Precision Runway Monitor

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The prevalence of delay in scheduled airline flights in recent years has caused great interest in the use of new technologies that promise increased airport capacity, especially in poor weather. One consequence of this interest in new technologies is development of the Precision Runway Monitor (PRM) system. The PRM system uses enhanced radar and display capabilities combined with automatic safety alerts to allow safe operation of independently sequenced approaches, in instrument meteorological conditions, to parallel runways separated by less than 4300 feet (the current minimum separation without PRM). During the past several years, Lincoln Laboratory has carried out a development program for the PRM that has included field data collections, demonstrations, performance evaluation, and risk analysis. Partly on the basis of the results of this program, the FAA recently authorized independently sequenced approaches to parallel runways separated by 3400 feet or more, when these approaches are monitored with a PRM system. The FAA also initiated an implementation program to install PRM systems at several major U.S. airports. This article reports the results of field activities carried out by Lincoln Laboratory, the use of these results to verify the performance and safety of the PRM system, and continuing development that is part of the Lincoln Laboratory PRM program.

One of the most troublesome aspects of air travel in the United States is the frequency and length of delays in scheduled airline flights. Although delays have many sources, widespread schedule delays are most often associated with inclement weather at the nation's busiest airports, or at airports that serve as hubs for the nation's major airlines. At many airports, poor weather requires changes in procedures that in turn reduce the number of runways in use or the rate at which aircraft can approach and depart from the runways that are available. In the recent past, there has been great interest in a variety of new technologies that promise to maintain arrival-and-departure capacities for poor weather at or near the corresponding capacities for good weather. The Precision Runway Monitor (PRM) development conducted by Lincoln Laboratory is an effort to use new technology to increase poor-weather capacity at airports having parallel runways.

The PRM system incorporates new secondary surveillance-radar systems capable of making aircraft position measurements that are more accurate and updated more frequently than the measurements made by current terminal-area sensors. In addition, the PRM provides new computer and video-display technologies to give controllers a clearer picture of aircraft location during final approach than has been possible in the past. The display system also includes automatic alerts designed to focus the controllers' attention on a potential problem before it becomes critical.

Motivation for Precision Runway Monitor

The minimum allowed in-trail separation (the distance along the approach course between two aircraft approaching the same runway) typically limits the maximum landing rate of aircraft on a single runway. For aircraft of the same general type and size, runway occupancy time usually determines the minimum in-trail separation. Runway occupancy time is measured from the moment the aircraft touches down on the runway to the time it has turned onto a taxiway and the runway is again clear. The minimum separation is normally set at 3 nmi, although runway configuration and taxiway layout allow a 2.5-nmi minimum separation at some airports. When a small aircraft is following a larger one, a longer in-trail separation is required because of wake-turbulence considerations. When more capacity is needed than is available for a single runway, the only solution is to add runways. One common configuration is the addition of a second runway parallel to the first. If aircraft arriving at each runway can be sequenced independently (as though the other runway did not exist), as they can for most parallel runways in clear weather, the second runway approximately doubles the arrival capacity of the airport.

One major concern associated with independently sequenced approaches to parallel runways is the possibility of an approach blunder, which is a situation that occurs when one aircraft turns away from the approach course in a direction that may endanger an aircraft on approach to the other runway. Depending on the ability of pilots to see nearby aircraft and thus to maintain safe separation with other aircraft approaching the parallel runways, Federal Aviation Administration (FAA) rules allow for independent sequencing of aircraft to parallel runways separated by as little as seven hundred feet in clear weather. When weather conditions are poor (in low clouds, heavy rain, or fog, for example), a pilot often cannot see nearby aircraft on approach to the other parallel runway. Thus direct visual contact is not sufficient to maintain safe separation.

Under these conditions, FAA regulations require air traffic controllers to staff a special radar-monitoring position dedicated to maintaining separation between aircraft, and (until recently) required that the parallel runways be separated by at least 4300 feet for the controllers to be able to use independently sequenced approaches. The restriction to runways separated by 4300 feet or more is due to inaccuracies in measurement and display of aircraft positions and delays involved in the machine and human reactions needed to detect and resolve blunders.

Many people believed, however, that new technology could improve aircraft position measurements and reduce the machine and human delays in the system, which could then reduce the minimum allowed inter-runway separation for independent sequencing of aircraft during poor weather. This reduced minimum separation, in turn, would allow additional airports to maintain arrival capacities in poor weather that are nearly equal to their capacities in clear weather, thus reducing schedule delays. In the late 1980s the FAA undertook to develop a system that provides these benefits, a system that became known as the PRM.

As part of the FAA's PRM program, Lincoln Laboratory carried out an extensive development, testing, and demonstration effort that produced the PRM system design and examined the feasibility of using a modified Mode S secondary surveillance radar for precision runway monitoring. The initial work on the PRM program was reported previously in this journal in an article that also provides more detailed background on parallel-approach procedures [1]. Additional work carried out since 1989, along with summaries of the major results of the Lincoln Laboratory PRM program, are reported here.

Overview of the PRM Development and Demonstration Program

To establish the feasibility of a PRM system and determine if it could be based on the Mode S sensor, we had to address a number of technical and human-factors issues. In support of this objective, Lincoln Laboratory developed a prototype Mode S PRM system that incorporated dual antennas mounted in a back-to-back configuration so that the surveillance-radar update interval was cut in half. This prototype secondary surveillance radar and the PRM display system developed by Lincoln Laboratory were installed at a PRM field site at Memphis International Airport. Most of the data collection and demonstration activities during the Lincoln Laboratory PRM program were performed at this field site. The primary issues and questions addressed during these data collection and demonstration activities were the following:

1. *Surveillance Performance.* What quality of surveillance data does a Mode S sensor configured with back-to-back antennas provide for aircraft on final approach and aircraft on missed approach during independently sequenced parallel-runway operations?

2. *Data Display.* How can the surveillance data best be provided to the monitor controller? The format of the data display is likely to be different from the format used for a non-monitor control position because of the different needs and responsibilities of the monitor control position.
3. *Automation.* What are the benefits of automatic caution and warning alerts, and how can the alert information best be presented to the monitor controller?
4. *System Performance.* What is the overall performance of the monitoring system? What are the machine and human components of the monitoring system? How well does each component of the monitoring system perform its function? What is the risk that the system will fail to detect and successfully resolve a blunder situation, given the performance of the human and machine components?
5. *User Acceptance.* Is the system acceptable to the user community, including pilots, air traffic controllers, airlines, and airport operators?

Early in the PRM program we concentrated on development of the prototype back-to-back Mode S sensor and the PRM controller workstation. When these prototype systems became available for field testing, the focus shifted to studies of surveillance performance and data-display formats. Examination of the benefits of automation and initial formulation of system performance issues also began during this time [1].

The following section of this article focuses on the results of data-collection, analysis, and system-demonstration activities that were designed to (1) characterize the performance of the human and machine components of the monitoring system; (2) estimate the risk associated with simultaneous, independently sequenced approaches when monitored by the PRM system; and (3) assess the acceptability of the system to the user community. Following the description of data collection and analysis activities, we summarize the current status of PRM implementation; discuss the Final Monitor Aid, which is a recent outgrowth of the PRM program; and give an overview of the continuing PRM development work going on at Lincoln Laboratory and the FAA.

PRM Data Collection and Analysis Activities

To characterize the overall performance of the PRM system, Lincoln Laboratory in cooperation with the FAA and other FAA contractors conducted extensive data collection and analysis. The components of this study are most easily understood if we first examine the sequence of events that occur during the onset, detection, and resolution of a blunder during independently sequenced parallel approaches. Figure 1 is a schematic diagram of an approach blunder. The diagram shows the sequence of events, identified by numbered dots, beginning with the onset of the blunder at location 1, and continuing through several machine or human actions until the two aircraft begin to diverge at location 6.

This sequence of events can also be characterized by a set of time and distance parameters that together determine the minimum separation between the aircraft. These parameters, which are depicted in Figure 1 as time-and-space intervals labeled with letters, are the following: (a) the time used by the sensor to detect the blunder and generate an alarm; (b) the time used by the monitor controller to recognize the alarm, decide whether a breakout instruction is needed, and determine when to issue the instruction; (c) the time required to communicate the instruction to the pilot of the endangered aircraft; (d) the time required for the aircraft crew to recognize the instruction and give the control inputs, and for the aircraft to respond to the control inputs and maneuver to the point where the separation between the aircraft is increasing; and (e) the lateral distance between the two aircraft at the start of the blunder.

A valid characterization of PRM system performance requires an understanding of the values that each of these parameters can be expected to have during blunder situations. This process is complicated by the fact that the parameters do not have a single characteristic value, but rather are statistical variables that take on a range of values with a characteristic distribution. Separate measurement and analysis efforts were carried out to provide realistic statistical distributions for each parameter. Evaluation of overall PRM system performance then used the measured statistical distributions as input.

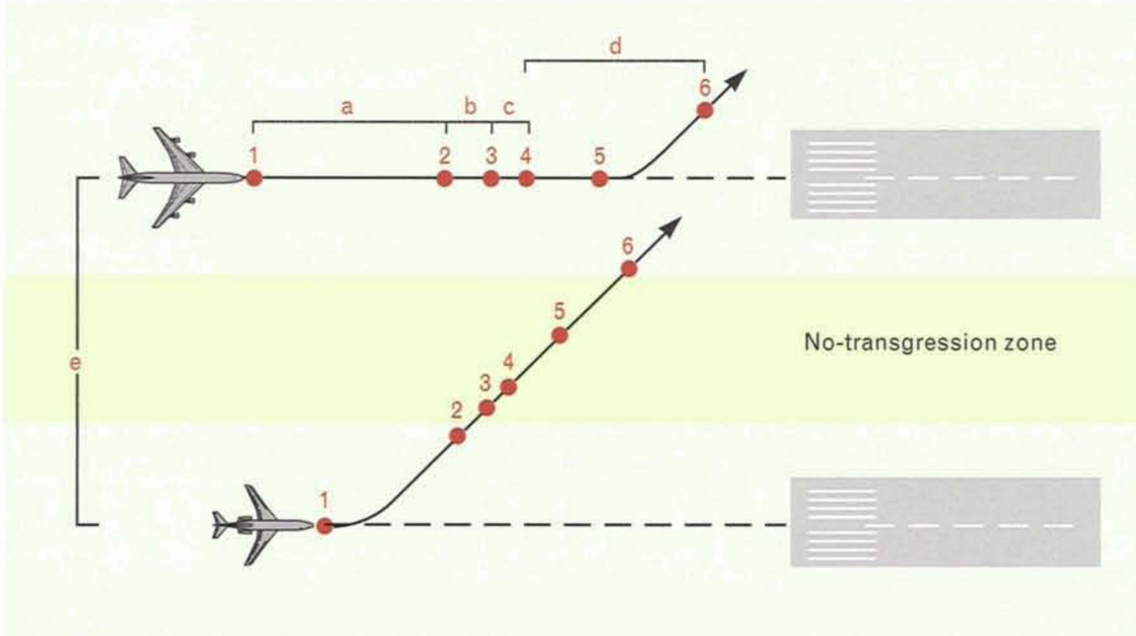

FIGURE 1. Sequence of events during an approach blunder: (1) the blunder begins, (2) caution alarm sounds, (3) breakout decision, (4) command received by endangered aircrew, (5) maneuver acceleration begins, and (6) increasing separation achieved. This sequence of events can also be characterized by a set of time-and-distance parameters, represented by the letters a through e, that together determine the minimum separation between the aircraft.

PRM Sensor Performance

The first step in successful blunder resolution is to detect the onset of the blunder situation. The amount of time required for the PRM automation algorithms to detect such a situation depends on the quality of surveillance provided by the PRM sensor, the details of the PRM alert algorithms, the location of the blundering aircraft prior to the beginning of the blunder, and the severity of the blunder, measured in terms of the angle through which the blundering aircraft turns toward the other runway.

