DOT-FAA-AFS-450-74

Federal Aviation Administration
Standards Development Branch
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Oklahoma City, OK 73125

Independent Converging FMS/LNAV Missed Approach Evaluation

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June 1997

Final Report

Document is available to the public
through the National Technical Information
Service, Springfield, Virginia 22161

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT-FAA-AFS-450-74		

4. Title and Subtitle	5. Report Date
Independent Converging FMS/LNAV Missed Approach Evaluation	June 1997
6. Author(s)	**7. Performing Organization Code**
Gerry McCartor, Frank Hasman, Alan Jones, Dr. James Yates, Shahar Ladecky	10302
8. Performing Organization Name and Address	**9. Type of Report and Period Covered**
Federal Aviation Administration Standards Development Branch P.O. Box 25082, Oklahoma City, OK 73125	Project report

10. Sponsoring Agency Name and Address

Federal Aviation Administration
Standards Development Branch
P.O. Box 25082, Oklahoma City, OK 73125

11. Supplementary Notes

12. Abstract

This report documents the results of the Converging Approach Standards Technical Working Group (CASTWG) evaluations of the FMS (Flight Management System)/LNAV (lateral navigation) performance and aircraft track dispersion during a missed approach turn prior to runway threshold. This investigation was carried out in two phases: (1) simulator flight trials to address technical/operational issues and provide pilot data for the risk assessment and (2) a Monte Carlo computer simulation to assess the risk that FMS aircraft would maneuver into the converging missed approach airspace. This report provides a discussion of the investigation and a summary of results.

13. Key Words	14. Distribution Statement
Converging Flight Management System (FMS) Lateral Navigation (LNAV) Missed Approach	Controlled by AFS-450
15. Security Classification of This Report	**16. Security Classification of This Page**
Unclassified	Unclassified

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EXECUTIVE SUMMARY

This report documents the results of the Converging Approach Standards Technical Working Group (CASTWG) evaluations of the FMS (Flight Management System)/LNAV (lateral navigation) performance and aircraft track dispersion during a missed approach turn prior to runway threshold. This investigation was carried out in two phases: (1) simulator flight trials to address technical/operational issues and provide pilot data for the risk assessment and (2) a Monte Carlo computer simulation to assess the risk that FMS aircraft would maneuver into the converging missed approach airspace. This report provides a discussion of the investigation and a summary of results.

BACKGROUND

Current procedure, as described in FAA Order 7110.98A, permits simultaneous ILS approaches to converging runways. To assure separation of aircraft in the event of simultaneous missed approaches, decision heights (DHs) are established so that the turning missed approach obstacle clearance areas do not overlap and the missed approach points are separated by three miles or more. Application of this order has resulted in decision heights of approximately 800' HAT (Height Above Touchdown). Even though several converging approach procedures have been developed with this order, the high DHs have provided only minimal capacity increases.

In recent years, with the introduction of FMS equipped aircraft utilizing DME/DME navigation, smaller missed approach areas have been developed than the areas as applied in order 7110.98A. These missed approach areas are described in FAA Order 8260.40A. In order to safely reduce DHs for converging approaches, it was proposed that the operation utilize properly equipped FMS aircraft and the missed approach area be based on the FMS/LNAV navigation.

RESULTS AND RECOMMENDATIONS

In order to determine the acceptability of the FMS/LNAV turning missed approach concept, proof of concept flight simulator trials were performed in September, 1995 at NASA Ames Research Center, utilizing a Boeing 747-400 simulator, and in October at TWA's Flight Training Center, utilizing a Boeing 767 flight simulator. From these 1995 trials, two major conclusions were reached. The risk of overshoot (exceeding defined airspace) significantly increased if (1) high times to activate the LNAV mode occurred or (2) the aircraft speed increased after initiating LNAV. In order to increase pilot awareness of these critical requirements, procedure briefing pages were developed and provided to flight crews for the 1997 trials.

The FMS/LNAV missed approach concepts were further refined for the 1997 flight simulator trials by increasing the turn to 96° (sample application for ORD). The larger turn angle was chosen to increase the likelihood that aircraft would initiate the turn more quickly and improve the probability of remaining in the designated missed approach area. The 1997 evaluations were flown according to the published test plan utilizing the B747-400 simulator. This B747-400 evaluation included DHs of 500', 550', 600', and 650'.

After extensive data analysis of the B747-400 trials and using data from past simulator evaluations, the results supported ILS converging approaches with FMS/LNAV turning missed approaches for DHs as low as 650'. However, this result is based on the following operational conditions:

(1) The operation be limited to reported surface winds no greater than 10 knots tailwind to the runway using the FMS/LNAV missed approach procedure.

(2) The operation be limited to runways that converge at angles no greater than 50°.

(3) The operation be limited to airports of 1000' MSL elevation or less.

(4) The pilot be provided sufficient information to assure that response times are timely, and the aircraft acceleration is minimized during the maneuver.

(5) The operation be limited to /E aircraft and AFS approved /F aircraft.

Several operational issues were not addressed by this study and include: requirement that air traffic control sort properly equipped FMS aircraft (/E and AFS approved /F) to the secondary converging runway; level of pilot information/education/training that may be required to assure actions are taken necessary to maintain the aircraft inside the missed approach area; redesign of the companion converging runway missed approach to accommodate the converging ILS/FMS missed approach; redesign of the missed approach procedure for the non-converging ILS procedure to the same runway to be the same as the converging procedure with 650' DH; consideration of system failures; and implementation of any special charting requirements.

1.0 INTRODUCTION

The need to increase capacity and decrease arrival delays at major airports has encouraged the development of several promising concepts for improving all weather operations utilizing existing runway configurations. The current procedure, described in FAA Order 7110.98A, Simultaneous Converging Instrument Approaches (SCIA) permits simultaneous ILS approaches to converging runways. To assure separation of aircraft in the event of simultaneous missed approaches, decision heights (DHs) are established so that the turning missed approach obstacle clearance areas do not overlap and the missed approach points are separated by three miles or more. Application of this order has resulted in decision heights of approximately 800' HAT (Height Above Touchdown). Even though several converging approach procedures have been developed with this order, the high DHs have provided only minimal capacity increases.

With the introduction of aircraft equipped with flight management systems (FMSs), utilizing DME/DME navigation, smaller missed approach areas have been developed than the areas applied in 7110.98A. These missed approach areas are described in FAA Order 8260.40A, Flight Management System (FMS) Instrument Procedures Development. In order to safely reduce DHs for converging approaches, it was proposed that one approach be restricted to properly equipped FMS aircraft and the missed approach area be based on the FMS/LNAV navigation.

Figure 1a shows the missed approach areas per Order 7110.98A. Figures 1b and 1c show the Order 8260.40A version with and without a shift in the missed approach course from Runway 9R.

In order to determine the acceptability of this concept, and develop standards for its application, the Federal Aviation Administration, in collaboration with airlines, aircraft and avionics manufacturers, airline and pilot associations, initiated an investigation of the FMS/LNAV performance and aircraft track dispersion during a missed approach turn prior to runway threshold. This investigation was carried out in two phases: simulator flight trials to address technical/operational issues and provide pilot data for the risk assessment and a Monte Carlo computer simulation to assess the risk that FMS aircraft would maneuver into the converging missed approach airspace. This report provides a discussion of the investigation and a summary of results and conclusions.

2.0 SIMULATOR FLIGHT TRIALS

Proof of concept flight simulator trials were performed in September, 1995 at NASA Ames Research Center, utilizing a Boeing 747-400 flight simulator, and in October at TWA's Flight Training Center, utilizing a Boeing 767 flight simulator. Candidate approaches 'ORD RWY 04R' and 'DFW RWY 13R' were employed in these trials and were flown by pilots from participating airlines and pilot associations. The procedures were based on flying the ILS to a specified DH and executing an FMS/LNAV turning missed approach. The missed approach was initiated by a TOGA (Take Off/Go Around) action followed by an LNAV action. The missed approach was initially straight ahead to accommodate transition to climb and 'clean up', followed by a 65° turn to a segment established by the runway threshold waypoint.

