Surveillance Accuracy Requirements in Support of Separation Services

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■ The Federal Aviation Administration is modernizing the Air Traffic Control system to improve flight efficiency, to increase airspace capacity, to reduce flight delays, and to control operating costs as the demand for air travel continues to grow. Promising new surveillance technologies such as Automatic Dependent Surveillance Broadcast and multisensor track fusion offer the potential to augment the ground-based surveillance and controller-display systems by providing more timely and complete information about aircraft. The resulting improvement in surveillance accuracy may potentially allow the expanded use of the minimum safe-separation distance between aircraft. However, these new technologies cannot be introduced with today's radar-separation standards, because they assume surveillance will be provided only through radar technology. In this article, we review the background of aircraft surveillance and the establishment of radar separation standards. The required surveillance accuracy to safely support aircraft separation with National Airspace System technologies is then derived from currently widely used surveillance systems. We end with flight test validation of the derived results, which can be used to evaluate new technologies.

SURVEILLANCE OF AIRCRAFT in today's National Airspace System (NAS) has been provided for decades by a system of terminal and en route track-while-scan radars. The separation distance that an air traffic controller is required to maintain between aircraft depends in part on the performance of these radars, which provide surveillance by processing both the reflected energy from high-energy pulses transmitted toward the aircraft skin (primary radar) and the replies to the interrogation messages transmitted to aircraft transponders (secondary radar). Ground-based antennas radiate fan-beam patterns at fixed rotation rates and transmit pulse sequences. The aircraft transponder responses and reflected energy are processed to present to controllers an image that depicts the identity, location, altitude, and separation between nearby aircraft. Because of the fixed radiation pattern, the accuracy of these radar systems in measuring separation within a particular operating environment changes only with the range of the aircraft from the sensor and whether both aircraft are being monitored by the same radar. For this reason, the present-day separation standards are expressed in limited radar terminology—*single sensor*, *mosaic of sensors*, and *range from a sensor*.

Historically, new surveillance systems have been improvements to track-while-scan radar design. This is not the case for several new surveillance technologies. Consequently, we need a fundamental change in the method of approving these new systems, which include Automatic Dependent Surveillance Broadcast (ADS-B), multifunctional phased-array radar

(MPAR), and multi-sensor track fusion. Under ADS-B, aircraft automatically broadcast a state vector, at fixed one-second intervals, that includes the aircraft position, velocity, identity, intent, and emergency status. A key advantage of this approach is that surveillance can be achieved through low-cost, listen-only ground stations; and position accuracy becomes dependent upon the source avionics that typically include a Global Positioning System (GPS) receiver. The surveillance accuracy does not depend on the range of the aircraft from the ground stations or the number of stations used.

The MPAR concept combines the function of today's long-range and short-range aircraft surveillance and weather radar into a single system [1]. With this concept, electronically scanned antenna modules are implemented in an overlapping subarray architecture to illuminate aircraft with a single electronically steered transmit beam, with returns received through a cluster of narrow beams to maintain azimuth and elevation accuracy. However, this system would not employ fixed-rotation rates and pulse sequencing similar to today's track-while-scan systems. Consequently, surveillance accuracy would depend on range, waveform design, beam steering schedule, and other factors that cannot be conveyed by today's separation standards.

Multi-sensor track fusion systems process reports from multiple sources to form a single track. Surveillance accuracy depends upon the available sensors, fusion algorithms, and coverage reliability. Again, separation accuracy could not be conveyed in terms of range from a single radar.

Surveillance requirements depend on the types of separation service being supported, i.e., three-mile separation or five-mile separation.* Consequently, international standardization is increasingly based on Required Total System Performance (RTSP) specifications that are independent of the particular technologies of implementation. The term Required Surveillance Performance (RSP) is the subset of RTSP that is concerned with surveillance requirements [2, 3]. In theory, when a type of air traffic service is specified, it should be possible to derive the RSP without reference to the particular technologies used to achieve the requirements. This article is concerned with the required surveillance accuracy, a subset of RSP. Other RSP attributes include integrity, availability, continuity of service, and probability of detection.

Early Sensor and Separation Standards

Before the introduction of radar, procedural separation was used by air traffic controllers to maintain safe distances between aircraft whenever pilots could not maintain visual separation. In procedural separation, blocks of airspace are reserved for one airplane at a time. Position reports are provided by pilots to the controllers, who then provide separation by clearing only one aircraft at a time into a block of airspace. Procedural separation is still used in the NAS today in areas without radar coverage.

A history of the origins of the initial radar separation standards for civil air traffic control is given by the Federal Aviation Administration (FAA) agency historian E. Preston [4]. Preston notes that the establishment of the separation standards "was the result of an evolutionary process that included close coordination with airspace users…" and that the standard "represented a consensus of the aviation community." It is clear that no specific analytical approach was used to derive the separation standards and there are, according to Preston, different accounts of how the specific standards were chosen. The separation standard for terminal procedures was set at three miles and for en route at five miles. Preston concluded that the basis for setting the standards "seems to have included such factors as: military precedent; reasoned calculations; a desire to choose a figure acceptable to pilots; and the limitations of both the radar equipment and of the human elements of the system. The use of five miles as the separation for flights over forty miles from the radar site was based on the greater limitations of the long-range equipment."

With the introduction of radar, separation standards were established on the basis of the performance of those early radar sensors. The first air traffic control radars used the primary broadband video return displayed on a cathode-ray screen, or scope, to separate aircraft. Because errors in azimuth measurement resulted in increased position errors as the range of the

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* All distances described in this article are nautical miles. All aircraft speeds are given in knots.

aircraft increased from the radar, separation standards were introduced that are functions of how far the aircraft are from the radar. There was no specific analysis done to justify the original separation requirements; however, in operational use, the standards proved safe and effective in the airspace of that day. As radar equipment accuracy and range improved, it was necessary to refine the standards; nevertheless, they have remained relatively constant over the last several decades.

The introduction of secondary (beacon) radar offered a significant improvement in the performance of radar sensors by utilizing the reply from an aircraft's transponder to measure position. The use of a transponder provides a higher power return and allows the aircraft to supply the system with data such as aircraft identification and altitude. Today's radars are a surveillance system comprising primary radar, secondary radar, and software for combining reports and for identifying individual aircraft paths or tracks. A target report that merges both a primary and secondary measurement is called a reinforced report.

Older surveillance systems use secondary radar systems known as sliding-window Air Traffic Control Radar Beacon System (ATCRBS) sensors, such as Beacon Interrogators BI-4 and BI-5. These sensors utilize replies from the aircraft's transponder across the entire beamwidth to make an azimuth estimate of the aircraft's position. The beamwidth is controlled by using sidelobe suppression. Newer Monopulse Secondary Surveillance Radar (MSSR) systems (e.g., Beacon Interrogator 6, Mode S) make an azimuth measurement for every transponder reply and are replacing the older sliding-window sensors in both the terminal and en route domains.

Display Methodology

The software function that accepts combined data from the primary and secondary sensors and determines which reports are assigned to a track for a given aircraft on a specific display is referred to as display system processing (DSP) in this article. The NAS uses a number of DSP packages, each with different characteristics. Regardless of the system in use, the position measurement displayed to the controller is, for the vast majority of the reports, the position estimate from the secondary (beacon) radar for facilities equipped with monopulse beacon systems, even though both beacon and primary measurements are taken. However, when the primary radar is collocated with a sliding-window secondary surveillance system, the position information for a reinforced report is the position estimate made by the primary radar.

Error Analysis

S.D. Thompson and S.R. Bussolari reviewed the error characteristics of long-range and short-range sliding-window ATCRBS and MSSR surveillance sensors [5]. Errors in the measured separation distance between targets were analyzed for both single-sensor cases in which the aircraft being separated were tracked by different radars. Monte Carlo simulations were run to compute the errors in measured separation as a function of range from the sensor. The DSP was explicitly excluded from the analysis so that the sensor errors could be directly compared and because the separation standards in use are independent of the DSP used.

An extension of this analysis technique is employed to derive the Required Surveillance Performance accuracy on the basis of the existing acceptable performance of legacy systems comprising both primary and secondary radars. In addition to sensor errors, errors in representative DSP are considered so that the Required Surveillance Performance accuracy requirements represent the total allowable error between the true separation of aircraft and the separation displayed to a controller on the scope.

Radar Separation Standards

The original standards were set at a time when only primary radar was available and the traffic was considerably slower and less dense than in today's airspace. The airspace structure and surveillance equipment are much different today, and so it has been deemed inappropriate to derive requirements based on what existed when the separation standards were originally instituted.

Current Standards

Radar separation standards are conveyed in FAA Order 7110.65N [6]. The order allows three-mile separation between aircraft as long as both aircraft are tracked by the same sensor antenna that is less than forty miles from the aircraft. Otherwise, the traffic must be separated by five miles. The order makes no distinction in separation requirements based on the performance of the radar, and applies equally to long-range and short-range radars.

In airspace covered by multiple radars, a mosaic display is often used. A separation of three miles is not permitted with a mosaic display; five-mile separation is required. In a mosaic display, the airspace is divided into geographical areas called radar sort boxes. Each sort box is assigned a preferred sensor and supplemental and tertiary sensors. As long as the preferred sensor of a specific sort box is measuring the aircraft position, the position reported by that sensor is displayed to the controller. Typically, contiguous sort boxes are assigned to the same preferred sensor and there are boundaries between geographical areas being covered by a preferred sensor. In general, these boundaries do not correspond to ATC sector boundaries. In a mosaic environment, it is possible for two aircraft being separated to have their position estimates provided by different radars.

In addition, a controller will not necessarily know when a track is lost by a preferred sensor and the position report is being provided by a supplemental sensor. Thus three-mile separation is not currently allowed in a mosaic environment. If there is a significant operational advantage to be obtained by modifying a radar site adaptation so that a particular control area can be served only by a single radar, then the separation can be reduced to three miles in en route airspace when both aircraft are within forty miles of that sensor and operating below Flight Level 180 (18,000 feet pressure altitude).

Role of Surveillance in Separation Standards

Although surveillance is an important factor in establishing separation standards, it is not the only factor, as illustrated in Figure 1. Consequently, any safety analysis comparing the separation measurement accuracy of different surveillance systems must constrain the other factors affecting separation. For example, an analysis of a theoretically perfect surveillance system that models only surveillance accuracy against a target level of

