AUTOMATING RADARS FOR AIR TRAFFIC CONTROL*

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ABSTRACT

Developments in digital signal processing over the past few years have improved the detection and false alarm properties of air surveillance radars to such an extent that automatic radar tracking of all aircraft within the radar's coverage volume has become a reality. This paper derives the radar requirements to support tracking in a fully automated air traffic control system.

INTRODUCTION

Over the past ten years there has been a concerted effort on the part of the Federal Aviation Administration to automate the Air Traffic Control system in the United States. The objectives of this automation effort are:

(1) To relieve the air traffic controller of some of his burden in the face of rising numbers of aircraft,

(2) To produce a more orderly flow of aircraft into and out of terminal areas so as to increase the efficiency of these terminals, and

(3) To improve airspace safety by further reducing the chances of mid-air collisions and the chances of encountering hazards such as hail and turbulence.

The first sensor system to be automated was the Air Traffic Control Radar Beacon System (ATCRBS). Automation of the primary radar function has been more elusive. This paper discusses the problems associated with the automation of primary radar in an air traffic control system and the means which have been developed to solve these problems.

Automation requires the automatic tracking of all aircraft within a sensor's coverage volume. Tracking of aircraft is required for positive control. Positions of all aircraft must be known and projected ahead if conflicts are to be avoided, and if airspace is to be used in an optimal manner.

Tracking is performed in a computer so that automation implies the digitization of sensor data and its introduction into a computer. ATCRBS was easily digitized, but primary radar signals were greatly contaminated by signals reflected from other clutter objects in the radar's field of view (e.g., ground objects, precipitation, birds, automobiles, etc.). Before describing the means used to overcome clutter, we will describe the requirements imposed on the sensor output data to allow its use in an automatic tracker.

TRACKING REQUIREMENTS

To acquire a good appreciation for tracking problems we will describe tracking in three stages: (1) optimum tracking of a single, isolated aircraft; (2) tracking in a dense aircraft environment; and (3) the effect of false alarms on tracking.

Single Isolated Aircraft Tracking

The objective when tracking a single aircraft is to optimally use the available data to provide the best estimate of the aircraft's position and velocity. A two-dimensional radar provides periodic aircraft position estimates of range and azimuth. In estimating its present and projected aircraft positions, two kinds of errors are involved; radar measurement errors and unknown aircraft accelerations.

To obtain accurate position estimates the tracker should average over many scans covering a long period of time. However, when unknown aircraft accelerations are likely to occur a very short time estimate should be employed to correspond approximately to the correlation time of the acceleration. Thus, for best accuracy there is actually an optimum averaging time which, when measured in scan times of the radar, is a function of (λ) the ratio of the acceleration motion of the aircraft to the rms measurement error of the radar. It is also parametrically a function of the correlation time of the random accelerations.

Starting with the time at which the aircraft is out of track because it has just entered the radar's coverage volume or because it was

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dropped from track for some reason, an initial detection is followed on the succeeding scan by search of a track association area whose radius is:

$$R = V_{max} T + kc$$

where: V_{max} is the maximum ground speed of aircraft to be tracked, T is the scan time, c is the rms radar measurement error and k is a constant to take into account the statistical nature of the measurement error. We take k = 2.5 and calculate the initial association areas for a typical Airport Surveillance Radar (ASR).

Assuming a second detection within this initial association area, the approximate velocity can be determined, the track can be projected, and a new association area can be determined. Studies have been made using Kalman filtering to optimally project the track so as to minimize the error in the projected position. Assuming random accelerations uncorrelated from scan to scan, one arrives at a so called $\alpha - \beta$ tracker where α and β measure the degree of smoothing of position and velocity respectively. The results of one such study(1) of track initiation are shown in Figure 1. Here the expected deviation of the succeeding position reports from the projected track positions