A previous study has characterized the quality of surveillance provided by the Mode S sensor in the terminal area [2]. Additional data collected at the Memphis PRM site verified the results of the previous study. The probability of receiving a valid surveillance report in each 2.4-sec update interval was 98% or better for all airborne targets within the area of interest for PRM surveillance, and azimuth position accuracy was measured at less than one mrad rms error. Similar performance was obtained by an experimental Electronically Scanned (E Scan) sensor located at Raleigh-Durham Airport. The E-Scan sensor provided surveillance update intervals of 0.5 sec and 1.0 sec. Additional details on measured surveillance performance of the back-to-back Mode S sensor at the Memphis PRM site are available elsewhere [1, 3].

One important new feature of the PRM system is the presence of automatic alerts. These alerts are valuable because of the rarity of approach blunders. Since a monitor controller is likely to work the monitor position for a period of months or years without observing an approach blunder, and since the job of the monitor controller is one of vigilance but seldom of action, an automated alert is useful because it can quickly focus the controller's attention at the beginning of a potential blunder situation.

To give as much advance notice as possible, the PRM system provides a two-level blunder alert. The first alert, called a *caution alert*, is generated when the PRM tracking and alert algorithms determine that an aircraft will enter the no-transgression zone (NTZ) within the next ten seconds. This event triggers both an audible indication (a synthesized voice that calls out the aircraft ID) and a visible indication on the controller's monitor display (a change in color of the aircraft symbol and data block from green to yellow). The caution alert is a predictive alert that depends on both the position and velocity estimates generated by the tracking algorithms and on the length of the prediction. These parameters can be tuned to give an early alert that has frequent false alarms or a later alert that gives almost no false alarms but also provides less advance warning of NTZ penetration. In practice, we would like an alert that occurs somewhere between these extremes.

The second alert, called a *warning alert*, is generated when the current position of an aircraft is determined to be within the NTZ. This second alert triggers a second visual indication on the controller's monitor display—a change in color of the aircraft symbol and data block to red. An audible indication is triggered for an aircraft entering the NTZ only if a caution alert was not active for that aircraft in the previous update period. This action guarantees that the audible indication is triggered the first time that either a caution or warning alert is active for a given aircraft. In designing the alerts we assumed that the first audible indication will focus the controller's attention so that additional audible indicators are not needed for that aircraft until the current conflict situation is resolved.

The combined performance of the PRM surveillance and alert system can be characterized in terms of caution-alert lead time, or CALT, which is defined as the time between the first generation of an alert (usually a caution alert) by the PRM automatic alert algorithms and the entry of the corresponding aircraft into the NTZ. Figure 2 shows the sequence of timing events from the start of a blunder to NTZ penetration, with the schematic location of CALT in this sequence. A positive CALT value indicates that the PRM automation algorithms generated an alert prior to entry of the aircraft into the NTZ, while a negative CALT value indicates that the first alert generated by the automation algorithms came after NTZ entry.

An analysis of CALT using measured and simulated aircraft tracks provided expected lead-time values, and also provided some information on the sensitivity of CALT to parameters such as sensor azimuth accuracy, update interval, and interrunway separation. Figures 3 and 4 show the average CALT values for a prediction time of ten seconds as a function of runway separation, with the dependence on sensor azimuth accuracy and update interval, respectively. Note that the mean CALT value is always less than the projected ten-second interval. Delays caused by the finite update interval of the surveillance sensor and the time lag introduced by the smoothing function of the tracking algorithms contribute to this effect. In addition, the blundering aircraft may continue to turn toward the NTZ after the caution alert is triggered, increasing the component of velocity toward the NTZ and further reducing the CALT.

When other parameters are held constant, CALT increases with increasing runway separation because an aircraft will usually be farther from the edge of the NTZ at the onset of a blunder, and therefore the turn toward the other approach course more likely will be

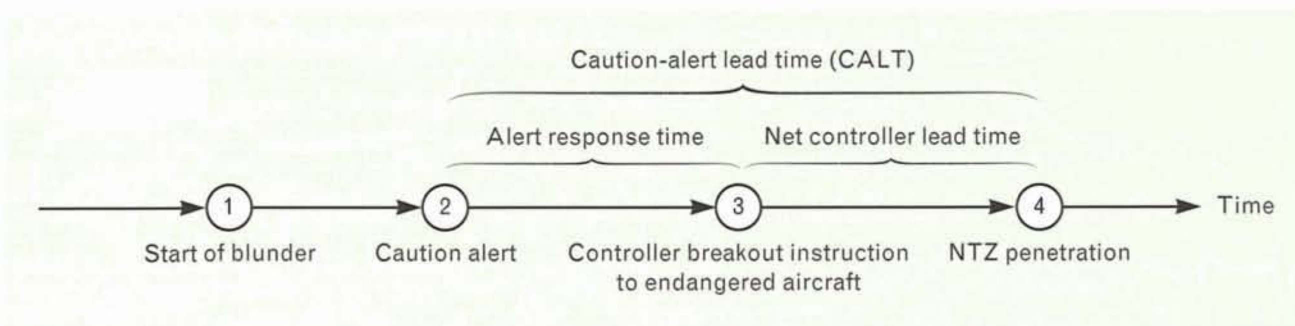

FIGURE 2. The sequence of timing events from the start of an approach blunder to penetration of the no-transgression zone (NTZ). The combined performance of the PRM surveillance and alert system can be characterized in terms of the caution-alert lead time, or CALT, which is defined as the time between the first generation of a caution alert and the entry of the aircraft into the NTZ.

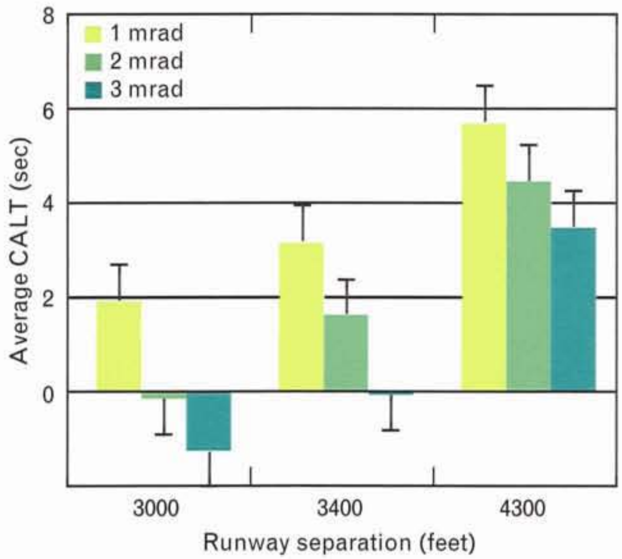

FIGURE 3. Effect of surveillance-sensor azimuth accuracy on the average CALT. The update interval is 2.4 sec, the blunder heading is 30°, and the blunder range is 2 nmi. The error bars represent one standard deviation.

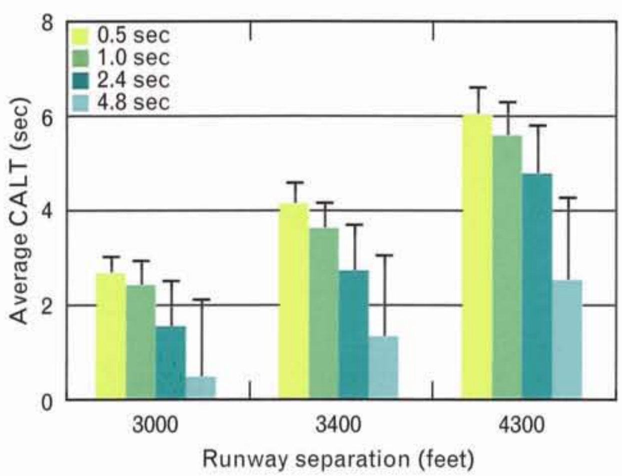

FIGURE 4. Effect of surveillance-sensor update interval on the average CALT. The azimuth accuracy is 1 mrad, the blunder heading is 30°, and the blunder range is 10 nmi. The error bars represent one standard deviation.

complete prior to generation of the caution alert. This trend is seen clearly in both Figure 3 and Figure 4. CALT also increases with decreasing errors or inaccuracies in sensor-surveillance performance. With increasing sensor errors, additional smoothing is needed in the tracking algorithms to keep false alerts to an acceptable rate, but this additional smoothing also increases the time lag before the tracking algorithms follow a real turn, thus delaying the caution alert. Finally, as sensor update interval decreases, CALT increases, primarily because the delay in detecting a maneuver that begins between updates decreases as well.

Approach Data Collection

As mentioned above, CALT depends in part on the distance of a blundering aircraft from the edge of the NTZ at the onset of the deviation. In addition, the total time to detect and resolve a blunder situation is dependent on the distances of both the blundering aircraft and the endangered aircraft from the edges of the NTZ. Finally, the combination of runway separation and the distribution of aircraft positions around the final approach course contribute to the frequency of unnecessary, or nuisance, alerts. Given a particular distribution, a significant number of aircraft will enter the NTZ during the course of normal flight if the interrunway separation is too small. Because these NTZ entries are difficult or impossible to distinguish from a true blunder, they require the monitor controller to turn aircraft on the parallel approach away from the approach, which decreases the benefit of simultaneous, independently sequenced approaches. Thus the distribution of aircraft around the final approach course and the resulting nuisance alarm rate limit the minimum runway separation for PRM purposes. Therefore, evaluation of the PRM blunder resolution performance requires knowledge of the distribution of aircraft positions around the final approach course.

Data collected by Lincoln Laboratory at the Memphis PRM site and by the FAA at Chicago's O'Hare International Airport provide information on the distribution of aircraft around the final-approach course during normal Instrument Landing System (ILS) approaches. This distribution is caused by a combination of the ability of the pilot or autopilot to follow the navigation information provided by the ILS, inaccuracies in the ILS navigation signals at any point in space, and errors in the airborne equipment that receives and displays the ILS navigation information. The aggregate of these errors is termed *total navigation system error* (TNSE).

Over 7000 approaches were collected at Memphis International Airport between 11 January and 15 No-

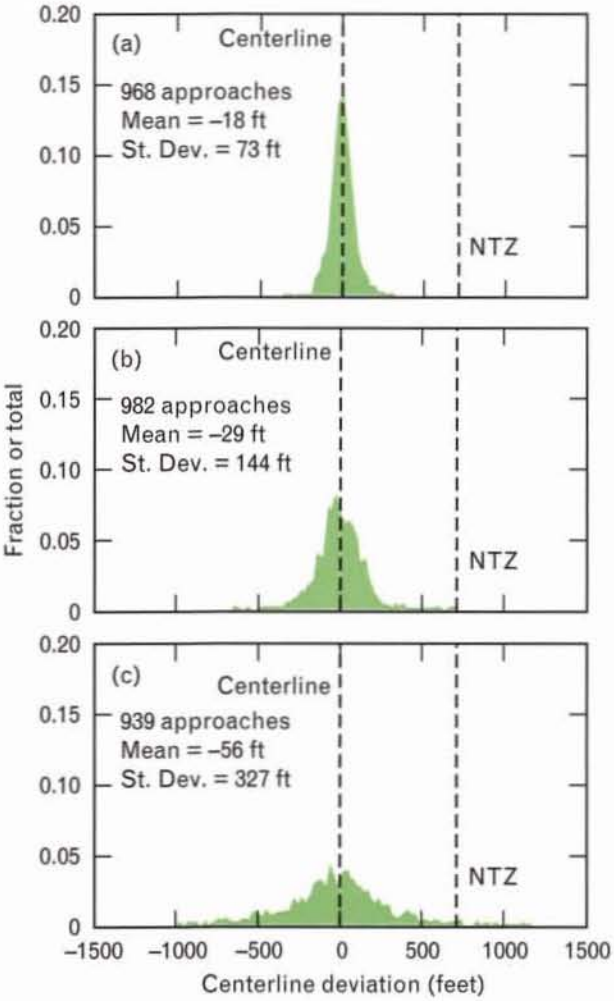

FIGURE 5. The Memphis IMC approach data distributions about the extended runway centerline at (a) 2 nmi, (b) 5 nmi, and (c) 10 nmi.

