IMPROVED TRACKING OF A SURROGATE TARGET USING CONTINUOUS ACTIVE SONAR

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Abstract: *Increasing the duty cycle of traditional Pulsed Active Sonar (PAS) to approach that of a Continuous Active Sonar (CAS) mode is being investigated for Anti-Submarine Warfare applications including littoral scenarios. CAS mode offers the potential advantage of increasing the target update rate through sub-band processing to improve tracking performance. A sea trial was carried out by the Littoral CAS Multi-National Joint Research Project in the gulf of Taranto in October of 2016. LFM PAS and CAS active sonar waveforms were simultaneously transmitted by the surface ship NRV ALLIANCE, to detect a surrogate target (echo repeater) towed by the surface ship CRV LEONARDO. In this work multi-static echo returns of the CAS and PAS waveforms, received by an autonomous underwater vehicle towing a linear array, are analysed at the output of an M-of-N distributed multi-hypothesis tracker. The CAS waveform is sub-banded into seven 5 second long sub-pulses with a 50% overlap. To simulate a more realistic target, the signal to noise ratio of the echoes from the echo-repeater target were adjusted based on a simple bi-static target strength model in post processing. The results demonstrate that, in the measured environment, CAS can reduce the false alarm rate compared to a conventionally processed PAS waveform at the output of a distributed multi-hypothesis tracker.*

Keywords: *Continuous Active Sonar, Tracking, High Duty Cycle, Continuous time LFM, Echo Repeater, Littoral*

1. INTRODUCTION

Interest in increasing the duty cycle of traditional pulse active sonar (PAS) to a continuous active sonar (CAS) mode has arisen recently for anti-submarine warfare (ASW) applications including littoral scenarios [1]. In PAS systems, a sonar signal is transmitted for a short duration followed by a long listening duration (upper frequency band of Figure 1). In CAS systems, a sonar signal is transmitted continuously while simultaneously listening for echoes (lower frequency band of Figure 1). CAS mode offers the potential advantage of increasing the target update rate through sub-band processing [1-3] to improve tracking performance [4]. However this advantage needs to be experimentally confirmed as reducing the sub-band duration reduces the energy per ping which can negatively impact the detection performance. Sub-bands can have a narrower bandwidth, as is the case for linearly frequency modulated (LFM) waveforms, which can also negatively impact the detection performance in reverberation limited environments.

This paper will compare tracking performance of simultaneously transmitted CAS and PAS waveforms against a surrogate echo repeater target. The Signal to Reverberation Ratio (SRR) of the echoes from the surrogate target are adjusted in post processing based on a simple target model to make the comparison more realistic.

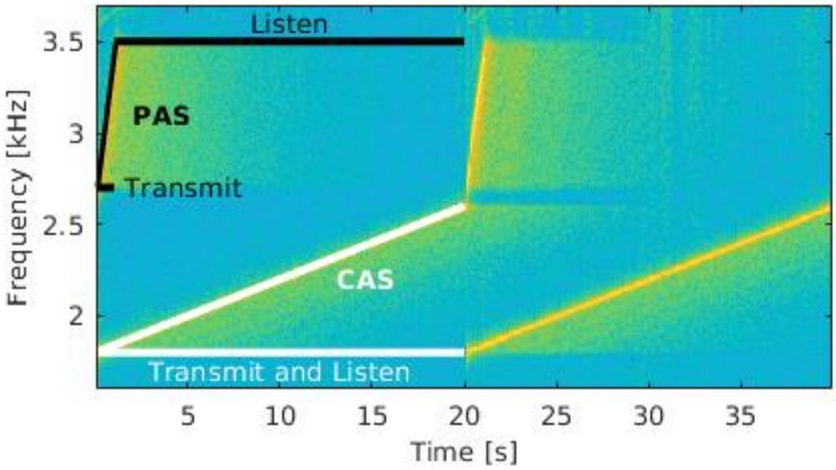

Figure 1: Spectrogram of an example LFM PAS (1 second long from 2.7-3.5 kHz, black labels) and LFM CAS (20 seconds long from 1.8-2.6 kHz, white labels) signals with a ping repetition interval of 20 seconds.