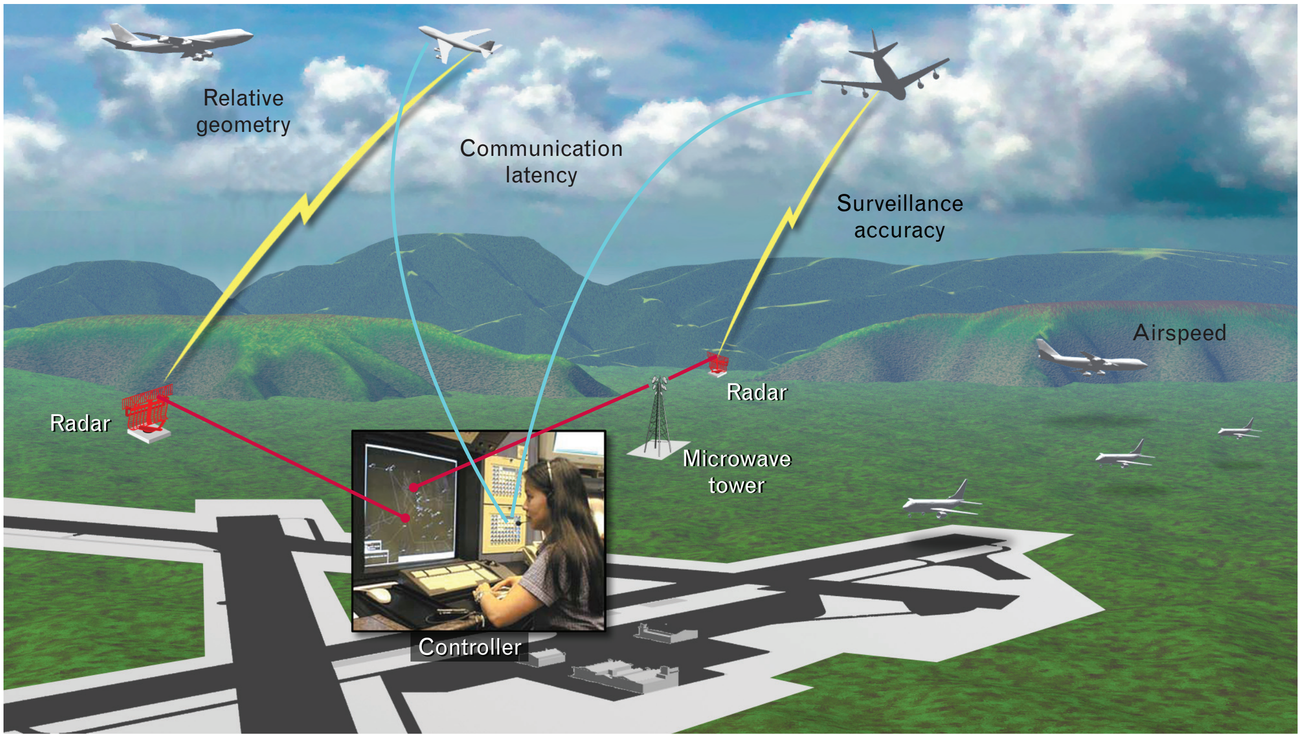


FIGURE 1. Role of surveillance in separation standards. Surveillance provided by radar and aircraft transponders are only one component of the separation process. Aircraft geometries, airspeed, and communications command and control latency also contribute significantly.

safety would indicate that existing separation standards could be reduced substantially. But this indication would not be supported by other elements that contribute to how far aircraft can move toward each other and be safely separated. The factors illustrated in Figure 1 include time (command and control latency) and relative velocity (airspeed and relative geometry).

The command and control loop between the controllers and the aircraft also affects separation specifications. Air traffic controllers provide the required separation by issuing clearances, including routings, vectors (headings), and altitude assignments, accomplished through a very high frequency (VHF) voice channel, with a common channel being assigned to a given airspace. Communications between the controller and pilots is subject to interference when more than one person attempts to speak at the same time. There is also opportunity for misunderstanding because of less than perfect reception or because of human error.

Airspeed is an obvious element affecting separation standards. Aircraft in the terminal area where three-mile separation is maintained are normally limited to 250 knots indicated airspeed, while aircraft in the en route environment may have ground speeds over 600 knots.

The relative geometry of the aircraft depends on the air traffic operations such as the traffic-flow patterns. For instance, it is clearly easier for a controller to provide separation to an incoming stream of arriving traffic in trail at the same airspeed, but more difficult to provide separation to crossing traffic or traffic that is climbing or descending relative to other traffic. Our approach is to determine the Required Surveillance Performance accuracy for the separation standards in the existing environment in which all of the other contributions remain constant.

Required Surveillance Accuracy and Error Analysis

The FAA has a goal expressed in its Operational Evolution Plan [7] and FAA Flight Plan [8] to increase capacity and reduce constraints in the NAS. One area that would provide benefits is increasing the airspace in which three-mile separation is allowed. Partly on the basis of a Lincoln Laboratory analysis of the performance of newer monopulse secondary systems [4], the FAA has recently issued approval to extend the range from a single-site sensor for which three-mile separation is allowed from forty miles to sixty miles for Airport Surveillance Radar 9 (ASR-9) with monopulse sensors. This extension was implemented by a change to FAA Order 7110.65. An extension past sixty miles would have required a software change, since current FAA terminal systems do not report targets beyond sixty miles.

A natural extension to this approach is to define the Required Surveillance Performance accuracy requirements for which any technology can be used to provide the currently approved three-mile and five-mile separation. This Required Surveillance Performance is based on existing legacy systems for which three-mile and five-mile separation is provided but will allow surveillance systems based on new technologies other than radar to prove that they can provide acceptable service. This relaxation of requirements offers the potential of further increasing the airspace in which three-mile separation and, in some specific cases, five-mile separation are approved by using alternative surveillance techniques such as ADS-B in airspace where radar coverage is unavailable.

In addition, an unambiguous standard, independent of a given technology, will facilitate potentially new surveillance applications such as multisensor track fusion. As new technologies are introduced and improvements to existing technologies are made, a Required Surveillance Performance based on service performance and not on a given sensor type could become a consistent standard by which innovative technologies and techniques can be compared and approved for use in the NAS. The separation standards need not be updated with each additional sensor improvement.

A recent precedent to this approach was taken in the field of navigation. The navigation performance requirements historically have been based on fielded equipment such as the VHF Omnidirectional Range (VOR) for en route navigation and the Instrument Landing System (ILS) for precision landing guidance. Now, the Required Navigation Performance sets requirements for services and allows any new technology to provide that service if it meets the requirements, which has permitted new navigation technologies such as GPS to be used in the NAS.

Required Surveillance Performance Accuracy Metric

The Required Surveillance Performance accuracy metric refers to the standard of measurement performance that must be met to support the separation services provided by air traffic control. One obvious surveillance accuracy metric is the accuracy of the sensor in making target position measurements. There are two problems with using position accuracy as the primary metric for Required Surveillance Performance. One is that air traffic control provides a separation service rather than a positioning service. The other is that errors in measured separation depend on whether the same or independent sensors are providing the position estimates. The use of independent sensors with the same position-measurement errors will result in relatively larger errors in measured separation. If the Required Surveillance Performance is based solely on position-measurement accuracy and set to allow the use of independent sensors, then currently acceptable single-sensor performance will not meet the standard.

The approach taken in this analysis is to quantify the Required Surveillance Performance both in terms of limits on errors in measuring target separation displayed to the controller and on geographical position accuracy. This approach allows a direct comparison between single-sensor surveillance and cases involving independent sensors or surveillance systems.

The Required Surveillance Performance accuracy derived in this analysis uses errors in displayed separation as the primary accuracy metric and expresses the requirement as limits on the probability distribution of the errors. Because controllers provide radar vectors to fixes and airports and are responsible for obstacle avoidance, the Required Surveillance Performance also includes a geographical accuracy requirement.

Reporting and Error Characteristics of Surveillance Systems That Include Primary Radar

At most terminal and en route facilities a primary radar is collocated with the beacon sensor. Both sensors independently make position estimates of targets. When the software determines that those position estimates are for the same aircraft, the target reports are declared a merged target and the position report is characterized as reinforced. In the event a target is not reinforced it may be beacon only, meaning the primary did not report a target in a near enough position to reinforce the beacon report, or it may be characterized as search only, meaning the primary reported target was not reinforced with a beacon report. The position estimate is reported as range (ρ) and angle (θ) from the sensor location. Beacon-only and search-only reports contain the ρ-θ measurement from the respective sensor. For merged targets the position estimate of only one of the sensors is reported.

Modern primary radars employ narrowband Doppler filtering and distributed processing to improve target detection and position accuracy and to lower false-alarm rates. In good weather and in the absence of clutter, the performance of modern radars in measuring aircraft position is better than that of a sliding-window beacon sensor, but not as good as a monopulse beacon sensor.

In the presence of weather, ground, and airborne clutter (e.g., birds), the performance of a primary radar will degrade; in the worst cases it will not be able to reinforce a target that is being declared by the collocated beacon sensor. For that reason, the sliding-window beacon performance is considered the baseline for acceptable performance.

Error Characteristics of Secondary Radar Sensors

Secondary radar error characteristics include errors in estimating range and azimuth to the target. Range errors are due primarily to errors in measuring the interval between the instant an interrogation is sent from the radar and the time a reply is received from the aircraft's transponder, including errors in the accuracy with which the sensor can measure the time interval and variations in the allowed turnaround time of the transponder. Range errors due to timing are relatively small (typically less than two hundred feet) and do not increase with range. Refraction effects are significant only at very long range and are excluded in this analysis. For the same reason, propagation anomalies such as atmospheric ducting are also not included in this analysis.

Azimuth Characteristics of Secondary Radar Sensors

Azimuth-measurement errors are primarily due to errors in estimating the target position within the beam-

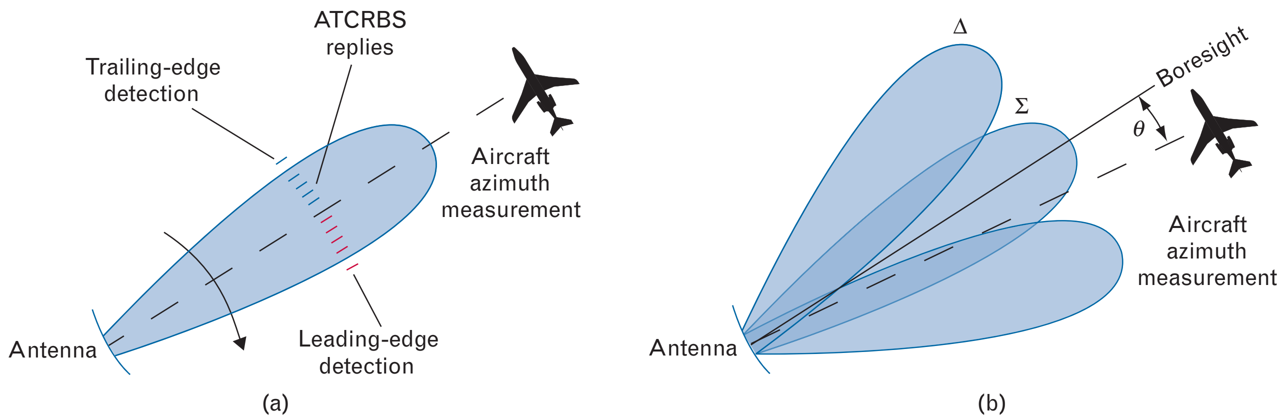


FIGURE 2. Azimuth estimation with secondary radar; (a) the sliding-window beacon interrogator and the Air Traffic Control Radar Beacon System (ATCRBS) replies; (b) the Monopulse Secondary Surveillance Radar (MSSR). The control pattern used for sidelobe suppression is omitted for clarity. Σ and Δ indicate the center lobe and side lobe of the MSSR, respectively. θ, the azimuthal angle deviation from the center, is calculated from the relative intensities of the center lobe and side lobe signals. These figures are reproduced from V.A. Orlando's article in the *Lincoln Laboratory Journal* [9].

width of the transmitted pulse. These errors depend on the technique used to estimate the target's position within the beamwidth. The older sliding-window ATCRBS and newer MSSR surveillance sensors use different techniques to make azimuth measurements.

Figure 2(a) shows the sliding-window technique, which 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 reply train. FAA Beacon Interrogator BI-4 and BI-5 sensors use the sliding-window technique. This technique is susceptible to azimuth inaccuracies or even target splits resulting from missing beacon replies. Interference from other interrogators or transponders can garble signals and cause missing replies. The performance also depends on whether the aircraft has a single transponder antenna on the bottom of the aircraft or two antennas, one on the top and one on the bottom of the aircraft. An aircraft with a single bottom-mounted antenna may miss interrogations or have its reply blocked during a turn when the bottom of the aircraft is pointed away from the sensor.

Newer MSSR sensors use multiple beam patterns for interrogations that allow an azimuth measurement from a single transponder reply, as shown in Figure 2(b). FAA Mode S and BI-6 sensors use this monopulse technique to attain a three-fold improvement in measuring azimuth. A detailed description of these two azimuth estimation techniques is given by V.A. Orlando [9]. M.C. Stevens's textbook provides an excellent description of secondary surveillance systems [10].

