

# DETECTION AND IMPACT ASSESSMENT OF IMPULSIVE UNDERWATER NOISE

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## 1 INTRODUCTION

It is now well established that anthropogenic underwater noise may have adverse effects on the marine animals, as first reviewed in 1995 by Richardson *et al.*<sup>1</sup>. In recent years, clear preliminary criteria have been proposed for assessing the physiological impacts (hearing threshold shifts and injury) of noise on both marine mammals<sup>2</sup> and fish<sup>3</sup> which primarily rely on the received noise level as an exposure metric. A more context-sensitive method has been recommended for the assessment of potential adverse behavioral reactions of marine animals to noise<sup>4</sup>, including factors such as the prior behavioral state of an animal and the novelty of the noise to that particular animal. Current procedures for monitoring underwater noise levels and assessing the likelihood of adverse impact on the marine environment utilize these criteria but often rely on manual analyses performed after acoustic recordings have been made. It is desirable to implement a standardized, automated methodology for such monitoring and impact assessment in order to reduce costs within offshore industries which require this monitoring.

For the purposes of this work we consider underwater noise on a given time scale to be made up of quasi-stationary components mixed with transient components. The types of noise which fall into each category will be determined by the time scale over which analysis is performed. For example, over the period of a day the noise of a passing ship is a transient event whereas on the time scale of a second the same noise would be quasi-stationary. Transient noise which consists of a rapid rise from the background (quasi-stationary or ambient) noise level to a peak amplitude followed by a longer period of decay and reverberation is considered to be impulsive. Due to their rapid onsets and high peak amplitudes, these noise impulses are of particular concern when addressing the potential for physiological impact on marine animals<sup>2</sup>. Thus it is necessary within any automated impact assessment methodology to isolate impulsive noise and subject it to additional analysis. In this application we wish to detect anthropogenic noise impulses with sources such as explosives, marine piling, seismic airgun arrays, sonar systems and acoustic harassment devices. The duration of these impulses may range from a few milliseconds to a few seconds<sup>5</sup>.

The primary metrics which are thought to influence the level of physiological impact which a noise impulse may cause are the peak acoustic pressure and the Sound Exposure Level (SEL)<sup>2</sup>. The SEL is a measure of the cumulative acoustic energy delivered over a period of time, beginning at  $t_{\text{start}}$  and finishing at  $t_{\text{end}}$ , defined by equation 1, where  $p(t)$  is the instantaneous acoustic pressure as a function of time.

$$\text{SEL} = \int_{t_{\text{start}}}^{t_{\text{end}}} p(t)^2 dt \quad [1]$$

If we wish to determine the SEL of an impulsive or transient sound present in a recording of underwater noise it is necessary to determine  $t_{\text{start}}$  and  $t_{\text{end}}$ , preferably in an automated and well defined manner. As can be seen from equation 1, the value of the SEL for a given waveform will be determined by these bounds and the time duration between them. In an idealized situation with no background noise it may be obvious where an impulse begins and ends, but in practice it is not so simple. An impulse detector must be used to isolate the impulse from the surrounding background

noise and thus determine the time window over which the SEL will be calculated. If different impulse detection methods give different values of  $t_{\text{start}}$  and  $t_{\text{end}}$  for the same impulse, then the resulting SEL values may differ. Thus the predicted adverse impact of a particular impulse or sequence of impulses may vary depending on the impulse detection method used. This effect will be investigated by applying different detection methods to a test waveform containing a noise impulse and comparing the impulse duration and SEL values obtained.

It is important to bear in mind that there is no correct value for the duration or SEL of this impulse. As discussed by Madsen<sup>6</sup>, different methods of calculating these values will give different results and it is critical that the calculation method is described alongside any such results. Madsen recommends that for transients with a good Signal-to-Noise Ratio (SNR) the Energy Flux Density (EFD, equivalent to SEL) is reported as 90% of the energy received in a time window containing the impulse and short sections of noise before and after the impulse. However this method may not be appropriate in low SNR conditions and is not directly applicable in an automated system without a method to determine when to begin and end this time window.

