Target Track Maintenance and Maneuver Handling with Optimal Revisit Control for Phased Array Radar

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Abstract: *The paper presents the challenges and techniques in handling maneuvering target tracking with phased array radar. The focus is to achieve of optimal revisit control for targets without breaking lock and maintain track on highly maneuvering targets. The constraint on tracking system comes from extended search requirements which results in more time on target and hence increased search scan time. This poses challenges to the target tracking system with requirements to handle high g maneuvers and maintain track on targets which can be as high as 500. The paper presents approach adopted for maintaining maneuvering tracks with optimal use of radar resources and emphasis to avoid track loss.*

I INTRODUCTION

The paper is organized as follows. Section A discusses the challenges involved in tracking with narrow azimuth beam and factors affecting choice of revisit to maintain track on target without breaking lock. Section B discusses the choice of suitable dynamic models for the targets. Section C describes a combination of design approaches adopted for suitable choice of revisit for target tracks based on its dynamics. Section D discusses the results achieved and section E summarizes the performance of the methods adopted.

II PARAMETRS AFFECTING TARGET REVISIT

The goal of any surveillance system is to quickly confirm the presence of the targets in its surveillance volume and maintain track on them as long as they are in the surveillance coverage. For the phased array radar system which has agile beam, the presence of target can be confirmed quickly by verification process. However, the key here is to manage the radar resources efficiently. The idea is to maintain tracks on targets which are already detected while quickly confirming presence of new targets entering the radar coverage. The tracking system also need to consider that a military target can exhibit sudden maneuver as high as 9g and the design needs to be robust enough to handle such maneuvers. The radar considered has narrow azimuth beam for accurate tracking and broad beam in elevation to obtain the desired coverage. The narrow beam in azimuth necessitates the proper choice of revisit for the targets, as the target can move away from angular beam quickly especially at ranges near to the radar.

Relationship between update time and resulting prediction error expressed in terms of variance reduction ratio and other system parameters[1][2]

$$T = 0.4 * pd\left(\sigma o * \frac{\sqrt{\tau m}}{\sigma m}\right)^{0.4} * \frac{\vartheta o^{2.4}}{1+0.5\vartheta o^{2}} \qquad (1)$$

τm and σm are target maneuver time constant and maneuver standard deviation respectively. For suitable choice of maneuver time constant applying the above equation to meet prediction error to be within 3dB of radar transmit beam the update time requirement for different g maneuvers at bore sight is shown in figure(1a) below for radar beam of 1.8 degree at bore-sight.

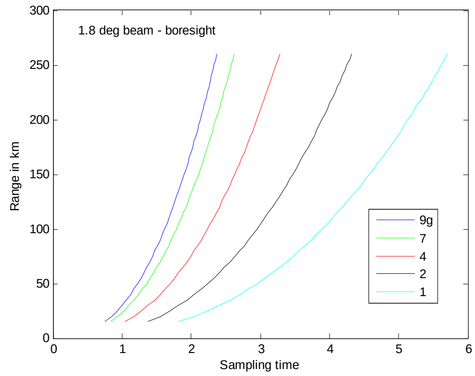

Figure 1a: Sampling requirements at boresight for azimuth beam of 1.8 degree

If the beam width is reduced further by one third the corresponding sampling required for the target increases as is evident in figure 1b.

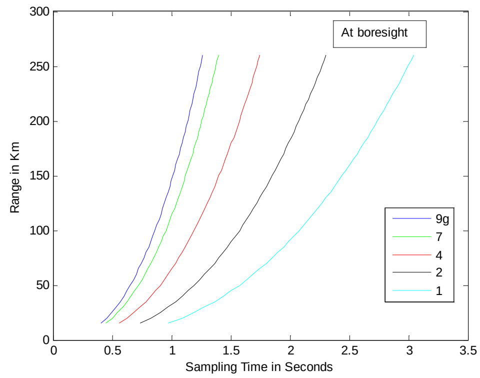

Figure 1b: Sampling requirements at bore-sight for reduced azimuth beam

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For maintaining target tracks, understanding dynamics during maneuver is key for design of tracking system. The computation of rate of turn gives indication of angular movement of target and time required to execute different g maneuvers. The figure(2) below shows rate of turn (w) in deg/s for different g turns

