ms time window.

Signal levels calculated using the latter analyses were also high enough, to indicate audibility for both species.

It is clear that the assessment of marine mammal responses towards echo sounders in general and high frequency echo sounder signals in particular, is hampered by a lack of empirical data. This is true for signal measurements, as well as studies of the probability of marine mammal responses towards these signals. The theoretical ability to detect a signal does not imply a behavioural response and the range at which a response might be observed should be based on actual field observations (Tougaard et al., 2009). In addition, signal propagation distances will vary with depth, bottom type and other site-specific environmental variables which can be complex especially in high tidal flow areas.

Therefore, in-situ measurements of peak as well as secondary frequencies of SIMRAD EK60 signals at varying ranges from the source are recommended, in order to assess possible detection distances above ambient noise in the study environment. It would furthermore be beneficial, to conduct *in-situ* behavioural response studies, aimed at assessing the probability of behavioural response of different species towards particularly the higher frequency components of widely used scientific and commercial echo sounders. Already available data from line-transect abundance surveys for marine mammals with and without operating active echo sounders might be useful to detect such responses for some species (Cholewiak et al., in prep.).

6. Conclusion:

Implications for using High Frequency Echo Sounders while Monitoring Marine Mammals

The presence of energy below intended target frequencies of 120 and 200 kHz EK60 signals raises the question of how these signals may impact research results when used alongside studies of marine mammal distribution and behaviour. While the intensity of these signal components are well below injury thresholds, measured signal levels suggest the potential detection of these lower frequencies by harbour porpoises and harbour seals, as is the case for other similar echo sounders (Deng et al., 2014). The SIMRAD EK60 is a widely used scientific and commercial echo sounder that is often used to assess predator-prey relationships (Benoit-Bird et al., 2009; Hazen et al., 2011; Benoit-Bird & Lawson, 2016), as well as during marine mammal abundance surveys (Cholewiak et al., in prep.). The potential for detection of these signals by marine mammals and hence behavioural responses towards them, should be taken into account during monitoring and environmental impact studies using these devices.

7. Acknowledgements

Thanks to Benjamin Williamson and Eric Armstrong for help with signal generation and set-up of the SIMRAD EK60 system, as well as to Marine Scotland for hosting us at the Marine Laboratory in Aberdeen and providing access to the test tank. Thanks to Douglas Gillespie and Klaus Lucke for helpful discussions on signal analysis and Danielle Cholewiak for providing access to an early draft of her manuscript.

8. Literature

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Appendix

Considerations for the Assessment of Signal Detection Probability

Aside from signal specific features such as source level, spectral and temporal characteristics and directionality, a variety of environmental factors affect signal propagation, including water depth, turbulence and bottom substrate. Furthermore, natural and anthropogenic ambient noise need to be considered when assessing the potential for signal detection in real world conditions (Erbe et al., 2016). Also, signal detection by the receiver is complex and dependent on several auditory characteristics and processes (Richardson et al., 1995; Erbe et al., 2016). In order to provide background to the choice of analysis metrics presented in this report and in support of conclusions drawn with respect to the audibility of the measured signals to harbour porpoises and harbour seals, some of these concepts will be briefly described here.

Absolute Hearing Threshold: Audiograms

Audiograms present absolute estimates of a species' hearing sensitivity, by presenting pure tone detection thresholds measured at a series of frequencies in quiet conditions. When using audiograms to assess signal audibility, it is firstly important to note that these are typically based on either behavioural or neurophysiological measurements and usually involve only a few individuals. However, hearing sensitivity may vary between individuals and is dependent on a variety of factors such as age, sex and condition of health (Erbe et al., 2016). Thus, audiograms are an estimate of a species' hearing sensitivity but are not necessarily representative for all individuals. Further, absolute hearing thresholds may also change as a function of depth (Kastak & Schusterman, 2002) but very few data are available to assess this relationship for most species. Finally, studies directly measuring detection thresholds of more complex signals (e.g. pile driving noise or active sonar signals) than the pure tones used in typical hearing studies, have shown that audiograms are not always accurate in predicting signal audibility and that sensitivity may be enhanced especially when sounds show strong harmonic components or are frequency modulated (Cunningham et al., 2014). All of these factors need to be borne in mind when interpreting species-specific audiograms such as those for harbour porpoises and harbour seals presented in Figure 1.

