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Closely Spaced Independent Parallel Runway Simulation

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Final Report

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16. Abstract

As an outgrowth of the recommendations of the Industry Task Force on Airport Capacity and Delay Reduction, a simulation of closely spaced independent parallel runway operations under instrument meteorological conditions was conducted at the National Aviation System (NAS) Simulation Support Facility (NSSF) of the Federal Aviation Administration Technical Center. The simulation was conducted to determine (1) the impact of reduced runway spacings on the air traffic controller's ability to detect and resolve potential conflicts, and (2) the surveillance sensor accuracy and update rates needed to support closer runway separation. The NSSF environment was configured to simulate a terminal radar control room conducting independent parallel runway operations. Sixteen full-performance-level field controllers with monitor controller experience participated in the simulation as monitor controllers; final and local control positions were manned by Technical Center controllers. Six experimental conditions were simulated involving 48 1-hour data gathering experimental runs conducted over a 4-week period. Results indicate safe operations can be conducted at 3,400 feet runway separation provided a surveillance radar of at least a 2-second update rate and 2-milliradian accuracy is used. Some increase in penetrations of the "no transgression zone" will likely result from this reduction.

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EXECUTIVE SUMMARY

This report describes an air traffic control (ATC) simulation of closely spaced independent parallel runway operations under instrument meteorological conditions. The effort was conducted to determine whether existing minimum parallel runway separation standards for this kind of operation can be reduced from the current 4,300 feet to as little as 3,000 feet. The effort supports an FAA/industry effort to increase airport capacities by allowing independent parallel operations at airports where existing or potential parallels are less than 4,300 feet apart.

Sixteen controllers served as monitor controllers in this simulation controlling arrivals under six experimental conditions. These conditions were made up of different combinations of the following: runways spaced 4,300, 3,400, and 3,000 feet apart; radar update rates of 5, 2, and 1 second(s); radar accuracies of 3, 2, and 1 milliradian(s) (mrad); and two displays, a standard digital radar display and one that was "magnified" in one dimension to increase the size of the area on the display between the two instrument landing systems (ILS's) by a factor of two. The one condition with 4,300-foot separation used a simulated ASR-8 radar (5-second update rate, 3-mrad accuracy); it represented the present minimum standard against which experimental variations were tested.

All of the conditions used a 2,000-foot no transgression zone (NTZ) between the ILS's with a normal operating zone (NOZ) between each localizer centerline and the NTZ boundary. The 4,300-foot separation provided NOZ's of 1,150 feet; the 3,400-foot separation, NOZ's of 700 feet; and the 3,000-foot separation, NOZ's of 500 feet.

The results of the simulation show that for normal aircraft approaches of the type seen in category I operations, the 3,400-foot separation can provide a safe operation in return for a moderate increase in controller activity if a more accurate and higher update radar rate is used. The radar must have an accuracy of no less than 2 milliradians and an update rate of no more than 2 seconds. Magnification of the controllers' display in the lateral dimension seems to help but is not essential. A 3,400-foot operation using the improved radar will produce additional NTZ entries (NTZE) and a corresponding need for additional controller warnings to pilots and other communications. It may also produce additional conflicts which result from aircraft presence in the NTZ; however, simulation results produced no cases of miss distances less than 2,000 feet. Landing rates and the number of missed approaches were equivalent to the 4,300-foot operation.

Going to 3,000-foot runway separation significantly increases the problems introduced by going from 4,300 to 3,400 feet. Workload, communications, NTZE's, and conflicts increase significantly. Controllers question the safety of 3,000-foot parallel runways unless some longitudinal separation is provided between aircraft on adjacent ILS's (such as in the dependent parallel approach operation).

The simulation introduced deliberate blunders. In this study, a blunder was an unannounced turn by an aircraft to a 30° heading towards the opposite ILS, usually in the presence of traffic there. This was considered the "worst case" event. There were no significant differences between several of the experimental conditions and the 4,300-foot standard in the ability to provide separation for

the blunders. Some very serious incidents occurred under all conditions. It appears that a standard rate of 30° off one ILS course towards traffic on the other is simply too severe a test for any of the conditions, and it must be noted that a 30° blunder rarely occurs during actual operations. The blunders did reveal that the 1- and 2-second radar update rates produced faster controller responses than the 5-second rate.

On the basis of this study, it is concluded that safe and efficient parallel runway operation can be conducted with runways spaced 3,400 feet apart provided that an ATC surveillance radar is used having an update rate of no more than 2 seconds and an accuracy of at least 2-mrad. The expanded display feature might help. Such an operation would see some increase in the number of warnings issued, number of NTZ entries, and number of conflicts; however, even with these increases, adequate separation seems assured.

Simulation results led to the following recommendations:

1. For operations with a 3,400-foot separation, provide a controller display magnification feature which can, at the controller's option, magnify the radar display in the lateral dimension, to aid the controller in performing independent parallel runway operations.

2. Consider the development and use of an automated monitor alert feature which would insure minimal reaction time to the occasional blunder. This feature would provide an audible or visible alert to the controller of any aircraft on the ILS that was deviating towards the NTZ with sufficient speed or distance that controller action might be required. The sensitivity of such an alert could be a controller-selectable parameter.

INTRODUCTION

PURPOSE.

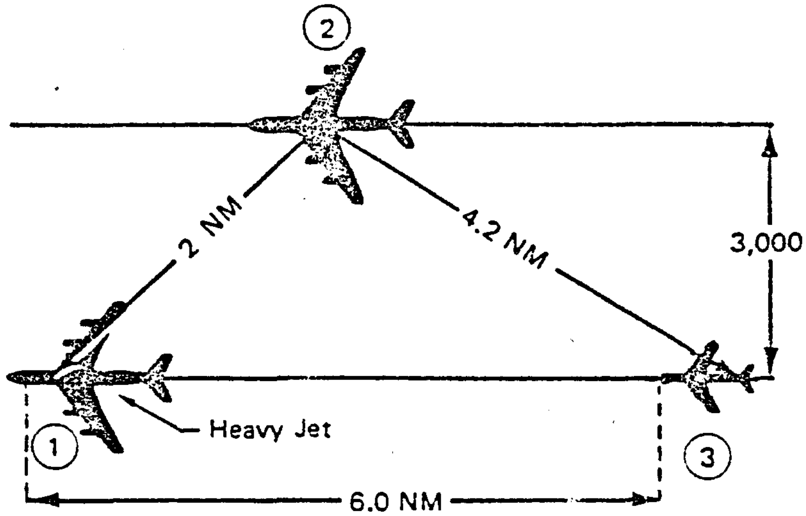
The purpose of the Closely Spaced Independent Parallel Runway Simulation effort is to provide information which will aid in determining the feasibility of, and prerequisites for, implementing independent parallel runway approach operations during instrument meteorological conditions (IMC) at airports where existing or potential runway spacing is less than the current minimum of 4,300 feet.

More specifically, the principal purposes of this simulation are to determine (1) the impact of reduced runway spacings on the controller's ability to detect and resolve potential conflicts, and (2) the surveillance accuracy and update rates needed to support closer runway separation.

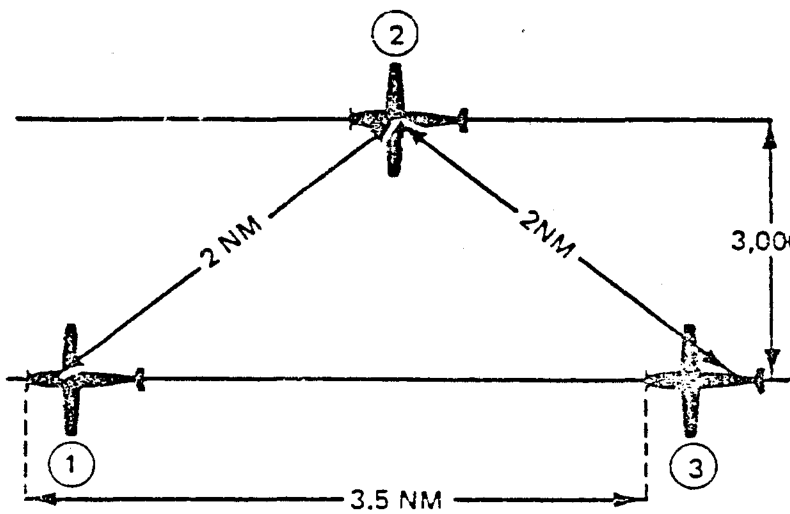
BACKGROUND.

Parallel runways are a frequently used means of increasing airport capacity. In the case of lightweight, single-engine, propeller-driven aircraft operating under visual flight rules (VFR), simultaneous same-direction operation is permissible on parallel runways with centerlines separated by as little as 300 feet. For other classes of aircraft, similar operation is permissible with as little as 700 feet of runway centerline separation, provided wake turbulence is not a factor. For mixed (wake turbulence) class aircraft operations, a minimum runway separation of 2,500 feet is permissible under VFR. Simultaneous parallel runway operation under IMC involves several other factors which necessitate an increase in the runway separation standards to maintain an acceptable level of safety. These factors include the accuracy and response time of the ground and airborne components of the instrument landing system (ILS), the proficiency of the pilot, the accuracy and update rate of the air traffic control (ATC) radar monitoring system, the response times of the controller and pilot, and whether the operations are independent or dependent. For independent operations, operations can be conducted on each runway without regard for the location of aircraft on the adjacent runway. For dependent operation, parallel runways may be separated by as little as 3,000 feet, but arriving successive aircraft on adjacent localizer courses must have at least a 2-mile radar separation (see figure 1). An increased capacity results from independent parallel runway operation since the latter 2-mile aircraft separation requirement does not apply. Arriving aircraft may even be parallel to one another. Current standards, however, require that the runways be separated by at least 4,300 feet for independent parallel operation.

Reducing the minimum runway separation standard for independent parallel runway operations during IMC has long been an interest of the Federal Aviation Administration (FAA) and the aviation community. In 1969, the Air Traffic Control Advisory Committee recommended the reduction of independent parallel runway separation standards from 5,000 feet to 2,500 feet as one of several steps that could be taken to double urban airport capacity. Subsequent experimental and analytical efforts have been conducted under FAA auspices by the MITRE Corporation, Lincoln Laboratories, Resalabs, and others for the purpose of developing a rational runway separation standard. As a result of these earlier efforts, the minimum separation standard was reduced from 5,000 feet to the current 4,300 feet. More



In this illustration, aircraft 2 is two miles from heavy aircraft 1. Aircraft 3 is a small aircraft and is six miles from aircraft 1. The resultant separation between aircraft 2 and 3 is 4.2 miles.



In this illustration, aircraft 2 is two miles from aircraft 1 and aircraft 3 is two miles from aircraft 2. Resultant separation between aircraft 1 and 3 is 3.5 miles.

FIGURE 1. DEPENDENT PARALLEL ILS APPROACH MINIMA

recent analysis, principally by the MITRE Corporation, indicates that runway separations may be safely reduced to 3,000 feet, provided the accuracy and update rate of the ATC surveillance radar is improved.

Reducing parallel runway separation standards could increase capacity at some airports immediately by permitting a switch from dependent to independent operations where existing parallels are less than 4,300 feet apart. In other cases, the savings will be in the time and cost that may be avoided for land acquisition if a new parallel runway can be built closer to an existing runway.

In recognition of these potential capacity improvements and cost savings that are achievable if minimum runway separation standards for independent instrument flight rules (IFR) operations can be safely reduced, the Industry Task Force on Airport Capacity Improvement and Delay Reduction recommended that the "FAA undertake the necessary testing, demonstration and, where necessary, development to permit safe introduction of independent IFR parallel approaches with runway spacing below 4,300 feet to as low as 3,000 feet." The task force also recommended that a simulation and a data collection effort be conducted. The simulation would help determine (1) the controller's ability to react to and resolve aircraft deviations at the reduced spacings, and (2) the surveillance sensor accuracy and update rates needed to support closer runway separation. The data collection effort would collect onsite data on actual aircraft lateral deviations about the ILS. Although extensive lateral deviation data currently exists, these data were obtained in the late sixties. Newly collected data would help validate existing normal operating zone (NOZ) widths or indicate a possibility for change. The task force further recommended that the FAA conduct live demonstrations if both efforts yielded positive results.

This report responds to the task force recommendation for an FAA-conducted simulation.

OVERVIEW OF MONITOR CONTROLLER'S POSITION

This effort is intended to simulate a realistic ATC environment (which incorporates changes in runway spacing, surveillance accuracy, radar update rate, and controller displays) and to evaluate the impact of these changes on the ability of experienced monitor controllers to maintain system safety and capacity. The monitor controller is the "subject" (in the experimental sense) of this simulation. The following describes the monitor controller's duties, both in the field and, as close as possible, in this simulation.

A normal instrument approach into an airport having radar coverage involves contact with approach control and local control position. Approach control is initially contacted as the aircraft passes from en route into terminal airspace. This may occur at a distance of 15 to 50 miles from the airport. For larger terminal areas, approach control will consist of one or more arrival controllers and one or more final controllers. The arrival controller vectors the aircraft as necessary to funnel them to the vicinity of the final approach course where the aircraft is handed off to the final controller. The final controller vectors the aircraft as necessary to achieve as efficient a flow onto the final approach course as possible, subject to the standard and wake vortices separation minima and other aircraft performance and safety factors. At a point, generally at least 2 miles from the approach gate (an imaginary point 1 mile from the final approach fix), the aircraft is given a vector to intercept the ILS and is advised to change to the local controller frequency. Control responsibility remains with the final controller, however, until the local controller provides visual separation. Once visual acquisition is attained, local control retains responsibility until the aircraft exits the runway.

At airports where conditions permit independent parallel runway operation under IMC, two additional controllers are involved in the above processes. Both of these controllers, called monitor controllers, are responsible for monitoring all aircraft on one ILS from the point it intercepts the ILS until the pilot or the local controller provides visual separation. The principal function of the monitor controller is to prevent lateral conflicts between arriving aircraft on adjacent approaches and maintain spacing between aircraft on the same ILS (i.e., prevent longitudinal conflicts). Lateral conflicts are prevented by advising errant aircraft whenever they are observed on a track which would penetrate the no transgression zone (NTZ). This is accomplished by advising the pilot that he is left or right of course and should "turn left (or right) and return to the localizer course." When an aircraft is observed penetrating the NTZ in a manner that could threaten adjacent traffic, the aircraft on the adjacent track is vectored off the approach course.

The aircraft on the adjacent track; i.e., the nonblundering aircraft, is immediately vectored off the ILS course instead of the blundering aircraft for two principle reasons: (1) the blundering aircraft has demonstrated an inability to adequately navigate and/or control his aircraft (possibly because of an inflight emergency) and, therefore, cannot be relied upon to accurately execute controller instructions, and (2) to increase the airspace between the two conflicting aircraft and thereby enhance the probability that they will not merge. To minimize the blundered aircraft's exposure to the airspace and consequent possible disruption of proximate traffic, the controllers attempt to land the aircraft using vectoring and/or speed control. As a last resort, the aircraft is broken off the approach and handed off again to the final controller for resequencing into the traffic pattern.

Although the monitor controller's raison d'etre is to insure lateral separation during parallel operations, blunders and the need for warnings occur so infrequently that most of the controller's communications and apparent workload are devoted to ensuring longitudinal separation and desired spacing. Separation is assured through the issuance of speed advisories, which are kept to a minimum except to achieve desired spacing or to prevent longitudinal conflict. Once inside the outer marker, generally no speed advisories are given. Any serious potential conflicts are prevented by vectoring the aircraft off the ILS course.

Throughout the approach operation, control responsibility routinely remains with the approach or local controllers and not with the monitor controller unless he acts to assure separation. His normally passive function requires no communication with the aircraft except during the infrequent occurrence when warning, advisory, or vectoring action is required. Since the monitor controller does not normally have control responsibility, he does not have a separate frequency but overrides the local controller's frequency when transmissions are required. Obviously, this frequency-sharing requires a close working relationship, teamwork, and the exercise of judgment on the use of the frequency. An even closer working relationship exists between the two monitor controllers whose actions in the handling of blundering aircraft are interdependent. To facilitate coordination, these controllers are co-located and generally share a single display.

Controller judgment is involved in the controller's handling of speed advisories, blundering aircraft, and actions taken to mitigate the potential consequences of potentially blundering aicraft. In the event of a blunder, the controller must quickly determine whether an aircraft on the adjacent approach is threatened and whether the blundering aircraft can be landed. If an aircraft appears unsteady and a potential blunderer, then the monitor controllers may jointly agree to provide speed advisories to minimize the time that the potentially blundering aircraft is parallel or near aircraft on the adjacent approach thereby minimizing the consequences of a potential blunder. The judgment and techniques which the controllers apply in these circumstances impact the safety and efficiency of the overall approach operation.

DESIGN OF THE EXPERIMENT

The design approach of this effort is intended to acquire maximum information on the safety of closely spaced runway operations within the capabilities of the National Airspace System (NAS) Simulation Support Facility (NSSF). The most significant limitation of the facility is the necessity to use a digital display similar in quality and appearance to the NAS en route plan view display instead of the primary radar, rho theta ARTS display which is used at terminal facilities. An earlier limitation that was rectified was the inability to modify aircraft flight paths once they were "flying" the ILS. This has been corrected through an NSSF software modification that enables aircraft on the ILS to respond to controller directives even though they have not been previously scripted. Additionally, aircraft flight trajectories were made more realistic by introducing some level of controlled variation for aircraft flying the localizer (see appendix A). The previous ILS model "flew" perfect approaches.

The choice of variables used in this study was based on the current Air Traffic Control Handbook standards, typical airport geographies, and previous analysis. They reduce to the following:

1. Distance between the parallel runways.

2. The accuracy of the surveillance system (radar) used to monitor aircraft on the ILS.

3. The update rate of the surveillance system.

Another variable introduced into the simulation is the "display" variable. This was included because of the apparent need to expand the scale of the display in the lateral dimension; i.e., the dimension which displays aircraft deviation from the localizer. Without expansion, the distance between the localizer and the normal operating zone (NOZ) boundary ranges from a maximum of about 0.17 inches to less than 0.1 inch depending on the runway separation. The magnification of this zone while retaining the overall display range is shown in figure 2.

The simulation was designed to evaluate the effect of the above-named four-system factors on the safety, efficiency, and capacity of airport operations. Considerations of time, resource availability and the desire to have meaningful information led to a simulation of six different experimental conditions, labeled "J" through "O" (see table 1), which differ from each other with respect to one or more of the above-named variables.

Condition J is intended to represent airport operations using 4,300-foot parallel runways. The NOZ boundary is 1,150 feet from the localizer. The NTZ in this, and all other conditions, remains fixed at 2,000 feet wide. The radar, which is intended to simulate the ASR-8, has an accuracy of 3 milliradian (mrad) and updates the display every 5 seconds. The display is set to show 15 miles edge-to-edge and is off-centered so that the ILS's are centered with the runways shown at one edge. It represents a best attempt at simulating a present field operation that is known to be safe.

Condition K also represents an operation using the ASR-8 radar. The runways are 3,400 feet apart and the NOZ boundary is 700 feet from the localizer. The radar is updated every 5 seconds and has an accuracy of 3 mrad. The display is set to show 15 miles edge-to-edge and offset to center the ILS's.

Condition L has the same geography as condition K, but the assumption is made that a higher accuracy, faster update rate radar is in use. The "new" radar has a 2-second update rate and a 2-mrad accuracy.

Condition M is the same as conditions K and L, except that the radar now has a 1-second update and 1-mrad accuracy.

Condition N simulates an airport with parallel runways 3,000 feet apart. It still has a 2,000-foot NTZ but the NOZ boundaries are 500 feet from the localizer. It uses a 1-second update and a 1-mrad radar. The display shows 15 miles edge-to-edge along the ILS axis but was expanded laterally by a factor of two; i.e., a line through the center of the display at right angles to the ILS represents a distance of 7.5 miles (see figure 2).

Condition O uses a spacing of 3,400 feet between runways and NOZ boundaries 700 feet from the localizer, 1-second update, 1-mrad accuracy, and lateral magnification of two as described in condition N.