## 2 IMPULSE DETECTION METHODS

Two impulse detection methods will be investigated in this study, both of which estimate a short-term average level and a longer-term average level for each sample in the waveform. The short-term averaging duration should be less than the expected impulse duration so that this average increases during an impulse, however the long-term averaging duration should be significantly longer than the maximum expected impulse duration to ensure that even during an impulse this average is dominated by the background noise. The ratio of these estimates is calculated to give an 'impulse factor' for each sample and this impulse factor is compared against a detection threshold. Where the impulse factor exceeds the threshold, an impulse detection occurs.

### 2.1 Method 1

The impact assessment criteria proposed by Southall *et al.*<sup>2</sup> takes its distinction between impulsive and non-impulsive noise from the work of Harris<sup>7</sup> on airborne acoustic noise. Two averaging measures are calculated, one with an integration period of 35 ms to give the impulse equivalent-continuous sound level ( $L_{IeqT}$ ) and one over the total analysis period  $T$  to give the equivalent-continuous sound level ( $L_{eqT}$ ).  $L_{IeqT}$  is calculated for each sample within the analysis period using the exponentially weighted averaging filter given in equations 2-4.

$$y_I[n] = e^{t_I} y_I[n-1] + x[n]^2 \quad [2]$$

$$L_{IeqT}[n] = 10 \log_{10} \left( \frac{y_I[n]}{t_I} \right) \quad [3]$$

$$t_I = 0.035 \text{ s} \quad [4]$$

Rather than using a filter to calculate  $L_{eqT}$  for each sample, the total energy in the analysis period is simply divided by the width of this analysis period as shown in equations 5-6.

$$L_{eqT} = 10 \log_{10} \left( \frac{1}{t_A} \sum_{n=0}^{N-1} (x[n]^2) \right) \quad [5]$$

$$N = f_s t_A \quad [6]$$

The maximum  $L_{IeqT}$  value obtained is compared to the  $L_{eqT}$  value to give a difference which we will call the impulse factor  $I$ , defined in equation 7.

$$I = \max(L_{IeqT}) - L_{eqT} \quad [7]$$

If this factor exceeds a threshold of 3 dB then the noise is considered impulsive<sup>2</sup>.

This method is not directly usable to detect impulses within a real-time continuous underwater noise monitoring system. For use in this application it is desirable to compute  $L_{eqT}$  for each sample in a similar way to the computation of  $L_{leqT}$ , with a time constant of 1 s to ensure that the averaging period is longer than the expected maximum impulse duration, as shown in equations 8-10.

$$y_S[n] = e^{t_S} y_S[n-1] + x[n]^2 \quad [8]$$

$$L_{eqT}[n] = 10 \log_{10} \left( \frac{y_S[n]}{t_S} \right) \quad [9]$$

$$t_S = 1 \text{ s} \quad [10]$$

This gives a per-sample impulse factor defined in equation 11.

$$I[n] = L_{leqT}[n] - L_{eqT}[n] \quad [11]$$

We can therefore say that an impulse begins when  $I$  exceeds the given threshold (3 dB) and finishes when  $I$  returns below this threshold and we refer to this as method 1a. Hysteresis may be added in order to reduce the likelihood of spurious detection of multiple impulses when  $I$  does not increase or decrease smoothly and for method 1b the threshold for the end of an impulse is reduced to 0 dB.