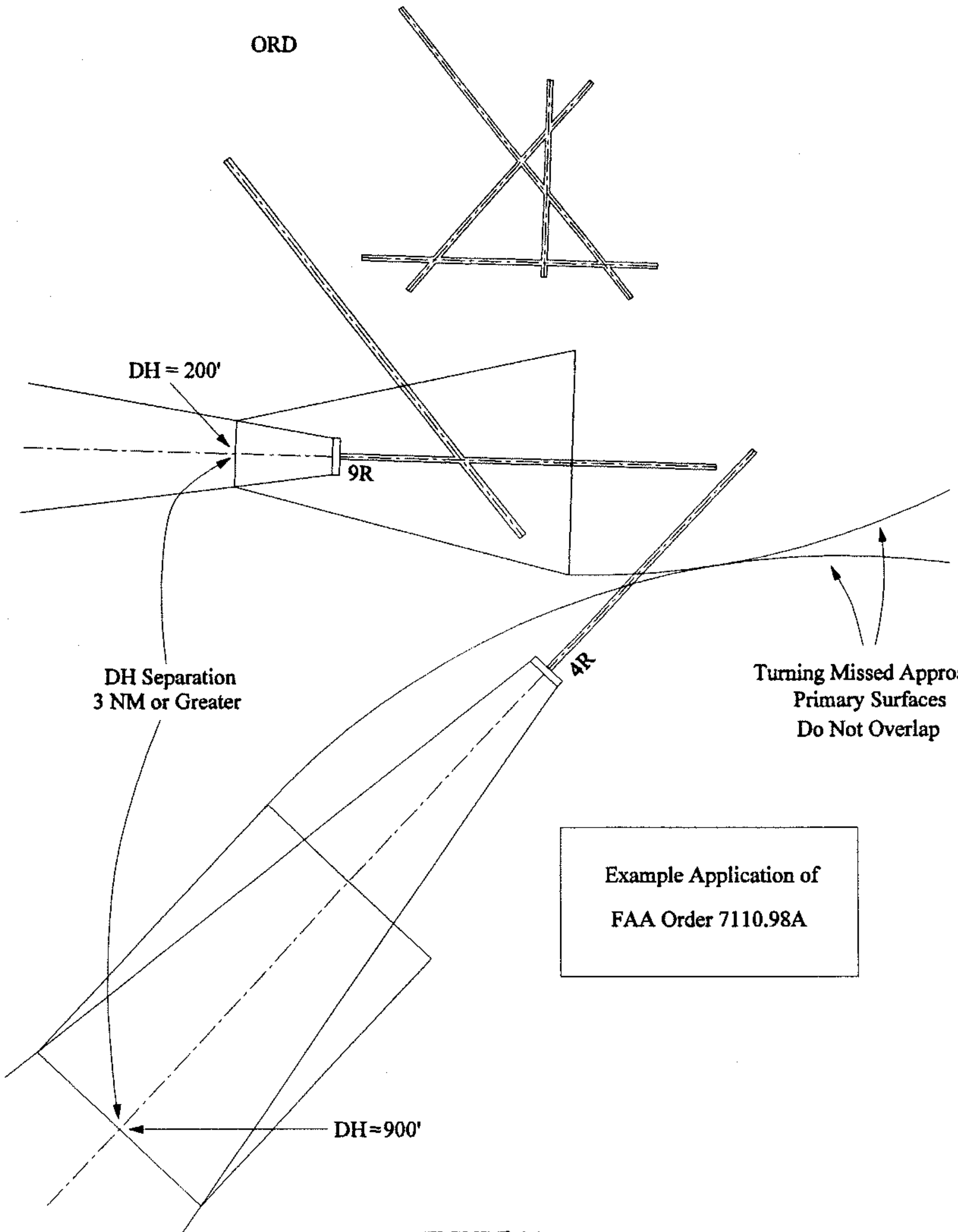
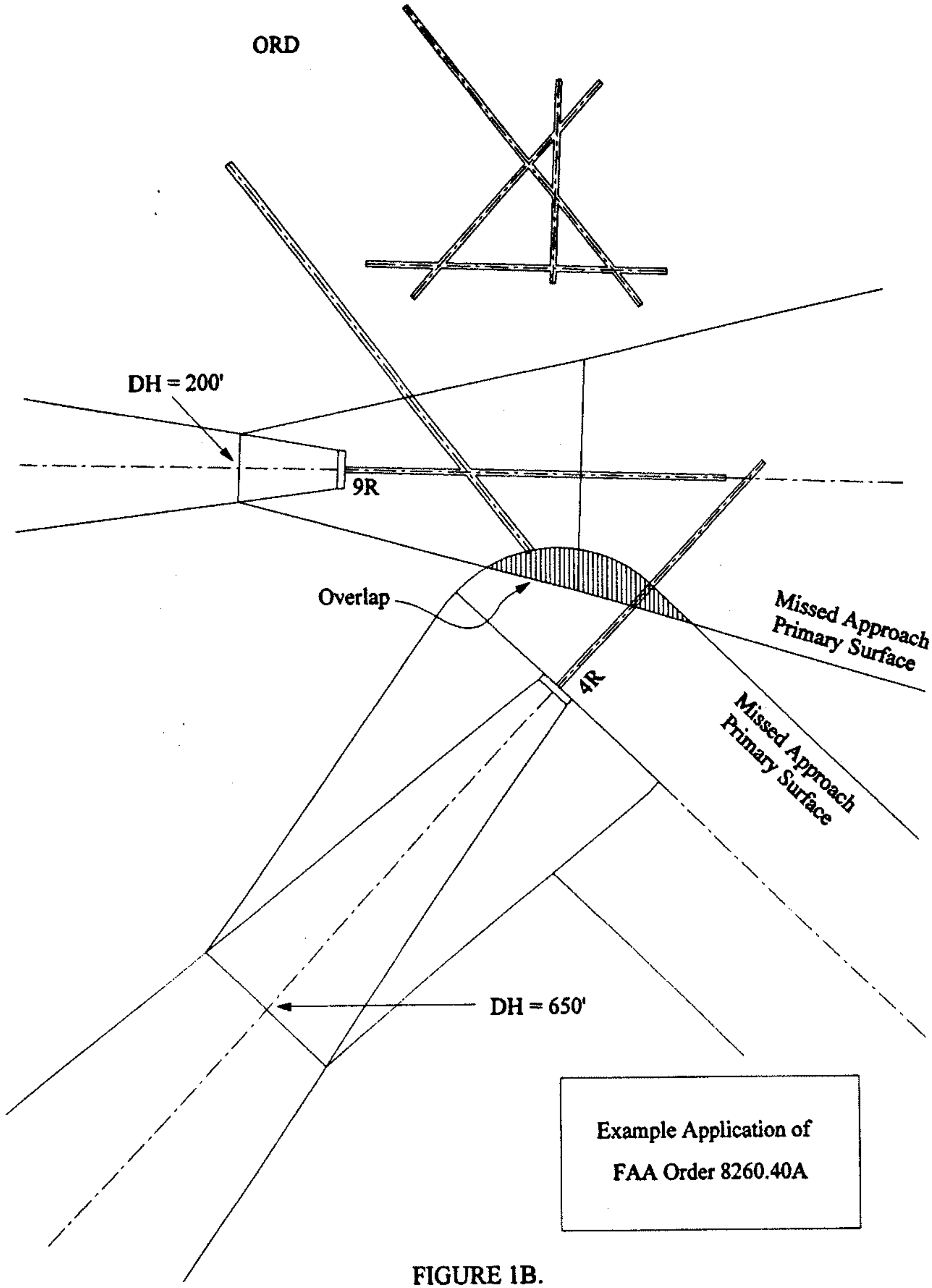

ORD
DH = 200'
9R
4R
DH Separation
3 NM or Greater
Turning Missed Approach
Primary Surfaces
Do Not Overlap
Example Application of
FAA Order 7110.98A
DH=900'

FIGURE 1A.



ORD
DH = 200'
9R
Overlap
Missed Approach Primary Surface
4R
Missed Approach Primary Surface
DH = 650'
Example Application of
FAA Order 8260.40A

FIGURE 1B.

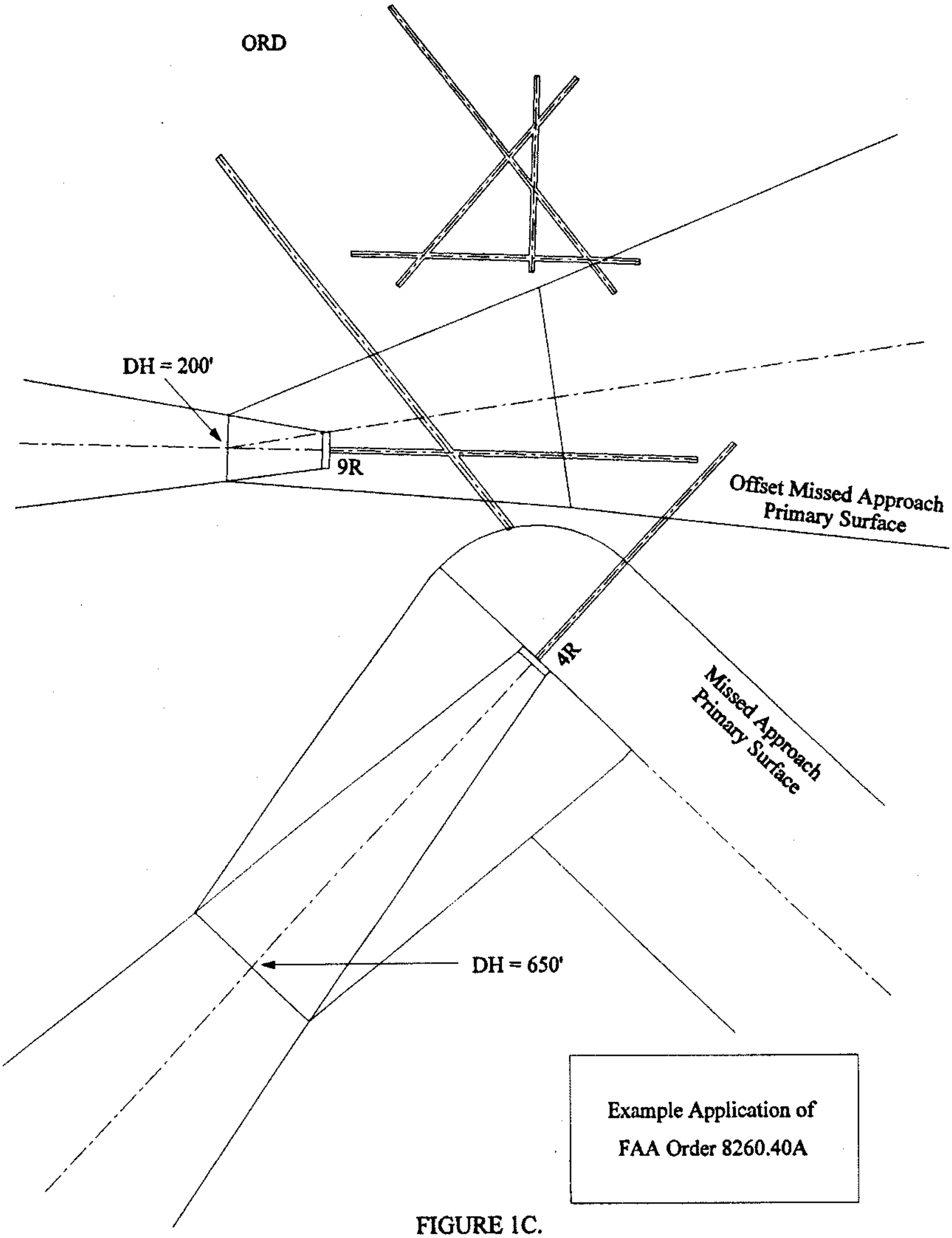

ORD
DH = 200'
9R
Offset Missed Approach
Primary Surface
4R
Missed Approach
Primary Surface
DH = 650'
Example Application of
FAA Order 8260.40A

FIGURE 1C.

