INVESTIGATION INTO THE UTILITY OF USING CFAR CLUSTER SIZE INFORMATION IN TARGET TRACK ASSOCIATION

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Abstract

During CFAR processing of low-resolution-radar data (e.g. from yacht navigation systems), the target is represented by a cluster of range-azimuth cells. The centroid is usually passed to the tracking system, however information on the size of the cluster, and therefore extent of location error is available from the CFAR. The main hypothesis of this paper is “would the use of the cluster bounding-box ‘corners’ allow better plot-to-track associations when compared to using the region centroid alone?”

1 Introduction

The common method for data association in target tracking is to represent the measurement as a single point. The size of uncertainty (error) associated with this measurement is represented in the form of measurement error (R matrix) within a Kalman Filter [1]. The Kalman Filter uses the information in the R matrix to adjust the size of covariance matrix (P) of the predicted state of the target, which is then used to set the size of the acceptance region in the plot-to-track association process. Measurements with large uncertainty (i.e. large R) will result in a large value P matrix so that the “true” target points can be captured. During data capture, the decision whether a measurement will be declared as a target point within the acceptance region is commonly made by calculating the distance between the single point measurement and the centre of the predicted covariance ellipse. If this distance is within the gating ellipse, the measurement is accepted. For the purpose of this paper, the single measurement is the centroid of the CFAR cluster and this method of data capture will be referred to as the *centroid* method.

With low-cost radar systems, the beamwidth may be in the region of 4 degrees. As the target is present in the beam for an extended dwell period, often RCS scintillation effects can create situations where only part of the azimuth extent is detected, leading to large deviations between the cluster centroid and the true target location. It is common for either the early or late section of the return to be missed; the target is often somewhere in the region bounded by the CFAR cluster however. The cluster bounding box could be used for testing against the gating ellipse and would provide an approximation to assuming the target location is distributed uniformly, rather than the Gaussian assumption inherent in the centroid method. When a large number of cells are reported in a cluster, the centroid is more likely to be accurate than when a small number of cells are reported. As the number of cells reported can be quite small, any statistical information gathered, such as variance, maybe inaccurate and incorporating this information directly into the R matrix is considered inappropriate. The alternative plot-to-track association method that is investigated in this paper tests to see if the track association gating ellipse intersects the cluster bounding rectangle defined by its upper/lower range and azimuth extent ‘corners’. This alternative association approach will be referred to as the *corners* method. The measurement is no longer represented as a single point; rather it is represented as a region whose size is determined by the size of the CFAR uncertainty (error) in both range and azimuth.

It is anticipated that this alternative approach to association (*corner* method) will perform better than the *centroid* method due to the following argument:

> As most of the uncertainty in the measurement will be represented in the CFAR cluster region, the *effective* size of the association gate using the *corner* method will be expected to be much smaller than if the *centroid* method is employed, as the *corner* method essentially adjusts the association gate behaviour based on target cluster size. Having larger association gates means potentially allowing more false association to occur, so the use of the *corner* method may provide a more effective way of achieving higher probability of target association (high P_A) with a lower number of false association (low P_{FA}), resulting in less track branching.

2 Description of the tracker

In this study, a target tracking system has been developed that may use either of the two target association methods under consideration in this paper. The tracker performs the standard functions as follows: a) track initialisation: new tracks are created from two consecutive measurements whose velocity is within a defined range (in this case, the maximum velocity allowed is 50 ms^{-1} in both x and y axis, suited to tracking small surface targets in a littoral environment), b) data association: during which the two methods to be investigated are implemented, and c) track maintenance: this includes allowing the track to branch and continuous pruning to prevent the explosion of branches. Track pruning is performed based on: i) track age, ii) track log likelihood ratio [2], and iii) similarity of branches within a single track (this occurs very frequently as few branches within a single track will continuously associate with a single measurement).

The tracking system uses an Unscented Kalman Filter (UKF) [3, 4] for maintaining track state and for providing the covariance for the plot-to-track association gating. The UKF uses a Cartesian form for the target location and velocity, and longitudinal and lateral accelerations in target body axes. The measurement update is transformed from a polar coordinate system with the radar as the origin, i.e. the measurement covariance matrix, R, is defined as range and azimuth extent, and the measurement covariance for the Cartesian track update is an estimate based on the transformed R matrix (in Cartesian space, the measurement ellipse rotates in sympathy with target bearing).

