Fused Tracking of Pulsed and Continuous Active Sonar Transmission Modes

Doug Grimmett
Naval Information Warfare Center Pacific
San Diego, California, USA
douglas.j.grimmett.civ@us.navy.mil

***Abstract*-- In recent years, the feasibility of using continuous-active-sonar (CAS) transmissions as an alternative to pulsed-active-sonar (PAS) transmissions has been explored. A CAS system transmits waveforms with high-duty-cycle (HDC) near or equal to 100%. CAS offers potential improvements over short-burst PAS signals by providing an order-of-magnitude or more increase in the number of detection opportunities with a faster revisit rate for improved target localization and holding. Much of the previous work has focused on understanding the performance benefits of CAS as well as the differences between PAS and CAS performance both at the output of the processing chain and at the output of a multitarget tracking algorithm. In this paper we explore a synergistic use of PAS and CAS transmissions occurring in parallel, at the same time. The LCAS'15 experiment provided a data set that included simultaneous transmissions of both PAS and CAS waveforms from a monostatic sonar. Signal and information processing were applied to both the PAS and the CAS received signals. A sonar tracking algorithm was modified to accept detection contacts from both PAS and CAS and provides various PAS-CAS fusion rules/schemes for evaluation. The tracker was applied to the sea trial data for PAS-only and CAS-only which establishes baseline cases, which are compared with other fusion cases that combined PAS and CAS waveform scans. The analysis shows encouraging results with synergistic improvements in tracker metrics by achieving the best performance (and avoiding the worst performance) of either PAS or CAS operating independently. A fusion rule with PAS track initiation /confirmation and CAS track termination provided the longest track holding and fewest false tracks, and provides the lowest uncertainty in target localization error.**

Keywords—sonar, fused tracking, continuous active sonar, pulsed active sonar

I. Introduction

Sonar target tracking for active sonar is challenging, especially in clutter-rich, shallow-water environments where many false alarms leading to false tracks, are prevalent. In recent years, the feasibility of using continuous-active-sonar (CAS) transmissions as an alternative to pulsed-active-sonar (PAS) transmissions in shallow-water reverberation-limited acoustic environments has been studied.

CAS acoustic transmissions are High Duty Cycle (HDC) signals, and offer potential improvements over PAS by providing an order-of-magnitude or more increase in the number of detection opportunities [1]. For continuously repeating Linear Frequency Modulated (LFM) waveforms, this is achieved by breaking the waveform transmission bandwidth down into smaller pieces (sub bands) for processing. This may come at the cost of a reduction in received SNR per individual detection but can still provide benefits at the output of a tracker, where more (and more frequent) detection opportunities can provide improved target holding and localization [2,3].

In this paper, we explore the potential of using a sonar capable of transmitting both PAS and CAS acoustic waveforms. This could be done by time-interleaving sequences of PAS and CAS waveforms cycles that occupy the same frequency band, or by concurrently transmitting PAS and CAS waveforms every cycle in different non-interfering frequency bands. This investigation will focus on the later of these modes, using the data from the LCAS'15 experimental data set. The objective is to develop a baseline CAS-PAS fusion/tracking architecture, and to explore a variety of fusion rules within the target tracker, to provide synergistically improved performance.

The introduction of a dual PAS-CAS sonar processor introduces a plentiful increase in necessary parameters, architecture configuration complexity and various fusion rules. This paper will attempt to make an initial assessment of a single architecture with a limited set of fusion rules. This will partially inform us of possible synergies to be exploited with systems that are capable of PAS and CAS transmission and reception.

Section II provides a description of the LCAS'15 experiment sonar configuration and of the baseline sonar signal and information processing chain, with some examples of the data under consideration. Section III provides descriptions of the legacy and fused PAS-CAS tracking algorithms' details. Section IV provides results of the PAS-CAS fusion approach compared to the non-fused baselines for the sea trial data. Section V provides a summary and conclusions.

II. The LCAS'15 Experiment and Sonar Processing

A. Experimental Configuration

The LCAS'15 sea trial was conducted in September 2015, in shallow waters off the coast of La Spezia, Italy, in conjunction with an international research project with the Centre for Maritime Research and Experimentation (CMRE). The experiment was conducted together with collaborators from NATO CMRE, Australia, Canada, Italy, New Zealand, Norway, U.K. and the U.S.A.

Water depths in the area ranged from 100-200 m and reverberation-limited clutter conditions were predominant. The research vessel *R.V. Alliance* towed an acoustic source capable of PAS and CAS transmissions over the frequency band of

1800-3500Hz. It also towed a monostatic triplet hydrophone receive array. The *R.V. Leonardo* ship towed an echo repeater (E/R) system which repeated the received signals as a surrogate target, with a 17 dB Target Strength (the amount of amplification that was applied to the repeated signal).

Fig. 1 shows the geometry for run E09, which was a structured run of duration 80 minutes, and which is analyzed in this paper. The R.V. Alliance and E/R tracks are shown with parallel headings of 144°T and speeds of approximately 3.5 kts, with nearly constant range separation (4.3 nmi). The sonar transmitter and receiver were deployed at 50 meters depth.

The monostatic sonar's transmitted signal was a composite waveform consisting of a 20-second upswept LFM from 1800-2600Hz (CAS) waveform and a one-second pulsed LFM (PAS) waveform transmitted simultaneously during the first second from 2700-3500 Hz, as depicted in Fig. 2. The CAS waveform was transmitted with 203 dB acoustic source level and the PAS waveform was transmitted with a level of 216 dB; the difference was intended to provide equal energy in the two signal components. This composite PAS-CAS waveform was repeated with a ping-repetition-interval (T_{pri}) every 20 seconds, achieving PAS and CAS duty cycles of 5% and 100%, respectively.

