Abstract
The United States is in the process of commissioning new consolidated Terminal Radar Approach Control (TRACON) facilities to serve large complex terminal areas. In addition to receiving surveillance data from radars formerly serving each individual TRACON, the consolidated TRACON facilities will receive surveillance data from all available sensors in the area including long-range en route radars. The new facilities will have the ability to use mosaic displays to combine surveillance data from multiple surveillance sensors.

Current terminal area separation requirements allow three-mile separation between aircraft provided both aircraft are within 40 miles of a single terminal radar. At issue is whether three-mile separation can be maintained throughout consolidated TRACON airspace using a mosaic display.

This paper reviews the error characteristics of long-range and short-range sliding-window Air Traffic Control Radar Beacon System (ATCRBS) and Monopulse Secondary Surveillance Radar (MSSR) surveillance sensors. Errors in the separation distance between targets displayed to a controller were analyzed for both single sensor and mosaic displays. Monte Carlo simulations were run to compute the errors in displayed separation as a function of range from the sensor.

It was found that MSSR sensors offer an approximately three-fold increase in azimuth accuracy over sliding-window ATCRBS and provides equivalent separation performance at a range of over 100 miles in single sensor mode. It was also found that MSSR sensors in a mosaic display offered separation performance equivalent to a single sliding-window ATCRBS sensor when each aircraft is within 40 miles of its respective sensor. Sliding-window ATCRBS short-range sensors in mosaic display mode offer acceptable performance when each aircraft is within 28 miles of its respective sensor.

Problem Statement and Approach
An Individual TRACON controlling traffic in it’s respective terminal area separates traffic by three nautical miles\(^1\) for aircraft less than 1000 feet apart in altitude. At issue is whether or not the current three-mile separation...
terminal separation standard can be applied throughout all of the airspace in a consolidated TRACON. The ability to use three-mile separation throughout the consolidated TRACON airspace will enable much more flexibility in airspace design and utilization. For this reason, the FAA Operational Evolution Plan has identified the expansion of the use of the terminal separation standard as one of its key goals.

Radar separation standards are contained in FAA Order 7110.65N [1]. The order allows three-mile separation between aircraft as long as both aircraft are less than 40 miles from and tracked by the same sensor antenna, otherwise the traffic must be separated by five miles. A separation of three miles is not permitted with a mosaic display; five-mile separation is required. The order makes no distinction in separation requirements based on the performance of the radar, and applies equally to short and long-range radars. In order to determine if FAA Order 7110.65N could be modified to permit three-mile separation in the mosaic environment of a consolidated TRACON, an analysis was undertaken of the surveillance errors associated with single-sensor and mosaic displays. The objective of this analysis was to determined the conditions under which a mosaic display would be equivalent to a single sensor display for the purposes of traffic separation.

The approach taken in this analysis is to examine the error characteristics of the various types of beacon sensors in the FAA inventory and to analyze their performance with regard to providing accurate separation measurements to controllers. The metric for performance is the error in the aircraft separation displayed to a controller. The error in measured or displayed separation is the difference between the true separation (actual distance between aircraft in the air) and the separation displayed to a controller on a radar display. The required surveillance performance is derived using this metric for current legacy sensors. This requirement is used to determine the range for providing acceptable separation performance for newer more advanced sensor systems in both single sensor and mosaic display modes.

**Surveillance Analysis**

The surveillance analysis begins with a summary of the error characteristics of the secondary sensors currently used by the FAA to provide separation. The additional errors in displayed separation introduced by mosaic display are then discussed. This is followed by a description of the Monte Carlo simulation that was performed to measure the errors in separation displayed to the controller for each of the sensor cases analyzed.

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**Error Characteristics of FAA Sensors**

Secondary (beacon) radar error characteristics include errors in estimating range and errors in estimating azimuth to the target.

Range measurement errors are due primarily to errors in measuring the interval between the time a pulse is sent from the radar to the time a reply is received from the aircraft’s transponder. This includes errors in the accuracy with which the sensor can measure the time interval and variations in the allowed turn around time of the transponder. Range errors due to timing are relatively small (< 200 feet) and do not increase with range. Refraction effects are only significant at very long range and were not included in this analysis. Propagation anomalies, such as atmospheric ducting, were also not included in this analysis. Likewise, errors introduced by aircraft not equipped to report altitude were not considered.

Azimuth measurement errors are primarily due to errors in estimating the target position within the beamwidth of the transmitted pulse. Typical 3-dB beamwidths are approximately $2.2^\circ$, which results in a beamwidth of 1.75 miles at a range of 40 miles. Azimuth measurement errors are less than the beamwidth and depend on the technique used to estimate the target’s position within the beamwidth. There are two azimuth measurement techniques used by sensors in the FAA inventory.

