SA-6326
U 352308

R.R. LaFrey

Parallel Runway Monitor

The availability of simultaneous independent approaches to parallel runways significantly enhances airport capacity. Current FAA procedures permit independent approaches in instrument meteorological conditions (IMC) when the parallel runways are spaced at least 4,300 ft apart. Arriving aircraft must be dependently sequenced at airports that have parallel runways separated by less than 4,300 ft, a procedure that reduces the arrival rate by as much as 25%. The need for greater airport capacity has led to intense interest in new technologies that can support independent parallel IMC approaches to runways spaced as close as 3,000 ft. This interest resulted in several FAA initiatives, including a Lincoln Laboratory program to evaluate the applicability of Mode-S secondary surveillance radars for monitoring parallel runway approaches. This paper describes the development and field activities of this program.

New surveillance radars and sophisticated computing systems developed during the 1970s and 1980s are now being deployed by the Federal Aviation Administration (FAA) as part of a National Airspace System development plan. Current research and development programs emphasize the application of these resources to solve system capacity problems and to reduce airline delay. One potential application of the Mode-S secondary surveillance radar is to provide an improved monitoring system to reduce the impact of bad weather on parallel runway operations.

Airport capacity is significantly enhanced when simultaneous independent approaches to parallel runways are available (Fig. 1). Current air traffic control procedures permit independent approaches when the flight crews can maintain visual contact with other aircraft and the airport. Independent approaches are also permitted when visibility is limited, if the parallel runways are spaced at least 4,300 ft apart, and if additional radar monitor controllers are provided to insure that separation standards are maintained [1]. See the box titled "Instrument-Approach Procedures" for a description of landings during periods of limited visibility, and see the box titled "Parallel Runway Simultaneous ILS Approaches" for a description of the approach procedures and radar monitoring.

Dependent-Approach Limitations

Parallel approaches to runways spaced less than 4,300 ft apart are restricted in instrument meteorological conditions (IMC) because of limitations in current radars and displays. These limitations require air traffic controllers to use dependently sequenced approaches, so that if an aircraft blunders toward the adjacent approach, the aircraft will pass through a gap and not into another aircraft.

The reduced airport capacity associated with dependent approaches can be estimated. Radar controllers establish in-trail spacings during independent instrument approaches, based primarily on wake-turbulence concerns. The minimum authorized distance is typically three nmi, as shown in Fig. 2, but wake-turbulence concerns increase the separation to four or five nmi, depending on aircraft weight class. Since the approaches to each runway are independent and managed by different controllers, the resulting airport capacity is approximately twice the single-runway IMC capacity.

Dependent instrument approaches require the controllers to establish a space of 2.0 nmi between aircraft on adjacent approaches [1]. In practice, controllers establish a 4.0-nmi in-trail spacing on each approach, which provides an adjacent spacing of 2.8 nmi. The effect of the

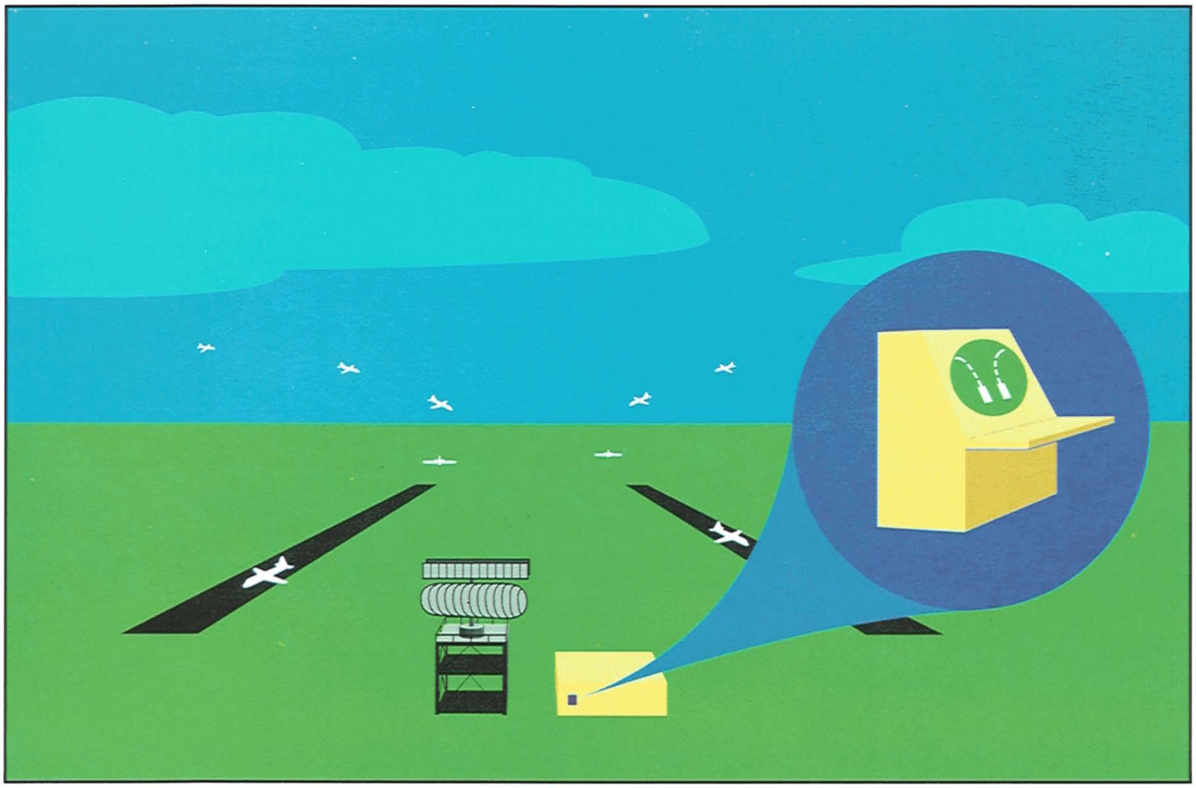


Fig. 1—Parallel-approach radar monitoring. A special radar monitoring system maintains safe separation between aircraft approaching parallel runways during periods of limited visibility.

additional mile of in-trail separation, and the burden of synchronizing the two approaches, results in arrival-rate reductions of as much as 25%. The current IMC capacity at the Memphis International Airport, which is 45 dependently sequenced aircraft per hour, could be increased to about 55 aircraft per hour if independent approaches were authorized [2].

Figure 3 shows the major domestic airports currently conducting parallel approaches [3]. Some of these airports, such as Los Angeles and JFK, have multiple parallel runways and are thus listed twice. At these airports, if one of the parallel runways is shut down, a more closely spaced parallel will be required. Several airports, such as Memphis and Raleigh-Durham, have recently become major hubs for Northwest Airlines and American Airlines, respectively, and are restricted to dependent parallel procedures.

The FAA estimated the delay costs associated with dependent approaches, relative to independent-approach costs. Figure 4 shows the

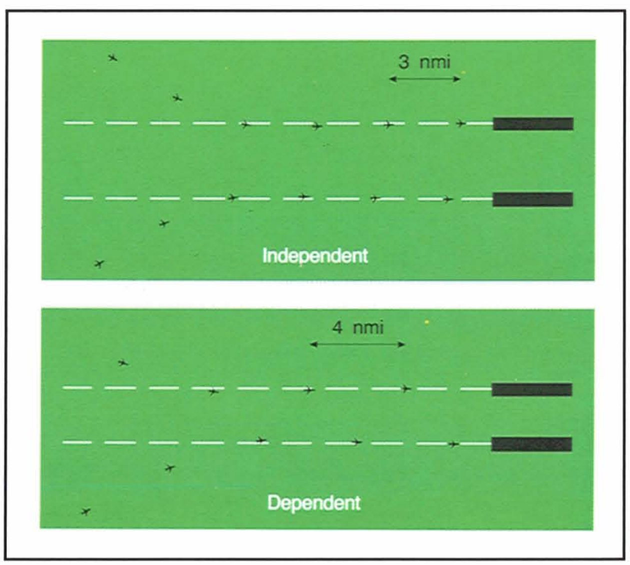


Fig. 2—Independent and dependent parallel approaches.

Instrument-Approach Procedures

During instrument meteorological conditions (IMC), a variety of procedures have been developed to guide appropriately equipped aircraft safely to the vicinity of the runway. The most precise procedure in common use is the Instrument Landing System (ILS). The ILS, shown in Fig. A, provides three radio-navigation signals that indicate lateral position, vertical position, and the occurrence of two or three checkpoints during the final approach to the runway. VHF and UHF signals provide lateral and vertical guidance, respectively, which is then displayed to the flight crew on an instrument that indicates the location of the specified flight path relative to current aircraft position. The flight crew then adjusts aircraft attitude and power to fly "to the needles." A third VHF signal indicates passage of the outer, middle, and in some instances inner markers, at published distances from the runway touchdown location. An approach plate developed by the FAA describes each instrument approach.

In operation, radar controllers vector aircraft to intercept the localizer signal (lateral guidance) 5 to 15 nmi from the runway threshold. The aircraft will stabilize on the localizer and begin descending when the glide-slope signal (vertical guidance) is detected. When the aircraft reaches the missed-approach point (MAP), typically 0.5 nmi from, and 200 ft above, the runway threshold, the flight crew must see the runway environment (typically a high-intensity lighting system) before they visually complete the landing. If the flight crew is unable to see the runway environment, they must reject the landing and follow a missed-approach procedure. Several categories of ILS landings exist, which permits approaches in reduced weather visibilities and ceilings, but they require a more precise ILS, additional avionics (such as a radar altimeter), and more stringent crew certifications.

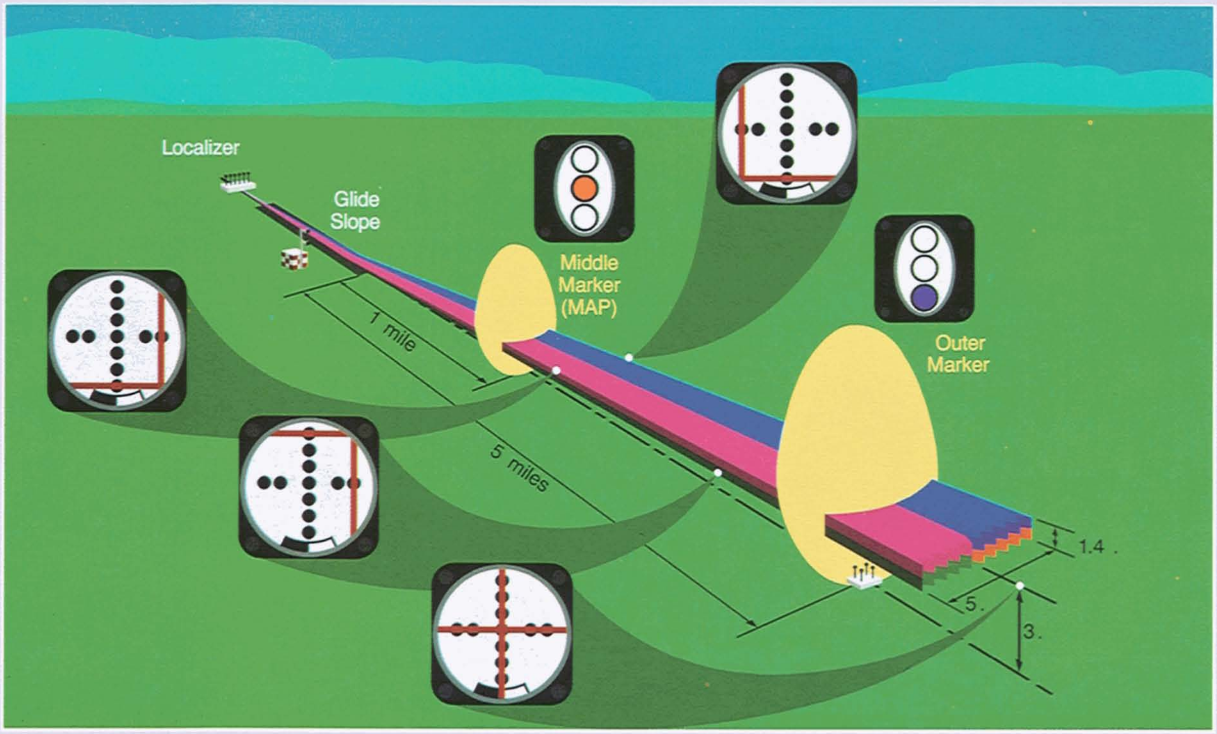


Fig. A—The Instrument Landing System (ILS). The course deviation indicator informs the flight crew of their horizontal and vertical location during final approach.

Parallel Runway Simultaneous ILS Approaches

During simultaneous ILS approaches to parallel runways, aircraft are vectored onto the two final approach courses with a 1,000-ft altitude buffer, as shown in Fig. A. The buffer assures that collisions will not occur if aircraft overshoot the localizer. Controllers also insure that both aircraft are stabilized on the final-approach course before the higher aircraft intercepts the glide slope.