## 2.2 Method 2

An alternative method is used by Zaugg *et al.*<sup>8</sup> for the detection of sperm whale clicks and impulsive shipping noise prior to classification. The background noise level is estimated by the median sample magnitude on a per-block basis with a block width of 85 ms and an overlap of 75%. A per-sample background noise estimate is then calculated by linear interpolation from these per-block estimates. The median magnitude is considered to be a better estimate of the background noise level than the mean energy as it is less influenced by high amplitude values observed during an impulse. A short-term level estimate is provided by a uniformly-weighted moving average filter with a window length of 10 ms operating on the sample magnitude signal. As in the previous method, the ratio of the short-term level estimate to the background level estimate is calculated and compared to a threshold. This threshold is set at 6 dB<sup>8</sup>, that is, the start of the impulse ( $t_{start}$ ) is determined by the ratio exceeding 2 and the end of the impulse ( $t_{end}$ ) is determined by the ratio returning below 2.

In the paper by Zaugg *et al.*<sup>8</sup>, the values of  $t_{start}$  and  $t_{end}$  for each impulse are not used directly as the bounds of the window over which feature extraction and classification is performed, instead the centre of the impulse is calculated as  $(t_{start} + t_{end})/2$  and an analysis window of a fixed length of approximately 21 ms is used, with the analysis window centred on the midpoint of the impulse. This fixed length analysis window is not suitable for the broad range of impulse durations highlighted in the introduction and so for this application the values of  $t_{start}$  and  $t_{end}$  will be used directly and this will be referred to as method 2a. The window lengths for both the short-term level estimate and the background noise estimate may also be inappropriate for the same reasons. In particular the block width used for estimating the background noise level is significantly shorter than the maximum expected impulse duration and so an alternative long-term block length of 1 s will be tested in this investigation as method 2b. The window length used to estimate the short-term envelope of the signal is longer than the minimum expected impulse duration and therefore method 2c will be tested with a short-term window length of 1 ms and a long-term block length of 1 s.

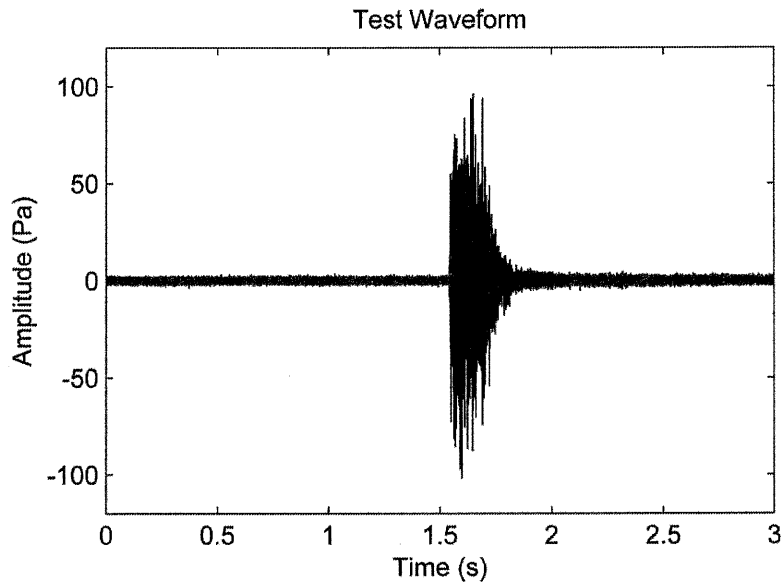


Figure 1: Test waveform.

### 3 TESTING

The impulse detection methods described above were applied to the test waveform shown in figure 1, a recording of a single hammer strike from a marine piling sequence. This recording was made on the morning of 17th April 2006 using a HS150 hydrophone at a depth of 7 m and a range of 1.8 km from the pile, connected via a low-noise preamplifier to an NI-DAQ 6062 E and sampled at a rate of 400 kHz with a sample size of 12 bits. Further details are available in the work of Robinson *et al.*<sup>9</sup>.