The older generation of Air Traffic Control Radar Beacon System (ATCRBS) radars use a “sliding window” technique to estimate azimuth. This technique (illustrated in Figure 1) requires detection of replies in the leading and trailing edges of the beam where the signal is weakest. The azimuth of the target is estimated as the center of the leading and trailing edges. FAA Beacon Interrogator BI-4 and BI-5 sensors use the sliding window technique.

![Figure 1 “Sliding window” azimuth measurement technique](image_url)
Hereafter, this paper will refer to sliding-window ATCRBS sensors as simply ATCRBS sensors.

Newer Monopulse Secondary Surveillance Radar (MSSR) sensors use two beam patterns for interrogation and require only a single reply. This technique (illustrated in Figure 2) offers an approximately three-fold improvement in azimuth measurement accuracy over the sliding window technique. FAA Mode S and BI-6 sensors use the monopulse technique for measuring azimuth.

**Figure 2. Monopulse azimuth measurement technique**

A detailed description of these two azimuth estimation techniques is given by Orlando [2]. Figures 1 and 2 were taken from that article.

Additional errors include residual registration errors caused by location and azimuth biases not removed by algorithms designed to align multiple sensors.

The position estimates are disseminated using the FAA Common Digitizer (CD) format. In this analysis the format resolution was not modeled as an additional error source but the position estimates were rounded to the allowed CD formats.

The scan time of the antenna determines the length of time between target updates. While the position estimates are not affected, the motion of the targets between their respective updates results in errors in displayed separation.

The radar source errors used in the analysis are presented in Table 1. The values of the errors used are based on radar specifications and field data from ARCON [3] for radars in Southern California TRACON, and from MIT Lincoln Laboratory [4] for radars in the northeast region.

### Table 1 Radar Source Errors Used in Simulations

<table>
<thead>
<tr>
<th>Sensor Error Sources</th>
<th>MSSR&lt;sup&gt;1&lt;/sup&gt;</th>
<th>ATCRBS sliding window</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Registration Errors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location Bias</td>
<td>200 ft. (0.033 nmi.) Uniform in any direction</td>
<td></td>
</tr>
<tr>
<td>Azimuth Bias</td>
<td>±0.3 Uniform</td>
<td></td>
</tr>
<tr>
<td></td>
<td>σ = 0.173</td>
<td></td>
</tr>
<tr>
<td><strong>Range Errors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar Bias</td>
<td>±30 ft. (0.005 nmi) Uniform</td>
<td></td>
</tr>
<tr>
<td></td>
<td>σ = 17 ft. (0.003 nmi.)</td>
<td></td>
</tr>
<tr>
<td>Radar Jitter</td>
<td>25 feet rms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>σ = 25 ft. (0.004 nmi.)</td>
<td></td>
</tr>
<tr>
<td><strong>Azimuth Error</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth Jitter</td>
<td>σ = 0.068 (0.8 ACP)&lt;sup&gt;3&lt;/sup&gt;</td>
<td>σ = 0.230 (2.6 ACP)&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>1/64 nmi.</td>
<td>1/64 nmi.</td>
</tr>
<tr>
<td></td>
<td>σ = 27 ft. (0.005 nmi.)</td>
<td>σ = 110 ft. (0.018 nmi.)</td>
</tr>
<tr>
<td></td>
<td>1/16 nmi.</td>
<td>1/16 nmi.</td>
</tr>
<tr>
<td></td>
<td>σ = 27 ft. (0.005 nmi.)</td>
<td>σ = 110 ft. (0.018 nmi.)</td>
</tr>
<tr>
<td><strong>Data Dissemination Quantization CD format</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>1/64 nmi.</td>
<td>1/16 nmi.</td>
</tr>
<tr>
<td></td>
<td>σ = 27 ft. (0.005 nmi.)</td>
<td>σ = 110 ft. (0.018 nmi.)</td>
</tr>
<tr>
<td></td>
<td>360 /4096</td>
<td>360 /4096</td>
</tr>
<tr>
<td>Azimuth</td>
<td>σ = 0.025</td>
<td>σ = 0.025</td>
</tr>
<tr>
<td><strong>Scan Time Uncorrelated Error</strong>&lt;sup&gt;2&lt;/sup&gt;</td>
<td>4-5 sec. (0.088 nmi.)</td>
<td>4-5 sec. (0.088 nmi.)</td>
</tr>
<tr>
<td></td>
<td>σ = 219 ft. (0.036 nmi.)</td>
<td>σ = 219 ft. (0.036 nmi.)</td>
</tr>
<tr>
<td></td>
<td>10-12 sec. (0.088 nmi.)</td>
<td>10-12 sec. (0.088 nmi.)</td>
</tr>
<tr>
<td></td>
<td>σ = 536 ft. (0.088 nmi.)</td>
<td>σ = 536 ft. (0.088 nmi.)</td>
</tr>
</tbody>
</table>

<sup>1</sup>Note: MSSR can deal with both Mode S and ATCRBS transponders in a monopulse fashion.