3 Performance analysis

3.1 Synthetic data generation

In this experiment, simulated radar data modelled to resemble the output from a low cost non-coherent marine radar have been used. The scene consists of a realistic simulation containing radial, crossing and spiralling targets moving amongst fixed targets and through heavy sea clutter regions. The simulated radar data are generated 250 times, each with different random noise and clutter. These data are then subjected to a spatio-temporal CFAR process [5] to provide detection clusters for the tracking system. The cluster sizes are determined by the size of the CFAR uncertainty (error) in both range and azimuth.

3.2 Unscented Kalman Filter tuning

UKF tuning involves choosing the best values for initial covariance spread (P_0), measurement noise (R), and process noise (Q). For this experiment, the effect of utilising a wide range of values for P_0, Q and R on the tracker performance is investigated.

Choosing the appropriate size for initial covariance spread P_0 appears to be very important during track initialisation. When the target track is not continuous and segmented, choosing the appropriate value for P_0 appears to allow the tracker to follow the target more continuously. Figure 1 shows the effect of varying the size of P_0 on the tracker. When a small P_0 is used, the tracker is often incapable of recapturing the target track after the break (see figure 1 (middle)). Increasing the size of P_0 to medium size, has however improved the tracker capability to recapture the target again after the break (see figure 1 (bottom)).

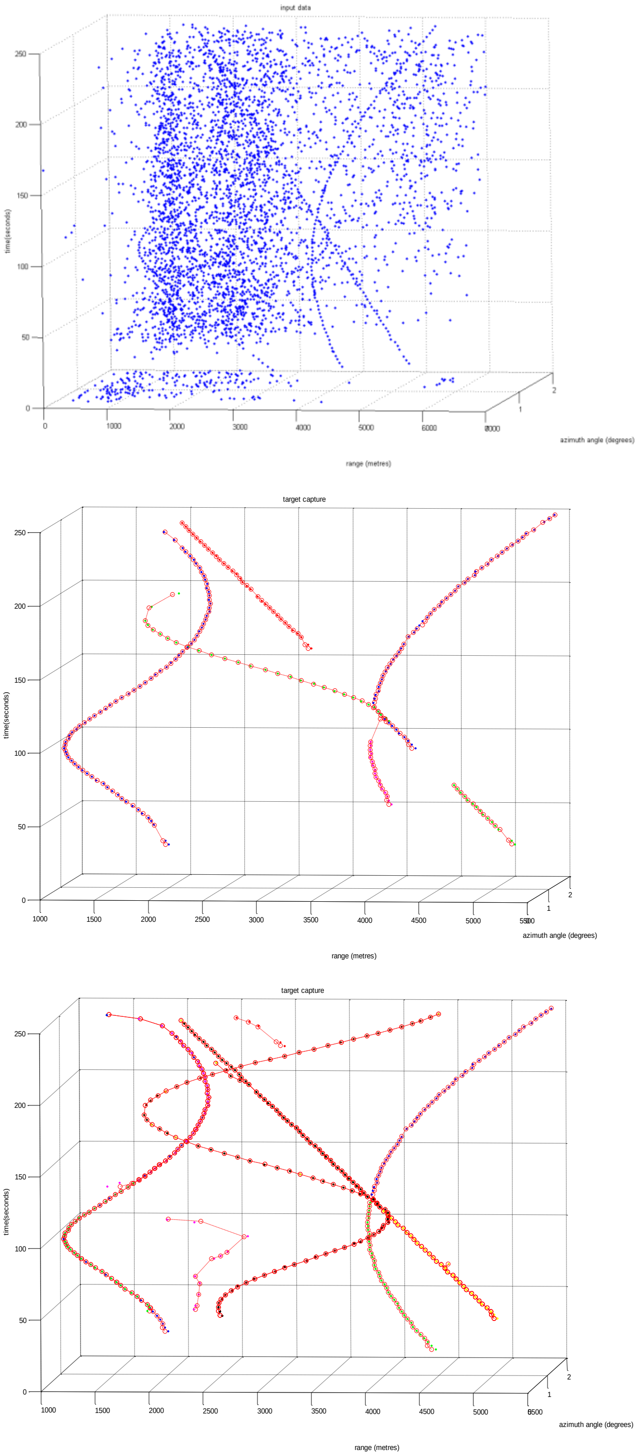

Figure 1.Effect of varying initial covariance spread P_0: initial data (top), tracking performance using small P_0 (middle), and tracking performance using medium P_0 (bottom)

Investigation on the effect of varying the size of the process noise Q shows that as long as Q is not too large, the tracker performance appears to be good. Varying the size of measurement error R, however, appears to have large impact on the tracker performance. The measurement error in this case comes from both azimuth (angle) and range errors.