Frequency Dependency: Critical Ratio and Critical Bands

While absolute hearing thresholds as presented in audiograms present the lowest signal levels detectable in quiet conditions, background noise levels influence detectability in real world conditions (Richardson et al., 1995). The concepts of critical ratios and critical bandwidths describe these relationships. Mammalian hearing is frequency-dependent and sounds are processed by separating them into their frequency components using auditory filters of varying bandwidths. These species-specific critical bandwidths determine the ability of an individual to distinguish signals in noise. Specifically, critical bands are defined as the noise bandwidth at which the detection threshold of a pure tone at the centre of that frequency band is not increasing any further when increasing the bandwidth (Erbe et al., 2016). Critical bands can be estimated from critical ratios, which describe the sound level by which a tonal signal has to exceed background noise in order to be just audible (Richardson et al., 1995). In general, critical ratios tend to increase with increasing frequency and critical ratios and critical bandwidths are related such that the smaller the critical ratio, the narrower the critical bandwidth and hence the auditory filter for signal processing. Narrower critical bands will increase frequency resolution and be less affected by broadband noise compared to wider critical bands (Tougaard et al., 2009). Thus, species-specific critical bandwidths are important to consider when estimating audibility and possible impacts of specific human-made signals on marine mammals. In the absence of direct measurements, and based on research on humans and other terrestrial vertebrate species, 1/3-octave or 1/12-octave band levels are commonly used as an approximation of critical bandwidth when comparing signal levels against marine mammal audiogram data (Erbe, 2002; Madsen et al., 2006; Tougaard et al., 2009; Erbe et al., 2016).

Temporal Integration and Duty Cycle

Auditory detection thresholds are also dependent on signal duration. For vertebrates, detection thresholds decrease with signal duration up to a certain duration defined as integration time, beyond which sensitivity does not improve further. Higher signal levels are, therefore, needed for the detection of signals that are shorter than the integration time (Kastelein, Hoek, de Jong, et al., 2010). Integration times vary by species and frequency, with longer durations needed to detect low frequency sounds and shorter durations for high frequency sounds. It is important to consider that integration times measured for pure tones, like those commonly used in audiometric studies, might differ from integration times for more complex signals such as the echo sounder signals considered in the current study (Kastelein, Hoek, de Jong, et al., 2010). Integration times for marine mammals are comparable to other mammals and lie between 100 and 200 ms. These time constants have been found to be relatively consistent across several marine mammal species (Kastelein, Hoek, de Jong, et al., 2010). However, at frequencies higher than 30 kHz, integration times for harbour seals appear to be shorter (27 ms at 40 kHz) (Kastelein, Hoek, Wensveen, et al., 2010).

Audiometric studies typically use signal durations that match or exceed known integration times of the test species. This suggests that short duration signals, such as the high frequency pulses produced by the EK60, may raise reported auditory thresholds above levels reported in species-specific audiograms, i.e. signal detection probability would be decreased. For example, the detection threshold for harbour seals at 40 kHz is raised by 5-7 dB when decreasing signal duration from 1 to 0.5 ms (Kastelein, Hoek, de Jong, et al., 2010). Inversely, the duty cycle of a signal is also important for its detectability and can decrease measured hearing thresholds, i.e. increase signal detection probability. For example, it has been shown that detection thresholds for harbour seals decreased by about 5 dB when pulse rate increased from 1 to 10 pulses per second (Turnbull & Terhune, 1993). Because of these temporal integration processes affecting auditory perception, it is important to take signal duration and repetition rate into account when assessing the audibility of a given signal.