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Safety Study Report on Triple Simultaneous Parallel Instrument Landing System (ILS) and Area Navigation/Required Navigation Performance (RNAV/RNP) Approaches at George Bush Intercontinental Airport (KIAH)

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Technical Report

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12. Abstract

FAA Order 7110.65P Air Traffic Control, section 5-9-7 (SIMULTANEOUS INDEPENDENT ILS/MLS APPROACHES- DUAL & TRIPLE) contains the current provisions governing air traffic control separation for independent ILS/MLS precision approach operations at airports with dual and triple parallel runway configurations and runway centerline separation of at least 4300 feet. With the evolution toward performance-based navigation in the National Airspace System (NAS), Air Traffic Control (ATC) will increasingly be required to factor in Area Navigation (RNAV) and Required Navigation Performance (RNP) approaches to the operations referenced above. A simulation was designed using the AFS-440 Airspace Simulation and Analysis Tool (ASAT) to look at all combinations of ILS and RNP/RNAV aircraft (RNP levels 0.1, 0.2, and 0.3 NM) performing simultaneous approach operations at George Bush Intercontinental Airport (KIAH).

Analysis of the results of the simulations indicated that all combinations of ILS, RNP 0.1, and RNP 0.2 aircraft meet the target level of safety for dealing with a 30 degree blunder for the KIAH runway configuration. RNAV aircraft with GPS sensors are expected to perform no worse than RNP 0.2 aircraft with integrity provided by the ATC system. RNP 0.3 aircraft could be safely paired on the 08L-09 and 26R-27 runway pairs but not on the 08R-08L or 26L-26R pairs. The study recommends that, if they are allowed, RNP 0.3 aircraft only be operated to the outboard runways.

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Executive Summary

FAA Order 7110.65P *Air Traffic Control*, section 5-9-7 (SIMULTANEOUS INDEPENDENT ILS/MLS APPROACHES- DUAL & TRIPLE) contains the current provisions governing air traffic control separation for independent precision approach operations at airports with dual and triple parallel runway configurations and runway centerline separation of at least 4300 feet. These standards were developed from simulations performed by the Federal Aviation Administration (FAA) based on Instrument Landing System (ILS) precision approach operations to determine the parameters necessary to meet the target level of safety for the blunder scenario.

With the evolution toward performance-based navigation in the National Airspace System (NAS), Air Traffic Control (ATC) will increasingly be required to factor in Area Navigation (RNAV) and Required Navigation Performance (RNP) approaches to the operations referenced above. The Terminal Safety and Operations Support Director (ATO-T) has received waiver requests from two Operational Evolution Plan (OEP) benchmark airports (Houston-KIAH and Pittsburgh-KPIT) to authorize such operations.

The Flight Operations Simulation and Analysis Branch, AFS-440, was requested by the RNP/RNAV Program Office to conduct a study to determine what combinations of RNAV or RNP simultaneous approach operations could be authorized by ATC. The branch's Airspace Simulation and Analysis Tool (ASAT) has been used for a number of similar studies related to simultaneous approach operations. The tool models all components of the scenario (aircraft, avionics, pilot, controller, etc.) and performs a Monte Carlo simulation where all significant parameters are varied according to appropriate probability distributions. The results of the study provide guidance for determining the allowable separation or operation of RNAV, RNP, and ILS approaches to parallel runways (dual and triple), without the necessity of waivers. Study results would also address acceptable mitigations against which waiver requests would be considered.

The case examined was George Bush Intercontinental Airport (KIAH). The airport can conduct triple simultaneous ILS operations and has a waiver in place to allow restricted RNAV/RNP approaches to the outer runways. Runway spacing is approximately 5000 feet between 08L/26R and 08R/26L with 1200 and 1650-foot runway threshold staggers respectively. The spacing is approximately 5800 feet between 08R/26L and 09/27 with 6600 and 7300-foot runway threshold staggers. See Figure 1 for the airport layout.

A simulation was designed to look at all combinations of ILS and RNP/RNAV aircraft (RNP levels 0.1, 0.2, and 0.3) performing simultaneous approach operations at the airport. Air Traffic personnel indicated that they had no means of sorting different RNP levels to particular runways so each scenario involved only one RNP level. Only Global Positioning System (GPS) equipped RNAV aircraft were considered. Although these aircraft are typically classified as RNP 0.3, all performance data collected to date indicate that RNP 0.2 containment or better is routinely achieved. All scenarios were run with

both east and west traffic flows. Forty-four test scenarios were examined with 50,000 runs performed for each scenario.

The simulation factored in the fleet mix for KIAH based on data provided by Houston Terminal Radar Approach Control (TRACON). Aircraft performance was based on data collected from prior flight simulator tests and data provided by aircraft manufacturers. Each type of aircraft in the KIAH fleet mix was matched to the closest model in the ASAT repertoire. ILS tracking performance was based on International Civil Aviation Organization (ICAO) Collision Risk Model (CRM) data for both the lateral and vertical. RNAV and RNP lateral tracking was based on nominal flight technical errors about a track selected from Gaussian distributions based on the RNP level. Vertical tracking was offset by a position error in the glideslope origin generated by the same Gaussian distribution. Pilot and controller response times were based on data collected during the Multiple Parallel Approach Program (MPAP) testing. Pilot response times were based on distributions collected from line pilots. ATC response times were based on testing done on simulated 5000-foot triple simultaneous approaches with a Data Entry and Display Subsystem (DEDS) display and an ASR-9 radar. Surveillance system errors and delays were based upon information obtained from MIT Lincoln Labs reports (Reference 10).

The target level of safety (TLS) for the triple approach configurations was determined to be 4×10^{-8} (see Appendix D). From the TLS, a maximum acceptable Test Criteria Violation (TCV) rate can be derived (also Appendix D). The TCV rate for at-risk blunders must be less than 5.1% overall and less than 6.8% for each of the embedded dual operations.

Analysis of the results of the simulations indicated that all combinations of ILS, RNP 0.1, and RNP 0.2 aircraft produced TCV rates that met the target level of safety for the KIAH runway configuration. RNAV aircraft with GPS sensors are expected to perform no worse than RNP 0.2 aircraft. RNP 0.3 aircraft could be safely paired on the 08R-09 and 26L-27 runway pairs but not on the 08R-08L or 26L-26R pairs. The study recommends that, if they are allowed, RNP 0.3 aircraft only be operated to the outboard runways. The study also notes that, regardless of blunder rates, aircraft that are actually performing at RNP 0.3 containment levels will be routinely (approximately 2-4% of the time) in the No Transgression Zone causing unnecessary breakouts.

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1.0 Introduction

1.1 Purpose and Structure of This Document

The purpose of this study is to provide a risk assessment for simultaneous independent parallel approach operations to George Bush Intercontinental Airport (KIAH) involving mixtures of Instrument Landing System (ILS) and Area Navigation (RNAV)/Required Navigation Performance (RNP) aircraft. The study will use a Monte Carlo simulation of the operation to evaluate the risk associated with a blunder where one aircraft deviates 30-degrees from the approach course toward other aircraft. The simulation will examine a series of scenarios involving different combinations of ILS and RNAV/RNP aircraft conducting approaches. It will consider RNP aircraft that are at performance levels of 0.1, 0.2, and 0.3 nautical miles (NM) and RNAV aircraft that are Global Positioning System (GPS) equipped. Larger RNP levels and RNAV based on DME/DME will be addressed in a later report. Based on the results of this study, those aircraft are not acceptable for simultaneous approach operations at KIAH.

The document defines the problem (Section 1.2), explains the technical approach that was used (Section 2.0), the structure of the Monte Carlo simulation involved (Section 2.1), details the inputs to the simulation (Section 2.2) and the outputs used for validation of some of the new parts of the model (Section 2.3). The analysis of the results of the simulation (Section 3) is based on substantial work previously performed and summarized in Reference 3. Relevant excerpts from that report are included (Appendix D). Conclusions and recommendations are given in Section 4. Appendices address the fleet mix, pilot and air traffic controller reaction time, risk analysis, the basis for RNP distribution assumptions, and other topics.

1.2 Statement of the Problem

Federal Aviation Administration (FAA) Order 7110.65P *Air Traffic Control*, section 5-9-7 (SIMULTANEOUS INDEPENDENT ILS/MLS APPROACHES- DUAL & TRIPLE) is the current provision governing air traffic control separation for independent precision approach operations at airports with dual and triple parallel runway configurations having runway centerline separation of at least 4300 feet. These standards were developed from simulation exercises performed by the FAA based on ILS precision approach operations.

With the evolution toward performance-based navigation in the National Airspace System (NAS), Air Traffic Control (ATC) will increasingly be required to factor in RNAV and RNP approaches to the operations referenced above. The Flight Operations Simulation and Analysis Branch, AFS-440, was requested by the RNP Division of Terminal Safety and Operations Support (ATO-T) to conduct a study to determine what combinations of RNAV or RNP approach operations could be authorized by ATC. The branch's Airspace Simulation and Analysis Tool (ASAT) has been used for a number of similar studies related to simultaneous approach operations. The tool models all components of the scenario (aircraft, avionics, pilot, controller, etc.) and performs a Monte Carlo simulation where all significant parameters are varied according to appropriate probability distributions. The results of the study should provide guidance for determining the allowable runway configurations (separation and stagger), surveillance requirements, and aircraft equipage for operation of RNAV, RNP, and ILS approach operations to parallel runways (dependent or independent, dual and triple), without the necessity of waivers. The final study results will also address acceptable mitigations against which any waiver requests would be considered.

As requested, the first case to be examined was George Bush Intercontinental Airport (KIAH). The airport can run triple simultaneous ILS operations from either set of runway ends and has a waiver in place to allow restricted RNAV/RNP approaches to the outer runways. Runway spacing is approximately 5000 feet between 08L/26R and 08R/26L with 1200 and 1650 foot staggers respectively. The spacing is approximately 5800 feet between 08R/26L and 09/27 with 6600 and 7300 foot staggers.
See Figure 1 for the airport layout.