An important consideration in any ATC simulation is the presence of individual differences among journeyman controllers. Variations in experience, background, and style can hide, or even distort, test results. To avoid, or at least minimize, this source of error, the experimental design allowed for every controller to participate in each of the experimental conditions.

This permitted a degree of precision in measurement that would only otherwise be possible by using several times as many controllers and extending the test period accordingly.

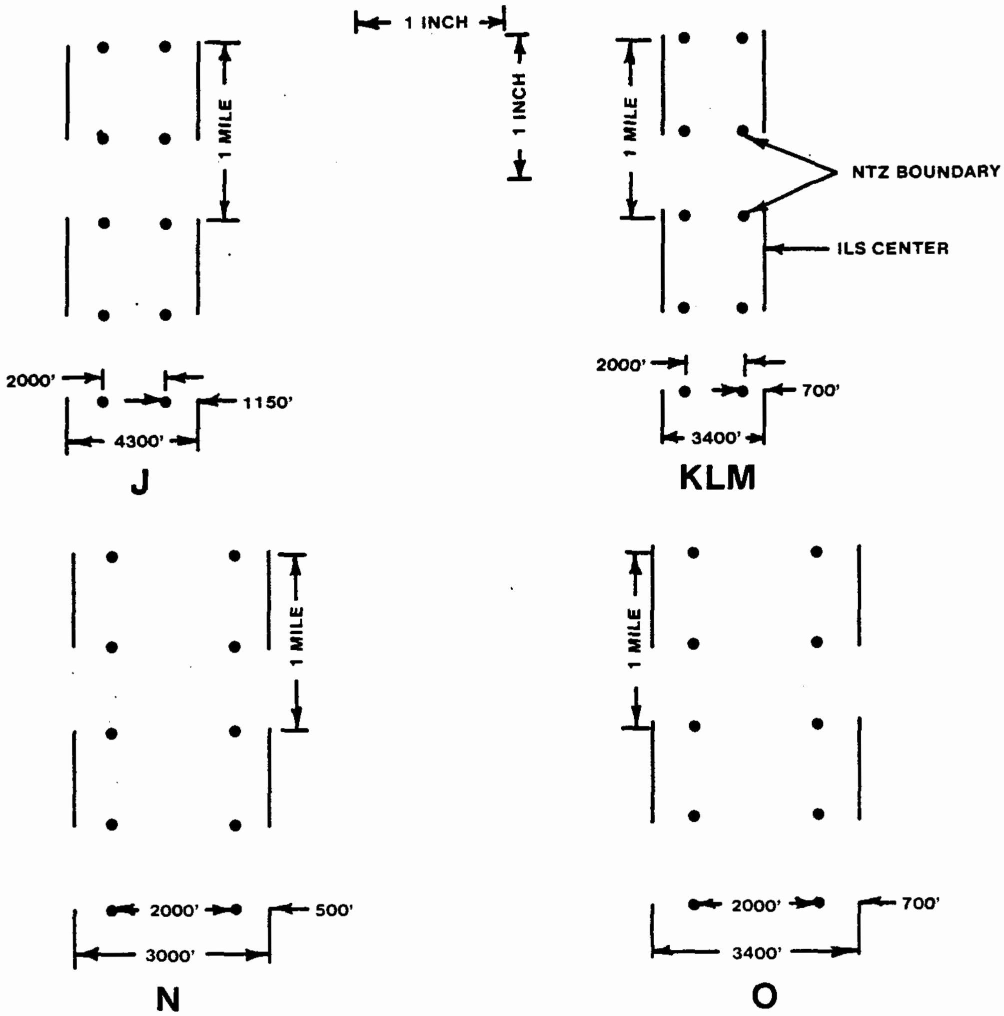


FIGURE 2. RADAR DISPLAY COMPARISON — ALL CONDITIONS

TABLE 1. SUMMARY OF EXPERIMENTAL CONDITIONS

Condition	Runway Separation	Normal Operating Zone	Radar Accuracy	Radar Update Interval	Lateral Deviation Magnification
J	4300 ft.	1150 ft.	3 mrad	5 sec.	1:1
K	3400 ft.	700 ft.	3 mrad	5 sec.	1:1
L	3400 ft.	700 ft.	2 mrad	2 sec.	1:1
M	3400 ft.	700 ft.	1 mrad	1 sec.	1:1
N	3000 ft.	500 ft.	1 mrad	1 sec.	2:1
O	3400 ft.	700 ft.	1 mrad	1 sec.	2:1

Another important factor in the conduct of ATC simulations is the fact that field controllers do a great deal of "learning" in the simulation environment. There are, of necessity, many differences between any simulation and any live operation; differences in the radar displays and communications equipment, differences in the responses of the pilots and the aircraft, new geography, and new procedures. If this learning process, which is usually associated with improved controller performance, is confounded with the experimental variables, those conditions tested later may appear to be better than they should. There are two ways to avoid this confounding. First, there could be several training runs, six or more, which bring all controllers to a plateau on the learning curve before starting data collection. The other approach is to minimize pretraining and also present the experimental conditions in a counterbalanced order. In this method, subjects work the conditions in different orders and, while for any one subject performance during the later conditions may improve as compared to performance during earlier ones, differences should average out over all the subjects. The experimental design accomplishes this by making order an experimental variable so that its effect can be isolated from that of the experimental conditions. This can be seen in the weekly schedule (table 2), where each group of four controllers is presented the six conditions in a different order. The average order of presentation for each condition in this design is the same.

Each group specified in table 2 consisted of four controllers who participated in the simulation at the same time. Each group of four was randomly divided into two teams of two and each team worked as a unit for the study. Each team was assigned to one of two identical airports (display positions) and continued at that position. Team members were asked to switch between the left and right runways (left and right sides of the display) after every 1-hour run. Since every test condition was repeated once on the subsequent run, every team member worked each condition once on the left runway and once on the right. For purposes of data analysis each team was considered as a single subject and the two successive runs on the same condition were treated as a single run. A single point then consists of the average (or sum) of the performance of two controllers at one airport over 2 hours. There was, however, a 20-minute break scheduled between successive 1-hour sessions.

For each of the many variables measured, the data consists of two teams times six conditions times 4 weeks (or orders) for a total of 48 data points. The experimental design can be described (reference 1) as a Split Plot Factorial-p.q or as a Mixed Model or Nested Design. The important features are that every controller works under all of the different experimental conditions (J, K, L, M, N, and O), but only two of the eight teams experience each order. The design makes it possible to remove "between subject" variations and to isolate the effect of learning on the differences between experimental conditions. If, for a particular variable, there is a significant difference (F test) among the experimental conditions, then the degree and direction of differences among specific experimental conditions can be examined and interpreted. These pairwise comparisons are called "contrasts" and the following are of particular interest:

TABLE 2. EXPERIMENTAL SCHEDULE

Time Of Day	Order:	Day 1				Day 2				Day 3		
	1	2	3	4	1	2	3	4	1	2	3	4
0815-0915		Training			K	N	N	K	N	K	K	N
0935-1035		Training			L	M	O	J	N	K	K	N
1055-1155	J	O	M	L	L	M	O	J	O	J	L	M
1330-1430	J	O	M	L	M	L	J	O	O	J	L	M
1450-1550	K	N	N	K	M	L	J	O		Make-up		

J versus K: The present minimum standard (4,300 feet) is compared to the proposed 3,400-foot separation, both using ASR-8 radar specifications.

J versus L/J versus M: The 4,300-foot/3,400-foot comparison is examined using successively improved radar specifications. (Can a higher update rate and more accurate radar permit reduced runway separation?)

M versus O: Using the highest performance radar, is performance improved if lateral deviations about the localizer are magnified or enhanced on the display by a factor of two?

N versus O: Using the highest performance radar and display enhancement, can runway separations be further reduced from 3,400 feet to 3,000 feet?

DESCRIPTION OF THE TEST ENVIRONMENT

The test environment includes the simulation facilities, the controllers, the traffic samples, and the simulation procedures.

SIMULATION FACILITY.

The parallel runway simulation was conducted using the National Aviation System Simulation Support Facility (NSSF) located at the FAA Technical Center. The NSSF is a general-purpose ATC simulator designed to provide a realistic test bed for developing, testing, and evaluating advanced ATC concepts, airspace management plans, and procedures. The facility consists of the Central Computer Facility, the Controller Laboratory, and the Simulator Pilot Complex.

CENTRAL COMPUTER FACILITY. The Central Computer Facility consists of a group of mainframes, minicomputers, and associated peripherals which host the operational and data acquisition simulation software. This software generated the specific ATC adaptation, drove the ATC displays, and generated the aircraft flight models used in this simulation.

CONTROLLER LABORATORY. The Controller Laboratory is a simulated en route or terminal control room which includes eight digital control displays and the associated keyboard entry and communication equipment. The laboratory is configured so that the subject controllers can function in a manner nearly identical to the way they do in the field. Controller-to-controller, controller-to-pilot (simulator operator), and pilot-to-controller communications are available and were utilized in this simulation.

In addition to the monitor controller position, final and local controller positions were used in the simulation. Their primary function was to simulate the background radio frequency usage that typifies actual operation. They accepted radio contact from incoming aircraft and issued clearances to scripted departures. As in the field, the monitor controllers shared their frequency with the local controller. When it was necessary to communicate with an aircraft, the monitor controller interrupted the local controller, who relinquished the frequency. For this simulation (in contrast to the field where the monitor controller actually overrides the local controller's transmissions), whenever the monitor controller depressed his microphone switch a buzzing sound occurred in the earphones of the local/final controllers signaling to them the need to stop their transmissions. This minor difference in procedure was necessitated by the limitations of the laboratory communications subsystem. Each test run involved the simultaneous simulation of two independent airports. For each airport, two monitor controllers shared a display and two local controllers shared a display; hence, there were eight controllers involved in each simulation run.

The display presented to the controllers in this simulation was designed to duplicate that used by monitor controllers in the field to the extent achievable with a digital display. For all experimental conditions, the display scale was set to display 15 miles along the axis of the ILS. For conditions N and O, the lateral scale was expanded by a factor of two (as discussed and illustrated in the Design of the Experiment section). The ILS is displayed as a segmented line with 1/2-mile-long segments separated by 1/2-mile spaces. The NTZ boundaries were displayed as dots at 1/2-mile intervals. Also displayed were symbols designating the two gates, the outer markers, and runways.

A standard ARTS alphanumeric tag accompanied each controlled aircraft. This consists of aircraft identifier on the first line, altitude on the second, and aircraft type and groundspeed alternating at 5-second intervals on the third. The aircraft target initially appeared on the display as an "A" which automatically changed to an "◊" when the simulator operator acknowledged the aircraft by switching it to the local control frequency.

SIMULATOR PILOT COMPLEX. The Simulator Pilot Complex houses the simulation pilots (or operators), their consoles, and other peripheral equipment. For this simulation, 16 of the 48 available simulator operator positions were used. The simulator operators are voice-linked with the controllers in the Controller Laboratory and convert their verbal directives into a keyboard entry which is transmitted to the Central Computer Complex, where the appropriate response is generated. The response is consistent with the flight characteristics of the simulated aircraft. Simulator operators are provided a display of data describing the status of the airplanes they control. These data include speed, heading, altitude, and intended flight plan and are used to answer queries from the controller. The "pilots" also initiate communications with the controllers to provide procedural reports, simulate emergencies, etc.

THE CONTROLLERS.

The 16 field controllers who participated in this simulation as monitor controllers are currently active, full performance-level controllers with experience in the monitor position. The participating controllers represented a wide range of terminal facilities including Atlanta, Hawkins (Mississippi), Miami, Memphis, Opa-Locka, and West Palm Beach. The controllers manning the local/final control positions are FAA Technical Center controllers who are full-performance-level controllers not currently engaged in ATC.

TRAFFIC SAMPLES.

Each traffic sample consisted of a schedule of 65 expected arrivals for each airport with approximately half arriving on each runway. Because the simulation was stopped at exactly 60 minutes, the final 5 to 10 aircraft were never landed. Thus, there were minor random differences in the composition of the six traffic samples.

There were six different orders in which the aircraft arrived and these orders were designated K-1 to K-6.

The mix of traffic used for this simulation was taken directly from the actual flight strips at the Memphis International Airport Tower. The behavior of the aircraft on the ILS was developed for this simulation to realistically simulate behavior of aircraft on the ILS and to assure that the statistics which characterize their aggregate behavior approximate those obtained from real-world measurements. The airspace used, including gates, outermarkers, and aircraft starting locations is shown in figure 3.

If all the aircraft fly perfect ILS approaches, the monitor controllers become passive observers of the system checking for longitudinal separation and making an occasional speed correction. Even a blunder in this context becomes an immediately obvious break in the pattern and can be dealt with routinely. For this reason, the determination of aircraft flight characteristics significantly impacts the study. In order to provide a rigorous test and maximize the amount of safety and system capacity information obtained, as pessimistic a view of available piloting skills as is consistent with a realistic test was chosen. This approach should enhance any operational differences among the six conditions and provide a lower bound on expected safety and capacity predictions. Appendix A describes the model used to generate aircraft flight paths on the ILS.

The "pessimistic profile" selected is based on data collected on aircraft flying ILS approaches at a number of airports and reported in 1972 (Resalab, see table 3). The data modeled are based on category I approaches, the least precise type of ILS approach. These approaches can be summarized by the standard deviations of a large sample of aircraft (at several airports) at various distances from the runway threshold (600 to 15,900 meters). Category I has a standard deviation of about 100 meters (i.e., approximately 68 percent of the aircraft would be 328 feet or less from the localizer centerline, 32 percent beyond) from their establishment on the ILS to about 5 miles from threshold. At this point accuracy improves (the standard deviation decreases) rather regularly to the 600-meter point (one-third of a mile from touchdown) where 68 percent of the aircraft are within 40 feet of the centerline. It should be noted that Resalab data (reference 2) on categories I and II combined are twice as good as this, and International Civil Aviation Organization (ICAO) data (reference 3) on aircraft using autopilot in category II landings are even better (see figure 4). The data for all aircraft for eight runs, excluding blunders and vectored aircraft, are plotted against a best fit of the Resalab data in figure 5. Each point is the standard deviation for about 110 aircraft.

SIMULATION PROCEDURES.

There are two types of procedures involved in the simulation effort: operational procedures and test procedures. Operational procedures refer to those that are intended to simulate real-world operations. Test procedures refer to those that were used to conduct the simulation.

OPERATIONAL PROCEDURES. As previously noted, to the extent possible, all procedures were identical to field procedures except where otherwise noted. The controllers were given a list of instructions which they were to use throughout the simulation. These instructions are contained in appendix B.

Starting points, used in traffic sample specification, are shown at bottom of map. "Other" airport map is identical except for computer-coordinates and designation used for starting points. This example shows a 3400-foot runway separation. (Note: J & K do not appear on any display. They are used as intermediate points to turn aircraft onto the ILS.)

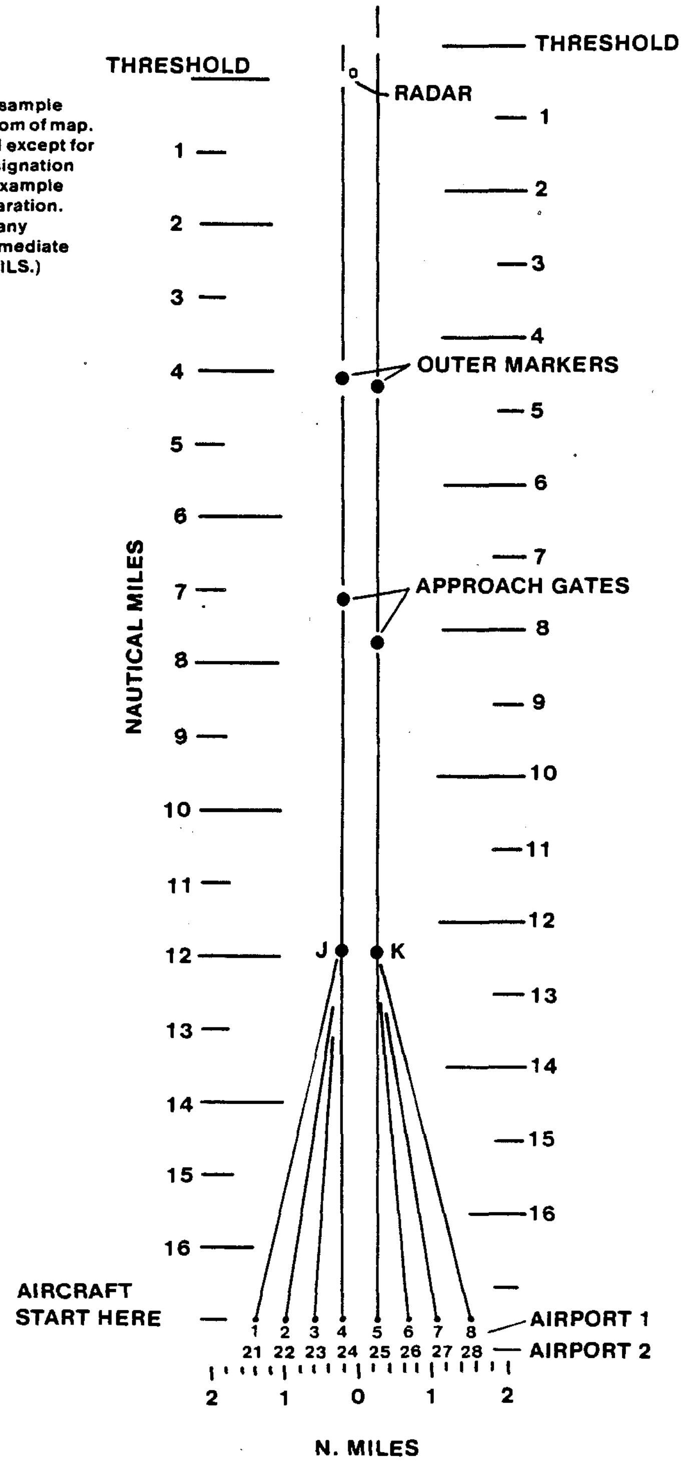


FIGURE 3. TYPICAL SIMULATION GEOGRAPHY

TABLE 3. RESALAB DATA ON CATEGORY 1 APPROACHES*

(Mean and standard deviation versus range for front course ILS, category 1, conventional takeoff and landing aircraft, lateral deviation from localizer centerline.)

Range (nmi)	Range (kilometers)	Number Of Samples	Mean (meters)	Standard Deviation (meters)	Standard Deviation (feet)
0.32	.6	513	- 0.0161	11.8943	39
0.65	1.2	618	- 3.0435	22.0739	72
0.97	1.8	633	- 5.2973	26.4976	87
1.30	2.4	642	- 6.7594	31.9236	105
1.62	3.0	644	- 2.8728	35.8971	118
1.94	3.6	638	1.6535	37.7171	124
2.27	4.2	622	8.9878	43.6031	143
2.59	4.8	631	8.3098	46.9545	154
2.91	5.4	630	8.4069	53.4125	175
3.24	6.0	631	6.9212	61.9026	203
3.55	6.6	629	2.9729	68.5199	225
4.05	7.5	513	14.4600	75.3000	247
4.37	8.1	500	11.8300	83.9900	276
4.70	8.7	490	7.6700	90.2000	296
5.02	9.3	468	6.3700	93.0000	305
5.35	9.9	447	4.8300	97.6000	320
5.67	10.5	423	12.9300	92.4500	303
5.99	11.1	387	16.3600	91.9800	302
6.32	11.7	342	17.4200	94.1100	309
6.64	12.3	324	21.3000	100.4300	329
6.97	12.9	307	26.2900	96.4100	316
7.29	13.5	283	28.5400	102.1200	335
7.61	14.1	245	28.9900	103.6300	340
7.94	14.7	224	33.0300	103.1400	338
8.26	15.3	181	27.4200	97.7500	321
8.59	15.9	134	25.5300	113.8400	373

* Reference 2, Volume II, Table E-4.