Errors in Measured Separation from Independent Surveillance Systems

The error in measured separation between two aircraft depends on whether the position of the two targets is reported by the same or independent surveillance sensors. Two factors add to the errors in the measured separation error displayed to a controller when independent sensors are reporting the aircraft positions; uncorrelated position-measurement errors and differences in track update.

Surveillance systems will generally have bias errors associated with their position estimates. When the same sensor is used to measure the position of both targets, bias errors in position estimates associated with that sensor are not reflected in the separation measurement.

When a controller is separating two aircraft by using the estimated positions on a display, the targets are updated at different times. This time differential 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 independent sensor systems, the target updates are asynchronous and the time difference between target updates is generally larger, depending on the update rates of the independent sensors. The asynchronous nature of independent sensor systems can result in increased errors in displayed separation.

Monte Carlo Analysis of Sensor Errors

We modeled sensor errors and performed a Monte Carlo analysis by using the methods described in Thompson and Bussolari [5]. Tables 1 and 2 list the radar source errors that are used in the analysis. The error values listed in the tables are based on radar specifications and field data from ARCON Corporation for radars in the Southern California Terminal Radar Approach Control (TRACON) [11], and from Lincoln Laboratory for radars in the Northeast [12]. 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. 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.

Table 3 summarizes the cases analyzed and compares the Required Surveillance Performance and the current technology model. The Required Surveillance Performance system modeled for three-mile separation was the short-range ATCRBS sliding-window sensor collocated with a primary radar. The primary-radar position reports are normally used in providing three-mile separation to aircraft, but the beacon-sensor reports are used and are acceptable when primary

Table 1. Sensor Error Sources Used in Monte Carlo Simulations for Beacon Sensors

		MSSR[1]		*ATCRBS sliding window*	
		Short range	*Long range*	*Short range*	*Long range*
Registration errors	Location bias	200 ft (0.033 mi) uniform in any direction $\sigma = 115$ ft (0.019 mi)			
	Azimuth bias	± 0.3° uniform $\sigma = 0.173°$			
Range errors	Radar bias	± 30 ft (0.005 mi) uniform $\sigma = 17$ ft (0.003 mi)			
	Radar jitter	25 ft RMS $\sigma = 25$ ft (0.004 mi)			
Azimuth errors	Azimuth jitter	$\sigma = 0.068°$ (0.8 ACP[2])		$\sigma = 0.230°$ (2.6 ACP[2])	
Data dissemination quantization Common Digitizer 2 format	Range	1/64 mi $\sigma = 27$ ft (0.005 mi)	1/16 mi $\sigma = 110$ ft (0.018 mi)	1/64 mi $\sigma = 27$ ft (0.005 mi)	1/16 mi $\sigma = 110$ ft (0.018 mi)
	Azimuth	360° (4096 pulses) $\sigma = 0.025°$	360° (4096 pulses) $\sigma = 0.025°$	360° (4096 pulses) $\sigma = 0.025°$	360° (4096 pulses) $\sigma = 0.025°$
Scan-time uncorrelated errors[3]		4–5 sec $\sigma = 219$ ft (0.036 mi)	10–12 sec $\sigma = 536$ ft (0.088 mi)	4–5 sec $\sigma = 219$ ft (0.036 mi)	10–12 sec $\sigma = 536$ ft (0.088 mi)

[1] MSSR (Monopulse Secondary Surveillance Radar) can process both Mode Select Beacon Systems (Mode-S) and Air Traffic Control Radar Beacon System (ATCRBS) transponders in a monopulse fashion.
[2] The Azimuth Change Pulse (ACP) is 1/4096 of a scan.
[3] A three-mile separation between aircraft is assumed in this trial at 200 kts.

Table 2. Transponder Error Sources Used in Monte Carlo Simulations for Beacon Sensors

	Mode S	*ATCRBS*
Range errors	± 125 ft (0.021 mi) uniform σ = 72 ft (0.012 mi)	± 250 ft (0.041 mi) uniform σ = 144 ft (0.024 mi)

performance degrades with interference or clutter. Thus it is the performance of the short-range sliding-window beacon sensor that is used to establish the unconditionally acceptable performance. The aircraft are assumed to travel at 250 knots (the speed limit in the terminal area) up to a range of forty miles from the sensor. It was assumed that there was no DSP and that the reports went directly from the sensor to the controller's display. The representative case for new systems is the MSSR system, approved for use to a range of sixty miles.

The Required Surveillance Performance model in widespread use for five-mile separation was chosen to be the long-range ATCRBS sliding-window beacon

Table 3. Summary of Cases Analyzed for Three-Mile and Five-Mile Separation Required Surveillance Performance Accuracy

	Required surveillance performance	*Current technology representative model*
	Three-mile separation	
Radar type	Short-range primary collocated with sliding window	Short-range MSSR
Range (nautical miles)	40	60
Display system processing	None	None
Aircraft speed and geometry	250 kts 3 mi in trail	250 kts 3 mi in trail
Sensor configuration	Single site	Single site
	Five-mile separation	
Radar type	Long-range sliding window	Long-range MSSR
Range (nautical miles)	200	200
Display system processing	HOST[1] processing	HOST[1] processing
Aircraft speed and geometry	600 kts 5 mi in trail	600 kts 5 mi in trail
Sensor configuration	Single site	Single site

[1] HOST is the NAS automation host computer.

sensor at a range of 200 miles, separating aircraft with a ground speed of 600 knots. These systems are normally operated in a mosaic environment. At the sort-box boundaries between radar coverage areas there is normally stitching and hopping of targets as they cross from a sort box that has one radar assigned as primary sensor to another sort box that has a different assigned radar. For the purposes of this analysis, it is assumed that it is conditionally acceptable for five-mile separation to use two different radars tracking the aircraft only as they cross sort-box boundary lines. This level of performance was not considered acceptable across all en route airspace. An MSSR long-range system is assumed for the new technology case.

Three-Mile Separation. The procedure followed for the three-mile separation cases was to determine the distribution of errors in measured separation observed, on average, for two aircraft that were three miles apart in trail, as illustrated in Figure 3. Aircraft speed was chosen to be 250 knots (speed limit in the terminal area), as listed in Table 3. The aircraft were randomly oriented relative to the radar by randomly choosing an angle ϕ, as illustrated in Figure 3, for each trial. The Monte Carlo simulations using the beacon error characteristics described in Table 2 were run for each of the cases listed in Table 3. Both the sliding-window beacon sensor and the collocated primary radar are listed for the Required Surveillance Performance case in Table 3 although, as described above, the sliding-window beacon performance is considered the baseline acceptable performance.

Five-Mile Separation. The procedure followed for the five-mile en route case was to model two aircraft five miles in trail traveling at a 600 knot ground speed and tracked by sensors, as described in Table 3 and shown in Figure 4. The Required Surveillance Performance case was modeled as a single long-range sliding-window sensor. The new technology case was modeled as a long-range MSSR sensor. The midpoint of the separation of the aircraft was kept at a constant range of two hundred miles, as described in Table 2.

Simulation Trials Results

The results of the one million trials for the Required Surveillance Performance case listed in Table 3 for three-mile separation are presented in Figure 5, which illustrates the errors in measured separation as a function of range. The highlighted distance slice is at forty miles, which corresponds to the results shown in Figure 6(a)—the distribution of sensor measured separations for aircraft that are actually three miles apart. The jaggedness in the distributions is due to the dis-

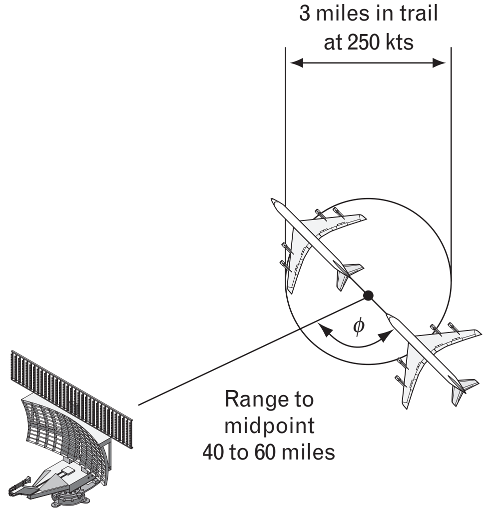


FIGURE 3. Relative geometry for three-mile separation cases with a single beacon sensor tracking both aircraft. Updates are at five-second intervals. Here, ϕ is the orientation of the aircraft in trail relative to the radar beacon.

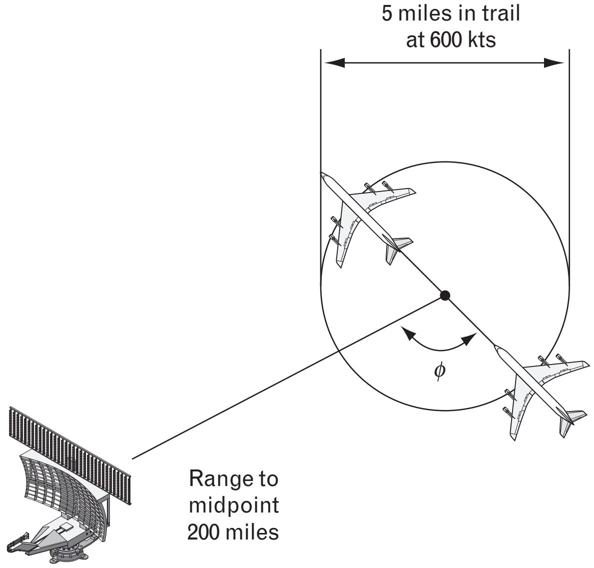


FIGURE 4. Relative geometry for five-mile separation cases with the aircraft tracking by a single beacon sensor or two independent beacon sensors tracking the aircraft. Updates are at twelve-second intervals. Here, ϕ is the orientation of the aircraft in trail relative to the radar beacon.

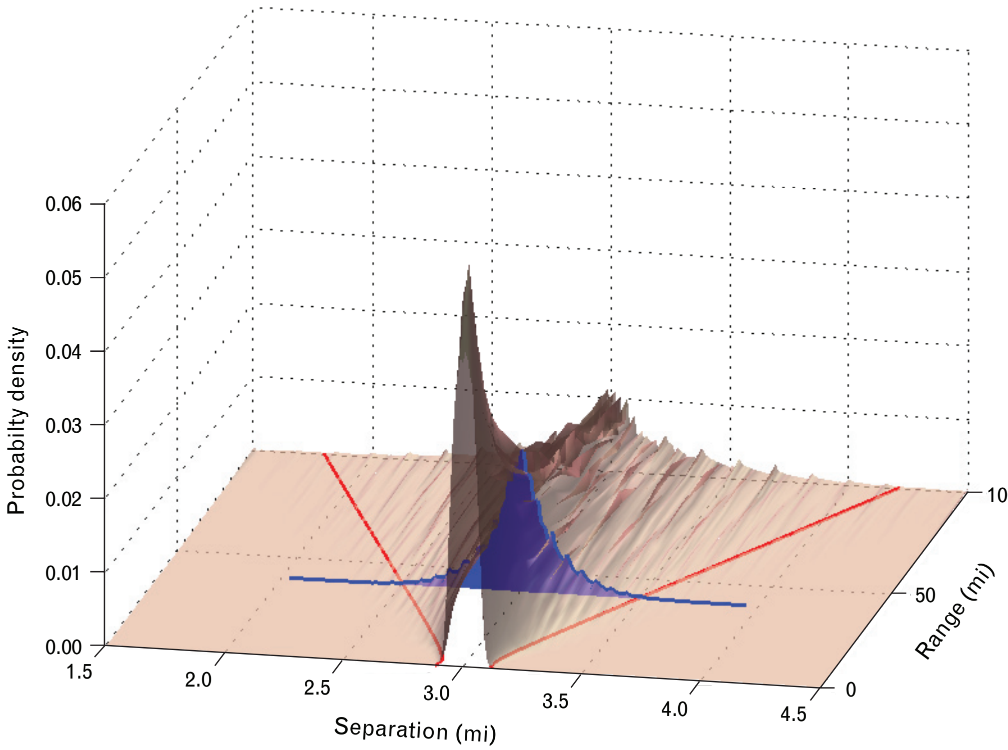


FIGURE 5. Probability density of measured separation as a function of range for an ATCRBS sliding-window short-range sensor and two aircraft separated by three miles. The blue slice shows the measured separation of two aircraft at 40 mi distance.

crete allowed position reports of the Common Digitizer 2 (CD2) format and the even distribution of the bin sizes in the histogram.