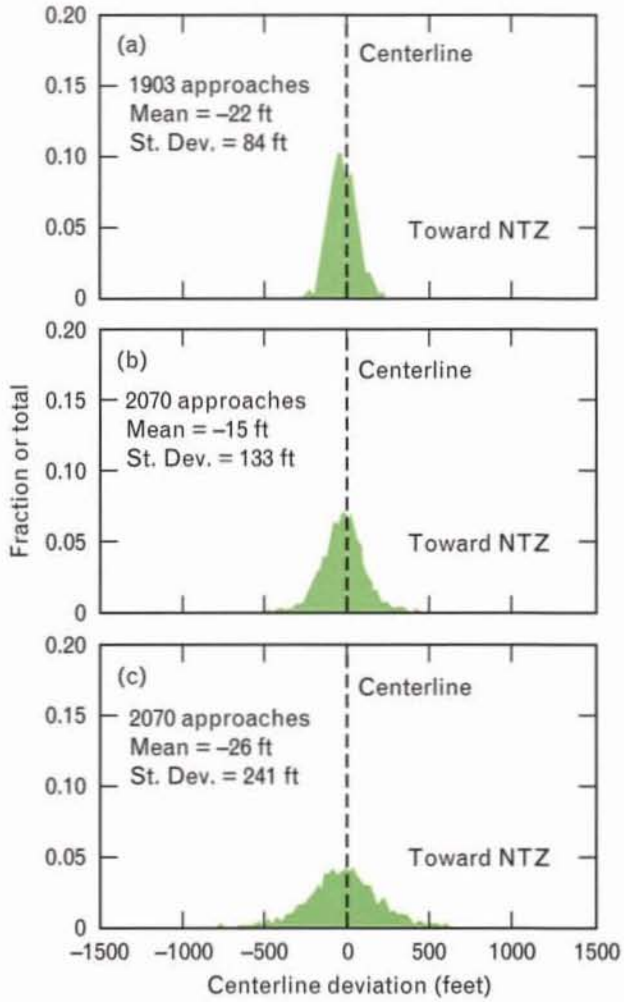

FIGURE 6. The Chicago O'Hare IMC approach data distributions about the extended runway centerline at (a) 2.1 nmi, (b) 5.1 nmi, and (c) 10.2 nmi.

vember 1989 during 162 separate data-collection sessions. Approximately 27% of the Memphis approach data were recorded during instrument meteorological conditions (IMC). When these conditions prevailed, the Memphis airport used dependent (staggered) parallel-approach procedures. The data collected at O'Hare International Airport included over 3000 approaches, most in IMC during times when simultaneous, independently sequenced parallel approaches were in use. In addition to aircraft position reports provided by the available surveillance-radar systems, both studies recorded current weather conditions, aircraft type, and flight ID. Both studies also made audio recordings of communication between air traffic controllers and pilots during approach. Additional details on the results of these two studies are available elsewhere [4, 5].

Figures 5 and 6 summarize IMC aircraft-position distributions measured at Memphis and at Chicago, respectively. Each figure shows the measured distribution of aircraft positions at 2 nmi, 5 nmi, and 10 nmi from the runway threshold. In all cases, the distributions are the result of combining data from all of the runways for which approach data were recorded. Note that the distributions of aircraft positions are nearly symmetric and are centered at values between –10 and –80 ft. The location of the runway extended centerline is defined as zero, and a negative value indicates a movement off the approach centerline away from the other runway. Figure 7 is a plot of the standard deviation of the distributions (a measure of distribution width) as a function of distance from the runway threshold. Note that the width of the distributions increases with distance from the runway threshold; this is expected because of the angular nature of the ILS approach system.

Analysis of the distributions in Figures 5 and 6 shows that they are slightly more peaked at the center, and have slightly thicker tails than a normal distribution. In Figure 5, the line labeled NTZ indicates where the edge of the NTZ would be located if independent parallel approaches were used at Memphis International Airport. Figure 5(c) shows that, at 10 nmi from the runway threshold, some aircraft would enter the NTZ as a result of TNSE, causing breakouts and decreasing the efficiency of independent parallel approaches. Figure 8 uses the Memphis data to give a quantitative measure of the number of aircraft that can be expected to enter the NTZ because of TNSE, as a function of both distance from the runway threshold and interrunway separation.

For the runway configuration at Memphis International Airport, with a 3400-foot interrunway separation, the edge of the NTZ is seven hundred feet away from the approach course centerline. Figure 8 shows

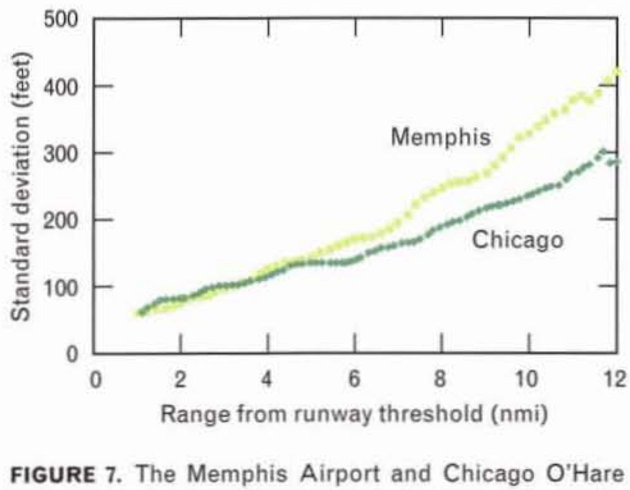

FIGURE 7. The Memphis Airport and Chicago O'Hare Airport final-approach standard deviations from the mean centerline deviations, as a function of distance from the runway threshold. The width of the distributions increases with distance from the runway threshold, which is expected because of the angular nature of the ILS approach system.

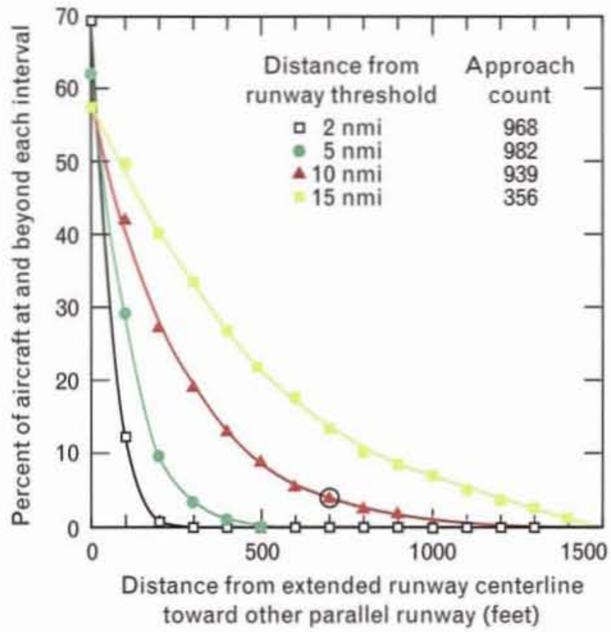

FIGURE 8. Memphis approach data showing the percent of aircraft at and exceeding each lateral 100-foot interval from the extended runway centerline toward the other parallel runway.

that, at 10 nmi from the runway threshold, about 4% of the aircraft would be more than seven hundred feet off the approach centerline toward the other runway, and therefore inside the NTZ. Air traffic controllers asserted that this relatively small frequency of TNSE-induced NTZ entries can be handled procedurally. In cases in which the NTZ extends to 15 nmi from the runway threshold, however, or if the interrunway separation is reduced to 3000 feet, NTZ entries can be expected to increase to the 10% to 15% level, which probably makes independently sequenced parallel approaches impractical unless means are found to reduce TNSE.

Controller Response Study

After the automatic alert system detects a potential blunder situation and generates an audible and visual alert, the responsibility of the monitor controllers is to assess the situation and determine which instructions must be given to both the blundering and the endangered aircraft. In general, as soon as the monitor controller responsible for the endangered aircraft determines that an NTZ entry is imminent, the controller will issue instructions to the endangered aircraft to break off the approach and turn in order to increase distance from the blundering aircraft. Thus controller response is an important component of the overall PRM system performance. The Lincoln Laboratory PRM program included an extensive study of controller response to approach blunders when the controllers used the PRM system to monitor the approaches. The study examined the effect of several parameters on controller response times, including sensor update interval, runway separation, blunder severity, and controller experience level.

From January through July of 1990, twenty-five pairs of controllers visited the Memphis PRM site to participate in the controller response study. Half of the participating controllers were assigned to the Memphis Terminal Radar Approach Control, or TRACON, facility at that time. The remaining controllers were recruited from other ATC facilities throughout the nation, with special emphasis placed on prior experience monitoring independently sequenced parallel approaches at airports with interrunway separations greater than 4300 feet. Each pair of controllers spent one week at the Memphis PRM site, with different activities scheduled each day. Monday's schedule included training and familiarization with the PRM concept and equipment. On Tuesday through Thursday the controllers monitored eighteen sessions of simulated independent parallel approaches, with each session lasting about one hour. Friday provided an opportunity to complete the data-collection sessions if any delays were encountered earlier in the week, and it also included a time for final debriefing and completion of the controller opinion survey.

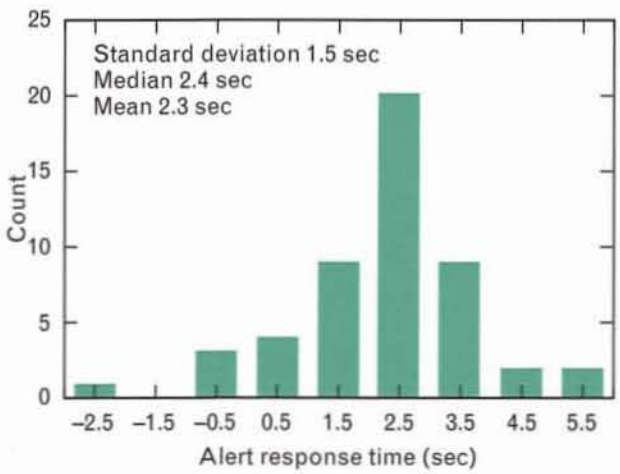

FIGURE 9. Controller alert response time for one particular blunder scenario. This scenario simulates the Memphis Airport runway configuration; blunder conditions were 30° blunder at 2 nmi, 3400-foot runway spacing, and a 2.4-sec update interval.

Controller response times are characterized in terms of *alert response time,* which is defined as the period of time between generation of an alert by the automatic alert algorithms and the beginning of the breakout instruction issued by the controller. Figure 9 is a histogram of alert response times for one particular blunder scenario—a thirty-degree blunder occurring about 2 nmi from the runway threshold. This scenario simulates the Memphis International Airport runway configuration with an interrunway separation of 3400 feet and a monopulse sensor with a 2.4-sec update interval. A negative alert response time means the controller started the breakout instruction before the first caution alert. In general, the controllers started issuing the breakout instruction after the first caution alert and before the blundering aircraft entered the NTZ. Table 1 provides summary statistics regarding the controller responses for this and for similar scenarios using different surveillance update intervals and blunder severity. Additional results are published elsewhere [3, 6].

Communication-Delay Data Collection

Once a monitor controller has determined that a breakout instruction must be issued, then that instruction must be transmitted to the pilot of the endangered aircraft. The instruction is transmitted over the radio communication frequency assigned to the tower controller. The communication equipment at the ATC facility is designed so that the monitor controller has override capability over the tower controller. In other words, even when the tower controller is speaking on the radio frequency, pressing the transmit key on the monitor controller's microphone allows the monitor controller to take over the frequency and transmit a message. However, even though the monitor controller does not need to worry about interference from the tower controller, the monitor controller must wait for any pilot transmitting on the tower frequency to finish to be sure that the breakout

Table 1. Alert-Response-Time Statistics for Runway Separation of 3400 Feet.