If a detection was made, the impulse duration, SEL and RMS Sound Pressure Level (SPL; defined in equation 14) were calculated between the start time ( $t_{start}$ ) and finish time ( $t_{end}$ ) of the impulse as reported by the detector, using equations 12 to 14.

$$T = t_{end} - t_{start} \quad [12]$$

$$SEL = \int_{t_{start}}^{t_{end}} p(t)^2 dt \quad [13]$$

$$SPL = \frac{SEL}{T} \quad [14]$$

The impulse observed in the test waveform has a high SNR and represents almost ideal conditions for an impulse detector to operate under. To properly assess the performance of the detectors tests were performed with different levels of additional continuous broadband noise introduced to the waveform. The first second of the test waveform can be seen to contain background noise of a roughly constant level and so was considered as the prototype for the introduction of additional noise. The frequency spectrum of this prototype noise was obtained via application of a Hamming window and FFT.

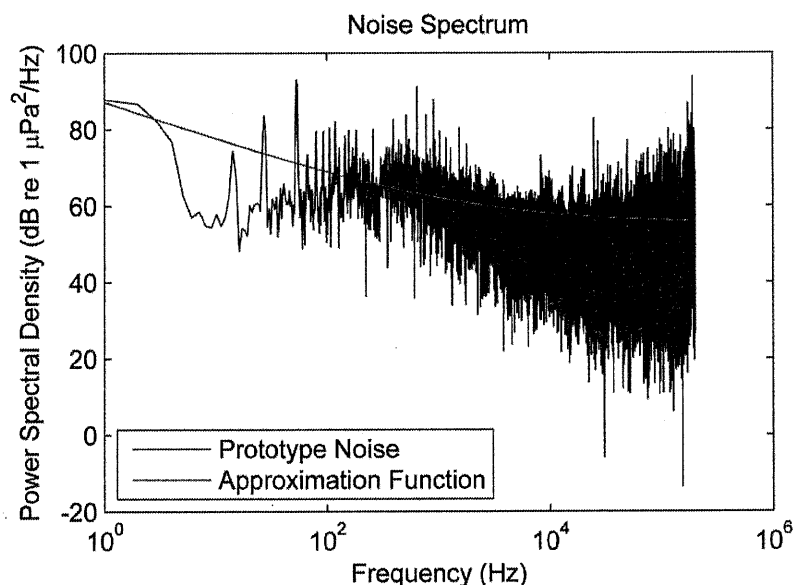


Figure 2: Background noise spectrum.

This prototype spectrum was not used directly as it may have contained tonal components which would interfere coherently with the test waveform if replicated exactly. Instead this spectrum was approximated by  $1/\sqrt{f}$  noise at low frequencies and white noise at mid and high frequencies. The crossover frequency was selected by hand to be 1500 Hz and the function was scaled to match the total energy in the original noise spectrum. The Power Spectral Density (PSD) function of this approximation is given in equations 15-16 and the approximation function is compared to the original background noise spectrum in figure 2.

$$P(f) = s \left( 1 + \frac{\sqrt{1500}}{\sqrt{f}} \right) \quad [15]$$

$$s = 574 \text{ (3 sf)} \quad [16]$$

White noise with a uniform PSD of unity was generated and filtered using the function in equation 15 to generate noise with a PSD approximately equal to the background noise in the original waveform but which would not sum coherently with the existing noise. This resulting noise was scaled and added to the original waveform to give test waveforms with amounts of additional noise in 6 dB steps up to a maximum of 24 dB. Beyond this point the peak amplitude of the original impulse was below the peak amplitude of the total noise signal and so it no longer represented a risk of additional physiological impact above that caused by the continuous noise.

The introduction of additional noise to the test waveform will have increased the resulting SEL and SPL values and therefore it is desirable to provide a point of comparison for the values given by the impulse detection methods. To provide this, and to enable a comparison with other commonly used methods of estimating the SEL of a noise impulse, the  $EFD_{90}$  as described by Madsen<sup>6</sup> was calculated over a fixed window from 1.5 s to 2 s (500 ms duration), chosen by hand to contain the impulse as well as short periods of background noise before and after.