This transmission scheme is only one possible configuration under which a PAS-CAS fusion processer could apply and offer benefits. Some sonars may be incapable of transmitting both signal types simultaneously. They may however, be able to be transmitted as sets of several cycles of CAS and PAS signals in a common frequency band that could be alternated (switched) between. This is referred to as time-interleaving. Also, in a multistatic scenario, different transmitters in the operation could be dedicated to different waveform types, allowing the network to still include both PAS and CAS waveform types.

B. Signal/Information Processing

Fig. 3 shows the receiver signal and information processing strings used in this analysis, which includes a customized PAS-CAS tracker. The FORA receive array is a triplet array, which provided port/starboard discrimination of the received acoustic energy [4]. The received hydrophone data were beamformed and then passed to the matched filter processing. One correlation replica is used for the entire PAS waveform (coherent processing interval T_p=1s and 800 Hz). For CAS, a bank of seven matched filter replicas are chosen which correspond to sub bands at different center-frequencies, each with sub-bandwidth, B_p =200 Hz and coherent processing interval of T_p=5s. The sub bands may be contiguous, or they may include some amount of time/frequency overlap. Here, the sub band overlap was chosen to be 50%.

Within every T_{pri}, (ping cycle) there is one PAS detection opportunity and 7 CAS detection opportunities, as shown in Fig. 2. Each of the matched filter outputs were normalized using a sliding split-window with guard and noise bands of 0.2 s length. This yields signal-to-background (SNR/SBR) ratios as a measure of echo strength. After applying the signal processing detector threshold of 10-12 dB, any time- and/or beam-contiguous threshold crossings were clustered into a set of "*contacts*" for this scan time. There are many contacts formed within each scan, each one containing estimates of echo time-delay (which can be mapped to range), echo bearing, and echo SNR. The contacts are then input to the PAS-CAS target tracker, which is described in more detail in a subsequent section.

Fig. 1. Run geometry; Alliance track (brown) and E/R track (yellow).

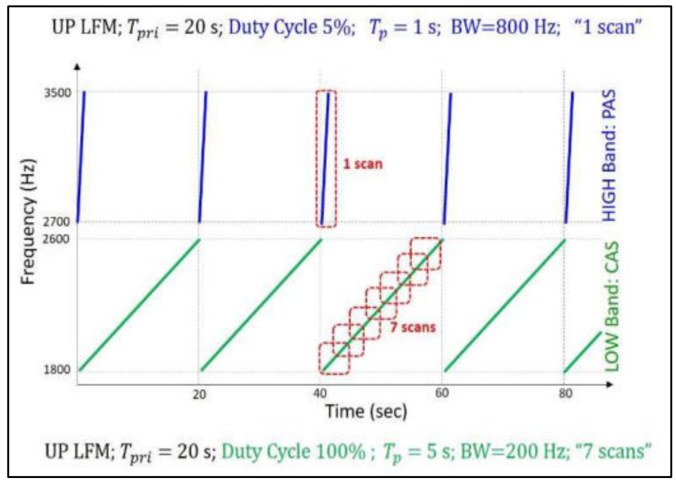

Fig. 2. LCAS'15 PAS and CAS transmission sequences during run E09.

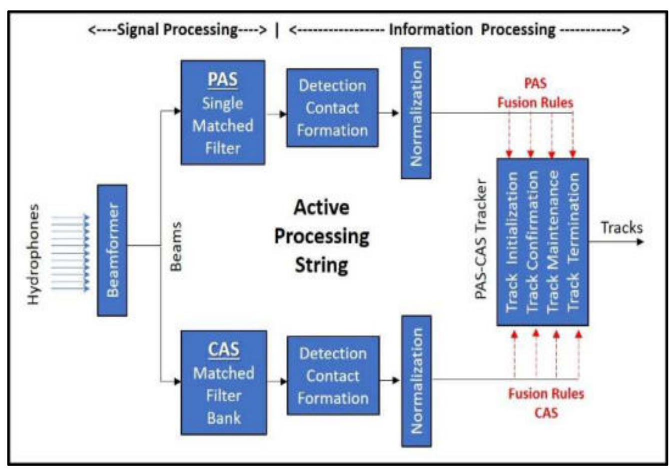

Fig. 3. Combined PAS-CAS signal and information processing strings.

Fig. 4 shows the output contacts from the CAS signal and information processing string that are input into the tracker Contacts are shown with their measured bearing coded in color vs. scan-time vs. echo time-delay. The image for the PAS signal is not shown here, but looks similar, albeit with 7 times lower resolution than for CAS, and with fewer than half the number of contacts formed. The total number of PAS and CAS contacts that were subsequently input to the tracker were 12,026 and 23,109, respectively, for the 15 km range (corresponding to 20-sec revisit time), and 360˚ field of view. The tracker thresholds h_{PAS} and h_{CAS} were chosen to be 22 dB and 14.5 dB, respectively, commensurate with the expected SNR differences between them. The more frequent CAS updating provides more clarity for recurring echo features than for PAS. The image shows the direct blast reception at near zero delay and 360˚ (end fire) bearing, and a lot of clutter features consistently detected in time windows around 3-6s and 8-12s echo delay. The target-originating echoes are received near broadside (90˚ bearing, blue color) and at a constant range corresponding to echo delay time of ~10.75 s. These are difficult to see amidst the abundant clutter, but they are more clearly observable in the zoomed view of Fig. 5, where the verified target-originating detection contacts are highlighted by the outlined red boxes. This image shows the extremely challenging detection and tracking scenario under consideration here, which serves as an ideal case with which to explore the advantages of fused PAS-CAS tracking for increased sonar performance.