Range (nmi)	Angle (deg)	Update (sec)	Number of Responses	Mean (sec)	Standard Deviation (sec)	Median (sec)
2	15	1.0	148	2.8	2.5	2.6
2	15	2.4	98	2.4	2.1	2.3
2	30	1.0	100	2.1	1.6	2.0
2	30	2.4	50	2.3	1.5	2.4
10	15	1.0	150	4.0	2.6	3.3
10	15	2.4	99	3.8	2.1	3.4
10	30	1.0	99	2.4	1.3	2.3
10	30	2.4	49	2.1	1.5	2.4

instruction will be sent without interference.

Thus we need distributions for the frequency of occurrence and length of pilot transmissions to develop a valid model of PRM system performance. Communications over local control frequencies were recorded in January 1989 during periods of peak arrival traffic at Memphis International Airport and Chicago's O'Hare International Airport. Dependent approaches were conducted at Memphis while simultaneous approaches were conducted at O'Hare. The lengths of all non-controller transmissions were extracted from the audio recordings. These were used to calculate statistics on pilot transmissions as well as to create probability distributions of how long a monitor controller might have to wait before transmitting.

Figures 10(a) and 10(b) show the duration of pilot transmissions for Chicago and Memphis, respectively, while Figures 10(c) and 10(d) show the probability distributions for controller delay because of the duration of pilot transmissions for Chicago and Memphis, respectively. The difference in channel usage—13.3% for Memphis versus 6.0% for O'Hare—is related to the difference in channel frequency allocation. One frequency was used for both approaches at Memphis while separate frequencies were used for each approach at O'Hare. Otherwise, the distributions were similar, with mean durations of 1.8 sec and 1.6 sec, respectively.

Communication-Blockage Data Collection

Another source of communications delay is *channel blockage*, which occurs when two or more sources transmit on the same frequency at the same time, and the individual messages become distorted or interrupted. If a pilot transmits while the monitor controller is transmitting an urgent instruction such as a breakout command, then the intended pilot might not receive the controller's instruction. In that case, the controller would have to retransmit the instruction, thus increasing the delay before the pilot responds. Blockage of monitor-controller transmissions by the local controller is not an issue because the monitor controller can override the local controller's transmissions.

To estimate how often an urgent message from the monitor controller might be blocked, we analyzed local-frequency voice communications collected at Raleigh-Durham International Airport to determine the frequency of simultaneous transmissions. Over twenty-four hours each of peak voice traffic during visual operations, staggered ILS operations, and simultaneous ILS operations were processed. The number of controller and non-controller transmissions, the weather, traffic counts, and the occurrence of simultaneous transmissions were tabulated for the three types of operations.

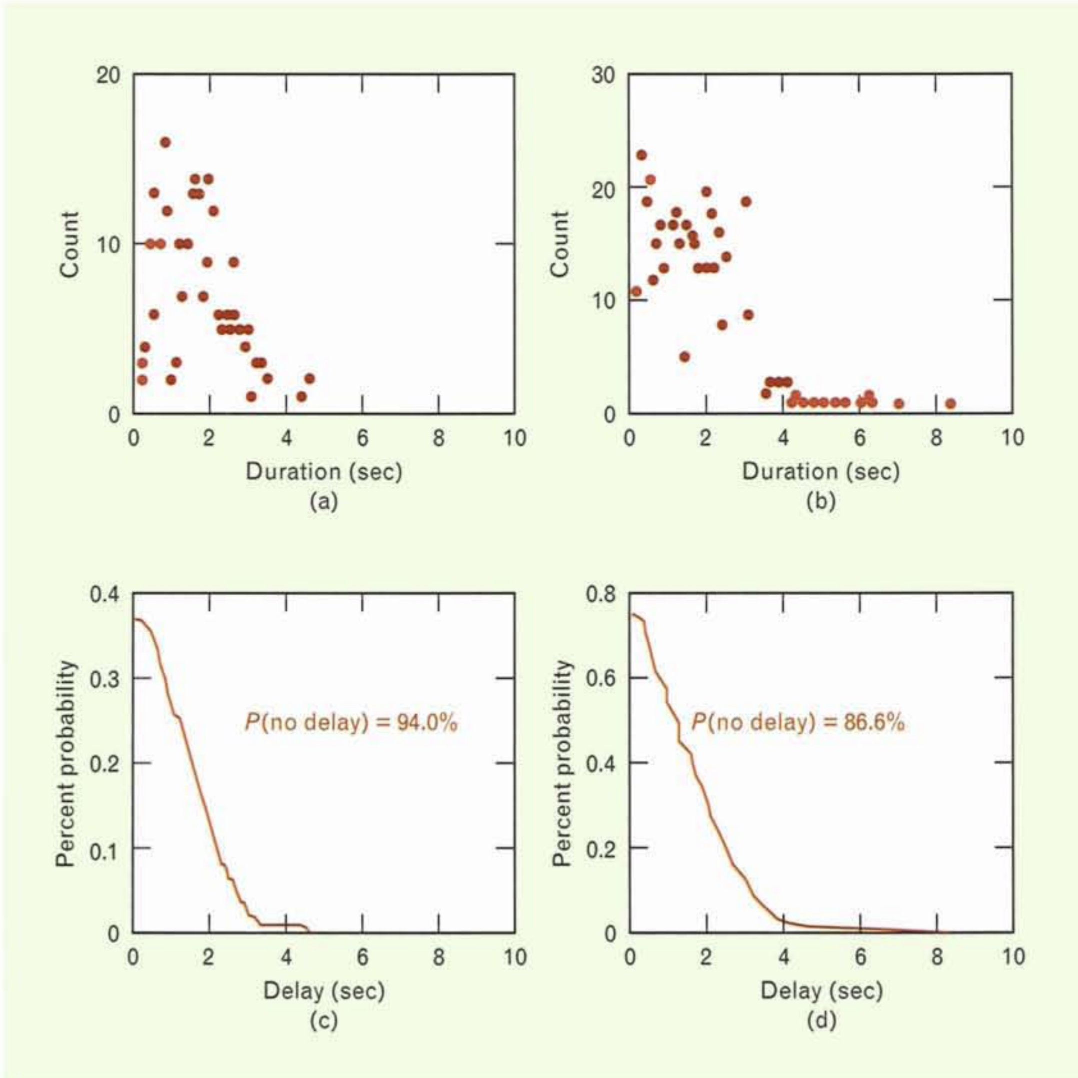

FIGURE 10. Pilot transmission data. Histograms of the duration of pilot transmissions are shown for (a) Chicago and (b) Memphis. Probability distributions for controller communication delay because of the duration of pilot transmissions are shown for (c) Chicago and (d) Memphis.

Analysis of the visual and staggered ILS data is complete [7]. Five simultaneous transmissions occurred during visual operations and two occurred during staggered ILS operations. All simultaneous transmissions involved a pilot and the local controller. In four events during visual approaches, a pilot and the controller started speaking simultaneously after a period of radio silence. There were no requests for repeats, and the appropriate people responded to both transmissions. In one visual event and one staggered ILS event, a pilot came in on top of a controller transmission during a period when the controller was dealing with several aircraft. A request for a repeat was made in both cases. In the other staggered ILS event, the receiving pilot briefly keyed the microphone during the controller transmission, announced he had blocked the transmission, and asked for a repeat.

Estimates of the probability that a controller transmission will be stepped on by a pilot during peak operations were made by using the observed number of simultaneous-transmission events and the number of controller transmissions. For staggered ILS approaches, the sample estimate $\hat{p}_{ILS}$ and the 95% confidence upper bound on the true value p_{ILS} were

$$\hat{p}_{ILS} = 0.00074, \quad p_{ILS} \leq 0.0023.$$

For visual approaches, the sample estimate $\hat{p}_{vis}$ and the 95% confidence upper bound on the true value p_{vis} were

$$\hat{p}_{vis} = 0.0014, \quad p_{vis} \leq 0.0031.$$

Preliminary processing of the voice data collected during simultaneous ILS operations at Raleigh-Durham Airport indicates that the frequency of blocked controller communications was higher than those observed during visual and staggered ILS operations. Several factors might be involved, including weather, controller work load, and traffic density. The processing of voice data during simultaneous ILS operations is currently in progress, so no conclusions can be made at this time.

Pilot Response Study

After the automation system detects the onset of a blunder situation, and a monitor controller decides that a breakout instruction is needed and issues the instruction on a clear communication channel, the pilot of the endangered aircraft must then understand the instruction and give the control inputs that will cause the aircraft to maneuver out of danger. In addition, once the control inputs are given, the aircraft does not change trajectory instantaneously. Therefore, both human and machine responses are involved in the breakout maneuver.

As part of the PRM program, the FAA Aviation Standards National Field Office and Lincoln Laboratory carried out two studies designed to measure the responses of airline pilots and the aircraft they fly when the pilots were given an instruction to break off an approach and turn "immediately" to a new heading. Active-duty airline pilots and FAA pilots flew the FAA Boeing 727 flight simulator in Oklahoma City, Oklahoma, and the McDonnell-Douglas DC10 flight simulator owned by Federal Express in Memphis, Tennessee. Test subjects flew simulated straight-in approaches to Memphis International Airport Runway 36L. The simulators provided IMC with either a one-hundred-foot decision altitude or a two-hundred-foot decision altitude. The command to turn issued by ATC occurred either near decision altitude or six miles out on the approach, resulting in three test conditions: (a) breakout at one-hundred-foot decision altitude, (b) breakout at two-hundred-foot decision altitude, and (c) breakout during initial approach stage. Digital tape recordings of aircraft configuration, position, and altitude were made during the tests.

Briefings given to the flight crews prior to testing stated that on some approaches the pilots would be given instructions to turn away from the final approach course, but the briefing did not include any instruction as to how the pilots should respond to such an instruction. The resulting pilot-response data were characterized in terms of time between the beginning of the breakout instruction and the beginning of the aircraft turn. For this purpose, the beginning of turn was defined as the time when the aircraft achieved a bank angle of three degrees, and maintained at least a three-degree bank angle throughout the rest of the turn. Figures 11 and 12 show representative histograms of pilot responses from the Boeing 727 simulator studies and the DC10 simulator studies, respectively. Detailed descriptions of the results are given elsewhere [8, 9].

In the majority of cases, the Boeing 727 pilots were able to begin a turn within thirteen seconds after receiving the controller's turn instruction, and the DC10 pilots were able to begin a turn within fifteen seconds after receiving the turn instruction. A few responses, however, were much longer. A later experiment, also carried out by the FAA Aviation Standards National Field Office, showed that familiarization with independent parallel-approach procedures and the specific meaning of the word "immediately" in this situation produced little change in the minimum and mean response times, but eliminated the long response times [10].

PRM Blunder Risk Model

To establish the effectiveness of the PRM system, we needed to evaluate the ability of the system to detect blunders and resolve them safely. All components, from airport runway configuration and surveillance radar performance through pilot/aircraft maneuver-

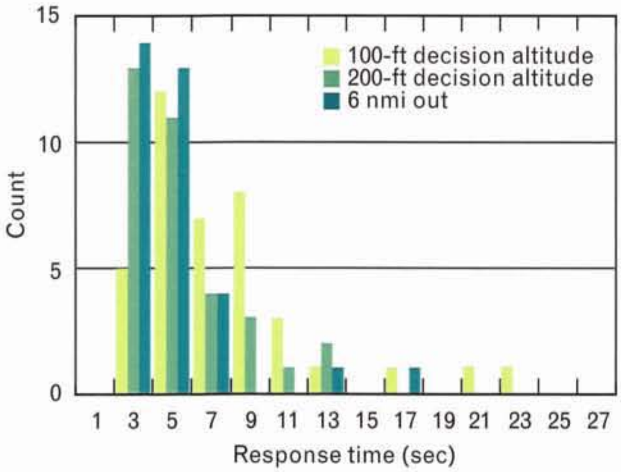

FIGURE 11. Histogram of pilot responses to start of turn from the Boeing 727 flight simulator study.