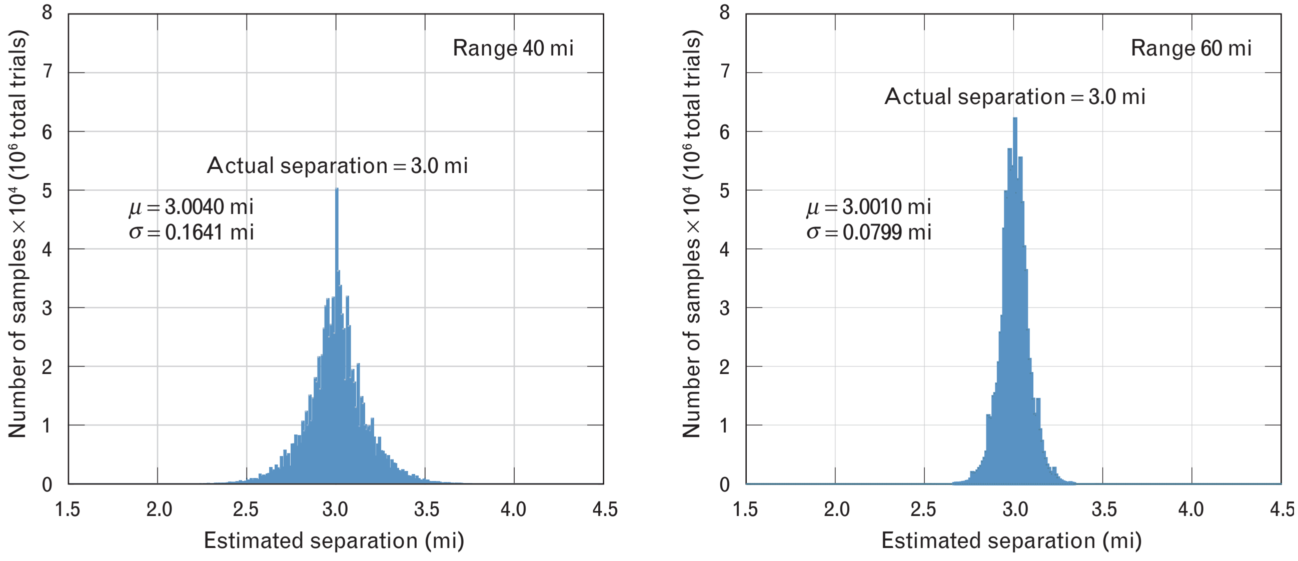
There are a finite number of allowed separations and, regardless of the size of the bins, the allowed reports will fall into one bin or another. If the number of trials is doubled, the graphs will look identical. If the histogram bin size is changed, then a different raggedness pattern will appear. The corresponding results of the one million trials for the tests represented in Table 3 for three-mile and five-mile separation are presented in Figures 6 and 7. Note that these are sensor error distributions and do not yet include the DSP errors that apply to the five-mile separation cases, as listed in Table 3.

Display System Processing Errors

DSP errors are included in the Required Surveillance Performance accuracy for the five-mile separation cases listed in Table 3. The three-mile separation cases representative of terminal operations were assumed direct to glass—presented to the operator's screen without any analysis. This is a conservative assumption, since many terminals use one of several available DSP systems.

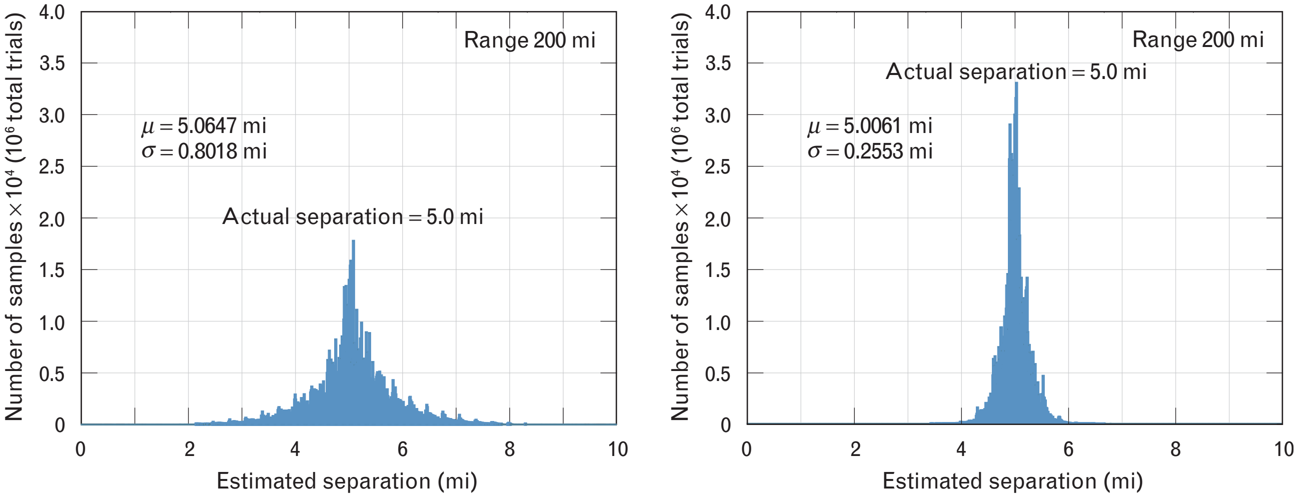
DSP errors are introduced by the system between the sensor reports and the separation displayed to the controller on the screen. The differences between separation as measured by sensor reports and separation displayed to the controller may result from display latencies, coordinate transformation, asynchronous updates, and missed updates or tracking errors. The DSP errors depend on the system design and automation software, as well as whether the aircraft are being tracked by the same radar or different radars. The NAS automation host computer (HOST) system in the Air Route Traffic Control Centers (ARTCC) was chosen as representative because it is in widespread use and because it is commonly used at ARTCCs and is acceptable for five-mile separation.

DSP errors were measured from data rather than modeled. This measurement was accomplished by



(a) (b)

FIGURE 6. Results of Monte Carlo simulation in measured separation error for three-mile separation (aircraft velocities 250 knots): (a) single ATCRBS sliding window long-range radar; and (b) single MSSR short-range radar. Here, μ is the mean value of the data and σ is the standard deviation.



(a) (b)

FIGURE 7. Results of Monte Carlo simulation in measured separation error for 5-mile separation (aircraft velocities 600 knots): (a) single ATCRBS sliding window long-range radar; and (b) single MSSR long-range radar. Here, μ is the mean value of the data and σ is the standard deviation.

comparing the separation of targets on the basis of sensor reports received at the Boston ARTCC to the separation of the same targets on the controller's display. The data reported by the sensors are recorded as U.S. Air Force's Radar Evaluation Squadron (RADES) format data as it enters the facility. The position reports are recorded in latitude and longitude and are based on the ρ-θ reports of the individual sensors. All reports of sensors tracking targets are recorded; consequently, there are multiple reports for each aircraft being tracked.

The separation displayed to the controller is computed from the position reports, as recorded on the system analysis report (SAR) tapes. The position reports include the beacon code, the time, and the Cartesian *x-y* position on the stereographic plane. Each ARTCC displays target positions on a stereographic plane with a point of origin ($x = 0$, $y = 0$) and point of tangency (where it touches the earth) defined for that facility's airspace. All target position reports received from field sensors are projected onto that common plane. The position report from only one sensor is provided to the controller's display for a given target, and that is the position report recorded in a file on the SAR tape. The SAR data, in a separate file, records which sensor is being utilized for reports for a given target as a function of time. Thus it is possible to determine which sensor's target data were presented to the controller and the *x-y* position on the stereographic plane that was used to present the target position. The time between the SAR recording and the display is assumed negligible.

To compare the separation reported by the sensors to that displayed to the controllers, recorded RADES data and SAR data tapes for a period of 1045–1415 universal time coordinated (UTC) on 6 October 2005 were obtained from the Boston ARTCC. The RADES data files were sent to Lincoln Laboratory and the copied SAR data tapes were sent to the FAA's William J. Hughes Technical Center (WJHTC) in Atlantic City, New Jersey.

The RADES data files were examined at Lincoln Laboratory and fifty aircraft pairs were manually selected, with criterion that the aircraft pair were in close horizontal proximity over an extended period of time (tens of minutes) and were at the same or nearly the same altitudes. The fifty cases were identified to WJHTC by providing the two beacon codes, the start and stop times, and the approximate latitude and longitude. On the basis of case descriptions, WJHTC then processed the SAR tapes and provided Lincoln Laboratory with the SAR data of the beacon codes of interest, which included two files for each case. One file contained the sensor used as a function of time for each of the two beacon codes and the other contained the time, beacon code, *x-y* position on the stereographic plane, and Mode C* reported altitude for each report.

The RADES data files, which contain data for all radars, were filtered to create files that matched the sensors identified by the SAR data as those used for display on the controller's screen. The separation as a function of time between the targets in the RADES data was computed by converting the RADES-formatted latitude and longitude reports to the earth-centered earth-fixed (ECEF) reference grid and computing the separation at each update report. This separation was computed each time a beacon target produced a new position report. The separation of the beacon targets as reported in the SAR data was computed directly from the *x-y* position reports representing position on the stereographic plane, and was also updated with each beacon report.

The computed separation between the two beacon targets as a function of time as recorded by the sensors (RADES data) and as presented to the controller (SAR data) was compared. Figure 8 shows an example of a plot comparing the RADES and SAR data. The difference between the two reported separations as a function of time was measured for each update to provide a histogram of the differences in separation for each case. This measurement represents a probability distribution of the errors introduced by the DSP between what was reported by the sensors and what was displayed to the controllers for a single case of two aircraft being separated for a period of time.

Of the fifty cases chosen, only thirty-nine were able

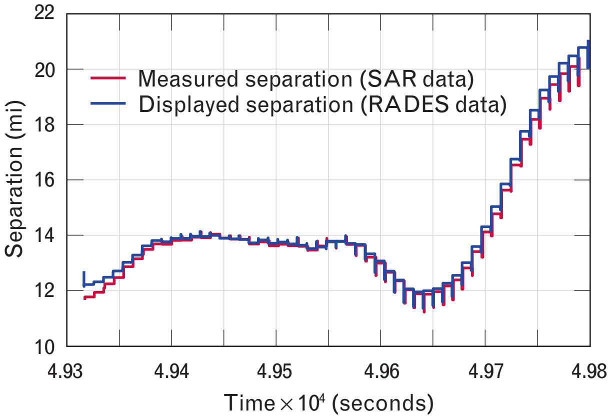


FIGURE 8. Comparison of measured separation (in miles) versus time for the Radar Evaluation Squadron (RADES) data and the system analysis report (SAR) data for a sample case. The differences evident in the figure represent the errors introduced by the Display System Processing (DSP).

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* Mode C is the transponder reply mode that includes altitude and coding.