RESALAB & ICAO DATA ON AIRCRAFT ILS
DISPLACEMENT VS. DISTANCE FROM THRESHOLD

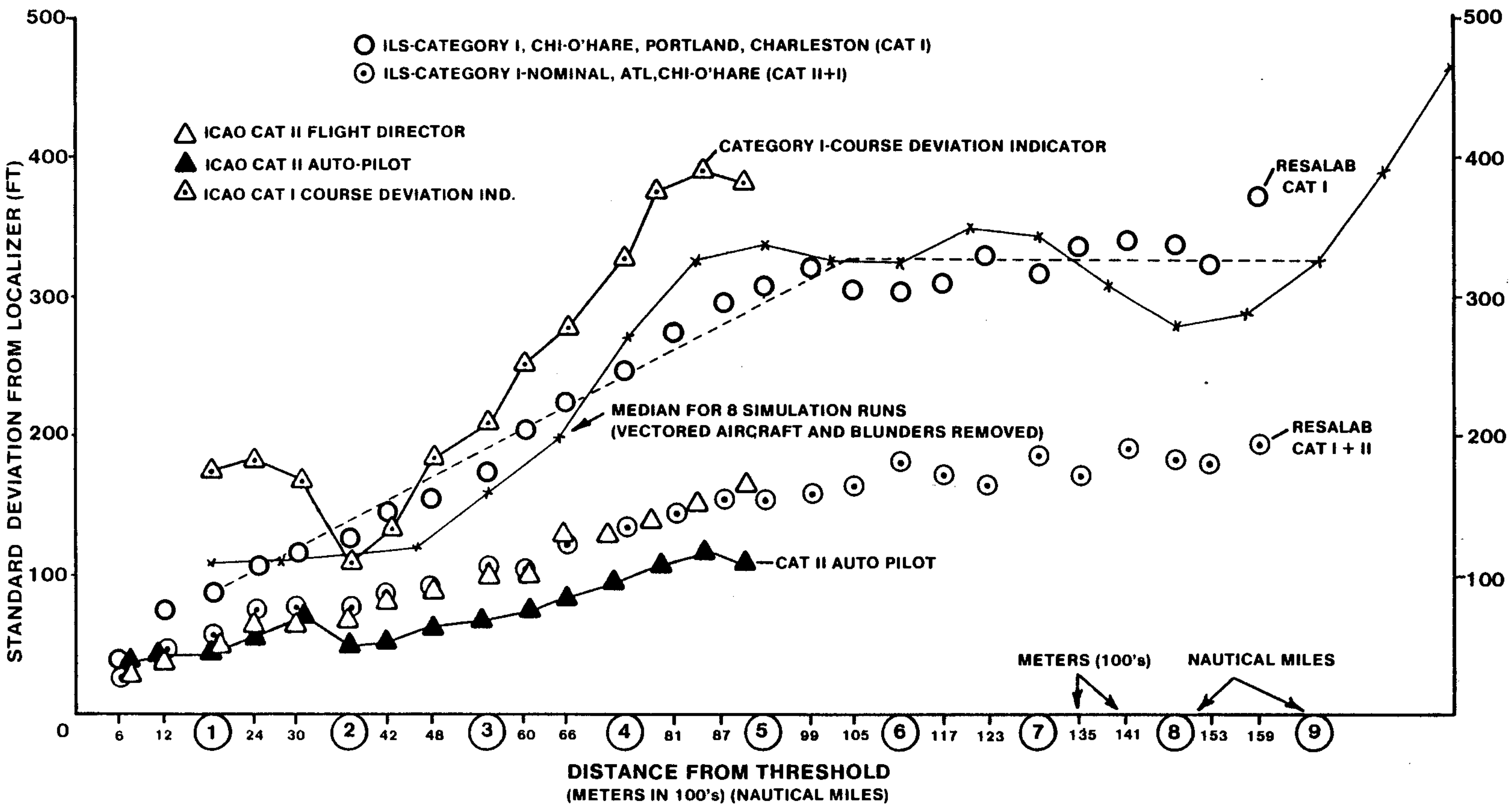


FIGURE 4. RESALAB/ICAO ILS PLOT

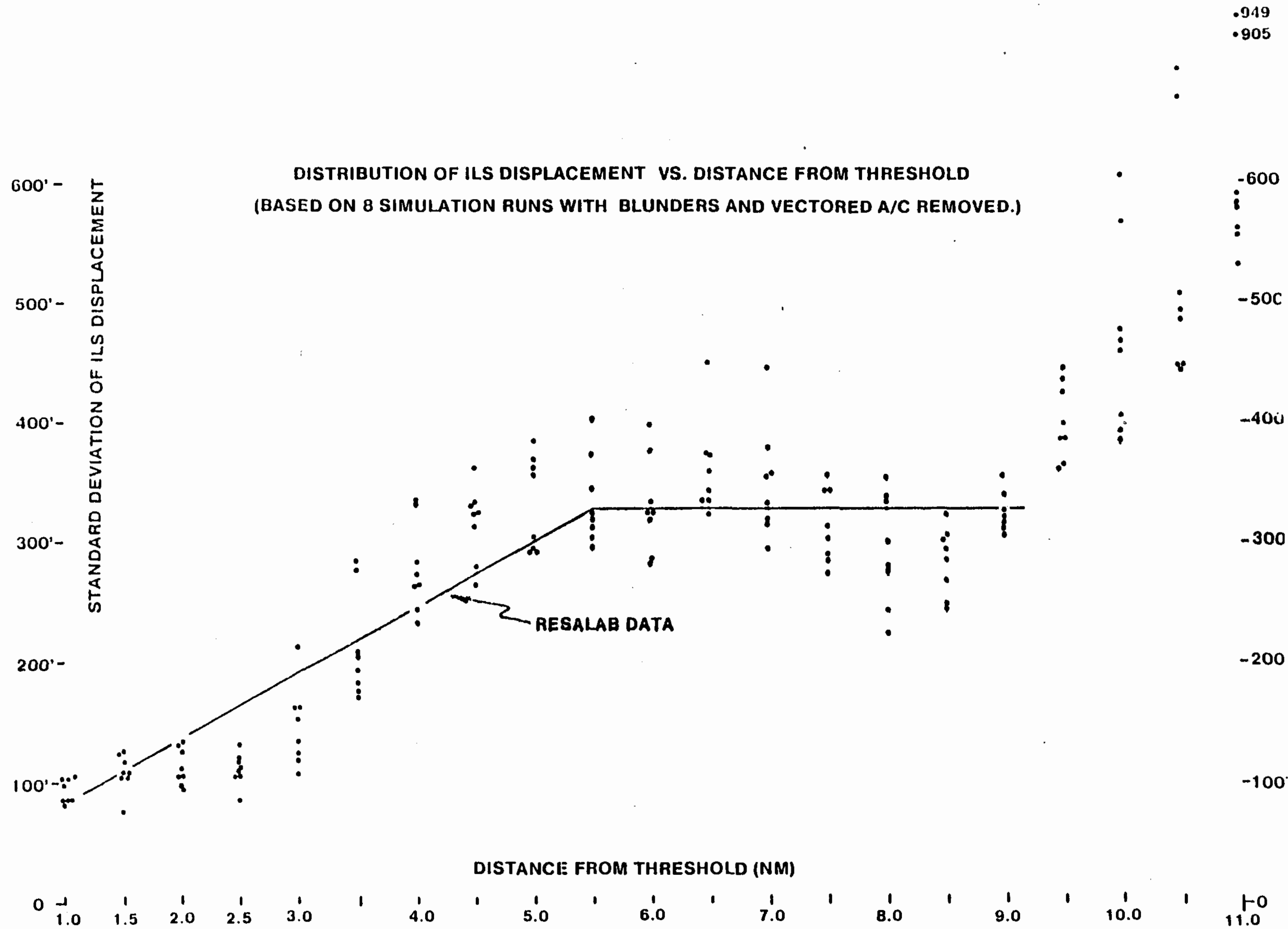


FIGURE 5. DISTRIBUTION OF AIRCRAFT DEVIATION

The simulator pilots (operators) in this simulation initiated all of the nonautomated flight functions of the aircraft in the traffic sample and handled all voice communication for their aircraft. Shortly after automatic startup, the simulator operators, each of whom controlled up to five aircraft, contacted the local controller to advise that they were on final approach. Routine altitude and speed changes associated with landing aircraft were handled automatically by the simulator as appropriate to each aircraft type. The simulator operators had to input any heading or speed changes requested by the monitor controller and acknowledge all voice communications. All warnings about departures from the ILS or drifting towards the NTZ were input by the simulator operators using their terminal. Blunders (left or right turns) were input by the simulator operator at the direction of the test director.

In order to make the blunders as realistic as possible for the monitor controllers, they were asked to regard them as a possible cockpit emergency which prevented the pilot from continuing his normal approach on the ILS. The simulator operators were directed not to reply to the monitor controllers' warning that they were off the ILS after a blunder had been initiated. Once on a blunder, the simulator operator only responded to a direct clearance to turn to a new heading or to change altitude (or to cancel).

TEST PROCEDURES. When the controllers arrived, they were briefed for about 45 minutes on the background of the simulation effort; how the simulation would be conducted and what would be expected of them. Essentially, the controllers were advised to function as they normally do, using the specific phraseology provided to them (see appendix B). The controllers were advised that the display they would be using was a full digital display rather than the primary radar rho theta display which they were accustomed to using. They were also advised of the previously noted minor difference in the simulation facility communication system (referenced in the Controller Laboratory section). The controllers were also advised that they would be given a questionnaire which had to be completed after every test run and that there would be a debriefing at the conclusion of their test participation. The purpose of the debriefing was to solicit feedback from the controllers on the overall simulation and any areas which could be improved.

The operation of the simulation facility was the responsibility of the test director. He coordinated with the technicians, simulator operators, computer operators, and other personnel and organizations associated with the test effort. In addition, the test director directed the initiation of blunders. The blunders were all scripted to occur on a specified runway at a predetermined approximate time. As the time approached, the test director examined the traffic on both runways and selected an aircraft on the designated runway for the blunder. His selection was made so that traffic on the adjacent runway would be threatened by the turn. The time that the simulator operator initiated the action was recorded by the computer. Events involving each blunder can be referenced from the blunder time.

DATA COLLECTION, REDUCTION, AND ANALYSIS

DATA COLLECTION.

Simulation data were collected in real time on nine-track computer tape via standard software provided by the simulation programs. The current position, speed, and heading of all aircraft were collected every second, as well as any simulator operator entries (pilot actions), controller identifications, and start of controller transmission messages. The geography of the airport, radar parameters, and traffic samples were recorded at the beginning of each tape when the simulation was brought up on the computers.

In addition to the real-time data collection provided by the computers, manual checks were made to assure that radar and other parameters were appropriate for the test condition scheduled for each run. Questionnaires were distributed to the monitor controllers immediately after each run to capture their comments and opinions about the test experience. At the end of each week of testing, a debriefing was held with the two controller teams for that week. At the time of the debriefing, each controller had seen all the test conditions and could add comments and comparisons not previously possible on the earlier questionnaires. Most of the controller comments at the debriefings confirmed the data on the questionnaires.

DATA REDUCTION.

Within 24 hours of each test run, the raw data tapes on aircraft position and communication data were processed to provide (1) summary reference printouts on all significant events (e.g., transgressions and conflicts) that happened during the test, (2) computer files containing pertinent data regarding transgressions and communications, and (3) aggregate computer file containing summary counts of warnings, missed approaches, conflicts, controller transmissions, pilot actions, aircraft landed, and parallel and longitudinal conflicts for each test run to date.

The reference printouts for each run provided an invaluable source for partial reconstruction of the events surrounding missed approaches and other significant occurrences.

The extracted computer files provided a basis for statistical analysis of summary data, transgressions, and conflicts.

STATISTICAL ANALYSIS.

The BMDP package of statistical software was used extensively. This comprehensive statistical package, originally written more than 20 years ago by the University of California, Los Angeles (UCLA), Department of Biomathematics, has been continually updated and expanded to incorporate the latest analytical and computational techniques.

Additional custom software was written at the FAA Technical Center to interface with the BMDP statistical software package and to provide functions not found in that package.

In general, the analysis of the data produced by the simulation followed the following steps.

1. An analysis of variance (ANOVA) was performed on each major variable.

2. If the main effect for experimental conditions was significant at or near the 0.05 level of significance and if there was no significant interaction with the order effect, the a priori contrasts described in the Design of the Experiment section were performed.

3. If some additional trends seemed to manifest themselves in the data, they were tested using Scheffe's S Test for a posteriori analysis.

RESULTS OF THE ANALYSIS

The results are organized under the premise that there are two major system elements that impact safety and efficiency: (1) the vast majority of aircraft controlled by the ILS flight path model and (2) the 279 blunders and their consequences for the controllers who attempted to deal with them so as to minimize interference with traffic flow, yet retain safety. The extent to which the controller can achieve this goal as a function of the six experimental conditions is an indication of how the conditions impact flow and safety. The data will be reported by looking at the normal aircraft flow first. Then the blunders and their consequences will be examined. Finally, overall effects, where blunder and nonblunder cannot be separated, will be examined.

NONBLUNDERING AIRCRAFT.

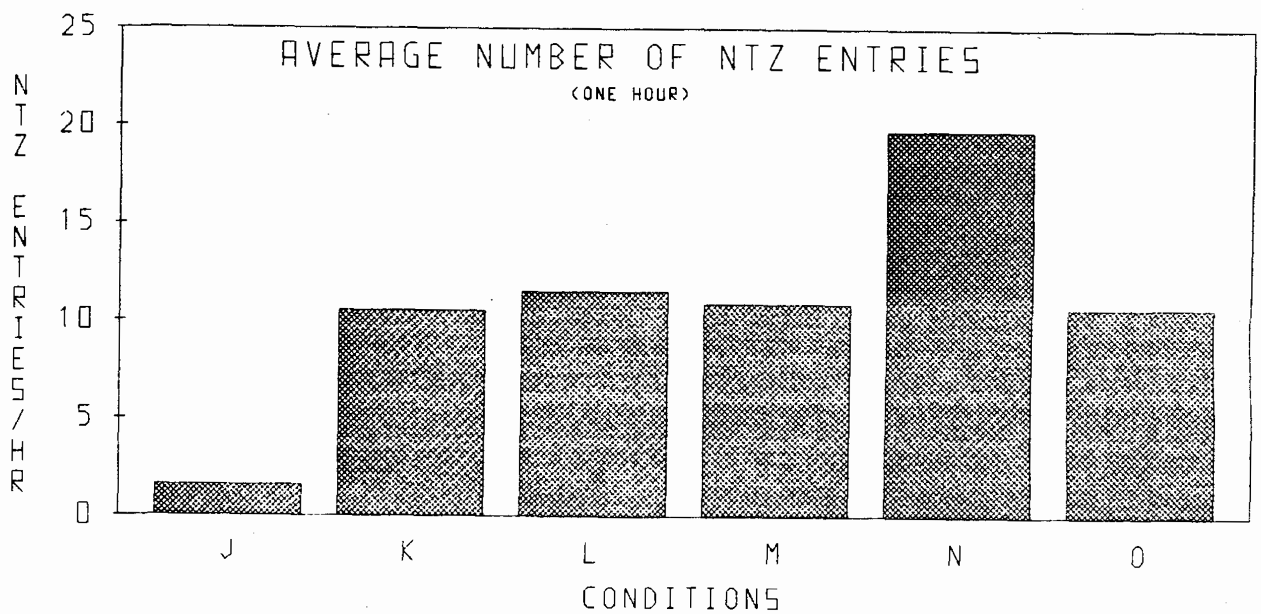
NTZ ENTRIES. NTZ entries (NTZE) refer to the count of aircraft exiting the NOZ of the ILS and entering the NTZ. The number of NTZE's was counted for both the real aircraft position (no radar noise) computed by the simulation model and for the aircraft position displayed on the monitor controller's scope (with radar noise). As stated above, initiated blunders and vectored aircraft were excluded from this portion of the analysis. All remaining aircraft between 1 and 9 miles from runway threshold were included. By 9 miles all aircraft were established on the ILS. The summary results for real NTZE's tallied by condition and team are in table 4.

The ANOVA showed significant differences in NTZE's among the experimental conditions. For each team, the number of NTZE's increased as the spacing between the parallel runways decreased. The statistical contrasts show that at the 95 percent confidence level, condition J (4,300-foot separation) had significantly fewer entries than all other conditions and that conditions K, L, M, and O (3,400-foot separation) had significantly fewer entries than condition N (3,000-foot separation). Averages are presented on a per team, per 1-hour run basis. During a 1-hour run, a team will have been exposed to approximately 62 aircraft of which, on the average, 6 will have executed missed approaches, 52 will have landed, and 4 will still be on the ILS at the end of the session.

TABLE 4. SUMMARY OF RESULTS FOR NUMBER OF REAL NTZ ENTRIES

(each entry is sum of two 1-hour runs)

Team	J	K	L	M	N	O
	Condition					
1	2	24	15	24	47	21
2	3	21	26	17	44	26
3	4	20	17	27	37	29
4	5	15	29	24	42	23
5	4	19	18	15	24	17
6	4	21	22	17	30	10
7	1	24	23	23	43	17
8	2	24	34	27	49	27
TOTAL	25	168	184	174	316	170
AVERAGE FOR 1 HOUR	1.6	10.5	11.5	10.9	19.8	10.6



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

The average number of real NTZE's for a run were as follows:

J	K	L	M	N	O
1.6	10.5	11.5	10.9	19.8	10.6

For conditions with identical runway separation (K, L, M, and O), the real NTZE's showed no significant differences. The displayed NTZE's showed a similar pattern of significant differences and slightly higher averages due to the presence of radar noise.

There are two factors that determine the likelihood of an NTZE: (1) the width of the NOZ, and (2) the precision with which an aircraft flies an ILS approach. Since all aircraft in the simulation fly the identical computer algorithm with random variations drawn from the same theoretical population, differences in the NTZE are determined by the width of the NOZ; i.e., the distance an aircraft had to depart the ILS localizer before it was counted as an NTZE.

Reducing the runway spacing from 4,300 feet (1,150-foot NOZ) to 3,400 feet (700-foot NOZ) resulted in an average 7-fold increase in NTZE's; reducing to 3,000 feet (500-foot NTZ) resulted in a 13-fold increase. By looking at the data in terms of rates rather than absolute values, the 1,150-foot NOZ reveals that 3 aircraft in 100 actually cross the boundary by 1 foot or more, but this number goes up to 21 per hundred with 700 feet and 39 per hundred with 500 feet. The nature of the simulation traffic and the very conservative model of precision on the ILS make it clear that these figures are an upper bound for the likely increase of NTZE's with 700- and 500-foot NOZ's. Nevertheless, even if the probable increases are half of what is obtained here, the result would be significantly increased monitor controller activity.

PARALLEL CONFLICTS. Of more direct concern than NTZE's is the potential increase in the number of resulting conflicts. When an aircraft entered the NTZ, a parallel conflict occurred with all aircraft on the opposite ILS less than standard separation distance from the transgressing aircraft. The ANOVA showed statistically significant differences in the number of parallel conflicts among the different experimental conditions.

For each team, the number of parallel conflicts increased as the runway separation decreased. The summary results tallied by the condition and team are shown in table 5.