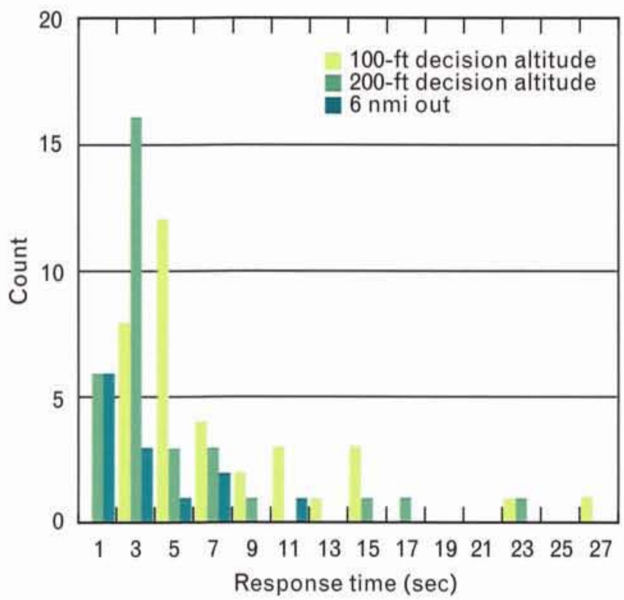

FIGURE 12. Histogram of pilot responses to start of turn from the DC10 flight simulator study.

ability, affect the ability of the controller to maintain safe separation between aircraft during a blunder event.

By utilizing the data collected during the PRM program, we developed a comprehensive model of the events during blunder resolution. To take into account the statistical nature of many of the factors affecting each event, such as radar accuracy, TNSE, controller response, and pilot/aircraft response, Lincoln Laboratory developed a new blunder model that is fundamentally statistical and includes the unique radar and display features of the PRM system. The Blunder Risk Model (BRM) is a fast-time Monte Carlo simulation that incorporates experimental and field data on human and equipment performance to estimate three-dimensional aircraft separation over time.

The BRM has been used to answer questions such as "What minimum runway separation can be supported safely by the different possible PRM configurations? In particular, what runway separation can the Mode S version of PRM support?" The BRM has also been used to conduct sensitivity analyses for various model components, and as part of preliminary analysis of proposed new operations.

Risk-Model Description. In general, a Monte Carlo simulation is a fast-time computer simulation of the sequence of events for the given real-world operation. Each event in the simulation is modeled as a distribution of possible values (e.g., radar error or controller response time). The simulation is then run many times to give a distribution of observed outcomes. During each run, or *trial*, a value for each event is randomly selected from the distribution for that event. The random values are then combined, resulting in a unique outcome for that combination of events. The distribution of outcomes from all the trials is then used as an estimate of what we can expect in the real world. By simulating the sequence of events during a blunder, as illustrated in Figure 1, the BRM provides a result that mimics years of field experience involving random mixes of airports, aircraft, pilots, and controllers.

To apply the Monte Carlo simulation, we defined the time required for blunder resolution τ_{res} as a series of events, each of which has its own distribution, or

$$\tau_{res} = \tau_{alert} + \tau_{cont} + \tau_{comm} + \tau_{pilot} ,$$

where τ_{alert} is the delay from the start of the blunder until the alert is generated, τ_{cont} is the time required for the controller to assess the situation, τ_{comm} is the communication delay in transmitting the breakout instruction, and τ_{pilot} is the time used by the pilot to begin the breakout maneuver.

The BRM is designed to simulate the events dur-

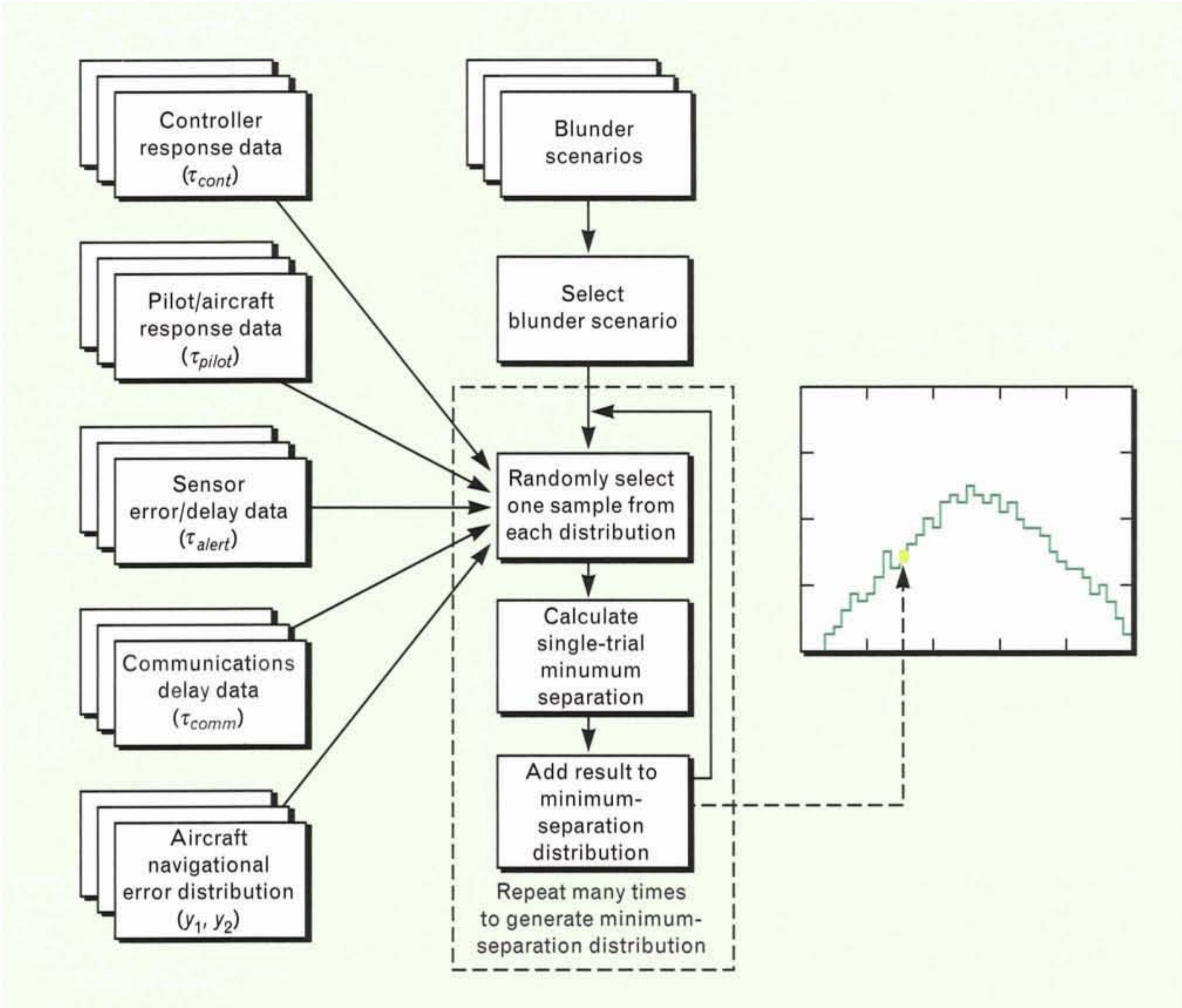

FIGURE 13. Operation of the blunder risk model (BRM). The blunder scenarios are determined by a series of user inputs that remain constant throughout a simulation run. These fixed inputs include the parallel-runway configuration, radar performance parameters, and the blunder configuration. In addition, a set of distributions corresponding to the various time components of blunder resolution are provided as inputs to each scenario. With these inputs and distributions, a number of trials are simulated and statistics are accumulated on the minimum separation between the aircraft during each trial.

ing a worst-case blunder scenario. By "worst case" we mean the intruder aircraft does not turn back and recover from its blunder in spite of directions from the controller to do so. The scenarios are determined by a series of user inputs that remain constant throughout a simulation run. These fixed inputs include the parallel runway configuration (separation, threshold offsets, headings, and altitudes), radar performance parameters (update interval and accuracy), and the blunder configuration (blunder angle, distance from threshold, and speed). In addition to the fixed inputs, a set of distributions corresponding to the various components of τ_{res} are provided as inputs for each scenario. With these fixed inputs and distributions, a given number of trials are simulated, and statistics are accumulated on the minimum separation between the simulated aircraft during each trial. The diagram in Figure 13 illustrates the operation of the simulation model. The actions taken for each individual trial are described in the following paragraphs.

Starting points for each aircraft are randomly determined at the beginning of each trial. The longitudinal position of the endangered aircraft at the start of the blunder is uniformly distributed between ±1.5 nmi from the blundering aircraft. Lateral positions for both aircraft are randomly chosen from an appropriate distribution. Starting altitudes are based on the glide slope and range from the threshold.

The scenario assumes that the blundering aircraft descends along the approach path to the right runway until it reaches the declared blunder range. It then turns toward the left runway, accelerating one degree per second each second until it achieves the standard turn rate of three degrees per second. The turn continues at this rate until the declared blunder heading is reached. The aircraft continues at this heading until the end of the trial. Before the blunder, the aircraft descends along a three-degree glide slope. During the blunder, the aircraft ascends or descends along a declared blunder slope. If the blunder slope is different from the glide slope, the aircraft slope is changed by three degrees per second until the blunder slope is reached. At the same time, the endangered aircraft descends along the approach path to the left runway.

The alert generation time (τ_{alert}) is calculated dynamically during each trial. The effect of radar scan period is taken into account, and randomly generated radar noise is added to the blundering aircraft position at each radar update. The position with noise is then passed to the PRM alert logic. An alert is declared when the aircraft is either inside the NTZ or projected to be inside the NTZ within ten seconds.

Once an alert is generated, values randomly selected from distributions describing controller delay (τ_{cont}) and communication delay (τ_{comm}) are added to the time progression. The two aircraft continue on their respective trajectories during this time. The response of the endangered pilot and aircraft is initiated at the start of the controller breakout instruction. Following a pilot-response delay (τ_{pilot}), the endangered aircraft maneuvers away from the blundering aircraft. The blundering aircraft is simulated to continue on the blunder trajectory.

The slant distance between the center of the blundering aircraft and the center of the endangered aircraft is updated every second, starting at the time of alert generation. Each trial is terminated when a minimum separation (miss distance) has been achieved. The minimum separation for each trial is added to the scenario's distribution of minimum separations, and the accumulated distribution generated during the trials is stored in an output file for future use.

Estimation of Risk for PRM. The BRM simulation was used during the PRM program to estimate how well the PRM system, with either the Mode S or E-Scan sensor, will keep aircraft from colliding in a variety of blunder scenarios during simultaneous approaches with a 3400-foot separation. The most extreme test scenarios had the blundering aircraft turn thirty degrees toward the adjacent parallel approach.

An internationally accepted definition of a collision for modeling purposes is that the measured center positions of the aircraft come within five hundred feet of one another. Thus, for the BRM, if a trial results in a separation of less than five hundred feet, then by definition that trial results in a collision. Table 2 lists the probability $P(x < 500)$ results of the Monte Carlo analysis for various radar update intervals [11]. These results indicate a significant benefit in using an update interval of 2.4 sec or less rather than the currently used interval of 4.8 sec, and a less significant difference between 2.4-sec and 1.0-sec update intervals.

The calculated per-blunder collision probability was then used to test which PRM configurations would meet a per-approach target fatal-accident rate of one accident per twenty-five-million IMC ap-

Table 1. P(x < 500) for 3400-foot Runway Separation*

Update (sec)	*P(x < 500)*
1.0	0.00165
2.4	0.00200
4.8	0.01405

* Blunder range: 9 nmi
Radar azimuth accuracy: 1 mrad rms

proaches during PRM operations. The per-approach rate was derived from actual accident statistics, and selected so as not to increase the ILS approach risk significantly.