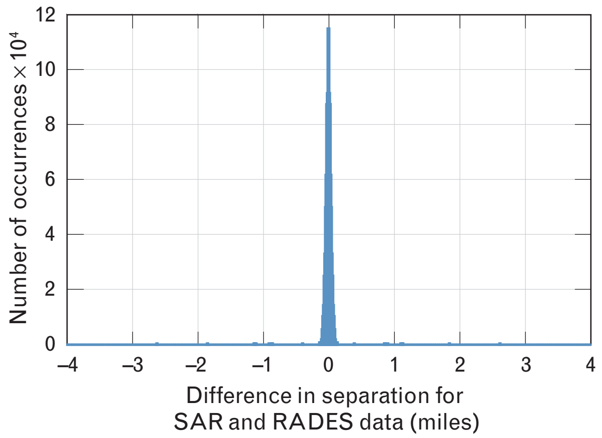


FIGURE 9. Histogram of NAS automation host computer (HOST) DSP errors for a single sensor measured from thirty-nine sample cases of aircraft pairs recorded at Boston Air Route Traffic Control Centers (ARTCC) on 6 October 2004.

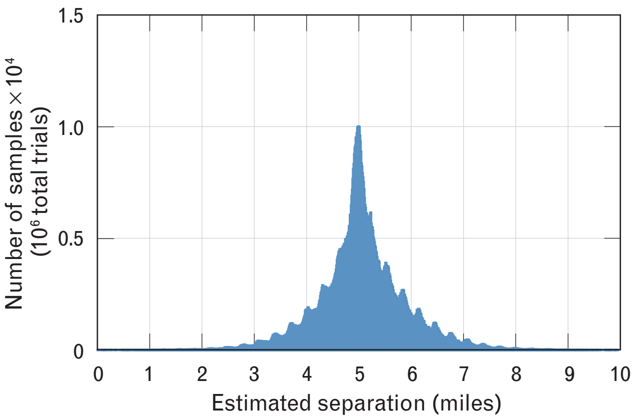


FIGURE 10. Total system error for long-range sliding-window sensor at two-hundred-mile range with single-sensor HOST system display processing.

to be reduced from the SAR data, in part due to multiple aircraft with the same beacon code in the SAR data and in part due to unavailable SAR tapes for the total time of interest. These thirty-nine cases were added together and normalized to take out any bias introduced by the particular selection of cases. The final results are the distributions of HOST DSP errors presented in Figure 9.

Total System Error

Figure 10 presents the results of numerical convolution of the DSP error with the sliding-window long-range radar error. This analysis was accomplished by adding a randomly sampled sensor error from the sensor error distribution, shown in Figure 7(a), to a randomly sampled DSP error from the DSP error distribution, shown in Figure 9. One million random samples were taken from each distribution and added together to create the data shown in Figure 10. This result represents the total system error for the five-mile separation Required Surveillance Performance case.

Flight Test Validation

The purpose of the flight test was to validate the modeled error sources of the sensors used in the analysis by comparing true separation, as provided by position recordings from GPS on board two aircraft, with sensor measured separation, as recorded from sensors at Boston ARTCC. This test was accomplished by flying two aircraft approximately three miles apart in trail over a large portion of Boston Center airspace. The flight path was designed to provide data from approximately ten sensors, including long-range and short-range sliding-window and MSSR beacon sensors. The use of two aircraft allowed a comparison of measured separation with true separation rather than measuring the accuracy of the position report of the aircraft. Measured separation error is the primary metric used in the analysis.

Data Recording

The flight test validation made use of Lincoln Laboratory's Falcon 20 and Gulfstream G2 jet aircraft. The Falcon 20 is shown in Figure 11, and the G2 is shown in Figure 12. Each of the test aircraft carried a GPS/laptop recording system and operator, and was equipped with a GPS antenna.

The airborne data recording portion of the flight test validation recorded WGS-84 ECEF reference position data from two GPS receivers, one in each aircraft. An Ashtech Model GG24 GPS plus GLONASS sensor was used in both aircraft. The GG surveyor provides position accuracy on the order of seven to twenty meters, and updates positions once per second [13]. This position information was sent to a laptop via a serial port connection. GPSLog, a custom-written program, wrote the updated reports to a file on disk. GPSLog utilizes a 9600 baud 8N1 serial com-

FIGURE 11. Falcon 20 lead aircraft in flight test.

FIGURE 12. Gulfstream G2 trailing aircraft in flight test.

munication format to communicate with the GG surveyor. The software uses a one-second timer to poll the GPS for its current position, allowing for a more robust connection. If the GPS fails to reply to a poll in a timely fashion, the operator is notified and can begin troubleshooting. Additionally, the GG surveyor has the capability of recording position updates to internal memory for later offline retrieval, providing a backup of the data recording.

After completion of the flight test validation, the recorded GPS data were post-processed to obtain time-stamped ECEF position reports in a form that could be read into MATLAB. All analysis was done in MATLAB. GPS time does not incorporate the leap-seconds used in UTC time, and the current offset between GPS and UTC time is thirteen seconds. This difference was subtracted and the data analyzed was in UTC time.

The ground data recording portion of the flight test validation consisted of two separate systems. The sensor data consisted of a recording of all the CD2 format messages from the fourteen radars in the USAF RADES format. Nine different sensors actually tracked the two test aircraft for significant time during the flight. The data view screen lists a row for each report of each sensor color coded by message type; red for beacon only, green for search (primary only), and blue for reinforced. The data can also be filtered by sensor(s) and beacon codes.

The RADES software was used to extract, time, ρ, θ, latitude, longitude, and altitude for both test aircraft from all sensors that tracked the two test aircraft. These data files were converted to a format that could be read into MATLAB.

The data displayed to the controller was recorded on SAR tapes. These tapes are produced by software running on the HOST computer, and they record all of the display updates sent to the Display System Replacement screen. These tapes were sent to WJHTC in Atlantic City, New Jersey, for post-processing. The product of this processing was a file containing time, aircraft ID, radar ID, *x-y* position on the stereographic plane, and altitude for the test aircraft. The SAR data contain only the data from the sensor that was used to display the target on the controller's screen. This file was then read into MATLAB for further processing and comparison of the displayed separation to the measured separation as well as the GPS truth data. Figure 13 illustrates the relationship between the various airborne and ground data recordings. An excellent treatment of the various coordinate systems and how to transfer between them is contained in P. Misra and P. Enge [14].

Flight Test Results

Radar reports from the sensors were recorded as they were received at Boston Center (RADES) and as presented to the controllers' display (SAR). The RADES data files were filtered for the two beacon codes of the flight test aircraft. Figure 14(a) is a plot of the radar data showing all reports for both test aircraft by all radars. The aircraft were tracked by nine different sensors in Boston Center's airspace during the flight test.

The GPS position data recorded on board the flight

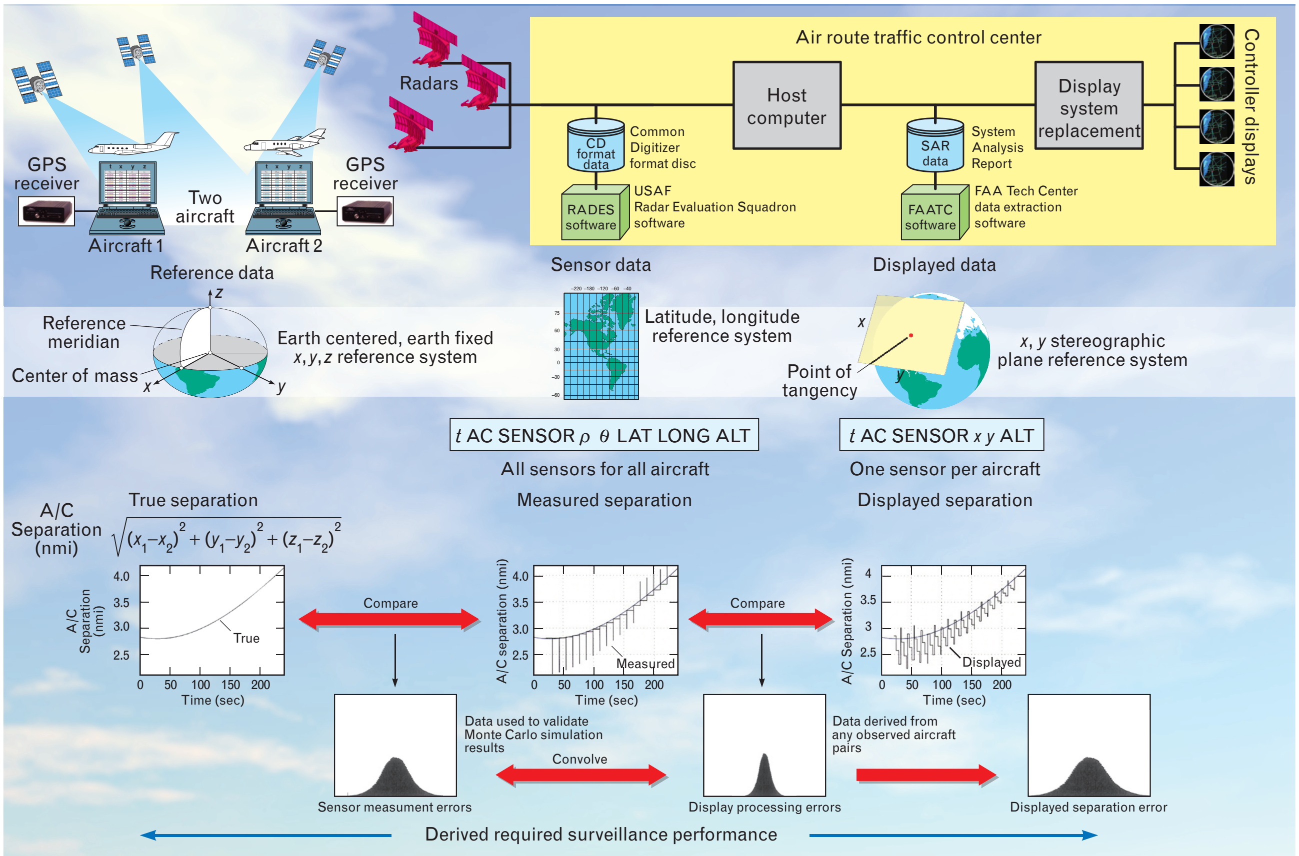
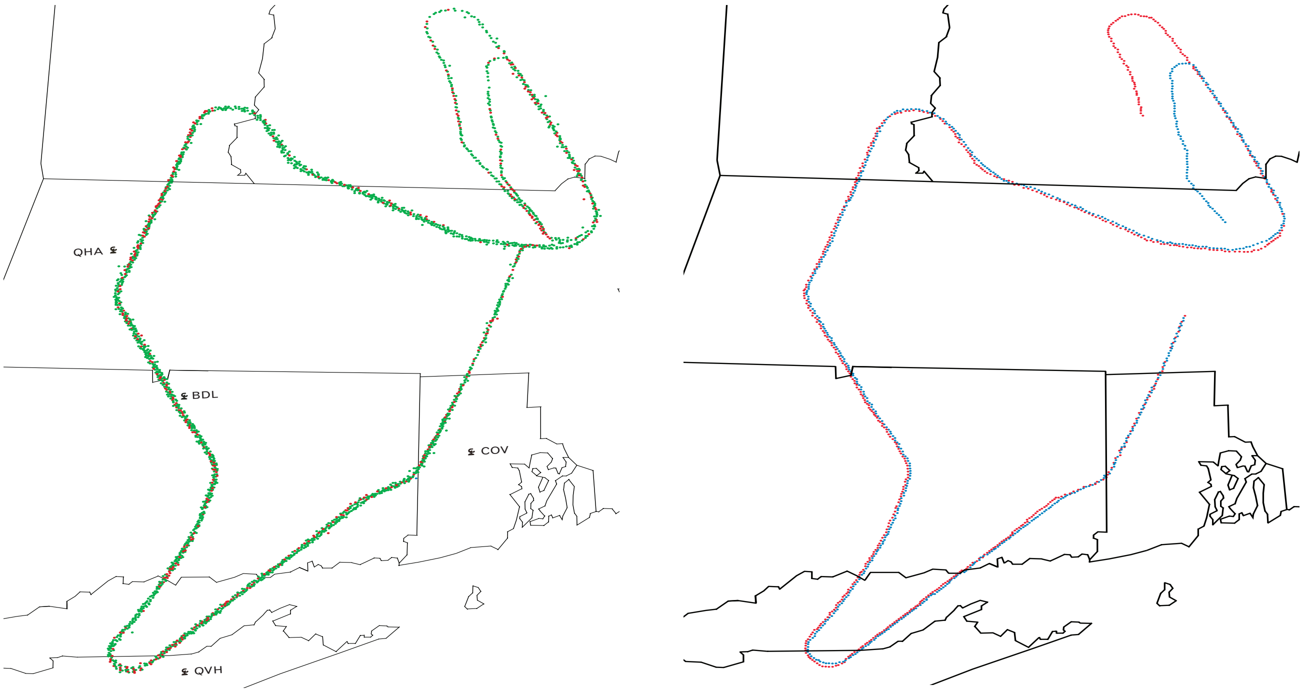