III. PAS-CAS Fustion/Tracking Algorithm

A. Baseline Tracker Description

The tracker used in this study is a simple scan-based tracker with hard data association [5]. The tracker ingests successive "scans" (or "updates") of data, resulting from the signal and information processing described previously. A subset of these processed contacts whose SNRs exceed the tracker threshold, h, are input to the tracker. These are then associated with existing tracks if they are within an association gate defined by a statistical distance measure in location and velocity dimensions. If more than one contact resides within the gate, the data associations between existing tracks and new measurements are made using the statistical "nearest-neighbor" method.

Newly associated contacts serve to update a track's state estimation using an extended Kalman filter; this is done for both target tracks and false-alarm tracks. Each successive scan, the tracks are ordered according to length, with longer tracks getting priority over shorter tracks for new contacts to be associated with them. Contacts that don't associate with existing tracks become a first estimate for a new "***tentative***" track to be "***initiated***". Subsequently, this tentative track may or may not be "***confirmed***" by subsequent scan data satisfying a confirmation criterion. A common confirmation method is the sliding M-of-N detector, where "initiated" tentative tracks become "confirmed" when contacts from M out of N successive scans are successfully gated and associated into a kinematically consistent track. This is the point at which the track is confirmed, outputted and becomes available/visible to the operator. The process operates as a sliding M-of-N window along the data-scan streams for each tentative track.

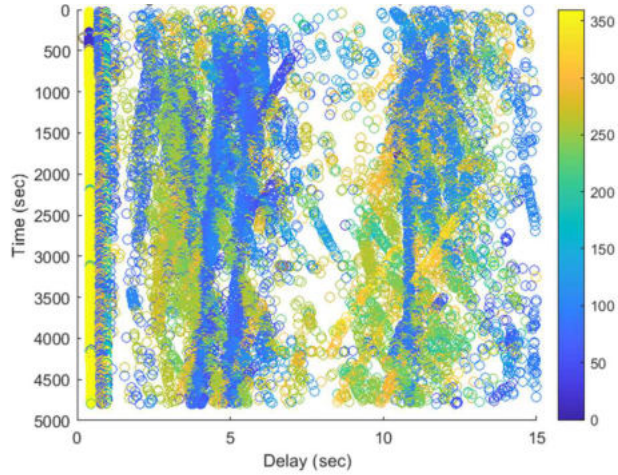

Fig. 4. CAS contacts input to the PAS-CAS tracker; contact bearing (colored) vs. scan-time vs. echo delay time.

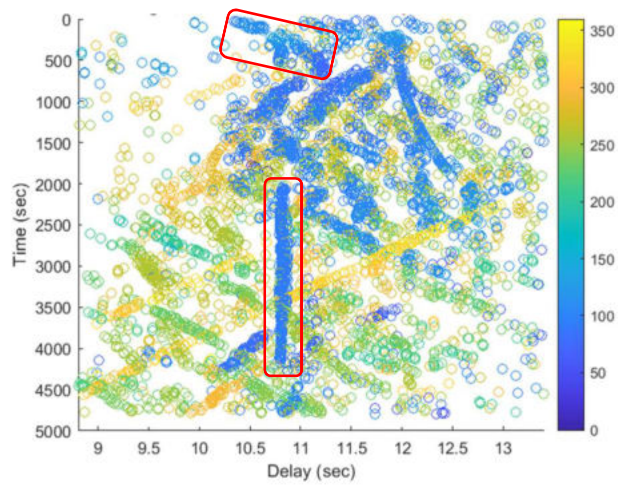

Fig. 5. CAS contacts as a function of scan-time, echo-delay time, and bearing (in color). Red outlines those that are attributable the the E/R surrogate target, amidst a large amount of trackable clutter in the same area.

Confirmed active tracks are "***terminated***" (killed) when K successive "coasts" (scans without any successful associations) occur. Likewise, tentative tracks are discarded when N successive "coasts" occur, and they are no longer eligible to become confirmed tracks. More sophisticated data association algorithms exist, like the Multiple Hypothesis Tracking (MHT) algorithms which use multiple scans to form various multi-scan association hypotheses and then chooses the optimum ones to use, at the cost of some reporting latency. However, for this analysis, this was not deemed appropriate because it unnecessarily complicates the comparative analysis and dependencies we endeavor to understand here. This will be considered in future work, however.

B. Fused PAS-CAS Tracker Description

The standard tracking algorithm previously accepted only PAS-only or CAS-only data. For the fused PAS-CAS tracking capability, the standard tracker was modified to be able to ingest mixed waveform types of PAS and CAS (see Fig. 2). The first step is to time-order and interleave the scans of contacts data coming from the output of the separate PAS and CAS signal and information processing strings. Within the tracker, scans are labeled to be identifiable as originating from PAS or CAS processing. The interleaved scan-stream is provided to the tracker and appropriate parameters are provided to control the possible fusion processes between the two (PAS and CAS) scan types. The new PAS and CAS parameters include: contact amplitude threshold at the tracker input for tentative track initiation and track updating (h_{PAS} and h_{CAS}), M-of-N track confirmation criteria (M_{PAS}-of-N_{PAS}, and M_{CAS}-of-N_{CAS}), and track termination criteria (K_{PAS} and K_{CAS}).