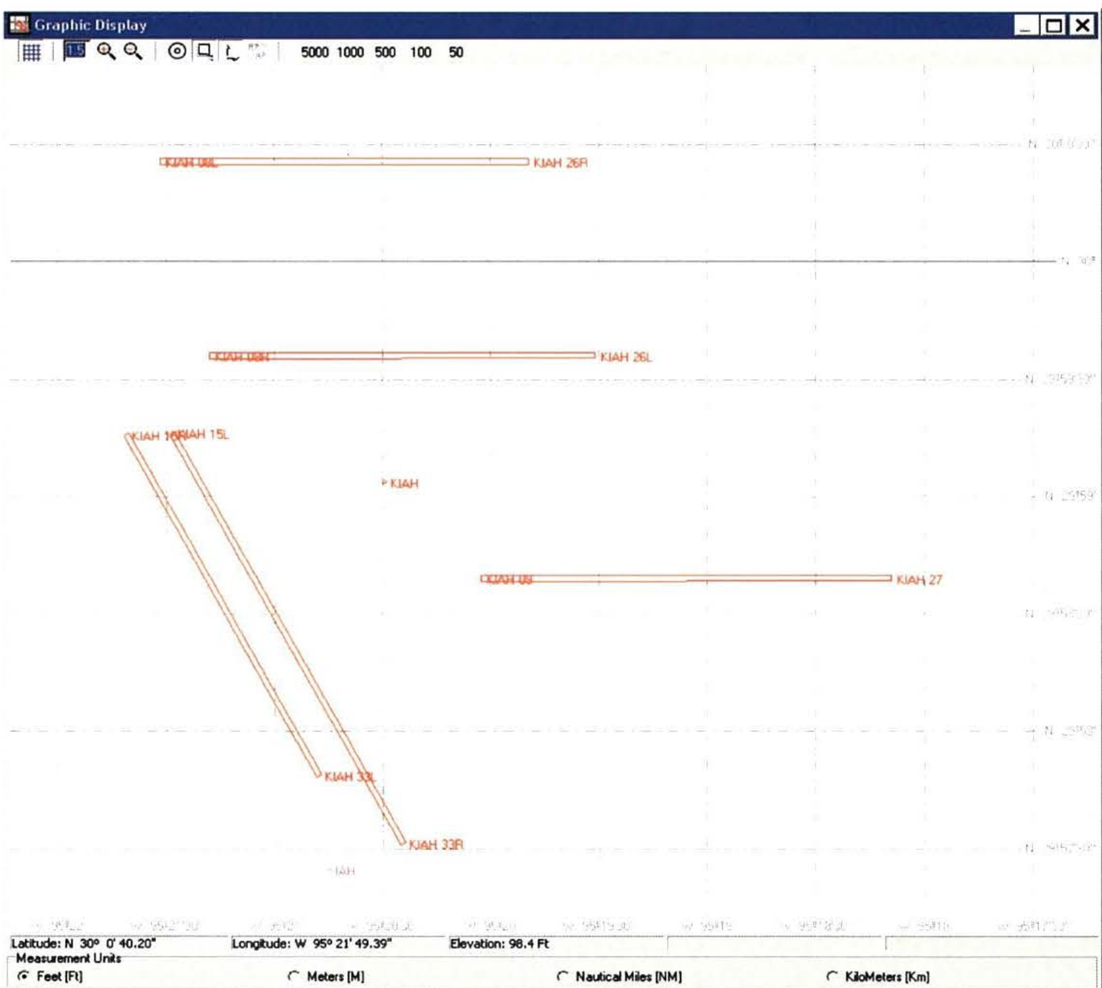

Figure 1. George Bush Intercontinental Airport Runway Diagram

The operation of interest is an independent simultaneous parallel approach procedure with an "at-risk" blunder. See Figure 2 for an illustration. This involves two or more aircraft established on approach (with vertical guidance), either ILS or RNP/RNAV, to parallel runways, where one of the aircraft deviates from the approach path towards the adjacent traffic. The ultimate requirement on the system is that ATC must be able to maintain at least a 500-foot slant range separation between the blundering and evading aircraft. For simultaneous independent approach operations, the Orders require a "final monitor controller" position for each runway. These controllers maintain longitudinal spacing between landings and are responsible for attempting to return a blundering aircraft to the correct course and, if that fails, direct threatened traffic to evade, usually by giving them an immediate turn command.

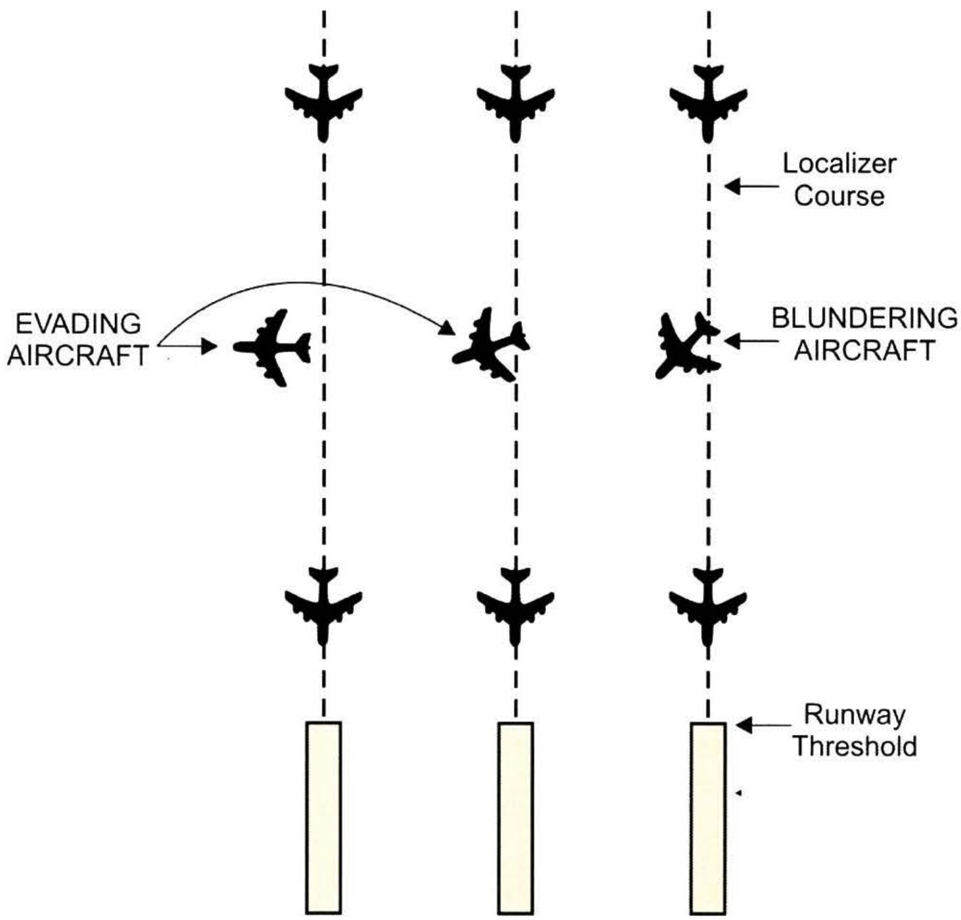

Figure 2. Triple Simultaneous Approach with Blunder

The "at-risk" term implies that if no corrective action is taken, the aircraft will come within 500 feet of each other and potentially collide. Violation of the 500-foot separation is referred to as a Test Criteria Violation (TCV). A 2000-foot wide No Transgression Zone (NTZ) is located midway between adjacent pairs of approach paths to aid controllers in determining that an aircraft is blundering. If an aircraft deviates from course far enough to penetrate the NTZ, the controller must assume that it is blundering and the adjacent aircraft must be directed to take evasive action. Controllers may determine that a blunder is occurring before NTZ penetration and act accordingly. However, due to the time and fuel costs associated with a "nuisance" breakout, the controllers should be reasonably certain that the blundering aircraft cannot be returned to its intended course before breaking the threatened aircraft out. The nuisance breakout may be a significant factor in RNP/RNAV operations.

The target level of safety (TLS) for approaches has been determined to be 4×10^{-8} fatal accidents per approach (see Appendix D). From the TLS, a maximum acceptable TCV rate can be derived for simultaneous operations (also Appendix D). The TCV rate for at-risk blunders in a triple approach must be less than 5.1% overall and no more than 6.8% for each of the embedded dual operations. This generates an unambiguous pass-fail criterion for each test scenario.

This study will determine the acceptable combinations of ILS and RNP/RNAV aircraft that can safely execute simultaneous approach operations to the triple runways at George Bush Intercontinental Airport.

1.3 RNP/RNAV Considerations/Background

The principal issue with RNAV and RNP aircraft on simultaneous approaches with other aircraft is that RNAV and RNP aircraft will not be following the localizer/glideslope guidance that the current ATC system has been built around. The navigation systems on the RNAV and RNP aircraft will generate their own three dimensional course to fly based on their onboard position solutions and database information. Because of position solution errors and possible database errors, the course the navigation system constructs may not line up with the existing localizer/glideslope course and the aircraft may appear off the course expected on the ATC display. The extent to which ATC will tolerate significant track deviations that are within the allowable range for the navigation system has yet to be determined. In a largely RNP/RNAV fleet, course deviations that previously would have generated immediate action for an ILS track may be routine. Therefore, in an RNP/RNAV environment, controllers may delay their decision to command an evasion in order to avoid nuisance breakouts.

Nuisance breakouts may also be caused by inadvertent NTZ penetrations. Purely as an example, an aircraft that exactly meets the RNP 0.3 containment requirement could be in the NTZ 5.1% of the time on the 26L/R/08R/L runway pairs at KIAH; that is, the aircraft could be more than 1500 feet off course (the width of the Normal Operating Zone

(NOZ)) and inside the NTZ when the internal navigation solution indicates that the aircraft is on the centerline.

2.0 Study Methodology

The study used a Monte Carlo simulation of the operation to evaluate the risk. The simulation examined a series of scenarios involving different combinations of ILS and RNAV/RNP aircraft conducting approaches. It considered RNP aircraft that were at performance levels of 0.1, 0.2, and 0.3 NM and RNAV aircraft that were GPS equipped. The primary result of the simulation was the percentage of TCVs occurring during each scenario (combination of ILS and RNP/RNAV aircraft). Those percentages, scaled as needed, were compared to the pass-fail requirements mentioned above and the scenarios were identified as acceptable or not.