FIGURE 13. Airborne and ground data recording during the flight test. The true separation is derived from the Global Positioning System (GPS) reference data of the two aircraft. The measured separation is derived from the ground sensor data as it enters the facility. The displayed data are recorded in SAR format.

test aircraft consisted of WGS-84 ECEF *x-y-z* positions of the aircraft updated every second. The GPS time was corrected to UTC time by subtracting thirteen leap-seconds from the recorded GPS time. The ECEF flight progress strip position data were converted to latitude and longitude for comparison with the radar data. Figure 14(b) is a plot of the position reports as recorded by the GPS units. Flight test aircraft safety procedures required that the data recording be off during take-off and landing, as seen by gaps in the tracks at the beginning and end of the flight test when compared to the radar observations shown in Figure 14(a).

The GPS position data were used to compute the three-dimensional separation of the aircraft. The one-second update data from the two GPS units were interpolated to common times. The three-dimensional separation was converted to horizontal separation by using the Mode C reported altitudes of the aircraft. Computations showed that the 100 ft resolution in the Mode C altitude reports contributed insignificant errors. The GPS separation was considered truth in the remainder of the analysis and used to measure the errors in the RADES and SAR data in separation measurement. Figure 15 shows the aircraft separation during the flight test.

The sensor azimuth-measurement errors result in position and separation measurement errors that increase with range from the sensor. To compare the flight test data with the error model it is necessary to compute the range from each sensor as a function of time. The aircraft GPS position data were used to compute the range to the midpoint of the two aircraft from each of the radars. Figure 16 depicts a sample plot of the horizontal range from the midpoint of the two aircraft to the Coventry (COV) radar.



(a) (b)

FIGURE 14. Flight test data for the Falcon 20 and Gulfstream G2: (a) flight racks from radar data (RADES) and location of sensors; (b) GPS recorded position of the flight test aircraft. The Falcon 20 is depicted in red, and the Gulfstream G2 is in blue. Sensor locations, specifically QHA, Hartford, are not necessarily located in the named towns. The five sensors not shown in the figure are QEA, North Truro, Massachusetts (ARSR/BI5); QXU, Remson, New York (ARSR/BI5); QHB, St. Albans, Vermont (FPS67B/Mode S); QRC, Benton, Pennsylvania (FPS67B/BI5); and QIE, Gibbsboro, New Jersey (ARSR/BI5).

The RADES data were examined to determine periods of time during the flight test when each sensor was tracking both aircraft with continuous updates. This determination was made by plotting the delta update times for both aircraft as a function of time and noting periods in which there were no points above the normal update rate. The position measurements for both aircraft for the periods of continuous coverage were then determined for each sensor.

The position measurement of the two flight test aircraft were used to compute the separation measurement of the sensor as a function of time. The sensor-

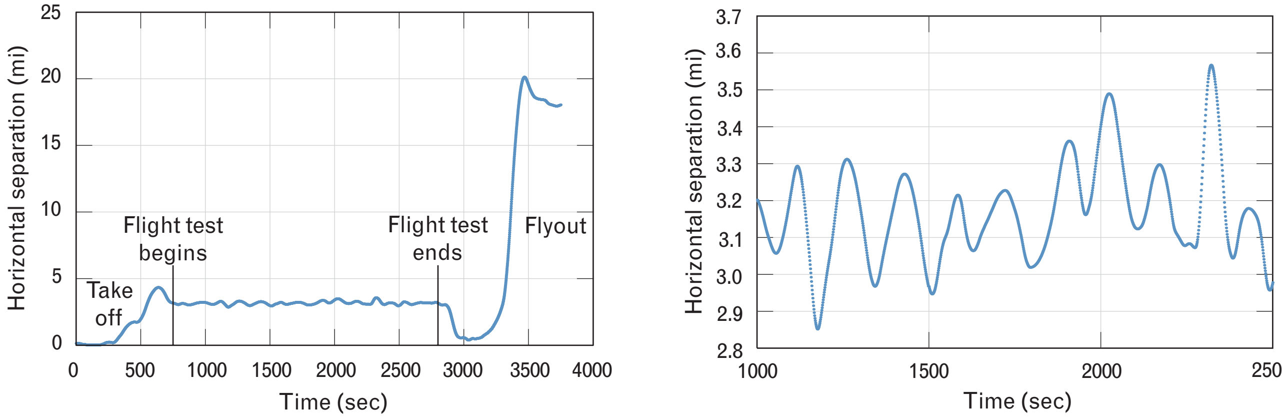


FIGURE 15. GPS recorded position of the flight test aircraft. The figure on the right is an expanded view of the figure on the left, covering the flight test period from 1000 to 2500 seconds.

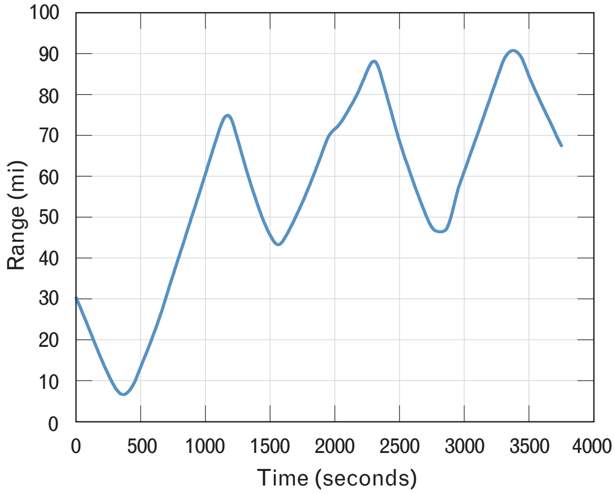


FIGURE 16. Range from the Coventry (COV) radar site to the midpoint between the two flight test aircraft as a function of time.

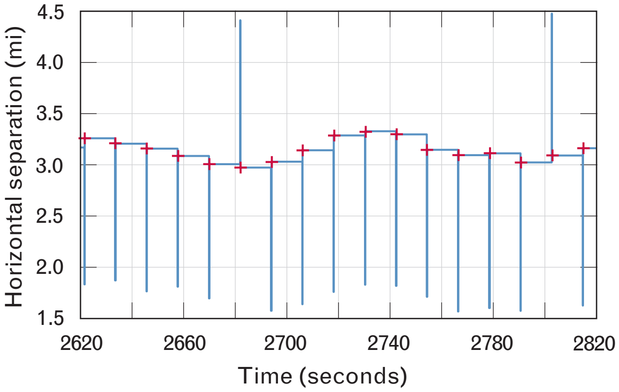


FIGURE 17. Sampled measurements of the separation of the aircraft by Hartford (QHA) radar. The blue lines represent the displayed separation as a function of time. The red plus signs are the sample separation compared to the GPS-provided *true* separation. The spikes occur as one aircraft position is updated prior to the other. The direction of the spikes depends on the order of the updates.

reported ρ, θ, and the aircraft-reported Mode C altitude were converted to a local Cartesian coordinate system, and the horizontal separation was computed for the aircraft as a function of time. Although the actual separation of the aircraft is a continuous function of time, the measured separation is a discrete function with each change in the value indicative of a radar report update of one of the aircraft. The two aircraft are updated within a short time period, but there is a brief gap between individual airplane updates. An algorithm was developed to determine the separation measurement immediately after the second aircraft update. With the Hartford (QHA) radar as an example, the red plus signs in Figure 17 illustrate the times

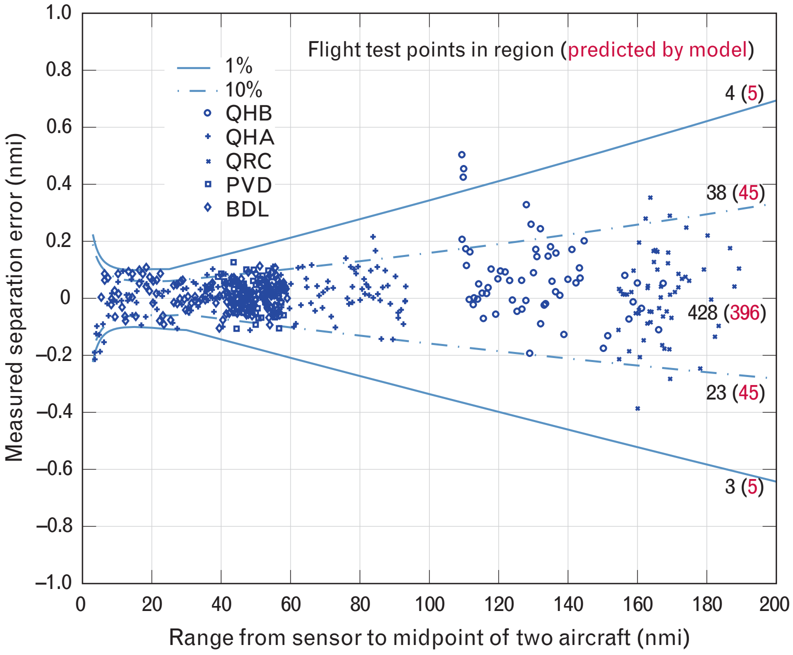


FIGURE 18. Modeled error limits versus range for an MSSR sensor. This figure includes reinforced data only. The total number of data points is 496.

sampled to compare the measured separation with the true separation. Each point in time represented by a red plus sign indicates a single data point for measured separation by the sensor.

These separation measurements, for each radar, were then compared to the GPS separation that is considered true, and the difference is recorded as a measured separation error. These measurements are plotted as a function of range, based on the range versus time plots computed earlier for each particular sensor. This procedure is used for all radars and is combined on plots designed to show the modeled sensor error limits. Figure 18 shows these data for the MSSR sensor and Figure 19 shows these data for the sliding-window sensor. The numbers in the regions above the 99% error line, below the 1% error line, and between the 90% and 99% error region and between the 1% and 10% error regions are the number of data points measured in these regions and the number predicted by the model. Note the expanded scale for the sliding-window sensor in Figure 19, compared to the MSSR plot in Figure 18. The total number of data points (496) was coincidentally the same for both the sliding-window and MSSR sensors.

Sensor Azimuth Performance

The sliding-window sensor performance as measured during the flight test was better than predicted by the error model, while the measured MSSR sensor performance was more closely predicted by the model. Because the only difference in the model of the MSSR and sliding-window sensors was the modeled azimuth-jitter errors, a more detailed investigation of the azimuth (θ) errors of the sliding-window and MSSR sensors was undertaken.