This target accident rate can be converted to a target collision probability, or $P(\text{COLL})_{target}$. First, the National Transportation Safety Board reports a collision as two accidents. Second, for a collision to occur, two aircraft on final approach must be in close proximity longitudinally. Thus the target collision probability can be expressed as the probability of a collision per approach pair, or

$$\begin{aligned} P(\text{COLL})_{target} &= \frac{1 \text{ accident}}{25 \times 10^{6} \text{ approaches}} \\ &\quad \times \frac{2 \text{ approaches}}{\text{approach pair}} \times \frac{1 \text{ collision}}{2 \text{ accidents}} \\ &= 4.0 \times 10^{-8} \text{ per approach pair}. \end{aligned} \tag{1}$$

Three events must jointly occur for a collision to take place during PRM operations. First, one of the aircraft must execute a blunder (BL). Second, given that a blunder has occurred, it must be a worst-case blunder (WCB | BL). Finally, the worst-case blunder must result in a collision (COLL | WCB). By using this relationship, we can express the probability of a collision in terms of the probabilities of these three events, or

$$\begin{aligned} &P(\text{COLL})_{target} \\ &\quad = P(\text{BL}) \times P(\text{WCB} \mid \text{BL}) \times P(\text{COLL} \mid \text{WCB}). \end{aligned} \tag{2}$$

The output from the BRM simulation, $P(x > 500)$, was used as an estimate of $P(\text{COLL} \mid \text{WCB})$. Since there is no direct evidence of how often worst-case blunders occur, we used the field experience of controllers from several facilities to estimate the frequency of worst-case blunders indirectly. On the basis of interviews with the controllers, we estimated that in only one percent of thirty-degree blunders would the pilot be unable to respond to a controller direction to return to course, or

$$P(\text{WCB} \mid \text{BL}) = 0.01. \tag{3}$$

The problem is that the true $P(\text{BL})$ is not known. Because no blunders of any severity have ever resulted in an accident, no statistics are available on the probability of occurrence for thirty-degree worst-case blunders. To overcome this lack of statistics, the target collision probability and the BRM results were used to compute a maximum-allowable probability of a thirty-degree blunder. The PRM system could then be accepted if the calculated blunder probability was greater than anyone's intuitive sense of how often thirty-degree blunders occur. By combining Equation 1 with Equations 2 and 3, we get

$$\begin{aligned} P(\text{BL}) &= \frac{P(\text{COLL})_{target}}{P(\text{WCB} \mid \text{BL}) \times P(\text{COLL} \mid \text{WCB})} \\ &= \frac{4.0 \times 10^{-6}}{P(\text{COLL} \mid \text{WCB})}. \end{aligned}$$

Selecting a value of 0.004 for $P(\text{COLL} \mid \text{WCB})$ results in

$$P(\text{BL}) = 0.001 \text{ per approach pair}.$$

On the basis of recent IMC arrival records, an actual blunder probability of 0.001 could exist if there were about ten thirty-degree blunders each year at Chicago O'Hare International Airport or fourteen thirty-degree blunders each year at Atlanta Hartsfield International Airport. Anecdotal evidence suggests that neither airport experiences this number of thirty-degree blunders per year, so the actual blunder probability is less than 0.001 for both airports. Thus test configurations (PRM system and airport configuration) with a $P(x < 500)$ value of 0.004 or less can be expected to meet the target risk level for safe operations.

System Demonstrations and User Opinion

By using flight tests and simulated scenarios, we demonstrated the PRM system to a diverse group within the air transport community. Controllers, managers, and technical personnel from the FAA, as well as pilots and airline industry representatives, saw the PRM system in action.

Opinion surveys were completed by pilots who participated in the flight testing and by controllers who participated in the simulation study. The full results of these surveys are reported elsewhere [3, 6]. The surveys indicated that a large majority of pilots and controllers agreed that, when PRM is used, independent approaches can be safely conducted in poor weather conditions at airports with parallel runways separated by 3400 feet. Controllers were queried regarding the display, and they had high praise for the following features: the rapid update interval, the automated alerts, the high-resolution color display, and the projected position vector. Pilots were queried regarding flight procedures and training. A large majority of the pilots surveyed agreed that a 1000-foot vertical separation provides an acceptable safety margin if aircraft maintain their assigned altitudes until glideslope intercept, and that an intercept of thirty degrees or less is adequate to guarantee localizer capture with an overshoot of no more than 1.5 deg. More than half of the pilots expressed the need for additional pilot-training and procedure-currency requirements to qualify pilots for simultaneous independent approaches to parallel runways separated by less than 4300 feet, and for special phraseology to be used by the controller in directing the breakout maneuver in order to emphasize the importance of a quick response. In addition, more than half of the pilots felt that closely spaced parallel approaches should not be conducted with a coupled autopilot.

FAA Approval of PRM

On the basis of the results of the PRM development and demonstration program, the FAA modified air traffic procedures to allow the use of simultaneous parallel instrument approaches to runways with 3400-foot separations when the approaches are monitored by a PRM system providing an azimuth accuracy of 1 mrad and an update interval of 2.4 sec. This decision was made with the understanding that pilots would be trained to address breakout procedures, especially in certain automated aircraft, and that the FAA would address concerns about blocked communications. The automated-aircraft issue refers to situations during a coupled or auto-land approach in which the crew would be required to disengage the autopilot and execute a turning breakout maneuver. This situation was not captured in the original Boeing 727 and DC10 pilot studies.

Implementation

The PRM program established that the Mode S sensor in back-to-back antenna configuration and the E-Scan sensor were both acceptable for 3400-foot parallel-runway PRM operations. Subsequently, Congress directed the FAA to procure five E-Scan PRM systems, and a production contract was awarded in 1991. Also, the demonstration E-Scan unit at Raleigh-Durham Airport was upgraded to serve as an interim operational unit until a production unit could be installed. The upgraded E-Scan system at Raleigh-Durham Airport was commissioned in June 1993, and following controller and maintenance crew training, the facility began monitoring simultaneous, independently sequenced arrivals on 11 August 1993. The first production E-Scan PRM unit is being installed at Minneapolis International Airport, and should be commissioned in fall 1995. Future production units will be installed at Raleigh-Durham Airport and Atlanta Hartsfield Airport. Sites for the remaining production units have not been selected.

In a separate acquisition effort, the FAA awarded a contract to develop a stand-alone commercial version of the display portion of the PRM system, which was designated the Final Monitor Aid. This effort was a fast-track development program that utilized the display and alert capabilities of the PRM system for triple-parallel-approach monitoring at the new Denver International Airport. Lincoln Laboratory provided technical support for both the E-Scan PRM and the Final Monitor Aid implementation efforts, which are described in more detail in the following sections.

PRM Site Surveys

Siting the PRM radar is unique because of considerations other than radar performance and obstruction-clearance requirements. Not only must the radar signal be protected from distortion and blockage, but radar coverage must extend through the airspace immediately above the runway surfaces. The PRM surveillance-radar coverage requirements are (1) range coverage shall be up to thirty nautical miles from runway end on the final approach course continuous to five nautical miles beyond the approach end, and (2) elevation coverage shall extend from no higher than fifty feet above the airport surface to at least fifteen hundred feet above the highest initial approach altitude.

The radar location thus must be selected to meet those coverage requirements and provide reliable target reports during each position update interval of 2.4 sec or less. To ensure the best PRM surveillance, Lincoln Laboratory has conducted PRM site surveys at candidate PRM airports, including Fort Lauderdale [12], Memphis [13], Minneapolis [14], and Raleigh-Durham [15]. Preliminary survey work has also been completed for Atlanta Hartsfield and Baltimore.

At each location, Laboratory personnel met with local airport representatives to discuss future construction plans and to select at least three candidate radar location sites to be surveyed. In the earlier surveys, panoramic photographs were taken at each of the selected sites with a camera with internal elevation grid lines. In the last two surveys, a self-leveling video system built and operated by Sterling Federal Systems for Lincoln Laboratory was employed. In post-analysis, the locations and elevations of objects in the photographs were correlated with their locations on airport layout plans.

The technical analysis of PRM performance at each site was divided into three areas. The first area was flight-path coverage, which explored the relation between aircraft trajectories and the conditions causing blocked surveillance. The second area was a general assessment of factors affecting sensor work load and tracking performance, such as false targets or multipath due to reflections off nearby structures. The third area examined PRM alert performance.

Part of the site survey analysis was to assess the effect of each candidate radar location on performance. For each parallel runway, a nominal trajectory was computer generated as it would be viewed at each site for an aircraft conducting a final approach and then flying fifty feet above the runway surface. The trajectories were then superimposed on the 360° panoramic photographs taken at each site to show the spatial relationship between aircraft trajectories, the radar, and potential signal obstructers such as buildings, towers, and trees. If an object were between the radar site and the trajectory, then the object would block surveillance during the time the aircraft is behind it. The duration of the signal blockage was estimated by the length of the obscured trajectory.

Figure 14 shows the aircraft trajectories generated for the approaches to runways 26R and 27L at Atlanta Hartsfield Airport. The runways extend east-west and the radar site is to the south of the runways on the airport surface. The dots represent nominal aircraft tracks, in one-second intervals. In the figure the Delta hanger blocks the landing portion of the trajectory to 26R, and the air traffic control tower (ATCT) blocks less than a second of radar coverage above runway 26R.

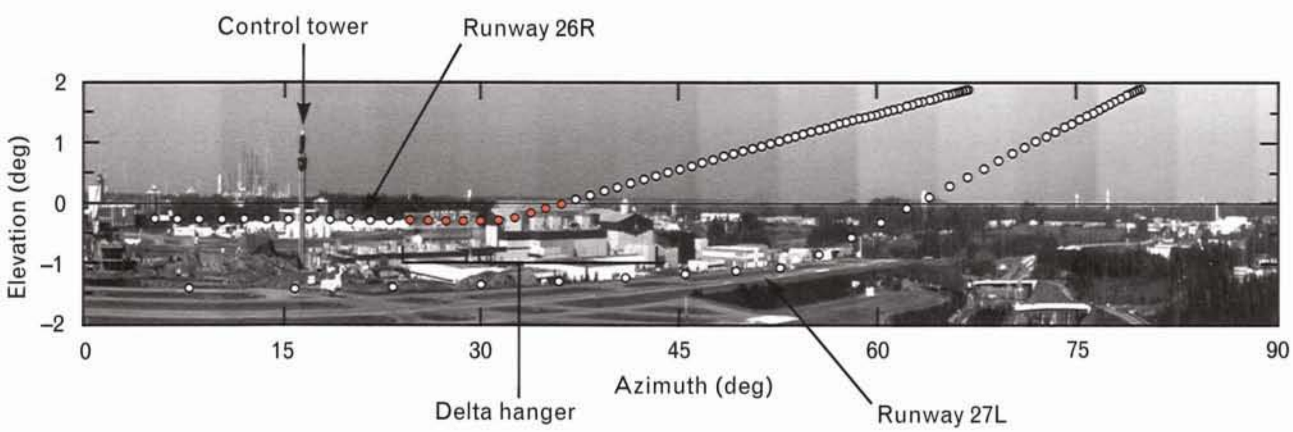

FIGURE 14. Flight-trajectory obstruction analysis for a candidate PRM site at Atlanta Hartsfield Airport. The panoramic photograph is taken from the point of view of a candidate sensor site south of the runways. The computer-generated dots, which are updated in one-second intervals, represent final-approach trajectories along the approach centerlines of Runways 26R and 27L. The Delta hanger blocks the landing portion of the trajectory to Runway 26R; this blocked portion of the trajectory is shown in red dots.