Radar monitoring begins when separation based on the 1,000-ft altitude buffer is lost as the higher aircraft begins descending on the glide slope. Two radar monitor controllers observe the parallel approaches and insure that if an aircraft blunders from the normal operating zone into a 2,000-ft no-transgression zone, as shown in Fig. B, any endangered aircraft on the other approach is turned away in time to prevent a collision. The controllers accomplish this by overriding the VHF communication frequency between the tower and aircraft on each approach.

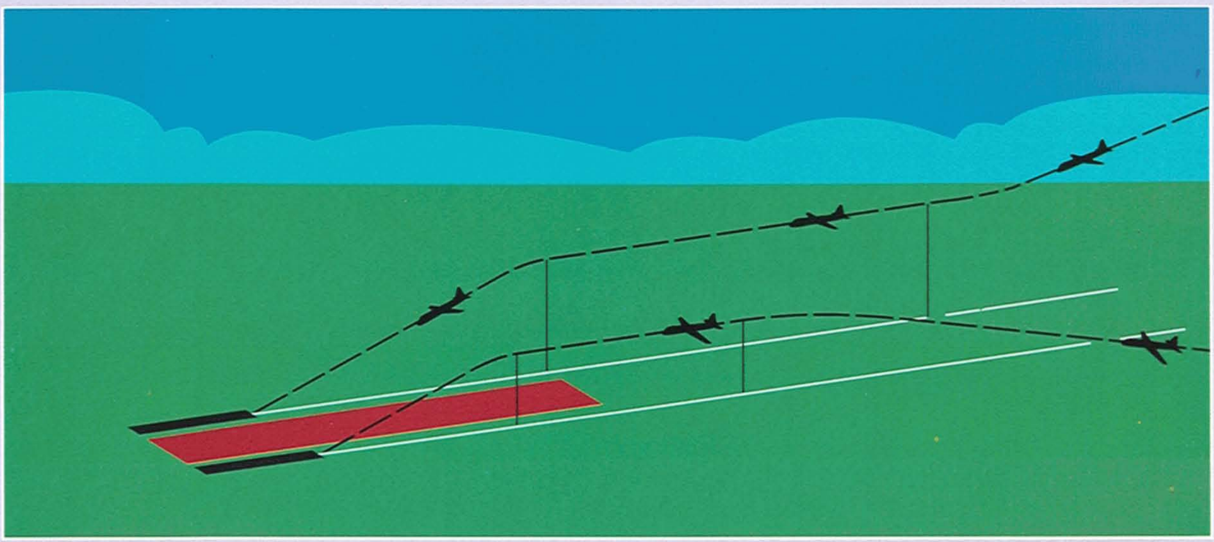


Fig. A—Parallel runway approaches. Aircraft are vectored onto the final approach course at different altitudes. Radar monitoring starts when the higher aircraft begins a descent on the ILS glide slope.

delay costs that were computed from estimated delay hours, where $1,600 is the approximate cost absorbed by an airline for one aircraft-delay hour [4]. These costs and similar passenger cost estimates are the major reasons for developing better radar monitoring systems.

Sensor Options

The need to reduce the impact of weather on parallel-approach operations led to several studies that examined sensor options and how well aircraft can be expected to stay within the normal operating zone [5–9]. The studies analyzed data collected from several airports to justify reductions in minimum runway spacing from 5,000 ft in 1963 to 4,300 ft in 1974. A Mitre Corporation study in 1981 examined the potential benefits of improved surveillance accuracy and update rate, and concluded that the minimum runway spacing for independent parallel approaches could be further reduced [10]. Table 1 shows the results of the Mitre study. Azimuth accuracy is a significant surveillance measure because sensors located near the runways use it to estimate localizer deviations.

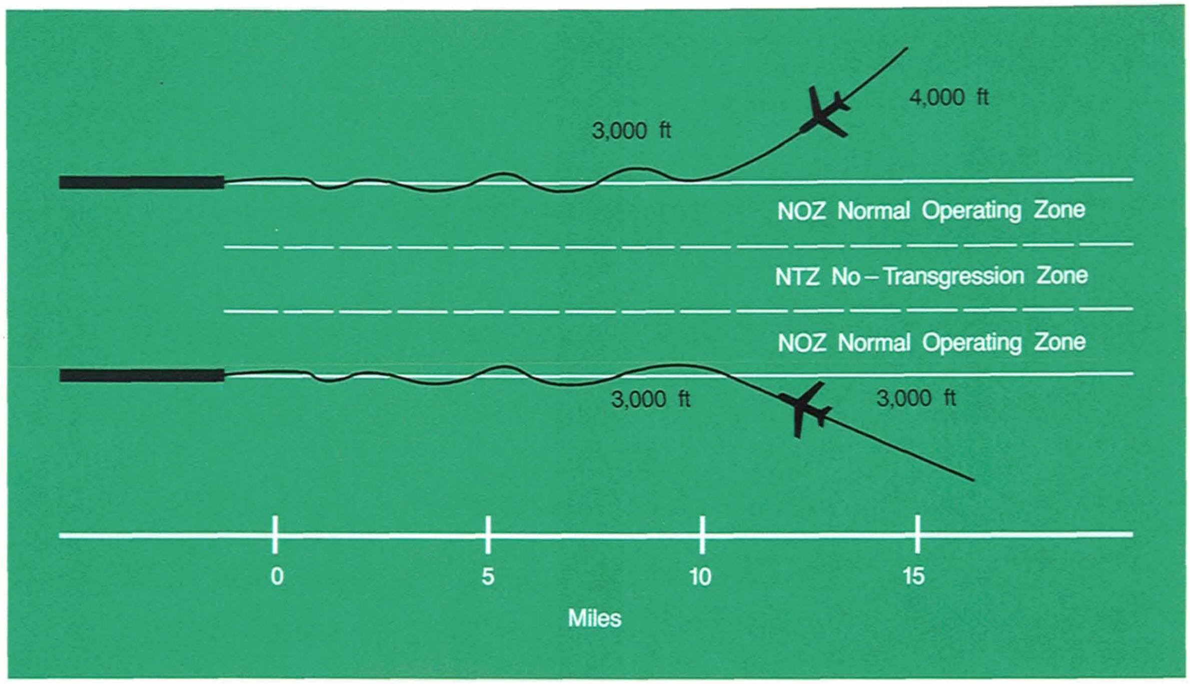


Fig. B—Parallel runway approach zones.

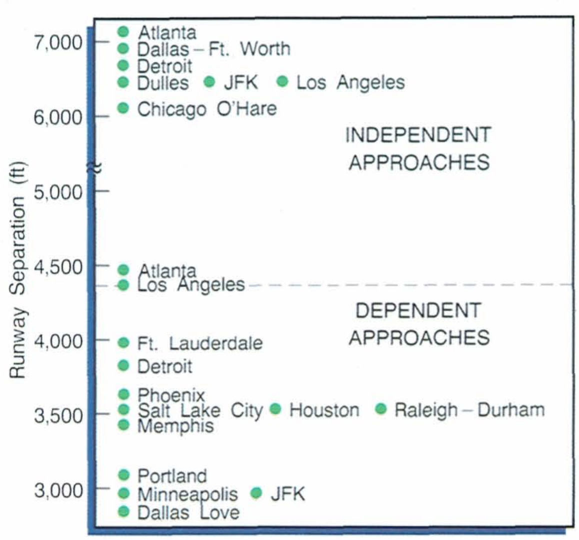


Fig 3—Parallel runway operations. Airports with multiple runway pairings, such as Los Angeles and JFK, appear twice.

The Mitre study suggested that two surveillance sensors have the required accuracy and update rates for some or all of the candidate airports. A Mode-S sensor, configured with back-to-back antennas, will provide 1.2-mrad (worst case, typically 0.5 mrad), 2.4-s surveillance and thus meet the requirements for runway spacings as low as 3,400 ft. The Mode-S option has an advantage in that it is in production and has well-characterized surveillance performance. The alternative, an E-Scan sensor proposed by Bendix Corporation, has a theoretical accuracy of 1.0 mrad and a 0.5-to-1.0-s surveillance-update interval. The E-Scan sensor would therefore support monitoring for 3,000-ft runway spacings. To verify the 1981 Mitre study and determine the appropriate monitor for each candidate airport, the FAA initiated two development activities to evaluate the relative merits of monitoring systems based on both sensors. Lincoln Laboratory

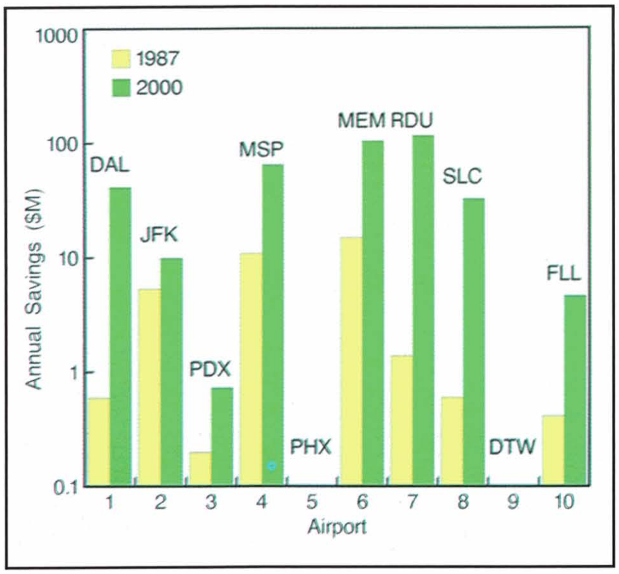


Fig. 4—Estimated annual airline-delay costs. These figures are derived from annual delay hours multiplied by $1,600 per aircraft-delay hour.

was selected to evaluate the Mode-S option.

Technical Issues For Improved Monitoring

A review of the literature and current parallel runway monitoring procedures suggests that the following technical issues should be addressed to develop an improved monitor.

Surveillance—what is the surveillance performance of a Mode-S sensor with back-to-back antennas during parallel-approach and missed-approach flight procedures?

Data Display—how should surveillance information be provided to the controller?

Automation—what are the benefits of automatic caution and warning alerts, and how should they be displayed to the controller?

System Performance—what is the overall system performance of the monitoring system? Specifically, what is the relationship between false alerts and late alerts, as system thresholds are varied, for postulated blunder scenarios?

User Acceptance—is the system acceptable to the user community, including pilots, air traffic controllers, airlines, and airport operators?

The remainder of this paper describes the current status of activity at Lincoln Laboratory with respect to each of these technical issues.

Sensor Development

To determine the surveillance performance of the Mode-S option, an experimental sensor was modified to operate with back-to-back antennas

Table 1. Minimum Runway Separation Summary

		Update Rate (Seconds)			
		4	2	1	0.5
RMS Azimuth Accuracy (milliradians)	5	4,300*	4,100	3,800	3,600 ft
	4	4,000	3,800	3,500	3,400
	3	3,700	3,600	3,300	3,200
	2	3,500	3,400	3,100	3,000
	1	3,400	3,200	3,000	2,900

*Current Airport Surveillance Radar Performance

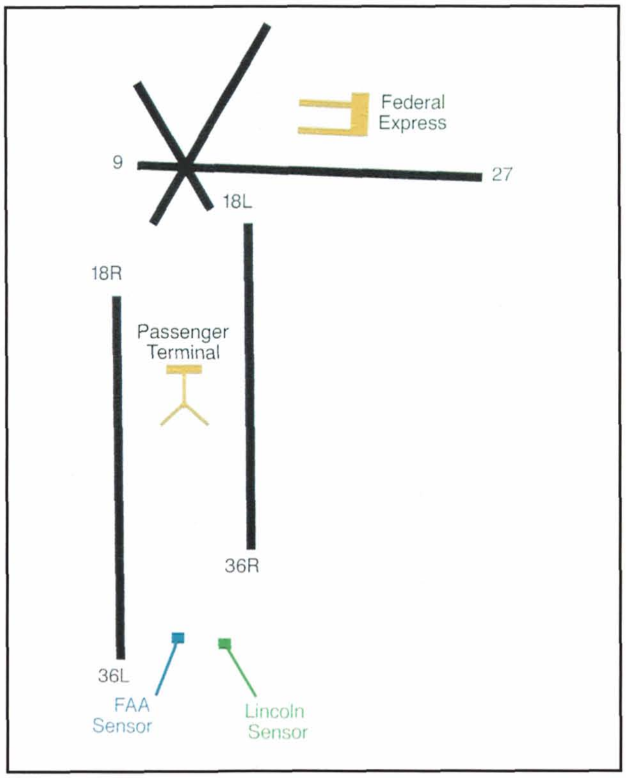


Fig. 5—Lincoln Laboratory test site at Memphis International Airport.

on a 4.8-s antenna pedestal, and deployed to Memphis International Airport in June 1988. The Memphis airport was chosen because its 3,450-ft runway separation makes it a candidate airport for simultaneous Instrument Landing System (ILS) operations, and because it has significant Northwest Airline and Federal Express air traffic. The experimental sensor is located near the existing FAA sensor, as shown in Fig. 5.

