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2pBAa9. Use of dolphin-like pulses to enhance target discrimination and reduce clutter

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Building on the earlier success of using twin inverted pulses to supress bubble scatter and so reduce clutter when detecting targets in bubbly water (proven in ship wakes in field trials), the same nonlinear processing scheme is generalized to make use of dolphin-like pulses. Their performance in reducing clutter and enhancing target discrimination is demonstrated in the laboratory, and the opportunities for using the same scheme to improve the detection of hidden electronic devices or semiconductor devices by radar are discussed.

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INTRODUCTION

The use of Twin Inverted Pulse Sonar (TWIPS) has previously been shown, in both tank tests and sea trials, to 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 (Leighton *et al*., 2010, 2011). 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 odontocetes emit such pulses (Leighton *et al*., 2010; Finfer *et al.*, 2012).

Intriguingly, the pulse-to-pulse variation in amplitude that is commonly observed in the echolocation emissions of odontocetes can also be processed using the same TWIPS scheme. Here 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 BiaPSS (Biased Pulse Summation Sonar) has been demonstrated in tank tests to be effective with a range of pulses, some similar to those emitted by dolphins (Leighton *et al*., 2012). In this paper a simulation is undertaken to demonstrate the efficacy of BiaPSS with a recognized representation of a type of dolphin pulse.

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 (Leighton *et al*., 2012). 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 $p(t) = \sum_{n=0}^{N-1} c_1(t - n\Delta) + c_2(t - \tau - n\Delta)$. 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 modeled 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 $y(t) = \sum_{n=0}^{N-1} y_1(t - n\Delta) + y_2(t - \tau - n\Delta)$ in which $y_k(t)$ (where $k = 1,2$) represents the convolution of the incident pulse and the impulse response function, specifically $y_k(t) = h(t) * c_k(t) = \int h(t-t')c_k(t')dt'$. 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 $y_2(t) = h(t) * c_2(t) = Gy_1(t)$. Assume that the detection system uses a matched filter (Burdic, 1984) 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 $Y_k(t)$ where $k = 1,2$, 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 (Clarke & Leighton, 2000) and ring-down (Leighton *et al*., 2004). 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 (Leighton *et al*., 2010, 2011), 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*. (2012).

METHODS

As with the TWIPS processing scheme, the BiaPSS scheme will work with many different forms of pulse, but the one selected for this study is the dolphin-like pulse described by Capus *et al.* (2007) (Figure 2). 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 (Au, 1993; Au & Nachtigall, 1997). Each click can be modeled as two synchronous chirps, each covering a distinct frequency range and both being down-chirps (i.e. decreasing in frequency as time progresses) (Capus *et al.*, 2007). 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 be targets of interest, but which might be confused as such by the dolphin when it interprets the sonar).

The simulation method is described by Chua *et al.* (2012). 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%. This is 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.* (2010, 2011) found that TWIPS was very effective at task (i), and could generate some improvement at task (ii).