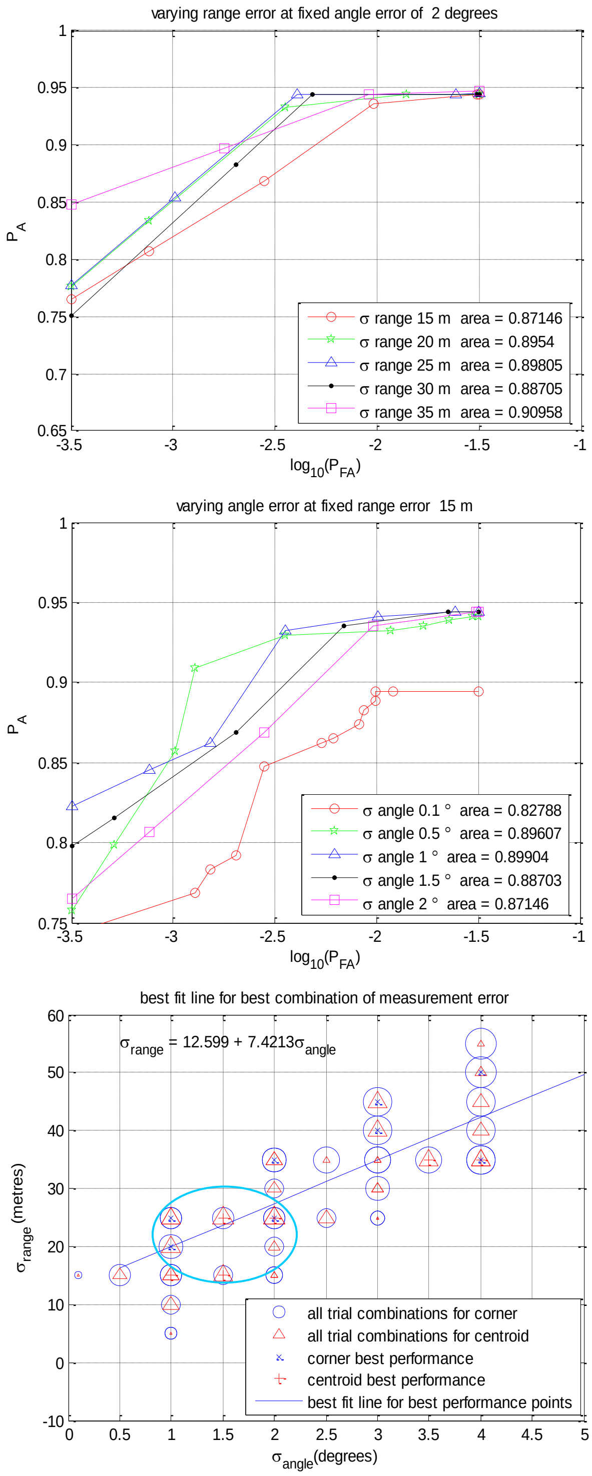

Figure 2. Finding 'optimum' measurement error (R): performance comparison using ROC: for varying range error while keeping angle error fixed (top), for varying angle error while keeping range error fixed (middle), and least square fit line representing best combination of angle and range errors (bottom).

Figure 2 shows the effect on the tracker performance of varying angle and range error standard deviation. The performance is analysed using a Receiver Operating Curve (ROC) [6] which shows the variation of probability of association (P_A) against false association rate (P_{FA}). The first two graphs in figure 2 suggest that there appears to be an 'optimum' combination between the range and angle error at which the best tracking performance can be achieved. Further simulation was performed to find a suitable combination for use in the study. To do this, the angle and range errors are varied and the performance analysed. Figure 2 (bottom) shows the combinations of range and angle that were explored, with larger circles/triangles indicating the superior parameter combinations. These best combinations (blue cross for corner method, and red plus for centroid method) are used to obtain the best fit line (blue line). The results for the centroid method indicate that the best performance is achieved when the angle and range error definition is small (approximately 2 degrees), whereas the ROC performance of the corner method is generally increasing with larger error allowances; the processing load is increasing under these conditions too and the extra increase in ROC performance cannot be justified for 4 degree error or more. A compromise solution has been taken which provides sufficient tracking performance, but with tolerable processing load.