If the amplitude threshold is not provided, the tracker will ignore scans of the indicated type (PAS or CAS). The threshold value also controls how many contacts are made available to the tracker for track initiation and track updating functions, which can be set separately for PAS and CAS scans. Track confirmation decisions can be made using: only PAS scans, or only CAS scans, or a combination of them both. Likewise, this is the case for track termination decisions. Separate, independent sliding windows are set up for PAS and CAS scans within the tracker for track confirmation (N) and track termination (K), and can operate simultaneously, in parallel.

The fused PAS-CAS tracking architecture allows for many fusion rules for track management. Specifically, for each of the two elements of: 1. (M-of-N) track confirmation, and 2. (K-misses) track termination; there are four possibilities as follows:

- PAS-only (only the PAS scans are used)
- CAS-only (only the CAS scans are used)
- PAS $\wedge$ CAS (Logical "AND"; i.e. both of the PAS and CAS decisions are required to be affirmative)
- PAS $\vee$ CAS (Logical "OR", i.e. one or the other or both of the PAS and CAS decisions are required to be affirmative)

For each of these two elements of track management there can be any of these four rules, resulting in a total of 16 (2^4=16) possible fusion rules. The next section compares results for only three of these rules, as an initial assessment of PAS-CAS fusion potential.

IV. Fused PAS-CAS Tracking Results

A. Case Descriptions

Of the many fusion rule possibilities, tracking was performed for only five different cases, as specified by Table I. The first two are baseline cases with no fusion: one with only PAS scans input to the tracker and no CAS scans (case 1), the other with only CAS scans input and no PAS scans (case 2). PAS contributes only 1 scan per (20-sec) ping cycle to the tracker whereas CAS contributes 7 scans per cycle.

The rest of the cases are non-baseline, fused cases. For these cases (cases 3-5), the single PAS scan per cycle and 7 CAS scans per cycle (total of 8 per cycle), are sequenced and time-interleaved to produce a combined input to the tracking algorithm. Contacts in both types of scans (PAS and CAS) are available to feed the tracker to update any existing confirmed tracks.

TABLE I. Case Details and Parameters

	CASE 1 PAS-Only	***CASE 2 CAS-Only***	***CASE 3 PAS: I/C/T***	***CASE 4 CAS: I/C/T***	***CASE 5 PAS: I/C CAS: T***
PAS scans (per cycle)	1	NONE	1	1	1
CAS scans (per cycle)	NONE	7	7	7	7
Track Initiation	$h_{PAS} \geq$ 22 dB	$h_{CAS} \geq$ 14.5 dB	$h_{PAS} \geq$ 22 dB	$h_{CAS} \geq$ 14.5 dB	$h_{PAS} \geq$ 22 dB
Track Confirm	M_{PAS}= 4 N_{PAS}= 6	M_{CAS}= 19 N_{CAS}= 42	M_{PAS}= 4 N_{PAS}= 6	M_{CAS}= 19 N_{CAS}= 42	M_{PAS}= 4 N_{PAS}= 6
Track Terminate	K_{PAS}= 6	K_{CAS}= 42	K_{PAS}= 6	K_{CAS}= 42	K_{CAS}= 42
Feeding Tacker Updates	$h_{PAS} \geq$ 22 dB $h_{CAS} \geq$ ∞ dB	$h_{PAS} \geq$ ∞ dB $h_{CAS} \geq$ 14.5 dB	$h_{PAS} \geq$ 22 dB $h_{CAS} \geq$ 14.5 dB	$h_{PAS} \geq$ 22 dB $h_{CAS} \geq$ 14.5 dB	$h_{PAS} \geq$ 22 dB $h_{CAS} \geq$ 14.5 dB

For case 3, all track management decisions (track initiation, confirmation and termination) are based only on PAS scans, like for case 1. For case 4, they are based only on CAS scans, like for case 2). Unlike Cases 1-2, Cases 3-4 accept both PAS and CAS scans to feed the tracker for updating existing tentative and confirmed tracks, but not both are used in track management.

For case 5, we evaluate a candidate fusion rule which relies only on PAS scans for tentative track initiation and subsequent confirmation decisions, and only CAS scans for track termination decisions. Here also, both PAS and CAS scans feed the tracking for updating existing tentative and confirmed tracks.

The relevant tracker thresholds and track management parameters are listed in the table. The difference between tracker thresholds accommodates the differences expected in SNR, with the smaller time-bandwidth product of CAS scans leading to smaller SNR than those for PAS. The sliding window lengths for track confirmation were chosen to be the number of PAS or CAS scans within a common two-minute sliding window (N_{PAS}= 6, N_{CAS}= 42). The window length for track termination was set to be the same value (K_{PAS}=N_{PAS}, K_{CAS}=N_{CAS}). The values for M, given our choices for N, were obtained using the method of Shnidman [6].

B. Visualization of Results

A summary view of the output of the tracker, for the entire run duration of PAS-only (case 1), is shown in Fig. 6. The target trajectory is shown in (sometimes obscured) yellow, the ship sonar track is shown in brown, and all the other tracks are shown in other random colors. We observe a number of false tracks which are likely due to clutter from the seafloor. Some of the tracks overlaying the target trajectory are indeed true tracks; others are false alarms from clutter features. Many clutter tracks are seen in the first half (northwest portion) of the run. Although not shown here, a very similar tracker output plot is obtained for case 3, where we allowed interleaved CAS scans to also contribute updates to the track. The same number of tracks are generated. There are differences in the number of track updates and localization, which will be shown later, in a more detailed view.