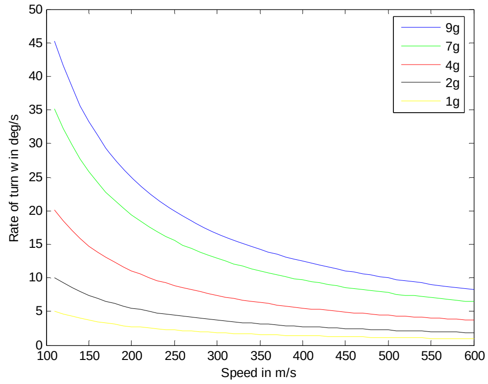

Figure 2: Rate of turn as function of speed

The rate of turn (w) depends on the speed and g with which turn is taken. This in turn decides the angular movement of target with respect to radar. Assuming that a target can take maneuver at any instant of time there is a minimum sampling rate required to maintain the track on target so that the target does not move out of the beam. Such a constraint on revisit time of target based on target geometry and range helps in track maintenance.

III DESIGN OF TRACKING FILTERS

For design of tracking filters the criteria was to arrive at a combination which gives maximum sampling interval and also handle maneuver efficiently. IMM tracks target maneuvers more efficiently[2]. The design of IMM tracking filters involves selection of appropriate aircraft models. In the current design we have incorporated a three-model-IMM algorithm for tracking maneuvering targets. Three different models are chosen to represent target dynamics: Constant velocity(CV) model to represent straight line level flight, constant acceleration(CA) model to represent changes in target velocity and co-ordinated turn(CT) model to handle g maneuvers. This combination of dynamic models gave an optimal revisit suitable for application. To isolate the errors associated with broader elevation beam a decoupled tracking scheme is adopted with range and azimuth information utilized in IMM filter and elevation incorporated in separate filter.

Target Kinematic Models

The discrete-time model for a dynamic system is given by two relationships – the first one describes the dynamics of the system

$$X_{k+1} = FX_k + w_k \qquad \textbf{(2)}$$

and, the second one describes the relationship of the state with measurement

$$Z_k = H_k X_k + v_k \qquad \textbf{(3)}$$

where,

X_k is the state vector

Z_k is the measurement vector

$w_k \sim N(0, Q_k)$ is the process noise, with zero-mean and covariance of Q_k

$v_k \sim N(0, R_k)$ is the measurement noise, with zero-mean and covariance of R_k

The state estimate from the three models at time instant, k are denoted by $x \;\; y \;\; \dot{x} \;\; \dot{y} \;\; \ddot{x} \;\; \ddot{y}$

$$X_k^1 = \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} \qquad X_k^2 = \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ \ddot{x} \\ \ddot{y} \end{bmatrix} \qquad X_k^3 = \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ \ddot{x} \\ \ddot{y} \end{bmatrix}$$

The constant velocity model considers nearly constant velocity for non maneuvering targets. The state transition matrix and process covariance matrix are given by,

$$F = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Q_k = \begin{bmatrix} \frac{T^3}{3} & 0 & \frac{T^2}{2} & 0 \\ 0 & \frac{T^3}{3} & 0 & \frac{T^2}{3} \\ \frac{T^2}{2} & 0 & T & 0 \\ 0 & \frac{T^2}{2} & 0 & T \end{bmatrix} \qquad (4)$$

Similarly for the acceleration model

$$F = \begin{bmatrix} 1 & 0 & T & 0 & \frac{T^2}{2} & 0 \\ 0 & 1 & 0 & T & 0 & \frac{T^2}{2} \\ 0 & 0 & 1 & 0 & T & 0 \\ 0 & 0 & 0 & 1 & 0 & T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

$$Q_k = \begin{bmatrix} \frac{T^4}{4} & 0 & \frac{T^3}{2} & 0 & \frac{T^2}{2} & 0 \\ 0 & \frac{T^4}{4} & 0 & \frac{T^3}{2} & 0 & \frac{T^2}{2} \\ \frac{T^3}{2} & 0 & T^2 & 0 & T & 0 \\ 0 & \frac{T^3}{2} & 0 & T^2 & 0 & T \\ \frac{T^2}{2} & 0 & T & 0 & 1 & 0 \\ 0 & \frac{T^2}{2} & 0 & T & 0 & 1 \end{bmatrix}$$