2. EXPERIMENT AND DATA ANALYSIS

In October 2016, the Littoral CAS (LCAS) Multi-National Joint Research Project (MN-JRP) held a sea trial off the coast of Taranto (Italy) to compare the detection capability of LFM PAS with LFM CAS. The NRV ALLIANCE attempted to detect an Echo Repeater (ER), acting as a surrogate target, towed by CRV LEONARDO.

On October 22, during run named ER-3, the NRV ALLIANCE towed a sonar source that transmitted a LFM PAS signal (from 2.7-3.5 kHz over 1 s) and a LFM CAS signal (from 1.8-2.6 kHz over 20 s with a source level $10\log_{10}(20s/1s)$=13 dB lower than the PAS signal) with a ping repetition interval of 20 s, as shown in Figure 1. Each pulse had equal total energy per ping. The source was towed at a depth of approximately 70 m. Ocean Explorer (OEX) Harpo, an Autonomous Underwater Vehicle (AUV), towed a linear array with 64 hydrophones at a depth of 85 m and was used as a bi-static receiver. The CRV LEONARDO towed an echo repeater at a depth of approximately 70 m.

The CRV LEONARDO sailed downslope and antiparallel to NRV ALLIANCE with a closest point of approach of approximately 6.2 km, as shown in Figure 2a. Both surface vessels travelled at approximately 3.5 knots (~1.75 m/s). OEX-C Harpo AUV travelled at 2 knots (~1 m/s). Figure 2a also shows the bathymetry of the operational area, acquired using an *EM 302 KONGSBERG* 30 kHz multibeam echo sounder.

The sound speed profiles were measured at 06:36UTC and 16:33UTC on October 22 using a *Sea-bird Electronics 9plus* conductivity, temperature, and depth (CTD) sensor and are shown in Figure 2b. The measured sound speed resulted in a downward refracting sound speed profile with a 35 m deep mixed layer. Note that source, receiver, and echo repeater were all below the thermocline.