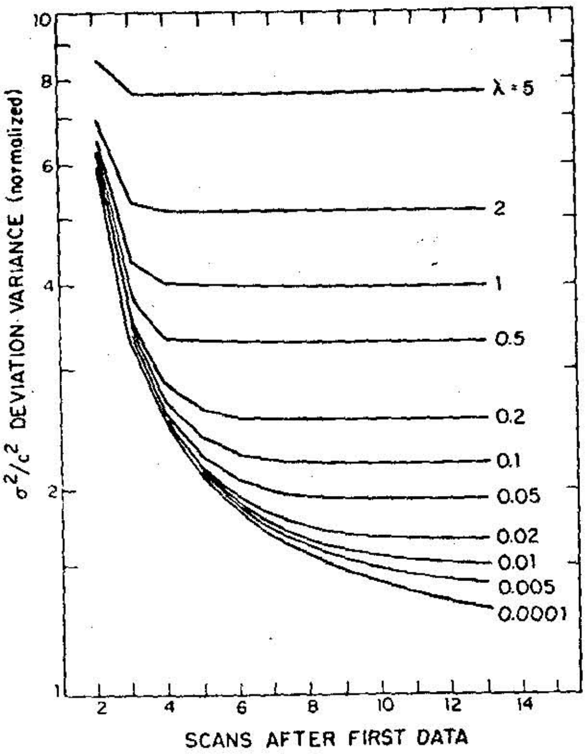

Figure 1 - Deviation Variance Behavior in Start-up Sequence

normalized to the radar measurement error are shown as the aircraft is detected on succeeding scans. The deviations approach certain steady state values depending on λ. The radius of the corresponding association area, assuming an isotropic error distribution, are taken as four times the deviation for high probability of including the aircraft return. The resulting steady state association areas, assuming random accelerations with a 0.5G standard deviation, are shown in Table I.

TABLE I

SURVEILLANCE RADAR PARAMETERS

	ASR
Instrumented Range	60 nmi
Azimuth Accuracy	0.003 radian
Scan Time (T)	4 sec
RMS Accuracy (C) at 1/2 Range	0.09 nmi
$\lambda = (aT^2/C)^2$ for $a = 16$ ft/sec^2	0.25
Initial Association Area (A_i) (V_{max} = 550 knots)	2.2 sq nmi
Steady-state Association Area (A_s)	1.1 sq nmi
f with 50 False Alarms per Scan	0.01
Number of Association Areas (N_A) on PPI using A_i	5100
Number of False Tracks (N_{FT}) on PPI	0.015

A continuation of the same study for the case of several missed detections is shown in Figure 2. The optimum association area grows quite rapidly with succeeding misses. Thus, with each missing scan the probability increases that the track will be continued on a false report or will interfere with another track so that at some point the track should be dropped.

The above type of analysis leads to the state diagrams for a tracker as shown in Figure 3. Starting with the aircraft out of track, P_o, successive detections cause the track to progress through P_1, P_2, etc. to the steady state, P_s When a miss occurs it drops back to a state which most nearly matches the optimum values of α and β. Note that when a detection occurs after several misses, the track drops clear back to the steady state. This is in agreement with the action shown in Figure 2.

With the state diagram, Figure 3, we can now study the probabilities of the tracker being in each state. The connecting arrows are marked p or q, where p is the single scan probability of detection and q = 1 - p is the probability of a miss. Both p and q are assumed uncorrelated from scan to scan.

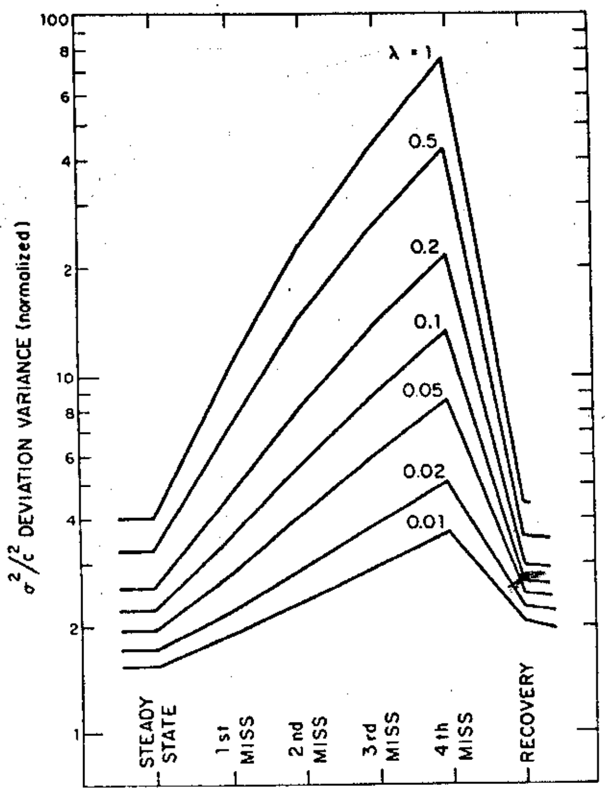

Figure 2 - Deviation Variance Behavior in Missing Data Sequence

In the steady state, a set of equations can be written connecting all the states noting that the probability of entering each state exactly equals the probability of leaving. Also employing the fact that the sum of the probabilities of all the states equals one, the state diagram can be analyzed to yield the probability of each track state.

