USE OF CLICKS RESEMBLING THOSE OF THE ATLANTIC BOTTLENOSE DOLPHIN (*TURSIOPS TRUNCATUS*) WITH BIASED PULSE SUMMATION SONAR (BiaPSS) TO IMPROVE TARGET DISCRIMINATION IN BUBBLY WATER

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1 INTRODUCTION

Odontocetes (toothed whales) routinely produce pulsed sounds, which many studies have shown to be used for echolocation [1]. The deliberate production by dolphins of bubble nets suggested that their echolocation may function well in bubbly water that would confound man-made sonar [2,3], an observation supported by the outstanding sonar performance of such animals in shallow waters. A sonar scheme - Twin Inverted Pulse Sonar (TWIPS) - which exploited the fact that bubbles would scatter closely-spaced pairs of equal-amplitude pulses nonlinearly, whilst other targets would not [2], was developed and tested successfully at sea [4, 5]. However TWIPS worked because consecutive pulses had inverted phase, and the only pulses resembling these to be found in odontocetes have been recorded to date at amplitudes too low to be of use in such a processing scheme [4, 6]. Their origin is not certain and their purpose (if any) has also not been determined [6].

However, it is well known that odontocetes, like the Atlantic bottlenose dolphin (*Tursiops truncatus*), emit sequences of pulses (a click train) when interrogating a target. Each pulse can have a high peak-to-peak amplitude [1]. If the pulse is of sufficiently high amplitude, bubble pulsations can become nonlinear [2]. These echolocation pulses take the form of broadband, short duration acoustic ‘clicks’. The dolphin’s performance in detecting and classifying targets, particularly in shallow water environments where the returned signal will usually be dominated by the scatter from the wave-generated bubble clouds if these are close to the target, is widely accepted to be superior to man-made sonar [7]. During target interrogation, there is considerable variation in the power and frequency of the dolphin clicks [1, 8, 9]. The hypothesis that two dolphin-like clicks of different amplitude can be combined to improve target discrimination in a bubble-filled environment is tested.

Here, the nonlinear theoretical responses of bubbles are incorporated into a simulation of the response of a bubble cloud which contains a linear target. The signal returned by the bubble cloud is then calculated, and subsequently processed with the intention of discriminating the presence of a linearly scattering object from the bubble cloud that surrounds it. In addition to target discrimination, a further test is carried out to evaluate the performance of the use of such pulse pairs for linear target detection in a bubble-filled environment using a Receiver Operating Characteristics (ROC) curve.

2 THEORY

It is common for a dolphin to emit multiple pulses during target interrogation. This may be for the orthodox purpose of monitoring changes in a target, relative motion between target and source, or for insonifying different aspects of a target. However, this paper will investigate if it can further be used in clutter reduction or target discrimination. As a form of simplification, it is assumed that a first pulse, $c_1(t)$, of duration *T*, is followed by a second similar pulse, $c_2(t)$, of different amplitude. The response from a pulse excitation of a target that scatters linearly can be represented by $y_1(t) = h(t) * c_1(t) = \int_{\mathbb{R}} h(t-t')c_1(t')dt'$ where $h(t)$ is the impulse response of the system. If $c_2(t)$ is greater than $c_1(t)$ by a factor of G, and used as the new excitation, the response $y_2(t)$ is then given by $y_2(t) = h(t) * c_2(t) = Gy_1(t)$.

A matched filter is commonly used in sonar systems [10]. Assuming the matched filter is scaled such that its overall gain is unity, then denoting the outputs of the matched filter for $y(t)$ as $Y(t)$, it follows that $Y_2(t) = GY_1(t)$. Therefore the subtraction of $GY_1(t)$ from $Y_2(t)$, which will be termed P_- in this paper, is zero for a linear scatterer. For nonlinear scatterers, P_- will, in general, give a non-zero value. This is because for a nonlinear system, the scattering from a pulse of different amplitude does not scale with the linear gain *G.*

The addition of $GY_1(t)$ and $Y_2(t)$, referred to as P_+ in this paper, tends to enhance the linear components of the scattered signal relative to the nonlinear ones. Such processing will not lead to the complete removal of nonlinear components, but only serve to partially suppress them. The processing scheme for the linear target enhancement and nonlinear scatterer enhancement by this Biased Pulse Summation Sonar (BiaPSS) is shown in Figure 1. It is worth noting that TWIPS [2, 4, 5] is based on a specific instance of BiaPSS with *G* = -1.