## 4 RESULTS AND DISCUSSION

It can be seen that despite the variation between methods in the detected impulse duration, all the calculated SEL values were approximately the same for the original test waveform except for the value calculated via method 2a. Of the detection methods addressed in this study, using the first method with hysteresis gave the most consistent impulse duration values and most closely tracked the increase in SEL as additional noise was added to the test waveform. Applying this method without hysteresis gave similar performance; there was a decrease in the estimated impulse duration at the highest level of introduced noise however the effect on the calculated SEL was relatively small.

The performance of the second detection method varied depending on the integration periods used to estimate the local envelope and the background noise level. With the respective integration periods of 10 ms and 85 ms used in the work of Zaugg *et al.*<sup>8</sup> the detector performed poorly for this test waveform. However using the modified block length of 1 s for determination of the background noise estimate gave SEL values on par with the first impulse detection method. This difference in performance can be explained by plotting the calculated estimates and the resulting detection threshold against time as shown in figure 4. As can be seen, the background noise estimate produced by method 2a was strongly affected by the presence of the impulse as the integration period of 85 ms was shorter than the impulse duration. In method 2b, the background noise estimate was much less influenced by the impulse as the integration period of 1 s was considerably longer than the impulse duration.

We can also compare methods 2b and 2c which share the same 1 s block length for background noise level estimate but differ in the window lengths used for short-term level estimate. The difference in performance became apparent at an additional noise level of 18 dB as seen in figure 3. The level estimates and detection threshold are plotted at this level of additional noise in figure 5. The local signal level estimate in method 2c was strongly affected by the short variations in signal level within the impulse, causing the detection to be cut short before the impulse had finished.

## 5 CONCLUSIONS AND FUTURE WORK

As SEL values are obtained by integration of acoustic energy over a time window, for a given waveform the SEL will be determined by the start and end bounds of this time window. Where these bounds are selected by an automated impulse detection system, the SEL will vary depending on the choice of impulse detection method and the parameters used. In particular, the relationship between the temporal parameters of the impulse detection system and the duration of the impulse in question may have a large effect on the calculated SEL. If such values are used in the impact assessment of impulsive noise then the severity of impact that is predicted may also be heavily dependent on the impulse detection method used.

This study should be followed up by testing the same impulse detection methods on different types of anthropogenic impulsive noise, such as seismic air gun impulses and short sonar pulses. Further impulse detection methods must also be addressed and the first method tested in this paper should be re-tested with different time constants for the exponentially-weighted moving average filters.

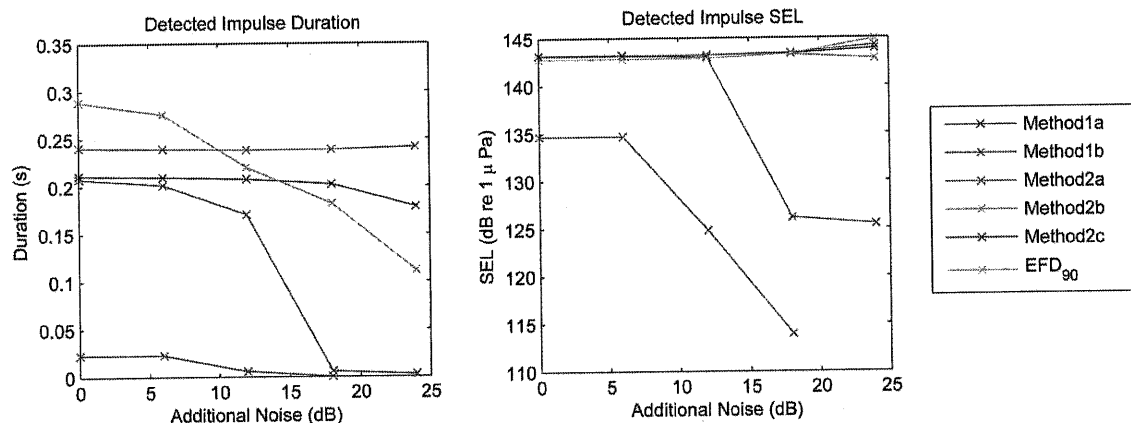


Figure 3: Results of a single run of the experiment.

