USE OF DOLPHIN-LIKE PULSES TO REDUCE CLUTTER AND ENHANCE TARGET DISCRIMINATION IN BUBBLY WATER

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Abstract: *A range of pulses (including dolphin-like pulses) are used in simulation and tank tests to show that BiaPSS (Biased Pulse Summation Sonar) processing is effective with sonar at reducing clutter and improving the discrimination between targets and clutter. BiaPSS is a generalized form of TWIPS (Twin Inverted Pulse Sonar), which had previously been shown to be successful at these tasks in simulation, tank, and sea trials. Both BiaPSS and TWIPS work on processing the differences generated by the nonlinear scattering by bubbles of pairs of pulses, but whereas TWIPS exploits the differences in phase between the two pulses in the pair, BiaPSS exploits the differences in amplitude. As such, it is much easier to produce the required sonar pulse. Indeed, whereas there is no conclusive evidence of dolphins producing TWIPS pulses, the tendency of some species to vary the amplitude of clicks in a train is well-known, and not wholly explained. The paper will conclude with a discussion of the possibility of using these schemes in radar.*

Keywords: *Sonar, dolphin, target classification*

1. INTRODUCTION

The authors previously demonstrated (in simulation and tank tests) that Twin Inverted Pulse Sonar (TWIPS) could enhance the detection of targets in bubbly water, and to allow the user to distinguish between genuine targets and the clutter generated by bubble clouds [1]. The method was then successfully deployed in the wakes of vessels having sizes ranging from rigid inflatable boats (RIBS) to vessels of up to 4580 dry weight tonnage [2]. The method relies on processing the nonlinear scatter from bubbles when they are insonified by two pulses, the second being identical to the first but with inverted polarity. However there is no conclusive evidence that any odontocete emit such pulses [1, 3].

Whilst there is no conclusive evidence that pulse-to-pulse variations in phase are controlled, there is evidence that dolphins can exercise some voluntary control of the form of their echolocation pulses [4], and a pulse-to-pulse variation in amplitude is commonly observed in the echolocation emissions of odontocetes. Here we test whether such a pulse-to-pulse amplitude variation can also be processed using a generalized TWIPS scheme. The enhanced detection and classification of true targets against bubble clutter is provided by the way that the nonlinear scattering by bubbles affects the two pulses differently because of their different amplitudes (as opposed to their different phases, as was used in TWIPS). This Biased Pulse Summation Sonar (BiaPSS) has been demonstrated in tank tests to be effective with a range of pulses, some similar to those emitted by dolphins [5]. In this paper, tanks tests and a simulation are undertaken to demonstrate the efficacy of BiaPSS with a recognized representation of a type of dolphin pulse.

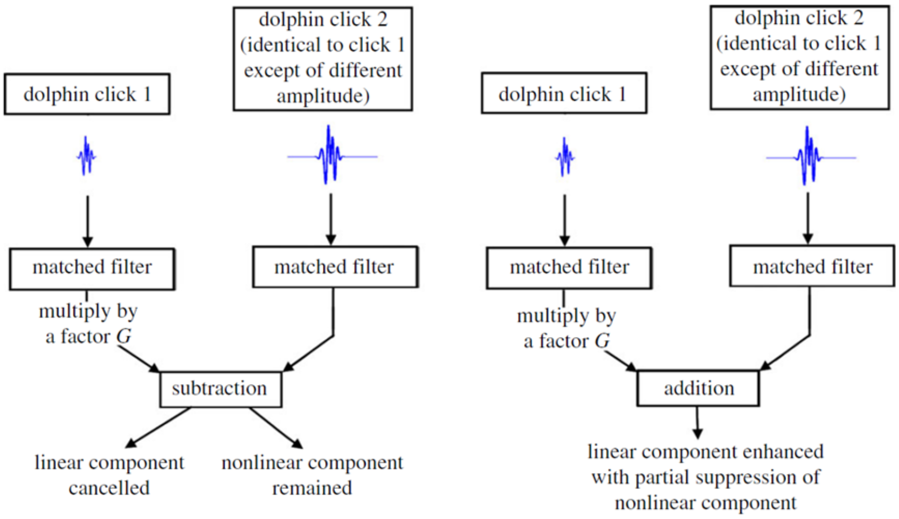

Fig. 1: Processing scheme by which the echoes from a pair of dolphin-like pulses of different amplitude are processed to enhance/cancel the nonlinear/linear components of the scattering through weighted subtraction and addition of the scattering. The magnitude of the second pulse is greater than that of the first pulse by a factor of G. From Leighton et al. [5].