Figure 4 shows the steady state tracker performance for the trackers shown in Figure 3. Here we describe the tracker by two numbers, n, the number of successive detections to put the aircraft into track and, m, the number of successive misses required to drop the track. In Figure 4 the probability that a track is in either the firm track state P_s or one of the coasting track states (directly below P_s in Figure 3) is plotted as a function of the probability of detection on each scan, p.

At the upper end of the curves in Figure 4 when the probability of detection is near 1, the curves can be expressed by

$$P_T = 1 - n\,(1-p)^m \quad (1 - p \ll 1)$$

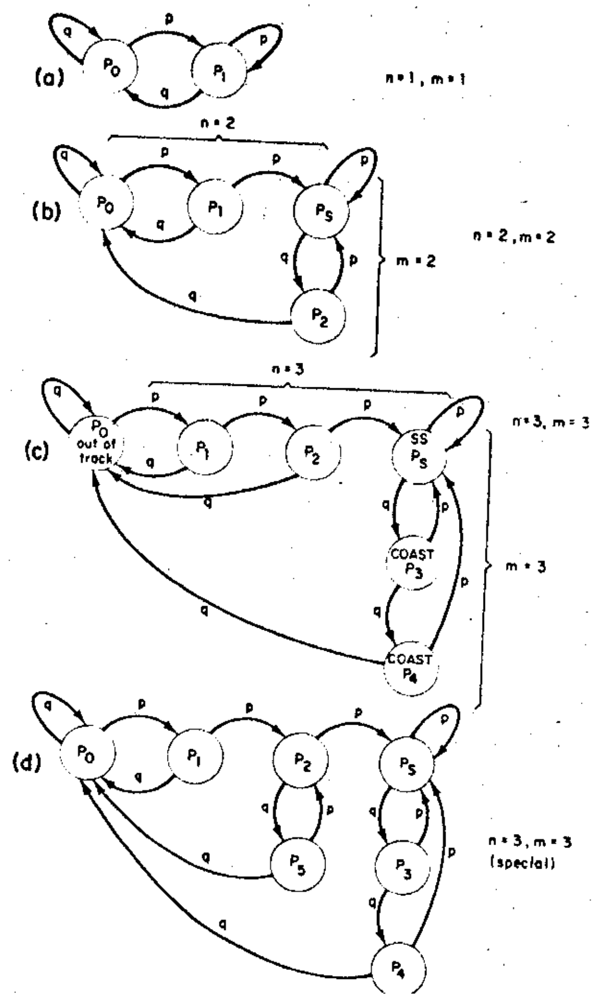

Figure 3 - Tracker State Diagrams

Thus requiring more misses to drop a track (increasing m) causes the high end of the curves to move to the right resulting in a lowered blip-scan ratio, p, for a given steady state track probability. The use of more coasting track states, however, enlarges the association area (see Figure 2) and thus causes a higher probability that a coasting track will pick up a false report. More will be said about this below.

False Track Initiation from False Reports

If we define f as the single scan false report probability per association area, then Figure 4 also depicts the probability that a false track exists in each association area. If f is very small