Additional evaluations were conducted in January, 1997 at NASA Ames Research Center utilizing a Boeing 747-400 simulator, and in February at United Air Lines Flight Training Center in Denver utilizing a Boeing 737-300 simulator to provide pilot and aircraft data for the risk assessment. The parameters recorded from these simulations are summarized in table 1. The procedures used in the evaluations were coded for the Boeing 747-400 FMS by Honeywell and for the Boeing 737-300 FMS by Smiths Industries and provided to the pilot through the FMS database.

Table 1. Recorded Parameters

Distance from Threshold (X)	Altimeter Setting	Autopilot L (discrete)
Cross Track Deviation (Y)	Simulator Time	Autopilot C (discrete)
Height above Threshold (Z)	Bank Angle	Latitude
Radio Altimeter	Hdg Conv	Longitude
Localizer Deviation	TOGA 1 (discrete)	Flap
Delta LNAV	TOGA 2 (discrete)	Gear
Indicated Airspeed (IAS)	EPR	Ident
Vertical Speed (ROC)	LNAV Switch (discrete)	Event
Altimeter	LNAV Engage (discrete)	

An analytical study conducted by the Standards Development Branch (AFS-450) in early 1996, determined the maximum pilot response times allowed for executing FMS turning missed approaches without overshoot for various DHs and aircraft groundspeeds. This study was based on calculating the time available from DH to the turn tangent point for various combinations of DHs and groundspeeds. The results of this study are given in table 2. Based on actual pilot response times obtained from early simulator testing, compared with times obtained from the analytical study, indicated 650' as the most viable DH. Though this study suggested that measured pilot response times matched a 650' DH, the CASTWG requested additional evaluations at 650', 600', 550', and 500'. Results of flight simulator trials at these lower DHs support the 650' DH conclusion.

Table 2. Maximum Time to Engage LNAV to Prevent Overshoot

Turn Angle	Ground Speed kts	Time from 700' DH to LNAV Engage	Time from 650' DH to LNAV Engage	Time from 600' DH to LNAV Engage	Time from 550' DH to LNAV Engage	Time from 500' DH to LNAV Engage
56°	140	35.7	31.7	27.5	23.6	19.6
	145	33.6	29.7	25.6	21.9	18.0
	150	31.6	27.9	23.9	20.3	16.6
	155	29.8	26.1	22.3	18.8	15.2
	160	28.0	24.4	20.7	17.4	13.8
	165	26.3	22.9	19.3	16.0	12.6
	170	24.7	21.3	17.9	14.7	11.4
	175	23.1	19.9	16.5	13.4	10.2
	180	21.7	18.5	15.2	12.2	9.1
65°	140	34.1	30.0	25.8	22.0	17.9
	145	31.9	28.0	23.9	20.2	16.3
	150	29.8	26.1	22.1	18.5	14.8
	155	27.9	24.3	20.4	17.0	13.3
	160	26.1	22.5	18.8	15.5	11.9
	165	24.3	20.9	17.3	14.0	10.6
	170	22.6	19.3	15.8	12.7	9.3
	175	21.0	17.8	14.4	11.4	8.1
	180	19.5	16.4	13.1	10.1	7.0
90°	140	28.3	24.3	20.1	16.2	12.2
	145	25.9	22.0	18.0	14.2	10.4
	150	23.7	19.9	16.0	12.4	8.6
	155	21.5	17.9	14.1	10.6	7.0
	160	19.5	16.0	12.3	8.9	5.4
	165	17.5	14.1	10.5	7.3	3.8
	170	15.7	12.3	8.9	5.7	2.4
	175	13.9	10.6	7.2	4.2	0.9
	180	12.1	9.0	5.7	2.7	-0.4
95°	140	26.9	22.8	18.6	14.8	10.7
	145	24.4	20.5	16.5	12.8	8.9
	150	22.1	18.4	14.4	10.8	7.1
	155	19.9	16.3	12.5	9.0	5.4
	160	17.8	14.3	10.6	7.2	3.7
	165	15.8	12.4	8.8	5.6	2.1
	170	13.9	10.6	7.1	3.9	0.6
	175	12.1	8.8	5.4	2.4	-0.9
	180	10.3	7.1	3.8	0.9	-2.3

Note: Based on constant groundspeed; i.e., no acceleration after LNAV engagement.

From the 1995 trials, two major conclusions were reached. The risk of overshoot was significantly increased if (1) high times to engage the LNAV mode occurred or (2) the aircraft speed increased after engaging LNAV. In order to increase pilot awareness of these critical requirements, procedural briefing pages were developed and provided to flight crews for the 1997 trials (Appendix I). The program objective, as previously noted, was to determine a decision height that would produce a high probability of turn completion in the required area while providing the desired operational benefit.

Missed approach concepts were further refined for the 1997 flight simulator trials by increasing the turn to 96° (representing O'Hare). The larger turn angle was chosen to increase the likelihood that aircraft would initiate the turn more quickly and improve the probability of remaining in the missed approach area. The FMS missed approach area for O'Hare RWY 04R, is bounded by a line 0.6 NM beyond and parallel to a line constructed from the threshold waypoint at 65° to the 04R centerline (see figure 1b or 1c). For the Dallas/Fort Worth RWY 13R, the line is 56° from the converging approach centerline.

The proof of concept trials also revealed several fundamental system and equipment differences. Data base coding in one case required a mandatory track to a 'fly over' waypoint at the threshold, whereas other systems permitted the required 'fly by' waypoint at the threshold. For one aircraft group, the map did not present the expected missed approach display, introducing a potential for pilot confusion during this critical phase of operation. In a third case, it was necessary for the pilot to manually load the FMS data prior to executing the missed approach.

3.0 DATA DISTRIBUTIONS AND ANALYSIS

The AFS-450 Airspace Simulation and Analysis for TERPS (ASAT) computer simulation system was used for analysis of critical parameters and to assess the risk of flying outside the protected airspace. In order to perform the ASAT simulation all input distributions were first established from the flight simulator data or other sources.

The TOGA and LNAV time data for the simulation were obtained from the 1995 and 1997 B747-400 flight simulator tests that included runs at DHs of 500', 550', 600' and 650'. The TOGA time measures the difference from the time the aircraft passes through the decision height as indicated by the aircraft altimeter until the TOGA function is activated. The LNAV value represents the time from TOGA activation to engagement of the LNAV function. Statistical testing was performed to determine validity of combining time data across the 1995 and 1997 tests. It was found that the times between DHs could be pooled, but the TOGA times from the 1995 testing were statistically smaller than the 1997 tests. However, the earlier tests were proof of concept evaluations and some of the crews were aware that a missed approach would be initiated and took immediate action at the DH. The 1997 evaluations were flown under normal crew discipline in which the decision was made at DH to determine whether to land or go around. The 1997 TOGA times are more representative of the operational environment and were used for the ASAT simulation.

The LNAV activation times were found to be independent of DH across the two tests. The activation of LNAV occurs after initiation of the go around decision and TOGA action, and thus is independent of the DH decision. To increase the statistical confidence, the 1995 and 1997 LNAV times were combined to establish the distribution for the simulation. Descriptive statistics for the TOGA and LNAV times are shown in table 3. Statistical test results of the TOGA and LNAV data are shown in table 4.