Figures 6 and 7 show the sensor at the Memphis location. The antenna assembly consists of a pair of 5-by-26-ft FAA open-array antennas on a modified FAA radar mount supported on a custom tower. High-speed RF solid-state switches provide antenna selection above the rotary joint. Interrogations (1030 MHz) and replies (1090 MHz) are routed from the antennas through a three-channel rotary joint to an equipment van located behind the site building. The van contains transmitters, receivers, digital processors, and a surveillance computer. Separate monopulse calibration tables are formed for each antenna face to insure compliance with the required azimuth accuracy. Surveillance data in the form of target reports with correlating track numbers are transmitted to the site building on

Fig. 6—Lincoln Laboratory experimental sensor at Memphis International Airport.

Fig 7. Lincoln Laboratory experimental back-to-back antennas at Memphis International Airport.

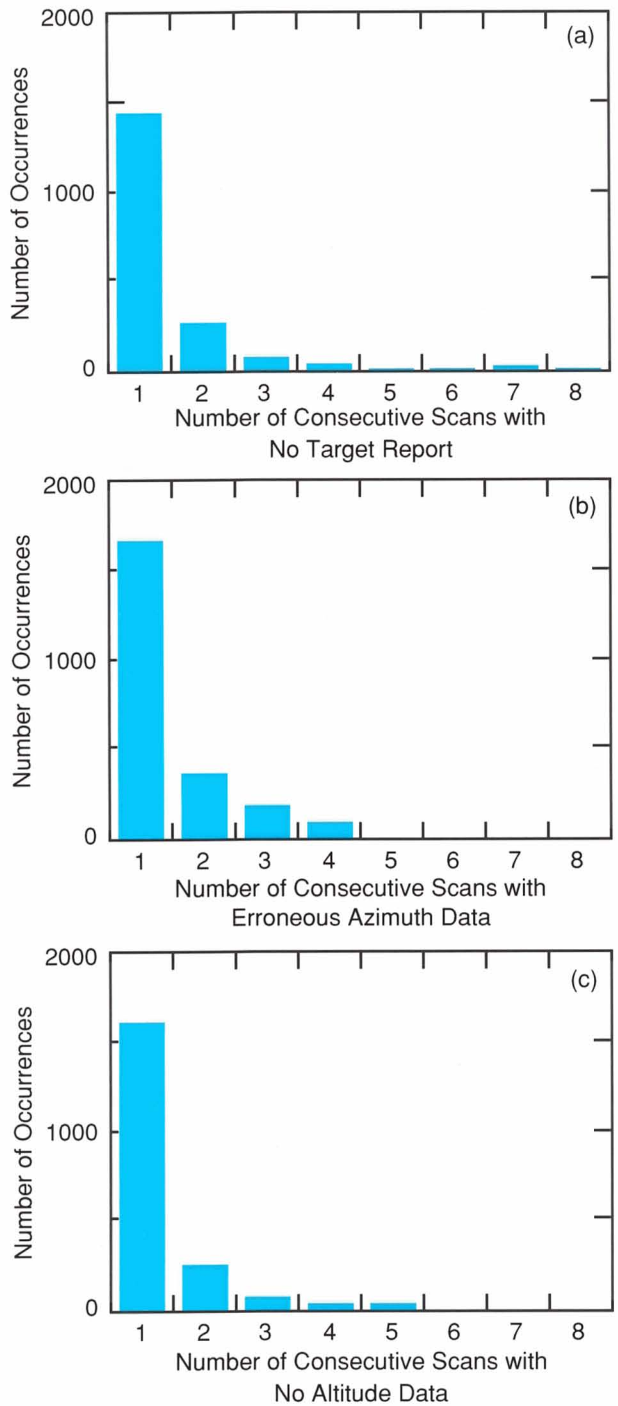


Fig. 8—Sensor Performance Simulation Results. (a) Probability of consecutive missing target reports. (b) Probability of erroneous azimuth data. (c) Probability of no altitude data. These data came from 150,000 scans during 500 parallel landings at Memphis International Airport, where the runway spacing is 3,450 ft.

a data line. The site building contains parallel runway monitor (PRM) displays and other equipment to be described later.

While the Mode-S sensor provides high-quality surveillance in dense traffic, parallel approaching aircraft present a particularly challenging case because of the close proximity of adjacent aircraft at ranges up to 20 mi from the airport. To confirm that the Mode-S sensor design would provide the required 1.2-mrad rms azimuth accuracy at the 2.4-s data rate, the

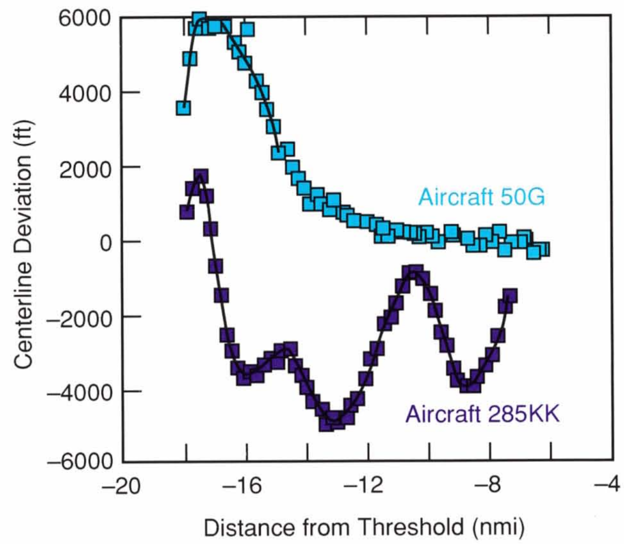


Fig. 9—Bedford Airport flight test data: close proximity surveillance performance.

sensor was tested both by simulation and by flight test.

A simulation was developed by using simplified but conservative processing algorithms that emulate the production-sensor surveillance design. Monte Carlo trials were conducted to determine the ability of the sensor to estimate correctly the range, azimuth, and transponder reply data (either identity or barometric altitude) during an approach and in the presence of nearby interfering aircraft. Figure 8 gives an example of the simulation results for Memphis. Figure 8(a) shows that the number of times a target report is missing for more than one or two consecutive 2.4-s scans is very small. Figures 8(b) and 8(c) show that it is unlikely that erroneous azimuth or missing altitude data will per-

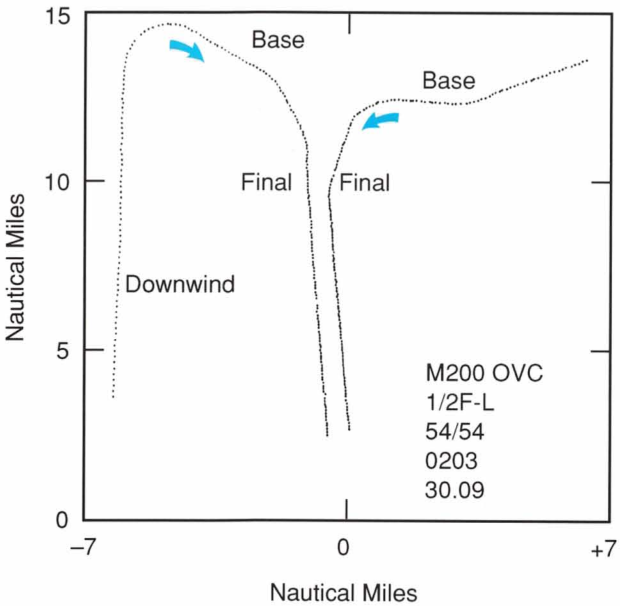


Fig. 10—Approach surveillance data from 29 January 1989. The visibility was less than 1/2 nmi in fog and light rain, and the cloud base was 200 ft above the airport surface.

sist. Other airports and runway spacings produced similar results.

Flight tests were conducted during the sensor shakedown tests at the airport in Bedford, Mass., prior to deployment at the Memphis field site. Two Cessna 421 aircraft conducted approaches involving close encounters. The unfiltered target-report data, shown in Fig. 9, indicates good surveillance when aircraft 285KK intentionally deviated toward aircraft 50G as 50G flew the runway 11 ILS approach.

Additional tests at Memphis further confirmed that the Mode-S sensor can provide reliable surveillance during parallel approaches. Figure 10 shows radar data for two aircraft during the downwind, base, and final-approach segments to runways 18 Left and 18 Right at Memphis. Each data point is a 2.4-s target report.

Tests were also conducted to determine the ability of the sensor to detect targets during missed-approach procedures. Figure 11 shows the target reports of an FAA AeroCommander 690 that flew a low 50-ft approach over runway 27, circled and landed on 18 Right, and taxied back to the north end of 18 Right before placing the transponder in standby. The two missing reports over runway 27 are believed to be due to blockage by trees.

During shakedown tests at the Bedford and Memphis sites, azimuth bias errors of two to five mrad were initially measured between the two antenna faces. Further analysis led to the discovery that the optical shaft encoder was not adequately aligned with the rotary joint. This misalignment caused a cyclic bias term consistent with observed surveillance errors. When a fixture was developed that insured shaft alignment to within 0.001 in, the cyclic bias was reduced to 0.02 to 0.03 mrad. An algorithm was also designed that will use target data to monitor bias errors and introduce correction factors in each 22.5° azimuth sector.

Analysis of surveillance tests on targets of opportunity also indicated the presence of multipath resulting from taxiing aircraft and large tractor-trailer vehicles on adjacent airport boundary roads. These specular reflections cause short-term false locations for real aircraft. The production Mode-S sensor can eliminate false targets due to stationary reflection sources but not moving reflection sources. As a result, additional false-target tests were developed that

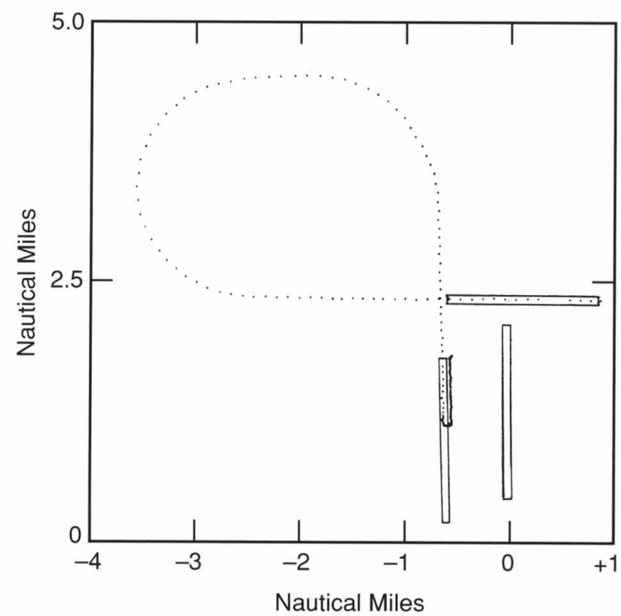


Fig. 11—Short-range surveillance data from 1 February 1989, during a low approach over runway 27, a landing on runway 18 R, and a taxi back to the north end of runway 18 R.

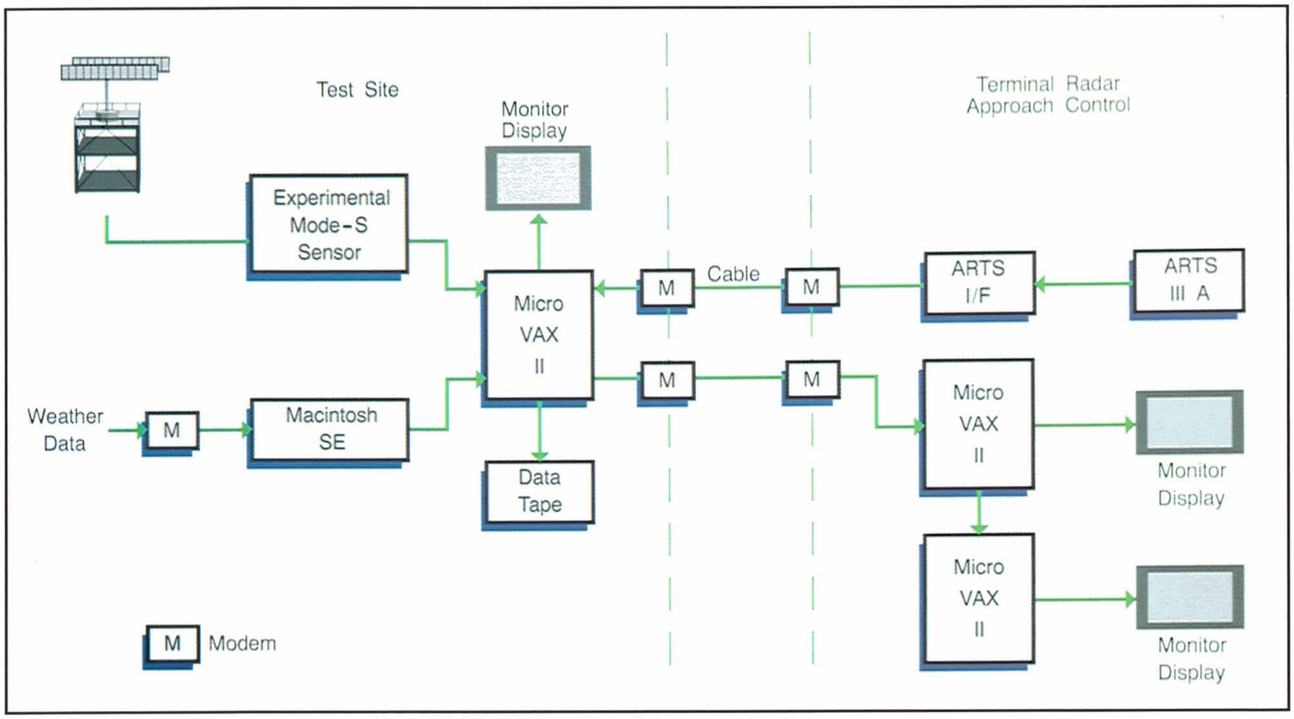


Fig. 12—Parallel runway monitor (PRM) system configuration at Memphis International Airport.

require stricter velocity and heading consistency between target reports and tracks for aircraft within 5 nmi of the airport. Early test results indicate that these tests will eliminate most or all of the false moving targets.