2.1 Model Description

The ASAT consists of a family of software components running on a collection of high-speed computers. The system performs Monte Carlo studies involving 10^4 to 10^6 runs to represent the full ranges of parameter values. The ASAT uses high fidelity models of all components of an aviation scenario to achieve the most realistic simulation possible with the information provided. Wherever available, manufacturer provided data were used as a basis for some of the components of the simulation. When empirical data were available from relevant tests, they were used to the extent possible as a basis for some of the components of the simulation. The various data components are discussed in detail in the next section.

The particular ASAT component used for this task was called ASAT4ILSRNP. Figure 3 shows the ASAT screen for a typical run. The aircraft approaching runway 08R (the middle runway on the screen), a SAAB turboprop, has blundered and the 08L traffic, an Embraer RJ, has successfully evaded. An Airbus A320 was approaching runway 09 and was not affected. The closest point of approach (CPA) was 1417 feet slant range or 1373 feet, ignoring vertical separation. All three aircraft were set to RNP 0.1 performance levels. The three dots to the left of the three tracks are the start of the next run.

Figure 3. Typical ASAT Run

The simulation was set to initiate blunders between 2 and 14 NM from threshold. Outside 14 NM, there was at least 1000-foot vertical separation per requirements for simultaneous operations. Inside 2 NM, the evader will have landed before the blunderer can cross its approach path.

RNP lateral offsets are limited to ± 3 standard deviations. Values outside that should have triggered alerts and corrective actions would already have been taken. The display can show both the actual and reported position of the blundering aircraft. When running in high-speed mode, all display features are not updated, to minimize run times.

An ASAT run consists of three phases.

Phase 1: Initialization. The aircraft types were selected randomly according to the fleet mix. Their performance data were loaded and approach airspeeds determined. They were assigned to a runway and the blunderer selected. The blundering aircraft was positioned at a random distance from the airport (uniformly distributed within the user selected range limits) with appropriate lateral and vertical errors. The adjacent evader aircraft was positioned laterally and vertically and then placed longitudinally to maximize the chance of a collision if corrective action was not taken in a timely manner. The time to the next surveillance system update was selected from a uniform distribution ranging from 0 to 4.8 seconds for ASR-9. All parameters that were based on probability distribution functions (pdfs), such as evader rate of climb, roll rate, pilot and ATC response times, etc., were selected.

Phase 2: Performance. The aircraft were "released" and the simulation advanced in simulated 50 millisecond steps with continuous updates of the aircraft state vectors based on their flight dynamics and performance data. Course deviations and corrections were based on the Flight Technical Error (FTE) filter and the navigation system models. Immediately after release, the blunderer started a 30-degree heading change and began converging on the evader aircraft. Surveillance system reports were generated at appropriate times with appropriate errors in range and azimuth. These errors affect where the targets were depicted on the controller's screen and, hence, when it was perceived by the controller as being in the NTZ, or, at least, definitely headed toward the NTZ. A certain percentage of target reports were randomly dropped per the surveillance system specifications. When the blunderer was identified as being within 500 feet of the NTZ or the ATC response time was reached, whichever was later, the evader was ordered to perform a 90-degree course change. After another delay for the pilot response time, the evader began to climb and roll into the course change (per the selected performance parameters). Slant range and system plane separation were continuously monitored and the simulation continued for approximately 20 seconds (simulation time) past the point where the slant range stopped decreasing and started increasing, i.e. the minimum separation point. The simulation did not detect collisions so that even if the slant range separation reached 0.0, the model kept running.

Phase 3: Reporting the run. For each run, critical parameters were recorded and saved to output files. These included the aircraft types and runways involved, the pilot and ATC response times, the range of the blunderer from the threshold when the blunder began, the minimum 2-dimensional and 3-dimensional separation, and a flag indicating that a TCV had occurred. For runs that included RNP aircraft, additional data were collected to verify that the track distributions matched the expected navigation performance for the RNP level involved. A sample output file is included as Appendix G.

The only variable between scenarios was the arrangement of ILS and RNP/RNAV aircraft across approach courses. Each scenario was performed 50,000 times so that all reasonable combinations of aircraft types, performance parameters, radar update times, and pilot and controller response times would be considered.

2.2 Summary of Data Used

The primary data components of the ASAT system are listed below.

a.) Geography: ASAT uses the latest FAA databases to establish runway coordinates (including elevation), localizer and glideslope antenna positions, and relevant obstacle and terrain feature locations.

b.) Aircraft: Aircraft fleet mix information was received from Houston TRACON (I90) (see Appendix A) and incorporated into the simulation. Aircraft types from the report were mapped into performance models in the ASAT. Typical performance data (roll rate, climb rate, achieved bank, indicated airspeed) for those types were collected in previous tests and from manufacturers and distributions were developed for use in the Monte Carlo process.

c.) Environmental conditions: The ASAT aerodynamics models automatically compensated for altitude effects based on the airport elevation and for any wind or turbulence conditions included in the model. Because the approach paths are relatively close and parallel, wind effects were considered to be negligible since all aircraft were equally affected. Earlier Multiple Parallel Approach Program (MPAP) studies have supported this assumption.

d.) Pilot response times: This time was the period from the start of the ATC evasion command until the aircraft achieved 3-degrees of bank. These distributions were based on data collected during the MPAP testing and are discussed in more detail in Appendix B.

e.) Air traffic controller response times: This time was the delay from the initiation of the blunder to the activation of the microphone by the evading aircraft's monitor controller to begin the evasion command. The MPAP testing looked at a range of surveillance systems, displays, and runway spacings and collected response times for each.
Appendix C includes a list of the configurations tested. One of the test configurations that the MPAP examined was 5000-foot triples with an ASR-9 radar and Data Entry and Display Subsystem (DEDS) displays. This was the closest to the KIAH configuration and was also the most conservative in terms of average controller response time, so it was selected for this simulation. The controller response times in the simulation were further restricted to occur no earlier than when the blundering aircraft was 500 feet from the NTZ. This was a conservative assumption to address the requirement in Order 7110.65P, para. 5-9-7.c.2 that the evasion command should only be given "when an aircraft is observed penetrating or in the controller's judgment will penetrate the NTZ."

f.) Navigation: Previous testing for evaluating ILS operations used the International Civil Aviation Organization (ICAO) Collision Risk Model to determine initial positions (lateral and vertical). The simulation proceeded along the localizer and glideslope using control filters to simulate FTE. For the RNP aircraft considered for this study, the initial lateral position was selected based on a Gaussian distribution derived from the RNP value. Vertical navigation was based on a glidepath whose ground path intercept was shifted due to the same Gaussian distribution. The aircraft then navigated along the adjusted path to the runway. RNAV tracking performance is poorly defined and thus difficult to model.

An RNP navigation system differs from an RNAV system since it has additional algorithms for detecting and alerting when the navigation system information is less reliable and might be providing incorrect information. Since the approach operations are under continuous radar surveillance by multiple controllers, integrity is not a major concern (if the navigation system is providing significantly misleading information, ATC will detect the course error and act accordingly.) Aircraft that are classified as RNAV and have a GPS primary navigation sensor are expected to perform very near to RNP 0.1- RNP 0.15 levels. There is a large set of TSO C-129 based data and a smaller set of actual RNAV/GPS approaches to KIAH that support this conjecture. RNAV aircraft that rely on DME/DME/IRU are extremely dependent on DME coverage and availability for their navigation solutions and, for an approach operation such as this, are flying into poorer coverage and decreasing signal quality as they descend. The expected performance of an RNAV/DME/DME/IRU aircraft would be marginally RNP .3-.5 where good coverage is available. For the purposes of this test, RNAV aircraft were assumed to be GPS based (as is required for the current special procedure at KIAH) and performance was assumed to be no worse than RNP 0.2.

g.) Surveillance system: An ASR-9 model, with appropriate errors and latencies was part of the simulation. The model was based on data provided by MIT Lincoln Labs and the William J. Hughes Technical Center.

2.3 Simulation Performance

The test scenarios are depicted in Table 1 below. As mentioned earlier, the only variable between scenarios is the arrangement of ILS and RNP/RNAV aircraft across the runways. Fifty thousand runs were performed for each combination of navigation types for each end of the airport. In discussion with Air Traffic during the program development, it was determined that there was no convenient way for ATC to sort different RNP capable aircraft to particular runways, i.e. they could not route all RNP 0.3 aircraft to runway X while allowing RNP 0.1 aircraft to land on runways Y and Z. As a result, all RNP aircraft were in the same category within a scenario (0.1, 0.2, or 0.3). RNAV aircraft were assumed to fall into one of the RNP levels (to be further discussed later).

For each scenario, the runs were evenly distributed across the three runways. From the outer runways, the blunder was always toward the other runways; from the center, it randomly went right or left. So a typical set of runs involved 25,000 interactions between the right and center runways and 25,000 interactions between the left and center.

The total distance between the two outboards was so great at KIAH (10,800 feet), that there was essentially no interaction between the two. When the blundering aircraft reaches the NTZ, it is generally on its 30-degree offset course and is closing the lateral distance between it and the other aircraft at between 100 and 120 feet per second (assuming typical approach speeds between 120 and 140 knots). For the worst-case configuration, the controller on the opposite outboard runway has more than a minute to get his/her aircraft out of the danger area.

Test Scenarios							
Scenario #	08L	08R	09	Scenario #	27	26R	26l
1E	ILS	ILS	ILS	1W	ILS	ILS	ILS
2E	ILS	ILS	.1	2W	ILS	ILS	.1
3E	ILS	.1	ILS	3W	ILS	.1	ILS
4E	ILS	.1	.1	4W	ILS	.1	.1
5E	.1	ILS	ILS	5W	.1	ILS	ILS
6E	.1	ILS	.1	6W	.1	ILS	.1
7E	.1	.1	ILS	7W	.1	.1	ILS
8E	.1	.1	.1	8W	.1	.1	.1
9E	ILS	ILS	.2	9W	ILS	ILS	.2
10E	ILS	.2	ILS	10W	ILS	.2	ILS
11E	ILS	.2	.2	11W	ILS	.2	.2
12E	.2	ILS	ILS	12W	.2	ILS	ILS
13E	.2	ILS	.2	13W	.2	ILS	.2
14E	.2	.2	ILS	14W	.2	.2	ILS
15E	.2	.2	.2	15W	.2	.2	.2
16E	ILS	ILS	.3	16W	ILS	ILS	.3
17E	ILS	.3	ILS	17W	ILS	.3	ILS
18E	ILS	.3	.3	18W	ILS	.3	.3
19E	.3	ILS	ILS	19W	.3	ILS	ILS
20E	.3	ILS	.3	20W	.3	ILS	.3
21E	.3	.3	ILS	21W	.3	.3	ILS
22E	.3	.3	.3	22W	.3	.3	.3

Table 1. Test Scenarios
(ILS indicates a conventional precision approach, .1 indicates an RNP 0.1 aircraft on the approach, etc.)