Table 3. Summary Statistics for Pilot Response Times

DH to TOGA Times	
Mean	1.23
Standard Error	0.090
Median	1.1
Mode	0.5
Standard Deviation	0.882
Sample Variance	0.777
Kurtosis	0.976
Skewness	1.184
Range	3.8
Minimum	0.2
Maximum	4
Sum	116.7
Count	95
Confidence Level (95.0%)	0.180

TOGA to LNAV Times	
Mean	10.32
Standard Error	0.148
Median	10
Mode	10
Standard Deviation	2.279
Sample Variance	5.194
Kurtosis	1.861
Skewness	0.470
Range	16.2
Minimum	3.6
Maximum	19.8
Sum	2455.3
Count	238
Confidence Level (95.0%)	0.291

Table 4. Statistical Test Results
t-Test Results for Toga to LNAV Times

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	10.23	10.45
Variance	6.161	3.757
Observations	143	95
Hypothesized Mean Difference	0	
df	230	
t Stat	-0.777	
P(T<=t) one-tail	0.219	
t Critical one-tail	1.652	
P(T<=t) two-tail	0.438	
t Critical two-tail	1.970	

t-Test Results for DH to Toga Times

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	0.8937	1.228
Variance	1.716	0.777
Observations	142	95
Hypothesized Mean Difference	0	
df	235	
t Stat	-2.351	
P(T<=t) one-tail	0.00976	
t Critical one-tail	1.651	
P(T<=t) two-tail	0.0195	
t Critical two-tail	1.970	

All pilot response time data collected in 1997 were examined by statistical tests of means and standard deviations to determine if the data could be pooled for increased confidence. The TOGA time was separated further into data collected during autopilot test runs and flight director test runs. The data were separated further by four values of DH. This resulted in sixteen sets of data: autopilot, DH to TOGA, four values of DH; flight director, DH to TOGA, four values of DH; autopilot, TOGA to LNAV, four values of DH; flight director, TOGA to LNAV, four values of DH.

The four flight director, DH to TOGA, data sets were tested to determine if the sets could be pooled into one data set. The tests indicated strong similarities in both means and standard deviations. The four sets were pooled into one set. In addition, the four autopilot, DH to TOGA, data sets were tested to determine if those sets could also be pooled into one data set. The tests indicated strong similarities in both means and standard deviations and the data sets were pooled. Finally, the resulting two data sets, autopilot and flight director, DH to TOGA, were tested to determine if those two sets could be pooled into one data set. Again, strong similarities in both means and standard deviations were indicated. Therefore, it was determined that all the DH to TOGA data could be pooled into one set.

In a similar fashion, the four flight director, TOGA to LNAV, data sets were tested to determine if the sets could be pooled into one data set. The tests indicated strong similarities in both means and standard deviations. The four sets were pooled into one set. In addition, the four autopilot, TOGA to LNAV, data sets were tested to determine if those sets could also be pooled into one data set. The tests indicated strong similarities in both means and standard deviations and the data sets were pooled. Finally, the resulting two data sets, autopilot and flight director, TOGA to LNAV, were tested to determine if those two sets could be pooled into one data set. Again, strong similarities in both means and standard deviations were indicated. Therefore, it was determined that all the data, TOGA to LNAV, could be pooled into one set.

Johnson distributions were fit to TOGA and LNAV pilot response times. The Johnson parameters and function types are included in table 5. Based on analysis of the data, the LNAV S-U distribution was truncated at 3.6 seconds on the low end and 20 seconds on the high end. The TOGA times were bounded by the Johnson S-B function based on the mathematical fitting routine.

Table 5. ASAT Simulation Distribution Data

Parameter	Data Source	Distribution Type
Init. Range from Thresh	As required	Uniform
Init. Lateral Position	ICAO CRM	CRM tables interpolated
Init. Vertical Position	ICAO CRM	CRM tables interpolated
Initial IAS	Test data	Gaussian (truncated)
TOGA Time	Test data	Johnson S-U (truncated)
LNAV Time	Test data	Johnson S-B
Acceleration	Test data	Gaussian (truncated)
ROC	Test data	Gaussian (truncated)
Turn point	DME Screening Model	Gaussian
Achieved Bank Angle	Test data	Gaussian (truncated)
Roll Rate	Test data	Gaussian (truncated)

Pilot Response Time Distribution Functions - Johnson Parameters					
	Type	Gamma	Delta	Lambda	Xi
TOGA (sec)	S-B	-0.0987	4.6640	0.8131	1.2987
LNAV (sec)	S-U	9.8202	2.8502	1.5442	-0.1847

Initial Position and DH Variations				
	Mean	St.Dev.	Min.	Max.
Distance (nm)	3.50	n/a	3.40	3.60
X-Track Error (ft)	Note 1			
Vertical Error (ft)	Note 1			
DH Error (ft)	0.00	25.00	-75.00	75.00

NOTE 1: Initial lateral and vertical deviations from the glideslope were extracted from the ICAO Collision Risk Model tables.

Flight Maneuver Parameter Distributions - Autopilot				
	Mean	St.Dev.	Min.	Max.
Bank (degrees)	25.80	0.70	24.00	28.50
Roll Rate (deg/sec)	3.01	0.50	1.50	3.75
ROC (fps)	2473.40	296.30	1900.00	3200.00
IAS (kts)	166.10	0.50	164.00	166.10
Accel. (kts/sec)	0.18	0.10	0.00	1.00

Flight Maneuver Parameter Distributions - Flight Director				
	Mean	St.Dev.	Min.	Max.
Bank (degrees)	25.60	2.50	16.00	32.00
Roll Rate (deg/sec)	1.95	0.54	1.20	4.50
ROC (fps)	2588.48	422.24	1500.00	3200.00
IAS (kts)	165.73	1.70	160.00	172.00
Accel. (kts/sec)	0.23	0.14	0.00	1.00

The previously described flight simulator tests were flown by either flight director guidance to the pilot or by the autopilot. The data indicated that variations in aircraft maneuver parameters were statistically less when executed by the autopilot. Therefore, with the exception of TOGA and LNAV times, all ASAT simulations were performed using either flight director or autopilot parametric distributions.

Achieved bank angle and roll rate distributions were based solely on the 1997 B747-400 simulator tests which made the 96° turn. Descriptive statistics for the bank angle and roll rate data for both autopilot and flight director are given in Table 6. Truncated normal distributions were used to model the roll rates and achieved bank angles in the simulation. Parameters for the distributions are given in Table 5.

Table 6. Statistics for Bank Angle (Deg) and Roll Rate (Deg/Sec) Data

Average Roll Rates - Autopilot	
Mean	3.01
Standard Error	0.09
Median	3.00
Mode	2.75
Standard Deviation	0.39
Sample Variance	0.15
Kurtosis	-1.11
Skewness	0.26
Range	1.25
Minimum	2.50
Maximum	3.75
Sum	63.25
Count	21.00
Confidence Level (95.0%)	0.18

Average Roll Rates - Flight Director	
Mean	1.95
Standard Error	0.13
Median	1.75
Mode	1.67
Standard Deviation	0.54
Sample Variance	0.29
Kurtosis	0.59
Skewness	1.05
Range	2.00
Minimum	1.17
Maximum	3.17
Sum	35.17
Count	18.00
Confidence Level (95.0%)	0.27

Achieved Bank Angles - Autopilot	
Mean	25.79
Standard Error	0.05
Median	26.00
Mode	26.00
Standard Deviation	0.68
Sample Variance	0.47
Kurtosis	0.18
Skewness	-0.30
Range	3.00
Minimum	24.00
Maximum	27.00
Sum	5855.00
Count	227.00
Confidence Level (95.0%)	0.09

Achieved Bank Angles - Flight Director	
Mean	25.60
Standard Error	0.20
Median	25.00
Mode	25.00
Standard Deviation	2.34
Sample Variance	5.46
Kurtosis	-0.40
Skewness	0.46
Range	10.00
Minimum	21.00
Maximum	31.00
Sum	3417.00
Count	133.00
Confidence Level (95.0%)	0.40

The turn initiation tangent point is calculated by the Flight Management Computer (FMC) based on the aircraft's ground speed and amount of turn. The Honeywell and Smiths FMC turn algorithms were available from previous studies. The Honeywell logic was used for the simulation since that system is installed on most B747s. This should produce a somewhat more conservative result since the Smiths system, widely used on 737s, assumes a faster roll rate and a lower airspeed, thus producing a shorter roll anticipation distance and a smaller turn radius.

One of the primary requirements for executing this maneuver successfully is careful attention to speed control. Normally, following TOGA activation, the aircraft tends to accelerate. However, as noted previously, if this acceleration continues after LNAV activation, significant overshoots will occur. If the speed is not increased, then the FMC can more accurately predict the required turning radius. It was agreed by the CASTWG that operational limitations must be placed on this procedure to assure the pilot would minimize acceleration after execution of go around.

For the ASAT simulation, indicated airspeeds (IAS) and accelerations in both lateral and vertical were matched to data generated from the 1997 NASA simulator tests. IAS and rates of climb were examined every 10 seconds following TOGA activation to give horizontal and vertical accelerations over the period of the maneuver. The 10 second sampling interval was based on an analysis of data. The resultant data is listed in Tables 7 and 8. The velocity was modeled as a normal distribution with a linearly increasing mean. Rate of climb was treated as a normal distribution following a period of vertical acceleration.

Table 7. Indicated Airspeeds (Knots At 10 Second Intervals)

	TOGA	TOGA+10	TOGA+20	TOGA+30	TOGA+40	TOGA+50
	Autopilot					
Mean IAS	166.13	169.30	171.26	173.48	173.91	175.13
Std. Dev.	0.46	3.73	4.01	3.12	2.89	3.91
	Flight Director					
Mean IAS	165.73	167.77	169.18	171.77	172.77	177.09
Std. Dev.	1.70	4.45	2.72	3.45	6.34	5.42

Table 8. Rates Of Climb (Fps At 10 Second Intervals)

	TOGA	TOGA+10	TOGA+20	TOGA+30	TOGA+40	TOGA+50
	Autopilot					
Mean ROC	-934.43	2350.52	2381.48	2559.43	2603.35	2471.91
Std. Dev.	28.67	143.88	342.97	342.97	303.26	348.43
	Flight Director					
Mean ROC	-910.27	2658.68	2541.19	2585.23	2568.81	2223.10
Std. Dev.	118.35	349.39	539.03	408.46	392.07	651.78

Since the implementation concept was based on DME/DME FMS/LNAV navigation, an along track error associated with the DME/DME solution was included in the ASAT simulation. Many FMS systems update their position when joining the localizer but there are considerable variations when further corrections are made. As a conservative scenario, the ASAT simulation assumes no localizer update and uses only the DME/DME, INS smoothed, Kalman filter generated position solution at LNAV activation.