In general, the tests confirm that a Mode-S sensor with back-to-back antennas for the 2.4-s data rate can provide high-quality surveillance data during parallel-approach operations, and should support the requirement for surveillance during missed-approach procedures.

Data Presentation

To determine how the improved surveillance information should be provided to air traffic controllers, Lincoln Laboratory developed a new radar monitor display system. The display system design incorporates high-resolution color graphics and provisions for format modifications by controllers. Figure 12 shows how the display system connects to the experimental Mode-S sensor. The initial display format design was derived from FAA air traffic requirements and refined by Memphis air traffic controllers.

Figure 13 shows a reproduction of the radar display, taken from recordings of aircraft in IMC at Memphis. Map features such as approach-corridor boundaries, the Mississippi River,

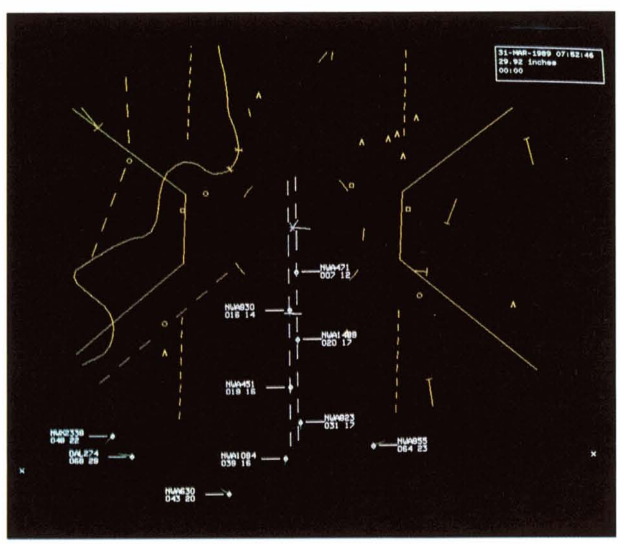


Fig. 13—PRM experimental monitor display.

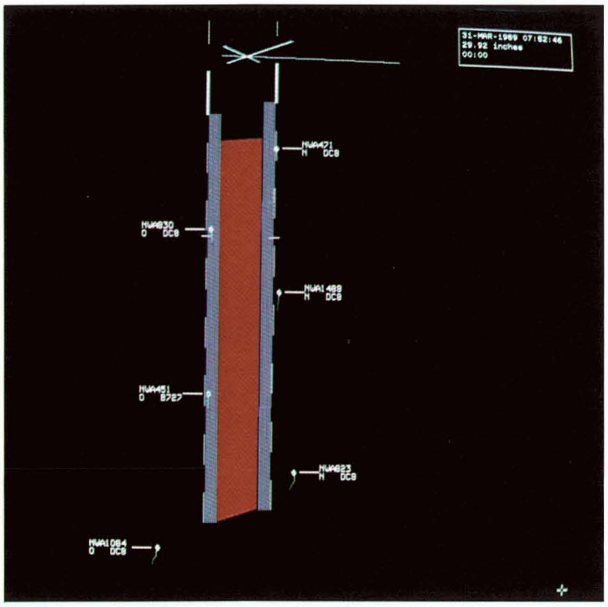


Fig. 14—Expanded PRM experimental monitor display. The east-west directon is magnified four times greater than the north-south direction.

bridges in downtown Memphis, and other navigation symbols have been incorporated to insure consistency with existing Memphis air traffic displays. The final approaches to 18 Left and 18 Right are shown with 1.0 nmi spaces and 1.0 nmi dashes. Aircraft locations are shown as ovals with a leader line connecting the aircraft to a data block. Optional history trails are shown as a green trailing line. Data blocks include the flight number (such as NWA 471) and a second line that alternates between altitude and ground speed (007 for 700 ft and 12 for 120 kts), as shown in Fig. 13, and runway assignment codes (O and N) and aircraft type (DC9), as shown in Fig. 14. The monitor obtains aircraft data through a special interface (developed by Lincoln Laboratory and illustrated in Fig. 12) to the existing FAA display computer, an ARTS IIIA Univac input-output processor.

The 19-in display screen includes a menu system that permits scale modifications, zooms, translations, and other modifications. Figure 14 has expanded the east-west scale by eight times and the north-south scale by two times. The blue lines indicate 100-ft deviations from the extended centerline, and the red area represents the 2,000-ft no-transgression zone (NTZ).

While the scale expansion allows accurate

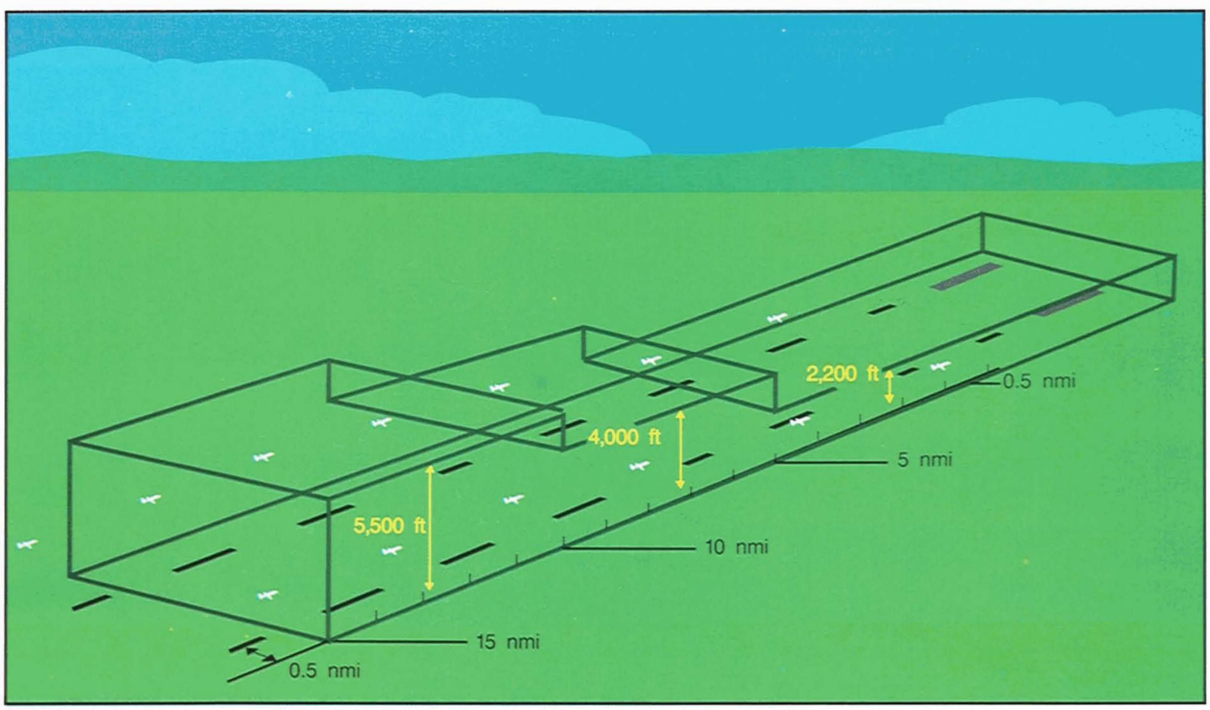


Fig. 15—Airspace dimensions for the automatic-alert algorithms.

location of the aircraft on a final approach course, it results in a distortion of heading and ground speed. This distortion is difficult to avoid because the monitor controller is required to observe aircraft during a 10- to 15-nmi final approach, and a 2-nmi missed approach, and insure that aircraft stay out of a 2,000-ft-wide NTZ centered between approach paths that can

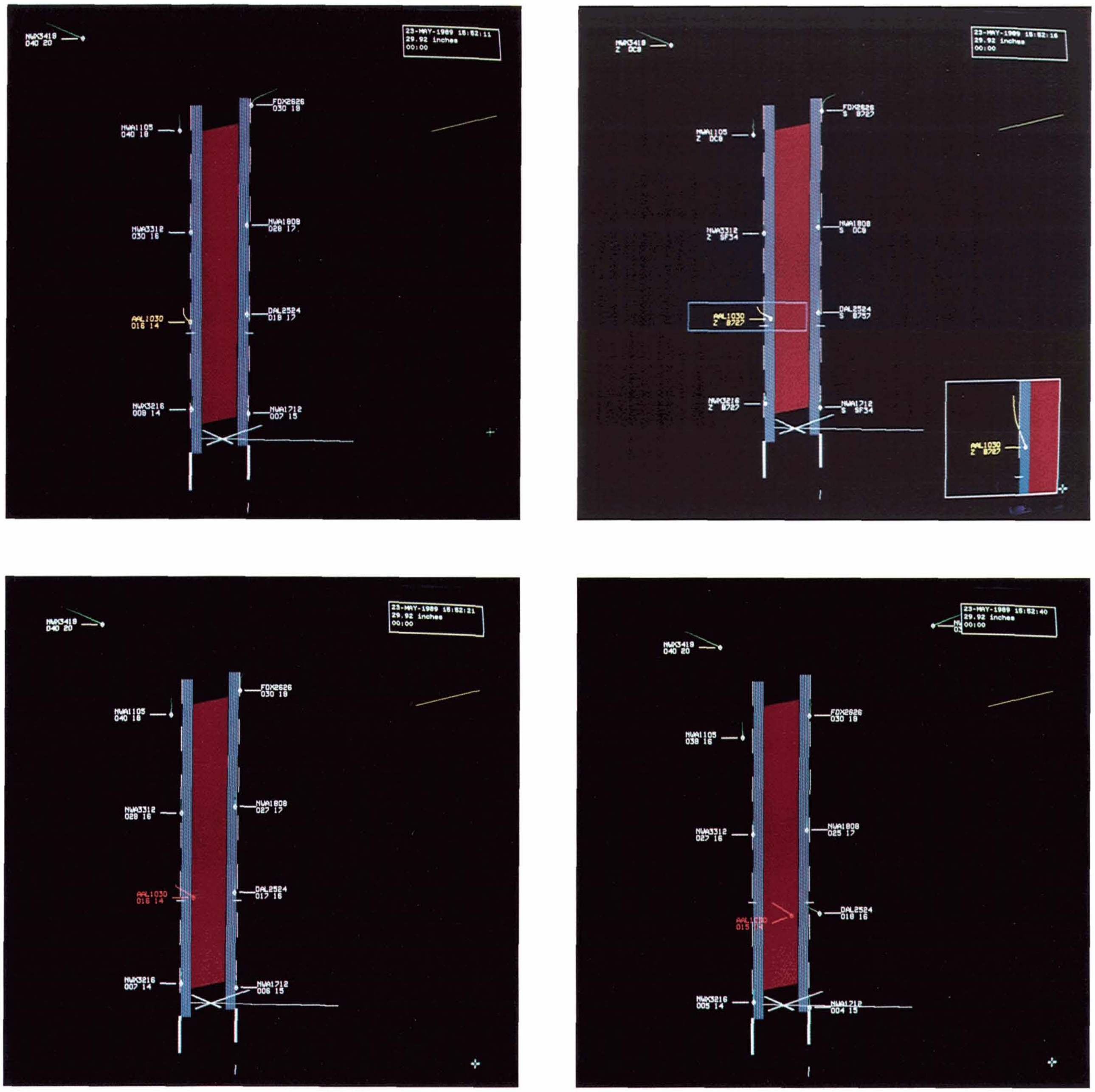


Fig. 16—Air Traffic Simulation. (top left) At 15:52:11 a caution alert occurs for American Airlines (AAL) flight 1030, on runway 18R, indicating NTZ penetration within 10 s unless the aircraft changes course. (top right) At 15:52:16 AAL flight 1030 is 200 ft from the edge of the NTZ. The blue box defines the window region. The controller monitoring runway 18L directs Delta Airlines (DAL) flight 2524 to turn left immediately. (bottom left) At 15:52:21 a warning alert occurs for AAL flight 1030 as the aircraft penetrates the NTZ. (bottom right) At 15:52:40 DAL flight 2524 has turned away; the separation between the two aircraft at closest point of approach was approximately 1,700 feet.