3.0 Summary of Data Analysis and Risk Evaluation

This section examines the results of the simulation and defines the acceptability of the results for operational implementation.

3.1 Summary of the TCV Probability Analysis

Table 2 lists the resultant TCV counts, number of runs for each scenario, and the associated TCV rate. The simulation included algorithms to longitudinally place evader aircraft relative to the blundering aircraft so that they were at-risk. However the significant runway staggers at KIAH reduced the efficiency of this algorithm and test cases ran without an evasion maneuver showed that only about 90% of the evader aircraft were at-risk. Therefore, the numerical result of the TCV count divided by the number of runs was scaled by 1.11. This assumes that an aircraft that was not at risk could not generate a TCV, a reasonable, but not absolute, expectation.

RNP 0.1 operations produced TCV rates very similar to ILS. RNP 0.2 operations produced TCV rates slightly greater than ILS and RNP 0.3 operations produced TCV rates greater than RNP 0.2. As the RNP level increases, so does the probability that the aircraft might be off the centerline by a significant amount. If the 26R traffic is off-course to the left and the 26L traffic off-course to the right, the separation distance is less, thus providing controllers and pilots with less time to react and achieve a successful evasion. Figures 4 and 5 show that the track dispersion distribution of RNP evading aircraft that experienced a TCV are shifted toward the blundering runway thus tending to have comparatively large deviations. This means there is a higher probability of a significant course deviation in aircraft that experienced a TCV. The plots also include Gaussian distributions for the appropriate RNP level to verify the navigation performance of the model.

The 800 feet of extra course separation and the considerable stagger between runways 08R/09 and 27/26L significantly affects the probability of a TCV. Based on the closure rate given in Section 2.3, the lateral separation provides 6.7 to 8 seconds of extra time to complete the evasion maneuver. The stagger generates more than 300 feet of vertical separation between the nominal glideslope paths. The effects of this are clearly seen in Table 2 in the differences in the TCV rate between the 08L/08R pair and the 08R/09 pair and between the 26R/26L pair and the 26L/27 pair.

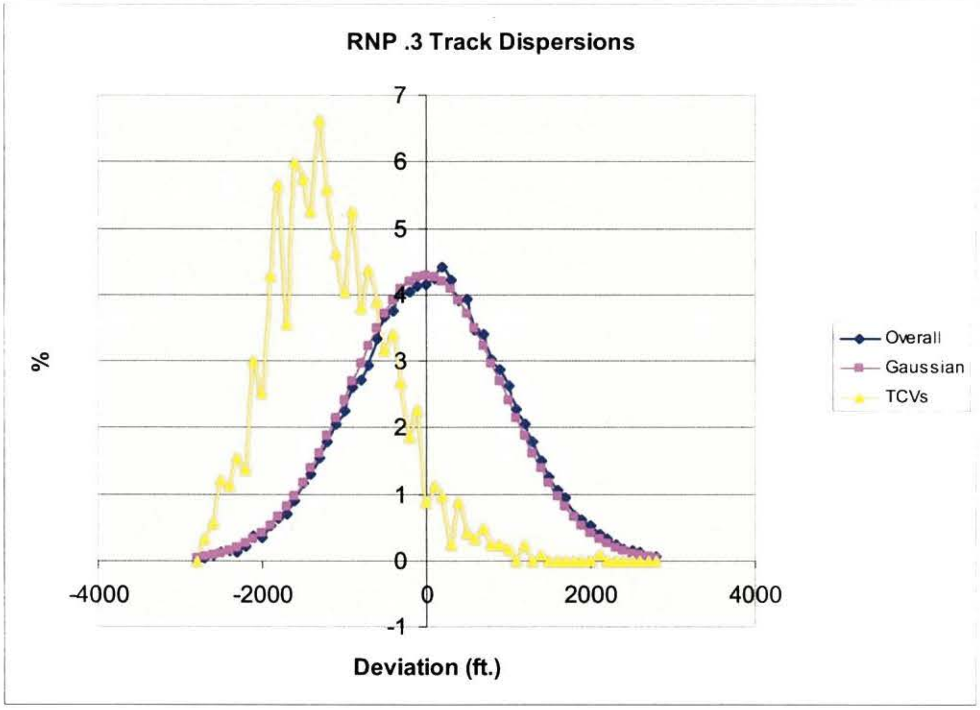

Figure 4. Comparison of track dispersions between overall distribution, Gaussian, and TCVs from aircraft avoiding blunders from the left

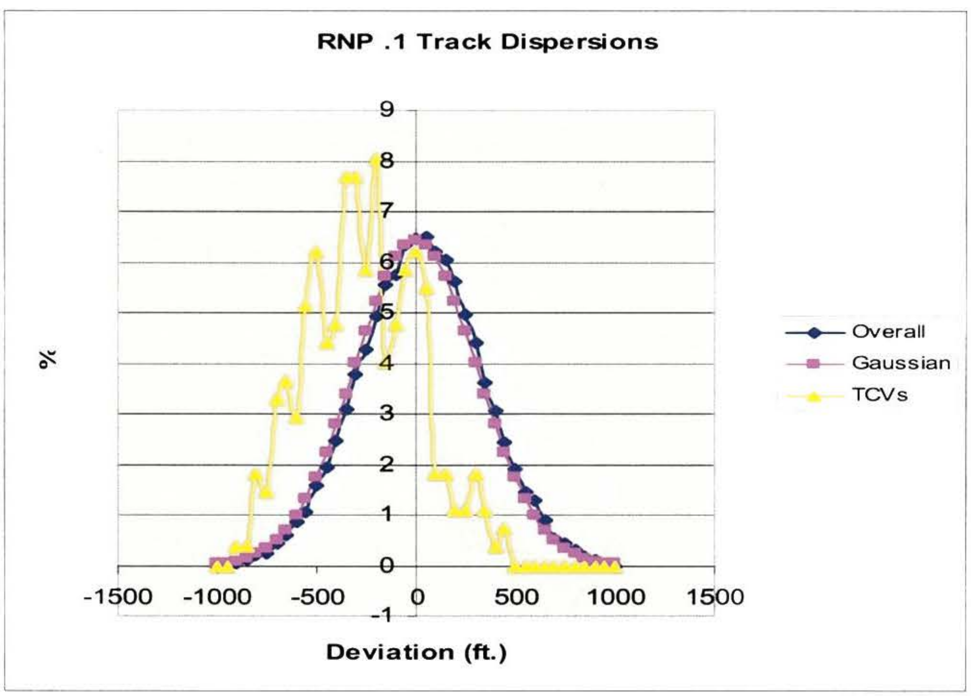

Figure 5. Comparison of track dispersions between overall distribution, Gaussian, and TCVs from aircraft avoiding blunders from the left

	Right-Center			Left-Center			Total
Scenario #	3-D TCVs	# of Blunders	%*	3-D TCVs	# of Blunders	%*	%*
1E	32	24690	0.14	189	25310	0.83	0.49
2E	23	24909	0.10	201	25091	0.89	0.50
3E	47	25100	0.21	264	24900	1.18	0.69
4E	61	24986	0.27	286	25014	1.27	0.77
5E	32	25070	0.14	249	24930	1.11	0.62
6E	39	25019	0.17	259	24981	1.15	0.66
7E	57	25021	0.25	337	24979	1.50	0.87
8E	63	24923	0.28	355	25077	1.57	0.93
9E	100	24914	0.45	222	25086	0.98	0.71
10E	157	24888	0.70	676	25112	2.99	1.85
11E	280	24958	1.25	673	25042	2.98	2.12
12E	26	24865	0.12	593	25135	2.62	1.37
13E	127	25147	0.56	581	24853	2.59	1.57
14E	171	25028	0.76	1019	24972	4.53	2.64
15E	269	24923	1.20	1051	25077	4.65	2.93
16E	318	24992	1.41	214	25008	0.95	1.18
17E	477	24902	2.13	1307	25098	5.78	3.96
18E	803	25131	3.55	1287	24869	5.74	4.64
19E	18	25185	0.08	1001	24815	4.48	2.26
20E	314	24951	1.40	1041	25049	4.61	3.01
21E	476	24867	2.12	1981	25133	**8.75**	**5.45**
22E	818	24928	3.64	1924	25072	**8.52**	**6.09**
1W	182	24994	0.81	25	25006	0.11	0.46
2W	221	24790	0.99	32	25210	0.14	0.56
3W	241	24930	1.07	40	25070	0.18	0.62
4W	277	24840	1.24	49	25160	0.22	0.72
5W	189	25033	0.84	35	24967	0.16	0.50
6W	225	24857	1.00	42	25143	0.19	0.59
7W	219	24932	0.98	50	25068	0.22	0.60
8W	291	24928	1.30	51	25072	0.23	0.76
9W	553	25033	2.45	24	24967	0.11	1.28
10W	577	25197	2.54	144	24803	0.64	1.60
11W	892	25048	3.95	162	24952	0.72	2.34
12W	171	25012	0.76	120	24988	0.53	0.65
13W	549	25115	2.43	108	24885	0.48	1.46
14W	545	25147	2.41	262	24853	1.17	1.79
15W	911	24878	4.06	256	25122	1.13	2.59
16W	1019	24941	4.54	16	25059	0.07	2.30
17W	1084	24893	4.83	409	25107	1.81	3.31
18W	1686	25118	**7.45**	398	24882	1.78	4.63
19W	191	24946	0.85	295	25054	1.31	1.08
20W	963	25096	4.26	295	24904	1.31	2.79
21W	1068	25042	4.73	715	24958	3.18	3.96
22W	1767	24996	**7.85**	766	25004	3.40	**5.62**

Table 2. Simulation Results by Scenario
(* Percentage is scaled by 1.11 to compensate for non-at-risk traffic.)
(Red bold values are unacceptable TCV rates.)