$$P_{FT} = m\, f^n \quad (f \ll 1)$$

and the number of false tracks N_{FT} showing on the

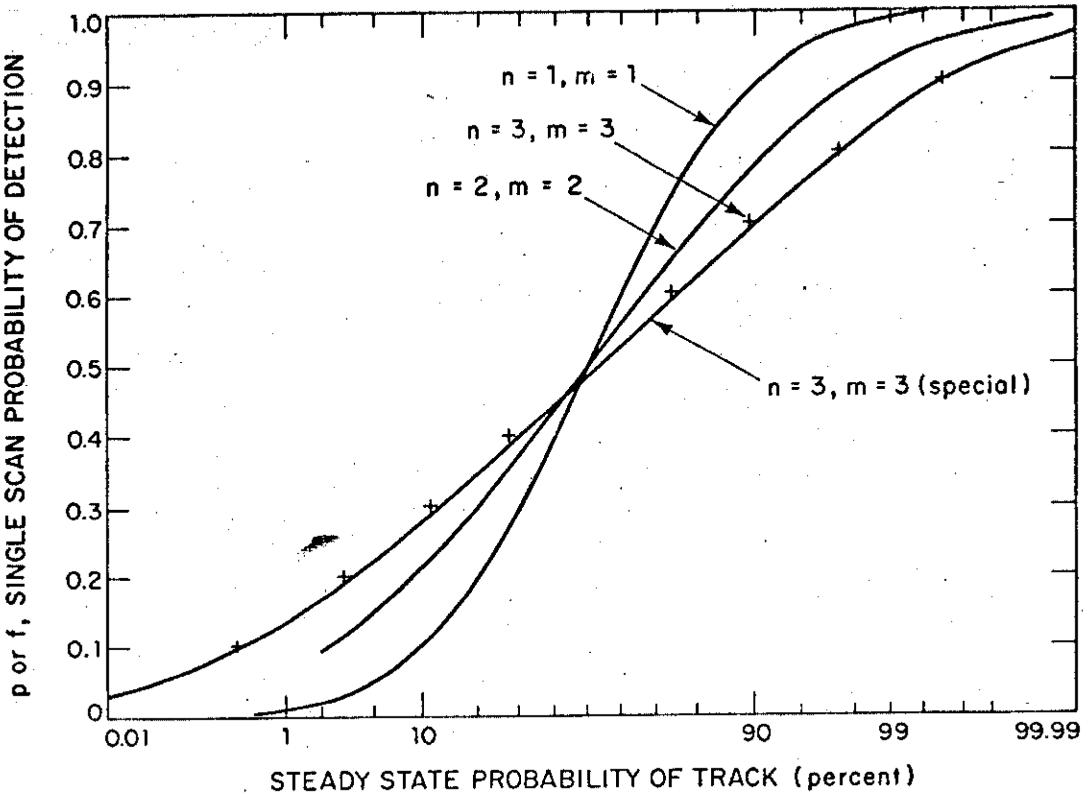

Figure 4 - Steady-State Tracker

PPI on any one scan will be

$$N_{FT} = N_A \, P_{FT} = N_A \, m \, f^n$$

where N_A is the number of association areas on the surface of the PPI.

As an example, if 50 false reports per scan are experienced on a full range PPI the resulting value of f, assuming association areas equal to the initial association areas, is about 0.01 (see Table I). Using the above equation the number of false tracks per scan was calculated (see Table I). For typical ASR radars with 50 false reports per scan and a n = 3, m = 3 tracker, approximately one false track is experienced per 200 scans and the false track life is short, usually only three scans.

It is clear from the above discussion that, n, the number of scans to initiate a track is chosen as a compromise between the desire to reduce false track generation (high n) and the desire to rapidly put an aircraft into track (low n). If the false report rate is too high in a given area, say due to a high false alarm rate in rain, the false track rate will increase very rapidly in that area. The false track rate varies as the nth power of the false alarm rate so that a doubling or tripling of the false alarm rate will cause a noticeable increase in the false track rate.

Dense Aircraft Environment

In this section we discuss the use of the tracker described in the above section in a dense aircraft environment.

One hundred aircraft within the coverage volume of an ASR out to 60 nmi represents a fairly dense environment. Assuming twice the density in part of the coverage we arrive at one aircraft for every 56 square miles. We see that approximately two percent of the association areas on any one scan in the dense target area will contain more than one target report. This is called the "crossing track" problem.

Several tactics may be used to resolve the crossing track problem and assign the proper reports to the correct tracks. (1) The reports may be ignored and the tracks continued as if no report were received. On the succeeding scan the situation should correct itself providing the aircraft are crossing at a steep enough angle. (2) Each track could form two tracks based on the two reports within the association volume. One of these would die out on succeeding scans for lack of further support. (3) If available, a radial velocity measurement could be used both to project tracks more accurately and to associate reports with the correct tracks. (4) If available, beacon identity or altitude reports which correlate cleanly with the separate reports could be used to resolve the track association problem. (5) Report amplitude or spectral distribution might help resolve crossing tracks. (6) If the radar is a three-dimensional radar, height could be used to associate reports correctly.