Table 2. Automatic-Alert Description

Figure	*Event*	*Automatic Alert*	*18L Monitor-Controller Response*	*18R Monitor-Controller Response*
16 top left	15:52:11 AAL 1030 deviates.	"CAUTION! AAL 1030 deviating." Target symbol turns yellow.		"AAL 1030, turn right to 180, maintain localizer."
16 top right	15:52:16 AAL 1030 heads toward NTZ.		"DAL 2524, turn left to 150 immediately, climb, maintain 2,000."	"AAL 1030, turn right to 210, rejoin 18R localizer."
16 bottom left	15:52:21 AAL 1030 enters NTZ.	"WARNING! AAL 1030 in protected 18R zone." Target symbol turns red.	"DAL 2524, turn left to 090 immediately."	"AAL 1030, turn right to 240, rejoin 18R localizer, you have entered the NTZ!"
16 bottom right	15:52:40 DAL 2524 completes evasive turn after a delay of 8 seconds.			

be as close as 3,400 ft or less. Controllers are examining several options, including the use of auxiliary windows and advanced 20-in square displays, to resolve this issue.

Automation

To utilize the improved surveillance performance provided by the Mode-S sensor, the PRM display system includes algorithms that estimate future aircraft locations. The algorithms provide a caution alert if an aircraft appears to be heading toward the NTZ and a warning alert when the aircraft actually penetrates the zone. The alert algorithms operate only on aircraft within the airspace defined in Fig. 15. Memphis controllers, if necessary, can change these airspace dimensions through the display menu system.

Figures 16(a) through 16(d) illustrate how the caution and warning alerts function, based on simultaneous ILS traffic generated by a computer traffic simulation. Table 2 describes the associated event sequence, the aural and visual automatic alerts, and the expected actions of the controllers. Figure 16(b) shows a window that is available to assist the monitor controller in assessing the seriousness of a deviation. The window, which is located by the blue box and has equal magnification in both directions, shows an actual heading of 25° for American Airlines flight 1030, rather than the apparent heading of 65° as shown in the main display.

The automatic-alert algorithms were developed to act only when an aircraft deviates from an assigned runway toward the NTZ. The recognition of runway assignment avoids unnecessary alerts when aircraft are cleared to cross the NTZ for an approach to the other parallel runway. Other design features act similarly to minimize the incidence of false alerts or to alert the controller if the beacon surveillance has become unreliable. For the latter circumstance, the sensor automatically substitutes a primary-radar target symbol (which is less accurate) for the missing beacon-radar target symbol. The controller will then decide whether to permit the approach to continue or require the aircraft to go around for a dependently spaced arrival.

Preliminary evaluations were conducted by air traffic controllers from Memphis, Dallas–Fort Worth, and Atlanta, along with FAA staff from Washington, D.C. They observed live traffic and staged approach blunders flown by Lincoln Laboratory test aircraft at the Bedford and Memphis airports. Several preliminary conclusions can be made on the basis of the initial display and automatic-alert evaluations:

(1) Controllers are very enthusiastic about high-resolution color traffic displays.
(2) Controllers and flight crews are impressed by the improved surveillance accuracy.
(3) Controllers strongly prefer higher data rates for monitoring simultaneous ILS approaches.
(4) The caution alert can significantly reduce the probability that a monitor controller will miss the onset of a serious deviation. The caution alert may also reduce the reaction time of the controller.
(6) Controllers and airline pilots prefer a display of primary-radar surveillance if the aircraft transponder should fail or become unreliable during parallel approaches.
(7) A display larger than 19 in is desired to reduce the distortion of heading and ground speed resulting from asymmetric magnifications.

As a result of the last conclusion, four 28-in displays have been obtained for site evaluations.

System Performance Analysis

Overall system performance must be assessed to insure that a monitoring system design will reduce weather-related delays and not compromise air traffic safety, and that it is both practical and effective. The two major systems issues to be addressed are:

(1) Will the monitor provide timely alerts that lead to acceptable miss distances for postulated blunder scenarios?
(2) Will the false-alert rate be acceptably small?

A model of PRM performance was developed to determine the false-alarm rate and the late-alarm rate of the system. The following section describes an analysis of the performance of PRM designs based on that model. The model is statistically consistent and capable of modular improvement. In particular, as field data becomes available, it can be inserted into the model framework.

Model Assumptions

There are three basic assumptions in the PRM model. First, blunders and normal approaches are assumed to derive from different processes and should be described by different probability distributions. This assumption is made because blunders do not result from the tails of the distribution of normal approach deviations. Special events (such as an engine failure or the sudden onset of hazardous weather) are more likely to cause deviations large enough to endanger aircraft. Thus, blunders and normal approaches must be subjected to separate study.

The second assumption is that only one aircraft will blunder at a time. Since available FAA and NTSB records do not reveal any parallel runway blunders, the actual number, including unreported occurrences, can be assumed to be small. Therefore the probability of simultaneous blunders can be considered negligible.

The third assumption is that only one non-blundering aircraft is threatened by a given blunder. This assumption is always true if aircraft have proper in-trail spacings, a condition that is rarely violated. When the blundering aircraft enters the NTZ, terminal separation rules require the air traffic controller to turn away any aircraft on the other approach that are within 2.0 nmi of the blundering aircraft. However, these other aircraft will not be in a collision risk with the blunderer.

Alarm Criteria

Two types of monitoring alarms were defined for the analysis. The first is a caution alarm that indicates a possible blunder has begun; in this case the controller should ask the blundering aircraft to return to the runway heading. The second is a warning alarm that indicates a hazard has developed; in this case an endangered aircraft on the adjacent approach path should execute an avoidance maneuver. Each type of alarm is accompanied by distinctive visual and aural cues that immediately inform the controller of the type of alarm and the aircraft that are associated with it. In the analysis that follows, only the warning alarm is analyzed, although the techniques are applicable to the caution alarm as well.

The central issue in the design of the PRM detection algorithm is the warning-alarm criteria. A straightforward approach that takes advantage of the improved Mode-S surveillance accuracy is a linear projection of crosstrack position tested against a threshold. An alarm will be issued then if

$$\hat{y} + \tau\hat{\dot{y}} > q$$

where $\hat{y}$ and $\hat{\dot{y}}$ are estimated crosstrack position and velocity, τ is the projection time (also called tau), and q is the threshold. The estimated y positions and velocities are derived from a simple α-β tracker. If $\tau = 0$, the result is a simple test upon the current cross-range deviation, and the current air traffic controller's NTZ criteria is a special case of the above alarm design. Figure 17 illustrates the alarm design along with the mentioned special case. The alarm design employs different values of τ and q for the caution and warning alarms.

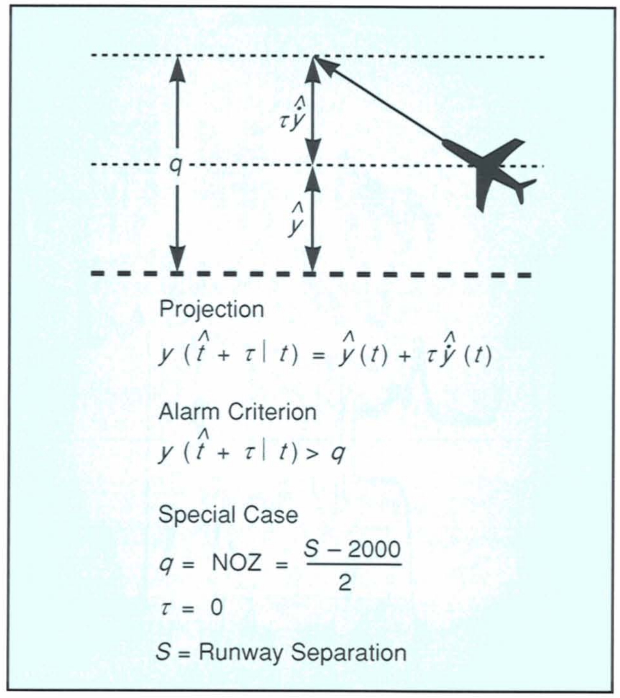


Fig. 17—The PRM alarm definition.

False-Alarm Rate

The false-alarm rate is the probability that the warning alarm will be given during an arbitrary approach even though no blunder exists. The probability of a false alarm (P_{FA}) for a given threshold can be calculated from a distribution of normal-approach trajectories.

Available normal-approach trajectory data [8,11] characterizes localizer deviations but does not include information on velocity. Normal-approach trajectories were synthesized, therefore, to calculate the false-alarm rate. The velocity can be derived from a sinusoidal model that approximates the normal-approach position

$$y(t) = \gamma \sin\left(\frac{2\pi}{T} t + \phi\right)$$

where γ is the amplitude representing the cross-range position deviations, T is the period, and ϕ is the phase. The amplitude was correlated to the peak-to-peak variation found in past studies [11]. The period and phase were represented with uniform distributions.

To derive the probability of a false alarm from the normal-approach model, an expression for

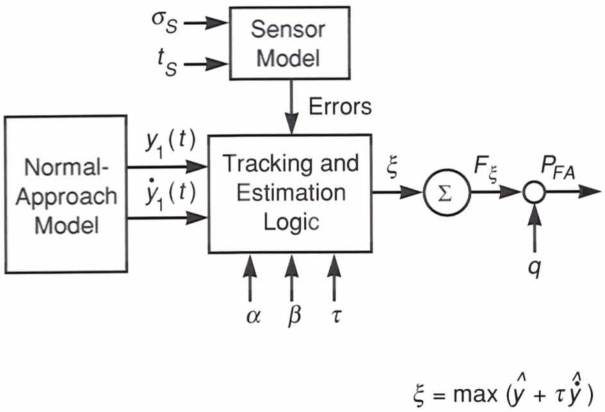
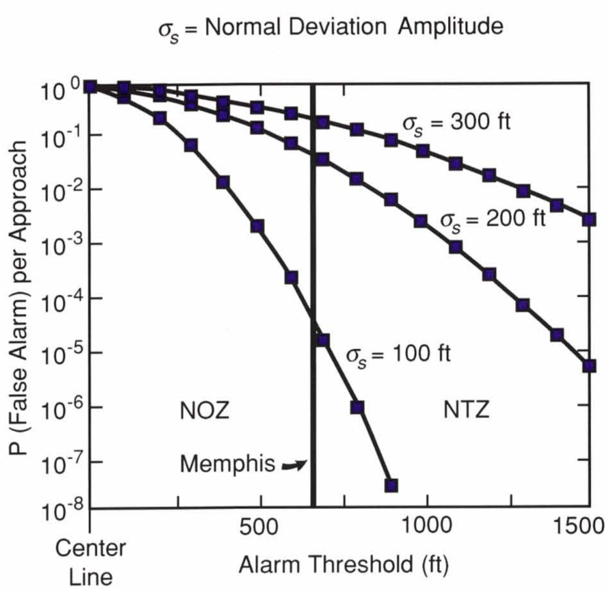


Fig. 18—Flow diagram of false-alarm simulation.

the maximum cross-range position was used. Then the alarm criterion was applied to the maximum position prediction for τ seconds. The probability of a false alarm is the probability that the maximum predicted position exceeds the alarm threshold q. This probability is equivalent to the probability that the amplitude γ will lie



Parameter	Symbol	Value
Normal Deviation Period	T	U(100,140) s
Projection Time	τ	10 s

Fig. 19—Probability of false alarm versus alarm threshold and normal deviation amplitude.

outside a two-sided confidence interval that corresponds to the region of no alarm. Defined in this way, the probability can be written

$$P_{FA} = 2 - 2F_\gamma\left(\frac{q}{\sqrt{1 + \left(\frac{2\pi\tau}{T}\right)^2}}\right)$$

where F_γ is the cumulative distribution function for γ. The tails of the γ distribution will provide the false alarms for practical operating points.

Figure 18 summarizes the process of determining the PRM false-alarm rate through simulation, where σ_S is the cross-range standard-deviation error and t_S is the sensor update interval. Figure 19 shows representative false-alarm rates, as well as the relationship of the false-alarm rates to the alarm thresholds and the normal-approach deviations. The estimated localizer deviations and velocities of the model will be replaced with the actual distribution of normal-approach trajectories from the Memphis data.

Late-Alarm Rate

The second part of the model determines the probability of a late alarm (P_{LA}). Given that a blunder is occurring, the late-alarm rate is the probability that the alarm will be issued too late for effective avoidance. The major effort in calculating the late-alarm rate is in modeling the aircraft blunder.

The blunder model is based on several assumptions about the sequence of events when an aircraft abnormally deviates (blunders) during final approach. Figure 20 illustrates the blunder scenario. The start of the blunder maneuver is assumed to be a randomly selected point on a normal approach. The deviating aircraft then accelerates with a constant rate until the crosstrack velocity W is achieved; thereafter the aircraft is constrained to W. The alarm criterion is based on the motion of the blundering aircraft, and not on the relative motion with respect to the threatened aircraft.