3.2 Summary of Acceptable Level of Risk

In 1988, the MPAP was initiated to investigate capacity enhancing procedures for simultaneous ILS approaches to parallel runways. The program established the MPAP Technical Work Group (TWG) to unite various areas of expertise for the evaluation of multiple parallel approaches in an effort to increase airport capacity in a safe and acceptable manner. FAA representatives from the Secondary Surveillance Product Team, Office of System Capacity, Flight Standards Service, Air Traffic Operations, Air Traffic Plans and Requirements, and various regional offices composed the MPAP TWG.

MPAP researchers extracted the total number of air carrier accidents as well as the number of fatal accidents on final approach from National Transportation Safety Board (NTSB) data for the time period, 1983-1989. This number, together with the total number of ILS approaches flown during this time period, lead to an estimated fatal accident rate during ILS operations performed during IMC of 4×10^{-7} fatal accidents per approach. There are a number of causes of accidents during final approach, such as structural failure, engine failure, or midair collision. An initial estimate was that there are nine possible causes of accidents on final approach. The implementation of simultaneous parallel approaches created a tenth possible accident cause, a collision with an aircraft on an adjacent approach. The researchers assumed that the risks of the ten potential accident causes are equal. Thus the contribution of any one of the accident causes would be one-tenth of the total accident rate. Based on this, the target safety level for midair collisions on simultaneous parallel approaches is 4×10^{-8}, or:

$$\frac{\text{1 accident}}{\text{25 million approaches}}$$

The MPAP test team adopted a method for determining a simulation's maximum acceptable TCV rate from work done on the Precision Runway Monitor (PRM) Demonstration Program. In the PRM Demonstration Report (Reference 1), researchers computed a TCV rate from the population of all worst-case blunders (WCBs). They found that a TCV rate not greater than 0.004 TCV per WCB would meet the target level of safety, provided that the overall 30-degree blunder rate did not exceed one 30-degree blunder per 2,000 approaches. The Monte Carlo simulation, however, measured a TCV rate based on at-risk WCBs, not the population of all WCBs. Therefore, for comparison purposes, the population TCV rate was converted to an at-risk TCV rate. Based on a simulation of aircraft speeds and types, a conservative ratio of 1/17 at-risk WCB per WCB was applied, resulting in an at-risk TCV rate criterion of 5.1% for triple approaches. The MPAP test team also determined that the criterion for dual approaches is 6.8%. For the triple approach operation, the MPAP TWG determined that 1) the triple approach must meet the criterion for triple approaches, and 2) each proximate pair must meet the criterion for dual approaches. This methodology was employed because it is possible that the criterion for the triple approach could be met, while one of the proximate pairs of runways did not meet the criterion for dual approaches.

To achieve a fatal accident rate that meets the target level of safety, a Monte Carlo simulation with the evader at-risk must result in a TCV rate (plus twice the standard error) that does not exceed 5.1% for the triple approach and 6.8% for each proximate pair of dual approaches. A Monte Carlo confidence interval that extends above 5.1% for the triple approach or 6.8% for the dual approach would indicate that the operation might not meet the target level of safety. For these simulations, the confidence intervals on the results are quite small (standard errors<0.1%) due to the large number of runs.

The risk analysis is covered in more detail in Appendix D, which is excerpted from Reference 3, Appendix C.

4.0 Results and Conclusions

This section summarizes the key results, the scenario risk evaluation, and the conclusions of the study.

4.1 Summary of Results

Table 3 summarizes the results by RNP level and runway spacing. Due to the significant runway threshold staggers, these results should not be considered as general guidelines for RNP runway spacing requirements.

RNP Level	Runway Spacing	Acceptable
.1	5000	Y
.1	5800	Y
.2	5000	Y
.2	5800	Y
.3	5000	N
.3	5800	Y

Table 3. Summary of Results by RNP Level and Runway Separation

4.2 Scenario Risk Evaluation

The study indicates that scenarios 21E, 22E, and 22W were above the 5.1% allowable TCV rate for the triples operation, and scenarios 18W, 21E, 22E, and 22W did not meet the acceptable level for the embedded duals. This would suggest that, if RNP 0.3 traffic is going to be involved, it should be directed to the farther outboard runway (09/27). Given ATC's restrictions on sorting traffic, this may present operational difficulties. The alternative is to require that only RNP aircraft certified to 0.2 level or better and equivalent RNAV aircraft be allowed to perform the approach.

4.3 RNAV Issues

If, as suggested in section 2.2.f, RNAV aircraft involved in the operation are restricted to GPS equipped models and assumed to perform no worse than RNP 0.2, then there is no difficulty with including them in the approach mix. Otherwise, if they are classed as equivalent to RNP 0.3 or even something larger, they fall into the group whose considerations are addressed in section 4.2.

4.4 Conclusions

In this study a risk analysis methodology was employed that was developed by the MPAP for simultaneous independent ILS approaches to parallel runways to determine the acceptability of including RNAV and RNP aircraft in the triple approach operation at George Bush Intercontinental Airport. The study used a high fidelity simulation of the operation to perform a Monte Carlo analysis. The study examined 44 test scenarios that mixed ILS and RNP 0.1, 0.2, and 0.3 traffic and determined that the only scenario that did not pass the test criteria involved simultaneous operations by RNP 0.3 aircraft to the closer spaced runway pair (08L/08R or 26L/26R). The simulation modeled RNP performance as Gaussian with the RNP level equivalent to 1.96 standard deviations. The study assumed RNAV aircraft performance would be equivalent to one of the RNP levels (0.1, 0.2, and 0.3 NM) and suggested that previous tests and data collection efforts could support the RNP 0.2 level as worst case performance for GPS equipped RNAV aircraft. It was assumed that the integrity, availability, and continuity functions inherent in RNP were provided for RNAV aircraft by the required Air Traffic surveillance and by the other conservative assumptions.

Appendix A

Aircraft Mix and Performance Modeling

The following information was provided by Houston TRACON.

Typical Daily Fleet Mix

KIAH Traffic	Count	ASAT Model
A300/600	5	A320
A300B	1	A320
A310	2	A320
A318	2	A320
A319	26	A320
A320	18	A320
A340-300	4	B757
Astra	1	*
B300 Super KingAir 350	2	*
727-200	2	B727
727 Stage3	5	B727
737-200	11	B737-200
737-300	158	B737-200
737-500	136	B737-200
737-700	71	B737-800
737-800	192	B737-800
737-900	37	B737-800
747-200	1	B777
747-400	4	B777
757-200	42	B757
757-300	24	B757
767-200	6	B777
767-300	4	B777
767-400	10	B777
777-200	16	B777
Beech Bonanza 35	1	*
Beech Bonanza 36	1	*
BeechJet 400	2	*
Beech A90 KingAir	1	*
Cessna 172	3	*
Cessna Caravan	4	*
Cessna 210	1	*
Cessna 501 Citation	1	F100
Cessna 525 CitationJet	1	F100
Cessna 550 Citation	8	F100
Cessna 560XL Citation Excel	2	F100
Cessna 650 Citation 3/6/7	3	F100
Cessna 680 Citation Sovereign	1	F100
Cessna 750 Citation 10	2	F100
Canadair CRJ-100	1	F100
Canadair CRJ-200	4	F100
Canadair CRJ-700	17	F100
Canadair CRJ-900	14	F100
DC-10	2	B727
DC-8-70	3	MD88
DC-8 Stage 3	2	MD88
DC-9-30	5	MD88

Embraer 135 RJ	87	ERJ
Embraer 145 RJ	374	ERJ
Embraer 170 RJ	29	ERJ
Embraer 145XR RJ	269	ERJ
Falcon 2000	2	F100
Falcon 900	2	F100
Falcon 50	1	F100
Gulfstream 2	1	F100
Gulfstream 4	5	F100
Gulfstream 5	3	F100
BAE 125-700	10	F100
LearJet 31	1	F100
LearJet 35	2	F100
AeroStar 200	2	F100
MD-11	2	B777
MD-80	4	MD88
MD-82	19	MD88
MD-83	5	MD88
MD-87	2	MD88
Rockwell Sabre 40/50/60	2	F100
Saab 340	94	Saab
Westwind 1124	5	*

*Not considered due to size of group

Table A-1. Fleet Mix and Model Assignments

One of the ASAT initiation files contains a section where the number of each type of aircraft is given. It automatically sets the frequency of occurrence for each aircraft type during the simulation. Based on the type, several aircraft performance distributions are loaded: approach speed, go around speed, deceleration, acceleration, rate-of-climb, and rate-of-change of rate-of-climb. Roll-rate distributions are also based on simulator testing. The achieved bank angle for this test was set to provide 10% more than a standard rate turn. Given that the evader pilot is attempting to avoid a mid-air collision, this is a conservative value.

Appendix B

Pilot Reaction Time Distribution Analysis

The MPAP testing included line pilots operating high-fidelity full motion simulators. The simulators were connected to the test facility at the William J. Hughes Technical Center by phone (so that the pilots were in direct contact with the controllers) and high-speed data lines. One of the parameters that was recorded during the testing was the time from the controller's initial evasion command until the aircraft achieved a 3 degree angle of bank in a roll that was determined to be part of the evasion maneuver. Every attempt was made to eliminate normal control motions from being considered as the start of the maneuver.

Test results that involved the use of the Precision Runway Monitor system to monitor closely spaced parallel runways led to the development of a training requirement to insure that the pilots did not delay their response to a "traffic alert" message. This training was not considered necessary for operations using conventional radar systems with runways spaced 4300 feet or more. Though not required, a significant part of the present pilot population has completed the training, which consists of a short video presentation.

A problem identified by the pilots during the testing in the late 1980s was controller's use of the word "immediate." The pilots, at that time, claimed that controllers frequently used the term when there was no need for an immediate response and this tended to lower pilot sensitivity to phrases that included the word. As a result, Air Traffic directives were modified to limit the use of the term except for real emergencies that did require "immediate" action. The current directive, FAAO 7110.65P, provides only three phraseologies that include "immediate," two of those are associated with simultaneous approaches; the third is when collision with terrain appears imminent. Contemporary pilots are aware of the urgency of action required when the word "immediate" is used.