At the 95 percent confidence level, condition J (4,300-foot separation) had significantly fewer parallel conflicts than all other conditions and conditions K, L, M, and O (3,400-foot) had significantly fewer conflicts than condition N (3,000-foot). By condition, the average number of conflicts for a 1-hour run were as follows:

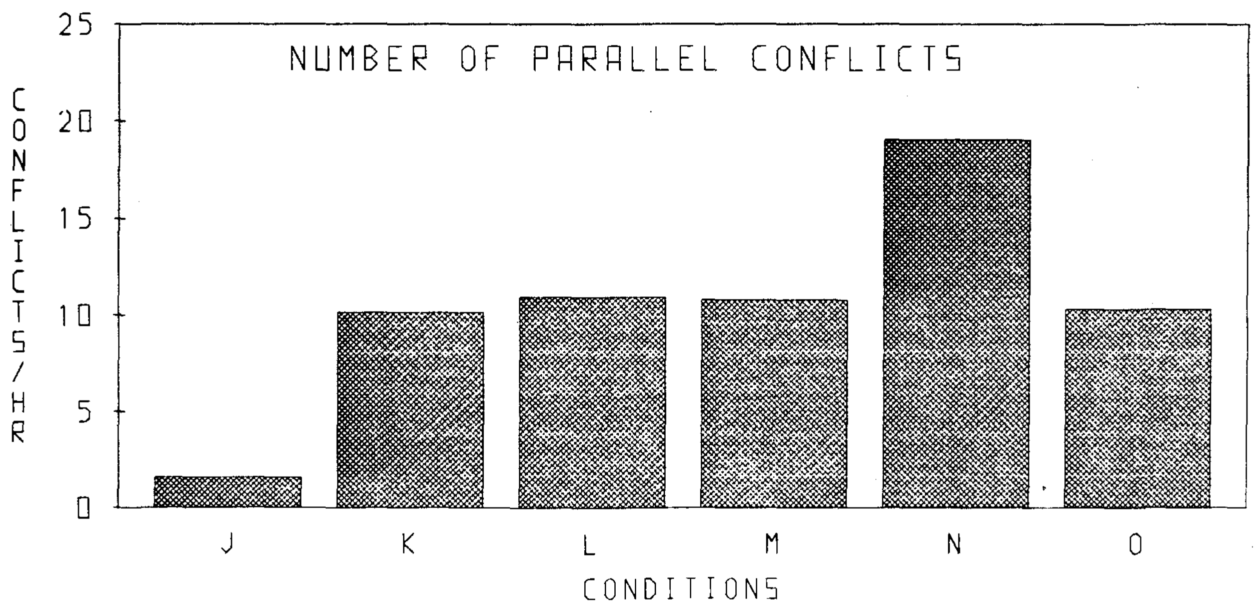
J	K	L	M	N	O
1.6	10.1	10.9	10.8	19.1	10.3

Since conflicts, by definition, only occur after an NTZE has occurred, it is only natural that the number of conflicts should increase with increasing NTZE's.

TABLE 5. SUMMARY OF RESULTS FOR PARALLEL CONFLICTS

(each entry is sum of two 1-hour runs)

	Condition					
Team	J	K	L	M	N	O
1	2	23	15	24	46	20
2	3	21	22	17	40	26
3	4	19	17	27	36	29
4	5	15	29	24	42	23
5	4	18	13	15	23	15
6	4	20	22	17	29	9
7	1	22	23	22	41	17
8	2	24	34	27	48	26
TOTAL	25	162	175	173	305	165
AVERAGE FOR 1 HOUR	1.6	10.1	10.9	10.8	19.1	10.3



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

There were almost six times as many conflicts produced with the 700-foot NOZ as the 1,150-foot zone. In terms of rates, there were 3.9 conflicts per hundred landings, 23 per hundred landings, and 41.5 per hundred for the 1,150-foot, 700-foot, and 500-foot NOZ's, respectively.

MISS DISTANCE. While a simple count of conflicts is indicative of increased activity for the monitor controllers as runways are brought closer together, there is important additional information to be obtained. For each conflict that developed, the computer tracked the distance between the conflicting aircraft and recorded the closest distance. All miss distances between 0 and 18,000 feet were recorded and grouped into 250-foot intervals. The data were graphed as frequency distributions for intervals between 0 and 4,500 feet; the frequency plotted against the upper bound of the miss distance interval. The distributions are shown in figure 6.

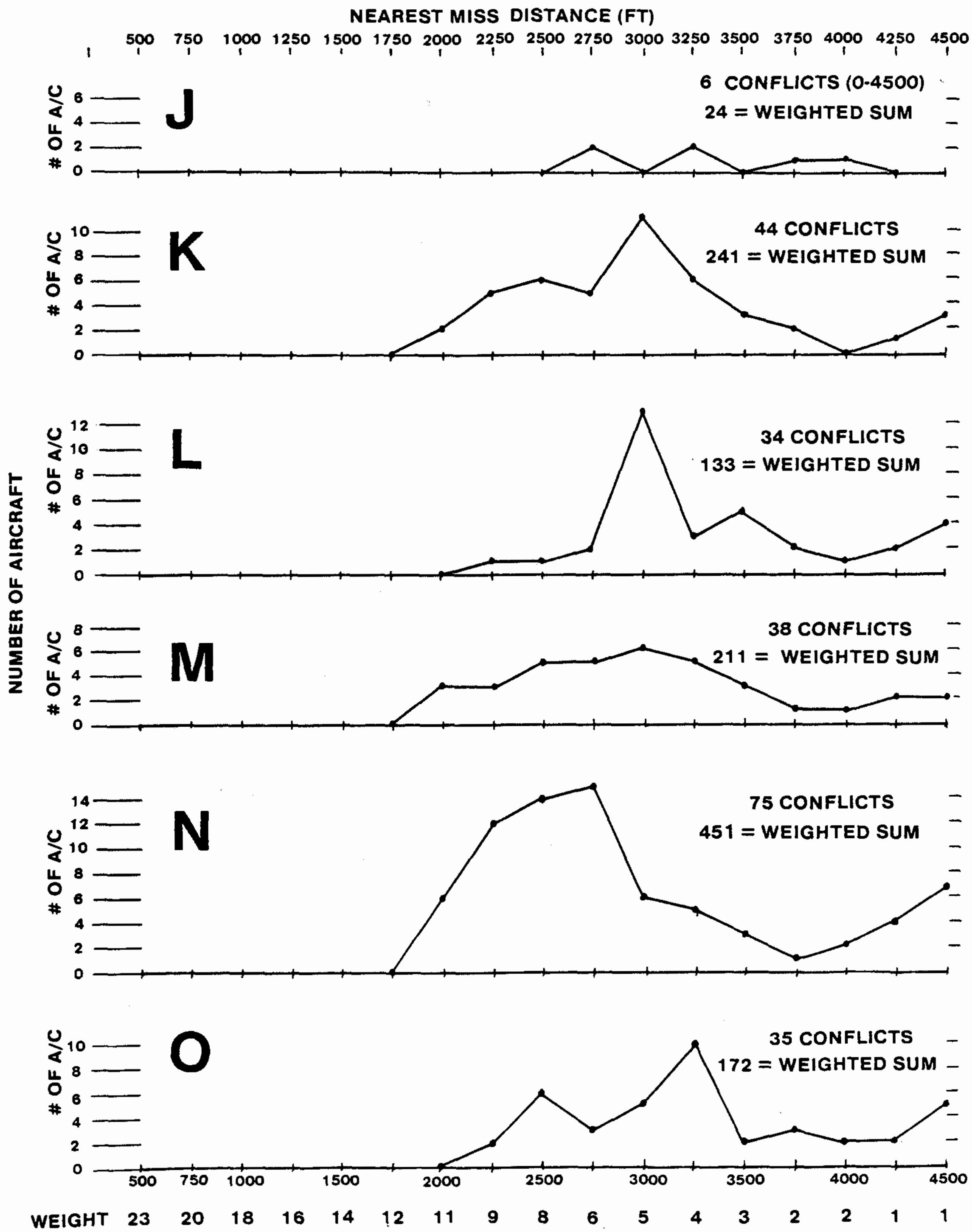
While the plots show the number and seriousness of the conflicts for each condition, something additional is needed to make a quantitative determination of relative risk. The additional factor is an index of risk which permits the assignment of relative weights to conflicts which miss by differing distances. Any set of weights is somewhat arbitrary, but even arbitrary weights are more useful than a simple count. Weights were chosen to give greater emphasis to closer misses. The index used here is inversely proportional to the square of the miss distance and consists of a series of integers from 25 (for a miss of 0 to 250 feet) to 1 (for a miss of 4,251 to 4,500 feet) and 0 (beyond 4,500 feet). The computational formula and weights are shown in table 6.

The sum of the weighted miss distances, number of aircraft in each miss distance interval times weight for the interval, is shown in figure 6 together with the weights used. The weighted values for each conflict were summed by team and condition (table 7) and an ANOVA computed. Results showed a statistically significant difference among conditions at the 95 percent confidence level. By condition, the average weighted sum for each run were as follows.

J	K	L	M	N	O
1.5	15.1	8.3	13.2	28.2	10.8

An ANOVA of these weighted sums indicates statistically significant differences among the conditions, with all pairwise contrasts between conditions with different NOZ's significant but no differences where the NOZ's were the same. To the extent that the weights applied are indicative of safety, reducing the NOZ increases risk. The results, however, are very much driven by the large differences in the numbers of NTZE's among the conditions. Could safety be more closely examined with these differences in number removed or at least reduced?

To look at this question, an attempt was made to define an "average risk" per run. The average risk is defined as the weighted sum of the miss distances for each two runs divided by the number of conflicts involved on a cell-by-cell basis (see table 8). For example, where one of the teams produced a weighted sum of 70 under condition N with a total of 13 conflicts over two 1-hour runs, the average was 70/13 = 5.385. If there were no conflicts at all, the average was designated a



DISTRIBUTION OF NEAREST MISS DISTANCE FOR NONBLUNDER INDUCED CONFLICT. (Every time two aircraft came into conflict--if neither was an initiated blunder or had been vectored--the closest lateral separation was recorded.) plotted is number of cases at distance indicated. Weighted sum (number times weight) is also shown.

FIGURE 6. DISTRIBUTION OF NEAREST MISS DISTANCE FOR NONBLUNDER-INDUCED CONFLICTS

TABLE 6. NEAREST MISSED DISTANCE WEIGHTS

Miss Distance	Weight
0 - 250	25
251 - 500	23
501 - 750	20
751 - 1000	18
1001 - 1250	16
1251 - 1500	14
1501 - 1750	12
1751 - 2000	11
2001 - 2250	9
2251 - 2500	8
2501 - 2750	6
2751 - 3000	5
3001 - 3250	4
3251 - 3500	3
3501 - 3750	2
3751 - 4000	2
4001 - 4250	1
4251 - 4500	1
4501 - 4750	0
4751 - 5000	0
5001 - 5250	0

$$\text{Weight} = \left(\frac{5250-D}{1000}\right)^2$$

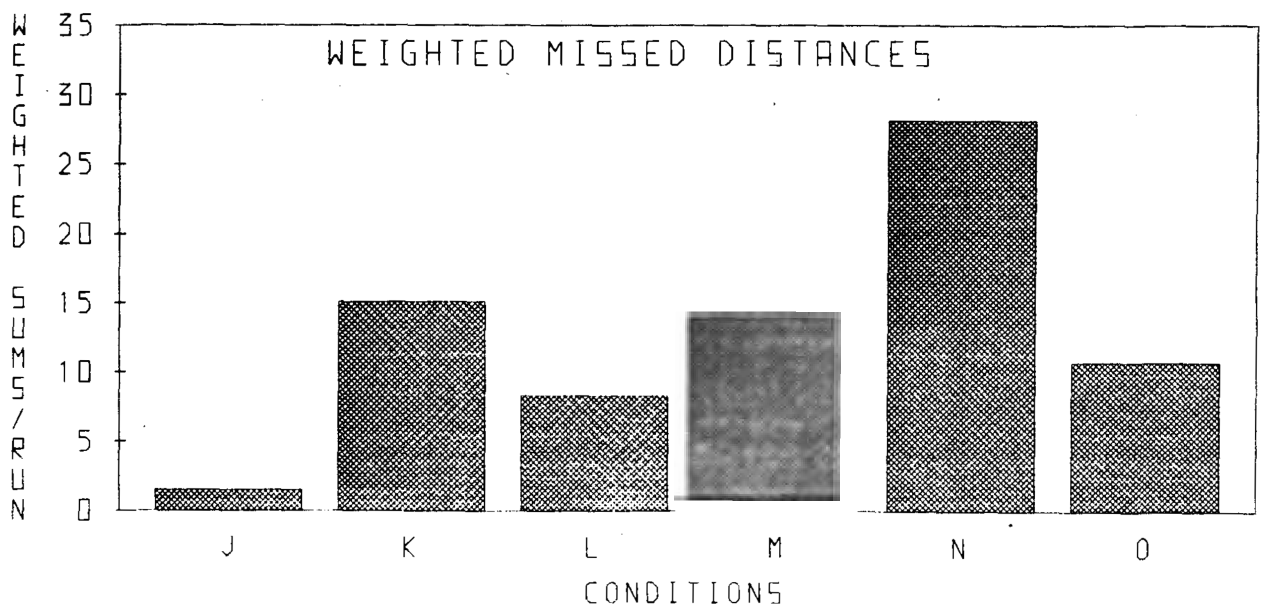
D = Upper bound of interval

Weights are rounded to nearest whole number

TABLE 7. WEIGHTED SUMS FOR MISS DISTANCES

(each entry is sum of two 1-hour runs)

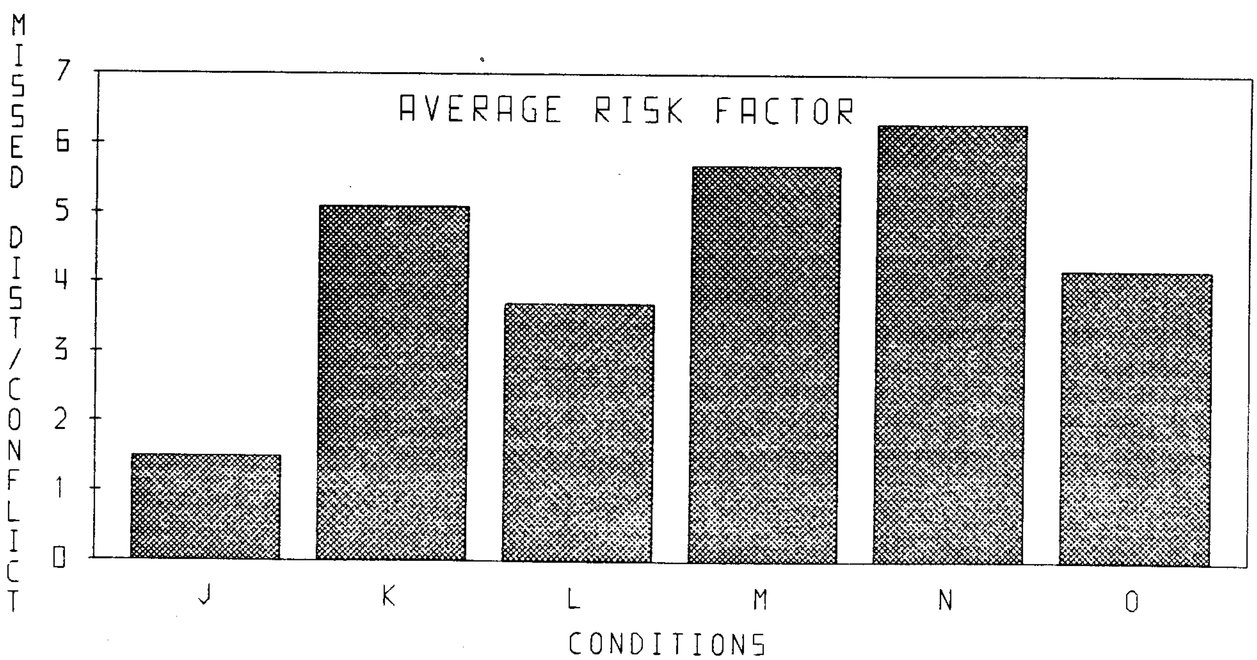
	Condition					
Team	J	K	L	M	N	O
1	0	33	12	22	70	32
2	0	37	18	23	55	23
3	8	22	19	59	105	25
4	2	17	36	38	61	29
5	0	5	6	17	26	14
6	12	59	3	17	32	25
7	0	9	15	14	29	5
8	2	59	24	21	73	19
TOTAL	24	241	133	211	451	172
AVERAGE FOR 1 HOUR	1.5	15.1	8.3	13.2	28.2	10.8



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

TABLE 8. AVERAGE RISK (WEIGHTED SUM OF MISS DISTANCES/CONFLICTS)

	Condition					
Team	J	K	L	M	N	O
1	0.0	5.5	4.0	4.4	5.4	5.3
2	0.0	5.3	4.5	7.3	6.9	3.3
3	2.0	7.3	4.8	5.9	6.6	4.2
4	2.0	4.3	4.5	6.3	6.8	4.8
5	0.0	2.5	3.0	4.3	8.7	4.7
6	6.0	7.4	1.0	8.5	5.3	5.0
7	0.0	3.0	3.0	3.5	5.8	2.5
8	2.0	5.4	4.8	5.3	4.9	3.8
AVERAGES	1.5	5.1	3.7	5.7	6.3	4.2



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

zero. An ANOVA performed on these averages was significant for the conditions. The contrasts were also significant in the usual direction, condition J less than conditions K, L, M, and O; and condition O less than condition N. The differences between conditions M and N and between conditions K and N are not significant. Condition O is significantly better than condition M if a one-tailed t test is used. This may provide limited support for the use of the expanded display.

NTZ PENETRATION. A different analysis of the NTZE's involves examining the degree of NTZ penetration. For each NTZ entry, the furthest distance into the NTZ was recorded at the time of leaving the NTZ. This parameter relates both to the width of the NOZ and to the precision of the aircraft flying the ILS. Plotting the frequency distribution of the penetration distances for the six conditions graphically demonstrates this relationship (see figure 7). Only two of the 1,037 nonblundering NTZE's penetrated further than 1,000 feet (more than half way), and both were under condition N.

By plotting the same data against a common coordinate system, distance from the localizer centerline, the underlying dynamics of NTZE activity can be seen (see figure 8). NTZE's seem to reflect the tail of a single frequency distribution which is centered on the localizer. The total number of aircraft in this distribution is approximately 5,000.

BLUNDERING AIRCRAFT.

The blunders are a special feature of this simulation. A blunder is a standard turn of 30° towards the other ILS. This definition is arbitrary but based on previous usage (reference 4). It has been deliberately introduced at a rate far higher than would ever be expected. At least one blunder was initiated per runway in each run. Occasionally, another blunder was added to prevent controllers from becoming complacent. Finally, it is the kind of event that can only be safely evaluated by simulation. Computer plots of some representative blunders are shown in figures 9 and 10. In these diagrams, MIKE KEY refers to the controller keying the microphone to initiate a transmission. All other communications were recorded and are shown on the diagram at the time when the simulator operator entered the command into the keyboard to start an aircraft turning (VECTOR message), climbing or descending (ALTITUDE message). These diagrams also indicate the location of the aircraft involved at the time of controller communications or when a simulator operator entered a controller-initiated instruction into the simulator.

MISS DISTANCE. The real test of safety in the blunder situation is the ability to maximize aircraft separation when a mishap occurs. Part of the outcome of a blunder incident will depend on chance; i.e., the position of the adjacent aircraft when the test director initiated the blunder. The rest will depend on the ability of the controllers to detect the blunder quickly and take corrective action when needed. With an average of over 45 blunders per condition, the chance factor should average out. Figure 11 shows the frequency distributions of miss distances up to 4,500 feet for the six conditions.