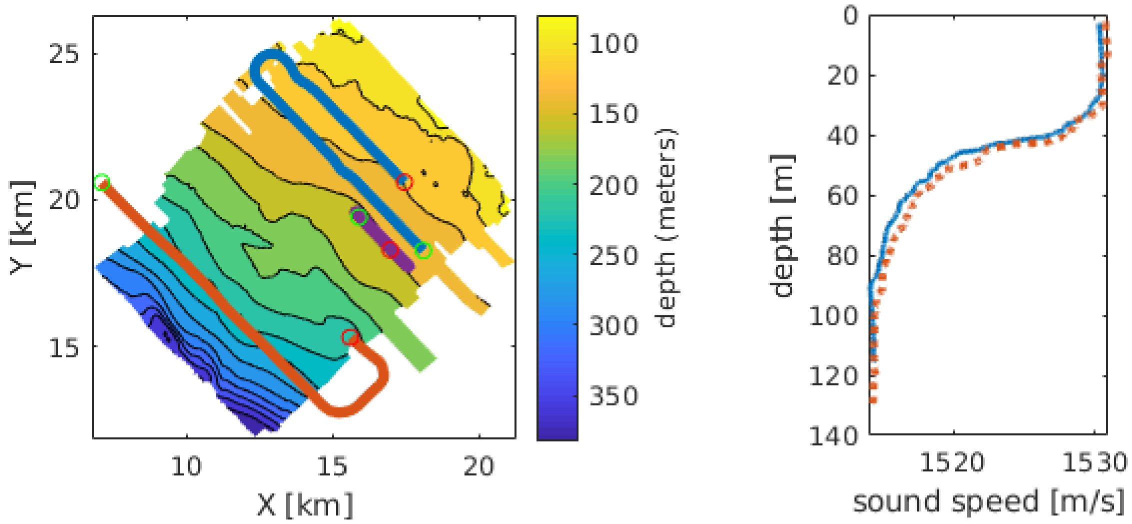

Figure 2: (a) NRV ALLIANCE (blue), CRV LEONARDO (red), OEX Harpo (purple) trajectory from green to red point. Background shows bathymetry of operational area. (b) Sound speed profile measured at 06:36UTC (blue) and 16:33UTC (dashed red) on October 22.

The sea conditions were sea state 3 (significant wave height of 0.6 meters), with waves coming from the south and a dominant wave power spectral density of approximately 0.4 m^2/Hz at 0.16 Hz, measured using a *Datawell oceanographic instruments MKIII* moored directional wave rider.

The hydrophone array data acquired by OEX-C Harpo were first beamformed into 64 cosine spaced beams. Next, the data were Matched filtered with a single replica for PAS and 7 sub-band replicas with Hann windows and a 50 % temporal overlap for CAS. The SRR was estimated using a sliding window median filter with a duration of 400 ms (normalisation). A threshold (discussed below) was applied to the normalised data followed by clustering. The resulting contacts were sent to the Centre for Maritime Research and Experimentation (CMRE) Distributed Multi-Hypothesis Tracker [5]. The DMHT is a multi-hypothesis M-of-N tracker, where M contacts out of N opportunities are required to initialize a track [6].

Three values for N were selected for CAS and PAS respectively, as shown in Table 1. Note that values of N for CAS and PAS are equal as measured in duration (seconds). Values for M were estimated using recent work on sliding M of N detectors by Abraham [7][8] and the parameters in Table 1. The estimated values of M as calculated by Abraham [7][8] are within 2 of the approximation given by Shnidman [9],

$$M_{opt} = 10^b N^a, \tag{1}$$

Using the Swerling II target model (with a=0.91 and b=-0.38) [9]. An initiated track was killed when the number of sequential missed detections exceeded a parameter K. K was set to N-M to best approximate a sliding M-of-N detector.

Initial values of the threshold (T) (square brackets in Table 1) were also estimated using work by Abraham [7][8] and the parameters in Table 1. To obtain a Receiver Operating Characteristic (ROC) curve the threshold was varied around the initial values by the values in the curly brackets in Table 1. Each value in square brackets in Table 1 is used with the corresponding value for a different parameter. For example, the following tracker parameters were used with N=84 for the CAS waveform; M=22, K=62, and thresholds of 1.5,2,3,6, and 9 dB above the initial estimate of 11.8 dB.

Parameter	*Value*
N	PAS: [6,8,12] CAS: PAS x $7_{\text{sub-bands=}}$[42,56,84]
M (Estimated using [7])	PAS: [2,3,4] CAS: [12,16,22]
K (Max missed detections=N-M)	PAS: [4,5,8] CAS: [30,40,62]
T (starting point Estimated using [7])	PAS: [14.5, 13.3, 12.7] +{0,0.5,1,2,3,6,9,12,15} dB CAS:[12.3, 11.97, 11.8] +{1.5,2,3,6,9} dB
Process noise	0.001 m^2/s^3
Spatial gate probability	99 %
Tracker depth	2
Signal modal type	Gaussian fluctuating
Independent samples in normalizer	126
Number of cosine spaced beams	64
Valid target bistatic range (R)	3<R<25.5 km
Contact time delay uncertainty (σ_τ)	0.03 s
Contact bearing uncertainty (σ_Θ)	¼ of beam spacing

Table 1: Processing parameters.