The BiaPSS processing scheme can be described in simplified form through the scattering of two adjacent pulses in a click train (Figure 1). Consider that, within a train of $2N$ pulses, a pulse, $c_1(t)$, of duration T, is followed, after an interval of τ seconds, by a similar pulse, $c_2(t)$, of different amplitude [5]. These pulse pairs are emitted with a period of Δ seconds. If this pair sequence is repeated (BiaPSS does not require this to be the case), the resulting pulse train can be expressed as:

$$p(t) = \sum_{n=0}^{N-1} c_1(t - n\Delta) + c_2(t - \tau - n\Delta) . \tag{1}$$

Assuming a linear model of propagation and scattering, including a linearly scattering target (which can be taken here to represent a fish excited at much higher frequencies than the resonance of its swim bladder), the signal at the receiver, $y(t)$, can be modelled as the convolution of this signal with an impulse response, $h(t)$. This impulse response models the two-way propagation from source to target and the target's scattering characteristics. Accordingly, the model for the received signal is:

$$y(t) = \sum_{n=0}^{N-1} y_1(t - n\Delta) + y_2(t - \tau - n\Delta) . \tag{2}$$

in which $y_k(t)$ (where $k = 1, 2$) represents the convolution of the incident pulse and the impulse response function, specifically:

$$y_k(t) = h(t) * c_k(t) = \int h(t - t')c_k(t')dt' \tag{3}$$

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:

$$y_2(t) = h(t) * c_2(t) = Gy_1(t). \tag{4}$$

Assume that the detection system uses a matched filter [6] which is scaled such that its overall gain is unity. In such circumstances, if the outputs of the matched filter for $y_k(t)$ are denoted $Y_k(t)$, 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 scatter. This applies not just the steady state linear scatter but also linear scatter associated with ring-up [7] and ring-down [8]. This allows BiaPSS to discriminate between such linear targets and nonlinear scatterers like bubbles, which will in general have a non-zero value for P_-. 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 $Y_2(t)$ and $GY_1(t)$, 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. This approach can be regarded as a generalization of the TWIPS principle [1, 2], with TWIPS corresponding to the choice of G=-1, albeit that in that instance the roles of P_+ and P_- are reversed. Further details are given by Leighton *et al*. [5].

2. METHOD

As with the TWIPS processing scheme, the BiaPSS scheme will work with many different forms of pulses, but the one selected for this study resembles dolphin-like pulse described by Capus *et al.* [9], but differs in certain aspects to bring its parameters within those that our transducer can generate (Figure 2). It contains most of its energy at frequencies between 50 and 110 kHz, which are within the typical range found in dolphins' clicks. However, to reduce demand and to keep within the capabilities of the transducer, the pulse used in this experiment (figure 2) has a lower amplitude (making this a conservative test from that perspective because lower amplitudes excite weaker nonlinearities from the bubbles), and has a duration of 120 ms (figure 2), longer than the 50–80 μs typical for dolphins. This is therefore not an actual dolphin pulse, but as representative a test as the hardware can deliver within the model outlined by Capus *et al.* [9].

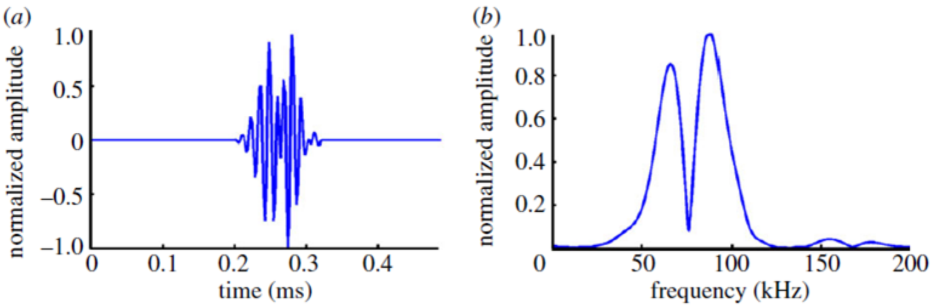

Fig. 2: The pulse used presented in (a) time domain and (b) frequency domain with a peak-to-peak amplitude of approximately 220 dB re 1 $\mu Pa\,m$. From Leighton et al. [5].