The model includes a delay between the alarm generation and the controller's transmission of the alarm to the aircraft. The avoidance maneuver of the threatened aircraft consists of

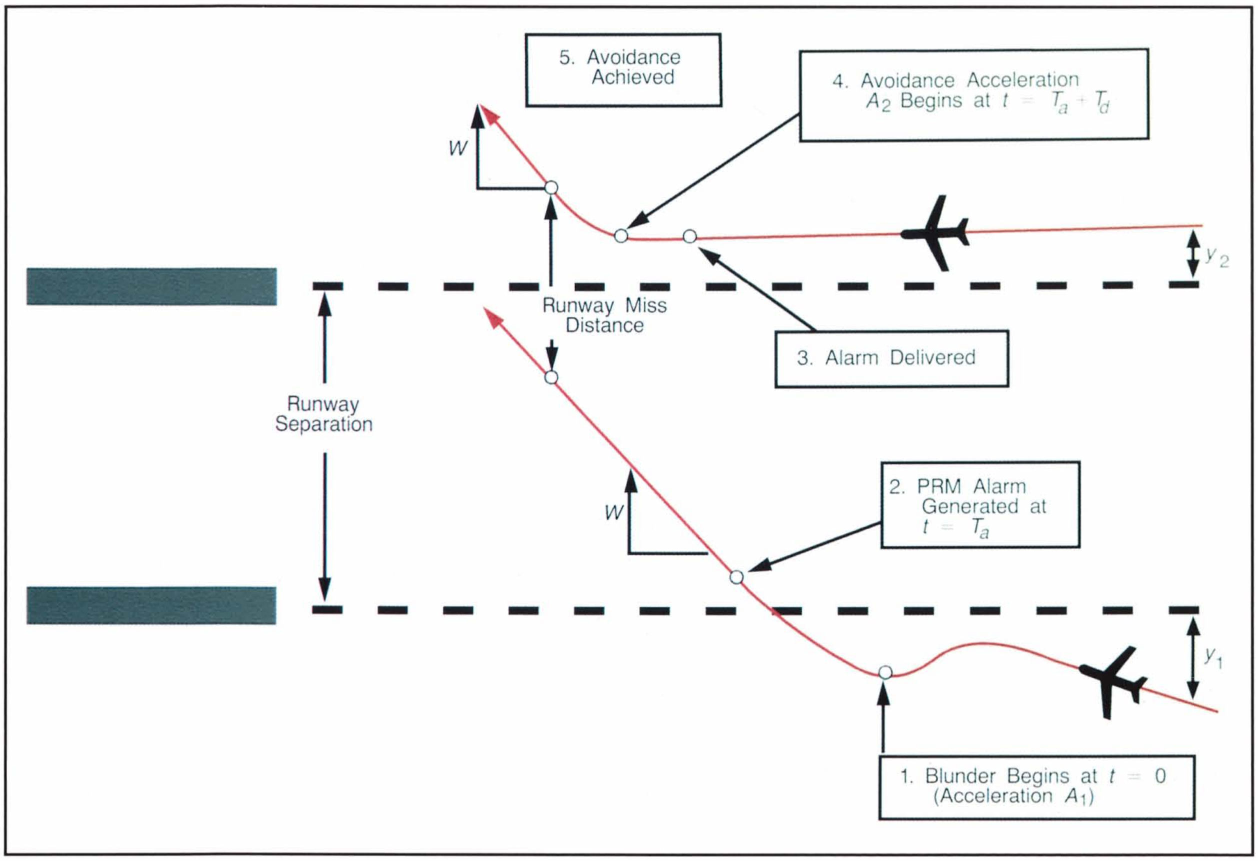


Fig. 20—Blunder-model event sequence.

another delay (due to the reaction time of both the pilot and the aircraft), followed by a constant acceleration that is also constrained by the crosstrack velocity W. Note that the time required for the controller to transmit an alarm to the aircraft and for the aircraft to respond is independent of the motion that generated the alarm.

The major concern with a blundering aircraft is that the warning alarm might be late. Therefore, an objective of the model is to examine the delay times inherent with each step. To examine delay times, the various delays were combined into two main delays. The first delay is the time T_a required to detect the blunder. The second delay is the time T_d required to issue the avoidance instruction and begin the avoidance maneuver. Note that T_d combines the controller delay in issuing the alarm and the aircraft delay in starting the avoidance maneuver. For the sake of mathematical simplicity, these delays are combined into one delay term in this formulation.

The next step in developing the model is to describe the positions of the blundering aircraft and the threatened aircraft when avoidance is achieved. The *miss distance* is the cross-range separation of the two aircraft at that time, and a specific miss-distance requirement determines the upper limit of a tolerable delay time, $\tilde{T}_d$. Any longer value of T_d will result in a late alarm. The equation for $\tilde{T}_d$ can be written in closed form:

$$\tilde{T}_d = \frac{S - m_{req}}{W} + \frac{y_2 - y_1}{W} - \frac{(W - \dot{y}_2)^2}{2A_2W} + \frac{(W - \dot{y}_1)^2}{2A_1W} - T_a .$$

The right side of the above equation has five terms. The first term is the warning time provided by that portion of the runway separation which is in excess of the required separation

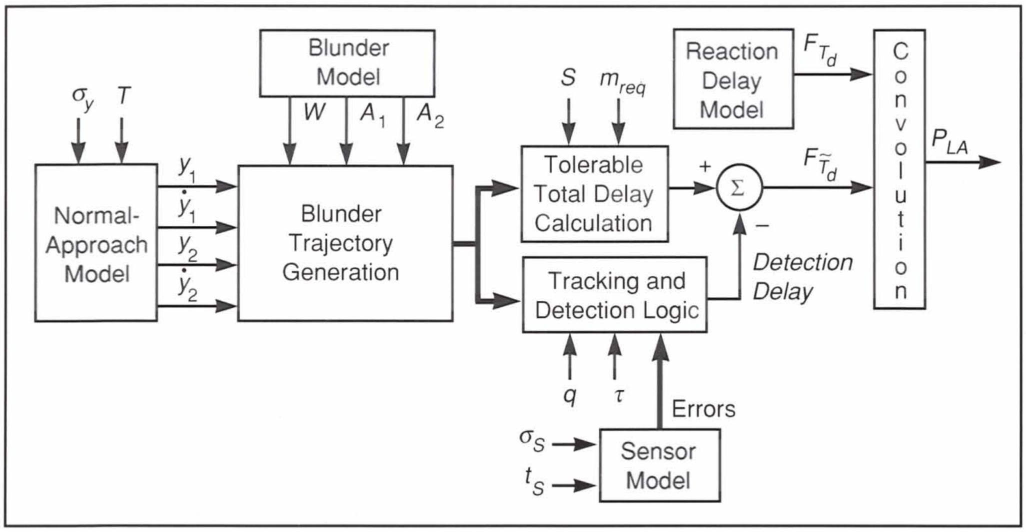


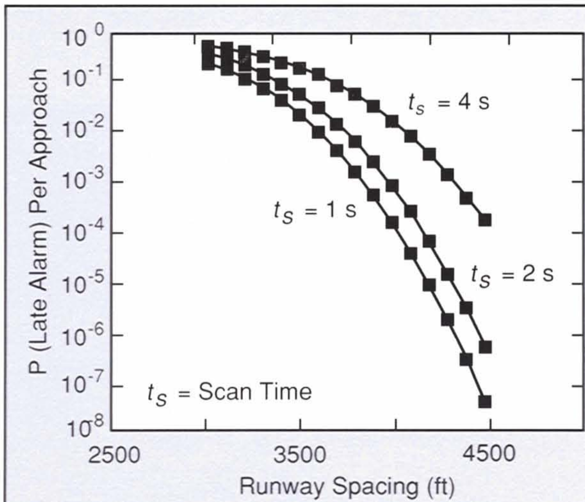
Fig. 21—Diagram of the late-alarm simulation.

between aircraft. The second term is the warning time generated by the initial deviation of the aircraft from the runway centerlines at the start of blunder (for aircraft 1) and start of resolution (for aircraft 2). This warning time can be either positive or negative. The third term is the warning time lost because of the finite acceleration capability of the avoiding aircraft. (If the avoiding aircraft could instantly accelerate to the needed escape speed, then this term would go to zero). The fourth term is the warning time gained by the fact that the blundering aircraft has finite acceleration (and does not achieve blunder rate W instantaneously). The fifth term is the warning time lost in detecting the blunder (i.e., the elapsed time from start of blunder until the alarm appears on the controller's display monitor).

The probability of a late alarm on a given trial is the probability that the delay time T_d exceeds the maximum tolerable delay time $\tilde{T}_d$. In mathematical notation this probability is

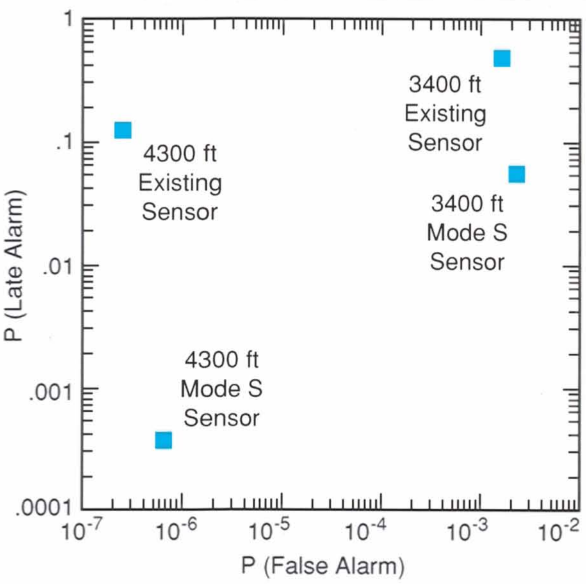
$$P_{LA} = P\left[\tilde{T}_d < T_d\right].$$

Recall that the delay T_d that is actually achieved depends on the response of both controller and aircraft, and is independent of surveillance and aircraft motion leading to the alarm. Thus, treating response T_d as the primary variable leads to a convenient formulation



Parameter	Symbol	Value
Normal Deviation Amplitude	γ	200 ft
Normal Deviation Period	T	100 s
Required Miss Distance	m_{req}	200 ft
Radar Cross-Range Error	σ_S	30 ft
Tracker Gains	α	0.8
	β	0.53
Alarm Threshold	q	1000 ft
Projection Time	τ	10 s
Final Cross-Range Velocity	W	70 kt
Acceleration	$A_1 = A_2$	0.5 g
Actual Response Delay	T_d	U(10, 20) s

Fig. 22—Probability of late alarm versus runway spacing and radar scan time.



Parameter	Current	Mode S
Update Rate	4.8 s	2.4 s
Prediction	0 s	5 s
Response (Td)	U (7.5, 15)	U (7.5, 15)

Fig. 23—Preliminary false-alarm late-alarm model results. These results suggest significant performance benefits when the Mode-S sensor is used as an approach monitor.

in which the distribution of $\tilde{T}_d$ can be determined by simulation, and the distribution of T_d can be determined from a separate probability distribution.

The probability of a late alarm can be rewritten as

$$P_{LA} = P\left[\tilde{T}_d - T_d < 0\right].$$

This equation can be evaluated by integrating the probability density function of $\tilde{T}_d$ (obtained from simulation) and the cumulative probability distribution function of T_d (specified from theory or experiment). When T_d is uniformly distributed from $t_{\max}$ to $t_{\min}$, then

$$P_{LA} = \frac{1}{t_{\max} - t_{\min}} \int_{t_{\min}}^{t_{\max}} F_{\tilde{T}_d}(\xi)\, d\xi$$

where $F_{\tilde{T}_d}$ is the cumulative distribution function for the tolerable delay time.

Figure 21 shows a block diagram of the simulation to determine the distribution of $\tilde{T}_d$.

Figure 22 shows representative late-alarm rates versus runway spacing and radar scan times.

Preliminary Model Results

Simulations that use preliminary assumptions for controller and aircraft response delays have produced two outputs: system operating points and a sensitivity analysis. System operating points, shown in Fig. 23, define the relationship between false alarm and late alarm for four cases that compare the current FAA monitoring system with a Mode-S-based monitor for runway separations of 4,300 ft and 3,400 ft, and for the current 2,000-ft NTZ. The results suggest the potential benefits of improved surveillance and the use of an automatic alert. While the assumptions used to generate the operating points are reasonable, performance comparisons cannot be made until the model uses measured probability density functions of controller-response, pilot-response, and aircraft-response times.