The pilot response time distribution selected for this test was based on data collected during two test programs performed in 1995 and 1996. It is averaged across the fleet so there was no attempt to correlate response time with aircraft type. A Johnson S-L distribution was fitted to the data resulting in the following parameters: (Johnson distributions are discussed in Appendix E.)

Parameter	Value
Type	S-L
Delta	2.04
Gamma	1.98
Lambda	12.7
Xi	0.5
Truncation-Low	1.0
Truncation-High	17.0
Offset	1.0

The truncation points were chosen to reflect the empirical data. No data points were collected greater than 15.5 seconds so the maximum value considered was set to 17.0. The offset value is to compensate for the time to roll the aircraft to 3 degrees of bank. In the model, the pilot response time is to the start of the maneuver, so 1.0 second is subtracted from the distribution value to compensate.

Figure B-1 shows the resultant distribution overlaying the histogram of the pilot response times. The dashed blue lines represent the approximate quartile (25%, 50%, and 75%) points of the histogram data and the 97.5% point (cumulative to +2 standard deviations). The solid red lines are the equivalent points for the Johnson S-L function fitted to the data.

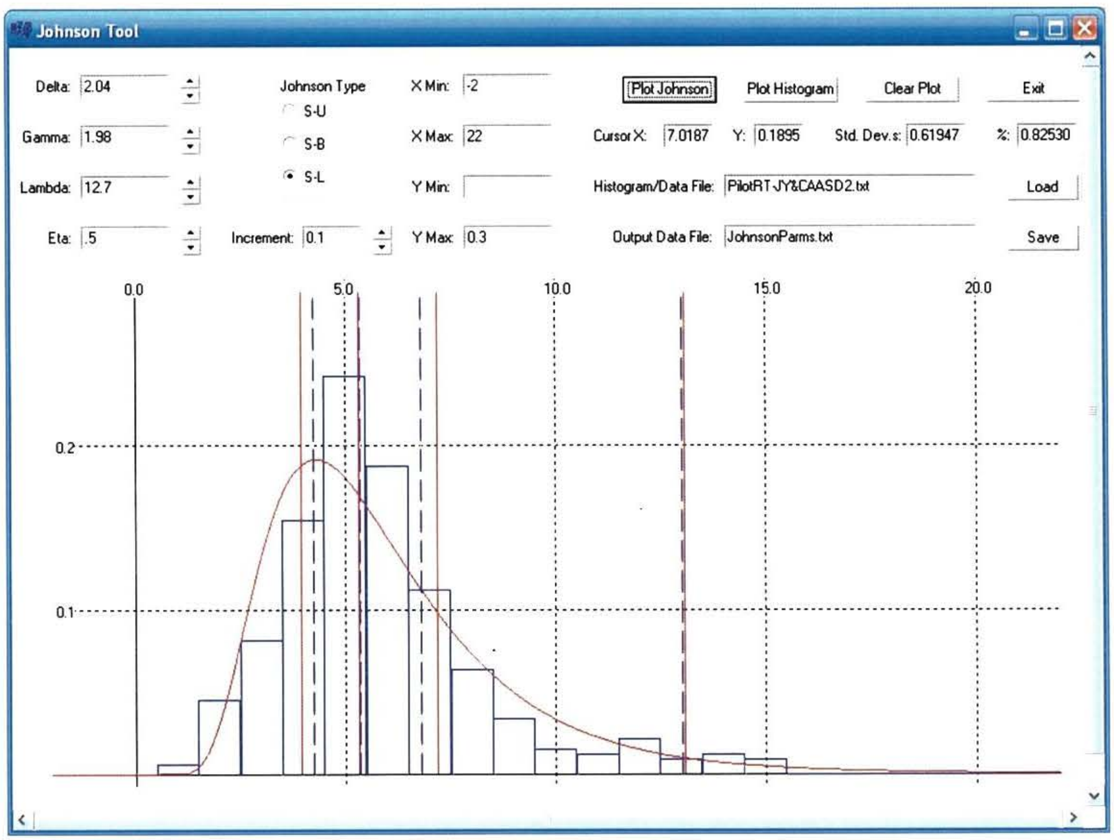

Figure B-1 Pilot Response Times Distribution

A Chi-square goodness of fit test was run on the distribution and did not show a very good fit, however the quartile and 2-sigma lines indicate the distribution errors should be primarily on the conservative side, especially for the longer times.

Appendix C

Air Traffic Controller Reaction Time Distribution Analysis

The MPAP testing used full performance level controllers from a number of facilities working in a test facility that was designed to be as close as practical to their actual working environment. Table C-1 shows the configurations of systems used during the various MPAP tests.

The test program, identified as IVB in Table C-1, examined triple approaches to runways spaced 5000 feet apart using standard ASR-9 radar and ASR/DEDS scopes. A histogram of the controller response times from that test was found in a draft document (Reference 7). The data were fitted with a Johnson S-B distribution resulting in the following. (Johnson distributions are discussed in Appendix E.)

Parameter	Value
Type	S-B
Delta	1.5
Gamma	0.5
Lambda	41.6
Xi	1.5
Truncation-Low	3.0
Truncation-High	30.0
Offset	0.0

Figure C-1 shows the resultant distribution overlaying the histogram of the controller response times. The dashed blue lines represent the approximate quartile (25%, 50%, and 75%) points of the histogram data and the 97.5% point (cumulative to +2 standard deviations). The solid red lines are the equivalent points for the Johnson S-B function fitted to the data. The distribution was truncated at 3 seconds on the low end. There were three very long controller response times collected during the 5000 foot triples test that were not considered representative of performance for controllers in modern final monitor environments. For this reason, the distribution of controller response times was truncated at thirty seconds. A thirty second interval would include at least six radar target updates after the blunder initiation, four of which would occur after the 30-degree course deviation was attained.

A Chi-square test for goodness of fit was run on the distribution and the base data set could only be accepted at the $\alpha = .01$ level. Because of the variation from cell to cell in the histogram a second test was done after combining adjacent cells (i.e. looking at the controller response times in 2 second intervals as opposed to 1 second intervals). That test showed that the hypothesis could be accepted at the $\alpha = .05$ level. Regardless of the quality of the fit, the comparisons of the quartile lines and the +2-sigma line shows that the distribution errors are on the conservative side.

Multiple Parallel Approach Program: 1988 – 1999

Approach	Sim Order	Dates	Purpose	Runway Spacing	Display	Simulated Radar	Other	TWG Recommendation	Documentation
Dual	NA	6/ 1990	National Standards	3400 ft	FMA	Mode S 4.8s / E-Scan 1.0s		Approved	Published Report Precision Runway Monitor Demonstration Report (DOT/FAA/RD-91/5)
Dual	9	9/16-9/23 1991	National Standards	3000 ft	FMA	E-Scan 1.0s	1-Degree Localizer Offset	No Decision Rendered See June '94	NO DOCUMENTATION
Dual	15	6/6-6/17 1994	National Standards	3000 ft	FMA	E-Scan 1.0s	1-Degree Localizer Offset	Not Approved	
Dual	16	7/11-7/22 1994	National Standards	3000 ft	FMA	E-Scan 1.0s	2.5-Degree Localizer Offset	Not Approved	Published Report (DOT/FAA/CT-96/2)
Dual	18	10/16-10/27 1995	National Standards	3000 ft	FMA	E-Scan 1.0s	2.5-Degree Localizer Offset	Approved	
Dual and Triple	4	4/24-5/3 1990	National Standards	4300 ft	ARTS III	ASR-9 4.8s		Not Approved	NO DOCUMENTATION
Dual and Triple	8	5/15-5/24 1991	National Standards	4300 ft	FMA	ASR-9 4.8s		Approved	Published Report (DOT/FAA/CT-92-16-I)
Dual and Triple	6	3/18-4/5 1991	National Standards	3000 ft	FMA	E-Scan 1.0s		Not Approved	Memorandum
Dual and Triple	12	7/27-8/14 1992	National Standards	4000 ft	FMA	ASR-9 4.8s		Inconclusive	Memorandum
Triple	10	9/24-10/4 1991	National Standards	4000 ft	FMA	ASR-9 4.8s		Inconclusive	
Triple	2	9/25-10/5 1989	DFW	5000 & 8800 ft	DEDS	ASR-9 4.8s		Approved	Published Report (DOT/FAA/CT-90-2)

Triple (IVB)	5	9/17-9/28 1990	National Standards	5000 ft	ARTS III	ASR-9 4.8s		Approved	Published Report (DOT/FAA/CT-91-31)
Triple	7	5/6/-5/14 1991	National Standards	3400 ft	FMA	Mode S 2.4s		Inconclusive	Memorandum
Triple	11	3/2-3/13 1992	Human Factors Study	3400 ft	FMA	E-Scan 1.0s	1 Mr Radar Accuracy	No Recommendation Made	
Triple	14	11/16-11/20 11/30-12/17 1992	DIA (DEN)	7600 ft 5280 ft	FDADS FMA	ASR-9 4.8s	Field Elevation 5431 ft	Not Approved Approved	Published Report (DOT/FAA/CT-94-36)
Triple	17	8/14-8/25 1995	National Standards	4000 ft 5300 ft	FMA	E-Scan 1.0s		Not Approved	Published Report (DOT/FAA/CT-TN02/16) Appendix
Triple	19	4/15-4/26 1996	National Standards	4000 ft 5300 ft	FMA	E-Scan 1.0s		Approved	
Quadruple	1	5/16-6/10 1988	DFW	5000 ft 5800 ft 8800 ft	DEDS	ASR-9 4.8s		Approved	Published Report (DOT/FAA/CT-90-15)
Dual and Quadruple	3	11/29/89-2/9 1990	DFW	5000 & 5800 ft 8800 ft	DEDS	ASR-9 4.8s		Approved	Published Report (DOT/FAA/CT-TN89/28-1)
Triple and Quadruple	13	9/8-9/25 1992	High-Altitude Study	7600 ft 5280 ft 5348 ft	ARTS III	ASR-9 4.8s	Field Elevation 5431 ft	No Recommendation Made	Memorandum
MPAP Summary Report	20	12/ 1999	National Standard and Site-Specific Results	Published Report (DOT/FAA/CT-TN99/24)					