The RADES data contained the azimuth (θ_{RADES}) measurement, based on the antenna position relative to true north for all sensors for both aircraft. The GPS data contained the aircraft position in ECEF coordinates, converted to latitude and longitude. Since the location of the sensors was known in latitude and longitude, the bearings from the sensors (θ_{GPS}) could be computed by using spherical trigonometry. The total errors in azimuth were defined as $\theta_{RADES} - \theta_{GPS}$, where the GPS measurements were interpolated such that there was a GPS value for each RADES measurement.

The total azimuth errors for both aircraft were plotted as a function of time. A curve fit using the low-

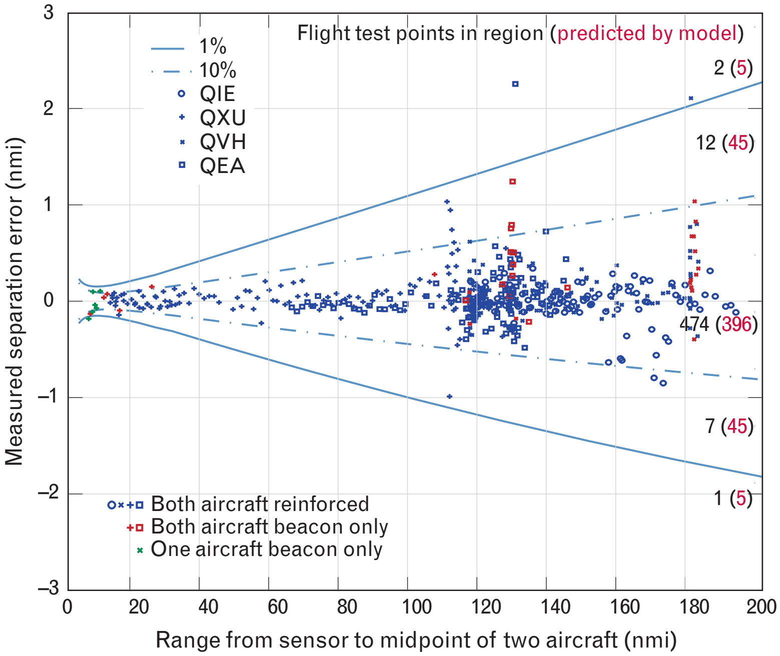


FIGURE 19. Modeled error limits versus range for a sliding-window sensor. The total number of data points is 496.

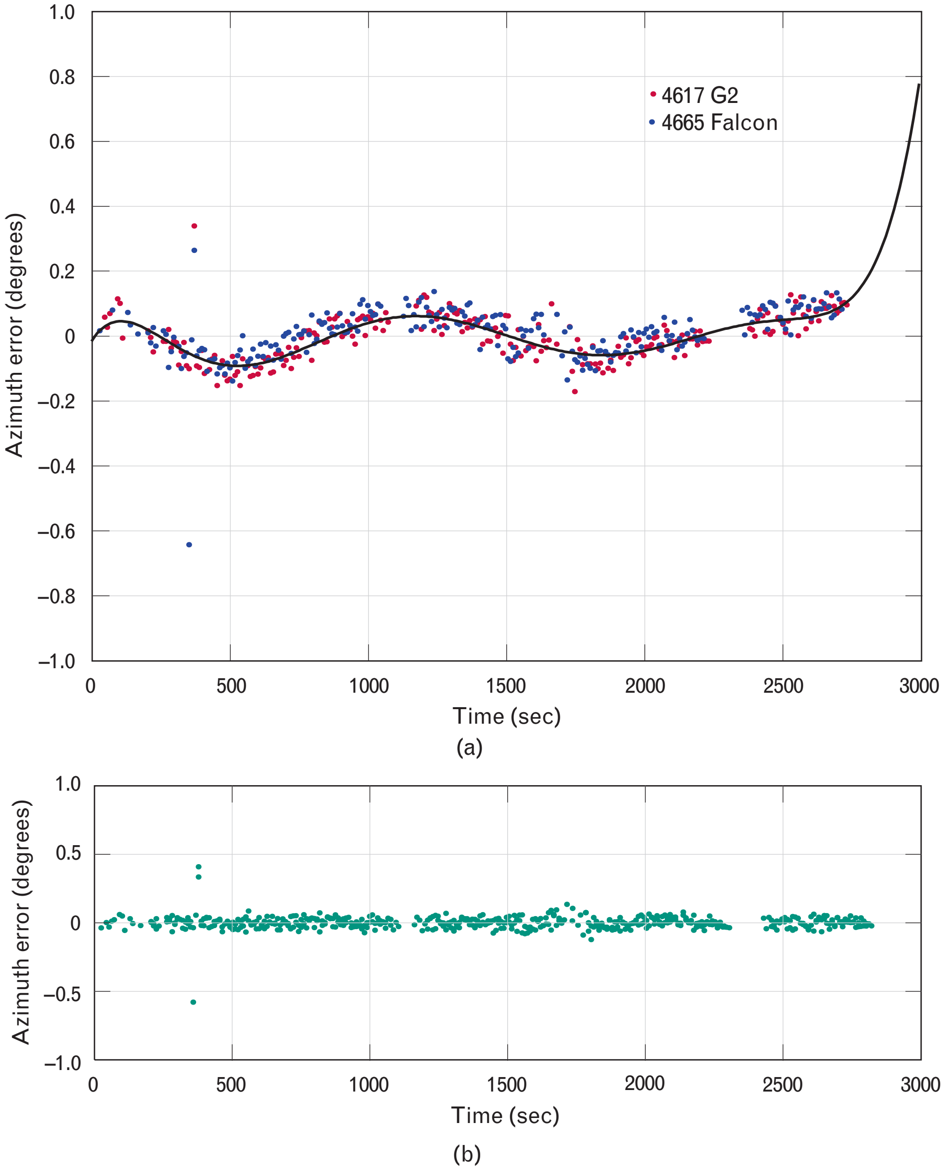


FIGURE 20. Azimuth error measurements ($\theta_{RADES} - \theta_{GPS}$) on both flight test aircraft as a function of time for the short-range MSSR sensor at Bradley (BDL): (a) error measurements with polynomial curve fitting and (b) residuals after curve fitting. The three outliers near 350 sec occurred during periods when the track was dropped and reacquired.

est-power polynomial that removed any bias from the residuals was used to determine the bias in the measurement. Azimuth bias in a sensor can be a slowly varying function of time or a function of the relative bearing from the sensor. The measurement of two test aircraft in trail made it possible to determine that a sensor bias was affecting both aircraft. The residuals about the curve-fitted bias were computed as the azimuth jitter. These measurements were used to generate a probability distribution of bias and jitter for each sensor, a process illustrated in Figures 20 and 21 for the short-range MSSR sensor at Bradley (BDL).

The procedure described above was performed for all nine sensors. The standard deviation (σ) of the azimuth (θ) jitter error of each sensor is plotted in Figure 22 and compared to the modeled error for the MSSR and sliding-window sensor. Four of the five MSSR sensors performed slightly better than the error model and one slightly worse. Because the performance of the St. Albans sensor (QHB) was close to three of

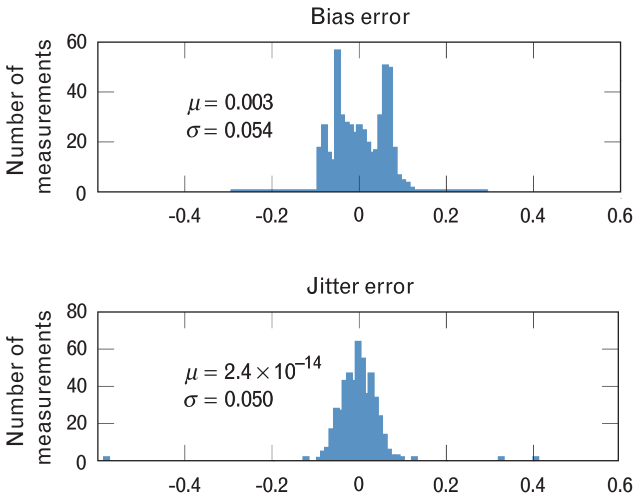


FIGURE 21. Separation of the azimuth error (θ) into azimuth bias and jitter for the Bradley (BDL) short-range MSSR sensor.

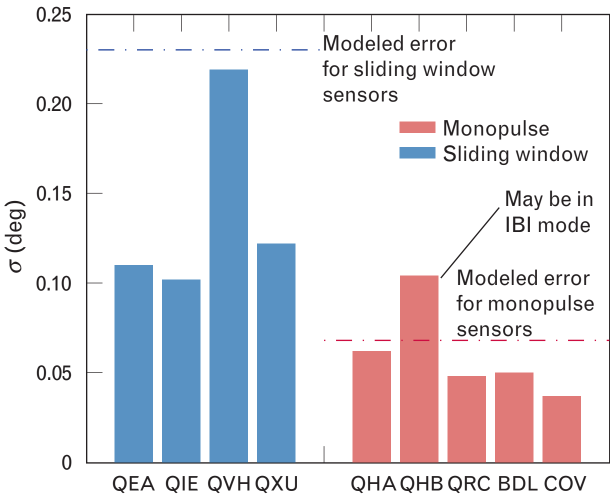


FIGURE 22. Standard deviation (σ) of azimuth-jitter errors for the nine sensors recording data for both flight test aircraft; errors for sliding-window sensors compared to MSSR sensors. IBI stands for Interim Beacon Interrogator.

the sliding-window sensors, it is not possible to rule out that the sensor may have been in Interim Beacon Interrogator (IBI) mode and acting as a sliding-window sensor. Three of the four sliding-window sensors performed much better than the error model and one performed very close to the model, indicating that there is a relatively wider spectrum of performance in the sliding-window sensor.

All of the measured jitter errors were combined for the five MSSR and four sliding-window sensors and the probability distributions for the respective jitter errors computed. These distributions are shown in Figure 23 for the MSSR sensors and in Figure 24 for the sliding-window sensors.

The cumulative average azimuth-jitter standard deviation for the MSSR sensors was $\sigma = 0.058°$, which is in very good agreement with the modeled error source of $\sigma = 0.068°$. The measurements from five sensors is not statistically significant enough to change the error model, if we keep in mind that the error model is for the least performing system, not the average performance of all systems.

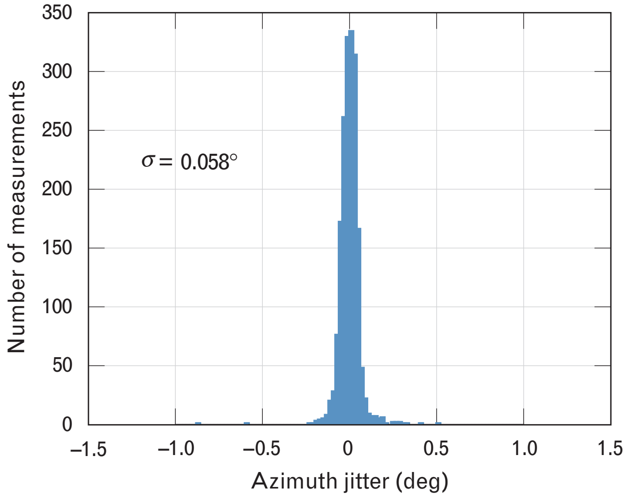


FIGURE 23. Distribution of azimuth jitter errors for the five MSSR sensors.