To date there has not been enough analysis or experience with automatic radar tracking systems to judge the efficiency of the above suggestions in a dense aircraft environment. If all the available solutions in combination result in too much track swapping it may be necessary to provide a higher update rate or to lower measurement errors.

All of our examples have assumed a circular error pattern and we have used the worst errors to determine the error circle's radius. If the tracker takes into account the elliptical shape of the error pattern, its area can often be reduced by a significant amount. In the case of crossing tracks it may be useful to recompute the elliptical error pattern to help resolve the association problem. This would only be required on two percent of the tracks in a dense aircraft environment.

Another approach is to calculate the separation between the predicted and measured report positions. An association measure can be defined equal to the square of the deviation of the measured position from the predicted aircraft position.

Track Branching to False Alarms

If the number of false reports per scan is maintained at a small fraction of the maximum number of aircraft for which the system is designed, the target branching problem to false alarms will be measured as a small fraction of the number experiencing the crossing track problem. For instance, with 50 false reports per scan an ASR will experience a false report in the same association area on only 0.5 percent of tracks in the heavy track area of an ASR. If the same technique is used to handle track branching to false alarms as is used to handle crossing tracks, there should be little difficulty from this source.

TRACKING REQUIREMENTS AND RELATED RADAR REQUIREMENTS

In an automated ATC system aircraft tracks must be automatically initiated and as continuous as possible. In this section we define desirable tracking specifications and how they lead to certain radar requirements.

The tracking requirements can be expressed in terms of the following specifications.

Steady-State Probability of Track

The steady-state probability that any aircraft within the radar's coverage volume be in track should be high, perhaps 99.5 percent. This implies a certain track life.

False Tracks

The average number of false tracks generated directly from false reports or by continuing true tracks with false reports should be very small, perhaps one in 30 minutes. The average duration of false tracks should be short, perhaps two to three scans.

Track Swapping

The frequency of false tracks due to track swapping in a specified dense aircraft environment should be very low, perhaps one per hour.

The decisions to be made are:

1. the order of the tracker (n and m)
2. the required minimum probability of detection, and
3. the required maximum false alarm rate.

Notice that the requirements for minimizing track swapping or continuation of a track using a false alarm both call for a high probability of detection. We may make the observation that if the probability of detection is high enough to reduce track swapping to a reasonable level and if the allowable false reports per scan (assumed perfectly random) are a small fraction of the track volume for which the system is designed, then very little trouble should be experienced from tracks being continued on false alarms. In terminal area trackers designed for 200 tracks, 25 to 50 false alarms per scan should be allowable.

It is clear that from an ASR the order of the tracker should be $n = 3$ or higher unless the false alarm rate can be lowered to 4 per scan or lower. Above order $n = 3$, the allowable false alarm rate increases at the slower rate.

Next, examining Figure 4 we see that the order m = 2 tracker is quite poor in producing a high probability of track. For 99 percent track probability a 0.93 detection probability is required with order m = 2, whereas the same detection probability causes a 99.9 percent track probability for the order m = 3 tracker. The only remaining consideration is transient response.

An n = 3, m = 3 tracker will, with high probability, put a new aircraft into track in three scans and eliminate a false track in the same time. A 250-knot aircraft travels 0.82 nmi in the time it takes for three scans (12 seconds) compared to a 3-nmi ATC separation rule so that this tracker should be quite acceptable in the terminal area.

RECENT RADAR IMPROVEMENTS

Over the last few years, significant developments have occurred which now allow completely automatic tracking. A good example is the Moving Target Detector(2,3) (MTD) which overcomes all forms of clutter encountered by an ASR. The reader should consult the references for specific details.

In the MTD the false alarm rate can be adjusted to a reasonable value of about 40 per scan from noise alone. Experience shows only a slight increase in false alarm rate over this value from all forms of clutter. In the MTD everything possible is done to avoid blind speeds so that the probability of detection per scan is 90 percent or more, even for tangentially flying aircraft. All missed detections and false alarms in the MTD are decorrelated(4) either spatially or temporally from scan to scan, thus satisfying assumptions in the above tracking analysis.

CONCLUSIONS

We have presented a detailed analysis of the detection and false alarm requirements for automatic radar tracking. The radar performance requirements are easily met with the Moving Target Detector developed by the FAA over recent years. These developments make possible the automation of primary radar into the air traffic control system.

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