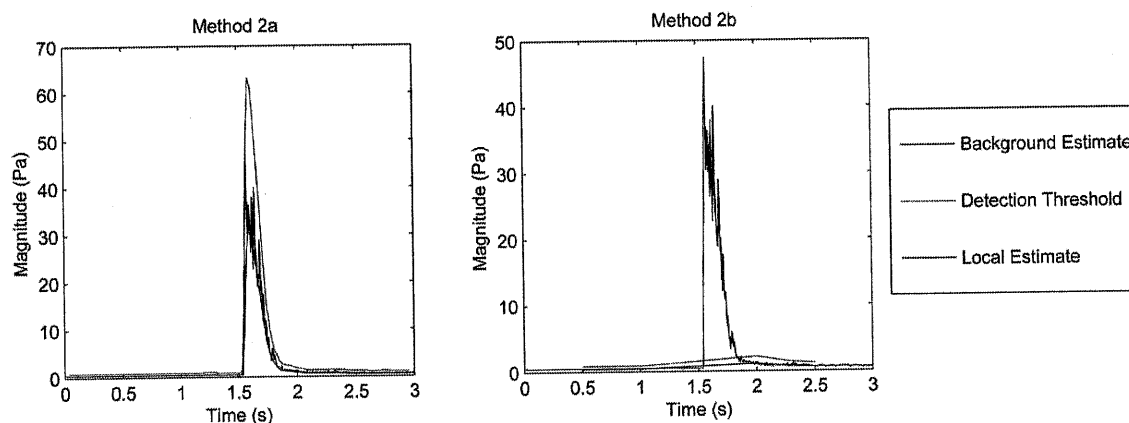


Figure 4: Comparison of detection methods 2a and 2b acting on the original test waveform with no additional noise.

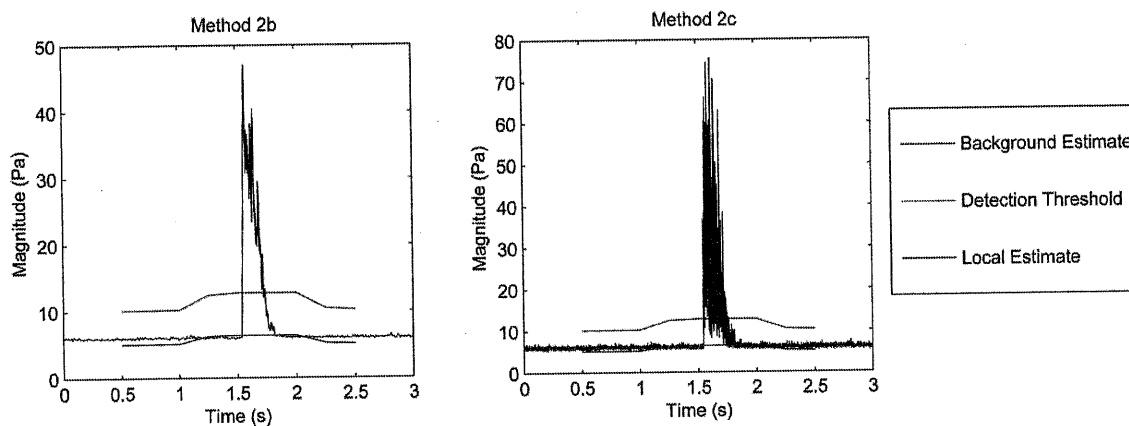


Figure 5: Comparison of detection methods 2b and 2c acting on the test waveform with the background noise level increased by 18 dB.

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