Initial Operational Assessment at Raleigh-Durham

Because Raleigh-Durham International Airport is the first airport at which simultaneous, closely spaced parallel operations can be conducted, the FAA instituted a transition period of PRM system operation. In the first phase, starting 11 August 1993, the PRM system was authorized for use only if the visibility was greater than three nautical miles and the cloud ceiling was higher than 4500 feet above ground level. These were visual flight rule (VFR) conditions. On the basis of performance reviews, the weather requirement was relaxed on 25 November 1993 to visibility greater than two nautical miles and the cloud ceiling higher than seven hundred feet above ground level. This meant the PRM system could be used under marginal VFR (MVFR) conditions and instrument flight rules (IFR) conditions. During the winter months, a requirement was added that the system could not be used if the airport temperature went below 47° F to ensure that sensor performance could not be degraded by undetected differential icing of the sensor antenna elements. Finally, the ceiling and visibility restrictions were removed on 9 March 1994. Since then the PRM system has been used in weather down to the Category I minimum of one-half nautical mile visibility and two-hundred-foot ceiling. Production E-Scan systems are expected to have heating elements that will remove the icing restriction.

The decisions to lower the weather minimums were based on work conducted by Lincoln Laboratory to collect and analyze simultaneous parallel approach (PRM operational) data from Raleigh-Durham Airport during the first year of operations, and to present the interim results to the FAA and airline industry representatives on a regular basis. The major PRM system analysis efforts, described below, were to evaluate TNSE and aircraft breakout events.

Total Navigational System Error. The lateral distribution of aircraft along the runway centerline is important to PRM for two reasons. First, the lateral separation between two aircraft is a factor in successful blunder resolution. The smaller the distance, the less time available during a blunder event for the controller and pilot to act. Second, aircraft flight characteristics affect the number of nuisance NTZ penetrations and PRM alerts. The frequency of nuisance alerts in turn affects controller work load. The greater the number of NTZ entries, the greater the number of aircraft that have to be broken out of the approach stream and vectored back in.

With regard to flight paths, we needed to ensure that no anomalies occurred in the ILS signal at Raleigh-Durham Airport that could cause unexpected behavior in aircraft on final approach. Significant ILS signal distortions can be detected by irregularities in TNSE statistics. Lincoln Laboratory conducted a TNSE evaluation similar to the one conducted at Memphis International Airport [4]. Figure 15 is a comparison of the TNSE standard deviations observed at Raleigh-Durham Airport with the Memphis data. The Memphis data are grouped by weather (IFR and MVFR), while the Raleigh-Durham data are grouped by phase (Phase 1 is all VFR, while Phase 2 is MVFR/IFR). The data show that TNSE at Raleigh-Durham is not affected by weather, because the Phase 1 data overlap the Phase 2 data. The data also show that TNSE at Raleigh-Durham was smaller than that

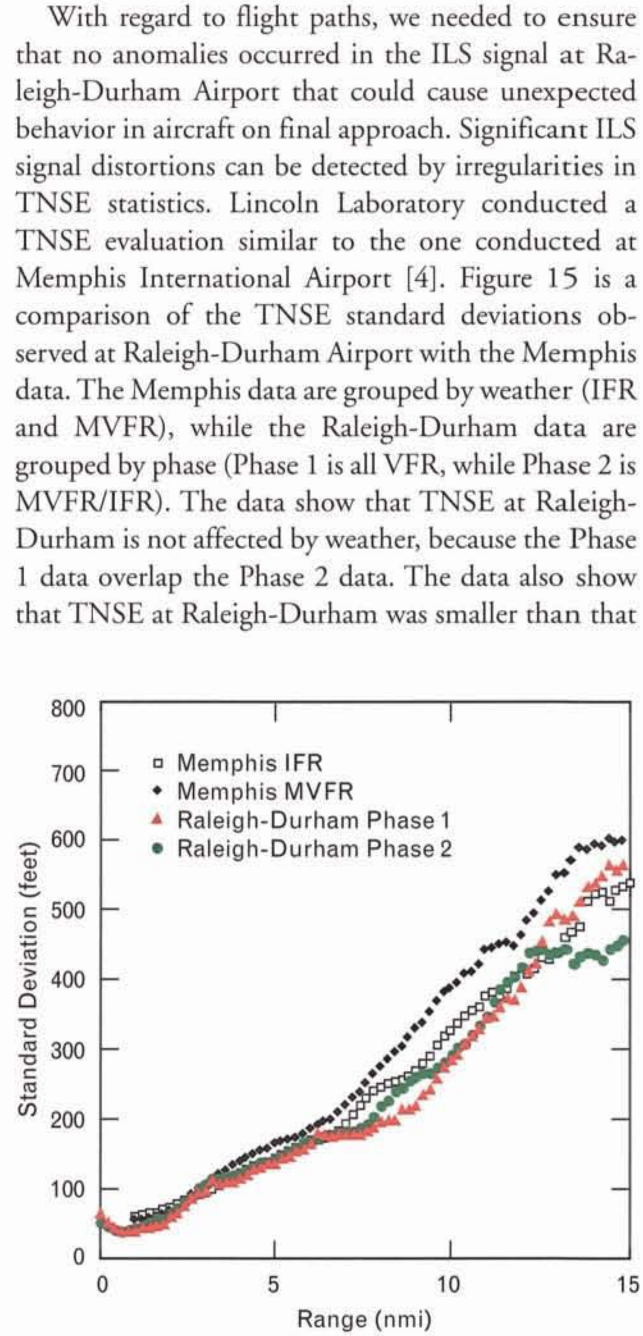

FIGURE 15. Comparison of the TNSE standard deviations observed at Raleigh-Durham with the Memphis data. The Memphis data are grouped by weather (IFR and MVFR), while the Raleigh-Durham data are grouped by phase; Phase 1 is all VFR while Phase 2 is MVFR/IFR.

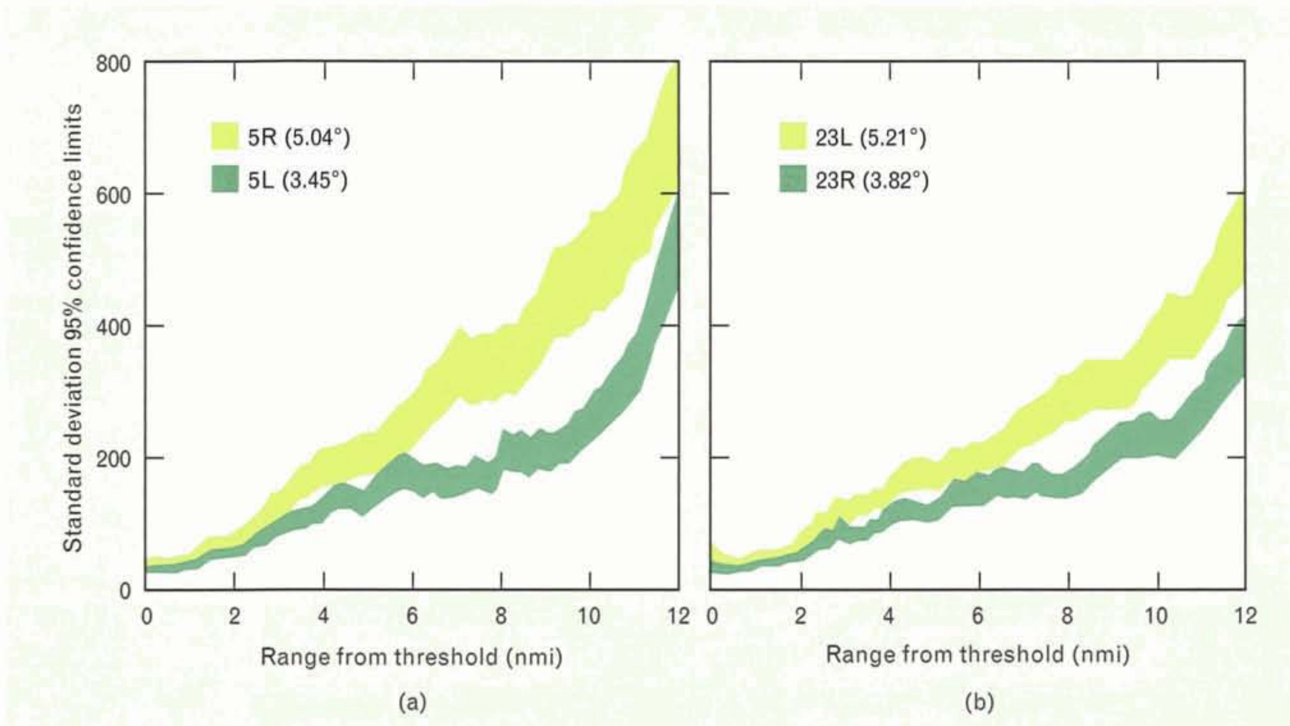

FIGURE 16. Raleigh-Durham TNSE standard deviation 95% confidence intervals by runway: (a) runways 5L and 5R, and (b) Runways 23L and 23R.

observed at Memphis. Because no anomalies were detected, TNSE analysis at Raleigh-Durham was stopped during Phase 2.

The Raleigh-Durham TNSE data were also analyzed by runway to test if the localizer beam width affects aircraft performance. Figure 16 shows the correlation between TNSE standard deviation and localizer beam width at the 95% confidence level. This result is different from that observed at Memphis, where TNSE standard deviation was not proportional to localizer beam width. One explanation for the difference in performance between the two airports is the aircraft populations. The major aircraft types at Memphis were McDonnell-Douglas DC9 (52%), Boeing 727 (13%), and Saab-Fairchild 340 (10%), while the major aircraft types at Raleigh-Durham were McDonnell-Douglas MD80 (29%), Boeing 727 (20%), and Shorts 360 (14%). Another factor might be procedural differences. In 1989, the majority of large aircraft had analog cockpits, and the majority of approaches were hand flown. In contrast, the newer digital-cockpit aircraft are designed for coupled autopilot approaches, and are more likely to be flown in that mode instead of hand flown. The autopilot logic uses the localizer signal, from full left-of-course deflection to full right-of-course deflection, to determine flight corrections. Because the localizer signal is angular, the lateral distance covered by the signal is proportional to the angular width. As the angular width increases, the full-scale deflection width also increases. This increase translates to greater lateral spread in the flight technical error

Breakout Events. During the PRM demonstration program, the TNSE data analysis suggested that about four percent of the aircraft at ten nautical miles would enter the NTZ during normal operations (see Figure 8). If a nearby aircraft were on the opposite approach, then these NTZ entries would require vectoring the opposite aircraft out of its approach stream. Such a breakout is termed a *nuisance breakout.* Because Raleigh-Durham is the first airport to use the PRM system, it provided an opportunity to compare the actual nuisance breakout rate with the expected rate. We would like to point out, however, that experienced controllers will not necessarily break out an aircraft that intrudes only slightly into the NTZ and is not clearly threatening the other approach path; similarly, a controller will not break out an aircraft if there is no aircraft on the other approach and within two nautical miles. The FAA and the airline industry were also interested in the frequency of breakouts caused by aircraft deviations, or blunders, into the NTZ at Raleigh-Durham.

Between 11 August 1993 and 27 August 1994 there were 1475 simultaneous ILS approaches at Raleigh-Durham. Of these, 37 approaches were canceled and the aircraft were vectored out of the approach stream. The majority of the breakouts (18) occurred because of loss of separation between aircraft on the same approach. Five aircraft were vectored out because they had received a TCAS resolution advisory, and ten breakouts were the result of aircraft behavior on the opposite approach. The remaining four breakouts were associated with other miscellaneous factors.

The ten PRM-related breakouts can be further classified by the action of the adjacent aircraft. In four cases, the adjacent aircraft had been stabilized on its approach, then deviated into the NTZ. The other six cases can be classified as nuisance breakouts: one case because the adjacent aircraft was straddling the NTZ boundary; three cases because the adjacent aircraft entered the NTZ during turn-on to the final approach; and two cases because the adjacent aircraft entered the NTZ while stabilizing after the turn-on. Thus, given the total number of simultaneous parallel approaches that were conducted, the frequency of PRM-related breakouts at Raleigh-Durham Airport (7 per 1000 approaches) appears to be at an acceptable level.