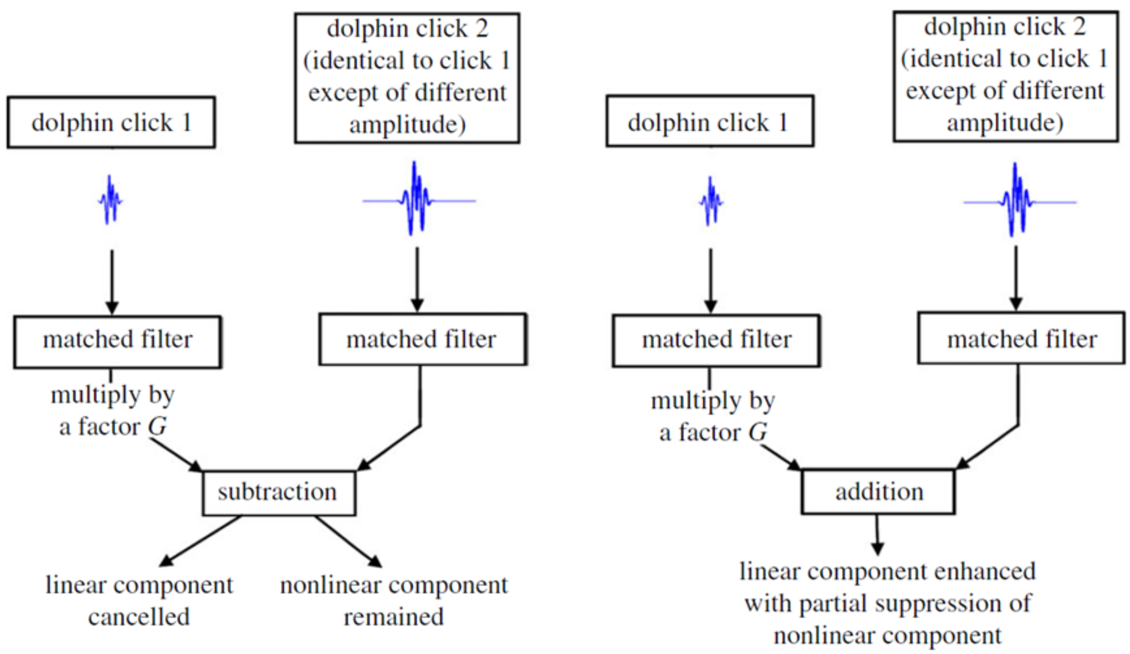

FIGURE 1. Processing scheme by which the echoes from a pair of dolphin-like pulses of different amplitude are processed to enhance/cancel the nonlinear/linear components of the scattering through weighted subtraction and addition of the scattering. The magnitude of the second pulse is greater than that of the first pulse by a factor of *G*. From Leighton *et al.* (2012).

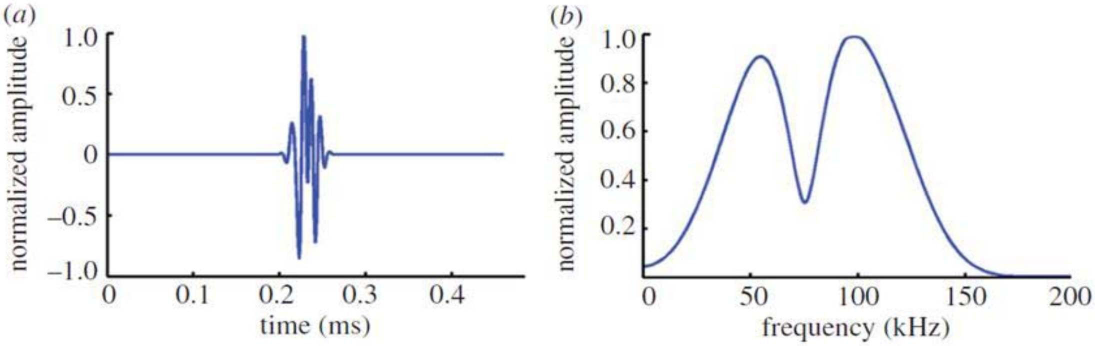

FIGURE 2. The 'dolphin' pulse used in the simulation presented in (*a*) time domain and (*b*) frequency domain with a peak-to-peak amplitude of approximately 226 dB re 1 μPa m.

The bubble-filled environment is represented in the simulation by a uniformly-distributed bubble population, with size distribution similar to those used in the tank tests described by Leighton *et al.* (2012), which were undertaken in a facility that was designed to produced bubble populations resembling those found in the oceanic environment (Leighton *et al.*, 2010). Here, the linear target will be represented by a linear scatterer with a target strength of -41 dB placed at a distance of 1.25 m from the 'dolphin'. This value of -41 dB is chosen as it is within the typical range of target strength of some fish species with fish length of approximately 15 to 30 cm (Au *et al*., 2007). 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 (Commander & Prosperetti, 1989), the attenuation of water (Francois & Garrison, 1982a, b) and geometric losses. ROC curves are calculated from the simulation data. ROC curves reflect the ability of a sensor to detect a target, though they are blind to the abilities in classification described above. 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^o line (shown in Figure 4) as this equates to 'flipping a coin' to decide whether a sonar contact is a genuine target or clutter.

RESULTS

Figure 3 shows the simulated results for the performance of the dolphin-like pulse shown in Figure 2, if it were to be deployed in a bubble-filled environment, when processed using (a) standard sonar processing techniques, (b) the BiaPSS function P_-, and (c) the BiaPSS function P_+. For this target and bubble population, standard sonar processing detects both target and bubbles (a much weaker target would not be detectable, of course). But standard sonar does not provide a way of proving which is which (the visual cues to the human of the straight line in Figure 3(a) would not be present when hunting a moving fish). BiaPSS is clearly able to identify the target by its appearance in Figure 3(c) and disappearance in Figure 3(b). In addition to this effectiveness at classification, the ROC curve of Figure 4 indicates BiaPSS also provides enhanced target detection with this 'dolphin' pulse pair. In the ROC curve, the probability of a true positive (before giving a single false alarm) improves from 46% (with standard sonar) to 70% (with P_+) and the area under the ROC curve increases by 4% with BiaPSS when compared with standard sonar. Figure 4 therefore shows 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 manmade sonar, they can needlessly delay a vessel's progress by causing it to reduce speed and deploy mine hunting divers, change mission plan, etc.