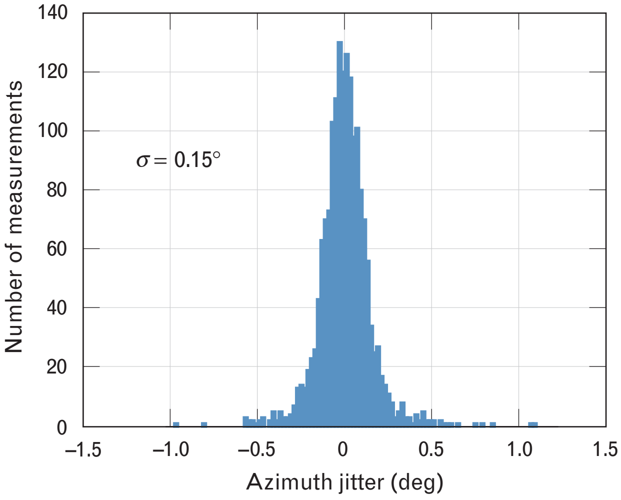


FIGURE 24. Distribution of azimuth jitter errors for the four sliding-window sensors.

The cumulative average azimuth-jitter standard deviation for the sliding-window sensors was $\sigma = 0.15°$, which is less than the error model source of $\sigma = 0.23°$. However, one sliding-window sensor performed very close to the error model, indicating a range of performance in sliding-window sensors. The error model is designed to model the least performing system of its design, and when there is a relatively wide range of performance, the average performance is statistically better than the lesser performing sensors. The ARCON report [11] notes a similar result in their field measurements of Air Route Surveillance Radar (ARSR) sliding-window beacon sensors in southern California TRACON with a $\sigma = 0.119°$ at a range of greater than sixty miles, although they list a typical modeled error of $\sigma = 0.23°$.

The difference in the way the sliding-window and MSSR sensors work provides an explanation of why the sliding-window sensor performance has a larger range in performance than the MSSR sensors. MSSR sensors with selective interrogation provide excellent surveillance in heavy traffic environments with high interrogation rates from multiple sensors. Sliding-window sensors perform very well when replies are received across the beamwidth, typically fifteen to twenty hits per beam. However, in dense traffic or a dense interrogator environment, the performance of a sliding-window sensor deteriorates. Interrogation efficiency decreases when many interrogators are active. This decrease includes other ground-based sliding-window or MSSR sensors as well as airborne interrogations from Traffic Alert and Collision Avoidance (TCAS) radars. The aircraft transponder may be suppressed or actively replying to another interrogation and not reply to a given interrogation from a sensor. In addition, the reply may be garbled if it overlaps with the reply from another transponder. This garbling can cause relatively large errors (on the order of a tenth of a beamwidth, or 0.25°) in azimuth measurements if the missed replies are near the edge of the beam. The data from the flight test were taken in a low interrogation environment at a time and altitude where there was not heavy traffic; the higher performance is consistent with the performance of sliding-window sensors in a benign environment. The error model must account for the performance in more challenging environments.

The bias data from all of the sensors were combined to provide a probability distribution of the bias errors, presented in Figure 25. The error model assumed a uniform bias error of ± 0.3°, which has $\sigma = 0.173°$. The data from the flight test have $\sigma = 0.15°$, which is in good agreement, although the distribution does not appear to be uniform. This non-uniform distribution would only affect cases using independent sensors when bias errors are not correlated. In the final analysis, there were no cases using independent sensors to establish an Required Surveillance Performance. The sensor azimuth-bias-error model will be modified for future analysis.

Measurement of Sensor Report Latencies

The flight test data position measurements were used to analyze the radar report latencies. The time difference between the GPS truth and the SAR data represents the total latency from sensor measurement to display to the controller. The time offset for each sensor was determined by finding the offset (Δt) that minimized the difference in position measurements between the sensor and GPS data for all measurements.

The SAR data errors were calculated by using ECEF x-y-z position reports. For the SAR data, the mathematical approach was to determine the Δt that minimized the sum of the differences in x, y, and z:

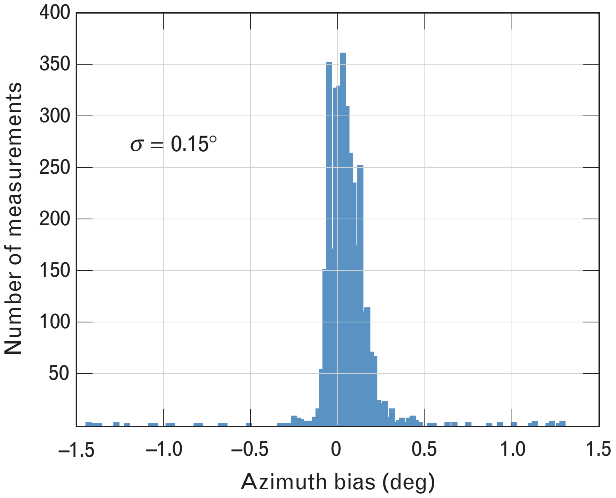


FIGURE 25. Distribution of azimuth bias errors for all sensors.

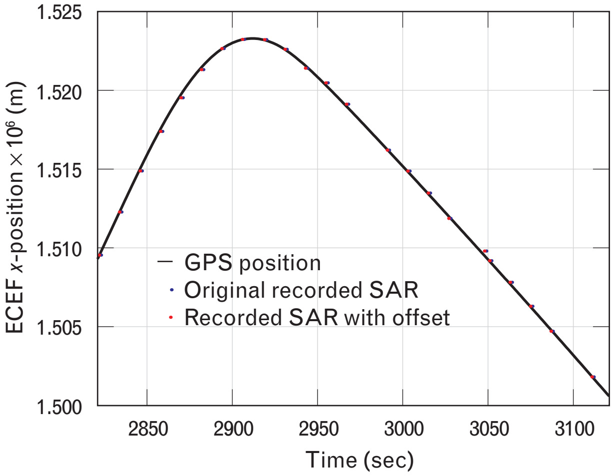


FIGURE 26. Example of SAR versus GPS data used to calculate absolute latency. The data were collected from the North Truro radar tracking the Falcon aircraft with a time offset of 1.1 sec.

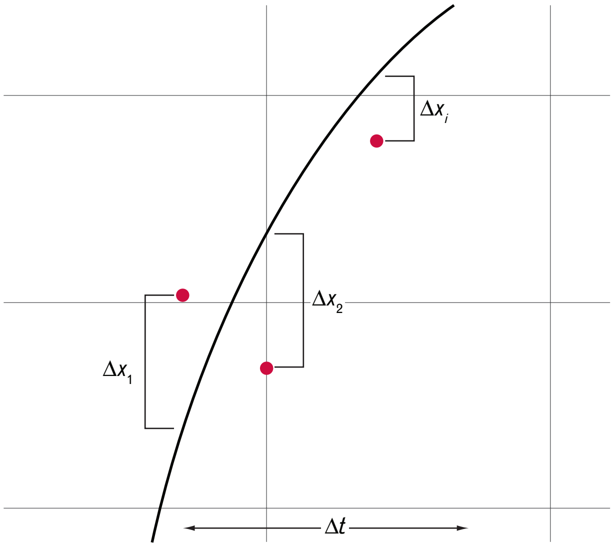


FIGURE 27. Illustration showing the relationship between Δt and Δx in Equation 1. Δt is adjusted to minimize the sum of $|\Delta x|$ (and $|\Delta y|$ and $|\Delta z|$).

$$\Delta t = \min \sum_i |\Delta x_i| + |\Delta y_i| + |\Delta z_i|. \qquad (1)$$

Figure 26 illustrates a time-offset computation for the SAR data, while Figure 27 illustrates the relationship between Δt and Δx_i. The Δt was varied until the sum of all Δx_i, Δy_i, and Δz_i for both aircraft was minimized.

Four sensors tracked the test aircraft that were displayed to the controllers and recorded on the SAR data. The latency measurements ranged from 1.2 seconds to 2.5 seconds with an average of 1.7 seconds.

Selection of Required Surveillance Performance

Required Surveillance Performance consists of many attributes, including accuracy, latency, update rates, capacity, availability, probability of detection, and continuity. The focus of this analysis was on surveillance accuracy required to support three-mile and five-mile separation. The accuracy requirements were derived from Monte Carlo simulations of modeled legacy sensor errors and validated with flight test data. Accuracy in measured separation was the metric chosen. However, geographical position accuracy is also available from the simulation and included as an additional attribute.

The Required Surveillance Performance accuracy requirement was derived from the unconditionally accepted widespread-use cases from Table 3 for three-mile and five-mile separation. The sensor in the three-mile separation case is the short-range primary sensor collocated with a sliding-window beacon sensor at a range of forty miles, tracking two aircraft three miles in trail at 250 knots. The baseline error in measured separation is taken to be that of the beacon sensor. Though the primary sensor is slightly more accurate, it can degrade in clutter environments; in those cases it is the beacon sensor that is used to provide separation. Also, MSSR sensors can be used to provide three-mile separation when they go into the IBI mode, and their performance is that of a sliding-window sensor. The sensor is in a single-site adaptation; that is, the same sensor is providing position information for both aircraft. No DSP errors were included. It was assumed the reports went direct to glass, as is the nominal case for TRACONs.

The five-mile separation case is for a single long-range sliding-window sensor at a range of 200 miles tracking aircraft five miles in trail at 600 knots. The total error in separation was determined by independently sampling from the sensor error distribution and the experimentally measured HOST DSP error distribution and adding these errors. This is the nominal system in use at ARTCCs today.

Table 4. Required Surveillance Accuracy

Accuracy in measured separation	*Three-mile separation*	*Five-mile separation*
Standard deviation	No greater than 0.16 mi	No greater than 0.8 mi
No more than 10% of the error distribution shall exceed	± 0.28 mi	± 1.4 mi
No more than 1% of the error distribution shall exceed	± 0.49 mi	± 2.4 mi
No more than 0.1% of the error distribution shall exceed	± 0.65 mi	± 3.3 mi
Geographical position accuracy	$\sigma < 0.20$ mi	$\sigma < 1.0$ mi
Latency	2.2 sec to display maximum	2.5 sec to display maximum
Update rate	4.8 sec maximum	12 sec maximum

The flight test data validated the accuracy and provided update rates and latency values. Table 4 lists the required surveillance accuracy attributes. The error distribution can be described by a single mathematical characterization, σ. However, the errors in the tails of the distribution are the paramount concern for safe separation. For this reason, Table 4 lists the requirements on potential new technologies in terms of the limits on the tails of the error distributions.

Summary and Conclusions

We have described the analysis and flight test validation for deriving the Required Surveillance Performance to support three-mile and five-mile separation. We examined the error characteristics of the various types of surveillance sensors in the FAA inventory and analyzed their performance with regard to providing accurate separation measurements to controllers.

The separation measurement accuracy, latency, and update rate have been established for the Required Separation Performance to support three-mile and five-mile separation in the NAS on the basis of existing legacy radar sensors regularly used in the NAS. The modeled performance of the sensors has been validated through flight test data. Flight test data on targets of opportunity were also used to measure the errors introduced through HOST DSP. The remainder of the Required Surveillance Performance values use the reference system approach based on the specifications of representative sensors. This Required Surveillance Performance is applicable to the extent that a surveillance system is similar in performance characteristics to the legacy systems used to derive a baseline.

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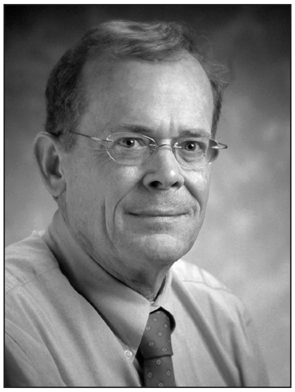

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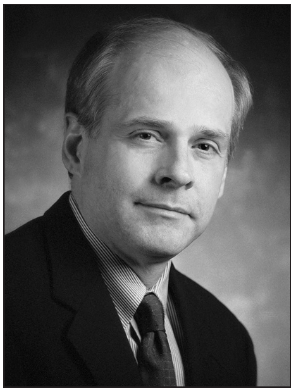

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