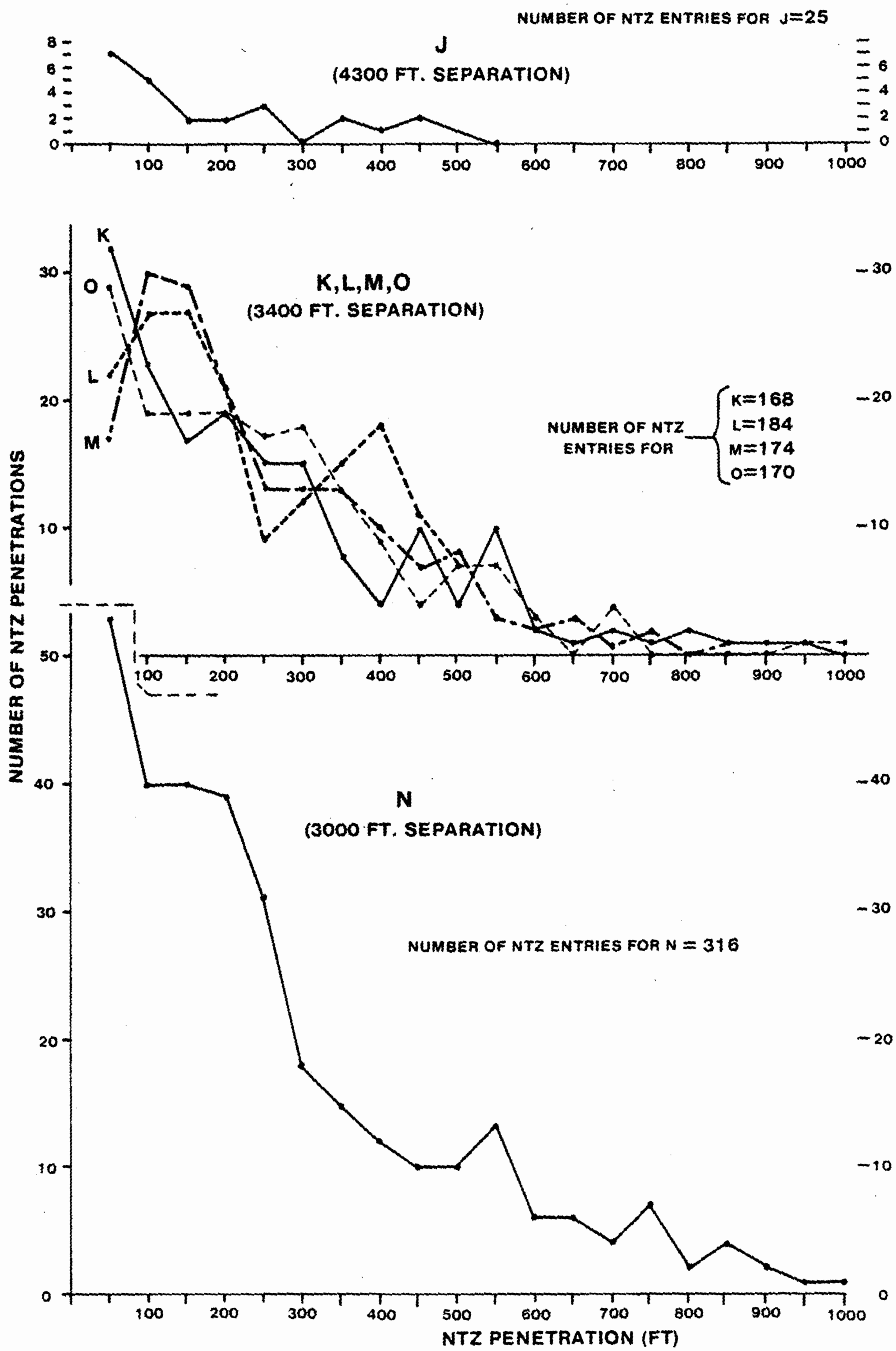


FIGURE 7. DISTRIBUTION OF PENETRATION INTO THE NTZ FOR NONBLUNDERING, NONVECTORED AIRCRAFT

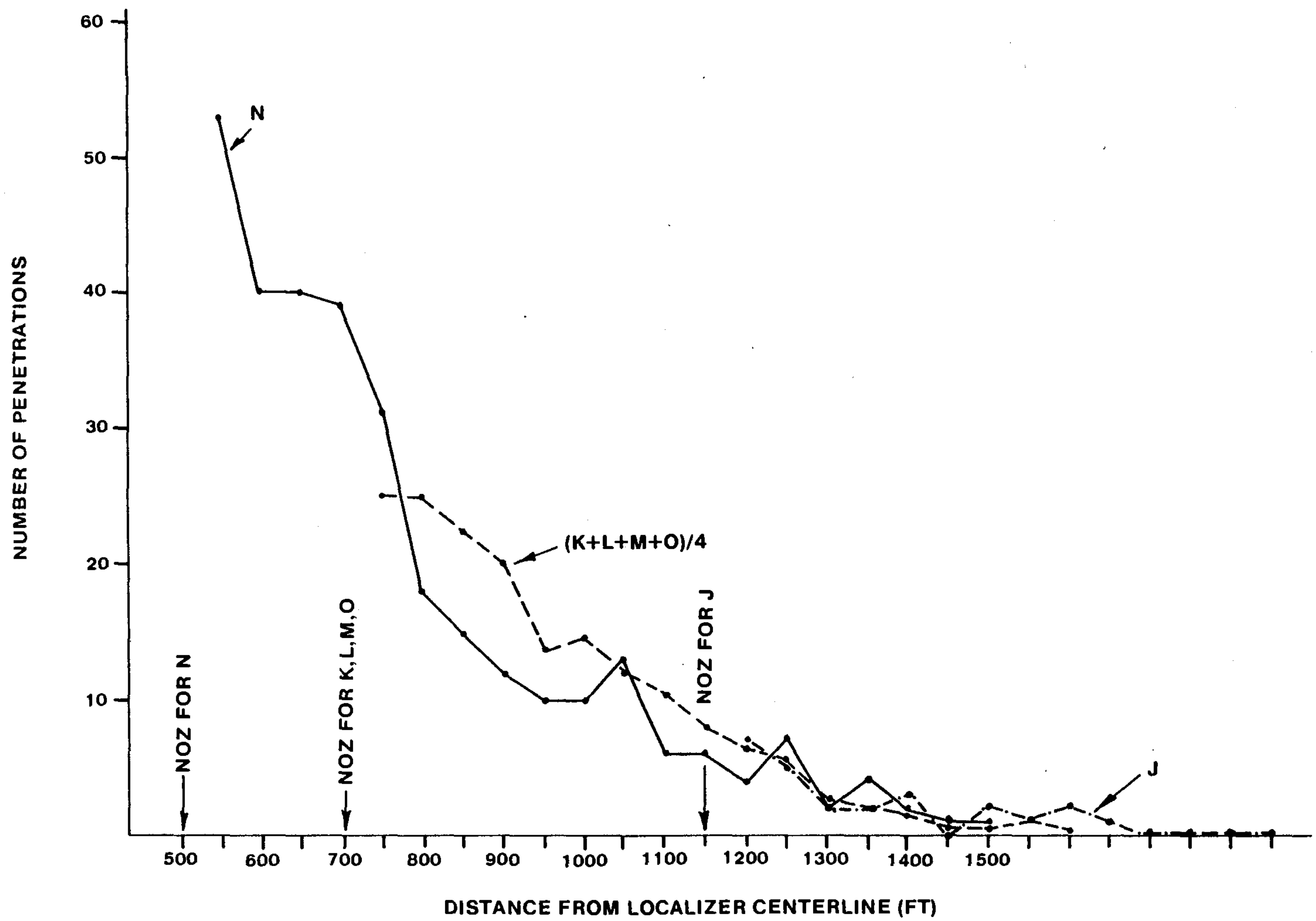


FIGURE 8. DISTANCE PENETRATION INTO NTZ PLOTTED AGAINST DISTANCE FROM LOCALIZER CENTERLINE

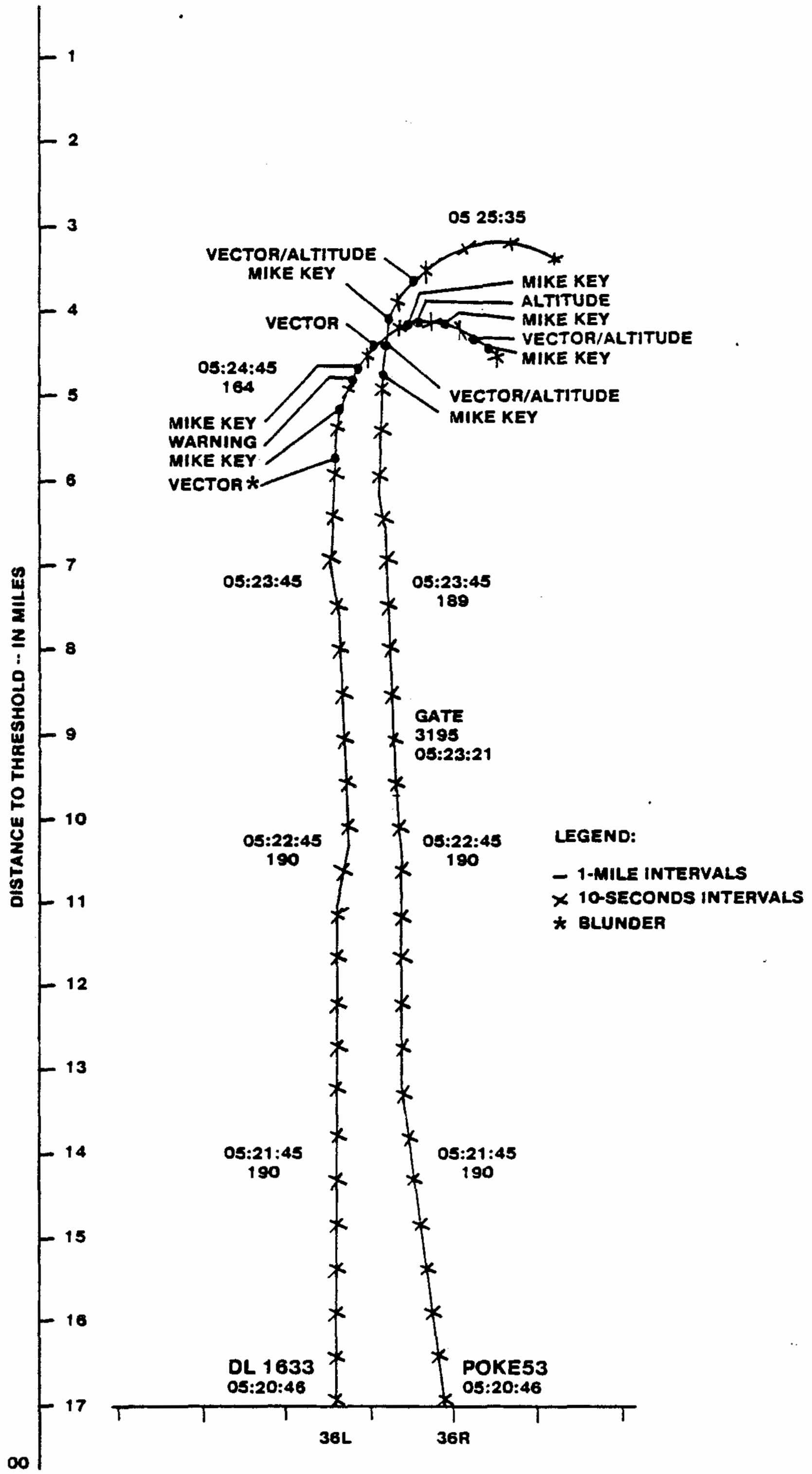


FIGURE 9. PLOT OF BLUNDERING AIRCRAFT WITH CONTROLLER RESPONSES — RUN 59

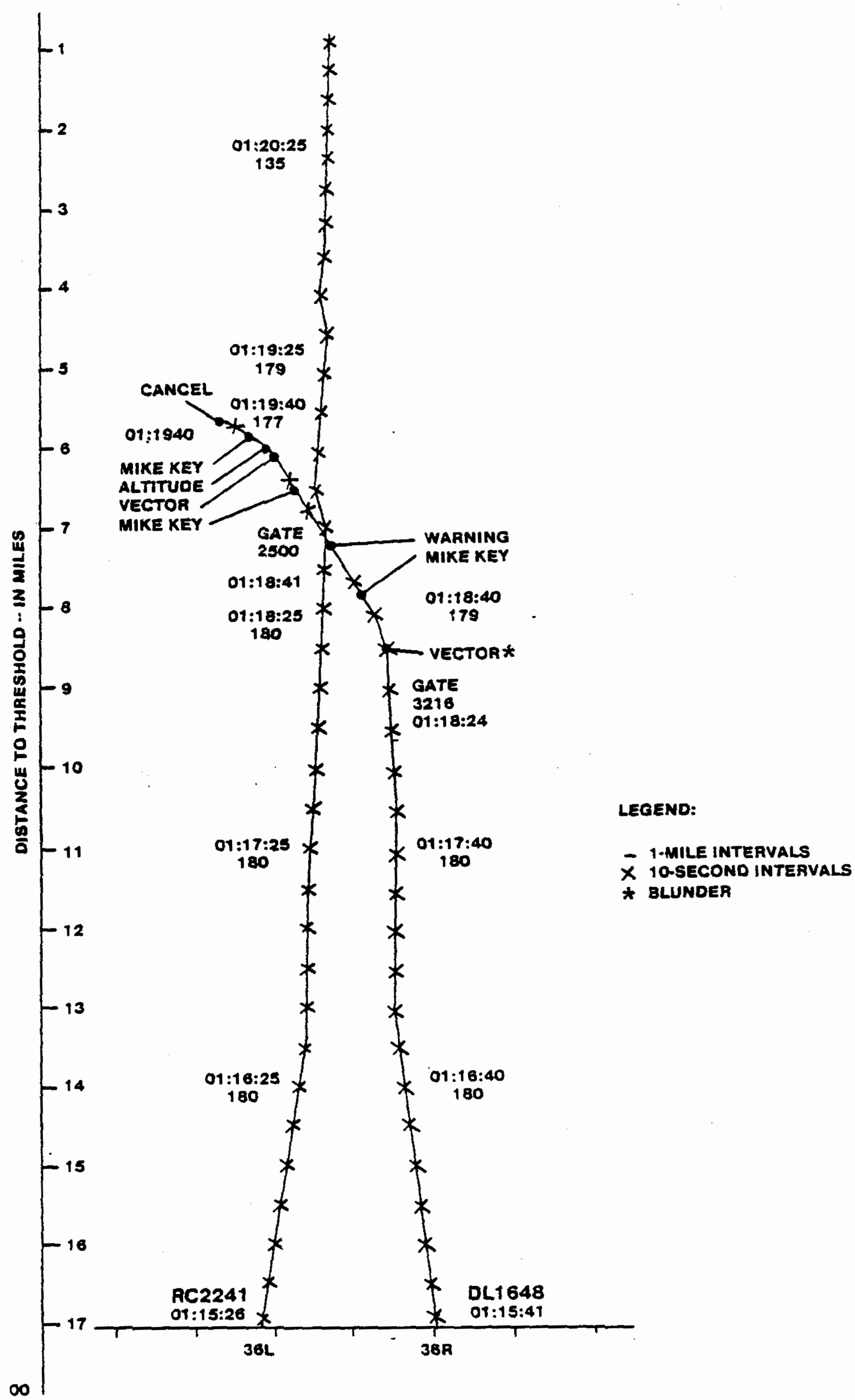
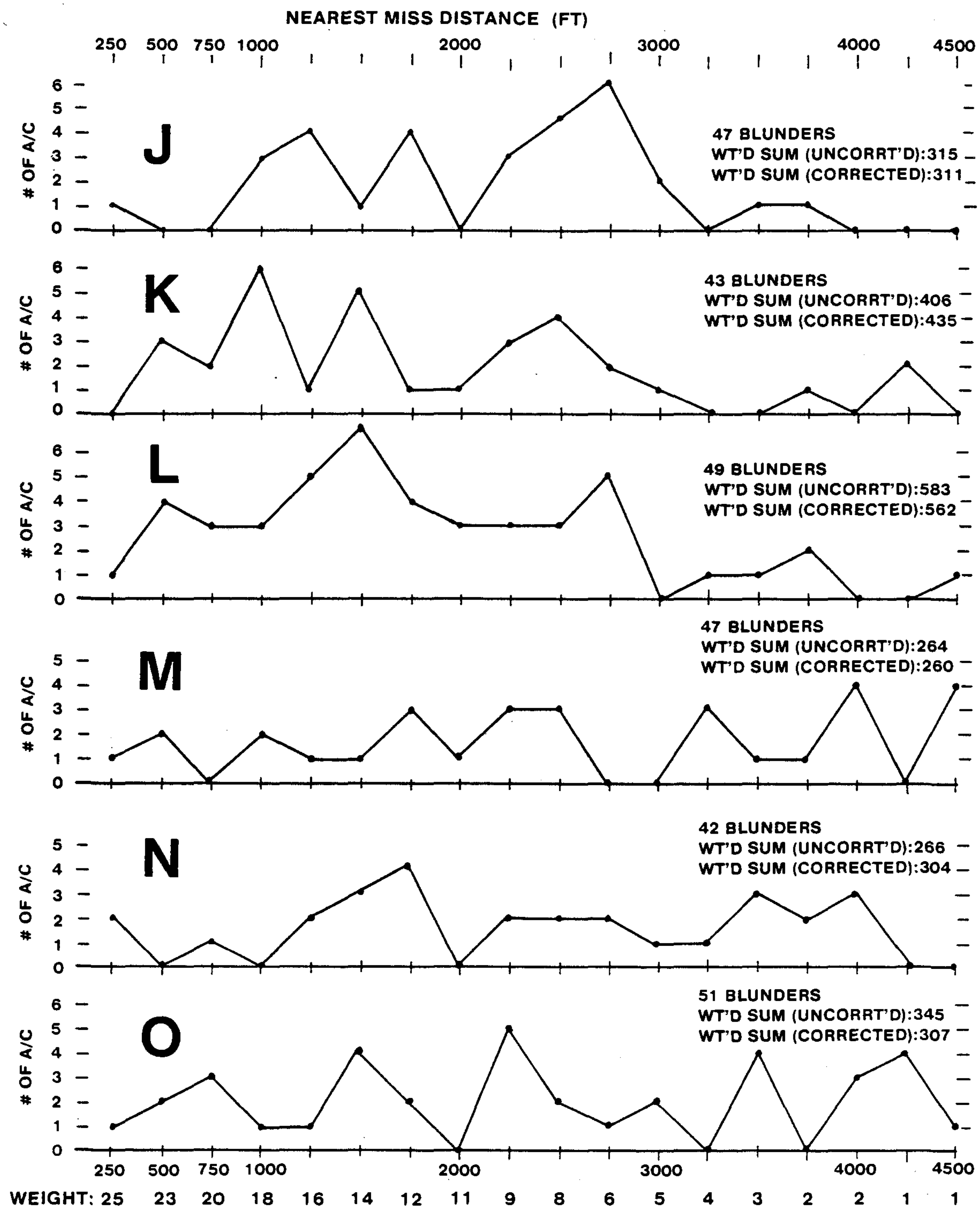


FIGURE 10. PLOT OF BLUNDERING AIRCRAFT WITH CONTROLLER RESPONSES — RUN 49



DISTRIBUTION OF NEAREST MISS DISTANCE FOR INITIATED BLUNDER INDUCED CONFLICTS. (Every time an initiated blundering aircraft came into conflict with an aircraft on the other ILS, the closest lateral separation was recorded.) Plotted data is number of cases that came as close as indicted. Weighted sum (Wtd sum), uncorrected is the total of number of cases times corresponding weight. Correction takes into account number of blunders.

FIGURE 11. DISTRIBUTION OF NEAREST MISS DISTANCE FOR BLUNDER-INDUCED CONFLICTS

To evaluate the safety of the responses to blunders, the same weighting scheme that was used for nonblundering conflicts was applied to the closest separation of blundering conflicts. The weights ranged from 25 for a miss of 250 feet or less to 0 for a miss of more than 4,501 feet. Figure 11 also shows the number of blunders per condition, which ranges from a low 42 (condition N) to a high of 51 (condition O). Because of these random variations in the number of blunders and since the number is an experimental variable rather than an outcome of the test, it was decided that an analysis of covariance of the weighted blunder miss distances would be more sensitive than a simple ANOVA. The analysis of covariance essentially "corrects" the data for the unequal number of blunders and shows what the relation between conditions and weighted sums would have been if the number of blunders had been equal. Table 9 and figure 11 show the weighted sum and the corrected weighted sum for each condition.

The analysis of covariance did show a significant main effect for the weighted blunder miss distance data. However, only one of the a priori pairwise comparisons was signficant; condition L was less safe than condition J. Condition K was also less safe the condition J but the difference is not statistically significant. Of perhaps more interest, conditions M, N, and O, the three 1-second updates, came out essentially equal to condition J in their ability to handle blunders safely, or perhaps more appropriately, unsafely.

None of the miss distance data considers altitude separation in evaluating the seriousness of a conflict. While its possible that enough altitude separation was present to avoid an actual midair collision, this cannot be relied on. The "worst case" blunders used produced some very serious situations. There were six incidents in which aircraft came less than 250 feet from each other and 14 cases where separation was less than 500 feet. The interpretation of these results is difficult. Two alternative hypotheses will be considered.

The first hypothesis is that the 4,300-foot ASR-8 condition, J, is close to existing conditions which have a verified history of safety and that conditions M, N, and O, which have roughly equivalent weighted sums, are also safe.