It appears that the best performance for both methods occurs in the region of angle error between 1 to 2 and range error between 15 to 30 metres (see overlaid ellipse on figure 2 (bottom)). As a compromise of providing sufficiently large association gate without putting the pressure on the processing load, the combination of range error of 27.5 metres and angle error of 2.0 degrees has been chosen for the purpose of the experiment. These errors compare well with the expected performance of the radar system.

	Small	*Medium*	*Large*
Initial covariance P_0	$1P_0$	$10\ P_0$	$100\ P_0$
Process noise Q	0.01 Q	Q	1000 Q

Table 1: Value range of P_0 and Q under investigation; P_0 represents 6 x 6 diagonal matrix with initial variance in position: $x^2 = y^2 = (1m)^2$, in velocity: $v_x^2 = v_y^2 = (5\ ms^{-1})^2$and in acceleration: $a_{lon}^2 = a_{lat}^2 = (1\ ms^{-2})^2$ (a_{lon} and a_{lat} are longitudinal and lateral acceleration respectively). Q represents 6 x 6 diagonal matrix with process noise variance in position: $x^2 = y^2 = (0.00001)^2$, in velocity: $v_x^2 = v_y^2 = (0.00001\ ms^{-1})^2$ and in acceleration: $a_{lon}^2 = a_{lat}^2 = (1\ ms^{-2})^2$

3.3 Performance analysis

The performance analysis is performed using 250 synthetic radar trials. The performance of both methods are assessed in term of their capability of providing high probability of track association (P_A) while maintaining low probability of false association (P_{FA}) with fast processing time. The processing time is evaluated by assessing the number of times the tracker has to perform plot to track data association (i.e. the number of evaluation of the centroid or the corners to the gate ellipse). This is directly proportional to the number of tracks and branches created (hence need to be processed). To assess the tracker performance under a wide range of false association conditions, the size of the association gate is varied from 0.5 to 6 standard deviations of the covariance matrix P. It is found that to achieve similar performance (i.e. equal P_A with similar P_{FA}), the gating size required by the centroid method is consistently around twice that required by the corner method. Thus in the corner method, some of the gate acceptance tolerance is now captured by the spread of the target cluster, not just the predicted track covariance used in the centroid method.

3.3.1 2D Performance assessment using ROC

In this assessment, the ROC is utilised to assess the tracking performance of both methods. Figure 3 (top) shows how P_A and P_{FA} behave following the increase of association gate size (i.e. related to the increase in the number of false associations). In this graph, the performance achieved by the corner method appears to outperform that of the centroid method, as in general, results using the former method appear to be capable of obtaining higher P_A for the same number of false associations.

To assess the significance of this early observation, the difference of area under the ROC between the results from the corner and the centroid methods is calculated and the histogram from the 250 trials is presented in figure 3 (bottom). If the two methods provide comparable performance, a null hypothesis given by H_0: $\Delta A = 0$ is supported. If, however, the results from corner method outperform that from centroid method, an alternative hypothesis H_1: $\Delta A > 0$ is supported. As can be seen in figure 3 (bottom), the mean value of the histogram lies in the positive area, indicating support for the alternative hypothesis H_1. The Student-t test is then performed:

$$Z = \frac{|\bar{X}|}{S/\sqrt{N}} = 21.23 \qquad (1)$$

Which gives a high Z value, indicating that the null hypothesis is rejected at 1% confidence level (Z>2.326). There is therefore strong evidence to reject the null hypothesis in favour of the alternative hypothesis, based on the comparison between P_A and P_{FA} alone.