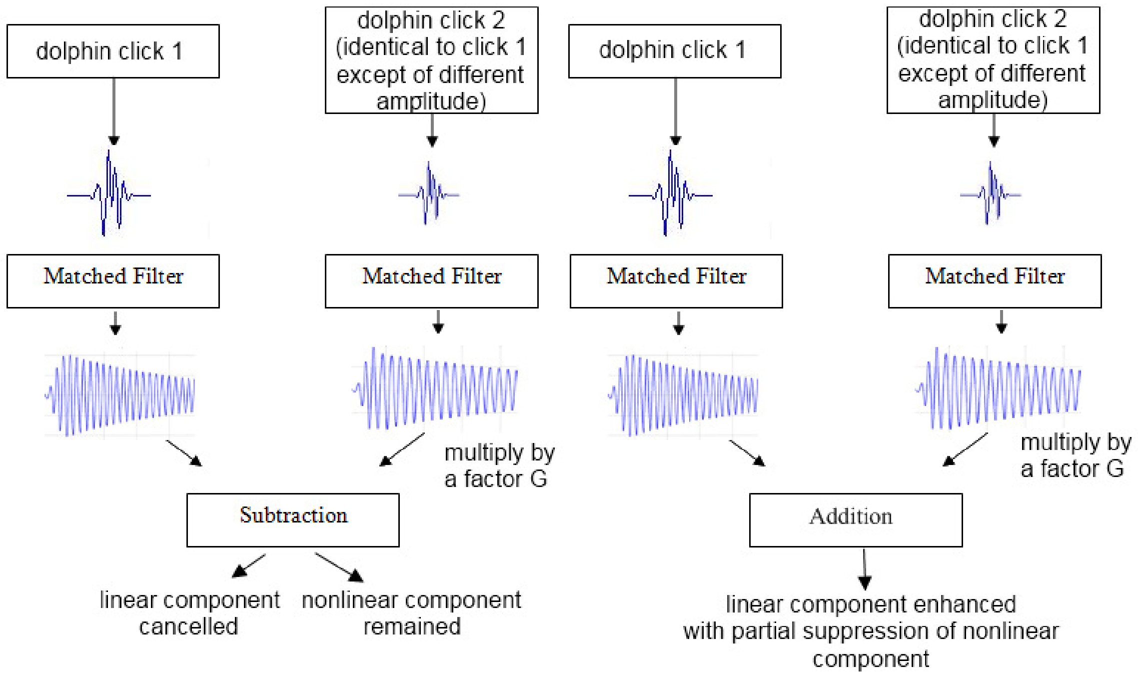

Figure 1: Processing scheme by which the echoes from a pair of dolphin-like pulses of different amplitude are processed to enhance/ cancel the nonlinear/ linear components of the scattering through weighted subtraction and addition of the scattering. The magnitude of the first pulse is greater than that of the second pulse by a factor of *G*.

3 METHOD

For the study carried out here, each pulse is approximately 60 μs in duration and consists of two chirps with nominal frequency band of 30 – 84 kHz and 76 – 130 kHz. The higher frequency chirp is delayed by 10 μs relative to the lower frequency chirp. This model is based on the one proposed by Capus *et al.* [8]. The time and frequency domain representations of the dolphin-like pulse used is shown in Figure 2. The frequency bandwidth of the pulse corresponds to a bubble resonant radius of approximately 25 to 110 μs at the sea surface. In the pair of pulses used in the simulation, the amplitude of the second pulse is 50% of that of the first pulse.