In shallow water environments with high compact clutter on the sea floor, the tracker often has a number of false tracks that are stationary. These tracks are fixed in space and therefore should have a velocity of 0 m/s. At each point along a track, the DMHT provides an estimate of the track velocity and an uncertainty associated. For the purpose of this analysis, a track is assumed stationary and is discarded if the velocity of the track is equal to 0 m/s within the estimated uncertainty for a majority of the track duration (greater than 68%).

The surrogate target was omnidirectional, which is unrealistic. To make the comparison of CAS with PAS more realistic, the target echoes were degraded (or enhanced) based on a simple target model [10] and on the known tactical geometry (Figure 3) in post processing. The target echoes were identified as the strongest SRR contact within ±0.75 seconds and ±4 beam of the expected target location.

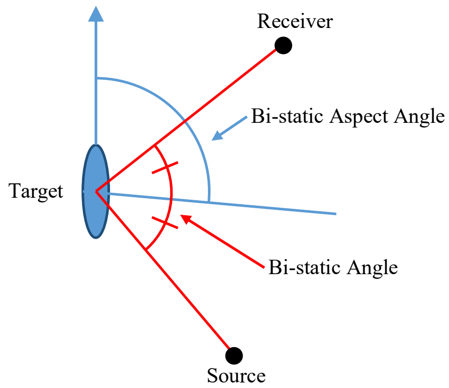

Figure 3: Bistatic active sonar geometry

3. EXPERIMENTAL RESULTS

Figure 4a shows the ROC curve for PAS and CAS with different values of N before adjustment of the target echoes. Each point along the curve gives the percent tracked time on target (TOT) and the average number of false alarms per minute using one set of tracker parameters. The tracker input threshold is varied while keeping all other parameters constant to generate each curve. Each ROC curve is colour coded by the different values of N as measured in duration (seconds). The continuous lines indicate CAS and the dashed lines indicate PAS. Figure 4b shows the tracking result with N=12 at the operating point indicated by the red circle in Figure 4a. The Green, blue, and dashed red lines in Figure 4b indicate the trajectory of the NRV ALLIANCE (source), OEX-C Harpo (receiver), and CRV LEONARDO (ER target) respectively. The solid red lines indicate the tracks.

The OEX-C Harpo towed a linear towed array which has port/starboard ambiguity. This ambiguity causes the tracks indicated by the black arrows in Figure 4b. Note that these excellent results (near perfect TOT and FAR) are not realistic due to the omnidirectional characteristic of the ER.