<sup>2</sup>Note: Aircraft assumed three miles apart in trail at 200 knots.

<sup>3</sup>Note: ACP=Azimuth Change Pulse (1/4096 of a scan)

### Transponder Error Sources

<table>
<thead>
<tr>
<th></th>
<th>Mode S</th>
<th>ATCRBS</th>
</tr>
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<tbody>
<tr>
<td><strong>Range Error</strong></td>
<td>±125 ft. (0.021 nmi.)</td>
<td>±250 ft. (0.041 nmi.)</td>
</tr>
<tr>
<td></td>
<td>σ = 72 ft. (0.012 nmi.)</td>
<td>σ = 144 ft. (0.024 nmi.)</td>
</tr>
</tbody>
</table>
The errors for individual radars are in good agreement with the errors for radars reported in a study conducted by Lockheed Martin and included as an Appendix in the ARCON report.

**Additional Errors in Displayed Separation Introduced by Mosaic Display**

The target position accuracy of an individual radar is unaffected by whether it is used as a single sensor or in a mosaic display. However, two factors add to the errors in the separation between targets displayed to a controller in mosaic mode compared to single sensor mode.

First, for a single sensor tracking two or more aircraft, the bias errors in range, azimuth, and sensor location affect the position estimates of all targets in the same way. That is, the errors are correlated. Thus even though the position of the targets may be in error, the errors are equally applied to all targets and have very little effect on the separation distance displayed to a controller on a radar display. However, in mosaic mode, when two different radars are used to track the targets, those bias errors are, in general, uncorrelated and will result in additional errors in the separation between targets displayed to the controller.

Secondly, when a controller is separating two aircraft using the estimated positions on a display, the targets are updated at different times. This introduces an error in the displayed separation because of the motion of one aircraft relative to the other between updates. With a single sensor, for two target aircraft relatively near each other, the time between updates can be explicitly computed and is generally small. However, in the case of mosaic display, the target updates are asynchronous and, in general, the time difference between target updates is larger for mosaic display. This in turn results in larger errors in displayed separation for the mosaic case.

**Statistical Analysis of Errors in Separation Displayed to a Controller**

The procedure followed in this analysis was to determine the distribution of errors in measured separation observed, on average, for two aircraft that were three nautical miles apart in-trail traveling at 200 knots. Monte-Carlo simulations using the sensor error characteristics described above were run for single sensor and mosaic display for long-range and short-range ATCRBS and MSSR sensors at various ranges (1,000,000 trials each).

All of the characteristic radar errors were independently re-sampled for each trial. Separation measurement errors are highly dependent on range and the relative geometry of the aircraft and the radars. The procedure used for the single sensor case was to randomly orient two in-trail aircraft that are separated by three miles about an angle $\varphi$ relative to the radar, with the midpoint of their locations at the specified range from the radar. This is illustrated in Figure 3.

![Figure 3. Relative geometries used for the single and mosaic (two-radar) measurements of errors in separation measurements](image)
randomly sampled according to the relative radar update rates for the mosaic display case. The additional error in displayed separation caused by movement of the aircraft between updates was added to compute the separation distance displayed to the controller.

Monte Carlo simulations of 1,000,000 trials were run for single-sensor and mosaic display for short-range and long-range ATCRBS and MSSR sensors at various ranges. Each simulation of 1,000,000 trials generated a distribution of separations displayed to the controller. This is the probability density function of displayed separation illustrated in Figure 4. The mean of the distribution was three miles, the actual separation, for each case. The shape of the distribution depended on the error characteristics for the particular sensor being simulated. The standard deviation, \( \sigma \), for each distribution was computed.

Simulations were run for the eight combinations represented by single-sensor and mosaic display, short-range and long-range sensors, and ATCRBS and MSSR sensors. All eight cases were run at various ranges.