The fixed center constant turn rate maneuver model takes the form of a second-order Markov process, given as

$$a = \omega^2 v + w$$

It leads to following discrete time model for each Cartesian

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coordinate with state x = [position, velocity, acceleration]'[4]

$$x_{k+1} = \begin{bmatrix} 1 & \frac{\sin\omega T}{\omega} & \frac{1-\cos\omega T}{\omega^2} \\ 0 & \cos\omega T & \frac{\sin\omega T}{\omega} \\ 0 & -\omega\sin\omega T & \cos\omega T \end{bmatrix} x_k + \begin{bmatrix} \frac{\omega T - \sin\omega T}{\omega^3} \\ \frac{1-\cos\omega T}{\omega^2} \\ \frac{\sin\omega T}{\omega} \end{bmatrix} w_k \quad \textbf{(6)}$$

where, the cov(w_k) is σ^2_w

The turn rate, *w* is estimated by using the acceleration estimates provided by the model. The turn rate is then approximated as the ratio of latest acceleration and velocity estimates of the target(under the assumption that the velocity and acceleration vectors are orthogonal), i.e

$$\omega = \frac{\|a\|}{\|v\|} \quad \textbf{(7)}$$

The *w* is estimated by using the velocity and acceleration estimates provided by the mixed state estimate of CT model.

IV REVISIT CONTROL

The revisit control design has to be robust so as to prevent track loss during target maneuver. Adaptive sampling capability due to electronic beam steering provides better tracking performance [5] as compared to fixed sampling. Moreover the adaptive sampling optimizes the use of radar resources. To track maneuvering targets without breaking lock on targets a combination of techniques have been utilized. The techniques are further described below:

a) To optimize radar resources an adaptive revisit selection is incorporated based on the predicted values of radar angle innovation standard deviation relative to radar beam width[6].To maintain track angular deviation of track is monitored for closed loop target and the error build up is restricted to be within 3dB angular beam width.

From the IMM models combine the predicted covariance of each model as

$$P_{k+1/k} = \sum [P^i_{k+1/k} + (\hat{x}_{k+1/k} - \hat{x}^{(i)}_{k+1/k})(\hat{x}_{k+1/k} - \hat{x}^{(i)}_{k+1/k})']\mu^i_k \quad (8)$$

$P_{k+1/k}$ is then converted in to polar coordinates as follows

$$P_{k+1/k(polar)} = C\, P_{k+1/k} C' \quad (9)$$

with, $C = \begin{bmatrix} \frac{x}{r} & \frac{y}{r} \\ \frac{y}{x^2+y^2} & \frac{-x}{x^2+y^2} \end{bmatrix}$

where, x, y are the target coordinates and r is the range of the target. The diagonal elements contain the innovation variances in range and azimuth which can be compared with 3db radar angular beam. Variance in azimuth(σ_a) can be written as

$$\sigma_a < k * BW \quad (10)$$

BW - Azimuth Beam width

For current application k = 1/4

b) As tracking filter has inherent lag in model switching the smoothed innovation of CV model is also monitored to keep check on innovation build up. From the CV model of IMM the track innovation build up is monitored, the motivation behind that is when a target starts maneuvering the innovation build up for target is markedly visible as is shown at start of maneuver in figure(3b) below.

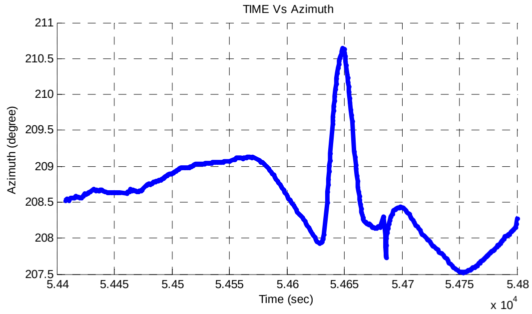

Figure 3a) Target Azimuth with time

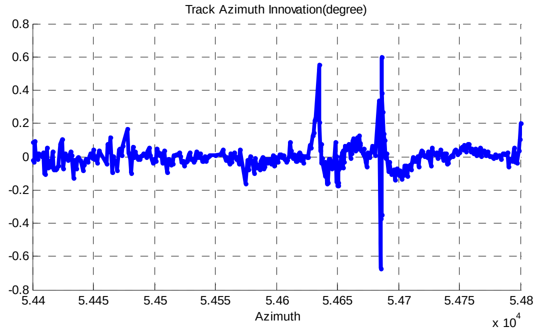

Figure 3b)Azimuth innovation

If the innovation reaches the threshold of 3db radar beam a beam is put within 500ms so as to capture the target maneuver.

c) To take into consideration the target acceleration and its range from the radar as parameters influencing the target revisit equation(1) is applied. The appropriate value of maneuver time constant is derived from the acceleration statistics of target. The track range and acceleration values are derived from IMM filter. selection of the target maneuver time constant is varied based on the acceleration information derived from IMM.