Fig. 7. shows a summary view of the output of the tracker for the entire run duration of CAS-only (case 2). The immediate observation is that almost three times as many tracks were output, compared with PAS-only (case 1) output. Also, the tracks (true and false) continue on for longer periods of time before termination. Although not shown here, negligible differences are seen in the tracker output plot obtained for case 4 as for this one (at least at the plot's level of resolution) where we allowed interleaved PAS scans to also contribute to the track. The same number of tracks were generated.

Fig. 8. shows a summary view of the output of the track for the entire run duration of case 5, where the fusion rule is that only PAS scans are used for track initiation and track confirmation determinations, and only CAS scans are used for track termination determinations. The reason we chose this fusion rule is that the baseline PAS-only (case 1) provided fewer false tracks, which is desirable, so we use PAS for track confirmation. And, because the baseline CAS-only case provided increased target hold time, we choose to use CAS for track termination here, to try to achieve that particular benefit. For this case, we see that the number of tracks is reduced and target holding increased. Hence, we have captured the best results of each of the individual baseline trackers with a single, synergistic PAS-CAS tracker configuration.

For track holding, the results for the fused tracker are more easily observed with a detailed zoomed view in the vicinity of the target's real trajectory. This is shown in Figs. 9-13, which show cumulative views of tracks for cases 1-5, respectively. Here, the true target track fragments are shown in red, with false tracks in other random colors.

Comparing cases 1 and 2 (Figs. 9-10), we see that whereas PAS-only has three true target fragments, CAS-only misses the first observed PAS target fragment. But it has increased track holding over the observed PAS 2nd and 3rd target fragments. Note how the challenging clutter environment produces many competing false tracks over the northwest section of the trajectory.

Comparing case 1 with 3 (Figs. 9,11) and cases 2 with 4 (Figs. 10,12) show very similar results, with the addition of CAS and PAS scans used in track updating, respectively. Note that case 3 has many more tracker updates than case 1, as we expect, and which is consistent with the addition of 7 CAS scans to the single PAS scan, per cycle.

Case 5 (Fig. 13) shows the results for the fusion rule of track confirmation provided by PAS scans and track termination provided by CAS scans. It achieves the best track holding, as shown in the two true track fragments, the 2nd of which spans across the fragmented track segments of PAS. This is due to the utilization of CAS track termination. In a previous plot (Fig. 8) we showed that case 5 also provided a much lower false track rate, due to using the PAS track initiation/and confirmation.

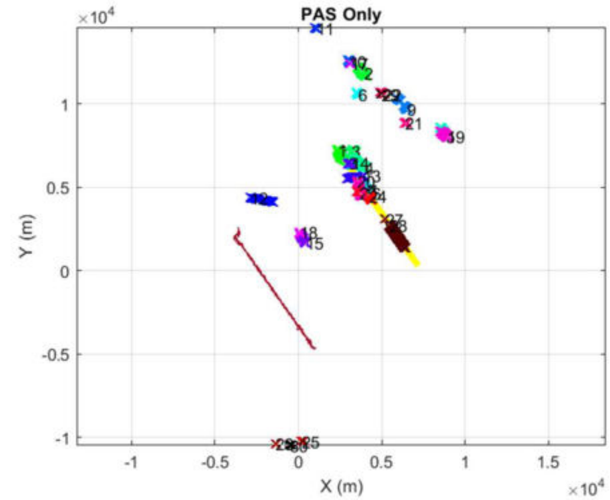

Fig. 6. PAS-only (case 1) tracking output over the run duration.

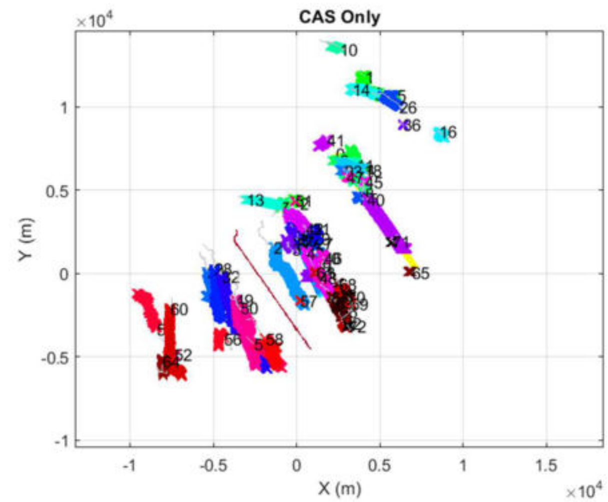

Fig. 7. CAS-only (case 2) tracking output over the run duration.

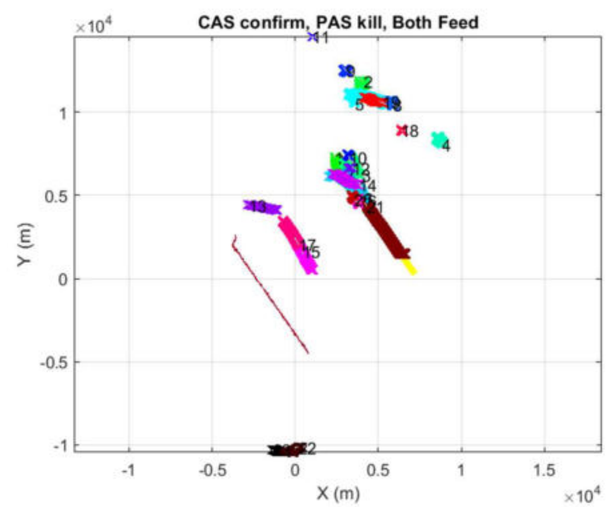

Fig. 8. Tracker output for PAS track initiation with CAS track termination (case 5) over the run duration.