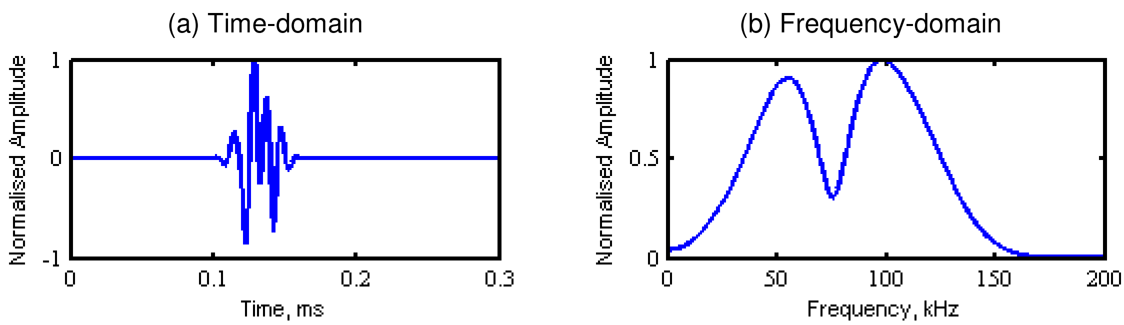

Figure 2: The pulse used in the simulation presented in (a) time-domain and (b) frequency-domain with peak-to-peak sound pressure level (SPL) of approximately 228 dB re 1 μPa .

The results shown here are obtained using the simulation method of Chua *et al.* [11]. The theoretical nonlinear responses for bubbles of different radii when subjected to a pair of pulses of different amplitude are first computed using the nonlinear Keller-Miksis equation [12]. These theoretical bubble responses are then incorporated in the simulation to assess the performance of such a pulse pair in the classification and detection of a linear target in a bubble-filled environment. An instantaneous linear scatterer with a target strength of -35 dB is used as the target.

The smoothed envelopes of the return signals (over consecutive runs) are processed as described in Figure 1, and for display purposes are then stacked (with amplitude represented by colour, as defined in the colour bar), forming image plots for comparison. The image plots show the repeatability of the test as the bubble cloud evolves. For the image plots shown, 100 separate runs have been stacked.

4 RESULTS

By comparing the responses of a scatterer from a pair of pulses of different amplitude (through weighted addition and subtraction), discrimination between linear and nonlinear scatterers can occur. To illustrate this, consider Figure 3, where a linear and nonlinear scatterer can be discriminated using a pair of pulses of different amplitude when a linear target is placed within a bubble-filled environment.

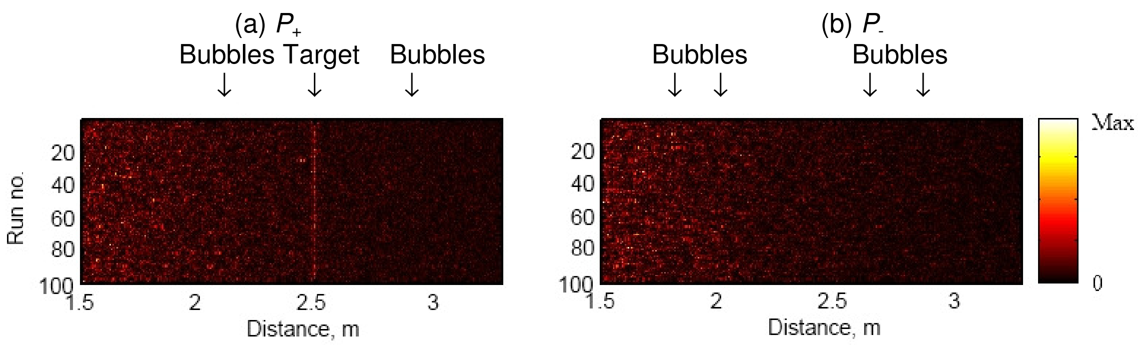

Figure 3: (Colour online) Simulation of target (TS= -35 dB) in a bubble-filled environment with the image plots of (a) P_+ and (b) P_-. The target is located at 2.5 m. Each colour scale has been normalized to a maximum value in each plot, which for (a) is 3.0 x 10^9, and (b) 2.7 x 10^9.

Figure 3(a) shows (on a linear colour scale) the results obtained when a pulse pair (of which the second pulse has an amplitude that is half of the first) were added, so highlighting the presence of the target. By subtracting the response from the first pulse with the correctly-scaled responses from the second pulse, the linear scatters are removed as observed in Figure 3(b). By comparing the plots of the sum and difference of the responses from the pulse pair of the same set of data, discrimination between linear (target) and nonlinear (bubble clouds) scatterers can take place.