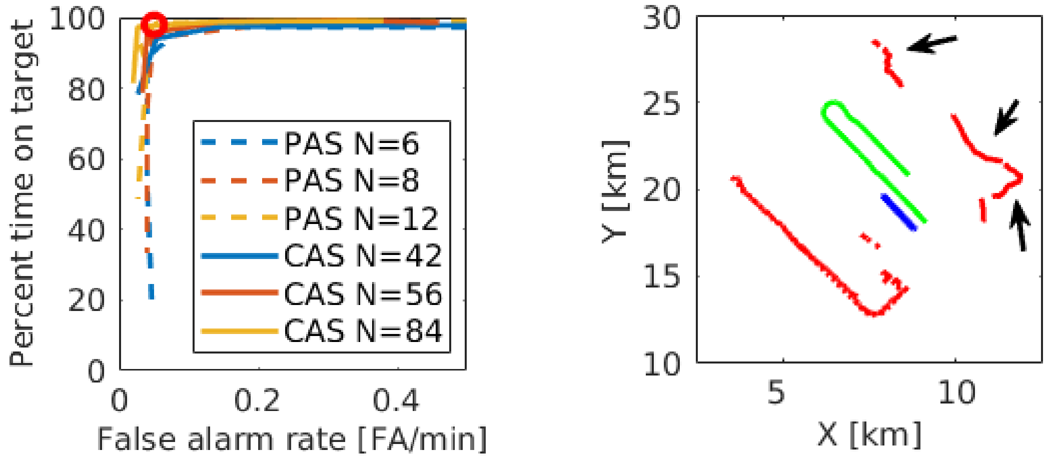

Figure 4: (a) ROC curve at the output of the tracker for 3 different values of N for CAS and PAS. Each point is given by the percent time on target and average false alarm rate for varying thresholds. Red circle indicates the results shown in (b). (b) Tracker results for N=12, M=4, T=18.7 dB resulting in FAR 0.05 min^{-1} and a time on target of 98%. Green, blue, and dashed red lines indicate the trajectory of the NRV ALLIANCE (source), OEX Harpo (receiver), and CRV LEONARDO (ER target) respectively. The non-stationary tracks are shown in red.

To compensate for the high echo repeater target strength, the target echoes were adjusted based on a simple target model [10] as described above. Figure 5 shows the ROC curve for PAS and CAS waveforms against the echo repeater target with adjusted echo SRR. Note that the CAS waveform outperforms the PAS waveform at the output of the tracker, as it has a higher TOT for a given FAR for all N.

Figure 6a and Figure 6b show the tracking results from the best CAS and PAS operating points in Figure 5 respectively (as indicated by the solid and dashed arrows). Note that there are approximately half the number of false alarms in CAS when compared to PAS and the time on target is approximately equal.

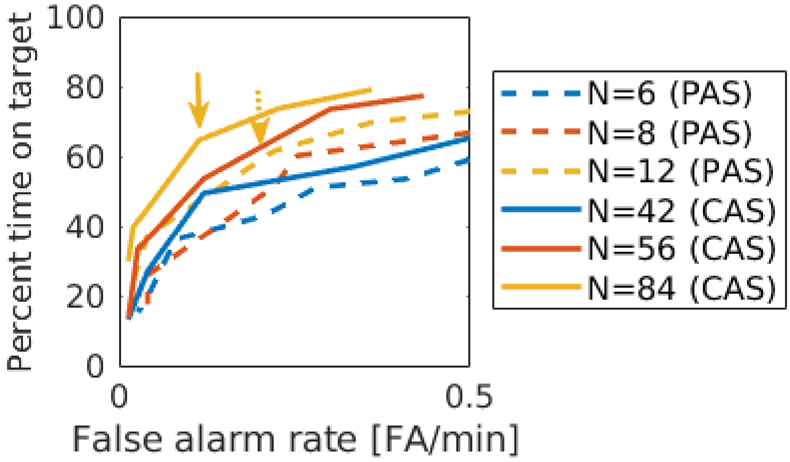

Figure 5: ROC curve for PAS (dashed lines) and CAS (solid lines). The matching colours have equal value of N as measured in seconds rather than updates. The solid and dashed arrows represent the operating points shown in Figure 6.

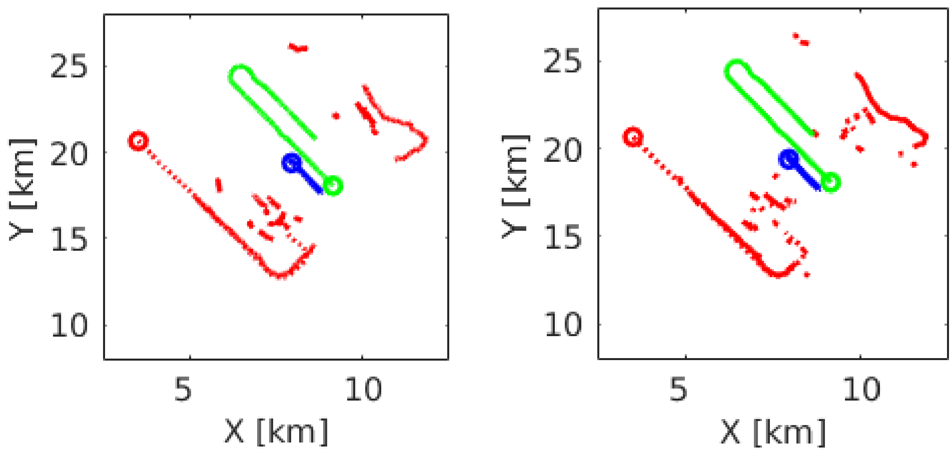

Figure 6: CAS vs. PAS tracker result with N=4 minutes. (a) CAS with N=84, M=22, and T=14.8, resulting in 7 false alarms per hour and 65% TOT. (b) PAS with N=12, M=4, T=15.7 dB, resulting in 13 false alarms per hour and 62% TOT.