Target Acceleration m/s2	Maneuver time constant τm s
0 -- 0.1	60 - 200
0.1--1	60<=τm <40
1-80	40<=τm <10

By appropriate manipulation of equation(1) and putting the constraint of angular variance to be within 3dB of radar beam the equation can be written as

$$T = 0.043*(\tau m *Rng/Acc)^{0.2} \quad (11)$$

d) Based on target geometry and range the sampling set is varied. This is to cater for narrow azimuth beam. At ranges near to radar there is requirement of obtaining the target sample before it moves out of radar beam. Hence the constraint on revisit

Sampling Sets tried out are:

For ranges beyond 100km

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{0.3 0.5 0.7 1 1.5 2 2.5 3 3.5 4}
For ranges up to 100km
{0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2}

e) For robustness in design recovery pattern is incorporated in case of target loss. Recovery Cycle is initiated to minimize track loss during maneuver due to absence of detections. In case of detection loss track beam is scheduled within 300ms. For two successive detection losses a recovery is attempted in angular direction with maximum up to 3 recovery cycles for every target.

The tracking cycle proceeds as follows:

1)Based on target range appropriate sampling set is selected from (d).

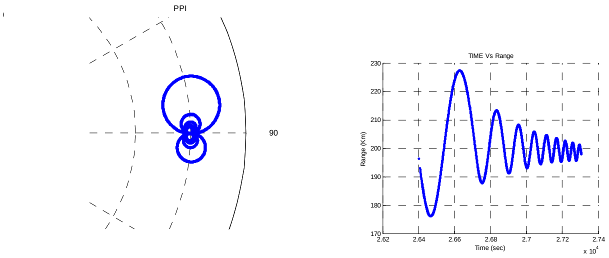
2) Innovation build up from constant velocity filter is checked, if it is above threshold a quick update < 500ms is scheduled.

3) If innovation build up is within threshold, highest revisit is tried (criteria a). Predicted angular deviation is checked to be within 3dB radar angular beam, if not the next lower interval is tried till the criteria is met. In Parallel the required revisit based on target range and acceleration and geometry is also computed. If this is found to be lower than that given by a, update is scheduled with this.

4)In case of detection loss recovery cycle is initiated A limited search along target bearing is carried out to reacquire the target.

V PERFORMANCE EVALUATION

The revisit control techniques discussed above were put along with three model IMM estimator and separate height filter and maneuver performance was evaluated with actual targets maneuvering up to 6g. The performance evaluation was also carried out for target maneuvers greater than 6g in simulation mode. Figure(4) simulates targets maneuver from 1g to 9g and corresponding acceleration estimates by IMM are depicted in figure(5a) and revisit time in figure(5b)



(a) (b)

Figure 4a: Simulation of target maneuvers from 1g to 9g
a:PPI plot b: range vs time

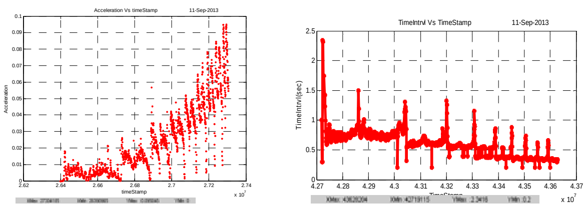


Figure: 5a) Acceleration statistics b) Revisit Time

Figure (6) depicts aircraft executing maneuvers between 4g and 5g with corresponding acceleration and revisit depicted in figure(7a) and figure(7b) respectively.