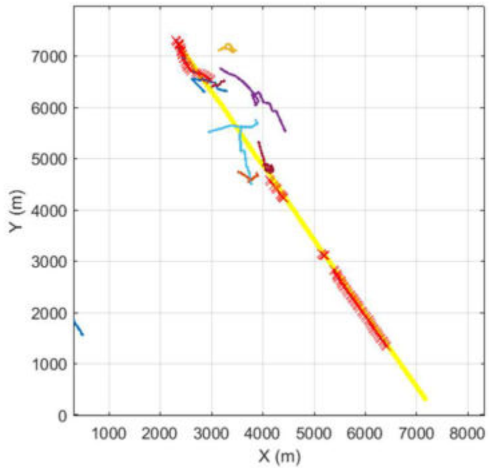

Fig. 9. Detail view of case 1 (PAS-only) tracker output; target trajectory (yellow); true target track segments (red), and other false tracks

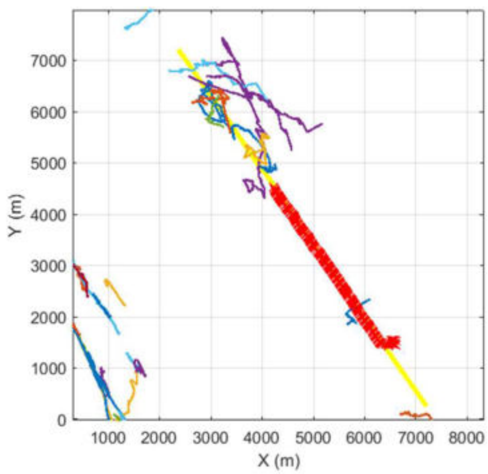

Fig. 10. Detail view of case 2 (CAS-only) tracker output; target trajectory (yellow); true target track segments (red), and other false tracks.

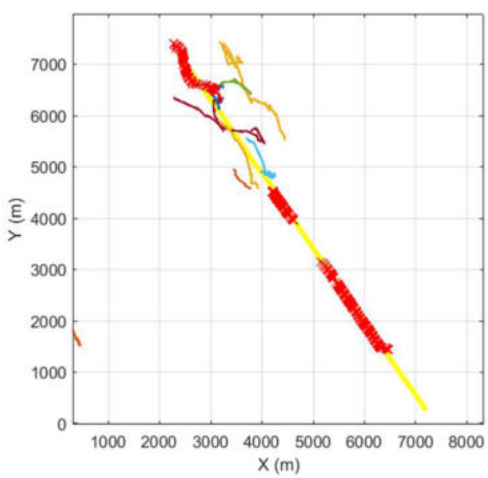

Fig. 11. Detail view of case 3 (PAS track management with CAS feeding track updates); target trajectory (yellow); true target track segments (red), and other false tracks.

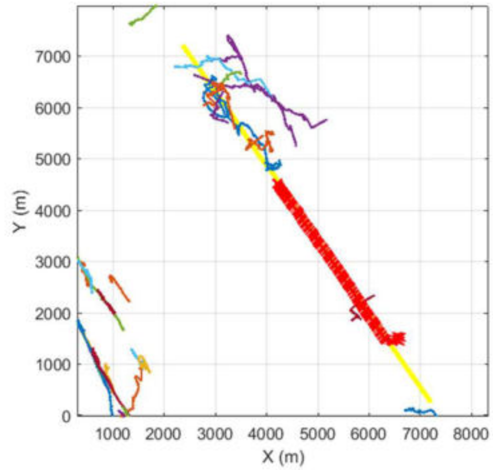

Fig. 12. Detail view of case 4 (CAS track managment with PAS feeding track updates); target trajectory (yellow); true target track segments (red), and other false tracks.

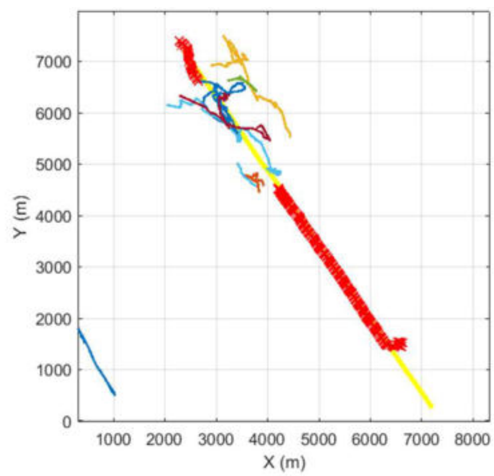

Fig. 13. Detail view of case 5 (CAS track intialize/confirm, PAS track termination, both PAS and CAS feeding track updates); target trajectory (yellow); true target track segments (red), and other false tracks

Another advantage of tracking with CAS is the reduction localization uncertainty [7]. This is referred to the "area of uncertainty ("*AOU*"), which is represented in the tracker by a 2-d gaussian distribution in x-y for target position and in x-velocity and y-velocity for target velocity. *AOU* ellipses are for an assumed probability of inclusion, and *AOU* areas can be computed at any time during the track, even in between tracker updates. Figs. 14 and15 show positional *AOUs* over a target track segment, in the same location at the same time period for PAS (case 1) and CAS (case 5). Here the *AOU* time updates were computed every 2 s and the probability of inclusion was set low (10%) in order to enable better visualization. The mean estimates of position are also shown. We observe significantly smaller *AOUs* obtained through CAS as compared to PAS.