The other hypothesis is that the blunder, an unexpected 30° turn to the other runway, usually in the presence of traffic there, is such a severe test that it could not be adequately handled, given the parameters simulated, under any of the experimental conditions. That would not support the conclusion that conditions M, N, and O are as safe as condition J, but that they were found to be inadequate when subjected to an extremely difficult, possibly unrealistic, test.

Whichever hypothesis is accepted, it is clear that the miss data of the blunders has not produced any evidence that it would be less safe with runway separation reduced from 4,300 feet to 3,400 feet under some conditions.

TABLE 9. SUMMARY OF RESULTS FOR WEIGHTED SUM OF BLUNDER MISS DISTANCES AND NUMBER OF BLUNDERS (IN PARENTHESES)

(correlation between weighted sums and number of blunders = 0.341)

	Condition					
Team	J	K	L	M	N	O
1	43 (7)	22 (6)	66 (7)	27 (6)	16 (5)	49 (7)
2	8 (5)	49 (4)	50 (6)	- (5)	15 (6)	56 (7)
3	8 (4)	46 (4)	34 (6)	38 (6)	59 (6)	36 (5)
4	39 (6)	100 (7)	77 (7)	35 (6)	17 (5)	32 (8)
5	33 (5)	54 (6)	126 (7)	47 (5)	46 (4)	73 (5)
6	58 (6)	32 (5)	76 (6)	37 (7)	39 (6)	39 (7)
7	44 (7)	47 (5)	54 (5)	55 (7)	41 (5)	34 (7)
8	82 (7)	56 (6)	100 (5)	25 (5)	33 (5)	26 (5)

Average Number Of Blunders (2 hours)

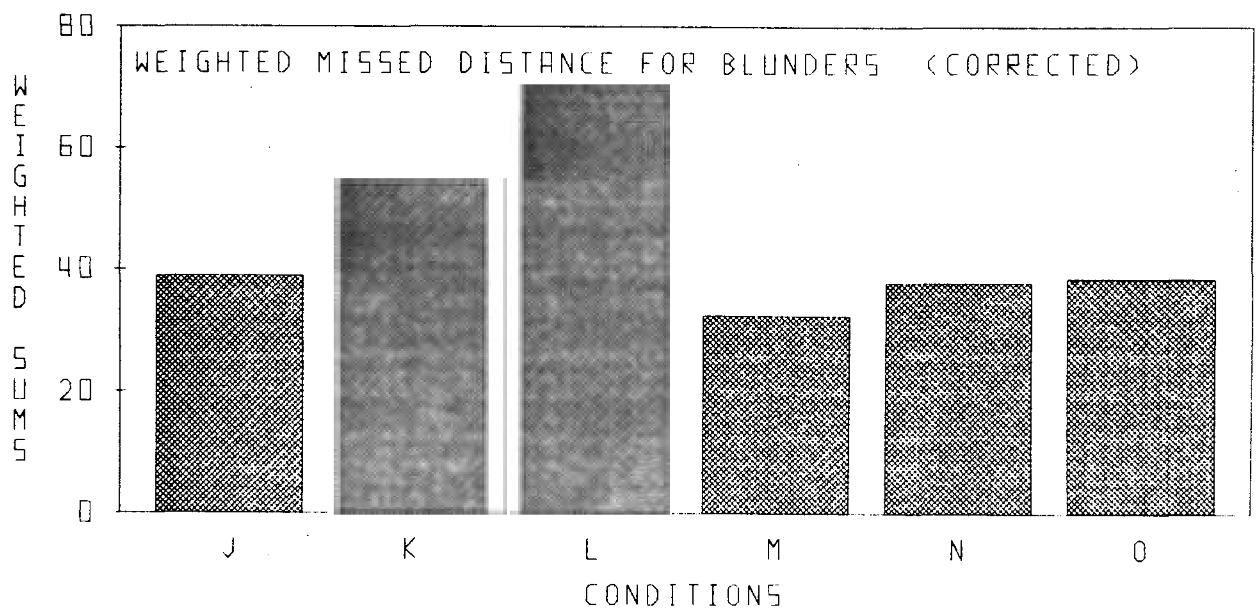
5.9	5.4	6.1	5.9	5.3	6.4

Average Weighted Sum (uncorrected)

39.4	50.8	72.9	33.0	33.3	43.1

Average Weighted Sum (corrected for number of blunders)

38.9	54.4	70.3	32.5	37.9	38.5



RESPONSE TIMES. In order to evaluate controller response times and controller actions, the following were recorded every second as they occurred: (1) time, (2) aircraft identity, (3) speed and heading, (4) position relative to the ILS, (5) type of action (controller keyed the microphone, type of pilot action entered, or warning received), and (6) if the message was a warning, the time to cross the NOZ/NTZ boundary was computed using the current heading and speed. From the beginning of a blunder (the vector instruction) until the aircraft has reached the other ILS takes between 25 and 35 seconds, depending on aircraft speed, ILS separation, and to a lesser extent, initial heading and location on the ILS. The threatened aircraft may be on the near side of the other ILS, allowing even less time. It seems appropriate to look at the time it took for controllers to make their first responses to the blunders, and to see if that time was influenced by the experimental conditions.

The data collected in the communications file were used to compute and analyze the response of the controllers when a major aircraft blunder occurred. For each blunder, the communication history was extracted for both runways from the time that the incident was initiated until some evidence was received that the incident was ended. The end of the incident was signaled by one of the following: a cancel message to the blundering aircraft, a transfer frequency command, or 15 seconds without any communication. Two of the histories were shown graphically in figures 9 and 10. From these incident histories, the following information was calculated.

RSTIME - Response time is the time to the first simulator operator computer entry (pilot action) on either runway after the blunder. This response time should correspond to the pilot beginning to take action in response to a controller's command.

COMTIME - Communication time is the time to the first communication to the blundering aircraft after the blunder was initiated. It is detected by a radio key closure.

ETIME - Elapsed time is the time betweem the blunder initiation and the first warning message to the blundering aircraft if a warning was given.

See figure 12 for sample incident histories of two blunders. In both incidents, the first action by the controller was a warning to return to the localizer. The respective response times to the first action were 26 seconds and 14 seconds. The times until the controller keyed the microphone were 19 seconds and 7 seconds, respectively.

Out of 279 initiated blunders, 10 blunders were eliminated from the analysis because they took place at the same time as another blunder and responses could not be separated. Responses taking place 2 seconds or less after the blunder was initiated were considered to have preceded the blunder incident and these were not used. Neither were responses taking place more than 35 seconds after initiation used. From the remaining blunder incidents, the following data were extracted.

RUN 59, CONDITION O

AIRCRAFT IDENT	MESSAGE/ ACTION TAKEN	TIME	COMMENTS
DL1633 (36L)	VECTOR	5:24:26	TURN 30 RIGHT
DL1633	CONTCOM	5:24:33	COMTIME (MIKE KEY) = 7 SEC.
DL1633	WARNING	5:24:40	RSTIME = 14 SEC. ELAPSED = 14 SEC.
POKE53 (36R)	CONTCOM	5:24:39	
POKE53	VECTOR	5:24:45	TURN RIGHT HEADING 060
POKE53	ALTITUDE	5:24:45	CLIMB AND MAINTAIN 3000
DL1633	CONTCOM	5:24:42	
DL1633	VECTOR	5:24:46	TURN RIGHT HEADING 110
DL1633	CONTCOM	5:24:59	
DL1633	ALTITUDE	5:25:03	MAINTAIN 2000
POKE53	CONTCOM	5:25:04	
POKE53	ALTITUDE	5:25:14	DESCEND AND MAINTAIN 2000
POKE53	VECTOR	5:25:14	TURN RIGHT HEADING 110
DL1633	CONTCOM	5:25:13	
DL1633	VECTOR	5:25:17	TURN RIGHT HEADING 180
DL1633	ALTITUDE	5:25:17	CLIMB AND MAINTAIN 3000
DL1633	CONTCOM	5:25:29	

RUN 49, CONDITION J

DL1648 (36R)	VECTOR	1:18:30	TURN 30 LEFT
DL1648	CONTCOM	1:18:49	COMTIME (MIKE KEY) = 19 SEC.
DL1648	WARNING	1:18:56	RSTIME = 26 SEC. ELAPSED = 26 SEC.
DL1648	CONTCOM	1:19:18	
DL1648	VECTOR	1:19:27	TURN LEFT HEADING 300
DL1648	ALTITUDE	1:19:30	CLIMB AND MAINTAIN 3000
DL1648	CONTCOM	1:19:37	
DL1648	CANCEL	1:19:41	

FIGURE 12. INCIDENT HISTORY FOR INITIATED BLUNDERS

The following averages summarize the results for response time, communication time, and elapsed time. When blunders were initiated, the selected aircraft were within the NOZ and may even have been located on the far side of the centerline of the ILS. Several seconds were required before an aircraft reached the NTZ and posed a threat to parallel aircraft thereby requiring controller action. The response times may seem overly long for that reason. The statistical significance for each variable is discussed after the averages are presented.

Response Time (Time to First Action)
253 blunder incidents

Condition	J	K	L	M	N	O
AVERAGE	15.54	16.44	13.52	14.50	13.23	12.05

The main effect for conditions was statistically significant at the 0.05 level but the only pairwise contrast signficant was J slower than O.

Communication Time (Time to First Controller Communication)
256 blunder incidents

Condition	J	K	L	M	N	O
AVERAGE	15.25	14.07	12.62	13.15	12.79	10.82

The main effect for conditions was not statistically significant.

Elapsed Time (Time to First Warning)
208 blunder incidents

Condition	J	K	L	M	N	O
AVERAGE	18.30	16.31	14.38	15.46	14.00	13.15

The main effect for conditions was statistically significant at better than the 99 percent confidence level. Significant pairwise contrasts were: J longer than L, M, and O. The Scheffe S test permits tsting hypotheses formed after looking at the data (a posteriori). A Scheffe S Test comparing J and K with L, M, N, and O (the two 5-second rates against the 1- and 2-second updates) produced means of 14.25 and 17.31 seconds, respectively, which were significantly different.

Significant differences in blunder response time (time to first action) are important because time is so limited in dealing with large aircraft errors in the restricted airspace of these parallel runways. For conditions J and K, using the ASR-8, it took an average of 16 seconds for the controllers to establish an error while the average for the faster update rates L, M, N, and O was 13.33 seconds. To test the hypothesis that the radar update rate was a factor in response time, a Scheffe S test was done on the average of the J and K, 5-second update, against the average of the faster 2-second and 1-second update rates. The differences of 2.67 seconds was not quite significant at the 0.05 level.

Communication time (time to first microphone keying) is probably a more direct measure of the controller's reaction time, since it occurs before the message can be transmitted to the simulator operator and entered. In fact, the responses are quicker. The main effect in the ANOVA was significant at only the 0.064 level and the pairwise contrast were unwarranted.

Elapsed time (time to first warning) showed condition J rather slower than any of the other conditions. It was significantly slower than conditions L, M, N, and O. Conditions J and K, the two 5-second rates, were compared to conditions L, M, N, and O, 1- and 2-second rates, and the average difference of 3 seconds was statistically significant.

The differences in time to respond to blunders, as measured by response, communication, and elapsed times, were small, on the order of 2 to 3 seconds. Two of the three failed to reached the 0.05 level of statistical significance for the condition effect. The time savings, however, were always in the same general direction, the 5-second rates slower than the 1- and 2-seconds rates, and the expanded display (condition O) faster than the standard (condition M).

COMMUNICATIONS DATA.

Since every input made by the simulator operator that affects an aircraft is recorded by the computer and virtually every control communication resulted in such a message, there is a fairly complete record activity. Fairly complete, rather than fully so, because only records that could be associated with a specific flight were recorded in the file. A summary of major message classes, tabulated by condition and controller team, is shown in table 10.

TABLE 10. CONTROLLER COMMUNICATION

Condition

Message	J	K	L	M	N	O	Total
Warnings	482	583	728	832	1378	1213	5216
Norturn	171	186	231	173	175	206	1142
Maxturn	2	6	4	8	6	2	28
Altitude	130	122	132	146	188	174	892
Speed	295	295	289	256	322	296	1753
Cancel	90	95	101	98	104	113	601
Others	77	87	86	62	77	71	460
TOTAL	1247	1374	1571	1575	2250	2075	10092

Frequency By Team

Message	1	2	3	4	5	6	7	8	Total
Warnings	533	610	1012	847	390	723	139	962	5216
Norturn	143	114	118	154	160	186	141	126	1142
Maxturn	5	0	0	12	1	5	5	0	28
Altitude	144	79	94	85	97	228	91	74	892
Speed	134	149	446	257	86	227	137	317	1753
Cancel	75	65	70	57	98	88	82	66	601
Others	53	62	42	60	72	59	44	68	460
TOTAL	1087	1079	1782	1472	904	1516	639	1613	10092

Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

Initial data reduction categorized all communications by test condition (J, K, L, M, N, and O) and controller team. An explanation of the major types of messages follows.

WARNINGS - Standard warning command, "turn left/right and return to the localizer course."

NORTURN - Normal turns, command to start standard rate turns (3° per second).

MAXTURN - Maximum rate turn commands.

ALTITUDE - Descent or climb commands.

SPEED - Speed control commands.

CANCEL - Cancel the aircraft in this simulation. This message was used when a flight was terminated for some reason. Most cancel messages were given to indicate the termination of the monitor controller's function in a missed approach situation. After a cancel instruction was given, no further data were recorded for the aircraft.

OTHER - A variety of other messages including identity requests and clearances. Controllers were not given specific instructions to use these messages but incorporated them from their everyday communications patterns.

The number of pilot messages received does not equal the number of controller communications, as defined by the count of microphone key closures. A controller communication, a single key closure, frequently preceded several commands to the same or different aircraft and some controller communications did not result in pilot actions. The number and type of communications varied tremendously from team to team. Team 7 initiated 139 warnings while team 3 had 1,012 warnings. Team 5 gave instructions for 86 speed changes in contrast to 446 for team 3 and 317 for team 8. Under statistical analysis, only the number of warning messages showed significant differences among differing test conditions.

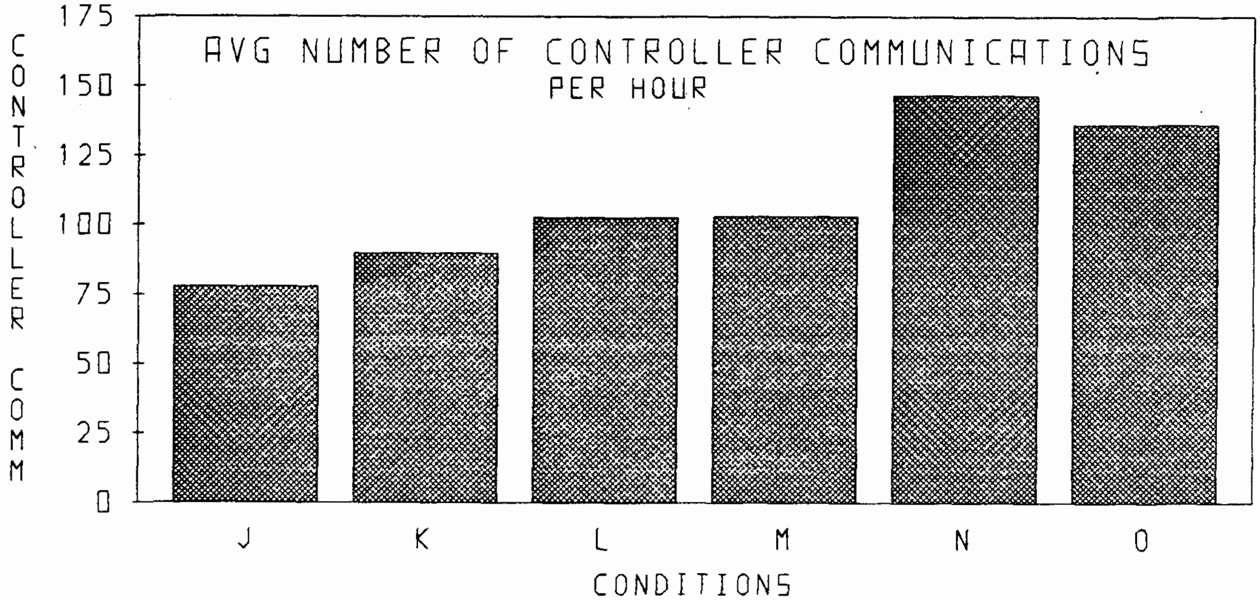
CONTROLLER COMMUNICATIONS (ALL TYPES). There are two related indices or measures of controller communications: (1) the number of times that the controller started a transmission as measured by microphone key closure, and (2) the number of resulting pilot actions and warning entries that resulted (pilot actions).

The number of communications as measured by microphone key closures did show significant differences among conditions at the 95 percent confidence level (see table 11).

TABLE 11. NUMBER OF CONTROLLER COMMUNICATIONS MEASURED BY KEY CLOSURE

(entries are computed for two 60-minute runs)

	Condition					
Team	J	K	L	M	N	O
1	165	171	142	224	235	216
2	131	160	198	170	259	260
3	243	283	344	240	369	407
4	86	203	206	281	488	413
5	113	112	94	126	204	185
6	201	203	259	300	334	249
7	104	92	119	68	98	99
8	204	214	283	244	359	352
TOTAL	1247	1438	1645	1653	2346	2181
AVERAGE FOR 1 HOUR	77.9	89.9	102.8	103.3	146.6	136.3



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

Using identical radar accuracies and update rates, condition O, using the expanded display, resulted in significantly more controller communications than condition M using the standard display. Condition O also resulted in significantly more controller communications than condition J which is the standard condition in current operation. By condition, the average number of controller communications were as follows.

J	K	L	M	N	O
77.9	89.9	102.8	103.3	146.6	136.3

These results confirm the significant differences reported for both pilot actions and warnings individually. A significant increase in controller communications exists when controllers use expanded rather than standard displays.

NUMBER OF WARNINGS. The standard list of procedures given to each controller directed that a warning be given whenever the monitor controller observed the aircraft deviating off the ILS towards the NTZ. The simulator operator entered the warning via a special key and the number of warnings was tallied by condition and team (table 12). The entry of a warning also ended the 10-second random excursion of a warned aircraft if it was given on time.

By condition, the average number of warnings given by each team during a 1-hour run was as follows.

J	K	L	M	N	O
30.1	36.4	45.5	52.0	86.1	75.8

ANOVA results showed statistically significant differences in the number of warnings given among experimental conditions. Conditions M, and O yielded significantly more warnings than condition J. Condition M (standard display) showed significantly fewer warnings than condition O (expanded display) using identical radar update rates and accuracy. For four out of the eight teams, the number of warnings increased by more than 50 percent when expanded displays were used.

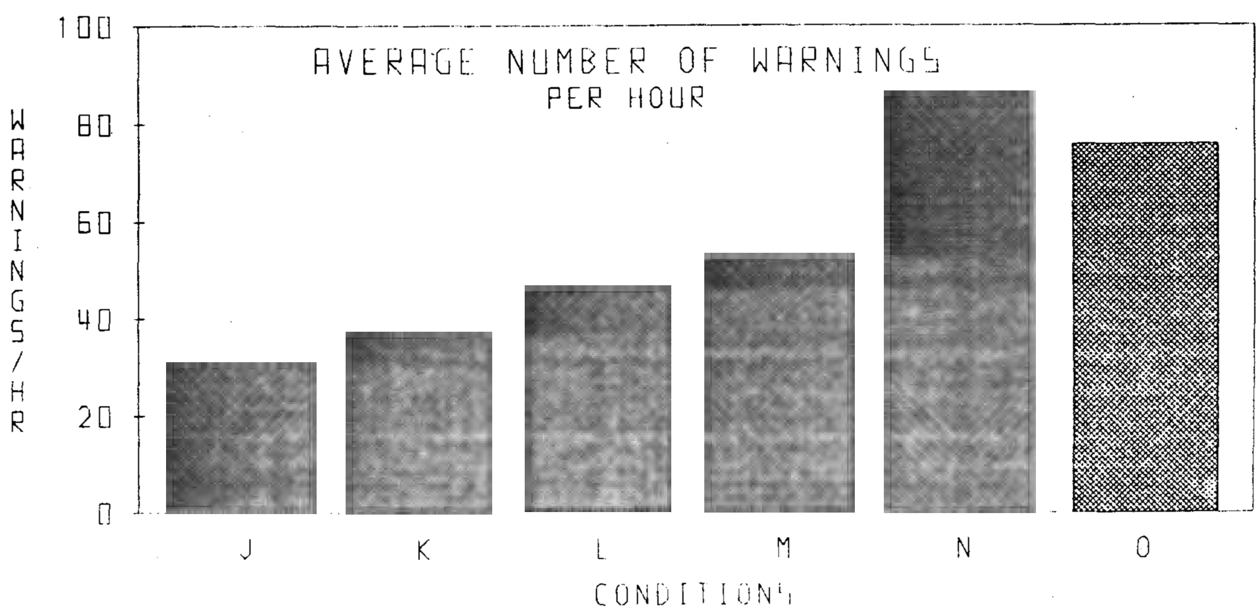
Using the Scheffe S test, the contrast of conditions using ASR-8 radar parameters (conditions J and K) to conditions using 1-second update and 1-mrad radar parameters (conditions M, N, and O) showed significantly more warnings were given under 1-second update and 1-mrad radars.