An FMS/LNAV DME/DME error screening model, developed by AFS-450, determined a 2 standard deviation 0.15 NM along track error for the ORD RWY 04R threshold waypoint and a 0.14 NM DME/DME fix error for the Dallas/Fort Worth RWY 13R. The FMS Screening Model uses basic navigation sensor error models and the DME environment to generate an upper bound for values that would be produced by certified systems.

4.0 ASAT SIMULATION PROCESS

The ASAT program modeled the operation in the following way: a Boeing B747-400 model was flown on an ILS precision approach to a 650' DH window based on the ICAO ILS model; a missed approach was executed based on a barometric altimeter error distribution; the pilot activated TOGA based on the measured pilot response time distributions; the aircraft maneuvering characteristics were based on the Boeing model; and the LNAV was engaged based on the pilot response time distributions.

The FMC calculated a turn arc tangent point using the turning algorithm and the DME/DME error model; and upon reaching the turn tangent point, the aircraft model flew around the turn to intercept the outbound course; roll rates, bank angles and accelerations were based on the data matched distributions. In the ASAT simulation, if the aircraft was off the desired track the bank angle would decrease or increase, to bank angle limits, in an attempt to achieve the desired track. If the pilot activation of the LNAV function occurred after the turn tangent point, the aircraft rolled into the turn almost immediately, but risk of overshoot was increased. The Honeywell FMC turn algorithm was used since it was the system installed in the B747-400 used in the flight simulator trials. As previously noted, the Smiths system installed in the UAL B737 and other FMSs generally calculate a smaller turn radius for equivalent speeds.

For analysis purposes, the ASAT produced a graphical display that indicated where the DH occurred, TOGA was activated, LNAV was activated and the turn initiated. The maneuver ended when the aircraft achieved a 96° course change. An output file was generated that contained all relevant parameters. For a more detailed description of the ASAT inputs and outputs (see Appendix II).

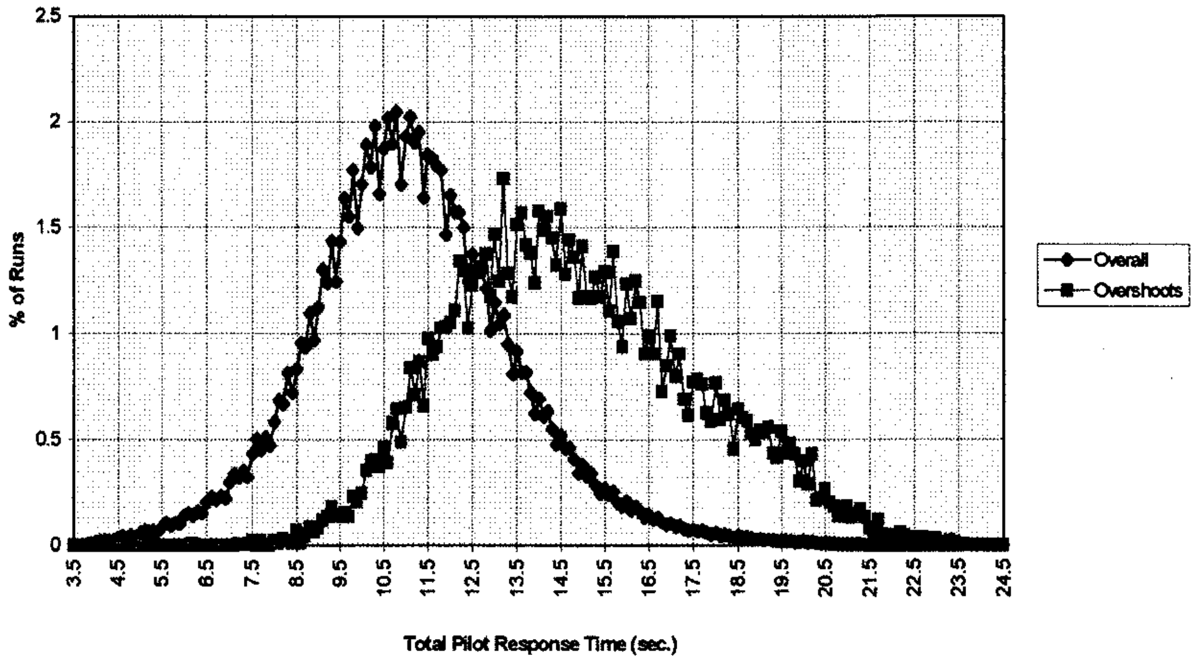
The ASAT was used to generate a large number of three dimensional flight tracks using a Monte Carlo process. The Monte Carlo process randomly selects parameter inputs for the computer simulation from statistical distributions fit to the selected parameters. Input probability density functions (pdf) are summarized in table 5, and include uniform, normal and Johnson. The Johnson functions are transformations of Gaussian distributions and are particularly effective for fitting continuous curves to data.

Approximately 2 million flight tracks were generated to determine the effects of various parameters on overshoot and to establish statistical distributions for calculating risk of overshoot. The parameter sensitivity analysis included TOGA and LNAV pilot response times, winds, bank angles, roll rates, and flight director versus autopilot.

5.0 FLIGHT PARAMETER ANALYSIS

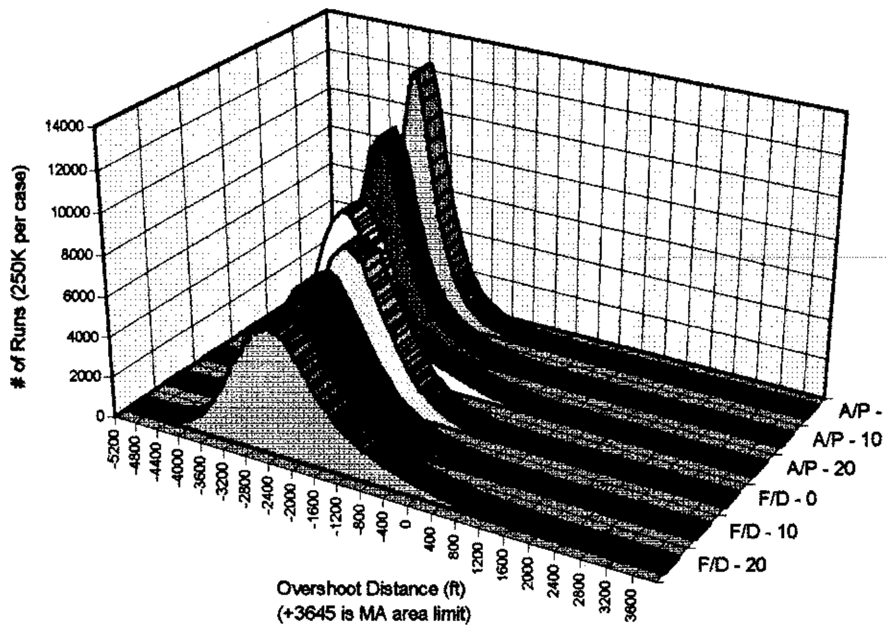
Figure 2 shows the pilot combined TOGA/LNAV response times for all runs versus runs where overshoot of the 65° line occurred. The 65° line was used as the base reference line for analysis. As can be noted from the figure, frequency of overshoots are significantly increased by the higher pilot response times.

Figure 2. Total Pilot Response Time (TOGA + LNAV)
Overall vs. Overshoots



Histograms of the overshoot/undershoot of the 65° boundary line for three wind conditions are shown in figure 3. As can be seen from the histograms, increasing wind increases track dispersion and the mean, increasing the probability of exiting protected airspace. Figure 3 also shows the autopilot dispersion to be less than the flight director runs.

Figure 3. Overshoot Distance vs Flight Mode and Wind Conditions



Figures 4 and 5 show the comparative distributions of achieved bank angles for runs that overshot the 65° line versus the overall population for autopilot and flight director, respectively. For the autopilot flown case, the figure shows no significant difference in the distributions. For the hand flown flight director case, with a much larger variation in achieved bank angle, the mean is 1° less for those that overshot the 65° line than the overall population. This suggests that comparatively low bank angles do significantly contribute to the probability of exiting protected airspace.