Figure 17 illustrates a breakout that resulted from a deviation. In the figure, green represents normal track updates, yellow represents updates for which a caution alert was generated, and red represents updates for which a warning alert was generated. The deviating aircraft (flight number 7166) was a Piper Cherokee (PA28) on approach to runway 5R, while the endangered aircraft (flight number 6073) was a Saab/Fairchild 340 (SF34) on approach to runway 5L. At twenty seconds flight 7166 started deviating toward the NTZ; at forty-one seconds it entered the NTZ. Shortly afterward, the monitor controller for Runway 5L vectored flight 6073 out of the approach. By fifty-five seconds flight 6073 had started turning away from the approach.

The Final Monitor Aid

The Final Monitor Aid is a recent outgrowth of the

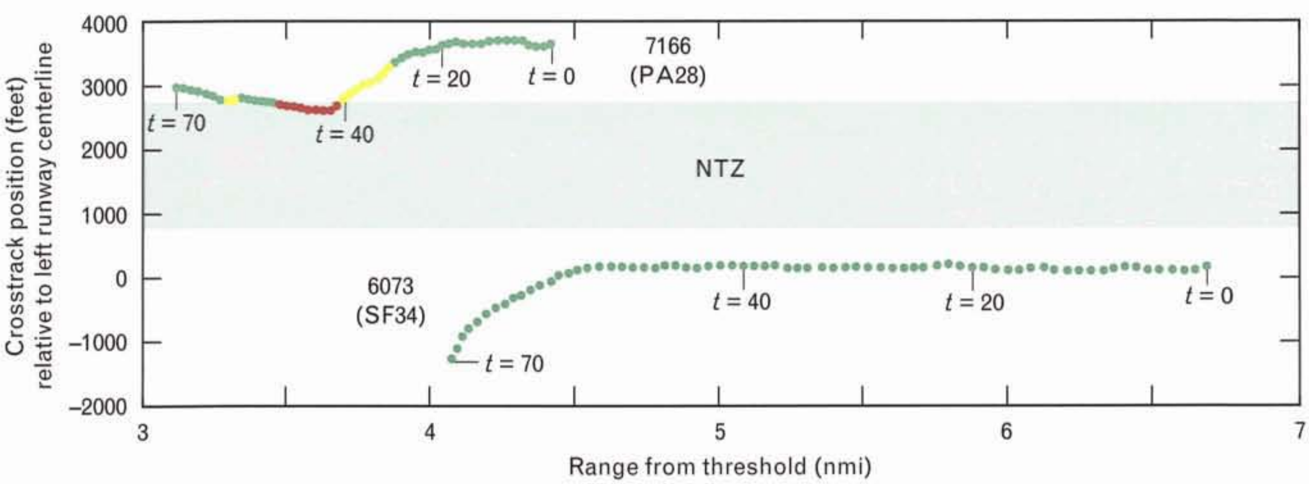

FIGURE 17. Breakout event at Raleigh-Durham. Green dots represent normal track updates, yellow dots represent updates for which a caution alert was generated, and red dots represent updates for which a warning alert was generated. The deviating aircraft (flight number 7166) was on approach to Runway 5R, while the endangered aircraft (flight number 6073) was on approach to Runway 5L. At twenty seconds, flight 7166 started deviating toward the NTZ; at forty-one seconds it entered the NTZ. Shortly afterward, the monitor controller for Runway 5L vectored flight 6073 out of the approach. By fifty-five seconds, flight 6073 had started turning away from the approach.

PRM program. It is essentially the ATC display portion of a PRM system, coupled with a more conventional radar system. This arrangement is capable of providing many of the advantages of the PRM system at a lower cost because a dedicated secondary surveillance-radar system is not needed. The possibility of using technology developed during the PRM program to create a Final Monitor Aid was recognized following completion of the PRM development program. However, a situation that developed at the new Denver International Airport provided the impetus for implementation of the idea.

Denver International Airport was built to handle significantly more traffic than Stapleton International Airport, Denver's previous major commercial airport. To support the large capacity, the new airport was designed with a complex of runways that, when completed, will include eight parallel north-south runways and four parallel east-west runways. These runways were designed to be used for independent sequencing in all weather conditions. Thus the first three north-south runways to be constructed have separations of 5280 feet (between 35R/17L and 35L/17R) and 7600 feet (between 35L/17R and 34R/16L). These separations are well in excess of the 4300-foot minimum for independent sequencing established by the FAA.

However, improved understanding of the important factors involved in detecting and resolving blunders during independently sequenced parallel approaches, due in part to work done during the PRM program, raised questions as to whether the FAA minimum separations are sufficient for parallel approaches at the new Denver airport, especially because the use of triple parallel approaches is planned. The primary reason for this concern was that the FAA established its regulations on the basis of the assumption that aircraft performance can be characterized for air densities typical at sea level. Because the vast majority of large commercial airports are at altitudes less than a thousand feet above sea level, this is generally a good assumption. The field altitude at the new Denver airport, however, is approximately 5300 feet, an altitude that causes a significant difference in air density for a given temperature and barometric pressure. This air-density difference, generally discussed in terms of *density altitude*, causes aircraft to perform quite differently from the way they do at sea level.

In particular, aircraft aerodynamic performance is related directly to indicated airspeed, a quantity measured directly by instruments on the aircraft. If an aircraft flies at a given indicated airspeed, its true speed with respect to objects on the ground increases as air density decreases. Thus at the Denver Airport, aircraft typically fly at a speed relative to the ground that is several tens of knots faster than the same aircraft would fly at an airport with a field altitude near sea level. For parallel approaches, this effect means less time is available to the monitor controller to detect a blunder and to give instructions to the aircraft pilots to maintain separation between the aircraft. Simulation tests carried out at the FAA Technical Center indicated that, because of the effect of density altitude, simultaneous, independently sequenced triple approaches could not be safely carried out at the new Denver airport with the ATC display equipment currently in use.

The PRM system is designed to allow controllers to detect and respond to approach blunders much more quickly than is possible with conventional approach-monitoring equipment. Therefore, installation of a PRM system at Denver International Airport would allow independently sequenced triple approaches. However, because the runway separations at the new Denver airport are much larger than the 3400-foot minimum separation allowed when monitoring is done by using the PRM, the FAA had reason to believe that an implementation of the Final Monitor Aid, coupled with the standard 4.8-sec-update Mode S sensor already installed at the airport, would also safely support independent triple approaches. Subsequent simulation tests carried out at the FAA Technical Center verified that the Final Monitor Aid/Mode S combination is sufficient. Therefore, to provide the new Denver airport with the capability to conduct safe, independently sequenced, triple-parallel approaches, the FAA carried out, with Lincoln Laboratory support, a program designed to develop, test, and install a Final Monitor Aid at Denver International Airport. This program began in late 1992, and was successfully completed in February 1994.

Continuing Developments

Since the initial operations at Raleigh-Durham Airport and the installation at the new Denver International Airport, other research activities are under way that address concerns about advanced cockpits and explore the use of PRM systems at airports with narrower runway spacings.

Advanced Avionics and PRM

Previous data of pilot delays and aircraft-response delays were collected by using analog cockpit simulators (Boeing 727 and DC10) in which aircraft attitude, speed, and other flight information are displayed on traditional electromechanical indicators. Newer aircraft have digital cockpit displays and more complicated coupling between the autopilot and flight-management system. While the simulation tests demonstrated that an older generation aircraft can be turned, on average, within six to seven seconds from initiation of a breakout instruction, some concern exists that the newer aircraft will have slower response times when they are flown in autopilot mode because of the additional time needed for the pilot to reprogram the autopilot or to disengage the autopilot and respond manually to the breakout instruction. There is additional concern about the use of the autopilot to execute the breakout maneuver in reaction to recent airline policies that require pilots to use the automation during missed-approach procedures.

Lincoln Laboratory and the FAA Aviation Standards Development Branch will be conducting pilot/aircraft response studies in 1995, using two advanced-avionics full-motion simulators: a Boeing 747-400 simulator at NASA Ames in Santa Clara, California, and an Airbus 320 simulator operated by Northwest Aerospace Training Corporation in Eagan, Minnesota. In addition to the scenarios tested in the earlier Boeing 727 and DC10 studies, these new studies will test pilot and aircraft performance during autopilot breakouts and hand-flown breakouts following an autocoupled approach. The tests will also assess pilot/aircraft responses to descend-and-turn breakouts issued above the minimum vectoring altitude. These descending breakout maneuvers have been requested by FAA air traffic control representatives but are viewed by the pilot community as inappropriate. The first part of each study will measure performance based on current pilot training. The second part will measure performance improvements when PRM-specific pilot training is given.

Further Reduction of Runway Separations

When the PRM Program was initiated in 1987, the ultimate goal was to develop new technology and ATC procedures that would allow simultaneous ILS approaches to be conducted at runway separations as small as 2500 feet. Because of the effect of TNSE on controller work load as runway spacing is reduced, the PRM system is currently approved for spacings of 3400 feet or greater. To extend the use of PRM to smaller runway spacings, the FAA is evaluating procedures that would allow simultaneous ILS approaches to be safely conducted at runway separations between 3000 and 3400 feet. If the procedures are approved, PRM equipment could then be installed at airports such as Philadelphia, Pennsylvania; Portland, Oregon; and John F. Kennedy Airport in New York.

Real-time simulations of operations at 3000-foot separations have been conducted at the FAA Technical Center in Atlantic City, New Jersey. The first simulation involved straight-in ILS approaches, and it confirmed the data in Figure 8—namely, that TNSE causes many aircraft to wander close to or into the NTZ during normal operations, generating a large number of nuisance PRM alerts. TNSE also caused the monitor controller to instruct each of these aircraft to return to localizer. Finally, if the aircraft entered the NTZ, the monitor controller was required to break out any potentially endangered aircraft on the opposite approach. As a result of the additional communications work load on the controller, the 3000-foot runway separation procedure was not approved for straight-in ILS approaches.

A second set of 3000-foot real-time simulations was conducted in 1994. In the first part of the simulation, the localizer beam for one of the ILS approaches was offset by 1°. In the second part, the localizer beam was offset by 2.5°. This simulation marked a milestone in that it included a large proportion of digital-cockpit flight simulators flying in autopilot mode. This study was also the first to incorporate the

Lincoln Laboratory Monte Carlo blunder simulation into the risk analysis.

When the results were assessed, neither 3000-foot configuration with localizer offset was approved by the FAA. The 1° offset did not provide sufficient lateral separation between aircraft, and the controllers were not able to resolve a significant number of blunders safely. Even though the 2.5° localizer offset provided sufficient lateral separation, procedural problems caused the second simulation to fail. Factors contributing to poor blunder resolution included long pilot/aircraft response times during breakout maneuvers involving glass cockpits, blocked or clipped transmissions, and inadequate controller procedure and phraseology. The results also suggested that a combination of improved pilot training, controller training, and enhanced communications would improve PRM performance.

Because of these findings, the FAA is evaluating antiblocking devices. In addition, the controller-training syllabus will be revised, and the effect of pilot training will be evaluated. If these solutions look promising, then the use of PRM at airports with 3000-foot runway spacings and 2.5° localizer offsets will be reevaluated.

Summary

The Precision Runway Monitor program has been successful in two ways. First, it developed a new radar monitoring system that enables parallel ILS approaches to parallel runways spaced significantly closer than before. Second, a process was developed that combines machine-performance and human-performance field data, Monte Carlo assessments, and operational demonstrations, to develop new procedures based on sound technical methods and user participation. This process can provide technically defendable assessments of other candidate technologies designed to meet civil aviation needs.

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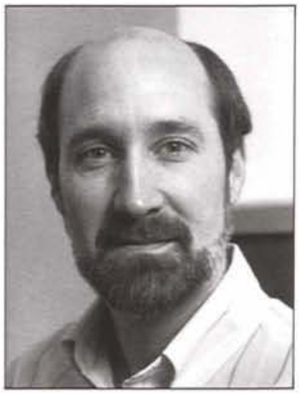

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