Several attempts were made to categorize the position and heading of aircraft at the time a warning message was entered by the simulator operator. (It was not possible to consistently correlate microphone keying time to warning messages.) When an aircraft was in the NOZ, the predicted time to cross into the NTZ (calculated using present lateral deviation, heading, and speed) was computed. At the time of warning, less than one-third of the aircraft were still in the NOZ. No straightforward relationship could be found between aircraft location and heading and the issuance of warnings, at least within the limits of the analysis.

TABLE 12. NUMBER OF CONTROLLER WARNINGS

(entries are computed for two 60-minute runs)

Team	J	K	L	M	N	O	Team Totals
	Condition						
1	74	68	65	108	120	98	533
2	65	73	110	100	147	115	610
3	103	151	197	118	224	219	1012
4	22	37	52	150	331	255	847
5	42	35	21	52	120	120	390
6	79	79	122	134	165	144	723
7	9	18	27	16	35	34	139
8	88	122	134	154	236	228	962
TOTAL	482	583	728	832	1378	1213	5216
AVERAGE FOR 1 HOUR	30.1	36.4	45.5	52.0	86.1	75.8	



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

NUMBER OF PILOT ACTIONS. All the pilot actions were tallied and categorized. Pilot actions included all turns, altitude changes, frequency changes, cancel messages, beacon identifications, and speed changes input by the simulator operator Warnings were not included. Results are in table 13.

Statistical analysis showed significant differences among experimental conditions. Condition M (standard display) yielded significantly fewer pilot actions than condition O (expanded display). Condition O also had significantly more pilot actions than condition J. By condition, the average number of pilot actions per team for a 1-hour run were as follows.

J	K	L	M	N	O
46.3	48.3	51.8	45.4	53.4	53.1

LONGITUDINAL CONFLICTS.

Another aspect of traffic control in the terminal area is longitudinal spacing on the ILS. Some longitudinal conflicts were built into the traffic samples in the belief that distractions caused by large numbers of NTZE's and parallel conflicts would be reflected in some slackness in dealing with longitudinal spacing. The criteria are based on the Air Traffic Control Handbook, 7110.65c, paragraph 1420, and are as illustrated below.

Terminal Separation Minima (nmi)

		Aircraft in Lead		
		SMALL	LARGE	HEAVY
Aircraft	SMALL	3	5	6
in	LARGE	3	3	5
Trail	HEAVY	3	3	4

The number of speed control messages was analyzed since controllers issue speed control messages to promote longitudinal separation. ANOVA showed there were no significant differences in the number of longitudinal conflicts or in the number of speed control messages given by the controllers as a function of the experimental condition. This is so even though there was a large increase in NTZE's and parallel conflicts as the NOZ went from 1,150 feet to 500 feet (see table 14).

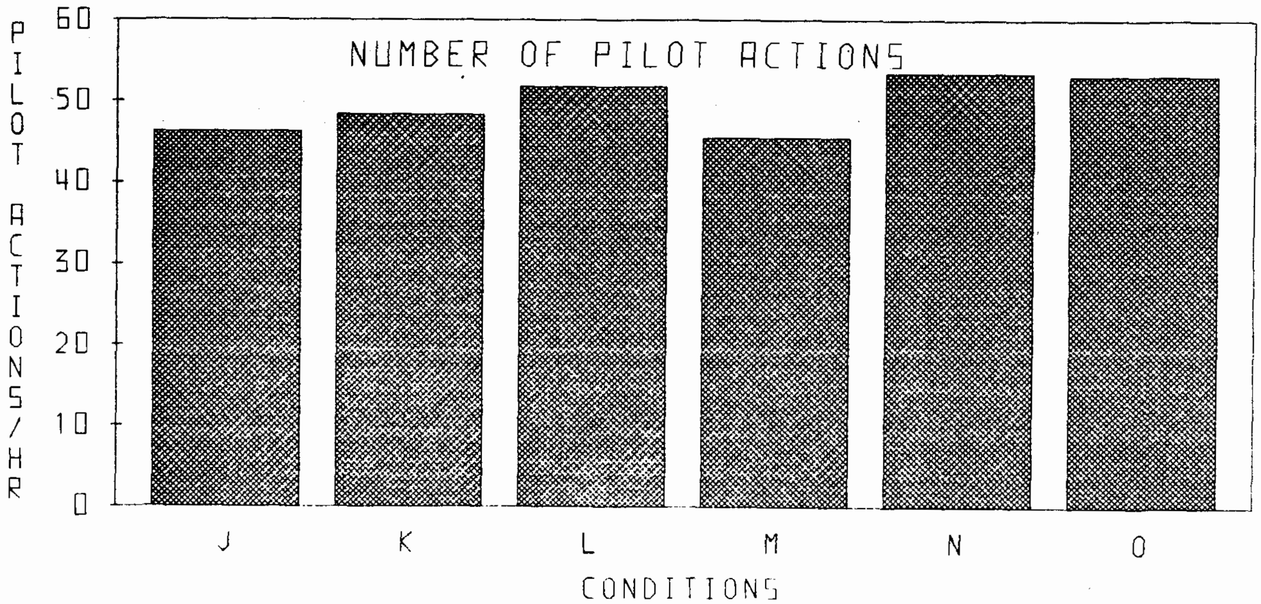
MISSED APPROACHES AND AIRCRAFT LANDED.

MISSED APPROACHES. The introduction of parallel conflicts and blunders led to a number of missed approaches; i.e., aircraft that were vectored off the ILS and returned to final for resequencing (or canceled). All computer files and reference records were examined for any aircraft which received a vector to determine the status of the aircraft when the vector was given to initiate a missed approach (see table 15).

TABLE 13. NUMBER OF PILOT ACTIONS

(entries are computed for two 60-minute runs)

	Condition					
Team	J	K	L	M	N	O
1	92	85	74	93	99	96
2	61	65	68	68	78	112
3	110	118	130	124	138	134
4	60	123	130	83	112	109
5	73	99	68	86	96	85
6	128	114	129	128	159	122
7	99	72	101	59	68	86
8	117	96	128	86	105	106
TOTAL	740	772	828	727	855	850
AVERAGE FOR 1 HOUR	46.3	48.3	51.8	45.4	53.4	53.1

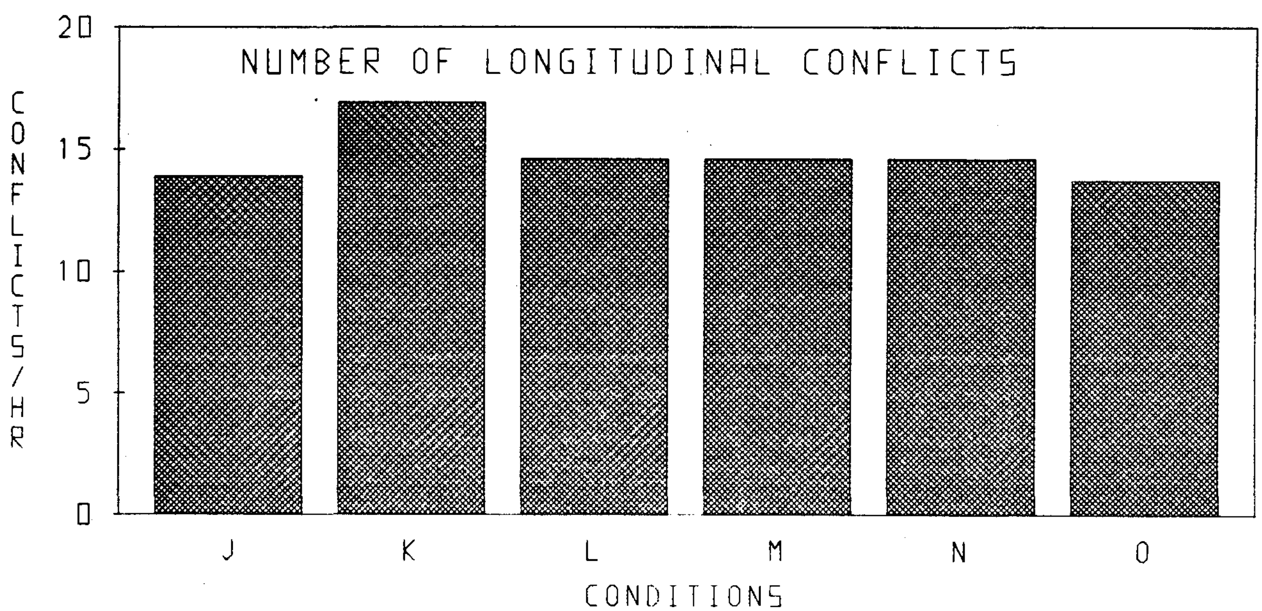


Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

TABLE 14. NUMBER OF LONGITUDINAL CONFLICTS

(each entry is the sum of two 1-hour runs)

Team	Condition J	K	L	M	N	O
1	42	34	29	29	33	24
2	32	37	28	39	34	30
3	21	28	24	22	28	22
4	25	46	39	32	29	25
5	27	31	27	30	32	23
6	30	32	23	32	18	22
7	29	30	38	30	28	41
8	17	32	26	20	32	32
TOTAL	223	270	234	234	234	219
AVERAGE FOR 1 HOUR	13.9	16.9	14.6	14.6	14.6	13.7



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

TABLE 15. MISSED APPROACH SUMMARY

Causes	Number Of Missed Approaches
Conflict during initiated blunders	432
Parallel conflict, no blunders in progress	135
Longitudinal conflict	5
Aircraft already in or across the NTZ	4
Simulation problem	4
Potential parallel conflict developing (conditions J J K M M)	5
Data not available	2
Longitudinal conflict nearby	2
TOTAL	589

Note: 8 aircraft did not get established on the ILS

The largest number of missed approaches resulted from initiated blunders. The test director's action which initiated the 279 blunders caused a missed approach for 274 blundering aircraft. When connection with the ILS is broken by such a large vector, it is difficult to reestablish aircraft on the ILS in the simulator. Although the initiated blunders were not expected to land, several creative subject controllers did land five blundering aircraft. Out of 432 missed approaches resulting from initiated blunders, 274 were blundering aircraft vectored off the ILS as part of the test and 158 were aircraft in conflict with the blundering aircraft.

As reported, there were a large number of parallel conflicts caused by navigational errors or excursions and these caused 135 aircraft to be vectored off the ILS. These were aircraft threatened by an aircraft operating on the opposite ILS which had penetrated the NTZ. Five aircraft were vectored off the ILS while the position and heading of another aircraft on the parallel ILS showed the aircraft to be possibly deviating toward the NTZ, and the positions of both aircraft were nearly parallel. Two of these aircrafts were vectored under condition J, two under condition M, and one under condition K.

Five aircraft were vectored off the ILS while in longitudinal conflict with another aircraft on the same ILS. Two aircraft were vectored while the controller was managing traffic flow with speed control messages, and longitudinal conflicts had developed either immediately ahead or behind the aircraft which was vectored off the ILS. Four missed approaches were caused by miscellaneous problems during the simulations.

Analysis of missed approaches failed to establish any relationship to the experimental conditions. Considering the fact that there were so few that did not arise directly from blunders, it is not surprising that no demonstrable relationship exists. It was very clear to those watching the simulation that the controllers were reluctant to interfere with the traffic flow unless absolutely certain it was necessary. Even when aircraft are flying erratically, the feeling was that the sooner they landed, the safer everyone would be. That attitude is supported by data on the number of aircraft that landed and controller comments during debriefing.

CONFLICTS WITHOUT MISSED APPROACHES. During the 96 hours of testing, 589 missed approaches were executed. Many parallel and longitudinal conflicts did not result in missed approaches. The following is a summary of those conflicts.

Out of a total of 1,414 longitudinal conflicts, 1,162 conflicts occurred in which neither aircraft was given a missed approach. Of these 1,162 longitudinal conflicts, 166 were given speed control messages by the controller while the conflict was taking place. The longitudinal conflicts which did not produce missed approaches averaged 12.1 per 1-hour run. Only 25 aircraft got closer than 2 miles in 1,162 longitudinal conflicts.

From a total of 2,373 parallel conflicts, 1,435 conflicts did not result in missed approaches. Warnings were given during 781 conflicts and no warnings were given for 654 conflicts. The significant differences among conditions for parallel conflicts in which no missed approach was given followed the pattern of significant differences for the total number of parallel conflicts; larger numbers for closer runway spacing.

AIRCRAFT LANDED. The number of aircraft landed was counted and categorized by condition. Since each condition was given a uniform traffic load, the number of aircraft landed should reflect differences in system capacity due to experimental conditions. The NSSF simulation program introduced some unwanted complexity in this measure. If the computer found an aircraft too far removed from the correct parameters for ILS approach, it forced an automatic missed approach. Since these missed approaches were not directed by the monitor controller, these aircraft were included in the count of aircraft landed.

There were no significant differences among conditions in the number of aircraft landed (see table 16). The overall average was 51.7 aircraft landed per hour on a set of parallel runways.

QUESTIONNAIRE DATA.

The questionnaires were completed by each controller as soon as a run was finished and represent an immediate and subjective response to the run. Each of the data points represent the average of the two controllers working as a team over the two runs on the condition. Figure 13 is a copy of the questionnaire.

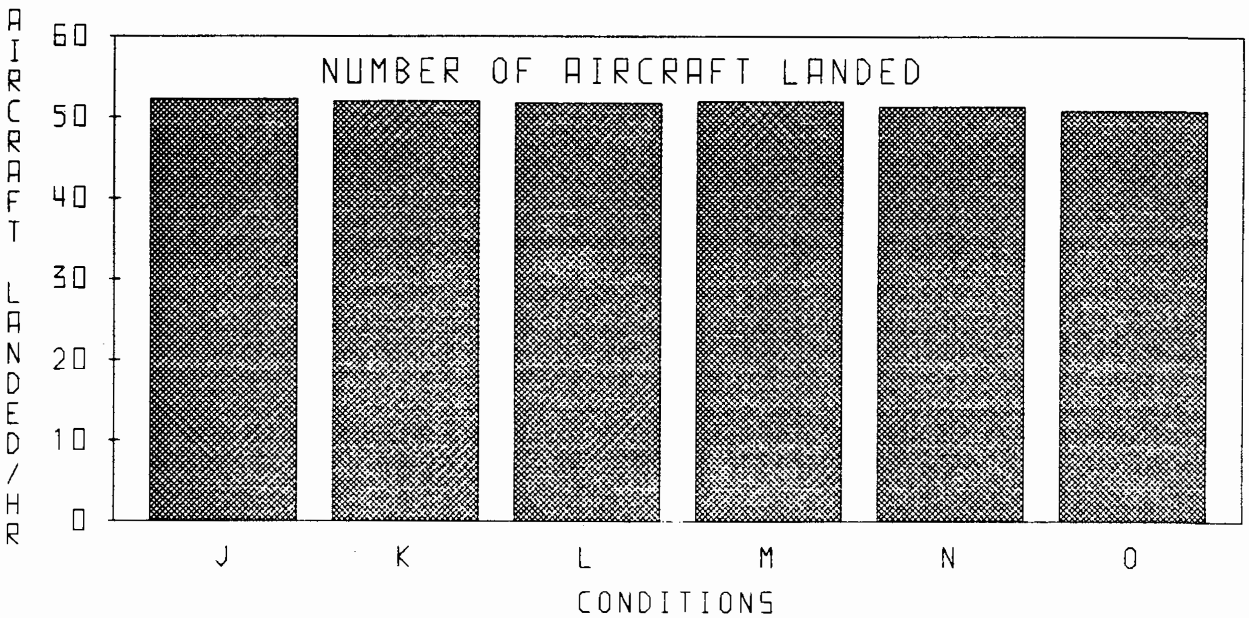
It should be mentioned that in every questionnaire ANOVA, including those that did not produce significant differences among the experimental conditions, there were significant differences among the orders. There was no interaction between order and condition, so that the interpretation of condition effects is unaffected. The most likely cause of this significance is that there were real differences among the controllers who participated from week to week. It serves as a reminder that there are important differences in the way controllers respond to a situation and that a group average gives only part of the whole picture.

The first question dealt with the realism of the simulated traffic. On a scale of one to four, the averaged responses under all conditions grouped near three, which indicates the controllers felt that the traffic was fairly realistic. No statistically significant differences were detected among the different experimental conditions.

TABLE 16. NUMBER OF AIRCRAFT LANDED

(each entry is the sum of two 1-hour runs)

	Condition					
Team	J	K	L	M	N	O
1	100	103	104	104	108	103
2	108	107	107	106	103	101
3	109	105	103	104	104	101
4	110	101	107	108	108	102
5	100	99	102	98	99	102
6	103	104	102	98	100	101
7	105	105	99	105	99	100
8	102	108	104	109	102	104
TOTAL	837	832	828	832	823	814
AVERAGE FOR 1 HOUR	52.3	52.0	51.8	52.0	51.4	50.9



Condition	J	K	L	M	N	O
Runway Separation	4300 ft.	3400 ft.	3400 ft.	3400 ft.	3000 ft.	3400 ft.
Normal Operating Zone	1150 ft.	700 ft.	700 ft.	700 ft.	500 ft.	700 ft.
Radar Accuracy	3 mrad	3 mrad	2 mrad	1 mrad	1 mrad	1 mrad
Radar Update Interval	5 sec.	5 sec.	2 sec.	1 sec.	1 sec.	1 sec.
Lateral Display Magnification	1:1	1:1	1:1	1:1	2:1	2:1

CLOSELY SPACED INDEPENDENT PARALLEL RUNWAY QUESTIONNAIRE

Controller Code No.______ Date________ Time________ POSITION: 5 6
(Start Run) 15 16

PLEASE FILL OUT THIS BRIEF QUESTIONNAIRE ON THE BASIS OF THE RUN YOU HAVE JUST COMPLETED.

1. Except for the deliberately introduced blunders, how realistic do you feel this traffic was?

0	1	2	3	4
VERY ARTIFICIAL				VERY REALISTIC

2. How hard do you feel you had to work on this run?

0	1	2	3	4
NOT HARD AT ALL				VERY HARD

3. How adequate do you feel the radar/display was for this run?

0	1	2	3	4
VERY POOR				VERY GOOD

4. How well do you feel this condition enabled you to control this traffic sample?

0	1	2	3	4
CONTROL IS QUESTIONABLE				CONTROL IS GOOD

5. If the conditions of this run (radar, display, and runway separation) were offered in a radar system at your facility, how would you feel?

0	1	2	3	4
STRONGLY OPPOSE				STRONGLY FAVOR

COMMENTS:

FIGURE 13. CONTROLLER QUESTIONNAIRE

The second question dealt with perceived workload - how hard the controller felt he was working. There was a statistically significant difference among the conditions and the amount and direction can be seen in figure 14. Under conditions J and L, the controllers felt that they were not working hard at all. Under conditions O, M, and K, they felt that the workload was greater, but under condition N, they felt they were working much harder. This was confirmed by contrasts that show statistical significance at the 95 percent confidence level for differences between conditions J (4,300 feet) and K (3,400 feet, 5 seconds) and also between conditions N (3,000 feet) and O (3,400 feet), both expanded displays. The results indicate that controllers felt condition K was harder than condition J and condition N was harder than condition O.