A further test is carried out to determine if the use of the sum of the responses from the pulse pair, P_+, can improve linear target detection compared to “standard sonar” processing. In this context, standard sonar processing consists of averaging the smoothed envelopes of the match-filtered responses from the pulse pair. This is compared with the processing scheme for the enhancement of linear scatterers (shown in Figure 1) where the match-filtered signal from the pulse pair is first linearly added before obtaining the smoothed envelopes.

A ROC curve [13] comparing the relative performance of the two processing is shown in Figure 4. The ROC curve is generated using the distribution of the backscattered response in the region around the target position in the target absent and target present cases. In Figure 4(a), linear axes are used for the ROC curve while in (b), logarithmic axes are used to display a more useful range of probability of detection and probability of false alarm. The sum of the responses from a pair of pulses of different amplitude gives a probability of detection of 46% before giving a single false alarm, compared to a probability of detection of 27% for standard sonar processing before giving a single false alarm. Depending on the scenario, even small levels of false alarm can be costly (for example, a false alarm in mine detection could entail closure of a sea route and deployment of divers) [4].

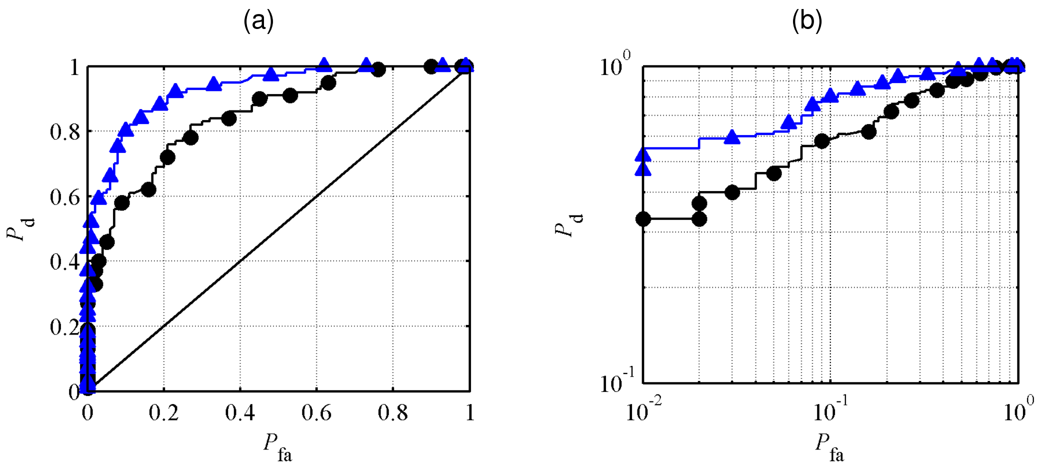

Figure 4: (Colour online) ROC curves of standard sonar processing compared with P_+ for case shown in Figure 3 where the solid circles are the ROC curve of the former and the solid triangles represent the ROC curve of the latter. P_d is the probability of detection while P_{fa} is the probability of false alarm. In (a), a linear scale is used for both axes while in (b), a logarithmic scale is used for both axes.

Although the results presented here suggest the use of a pair of dolphin-like pulses of different amplitude allow for discrimination between linear and nonlinear scatterers and can potentially improve the detection of a linear target in a bubble-filled environment, the authors are not aware of evidence which shows that dolphin can process pulses of different amplitude in the same manner, despite some studies suggesting that dolphins can combine multiple echoes for target detection and estimation [14, 15].

In general, the effectiveness of the signals with different amplitude increases when a greater proportion of the bubble population scatter nonlinearly, and it is easier for a bubble to scatter nonlinearly if the pulse frequency is close to the bubble resonant frequency. It is also intriguing to note that the frequency band of the dolphin ‘clicks’ in which the dolphin clicks’ energy is most concentrated coincides with the resonant frequencies of bubble sizes which are most numerous in typical oceanic conditions.

5 CONCLUSION

The simulations suggest that the use of a pair of dolphin-like pulses of different amplitude can discriminate between linear and nonlinear scatterers using BiaPSS. For the bubble population used in the simulation, the detection performance of the linear target in the bubble-filled environment is also shown to outperform standard sonar processing in the ROC curves.

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