The Atlantic bottlenose dolphin (*Tursiops truncatus*) is typical of dolphin species in that, when echolocating for a target (e.g. prey), they emit a sequence of consecutive clicks. There are numerous echolocation studies on the Atlantic bottlenose dolphin which indicate that such signals are of short duration (50 – 80 μs), high intensity (up to 228 dB re 1 μPa peak-to-peak at 1 m range), and broadband [10, 11]. Each click can be modelled as two synchronous chirps, each covering a distinct frequency range and both being down-chirps (i.e. decreasing in frequency as time progresses) [9]. These clicks will be reflected back from scattering objects in the water, some of which might be targets of interest (e.g. prey) and some of which will be 'clutter' (strong scatterers which are not targets of interest, but which might be confused as such by the dolphin when it interprets the sonar returns).

The method has been detailed by Leighton *et al.* [5]. A bubble cloud is generated in a freshwater tank measuring 8 × 8 × 5 m^3 at the Institute of Sound and Vibration Research, University of Southampton, UK. The bubbles in the cloud have a size distribution and density resembling that found in the ocean (see Leighton *et al*. [1] for details). The sonar source is placed in the water tank with a target (of target strength of −38 dB) placed at a distance of 0.8 m from the source. The target is a 0.05 m diameter solid steel sphere. The sonar source used is a custom-made transducer, supplied by Neptune Sonar Ltd. This source operates within a frequency bandwidth between 30 and 120 kHz, powered by a wideband amplifier designed to improve the fidelity of the waveform generated. The source's beamwidth has been measured in the 40–100 kHz range, where the 3 dB beamwidth is reported as 10° to 30°. A single omnidirectional hydrophone is used (Blacknor Technology, D140 with built-in preamplifier, calibrated by the National Physical Laboratory) with a flat frequency response (±3 dB) up to 150 kHz.

A train of pulses is emitted, such that the interval between each pulse pair is 0.5 s. The separation between the pulses in each pulse pair is kept at 15 ms. Every other pulse is as shown in Figure 2(a), but between them are pulses which have the same form as that of Figure 2(a) but with the amplitudes all scaled down by approximately 30%. The tank data are also compared with the results of simulation, and the simulation method is described by Chua *et al.* [12]. The bubble-filled environment is represented in the simulation by a uniformly-distributed bubble population, with size distribution based on that used in the tank tests, which in turn resemble those found in the oceanic environment [1]. In the simulation, the losses during transmission to and from the bubble cloud are imposed by applying the attenuation that would be given by linear bubble pulsation [13], the attenuation of water [14, 15] and geometric losses.

This experiment was done to investigate whether this change can be exploited using a proposed detection algorithm BiaPSS. The algorithm is used with the pulses of Figure 2 specifically to test (i) whether BiaPSS is effective at classification, i.e. at distinguishing between genuine targets and clutter; and (ii) whether BiaPSS improves target detection, which is tested using the standard method of producing Receiver Operating Characteristics (ROC) curves. Leighton *et al.* [1, 2] found that TWIPS was very effective at task (i), and could generate some improvement at task (ii). The ROC curves reflect the ability of a sensor to detect a target, though they are blind to the abilities in classification described above. The ROC curves plot the probability of a true positive (P_d) on the vertical axis, against the probability of a false alarm (P_{fa}) on the horizontal axis. The most useless sonar system follows the 45° line (shown in Figure 4) as this equates to 'flipping a coin' to decide whether a sonar contact is a genuine target or clutter.