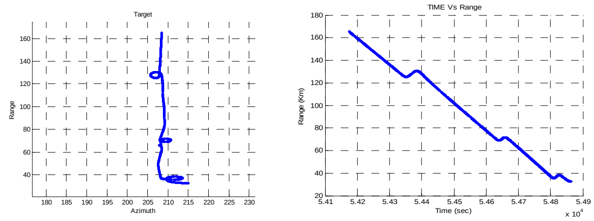


Figure 6: Target maneuvers 4g-5g (a):B-Scope (b):range vs time

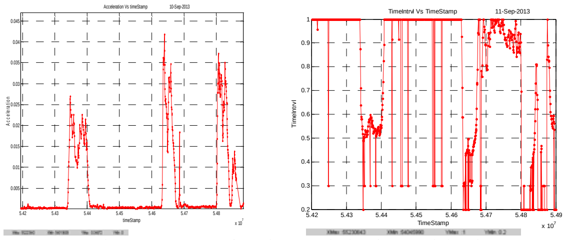


Figure: 7a) Acceleration statistics b) Revisit Time

Figure(8a) below depicts an helicopter executing multiple maneuvers at ranges less than 26km from radar. Figure(8b) shows corresponding radar track output in B-scope

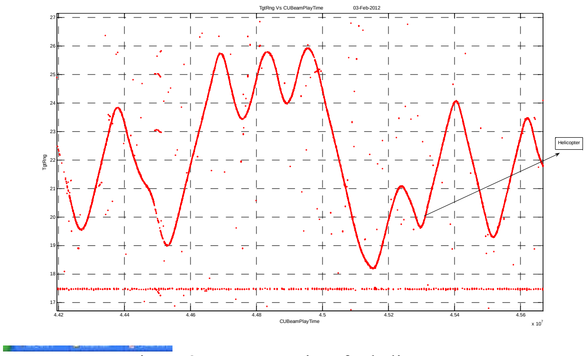


Figure 8a: Range vs time for helicopter

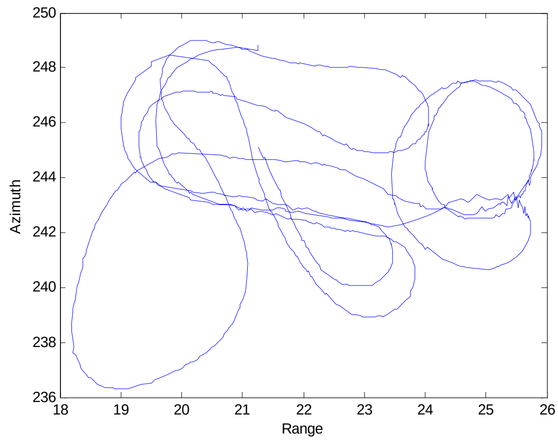


Figure 8b: B-Scope (Track maintained by radar)

Figure(9) depicts fighter executing high g horizontal maneuver followed by vertical maneuver. The corresponding revisits scheduled by tracker is plotted in Figure(9b).

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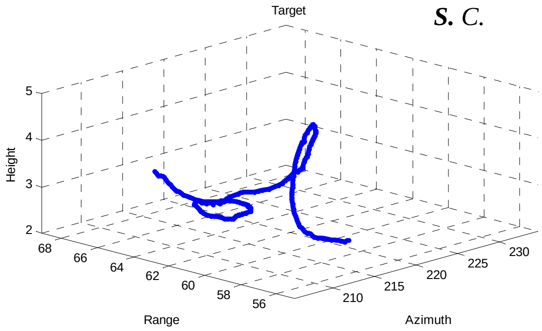

Figure 9a: Aircraft executing horizontal & Vertical maneuver

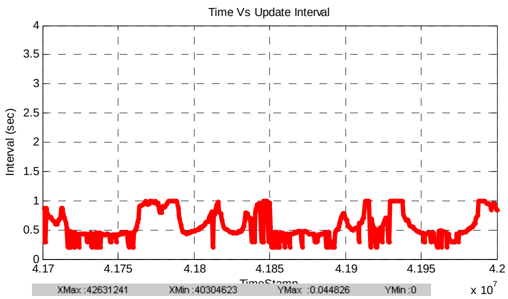

Figure 9b: Revisit time

VI CONCLUSION

Through this paper we have tried to address the issues encountered during tracking of target maneuvers. The emphasis was to avoid track loss and make design robust to handle widely different target dynamics. Choice of IMM algorithm consisting of co-ordinated turn model in conjunction with the revisit control techniques discussed has led to successful handling of target maneuvers.

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Aparna Rathi**,** received the M.Tech degree in Electronics Design Technology from Center of Electronics Design Technology of India, Aurangabad, in 1997. She is a scientist in Electronics and Radar Development Establishment, Bangalore since 1999. She has worked for development of target tracking and radar data simulation software for different radar applications.

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