C. *Tracker Metrics*

Fig. 16 shows the eight computed tracker performance metrics for each of the cases. A brief description of the metrics follows; more comprehensive descriptions are available in [8]. The target Track Probability of Detection (TPD) can also be

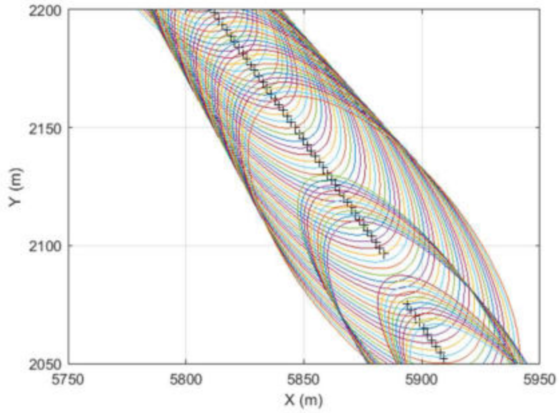

Fig. 14. Positional *AOU* ellipses (in colors) corresponding to PAS (case 1); mean estimated positions are shown by black markers.

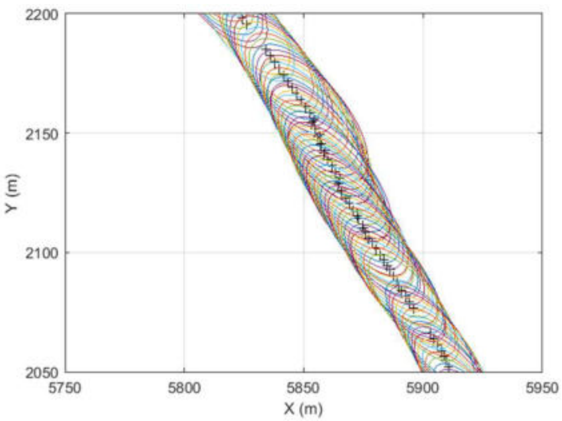

Fig. 15. Positional *AOU* ellipses (in colors) corresponding to CAS (case 5); mean estimated positions are shown by black markers.

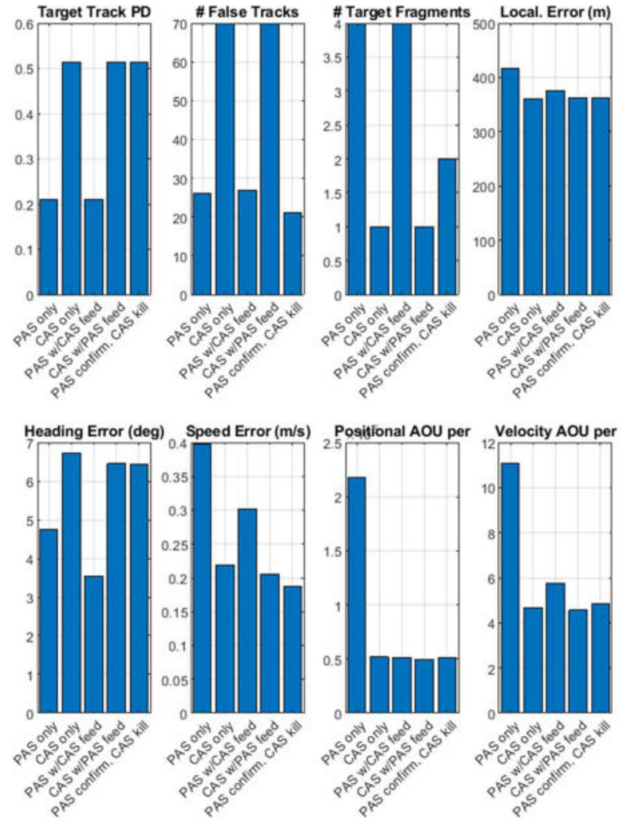

Fig. 16. Performance metrics for the five target tracking cases: PAS-only, CAS only, PAS with CAS feeding the tracker, CAS with PAS feeding the tracker, and PAS track initiation with CAS termination with both CAS and PAS data feeding track formation.

referred to as the target "Hold Time". It is the time that the true target was successfully tracked divided by the total run duration. A value of 1 indicates the target was tracked over the entire run period. The number of False Tracks metric is the count of all confirmed tracks output over the run duration that did not contain sufficient numbers of true target echoes updating the track. Good system performance requires low false track rates.

The number of target fragments metric indicates the number of separate track fragments for true targets over the duration of the run. Tracking can reasonably drop and restart when there is a time window with insufficient numbers of target echoes. Normally, a low fragmentation rate indicates good tracking performance. When tracks terminate and then immediately restart, this would be considered a tracker fragmentation issue.

All the remaining metrics have to do with target localization. These can only be computed under controlled experimentation where the target trajectory ground-truth information is available. The localization error metric is the average separation distance between the target's true locations and the tracker's estimated target positions throughout the run. The heading/speed error is the average difference between the target's true heading/speed and the tracker's estimated heading/speed of the target.

The final two metrics capture the uncertainty of the tracker's estimates in position and velocity, using the *AOU* metric described previously. We compute the average *AOU* area for both position and velocity for time steps of 0.0625s and 99% probability of inclusion. Smaller positional and velocity *AOU* (area per time step) indicates better tracker performance with lower uncertainty.

D. Tracker Results and Comparisons

We now discuss and summarize the performance for the tracking cases:

- Case 1 (PAS-only) and Case 2 (CAS-only).