3. RESULTS

Figure 3(a) stacks side-by-side the received echoes from pairs of pulses to form an 'echogram' image. The pairs of pulses are processed using 'standard sonar processing' (which for each plot shows the average energy of the two clicks with that energy being calculated by first matched filtering the return signals, and then temporally averaging the envelope of the resulting signal over a time based on the spatial resolution of the matched filter). In figure 3(a), the target cannot be distinguished from the bubble clutter (both labelled), which would enable prey to hide from the echolocation of a dolphin, and mean that during bubble netting, or under breaking waves, a dolphin would have to rely on vision only to hunt. Figure 3(b) uses exactly the same set of raw echo data as figure 3(a) but processes them in the BiaPSS manner to ensure that, whatever is a real target, disappears from the image, leaving only the bubbles. To be specific, the subtraction of the return signals from the two pulses, with the smaller wave form of the pair scaled up by $1/0.3 \approx 3.3$, is matched-filtered, and then temporally averaged. This is denoted by P_-. The computed values of P_- are then similarly stacked side-by-side over 100 runs and presented in figure 3(b). The environment is not completely static as in the thought experiment, as the bubble cloud moved between the two pulses, but the level of degradation this causes in the cancellation of the target scatter is not sufficient to impair the result significantly.

In similar vein, if the echo from the second pulse were to be multiplied by 3 (or by whatever factor the dolphin from the thought experiment used in reducing the amplitude of the second click with respect to the first), then when the echoes of the consecutive pulses were added to one another, the backscatter from the linear target would remain in the image. Figure 3(c) shows the normalized plot with the addition of the returned signals from the two pulses after multiplication by the appropriate gain constant, 3.3 (denoted as P_+). For consistency, matched-filter processing and temporal averaging have been implemented in figure 3(c) as in all plots in figure 3. However, it is noted that the backscatters from the target can be similarly distinguished from the bubble clutter by simple subtraction and addition of appropriately scaled return signals without using matched-filter processing. In this way, a dolphin could (if it could perform subtraction and addition) distinguish the target (which remains in figure 3(a) and (c), but is suppressed in figure 3(b)) from the bubble clutter (which is enhanced in figure 3(b)). This can be done for the same set of received echoes, as there is no need to send out different pulses for the two processes. A human operator could readily identify the target by visually alternating between the P_- and P_+ images, the target being the object that flashes 'on' in P_+. This ability to distinguish between a target and clutter would remove the confusion inherent in standard sonar processing of exactly the same data (as shown in figure 3(a)). The earlier mentioned example illustrates the ability of BiaPSS to discriminate between targets and bubble clutter. As with TWIPS [1,2], such effectiveness at discrimination is seen as its primary advantage, an enhancement of the ability to detect the target in the first place (prior to classifying it) being a secondary, lesser advantage.

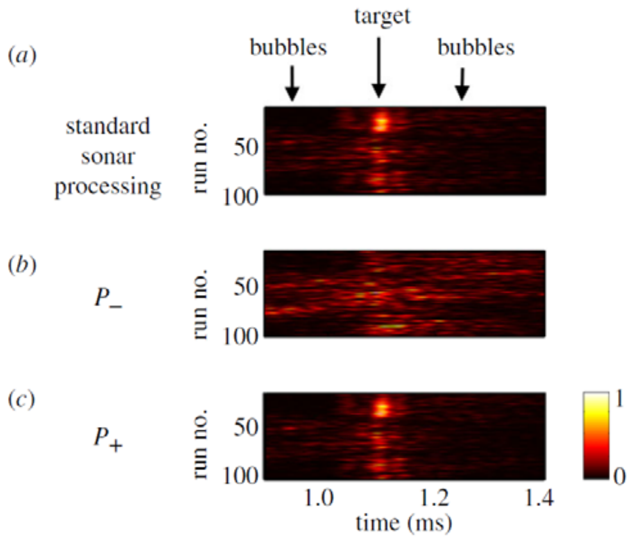

Fig. 3: Normalized plots of tank test data using a 'dolphin' pulse pair of Figure 2. Panel (a) is the standard sonar processing, (b) P_- and (c) P_+ processing of the two return signals with one appropriately scaled. The plot is normalized to the maximum value within each plot. The values are 2.2×10^2, 5.5×10 and 1.7×10^3 for (a), (b) and (c), respectively. Arrows above each panel indicate the position where the target should appear, and some of the bubble locations (which are present throughout the frame). From Leighton et al. [5].