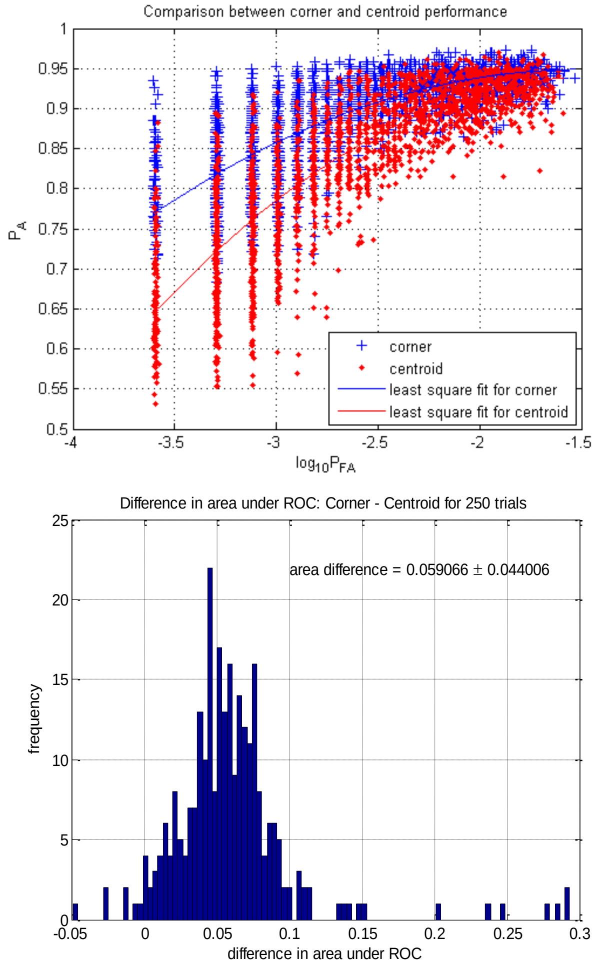

Figure 3. Performance assessment using ROC: tracking performance of corner method (blue +) and centroid (red dots) (top), and histogram of difference of area under ROC (bottom)

3.3.2 3D Performance assessment

The previous 2D assessment suggest that the corner method provides better tracking performance compared to the centroid method, as it appears to be capable of obtaining a higher P_A for similar levels of false associations. However, this result does not compare the processing time involved while employing both methods. It is envisaged that as the corner method uses a more relaxed data association process than the centroid approach, the processing time of the corner method will be higher. 3D performance assessment which evaluates the tracker performance, not only based on their P_A and P_{FA} performance, but also their processing time was therefore undertaken.

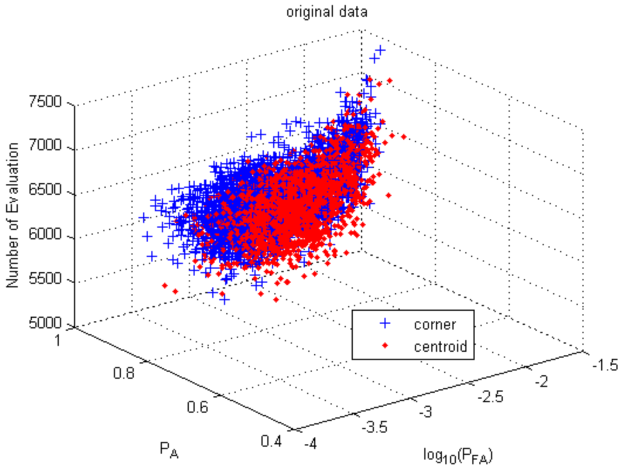

Figure 4. 3D plot of P_{FA}, P_A and number of evaluations (N_E) for both corner (blue +) and centroid (red dots) methods

Figure 4 show a 3D plot of P_A, P_{FA} and the number of gate association evaluations (N_E**)** for both corner and centroid methods. As can be seen, the results from both methods appear to form two overlapping clusters. The overall shape is nonlinear, and therefore simple statistical analysis is inappropriate. Observation of the data suggests that for a given small interval of the P_{FA} axis, the data when viewed in the P_A – N_E plane appears sufficiently Normal in distribution.

The P_{FA} dimension was subdivided into 10 slices and the P_A – N_E performance of each slice analysed. The analysis method was to calculate the vector separation between the mean of the two clusters and normalise the vector with respect to the co-standard deviation and sample sizes as described below:

$$Z = \frac{\sqrt{N_1 + N_2}\left(\vec{\mu}_1 - \vec{\mu}_2\right)}{\sqrt{C}} \qquad (2)$$

Where N1 and N2 are the size of the two data clusters in each slice, $\vec{\mu}_1$ and $\vec{\mu}_2$ are the mean vectors of the corner and centroid respectively, and C is the covariance matrix of total data clusters in each slice.