Figure 4. Auto-Pilot Achieved Bank Angles
Overall vs. Overshoots

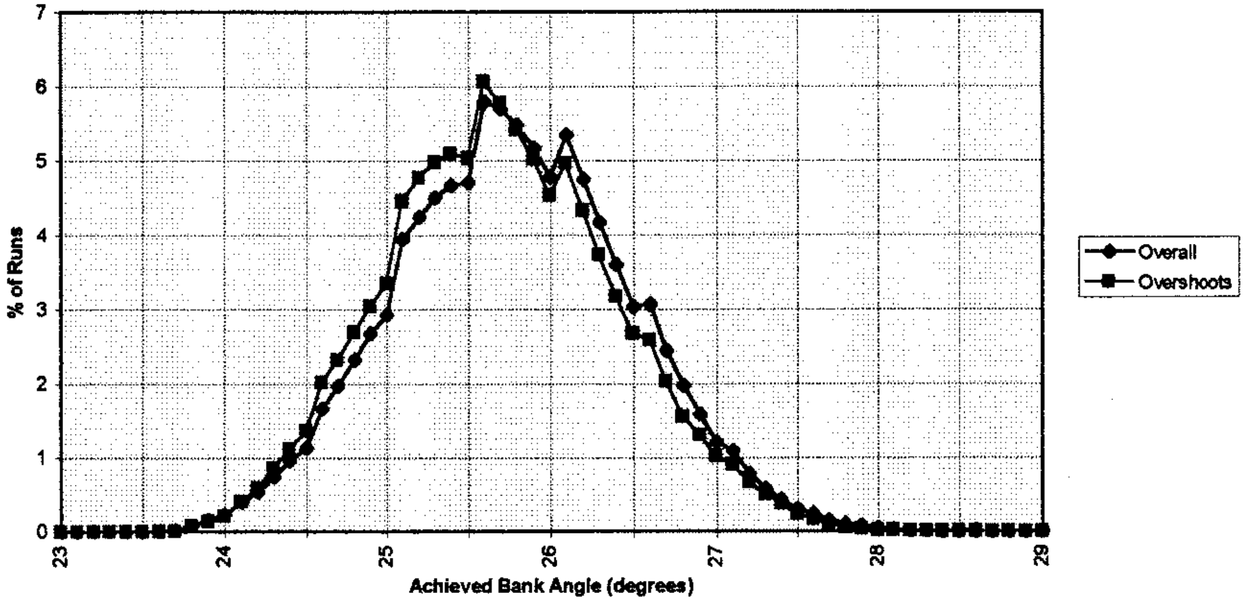
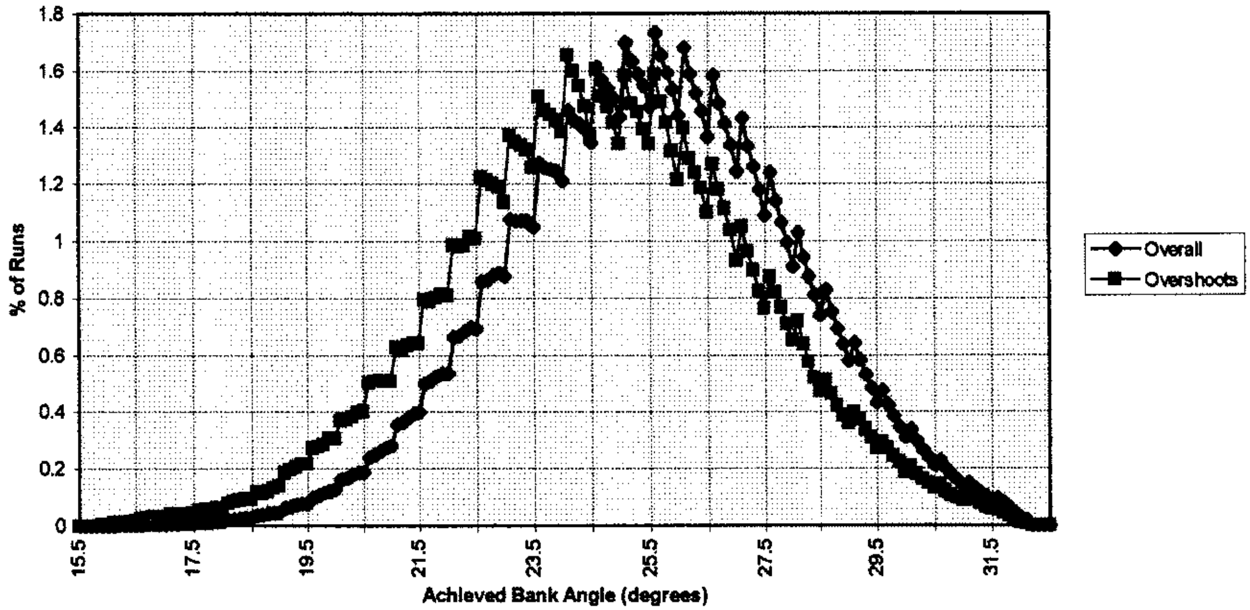


Figure 5. Flight Director Achieved Bank Angles
Overall vs. Overshoots



Figures 6 and 7 show the same comparisons for average roll rates. Though not statistically tested, both autopilot and flight director histograms indicate that low roll rates also significantly increase the probability of exiting the protected airspace.

Figure 6. Auto-Pilot Roll Rates
Overall vs. Overshoots

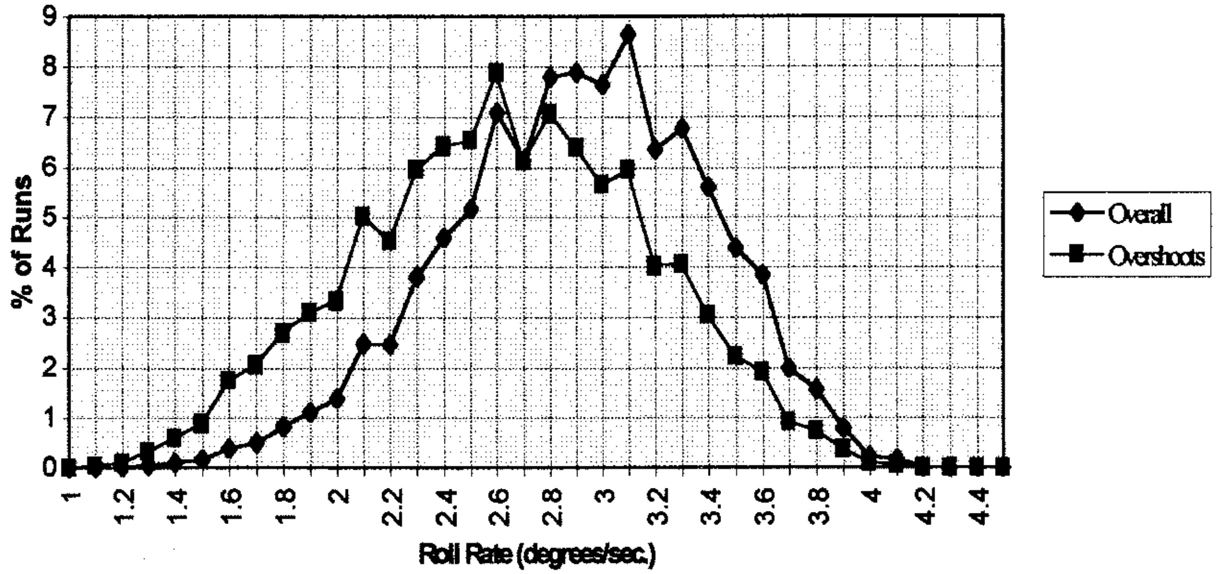
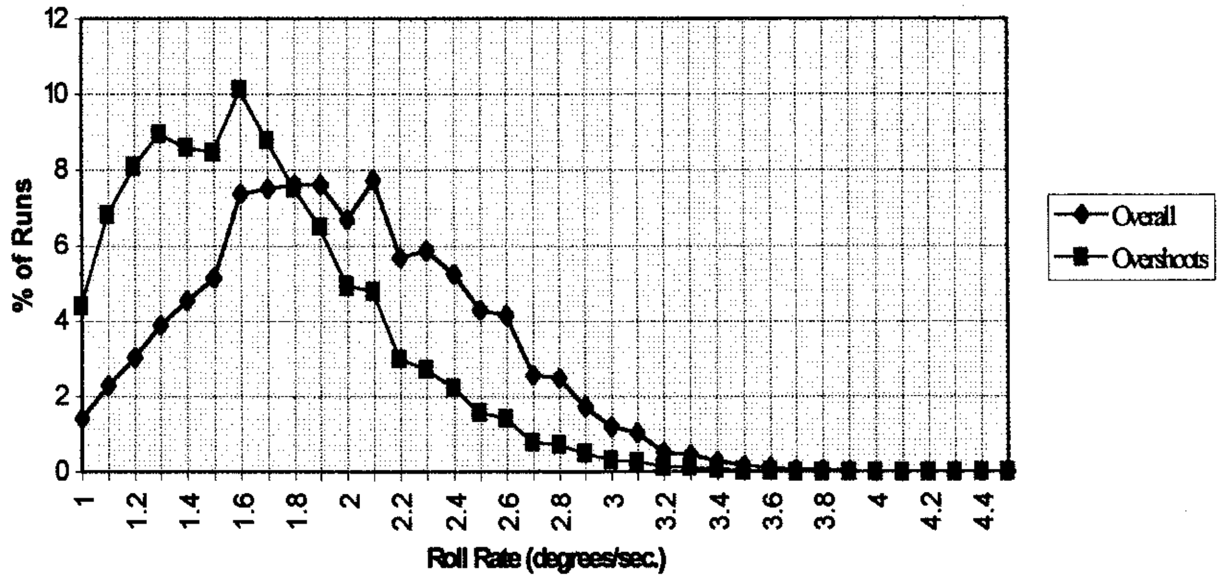


Figure 7. Flight Director Roll Rates
Overall vs. Overshoots



6.0 RISK ANALYSIS

As described previously, the ASAT simulation generated a large number of three dimensional flight tracks for various flight conditions, including autopilot and flight director missed approaches with winds of 0 knot, 10 knot, 20 knot, and 30 knot. The maximum (plus or minus) distance from each flight track to the sixty five degree line was recorded for analysis. This resulted in eight sets of missed approach data, each containing a minimum of 250,000 data points. A Johnson pdf was fitted to each data set. Refer to Table 9 for distribution type and parameter values. The objective was to estimate the probability that an aircraft will cross the 0.6 nm line which bounds the protected airspace. Using the fitted pdfs, the probability of crossing the 0.6 nm boundary of the FMS missed approach primary surface was determined for each data set. The probabilities are presented in Table 10.