A sensitivity analysis determined the relative importance of various system parameters. A set of parameter values were chosen to establish a system baseline. Each parameter was then varied to determine the change in false-alarm

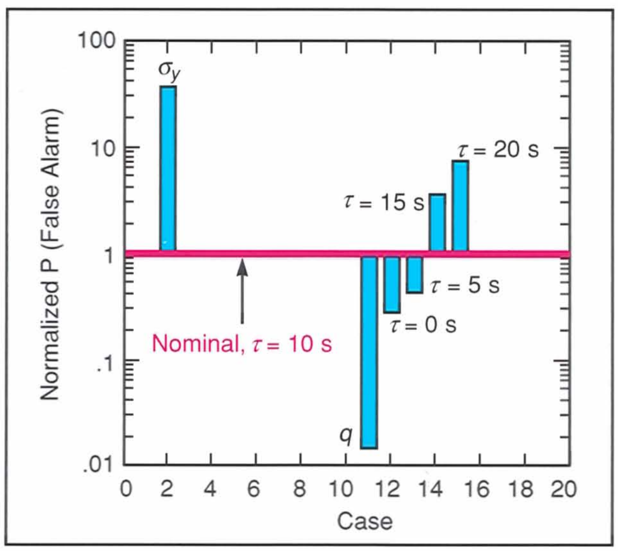


Fig. 24—Preliminary model results for false-alarm sensitivity analysis.

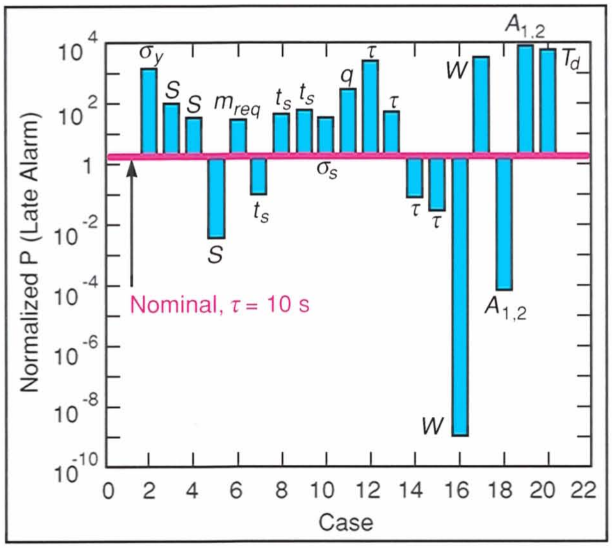


Fig. 25—Preliminary model results for late-alarm sensitivity analysis.

and late-alarm rates relative to the baseline performance. The results are shown in Table 3 and Figs. 24 and 25.

The sensitivity analysis results for false alarms show expected effects when parameters such as aircraft deviation and alarm threshold change. Interestingly, the cost of introducing a 10-s tau prediction is only a threefold increase in false-alarm rate (case 12 in figure 24 and Table 3). This analysis focused subsequent work on those parameters which have the greatest effect on system performance.

While most of the parametric variations shown in Fig. 25 have some effect on late-alarm statistics, the assumptions concerning the human-response and aircraft-escape times have major consequences in monitor performance. Realistic estimates of aircraft deviations, controller-response delay, communications delay, pilot delay, and the endangered aircraft's response delay must be developed and validated to complete the system performance analysis. Also, with regard to aircraft deviations, the weather conditions in which aircraft can maintain flight within the normal operating zone must be characterized. Activities to characterize each of these parameters are discussed in the following paragraphs.

Aircraft-Deviation Data Collection

To obtain statistical descriptions of aircraft deviations, the test facility at Memphis was provided with extensive instrumentation. Figure 26 illustrates the Memphis recording facilities. Surveillance, weather, and flight data were collected during most major arrival periods requiring instrument flight. The weather data included visibility as reported by the tower controller, ceiling reported by the Automatic Terminal Information System (ATIS), predicted winds aloft obtained through Weather Systems Incorporated (WSI, a commercial weather source), additional ceiling measurements taken from laser ceilometers located at the north and south ILS outer markers, and flight data obtained from the FAA ARTS computer system.

From November 1988 to June 1989 approximately 10,000 IMC approaches to the parallel runways at Memphis Airport were measured to characterize the effect of weather and aircraft type on localizer deviations. Federal Express is currently assisting in the collection of additional data to characterize the effect of flight mode (autopilot versus hand-flown) on approach deviations.

Figure 27 shows a typical data set. During the 29 January 1989 recording session, 57 aircraft

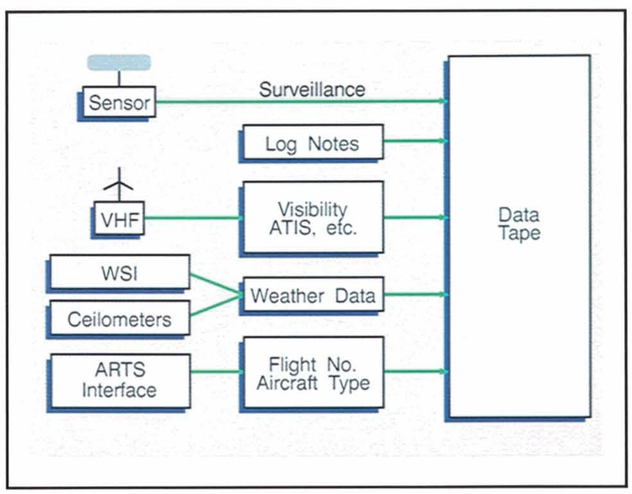


Fig. 26—PRM data recording facilities at Memphis International Airport.

Table 3. Sensitivity Analysis Parameters For Figures 24 & 25

Case	*Parameter*	*Symbol*	*Nominal Value*	*Varied Value*
2	Normal Deviation Amplitude	σ_y	157.4 ft	346.0 ft
	Normal Deviation Period	T	100 s	–
3	Runway Separation	S	3,400 ft	3,000 ft
4				3,200 ft
5				3,600 ft
6	Required Miss Distance	m_{req}	200 ft	400 ft
7	Radar Scan Time	t_S	2.4 s	2.0 s
8				4.0 s
9				4.8 s
10	Cross-Range Error of Radar	σ_S	30 ft	100 ft
11	Alarm Threshold	q	700 ft	1,000 ft
12	Alarm Logic Projection	τ	10.0 s	0 s
13				5 s
14				15 s
15				20 s
16	Final Cross-Range Velocity	W	70.0 kt	50.0 kt
17				90.0 kt
18	Blunderer's Acceleration	A_1, A_2	0.25 g	0.1 g
19	and Avoiding Aircraft's Acc.			0.4 g
20	Actual-Response Delay Time	T_d	U[5, 10] s	U[10, 18] s

arrived on runways 18 Left and 18 Right. Most aircraft were Boeing 727, DC-9, Boeing 757, and a few turboprop commuter aircraft. Each point represents the radar target-report position estimate at each 2.4-s update interval. The scale was expanded in the east-west direction to clarify deviations, and a 2,000-ft NTZ was added. The weather during this data set consisted of a measured 200-ft overcast ceiling, 1/2-mi visibility in fog and light rain, a 54° temperature and dew point, a 3-kt wind from 020 degrees, and a barometric setting of 30.09 inches.

Figure 28 compares the 29 January data and IMC data from 26 January. The 9-kt surface-level crosswind on 26 January is a possible explanation for the larger approach deviations

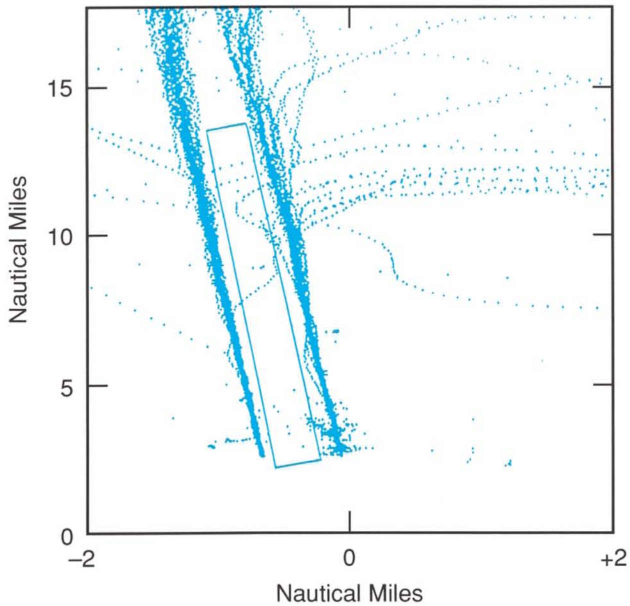


Fig. 27—Approach data for 57 aircraft at Memphis International Airport on 29 January 1989 from 14:30 to 15:50.

that day. However, an examination of the winds-aloft estimates in Table 4 shows significantly greater crosswinds on 26 January at the approach altitudes where the deviations occurred. Also, the velocity-versus-altitude gradient suggests strong turbulence. These data indicate that aircraft on 26 January experienced a much stronger west wind and probable turbulence during the final approach. Similar analysis of other approaches will establish the specific weather conditions in which flight crews can be expected to avoid the NTZ during parallel-approach operations.

The FAA Technical Center staff at O'Hare Airport in Chicago collected data during 3,000 simultaneous ILS approaches in IMC. The Chicago data, along with data collected at Raleigh-Durham Airport by FAA contractors at an E-scan PRM sensor site, will be added to the Memphis data for analysis of aircraft behavior.

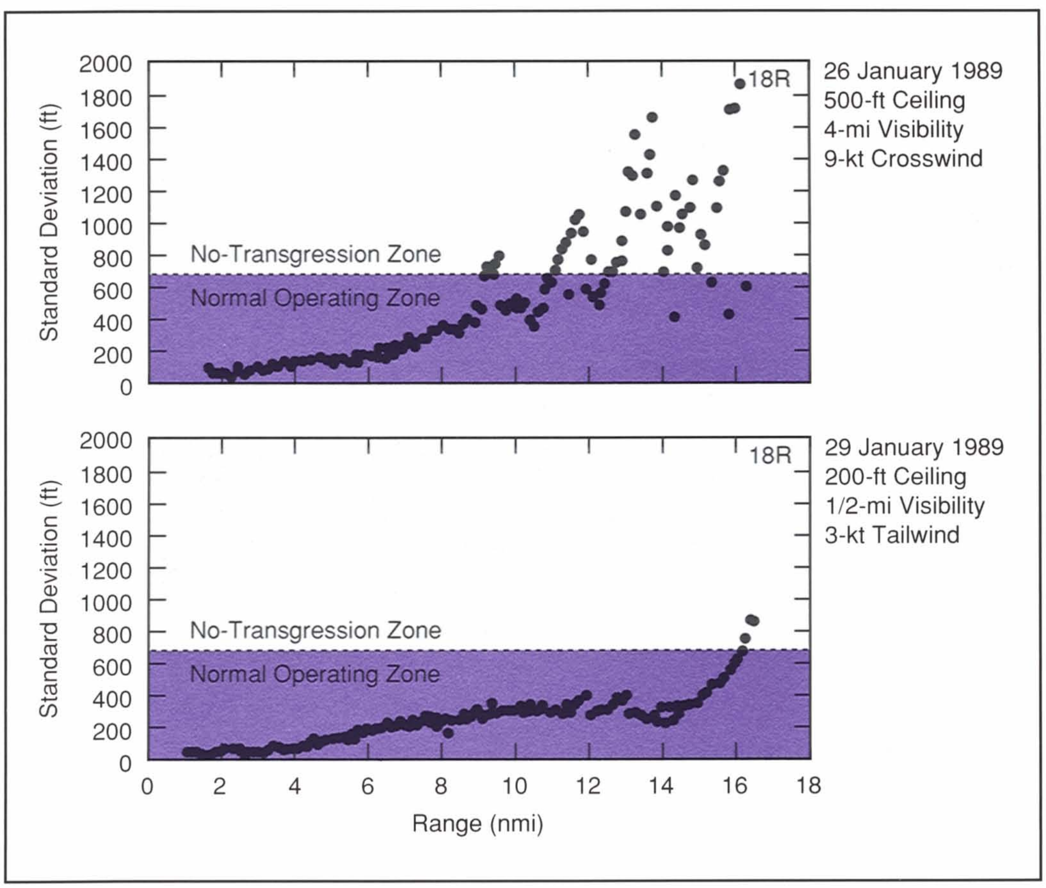


Fig. 28—Analysis of approach data at Memphis International Airport on 26 January 1989 and 29 January 1989.

Table 4. Winds Aloft Estimates (National Weather Service)

	26 January Winds		*29 January Winds*	
Altitude Feet MSL	*Velocity Knots*	*Direction Deg. Magnetic*	*Velocity Knots*	*Direction Deg. Magnetic*
1,000	39	234	20	231
2,000	39	232	24	244
3,000	47	225	28	236
4,000	64	258	33	230
5,000	65	261	40	253

Controller-Response-Delay Data Collection

Past activities to measure monitor-controller responses have not included the effect of high-resolution color displays and predictive alerts. To understand these effects a human-factors investigation of the reaction time of controllers in various potentially hazardous conditions has begun. A simulation was chosen to insure careful control of the experimental variables under study.