Table C-1

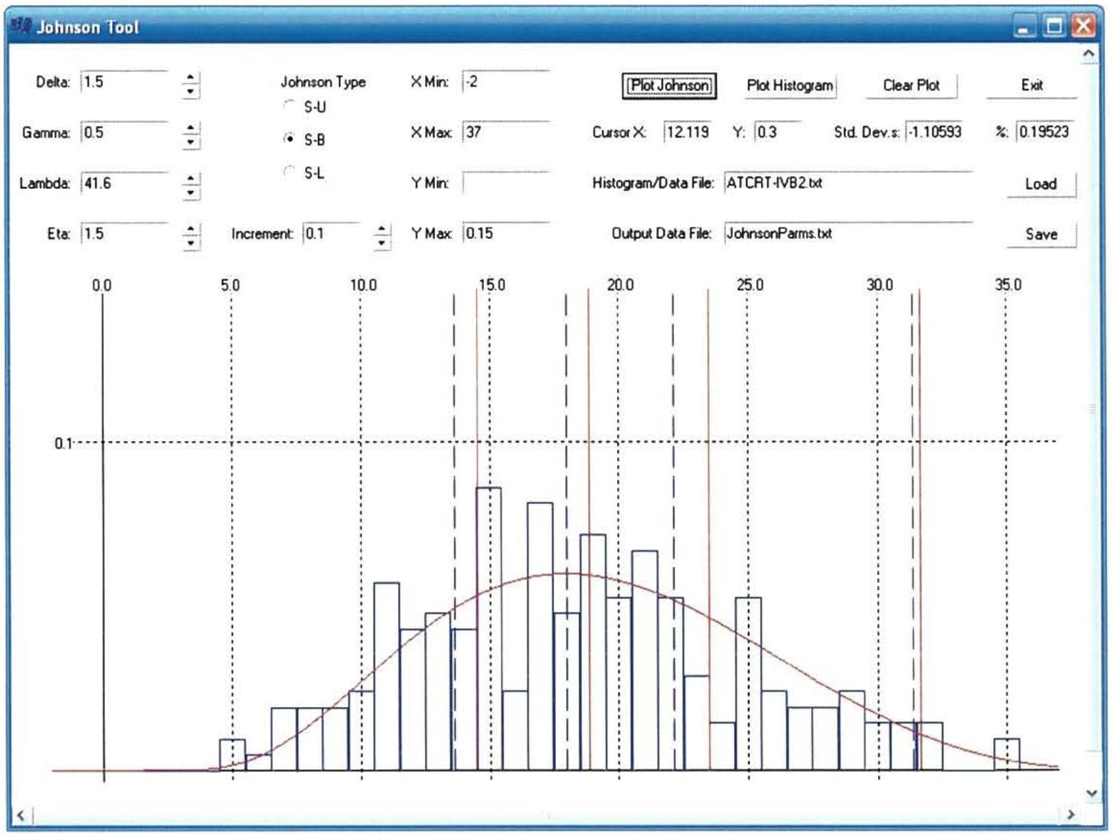

Figure C-1. ATC Response Time Distribution

Appendix D

Risk Analysis

Several events must occur simultaneously for a collision to occur during simultaneous instrument approaches. Clearly, a blunder must occur, or there would be no significant deviation from course. Previous testing has shown that blunders other than WCBs are of negligible risk, so the blunder must be a WCB. Also, the blundering aircraft must have a critical alignment with an aircraft on an adjacent course (i.e., it must be at risk). If all of the above events develop, a TCV will occur if the controller and pilots cannot react in sufficient time to separate the blundering and the evading aircraft. In addition, one collision will involve two aircraft and will probably produce two accidents, as defined by the National Transportation Safety Board (NTSB).

Assuming that a TCV will result in a collision, the probability of a collision accident can be expressed in mathematical terms by:

(1) P(Accident) = P(TCV and At-risk and WCB and Blunder) x 2

or

(2) P(Accident) = P(TCV|At-risk and WCB and Blunder) x
P(At-risk|WCB and Blunder) x
P(WCB|Blunder) x
P(Blunder) x 2

Where:

- P(TCV and At-risk and WCB and Blunder) is the probability of all relevant events occurring simultaneously (i.e., an at-risk WCB that results in a TCV).
- P(TCV|At-risk and WCB and Blunder) is the probability that a TCV occurs given that an at-risk WCB has occurred. This quantity is estimated by the simulation of at-risk WCBs in the real-time and Monte Carlo simulations (i.e., the TCV rate in the simulation).
- P(At-risk|WCB and Blunder) is the probability that a WCB has critical alignment with an aircraft on an adjacent approach. Analysis conducted in preparation for this simulation indicates that a value of 1/17 is a good approximation of this quantity, given 3 NM in-trail spacing.
- P(WCB|Blunder) is the probability that a blunder is a WCB. This probability is unknown, but is estimated to be approximately 1/100 (PRM Demonstration Report, 1991).
- P(Blunder) is the probability that a blunder occurs during a simultaneous instrument approach. This rate is also unknown, but is estimated to be no more than 1/2000 approaches (or 1 for 1000 dual approaches). This is a conservative value derived from the risk analysis conducted during the PRM demonstration

program. Until a blunder rate estimate can be derived from field data of actual blunder occurrences or other evidence suggests using a different value, the TWG has agreed to use 1/1000 30-degree blunders per dual approach pair. Researchers can show the rate for triple approaches to be 1/1500 30-degree blunders per triple approach trio.

- The factor of 2 represents two accidents per collision.

Target Level Of Safety

The total number of air carrier accidents, as well as the number of fatal accidents on final approach, has been extracted from NTSB data for the time period, 1983-1989. This number, together with the total number of ILS approaches flown during this time period, leads to an estimated fatal accident rate during ILS operations performed during IMC of 4×10^{-7} fatal accidents per approach. There are a number of causes of accidents during final approach, such as structural failure, engine failure, or midair collision. An initial estimate is that there are nine possible causes of accidents on final approach. A tenth possible accident cause, a collision with an aircraft on an adjacent approach, is created with the implementation of simultaneous parallel approaches. For simplicity of model development, it is assumed that the risks of the ten potential accident causes are equal. Thus the contribution of any one of the accident causes would be one-tenth of the total accident rate. Based on this, the target safety level for midair collisions on simultaneous parallel approaches is 4×10^{-8}, or:

1 accident / 25 million approaches

Maximum Allowable Test Criterion Violation Rate

Since the only undefined variable in equation (2), used to compute the maximum acceptable accident rate, is the TCV rate, it is possible to determine the maximum allowable TCV rate which would meet the target level of safety. Knowledge of this number would allow the TWG to quickly decide if the simulated operation would meet the target level of safety. The maximum allowable TCV rate may be found from following analysis.

Given the target level of safety, P(Accident) = 4×10^{-8}, then the equation (2) becomes:

$$P(TCV|\text{At-risk and WCB and Blunder}) \times P(\text{At-risk}|\text{WCB and Blunder}) \times P(WCB|\text{Blunder}) \times P(\text{Blunder}) \times 2 = 4 \times 10^{-8}$$

or,

(3) P(TCV|At-risk and WCB and Blunder) =

$$\frac{4 \times 10^{-8}}{1} \times \frac{1}{P(\text{At-risk}|\text{WCB and Blunder})} \times \frac{1}{P(WCB|\text{Blunder})}$$

$$\times \frac{1}{P(\text{Blunder})} \times \frac{1}{2}$$

Substituting values from (2) into (3):

(4) P(TCV|At-risk and WCB and Blunder) =

$$\frac{4 \times 10^{-8}}{1} \times \frac{17}{1} \times \frac{100}{1} \times \frac{1500}{1} \times \frac{1}{2} = 5.1\%$$

Thus, if the simulation results support the assertion that the probability of a TCV, given that an at-risk WCB occurs (P(TCV|At-risk and WCB and Blunder)), is less than 5.1 percent, then the simultaneous approach procedure simulated should have an acceptable accident rate. For the embedded duals, the factor 1500 was replaced by 2000 and the allowable percentage became 6.8 percent.

Appendix E

Johnson Distributions

The Johnson family of empirical distributions is based on transformations of a standard normal variate. An advantage of such a transformation is that estimates of the percentiles of the fitted distribution can be obtained either from a table of areas under a standard normal distribution or from a computer program which computes areas under a standard normal distribution. Another advantage is that during a Monte Carlo simulation, variates from the distribution are readily computed from the standard normal distribution. The Johnson distributions also can be fitted to the data with relative ease compared to the Pearson distributions. The Johnson distributions are divided into three families as follows:

1. The S_L family is characterized by the transformation:

$$z = \gamma + \delta \ln\left(\frac{x-\varepsilon}{\lambda}\right),\ x > \varepsilon, \quad (1)$$

Where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is bounded on the left by ε and is unbounded on the right. By performing a certain transformation of the parameters δ and γ the curves can be converted to the log-normal distribution.

2. The S_B family is characterized by the transformation:

$$z = \gamma + \delta \ln\left(\frac{x-\varepsilon}{\lambda+\varepsilon-x}\right),\ \varepsilon < x < \varepsilon + \lambda. \quad (2)$$

Where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is bounded on the left by ε and on the right by ε + λ. These curves resemble the Weibul or extreme-value families. The parameters γ and δ are shape parameters, ε is a location parameter, and λ is a scale parameter.

3. The S_U family is characterized by the transformation:

$$z = \gamma + \delta \sinh^{-1}\left(\frac{x-\varepsilon}{\lambda}\right),\ -\infty < x < \infty. \quad (3)$$

Where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is unbounded and unimodal. The parameters γ and δ are shape parameters, ε is a location parameter, and λ is a scale parameter.

In order to use the Johnson family of curves it is necessary to invert equations 1, 2, and 3, i.e., each of the equations must be solved for x.

1. The S_L transformation after inversion is:

$$x = \varepsilon + \lambda \exp\left(\frac{z-\gamma}{\delta}\right), \quad -\infty < z < \infty. \qquad (4)$$

2. The S_B transformation after inversion is:

$$x = \varepsilon - \frac{\lambda}{1-\exp\left(\frac{\gamma - z}{\delta}\right)}, \quad -\infty < z < \infty. \qquad (5)$$

3. The S_U transformation after inversion is:

$$x = \varepsilon + \lambda \sinh\left(\frac{z-\gamma}{\delta}\right), \quad -\infty < z < \infty. \qquad (6)$$

Since the variable z in each transformation is a standard normal variate, the probability distribution of each Johnson family of curves may be determined from a normal table.