DISCUSSION AND CONCLUSIONS

BiaPSS has been shown in simulation with dolphin-like pulses to improve target detection, reduce false alarms, and enable true targets to be distinguished from bubble clutter. As with TWIPS, BiaPSS required 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 (Leighton *et al.*, 2008).

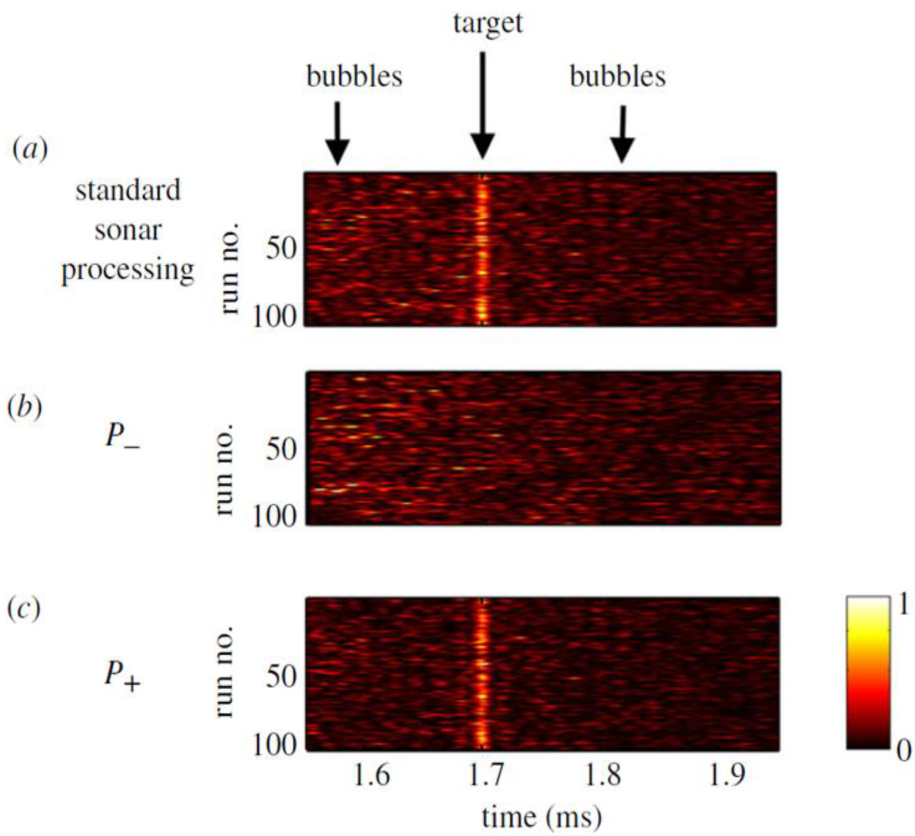

FIGURE 3. Normalized plots of simulations using a 'dolphin' pulse pair of Figure 2. Panel (*a*) is the standard sonar processing, (*b*) P_- and (*c*) P_+ processing of the two return signals with one appropriately scaled. The plot is normalized to the maximum value within each plot. The values are 1.3×10^9, 3.1×10^9 and 7.8×10^9 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.* (2012).

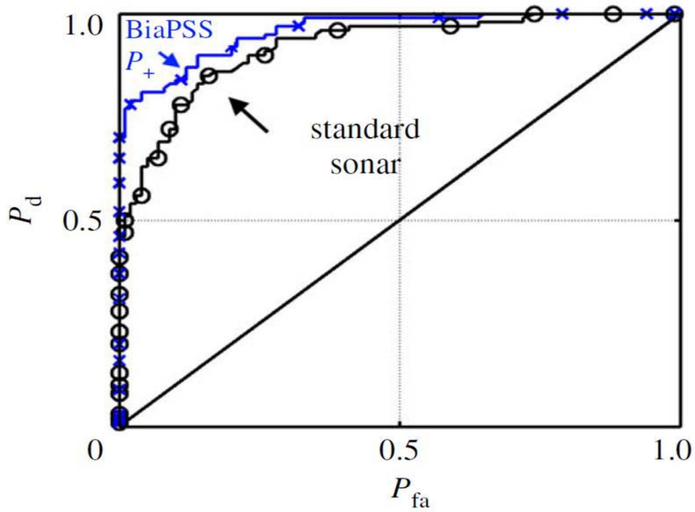

FIGURE 4. ROC curves for the 'dolphin' pulse pair simulated data of Figure 3. The results for BiaPSS P_+ (cross symbols) are compared with the results for standard sonar processing (circles). The solid line without symbols shows the 45^o line, which represents the most useless form of sonar (see text). From Leighton *et al.* (2012).

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