P_{FA} *range*	Z_{PA}	Z_{NE}
-3.60 to -3.40	1.47	-0.17
-3.40 to -3.19	1.23	-0.03
-3.19 to -2.98	1.07	-0.23
-2.98 to -2.77	0.98	-0.14
-2.77 to -2.57	1.06	0.51
-2.57 to -2.36	1.13	-0.18
-2.36 to -2.15	0.97	0.19
-2.15 to -1.95	0.79	0.16
-1.95 to -1.74	0.66	0.21
-1.74 to -1.53	0.68	0.53

Table 2. Z values of P_A and N_E for 10 P_{FA} range slices

The results in table 2 show that the variation of performance with the number of evaluations is small and not statistically significant. Additionally, the direction of the test statistics suggests that neither method is superior in terms of processing time. However, the results for P_A indicate that the corner method consistently provides better plot to track association for the same level of P_{FA} when compared to the centroid approach. However, the results do not indicate statistical significance to a level of 1%.

Section IV. Conclusion and analysis

Results of performance analysis using 250 synthetic radar trials have suggested that the corner method appears to outperform the centroid method both in term of: 1) high probability of associations can be achieved for a similar level of false alarm associations, and 2) the number of gate evaluation (i.e. the processing time) of both methods is equivalent.

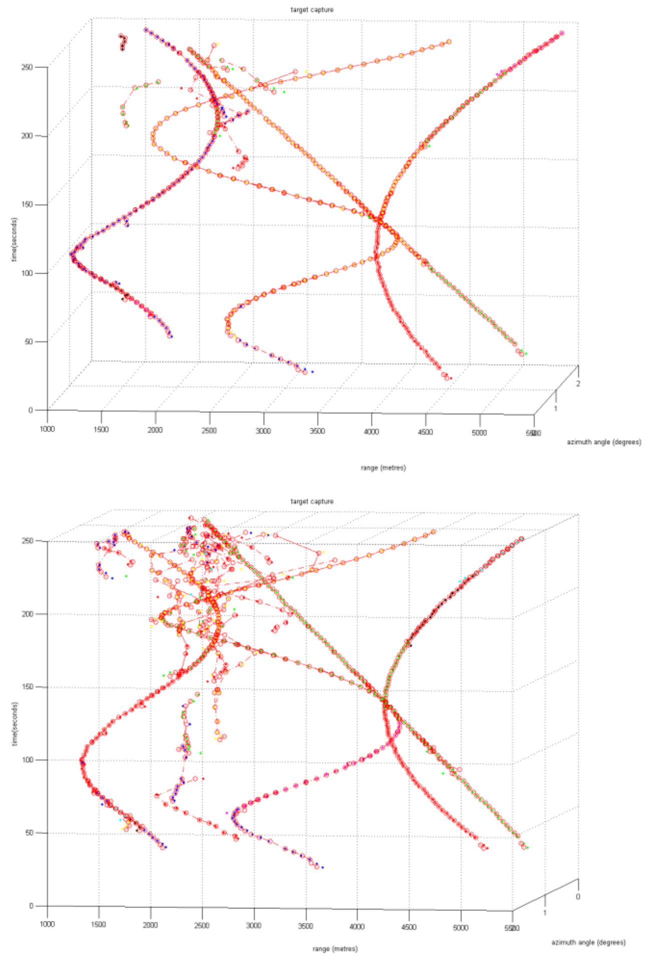

Figure 6. Tracking results from corner (top) and centroid (bottom) methods.

Our current hypothesis for the improved performance of the corner approach is that the measurement error of the target is highly range dependent, and is being accounted for directly in a dynamic way by using the corner information from the CFAR in the association process; The association ellipse represents the tracking error alone. Conversely, in the centroid method, the association ellipse must capture both the tracking error and the measurement error. Although the R matrix is scaled correctly with range, the centroid approach appears to be more sensitive to incorrect associations, suggesting that this ‘compound’ ellipse is a poor approximation.

Figure 6 shows the tracking results from both the corner (top) and centroid methods (bottom) for one radar trial at their optimum association gate size (i.e. when highest P_A can be achieved at lowest number of false associations). The association gate size is 2.5 standard deviation for corner, and 5.5 for centroid method. As can be seen from the above figures, while both methods manage to follow the target tracks consistently, the number of false associations obtained by tracker using corner method appears to be less than that of centroid method.

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