  A comparison of the baseline (non-fusion) cases shows that the TPD (target track holding) metric for CAS-only was more than 2 times better than that obtained for PAS-only, whereas the number of false tracks for CAS-only worsened by nearly 3 times that of PAS. This indicates that while CAS-only is better for target track holding, PAS is better for false track reduction. CAS-only also yields fewer target fragments than PAS-only which is consistent with its superior track holding. Localization error for CAS-only is slightly better (i.e. lower) than PAS-only and heading and speed errors vary only slightly. A more significant finding is that PAS-only, without the frequent updating of CAS-only, has much worse (i.e. larger) localization and velocity uncertainty (*AOUs)*. CAS provides a clear advantage here.

The PAS-CAS fusion/tracking algorithm attempts to capture the respective strengths of PAS-only and CAS-only, as shown in the subsequent cases.

- Case 3 (PAS with CAS feeding tracker updates) and Case 4 (CAS with PAS feeding tracker updates).

In cases 3 and 4, the tracker ingests PAS-CAS interleaved scans for track updating, while track management is controlled exclusively by PAS and CAS scans, respectively. Here, the results obtained for TPD, number of false tracks and track fragmentation metrics are the same (or very close) to the PAS-only and CAS-only cases previously discussed (cases 1-2). The largest difference is seen in the *AOU* metrics, where we observe that the larger PAS *AOU* (case 3) size is reduced from the large value of case 1 to the smaller size obtained by CAS (in cases 2 & 4). The benefit of adding more frequent CAS scans is to reduce the time between tracker updates, which prevents the *AOU* from increasing excessively in size while projecting uncertainty to the next update time [7]. The localization, heading and speed errors show some minor differences, but without any clear trends to favor any one configuration over the other.

- Case 5 (PAS track initiation and confirmation, CAS track termination).

In this case we control track initiation and confirmation decisions only with CAS scans and track termination decisions only with PAS scans. As in cases 3-4, both PAS and CAS scans are available to support the updating of any gated existing tracks. This fusion rule has superior performance to all the other cases. It achieves the best case TPD of CAS (as in cases 2 & 4) while mitigating the number of false tracks using PAS (as in cases 1 & 3) for track initiation and confirmation. Also, the use of CAS for track termination allows reduces track fragmentation by half. The localization, heading and speed errors are commensurate with other cases, and the *AOU*s obtained achieve the small sizes seen in other CAS cases. In this manner, through combined/fused tracking with appropriate parameter PAS-CAS fusion rule selections, we achieve the best performance (and avoid the worst performance) of either PAS or CAS operating independently, exclusively on their own.

V. Summary and Conclusions

A PAS-CAS tracker algorithm with various fusion rules has been developed. A first analysis of PAS-CAS fused tracking using the data from the LCAS'15 data, run E09, has been made. Baseline cases of PAS-only and CAS-only established the performance without fusion, with PAS showing good capability to minimize false-track rate and CAS showing good target holding. Inputting both PAS and CAS data types the tracker (while maintaining exclusive PAS or CAS track management) provide similar performance except that when CAS is included, the uncertainties in positional and velocity *AOU* were much reduced. Finally, an initial evaluation of a candidate tracking rule with PAS controlling track initialization/confirmation and CAS controlling track terminations provided the superior performance of both PAS false-track reduction and CAS track-holding capabilities in one synergistic fused tracker output.

Future work will focus on the evaluation of many other possible PAS-CAS fusion rules which the algorithm already supports. One challenging aspect is to observe and understand the impact of the many new combinations of parameter settings and fusion rules that are possible. The goal is to know how to best combine the for improved robust performance. The method can also be extended to more sophisticated tracking methods such as multiple hypothesis tracking (MHT) in the future.

Acknowledgment

We acknowledge the NATO CMRE LCAS Multinational Joint Research Project participants for their resources and support and in the planning, execution and analysis of the at-sea experimentation. We acknowledge the Office of Naval Research for funding under which this work was performed.

References

[1] R. Plate, D.J. Grimmett, High Duty Cycle (HDC) Sonar Processing Interval and Bandwidth Effects for the TREX'13 Dataset, *Proceedings of the MTS/IEEE Oceans'15 Conference, May, 2015, Genova, Italy.*

[2] D. Grimmett, R. Plate, High Duty Cycle sonar Performance as a Function of Processing Time-Bandwidth for LCAS'15 Data, *in Proceedings of the 2nd International Conference on Underwater Acoustics*, September, 2017, Skiathos, Greece.

[3] D. J. Grimmett, J. J. Itschner, D. A. Abraham, L. Mazutti, High Duty Cycle Sonar Tracking Performance as a Function of Coherent Processing Interval for LCAS'15 Data, Editor, in Proc. of the 5th International Conference on Underwater Acoustics, Skiathos, Greece, July 2019.

[4] Becker, K. M. and Preston, J. R., "The ONR Five Octave Research Array (FORA) at Penn State," Proceedings of IEEE/MTS Oceans 2003 Conference, vol. 5, pp. 2607--2610, 2003.

[5] S. Coraluppi and D. Grimmett, Multistatic Sonar Tracking, in Proceedings of the SPIE Conference on Signal Processing, Sensor Fusion, and Target Recognition XII, April 2003, Orlando FL, USA.

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

[7] D. J. Grimmett, Target AOU Growth Containment using LFM High Duty Cycle Sonar Editor, in Proc. of the 2nd International Conference on Underwater Acoustics, Rhodes, Greece, June, 2014.

[8] S. Coraluppi, D. Grimmett, and P. de Theije, Benchmark Evaluation of Multistatic Trackers, in Proceedings of the 9th International Conference on Information Fusion, July 2006, Florence, Italy.