Figure 4 compares the ROC curve for BiaPSS processing of this dolphin-like pulse for tank data (figure 4(a)) and for simulation (figure 4(b)). The difference between the ROC curves for the experiment and simulation in figure 4 is explained by the fact that the model fails to reproduce certain aspects of the specific bubble cloud in the tank. In particular, the cloud formed in an experiment will exhibit spatial and temporal heterogeneity that the model is unable to replicate precisely. The absolute performance, as measured by the ROC curves, of the model relative to the experiment suggests that this environmental feature is not perfectly modelled. Both ROC curves in figure 4 show improved performance for BiaPSS over standard sonar processing, as the BiaPSS curve is consistently above the standard sonar, meaning that, for every detection, it produces fewer false alarms. False alarms can be damaging to missions. They could cause a dolphin to be distracted from a genuine fish by bubbles and waste valuable energy chasing bubbles during a hunt. If false alarms occur in man-made sonar, they can needlessly delay a vessel's progress by causing it to reduce speed and deploy mine-hunting divers, change mission plan, etc.

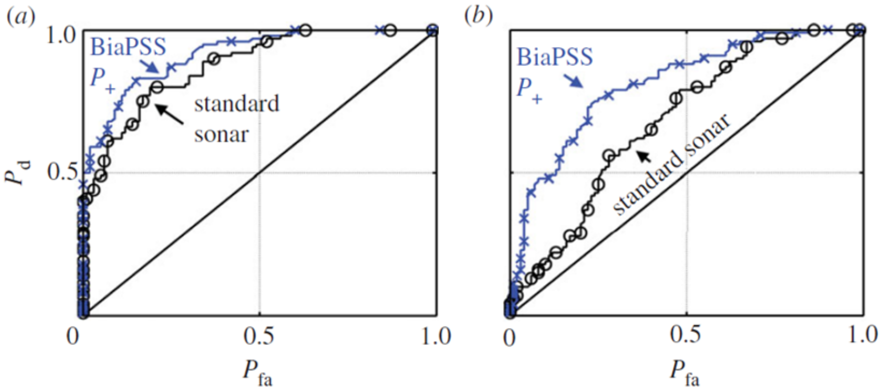

Fig. 4: ROC curves computed from (a) the tank data and (b) simulated data, for the scenario described in this paper. The results for BiaPSS P_+ (cross symbols) are compared with the results for standard sonar processing (circles). The solid line without symbols shows the 45^o line, which represents the most useless form of sonar (see text). From Leighton et al. [5].

4. DISCUSSION AND CONCLUSIONS

The BiaPSS processing has been shown to improve target detection, reduce false alarms, and enable true targets to be distinguished from bubble clutter. The target is identified because it stands out in figure 3(c) but is supressed in figure 3(b), and bubble clutter is distinguished from it because it exhibits the opposite behaviour. As with TWIPS, BiaPSS requires there to be a difference between consecutive pulses, and in BiaPSS that difference is in terms of amplitude (whereas with TWIPS it was in terms of phase). Whilst a click-to-click variation in amplitude has been observed in dolphins, and has never fully been explained, the results of this paper do not prove that dolphins do use BiaPSS processing, and indeed to do so they would need to be sensitive to echo information at twice the main frequency of the emitted pulse, which is certainly not always the case. What has been shown is that click-to-click variations in amplitude can be used by a BiaPSS scheme to enhance target detection and classification.

The efficacy of BiaPSS processing is not limited to sonar. Certain important targets scatter nonlinearly with EM radiation e.g. combustion products with LIDAR, and metal-to-metal and semiconductor junctions with RADAR, as such can be distinguished from linearly-scattering objects (foliage, soil etc.). Of course the fundamental requirement of TWIPS and BiaPSS remains, that the amplitude of the driving signal be sufficiently strong at the target to excite nonlinearities, and this may require a bistatic arrangement for some deployments, placing the source close to the target whilst leaving the receiver at a safer distance [16].

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