Responses to the question on the level of work required indicate the controllers felt that some of the conditions required more effort or concentration than others. While conditions J and L seemed extremely undemanding, it is interesting that condition N, which required a great many warnings, a lot of communication in general, and produced a large number of conflictions was still reported to be only slightly below the middle of the controllers subjective workload continuum. Condition N was clearly the hardest condtion of the six, which is not very surprising. It was significantly harder than condition O to which it was identical except for the closer runways.

Conditions J and K are identical except for runway spacing and condition K is significantly harder. Interestingly, condition J was not significantly easier than conditions L, M, or O, which suggests that variables such as update rate, radar noise, and display magnification do change at least the perceived difficulty of the task.

The third question dealt with the adequacy of the radar/display for the run. On a scale of zero to four, the responses clustered about a rating of three indicating that the controllers felt the radar display was good. No statistically significant differences were found among the conditions.

This question on the adequacy of the radar/display was included in the hope of detecting differences among such features as the radar update rate or the display magnification feature. No overall significance was obtained. It might be noted that there were two pairs of identical radar/displays, conditions J and K and conditions N and O, and the differences within these pairs were fairly large and in favor of the larger runway separation. The controllers seemed to evaluate the hardware in the context of the task at hand.

The fourth question dealt with how well the controller felt he could control traffic under the given condition. Responses to this question varied significantly among the different conditions.

Statistical contrasts showed that perceived control under condition J was significantly better than condition K at the 99 percent confidence level and better than condition L at the 95 percent confidence level. Also, condition O was significantly better than condition N at the 99 percent level of confidence. Controllers felt that they could control traffic better with 4,300-foot separation using the ASR-8 than they could with 3,400-foot and the same radar. Even with the 2-second update rate of condition L, condition J was better. Similarly, controllers felt that they could control traffic better at 3,400-foot separation than at 3,000-foot separation under identical 1-second update rate and expanded display conditions.

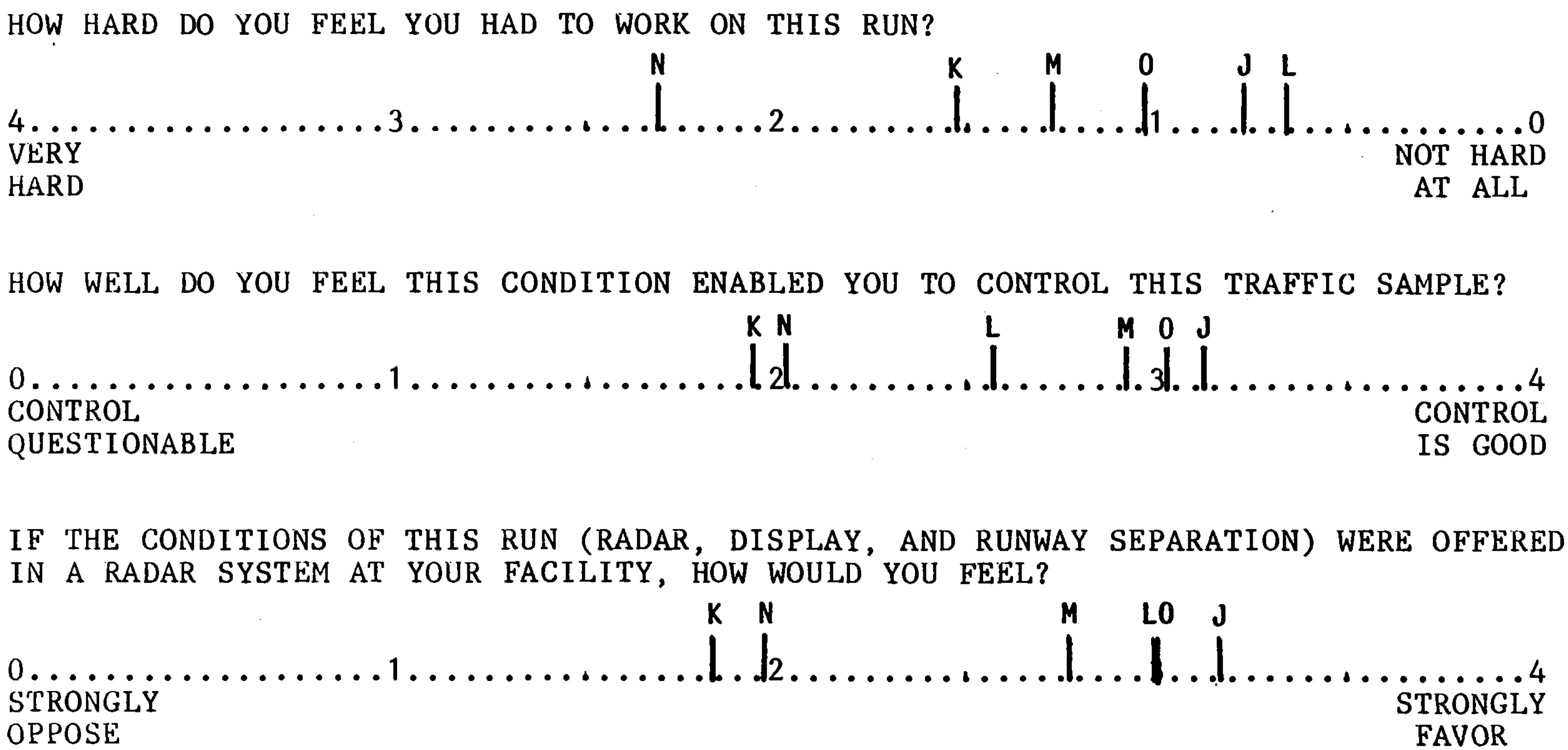


FIGURE 14. AVERAGE CONTROLLER RESPONSES FOR SIGNIFICANT QUESTIONS

Ability to control is at the core of the simulation and the differences are quite pronounced. Condition J, the 4,300-foot condition, and conditions M and O, both of the 3,400-foot conditions with 1-second update, were rated favorably and close together. Conditions K and N, 3,400-foot and 5-second update and 3,000-foot and 1-second update, are close together and in the middle of the scale. Condition L, at 3,400-foot and 2-second update, falls in between. The question of control was considered by the experimenters to be a subjective and indirect assessment of safety. The responses of the controllers are not inconsistent with that view.

The final question asked how the controllers felt about implementing the given condition at his own facility; that is, whether they favored the idea or opposed it. Again, we found significant differences under the various conditions. Similar to the results of the previous question, condition J was significantly favored over condition K and condition O was significantly favored over condition N at the 99 percent confidence level. Thus, while the average rating of 3,400 feet with the ASR-8 radar was halfway between "favor" and "oppose," it was significantly less well received than 4,300 feet with ASR-8, the present minimum. When comparing 3,000-foot separation to 3,400-foot separation with identical display and radar characteristics, the controllers strongly favored the 3,400-foot separation.

This question was an attempt to look at the run just completed in practical terms; i.e., in an operational setting they were familiar with. The response was very similar to the question of control, except that conditions L and M seemed to have traded places. The important distinction is that conditions K and N are significantly less acceptable than the others, conditions J, L, M, and O. Even conditions K and N would be treated only with neutrality, not opposition, based on average response. However, teams 1 and 2 gave both conditions K and N mean ratings of 0.37 and 0.50, respectively, indicating fairly strong opposition. The four controllers who comprised these teams represented 25 percent of the sample.

After answering the five questions, controllers added their own comments to the bottom of the questionnaire after each run. Not every run produced comments from all controllers. These comments were later grouped by condition. Several trends appeared among the comments.

Condition J had the fewest comments; over three-quarters of the questionnaires were returned with none. Condition K produced the most comments and the majority were negative. Nineteen out of the 23 comments referred to unsatisfactory update rate. One controller summed up the negative reaction with his comment "with the 5-second update rate, you have to wait 10 seconds to determine if an aircraft is leaving the localizer and by that time, it is too late." Condition L with the 2-second update rate produced more favorable comments. Seven out of the 13 controllers commenting said that the 2-second update rate was better. Half the questionnaires had no comments on condition M. Under the 1-second update, controllers made comments on the expanded versus the standard display.

The expanded display in conditions N and O seemed to take a little time for the controllers to become accustomed to. The expansion in only one direction exaggerated the deviations from the ILS. One controller characterized it as "excessive movement," but most controllers found it acceptable and workable. Several controllers preferred the expanded display to the standard display. The comments on condition N (3,000-foot separation) showed a concern with limited reaction time. Twenty-five percent of the controllers wrote comments such as "time to react extremely limited." Two controllers mentioned lack of margin for error and two other controllers suggested staggered (dependent) rather than independent approaches under this condition. Condition O produced a wide variety of comments but no trends.

DISCUSSION OF RESULTS

Whereas the preceeding section presents results in terms of each separate variable, the following examines the results in relation to the experimental conditions.

Condition J, with 4,300 feet between runways and an 1,150-foot NOZ, was included in this experiment as a standard against which a number of innovations can be tested. Questionnaire results indicated the controllers found it the easiest to work with, a system with which they could control aircraft comfortably and one they felt they could use effectively at their own facility. Condition J produced by far the fewest NTZE's, the fewest parallel conflicts, the least risk from the ones produced, the fewest warnings, the least communciations, and so on. Whenever there was a significant difference, it seemed to invariably favor condition J. Only in the separation available for blunders did condition J not outperform the other conditions, and even there, it did not do significantly worse than any other condition. Condition J (and K) were slower on some of the response time measures associated with blunders, but there is no evidence that performance with condition J suffered because of it.

Although condition K was identical to condition J in every respect except for the closer runways (3,400 feet versus 4,300 feet), the differences between conditions J and K are substantial; clearly condition K is the poorest of the four 3,400-foot runway separation conditions. It is the hardest to work except for condition N, it offers the least amount of control along with condition N, and it is close to condition N as being the least preferred system for one's own facility. By and large, it shared performance with the other 3,400-foot conditions on such measures as NTZE's, parallel conflicts, and parallel conflict miss distance, but it also seemed to share the slower response of the ASR-8 it shares with condition J. Almost all the controllers who tried condition K after a faster update condition, disliked the 5-second update rate. Of the six conditions tested, condition K shares the bottom rank with condition N, the 3,000-foot condition.

Condition L introduces some new radar features. The 5-second update, 3-mrad ASR-8 has been "improved" to a 2-second update and 2-mrad accuracy. All the controllers prefer the 2-second to the 5-second, and some prefer it to the 1-second. Condition L ranks very close to condition J on all the questionnaire items except control, where it ranks about midway between condition J at the top and conditions K and N at the bottom. Condition L was subject to about the same number of NTZE's and parallel conflicts as the other 3,400-foot conditions, but controllers indicated they had better control than under condition K and were not working as hard as they were under the other conditions. Miss distances for the weighted sum of the parallel conflicts were half those of condition K and less than conditions M and O, and miss distance divided by the number of conflicts was also less than for any condition but J. On the other hand, condition L had the poorest record in dealing with blunders and the miss distances were significantly poorer than condition J. There do appear to be some contradictions in this picture, but this may be due to condition L's status as a transition between present equipment and hypothetical equipment. Condition L might be summarized as a large step in the right direction.

Condition M had a 1-second update and 1-mrad radar accuracy. None of the questionnaire responses show it to be significantly poorer than condition J. Some of the controllers who worked condition M after working the expanded display indicated they felt the standard display was easier to use; about an equal number preferred the expanded display. In terms of NTZE's, parallel conflicts, and blunder miss distance, condition M seems typical of the 3,400-foot separation. When compared specifically to condition O, the 3,400-foot with expanded display, condition M produced slower responses to blunders, produced fewer controller communications and resultant pilot actions, and gave fewer warnings. Condition M produced the greatest (safest) blunder miss distance, but the differences with conditions J and O were not significant. Condition M seems, in summary, a reasonable approach to 3,400-foot runway separation.

Skipping to condition O, the last of the 3,400-foot conditions, the only difference with condition M was the expanded display. The controllers tended to rate condition O rather well with no significant differences from conditions J or M. Comments on condition O were generally favorable and indicated that practice with the expanded display tended to make the controllers feel more comfortable with it. A few said they preferred the expanded display with a 2-second update but an equal number preferred the 1-second update. Condition O was typical of the 3,400-foot conditions in terms of NTZE's, parallel conflicts, and parallel conflict and blunder miss distances. It consistently had the fastest of the blunder response measures. In terms of total warnings, it produced more than any condition except condition N and significantly more than either conditions J or M. It should be noted that in addition to expanding the physical dimensions of the NOZ on the display, the expansion exaggerates all lateral movement and doubles the apparent angle with which aircraft depart from the ILS. For the monitors who are trying to catch deviations, this is a potential advantage.

Condition N, with its 3,000-foot separation and 500-foot NOZ, certainly tested the limits of the parallel runway geography in this study. It produced by far the most NTZE's, the most parallel conflicts, and the riskiest parallel conflicts. The controllers rated it the least realistic and the hardest, but did not consider it worse than condition K for controlling traffic or for use in one's own facility. Controllers tended to work condition N at the edge of their seats. It was a challenge and was accepted as such. One or two teams introduced extra speed control in anticipation of possible blunders between two aircraft flying alongside each other. Perhaps because of the extra effort, ability to cope with blunders was not measurably worse than the other 1-second update conditions. Condition N produced a lot more communication and more pilot actions than any other condition, but not significantly more warnings than condition O, the other expanded display condition. It was the only condition in which controllers expressed specific reservations about safety, although only six indicated it was either unsafe or required staggered (dependent) operations to be safe.

CONCLUSIONS

1. Independent parallel operation with 3,400-foot runway spacing is safe and feasible provided it is supported by a radar having an update rate of no more than 2 seconds and an accuracy of no less than 2 mrads. Controllers feel that the conditions which presented these combinations of features were safe and workable. Compared to 4,300 feet, 3,400 feet will produce more NTZE's, more parallel conflicts, and more controller warnings to aircraft. Adequate separation was maintained, however, under all of the specified 3,400-foot conditions except for scripted blunders, discussed below.

2. The use of the ASR-8/9 radar to support independent parallel operations for runway spacings of 3,400 feet and below is unacceptable. Controller responses and measured data indicate that the 5-second update rate is too slow to allow adequate detection of aircraft deviations.

3. Independent parallel operation at 3,400 feet runway separation provides virtually the same capacity as operation at 4,300 feet separation. Essentially, the same number of landed aircraft and missed approaches occurred under both conditions.

4. Independent parallel operations with 3,000-foot spacing is unacceptable. Reducing runway separation from 4,300 feet to 3,000 feet increased NTZE's 13-fold. Controllers do not believe they can respond to potential conflicts with sufficient speed at the reduced spacing.

5. The worst case blunder used throughout this study, an unexpected standard turn of 30° toward the opposite runway in the presence of traffic there, produced equally unacceptable near misses under all experimental conditions. This is not the kind of maneuver controllers ever see in the field and may be too severe for use as a test or a design criterion.

6. The reduction of runway spacing has no affect on the number of longitudinal conflicts or speed control messages. The additional workload caused by increases in NTZE's did not measurably affect longitudinal spacing.

RECOMMENDATIONS

1. For operations with a 3,400-foot separation, provide a controller display magnification feature which can, at the controller's option, magnify the radar display in the lateral dimension, to aid the controller in performing independent parallel runway operations. (Controller questionnaire results indicate that many controllers believed this feature aided their ability to detect aircraft deviations.)

2. Consider the development and use of an automated monitor alert feature which would insure minimal reaction time to the occasional blunder. This feature would provide an audible or visible alert to the controller of any aircraft on the ILS that was deviating towards the NTZ with sufficient speed or distance that controller action might be required. The sensitivity of such an alert could be a controller-selectable parameter.

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APPENDIX A

DESCRIPTION OF AIRCRAFT ILS FLIGHT PATH MODEL

An improved aircraft simulation model was developed for this effort to simulate the behavior of aircraft on final approach more realistically than the resident NSSF model and to assure that the gross statistics which characterize the aggregate behavior of the simulated aircraft correspond with those of real-world experimental data. The modeled aircraft exhibit normal self-centering oscillations about the ILS centerline and longer term navigation errors including "blunders" as described below. Positional noise is added to the radar display to simulate a realistic controller radar display.

The simulation model aircraft normally "fly" within a pencil-shaped area centered on the ILS centerline. This pencil is totally within the NOZ, and the width of the pencil is defined and controlled by the localizer fan angle (ALPHA). The width of the pencil expands until the outer marker and then remains constant from the outer marker to the gate. This angular expansion followed by constant width is similar to the shape of a sharpened pencil, hence it is called by that name. An ALPHA angle of 0.5° was used for this simulation. Without the introduction of navigational errors and/or radar noise, aircraft execute standard-rate-turns back towards the centerline of the ILS whenever the outer edge of the pencil is reached. This undulating flight approximates the manner that pilots fly an ILS. A more realistic aircraft flight path was created by adding flight errors and radar noise to the above undulating motion.

Random navigational errors were introduced in the flight path on a probability basis. The probability of an error is an optional input quantity that was set to one-eighth, the same for all aircraft. On the average each aircraft had an excursion once in eight sweeps. On a "hit," the aircraft made a standard rate turn to a new heading and continued for a fixed period of time. The magnitude of the angular deviation from the aircraft's current heading is a random value drawn from a normal population with a mean of zero and a 10° standard deviation outside the outer marker. A smaller distribution, 4°, was used inside the outer marker. Aircraft turn to and fly the new heading for a period of 10 seconds unless interrupted by a controller warning. The excursion terminates and, if it has exceeded the outer limits of the pencil, the aircraft turns back toward the ILS when the simulator operator heeds the controller's warning through a keyboard entry. Aircraft are ineligible for new navigational errors whenever outside the pencil or less than 1 mile from the runway. Navigational errors are also suspended whenever the aircraft is in the process of correcting from a prior error. All corrections and turns are at the standard rate of turn (3° per second).

Initiated blunders differ from excursions in several respects: (1) blunders are always scripted and are initiated at a predetermined time by the test director, (2) blunders are always standard turns of 30° toward the "opposite" ILS, and (3) blunders do not automatically return to the localizer.

Radar noise is introduced as a random variable from a normal distribution. A random value from the distribution (with mean equal to zero and the standard deviation variable) is added to the azimuth position of each aircraft at each update from the radar. The standard deviation was set to correspond to the uncorrelated noise component of the simulated 3-, 2-, or 1-mrad accuracy radar.

APPENDIX B

CONTROLLER INSTRUCTIONS

SUBJECT: To establish standardized procedures and responsibilities and duties for the monitor controller conducting simultaneous ILS approaches

1. ACTION: Responsibilities and Procedures

A. Monitor

(1) Monitoring shall be performed on all aircraft flying the ILS.

(2) The monitors will obtain a transmitter receiver check prior to monitoring.

(3) All aircraft data blocks will be automatically forced on the monitor screen. In lieu of primary target, the symbol "◊" will be used for separation purposes.

(4) The monitor controller assumes longitudinal/lateral separation responsibility for aircraft when following conditions must exist:

*(a) The aircraft is established on the localizer.
(b) The aircraft is on the monitor controller scope.
(c) the aircraft is on the appropriate local control frequency.

(5) Monitors will be responsible for maintaining appropriate longitudinal spacing of aircraft on their ILS using speed control outside of the outer marker.

(6) The monitor shall issue a warning to the pilot when he observes an aircraft deviating off the ILS.

PHRASEOLOGY: TURN (left/right) AND RETURN TO LOCALIZER COURSE.

(7) When an aircraft violates the NTZ, coordination must be made with the monitor of the other ILS so that any threatened aircraft on that ILS can be turned away from the blundering aircraft.

PHRASEOLOGY: TURN (left/right) HEADING 300/060 IMMEDIATELY, CLIMB AND MAINTAIN 3,000 feet.

(8) When the monitor controller initiates a missed approach or turns off the final approach course to insure separation, timely coordination shall be affected with the appropriate local/final position.

(9) The monitor separation responsibilities terminates 1 mile from the runway.

*For the purposes of this simulation, when aircraft are initiated on the scope, they will be established on the ILS.