Table 9. Probability Density Functions from ASAT Simulation

Nav. Mode	Wind Spd.	Johnson type	gamma	delta	lambda	xi
Autopilot	0	S-U	-3.0300E+00	3.3176E+00	1.1988E+03	-4.2971E+03
Autopilot	10	S-U	-3.4798E+00	3.1947E+00	1.1794E+03	-4.5807E+03
Autopilot	20	S-B	5.0339E+00	2.8886E+00	1.9258E+04	-5.7343E+03
Autopilot	30	S-B	3.4315E+00	2.4134E+00	1.6600E+04	-5.8860E+03
Flight Dir.	0	S-U	-3.5316E+00	4.7743E+00	2.6192E+03	-4.4950E+03
Flight Dir.	10	S-U	-3.7553E+00	4.2976E+00	2.4075E+03	-4.7306E+03
Flight Dir.	20	S-B	7.8704E+00	3.7767E+00	3.8217E+04	-6.4559E+03
Flight Dir.	30	S-B	3.5750E+00	2.7775E+00	2.0317E+04	-6.3746E+03

Table 10. Probability Of Crossing the Outer Boundary of the FMS Missed Approach Primary Surface Based on 650' DH

	0 kt Wind	10 kt Wind	20 kt Wind	30 kt Wind
Flight Director	5.46×10^{-8}	1.52×10^{-6}	3.11×10^{-5}	2.33×10^{-4}
Autopilot	1.33×10^{-8}	3.60×10^{-7}	5.19×10^{-7}	1.64×10^{-5}

In summary, the probability of crossing the 0.6 nm boundary of the FMS missed approach primary surface, ranged from a high of 2.33 occurrences per 10,000 missed approaches (flight director with 30 knot winds) to a low of 1.33 occurrences per 100,000,000 missed approaches (autopilot with a 0 knot wind). It should be emphasized that these are probabilities for excursions into missed approach airspace of converging traffic and not the probability of a collision with a converging aircraft.

It can be seen that for each 10 knot increase of wind, the risk of crossing the missed approach boundary line increases by almost one order of magnitude, e.g., for autopilot : 5.46 occurrences per 100,000,000 missed approaches (0 knots), 1.52 occurrences per 1,000,000 missed approaches (10 knots), 3.11 occurrences per 100,000 missed approaches(20 knots), 2.33 occurrences per 10,000 missed approaches (30 knots). In a similar manner, use of an autopilot versus a flight director decreases, by almost one order of magnitude, the risk of crossing the boundary line.

7.0 SUMMARY AND CONCLUSIONS

Given the following conditions:

(1) surface tailwind of 10 knots or less,

(2) runway convergence of 50° or less,

(3) airport elevation of 1000' MSL or less,

(4) no pilot blunder or system failure,

(5) pilot sufficiently informed to assure response times similar to the test,

(6) minimal acceleration, not more than 15 knot increase,

(7) FMS aircraft that qualify to file /E and other approved /F,

(8) missed approach at 650' DH or above,

(9) at least a 90° turn initiated prior to the runway threshold,

this analysis indicates that the FMS/LNAV system will provide an acceptable risk in maintaining an aircraft within the turning missed approach area specified in Order 8260.40A.

This conclusion was based on applying the ICAO Pans Ops risk assessment concept. For an ILS, obstacle collision risk in the missed approach cannot exceed 1×10^{-5}, or 1 occurrence per 100,000 missed approaches. This is based on the concept of a 1×10^{-2} probability of a missed approach times 1×10^{-5}, the obstacle collision risk, to obtain the Pans Ops accepted risk of 1×10^{-7}. For 10 knot winds, the risk of exiting the missed approach area is 1.52×10^{-6} for flight director and 3.60×10^{-7} for autopilot. When multiplied by a 1×10^{-2} probability of a missed approach, both risks are less than the accepted obstacle collision risk of 1×10^{-7}. In addition, these products are not collision risk values but the probability that an aircraft will execute a missed approach <u>and</u> exit the missed approach areas.

It is critical that a decision to implement ILS converging approaches with FMS/LNAV turning missed approaches for DHs as low as 650' be done with appropriate operational guidance to achieve the levels of safety suggested by this evaluation. This result is based on the following operational requirements:

(1) The operation be limited to reported surface winds no greater than 10 knots tailwind to the runway using the FMS/LNAV missed approach procedure. This should be an acceptable value, since air carriers are limited to no more than 10 knot tailwind for landing.

(2) The operation be limited to runways that converge at angles no greater than 50°.

(3) The operation be limited to airports of 1000' MSL elevation or less.

(4) The pilot be provided sufficient information to assure that response times are timely, and the aircraft acceleration is minimized during the maneuver.

(5) The operation be limited to /E aircraft and AFS approved /F aircraft.

Several operational issues will need to be addressed before implementation, including:

(1) determining procedures for air traffic control to sort properly equipped FMS aircraft (/E and AFS approved /F) to the secondary converging runway,

(2) determining the level of pilot information/education/training that may be required to assure actions are taken necessary to maintain the aircraft inside the missed approach area,

(3) redesigning the companion converging runway missed approach to accommodate the converging ILS/FMS missed approach,

(4) redesigning the missed approach procedure for the non converging ILS procedure to the same runway to be the same as the converging procedure with 650' DH,

(5) consideration of risk due to system failures, and

(6) establishing any special charting requirements.

Several directives and other guidance materials will need revision, including:

(1) FAA Order 8260.40A,

(2) FAA Order 7110.98A,

(3) issuance of a Flight Standards Information Bulletin (FSIB),

(4) charting standards,

(5) Aeronautical Information Manual (AIM), and Aeronautical Information Publications (AIP).

Appendix I

PROTOTYPE CHART.
SUPPLIED TO FAA FOR EVALUATION PURPOSES ONLY.

CHICAGO-O'HARE INTL
KORD
CONVERGING ILS Rwy 4R-FOXTROT

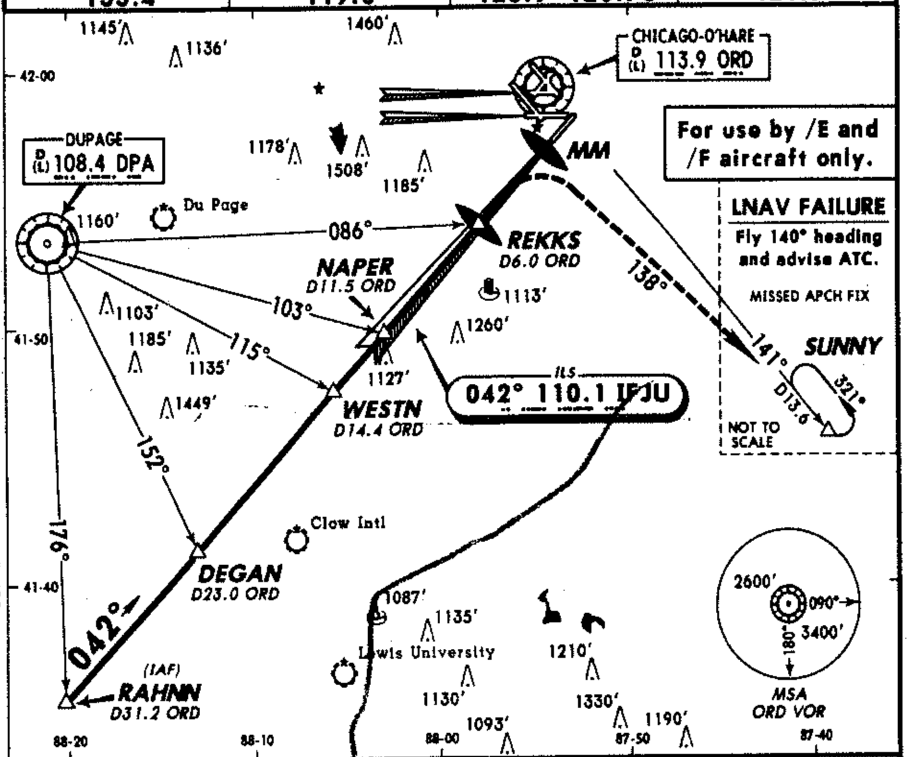
LOC IFJU	Final Apch Crs	GS REKKS	(FULL) ILS DA(H)	Apt Elev 667'
110.1	042°	2128'(1467')	1311'(650')	TDZE 661'

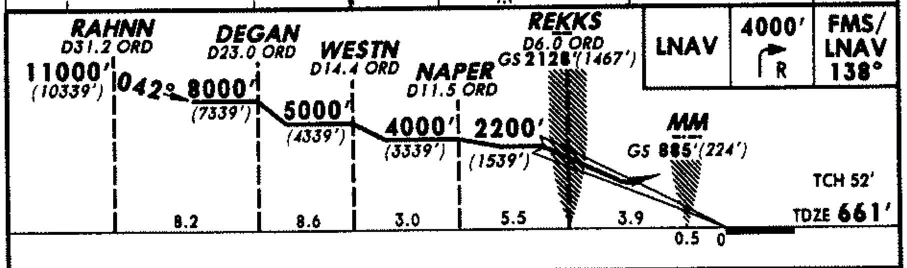
1. Review page FAA-2.
2. RADAR required.
3. Authorized with Rwy 9R/9L.