The study exposes 25 pairs of experienced air traffic controllers to audio-visual simulations of

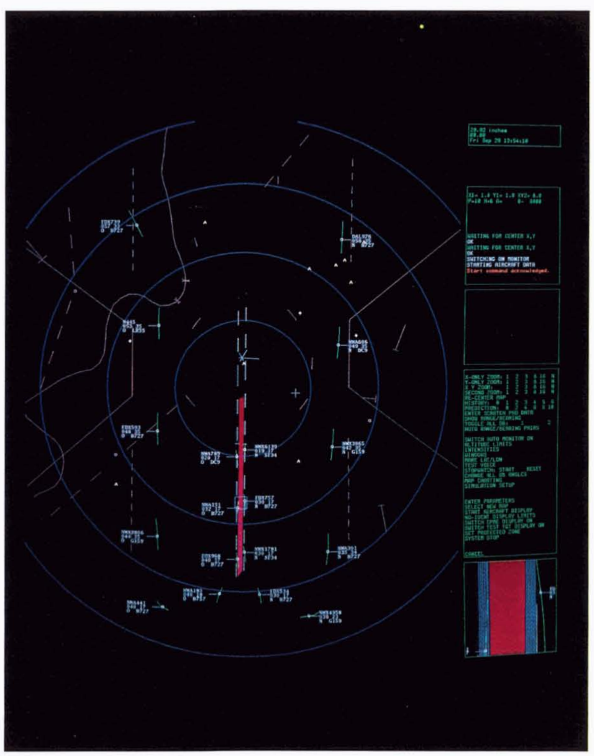


Fig. 29—Computer simulation of simultaneous ILS at Memphis International Airport.

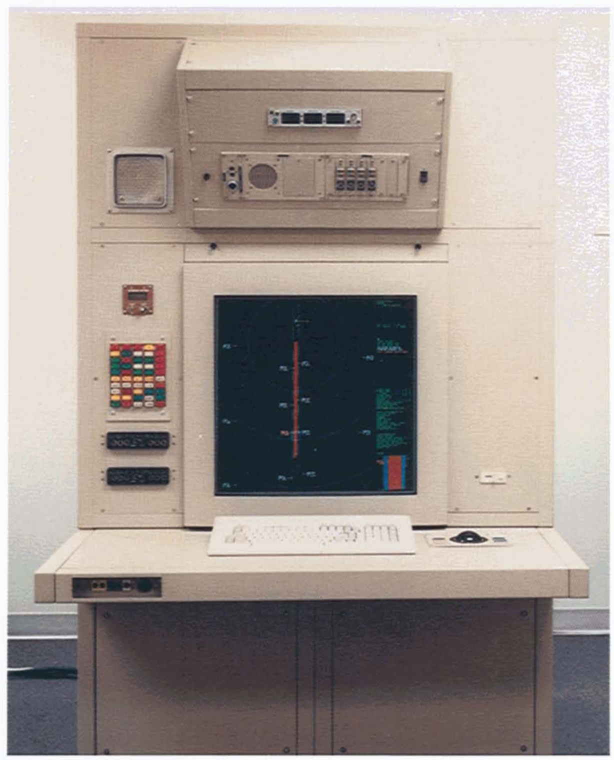


Fig. 30—Photograph of the PRM controller test console at Memphis International Airport.

approach blunders during simultaneous arrivals at Memphis Airport. The simulation has been designed with the assistance of Memphis tower staff and controllers, and is based on actual air traffic. Figure 29 shows an example of the traffic simulation that will be used; Fig. 30 shows the experimental console.

While speed of response is one measure of the effectiveness of the new monitoring technology, the accuracy of the response is also a concern of the study. The controller must not break out an aircraft because he misinterpreted the trajectory of another aircraft that was not blundering. The study specifically examines the changes in controller reaction time that may be attributed to a number of variables, including type and degree of blunder, sensor update rate, and flight-path conditions. The data will be collected during the first six months of 1990.

Communications Delay

The monitor controller has the ability to override the tower controller to communicate an urgent evasive command to an endangered aircraft. Since the controller cannot override a pilot's transmission, a delay will occur while the controller waits for the pilot to finish transmitting. To characterize the likely rate and length of these delays, audio tape recordings from Memphis and Chicago are being analyzed.

Pilot and Aircraft Evasion Response Delay

Pilot delay and aircraft response-delay data were measured at the FAA Mike Monroney Aeronautical Center in Oklahoma City, Okla. FAA staff, with recommendations from Lincoln Laboratory, used a full-scale Boeing 727 cockpit simulator to measure the response of air carrier flight crews to sudden and urgent evasive maneuvers while flying final approach. The maneuvers were commanded at random times and various distances from the runway threshold. The data is being analyzed by the FAA and will be provided to Lincoln Laboratory.

User Acceptance

While careful technical justifications for new air traffic procedures must be established within the framework of Federal Air Regulations, the acceptance of the user community—air carriers, airline pilots, airport operators, and the general public—must also be obtained. A variety of representatives from various aviation groups have visited the Memphis test site and observed live, recorded, or simulated traffic, and participated in flight tests. The demonstrations provided the user community with a firsthand experience of the benefits of improved surveillance, displays, and automatic alerts. Reactions thus far have been occasionally cautious but generally positive. The major concern for many visitors is not whether the approaches can be safely monitored. Rather, it is that aircraft must be monitored when simultaneous missed-approach procedures occur to insure that the two aircraft don't drift toward each other before they have established diverging courses. This concern is the reason for the current work to improve surveillance in the immediate vicinity of the runways.

Conclusions

While the parallel runway monitoring development continues, several conclusions can be made. First, the Mode-S sensor can operate in the 2.4-s back-to-back antenna mode and provide high-quality surveillance data during parallel-approach operations. The sensor is expected to support the requirement for surveillance during missed-approach procedures. Second, new displays and automatic alerts significantly improve the ability of the controller to monitor arriving traffic and detect deviations. Third, modeling and analysis have led to additional data-collection activities to characterize various delay factors, including a major human-factors study, and a significant data base has been established to characterize how well aircraft fly parallel approaches. Finally, user-community acceptance has thus far been very positive.

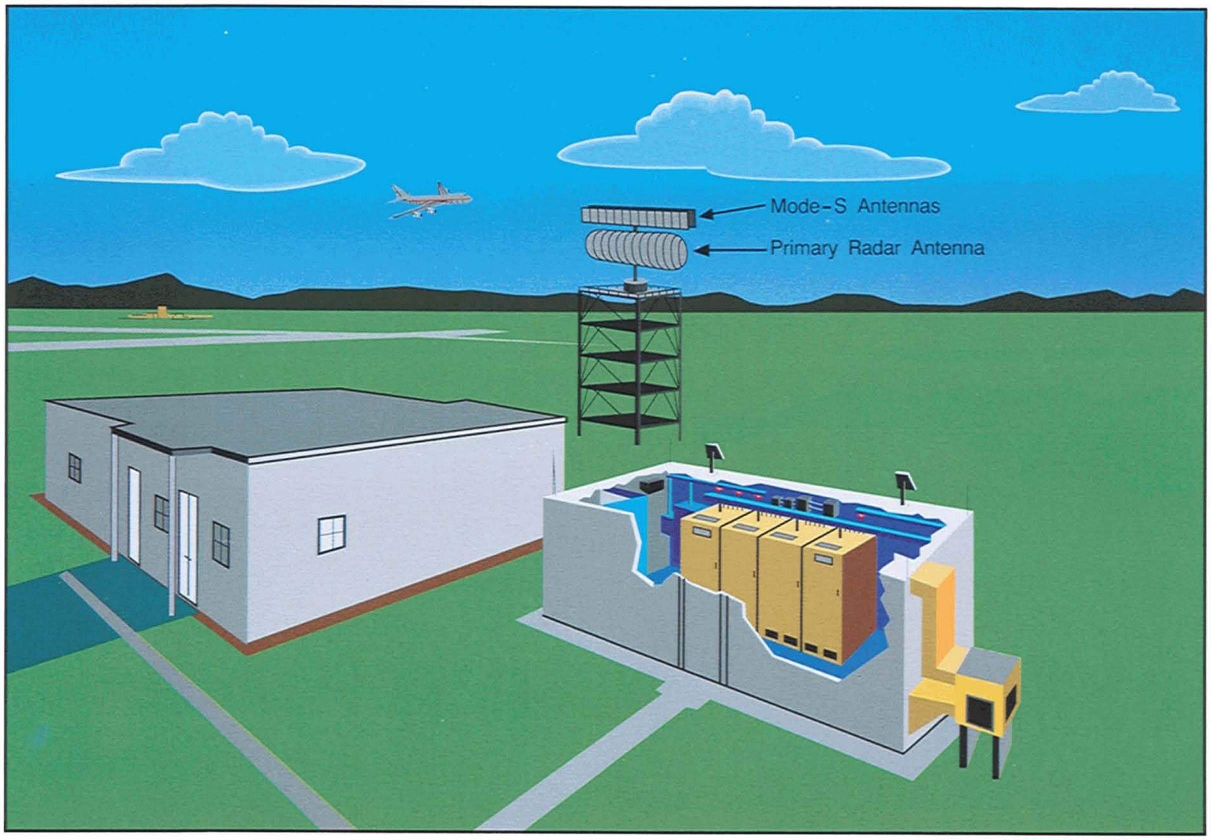


Fig. 31—Operational implementation of Mode-S approach monitor.

Future Work

The data-collection activities are expected to be completed by the middle of 1990, and data analysis results will be available to support FAA implementation decisions by late 1990. Figure 31 shows the expected configuration of a Mode-S-based PRM sensor, colocated with a primary radar.

Acknowledgments

The results reported in this article are due to the dedicated efforts of many people in the System Design and Evaluation Group at Lincoln Laboratory. The successful collection of field data, and the demonstration of the monitoring system to hundreds of visitors at the Memphis International Airport experimental field site, was due to the fine support provided by the on-site personnel. Considerable assistance was also provided by air traffic and airways facilities personnel at the Memphis Air Traffic Control Tower, Northwest Airlines, and Federal Express.

Finally, I would also like to acknowledge FAA headquarters management for their continuing support during this effort.

References

1. "Parallel ILS/MLS Approaches", *Air Traffic Controllers Handbook*, Federal Aviation Administration, Par 5-125,126.
2. Estimated by Memphis Air Traffic Control Tower management personnel.
3. "Parallel and Converging Runway Program," *FAA Research, Engineering and Development Conference, Washington, D.C., 18 Aug. 1987*, Conference presentation reproduction.
4. "Airport Capacity", *FAA Research, Engineering, and Development Conference, Washington, D.C., 18 Aug. 1987*, Conference presentation reproduction.
5. J.A. Fantoni and R.D. Rudich, "Evaluation of Parallel Runway Spacing," *Interim Report Task No. 412-3-2T,*

Federal Aviation Agency, National Aviation Facilities Experimental Center (July 1961).
6. J.R. Speckart, "An Operational Evaluation of the Parallel ILS System—O'Hare International Airport," Flight Standard Service, Flight Inspection and Processing Division, Standards Branch, Federal Aviation Administration (Nov. 1962).
7. "Lateral Separation," *Report FAA-RD-72-58* **1, 2,** Resalab Inc, (July 1972).
8. A.L. Haines, "Reduction of Parallel Runway Requirements," MITRE Corporation (Jan. 1973), FAA-EM-73-9.
9. A.L. Haines, "Requirements for 3500 Foot Spacings for Simultaneous Parallel IFR Approaches," MITRE Corporation (Jan 1975) MTR-6841.
10. A.L. Haines and W.J. Swedish, "Requirements for Independent and Dependent Parallel Instrument Approaches at Reduced Runway Spacing," MITRE Corporation (May 1981), FAA EM-81-8.
11. D. Buckanin and R. Biedrzycki, "Navigation Performance of Aircraft Making Dependent ILS Approaches at Memphis International Airport," FAA Technical Center (Feb. 1987) DOT/FAA/CT-TN86/59.

RAYMOND R. LaFREY is an associate group leader in the System Design and Evaluation Group. He is currently program manager of the Parallel and Converging Runway Monitor Program, and oversees development programs in Mode-S Data Link Avionics and Mode-S Surface Surveillance and Communications. He is also the leader of a technical team supporting the FAA in the development of a joint U.S.–Soviet satellite navigation capability for civil aircraft.

Ray began working on FAA programs in 1974, designing digital and analog hardware for an instrument-approach monitor. In 1979 he managed a design team that developed TCAS II flight hardware, and led several TCAS II flight-test activities on various aircraft, including a Boeing 727. During the 1980s he managed the development of various Mode-S data-link avionics; a GPS navigation set for small general aviation aircraft; and the design of TCAS II air-to-air coordination logic, which involved several hundred staged midair encounters.

Ray received B.S.E.E. and M.S.E.E. degrees from Michigan State University in 1961 and 1963, respectively. He served as a research and development test officer in the U.S. Army from 1963 to 1969, with assignments in the United States, Vietnam, Europe, and Africa. He is a member of the Institution of Electrical Engineers, Eta Kappa Nu, Tau Beta Pi, AOPA, and NAA. Ray received an FAA commendation for his efforts in the development of TCAS II. He is also a licensed private pilot and owns a Piper Archer II.