4. CONCLUSIONS

A LFM CAS waveform was demonstrated to have fewer false alarms and equivalent time on target at the output of a tracker when compared with a LFM PAS waveform with equivalent bandwidth and energy per ping. The result was determined experimentally in a littoral environment with the echo repeater target strength adjusted in post processing to represent more realistic operating conditions. Reducing the false track rate is especially important for AUV platforms where decision making process needs to be automated due to the minimal ability for humans to directly interpret the AUV's underwater picture. Future work involves investigating if the results hold for more realistic targets and scenarios in a wide variety of environments. These results should also be investigated with respect to scenarios with a human in the loop.

5. ACKNOWLEDGEMENTS

This work was funded by NATO Allied Command Transformation (ACT) Future Solutions Branch under the Autonomous Security Network Programme. This work was made possible by the LCAS Multi-National Joint Research Project (MN-JRP), including as participants the NATO Centre for Maritime Research and Experimentation, the Defence Science and Technology Organisation (AUS), the Department of National Defence of Canada Defence Research and Development Canada (CAN), the Defence Science and Technology Laboratory (GBR), Centro di Supporto e Sperimentazione Navale-Italian Navy (ITA), the Norwegian Defence Research Establishment (NOR), the Defence Technology Agency (NZL), and the Office of Naval Research (USA).

REFERENCES

[1] **P.C. Hines**, Experimental comparison of continuous active and pulsed active sonars in littoral waters, In *Proc. 1st International Conference and Exhibition on Underwater Acoustics*, Corfu, Greece, pp. 51-58, 2013.

[2] **S.M. Murphy P.C. Hines**, Sub-band processing of continuous active sonar signals in shallow water, In *Oceans 2015 - Genova*, Genova, Italy, pp. 1-4, 2015.

[3] **R. Plate and D. Grimmett**, High Duty Cycle (HDC) sonar processing interval and bandwidth effects for the TREX'13 dataset, In *Oceans 2015 - Genova*, Genova, Italy, pp. 1-10, 2015.

[4] **D. Grimmett**, Target AOU Growth Containment using LFM High Duty Cycle Sonar, In *Proc. Of the 2nd International Conference on Underwater Acoustics*, Rhodes, Greece, pp. 839-846, 2014.

[5] **C. Carthel, S. Coraluppi,** The NURC Distributed Multi-Hypothesis Tracker (DMHT): Scientific User Documentation, 2007.

[6] **S. Coraluppi and C. Carthel**, Distributed tracking in multistatic sonar, *IEEE Transactions on Aerospace and Electronic Systems*, vol. 41, no. 3, pp. 1138-1147, July 2005.

[7] **D. A. Abraham,** Optimization of m-of-n detectors in heavy-tailed noise. In Proc. IEEE/MTS OCEANS18, Charleston, US, 2018.

[8] **D. A. Abraham,** Analysis and Design of Sliding m-of-n Detectors. Technical report, CausaSci LLC, 2011.

[9] **D. A. Shnidman**. Binary integration for swerling target fluctuations. IEEE Transactions on Aerospace and Electronic Systems, 34(3):1043–1053, July 1998.

[10] **D. Grimmett et. al.** AMOC Multistatic Decision Aid Methodologies and Cross-Evaluation. *TTCP Technical Report*, TR-MAR-8-2012, 2012.