MALSR

FMS MISSED APPROACH: Climbing **RIGHT** turn to **4000'** via **FMS/LNAV 138°** track to **SUNNY INT** and hold.

ATIS	CHICAGO Approach (R)	O'HARE Tower North	O'HARE Tower South	Ground
135.4	119.0	126.9	120.75	121.9





STRAIGHT-IN LANDING RWY 4R
ILS
DA(H) **1311'**(650')

	FULL	RAIL or ALS out
A	2	2¼
B		
C		
D		

Gnd speed-Kts	70	90	100	120	140	160
GS 3.00°	377	484	538	646	753	861

CHANGES: Prototype chart, for evaluation purposes only.

Converging ILS Runway 4R - Foxtrot Approach

LNAV/NAV is **mandatory** for the Converging ILS RWY 4R - Foxtrot Appraoch

LNAV/NAV MISSED APPROACH PROCEDURES

1) LNAV/NAV mode must be selected and verified as soon as possible after selecting TOGA (Go-around mode).

2) Remain in TOGA.

3) DO NOT increase speed.

4) DO NOT engage VNAV or FLCH or change speed mode until completion of the turn to SUNNY Int.

CHANGES: Prototype chart, for evaluation purposes only.

JEPPESEN (FAA) (FAA-3) PROTOTYPE 24 MAY 96

DALLAS-FT. WORTH, TEXAS
DALLAS-FT WORTH INTL
CONVERGING
KDFW ILS Rwy 13R - FOXTROT

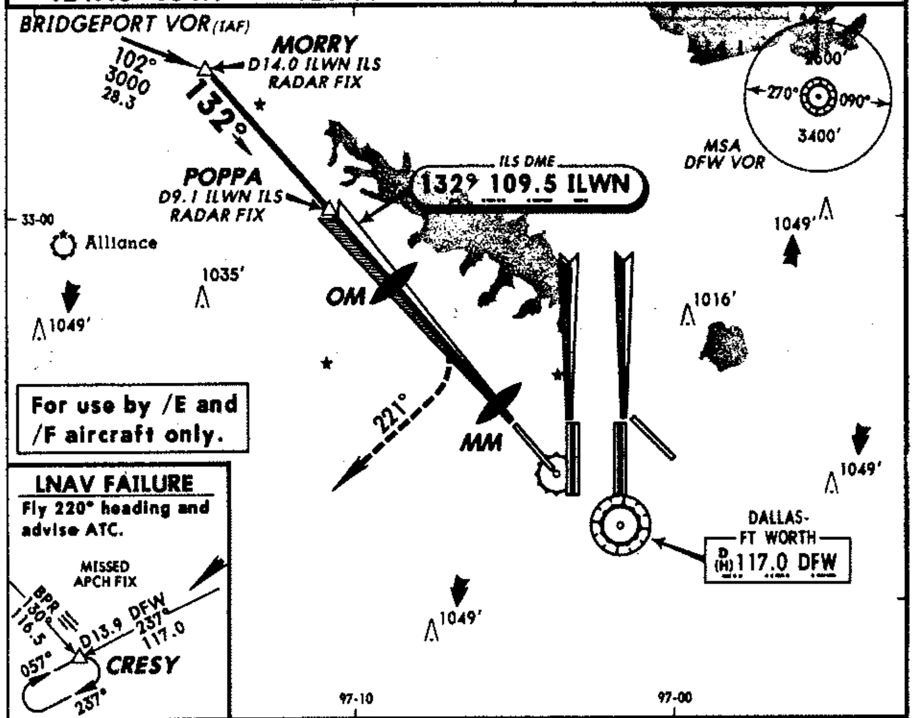
LOC ILWN	Final Apch Crs	GS OM	(FULL) ILS DA(H)
109.5	132°	2235' (1644')	1241' (650')

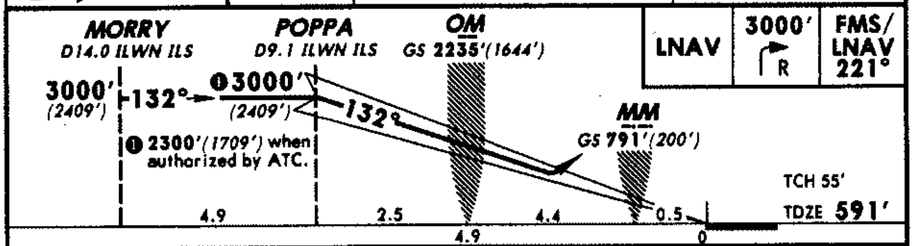
Apt Elev 603' TDZE 591'	1. Review page FAA-4. 2. RADAR required. 3. Authorized with ILS Rwy 18R, ILS Rwy 18L, ILS Rwy 17R and ILS Rwy 17L.	MALSR	FMS MISSED APPROACH: Climbing RIGHT turn to 3000' via FMS/LNAV 221° track to CRESY INT and hold.

ATIS Arrival	REGIONAL Approach (R) West	REGIONAL Approach (R) East
123.77	125.8	119.05

DFW Tower West		DFW Tower East		Ground West	Ground East	
124.15	134.9	126.55	127.5	121.85	121.65	121.8

PROTOTYPE CHART.
SUPPLIED TO FAA FOR EVALUATION PURPOSES ONLY.





STRAIGHT-IN LANDING RWY 13R

ILS

DA(H) 1241' (650')

	FULL	RAIL out
A		
B	2	2¼
C		
D		

Gnd speed-Kts	70	90	100	120	140	160
GS 3.00°	377	485	539	647	754	862

CHANGES: Prototype chart, for evaluation purposes only.

SUPPLIED TO FAA FOR EVALUATION PURPOSES ONLY. PROTOTYPE CHART

Converging ILS Runway 13R - Foxtrot Approach

LNAV/NAV is **mandatory** for the Converging ILS RWY 13R - Foxtrot Appraoch

LNAV/NAV MISSED APPROACH PROCEDURES

1) LNAV/NAV mode <u>must be selected and verified</u> as soon as possible after selecting TOGA (Go-around mode).

2) Remain in TOGA.

3) <u>DO NOT</u> increase speed.

4) <u>DO NOT</u> engage VNAV or FLCH or change speed mode until completion of the turn to CRESY Int.

CHANGES: Prototype chart, for evaluation purposes only.

Appendix II

Appendix II

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==========================================================================

                AFS-450 Multisim Flight Simulation System.
                ==========================================

Date (Year-Month-Day): 1997 14 5

Time (Hour-Min-Sec)  : 5 6 3

Airport : CHICAGO O'HARE INTL..

Case    : FMS MISSED APPROACH RUNWAY 04R.

RWY ELEV: 661[Ft].

DH      : 1311[Ft] (650[Ft] Above Threshold Elevation).

Legend : BANK = FMS commanded roll angle.

         TOGA = Delay from DH to TOGA ON.
         LNAV = Delay from TOGA ON to LNAV ON.

         OSFMS  : if < 0.00 ==> proximity to the FMS leg line.
                  if > 0.00 ==> overshoot of the FMS leg line.

         OSBOUND: if < 0.00 ==> proximity to the BOUNDARY line.
                  if > 0.00 ==> overshoot of the BOUNDARY line.
```

AC Type [-]	IASIC [Kts]	RANGEIC [Ft]	CRMLAT [Ft]	CRMALT [Ft]	DH [Ft]	BANK [Deg]	D1BANK [D/Sec]	TOGA [Sec]	IAST [Kts]	LNAV [Sec]	IASL [Kts]	OSFMS [Ft]	OSBOUND [Ft]	LTFMS [Ft]	NOSF [-]	NOSB [-]
B747	167.2	21242	-37	15	1294	25.6	2.4	0.1	167.2	12.3	171.4	706	-1626	-2541	1	0
B747	164.1	21145	-213	-88	1310	26.6	2.7	0.3	164.1	9.8	165.3	377	-1619	-2778	2	0
B747	167.1	20914	173	-71	1268	26.1	2.5	0.9	167.2	13.7	170.2	2764	336	-5084	3	1
B747	163.8	21376	65	-26	1313	25.9	1.6	0.5	163.9	11.6	166.3	985	-1234	-2218	4	1
B747	165.6	20963	-63	26	1285	26.4	1.6	0.9	165.8	9.6	167.9	431	-1681	-1583	5	1
B747	165.1	20877	-11	-4	1301	27.9	1.5	0.2	165.1	9.3	166.9	56	-1945	-1562	6	1
B747	165.8	21582	191	79	1316	24.7	1.4	1.3	166.3	8.2	168.7	-368	-3019	483	6	1
B747	168.2	21291	-67	-27	1329	29.5	2.0	2.7	168.8	11.2	171.3	1074	-956	-3603	7	1
B747	165.3	21680	-74	-31	1308	26.6	2.1	2.2	166.0	9.6	169.2	1018	-1211	-2742	8	1
B747	164.3	21254	138	57	1320	19.7	1.3	0.5	164.4	6.4	165.9	1622	-1320	-385	9	1

Sample Output File from Simulation Routine