As an illustration, results for single-sensor ATCRBS, single-sensor MSSR, and mosaic display MSSR short-range sensors are compared at four different ranges in Figure 5. Note that the shapes of the distributions as well as their standard deviations are different and expand with range. The single-sensor MSSR has the lowest average error and the single-sensor ATCRBS and mosaic MSSR have similar errors although the distribution shapes are different.

It is important to note that these distributions are not Gaussian. The assumption that they are Gaussian and the use of the Gaussian standard deviation \( \sigma \) to draw conclusions regarding the percentages of trials in the tails of the distribution would lead to serious errors. An example computation illustrates the point. In a Gaussian distribution, 0.26% of the trials will fall outside the 3\( \sigma \) limits in the tails of the distribution. This is not the case for the distributions shown in Figure 5. For the mosaic short-range MSSR distribution at 30 miles 0.32% of the trials were outside the 3\( \sigma \) limit. For the ATCRBS short-range single-sensor distribution, 0.94% of the trials were outside that distribution’s 3\( \sigma \) limit. For the MSSR short-range single-sensor distribution it was 0.44%.

Figure 4. Procedure for generating error distributions for displayed separation

Figure 5. Probability distributions of displayed separation errors as a function of range for ATCRBS, MSSR, and MSSR mosaic display
Results

The results of the Monte Carlo simulation runs are presented as plots of displayed separation error ($3\sigma$) versus range for single sensor and mosaic display ATCRBS and MSSR sensors. The results for short-range radars are presented in Figure 6 and the results for long-range radars are presented in Figure 7. The line indicating currently acceptable performance (i.e., consistent with FAA Order 7110.65N) is derived from the separation performance of a single short-range ATCRBS sensor at a range of 40 miles.

It is apparent from Figure 6 and 7 that MSSR performance is significantly better than ATCRBS, especially at long range. This is because of the three-fold increase in azimuth accuracy for MSSR.

For single sensor ATCRBS and MSSR sensors the separation performance of the long-range sensors is almost equivalent to the performance of the short-range sensors. This is because the slower rotation rate of the antenna does not contribute significant error when aircraft are relatively near each other and are under surveillance by the same sensor. At long ranges, the time difference between target updates does not go up significantly at the slower rotation rates because the azimuth angle between the targets is so small and the motion of the aircraft between updates is small. At closer ranges, this error does increase for long-range radars relative to short-range radars because the relative azimuth angle of the targets is greater, but the performance is better than the currently acceptable level at close range. The only other difference for long-range radars is the lower resolution in the CD reporting format for range and this does not appear to make much of a contribution to the separation performance.

Comparing Figure 6 and Figure 7, the separation performance of long-range mosaic ATCRBS and MSSR sensors is significantly degraded over short-range mosaic sensors. This is because in the mosaic mode the target updates are asynchronous and the slower rotation rates of the long-range sensors now make large error contributions compared to the single-sensor surveillance because the aircraft can move a significant distance between updates.

Figure 6 shows that the short-range mosaic MSSR performance is better than the single-sensor ATCRBS performance at ranges greater than about 32 miles. This is because at longer ranges the increased azimuth accuracy of MSSR begins to dominate over the errors in displayed separation introduced by mosaic display. At closer ranges, mosaic MSSR performance is not as good as single sensor ATCRBS but is still better than the currently acceptable performance of single sensor ATCRBS at 40 miles.
Conclusions

Based on the results of the analysis presented above and the currently acceptable separation performance of single sensor ATCRBS sensors at a range of 40 miles, the following conclusions are drawn:

MSSR sensors (both short-range and long-range) offer acceptable separation performance for three-mile separation out to a range of at least 100 miles for a single sensor.

MSSR short-range sensors in mosaic display mode offer acceptable separation performance when each aircraft is within 40 miles of its respective sensor.

ATCRBS short-range sensors in mosaic display mode offer acceptable separation performance when each aircraft is within 28 miles of its respective sensor.

Long-range ATCRBS and MSSR sensor update rates are not sufficient to support three-mile separation with mosaic display at any range.

In summary, a technique has been developed to derive surveillance requirements for three-mile separation in the extended terminal environment using existing standards and sensors as a baseline. The analysis reported here supports the significant expansion of the use of three-mile separation standards with existing MSSR sensors and data dissemination formats in both single sensor and mosaic environments. The choice of single sensor vs. mosaic for a particular facility will depend upon the desired airspace design. Further expansion may be possible using fusion trackers that reduce the mosaic asynchronous update errors, but additional analysis is required to estimate the potential benefits of this technique.

References


Key Words

Terminal Separation
Terminal Surveillance
Consolidated TRACON
Separation Standards
Radar Performance

Biographies

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