1. The probability density function of a member of the Johnson S_L family has the following form:

$$f_1(x) = \frac{\delta}{(x-\varepsilon)\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\gamma + \delta \ln\left(\frac{x-\varepsilon}{\lambda}\right)\right]^2\right\}, \quad x \geq \varepsilon,$$

$$\delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$$

2. The probability density function of a member of the Johnson S_B family has the following form:

$$f_2(x) = \frac{\delta\lambda}{(x-\varepsilon)(\lambda - x + \varepsilon)\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\gamma + \delta \ln\left(\frac{x-\varepsilon}{\lambda - x + \varepsilon}\right)\right]^2\right\},$$

$$\varepsilon < x < \varepsilon + \lambda, \delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$$

The probability density function of a member of the Johnson S_U family has the following form:

3.

$$f_3(x) = \frac{\delta}{\sqrt{2\pi\left[(x-\varepsilon)^2 + \lambda^2\right]}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \ln\left\{\left(\frac{x-\varepsilon}{\lambda}\right) + \left[\left(\frac{x-\varepsilon}{\lambda}\right)^2 + 1\right]^{1/2}\right\}\right)^2\right],$$

$$-\infty < x < \infty, \delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$$

Sampling From a Johnson Curve.

After the appropriate Johnson curve has been selected and the parameters γ, δ, ε, and λ have been determined, then it is a simple matter to select random variates from the Johnson distribution. The method involves the following steps:

1. Select two random numbers r_1 and r_2 from the uniform interval (0, 1).

2. Use one of the *Box-Muller* equations to compute a random variate z from the standard normal distribution, N(0, 1).

3. Substitute z into the appropriate Johnson transformation. If the Johnson curve is of type S_L then substitute z into equation (4) to obtain the random variate x. If the Johnson curve is of type S_B then substitute z into equation (5) to obtain the random variate x. If the Johnson curve is of type S_L then substitute z into equation (6) to obtain the random variate x.

Appendix F

ASAT Input Files

1. APF file: Fleet mix, Aircraft actions, Links to airport and CRM data, and Air Traffic and Pilot response time parameters

```
---------------------------------------------------------
Description: KIAH Runways 08L 08R and 09
;
;       Aircraft types and % of overall traffic
;       ---------------------
Aircraft:       DATA\\A320.TXT
PercentageMix:       54                    ;

Aircraft:       DATA\\ATR42.TXT
PercentageMix:        8           ;

Aircraft:       DATA\\B727.TXT
PercentageMix:       11                    ;

Aircraft:       DATA\\B732.TXT
PercentageMix:       305                   ;

Aircraft:       DATA\\B738.TXT
PercentageMix:       300                   ;

Aircraft:       DATA\\B752.TXT
PercentageMix:        70          ;

Aircraft:       DATA\\B777.TXT
PercentageMix:       41                    ;

Aircraft:       DATA\\ERJ.TXT
PercentageMix:       759                   ;

Aircraft:       DATA\\F100.TXT
PercentageMix:       87                    ;

Aircraft:       DATA\\MD88.TXT
PercentageMix:       40                    ;

Aircraft:       DATA\\SAAB.TXT
PercentageMix:       94                    ;
```

```
AirportFile: Airports & ASAT Projects\\KIAHE.out

ScenarioNumber:     1
;       Active runways (from LEFT to RIGHT)
;       ------------------
;       Make sure the BLUNDER is [0] and the EVADER is [1] !!!
Runway:             08L
FlightMode:     REJECT
Runway:             08R
FlightMode:     REJECT
Runway:             09
FlightMode:     REJECT

;       Air Traffic Control Response Time Definition
;       ------------------------
; GRM22 TC tests with 5000 triples & ARTs GRM PDF 11/28/05
AtcJohnsonType:     1
AtcXi:              1.5
AtcLambda:      41.6
AtcDelta:       1.5
AtcGamma:           0.5
AtcMin:         3.0
AtcMax:         30.0
AtcDeltaTime:       0.0
; GRM22

;       Pilot response type
;       ----------
; GRM18
PilotJohnsonType:  2            ;1:SB  2:SL  3:SU  pdf by grm 12/01/05
PilotXi:        0.5
PilotLambda:        12.7
PilotDelta:     2.04
PilotGamma:         1.98
PilotMin:       1.0
PilotMax:        17.0
PilotDeltaTime:            -1.0           ;roll time to 3 degrees which is what times
are based on
; GRM18

CrmData:      DATA\\CAT1030.TXT                  ;         CRM distributions
```

2. Air Description: Airport and runway coordinates

```
-------------------------------------------------------------------------------------------
AirportName       : HOUSTON INTERCONTINENTAL
AirportIdentifier : KIAH
AirportLocation   : HOUSTON
AirportState      : TX
AirportLatLon     : 29 58 49.73,     095 20 22.98
AirportElevation  : 98
AirportMagVarYr   : 1985
;- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
RunwayName         : 26L
RunwayTrueBearing  : 270
RunwayLength       : 9401
RunwayThLatLon     : 29 59 36.38, 095 19 30.95
RunwayThElevation  : 93

RunwayName         : 26R
RunwayTrueBearing  : 270
RunwayLength       : 9401
RunwayThLatLon     : 30 0 25.86, 095 19 49.29
RunwayThElevation  : 93

RunwayName         : 27
RunwayTrueBearing  : 270
RunwayLength       : 9999
RunwayThLatLon     : 29 58 39.41,  095 18 09.09
RunwayThElevation  : 85
```

Appendix G ASAT Output File

ASAT Output file for C:\ASAT4ILSRNP\Airports & ASAT Projects\KIAH

RunNumber	AcType2	AcType1	CPA2D	CPA3D	BATCRT	BPRT	EATCRT
1	ERJ	B732	4607.3	4614.6	15.4	3.2	13.6
2	B732	F100	2926.1	2932.8	27.8	3.1	17.4
3	B732	ERJ	1666.6	1666.7	18.7	3.1	25.2
4	F100	F100	3042.4	3042.6	15.1	2.4	9.7
5	B738	ERJ	2399.8	2431.7	10.7	5.0	19.1

Total Number of Runs : 5

Right half of output -----→
on next page -----→

TCV Range: 500[Ft]
NTCV2D(LCR): 0 / 5
NTCV3D(LCR): 0 / 5

NTCV2D(LC) : 0 / 3
NTCV3D(LC) : 0 / 3

NTCV2D(CR) : 0 / 2
NTCV3D(CR) : 0 / 2

Notes:
RunNumber: Run Number
AcType2: Aircraft Type of Evader aircraft
AcType1: Aircraft Type of Blundering aircraft
CPA2d: Closest Point of Approach in system plane (2-dimensional)
CPA3d: Closest Point of Approach – slant range (3-dimensional)
BATCRT: Blunderer ATC Response Time
BPRT: Blunderer Pilot Response Time
EATCRT: Evader ATC Response Time
EPRT: Evader Pilot Response Time
TCV2D: Flag
TCV3D: Flag
BlunderStatus: Which aircraft blunders which way
TCV: Same as TCV3D
Rwy: Evader Runway
NAV: Evader Nav Mode (1=RNP 0.1, 2=RNP 0.2, 3=RNP 0.3)
Blunder Range: Range from thld when blunder initiated
Edev: Evader crosstrack deviation at ATC response to blunder

27 26L 26R.apf ASAT project input file

EPRT	TCV2D	TCV3D	BlunderStatus	TCV	Rwy	NAV	Blunder Rge	Edev
3.1	0	0	C_Blunders_to_Left	0	0	3	73016.4	-401.3
6.9	0	0	L_Blunders_to_Center	0	1	3	26372.5	789.4
2.5	0	0	C_Blunders_to_Right	0				
2.9	0	0	C_Blunders_to_Right	0				
3.6	0	0	L_Blunders_to_Center	0	1	3	89558.6	-335.8

Appendix H

RNP Distribution Rationale

The following e-mail from Bruce DeCleene, AIR-130 addresses RNP parallel approaches. Relevant portions are highlighted. Most of the points in the message will be addressed in the final report to support development of generic criteria.

All-

With respect to our discussion today on RNP-based parallel approaches:

* We can define the RNP as part of the approach design. **It is appropriate to use a Normal distribution with a 95% value equal to the RNP value as a bound on the total system accuracy.** I.e., to achieve a 95% total error equal to 1500' we could specify RNP-0.24 (1500' might be appropriate, assuming 5000' runway spacing and 2000' NTZ centered between runways).

* In reality, the "ANP" displayed in the aircraft in driven by the two-RNP containment requirements and not the 95% accuracy. The fault-free total error distribution (neglecting satellite faults, FMC faults, etc which would be detected through controller intervention) is driven by the flight control mode and sensor input. Data from Boeing is provided in the various RNP Capability documents, and is summarized as follows (also captured in the attached matrix):

+ Flight control mode (FTE): Autopilot<= 0.088 NM (95%), flight director <= 0.206 NM (95%), Normal distribution with zero mean
+ Position estimation error (NSE): Real GPS error < 36 m (GPS SPS Performance Standard), certified value is <= 100 m (95% {was when selective availability was on}
+ Path definition error is negligible

+ Yields total error (95%) of 637' for autopilot and 1293' for flight director (using the conservative 100m number for GPS)

Note that routine operations should be substantially better than the above numbers indicate. See the B757/767 document for a long discussion of the Boeing data, they basically took a lot of data for the 747 FTE and a small amount of data for the 757 and determined that it is an appropriate hypothesis to take the 747 data and apply it to the 757. The 747 data is not the 95% FTE directly, but the 99%-confidence estimate of the 95% error. In addition, the GPS error is actually more like 10 m (excluding latency) based on FAA TC data.

My recommendation for the analysis is:
a) use Normal distribution with zero mean (appropriate when considering a single aircraft)
b) define the NOZ to be equal to the RNP (operationally conservative since RNP is constrained by monitoring requirements)
c) center the NOZ between the paths (consistent with past practice)
d) determine the RNP that is required to support various runway spacings of (4300' out to whatever is supported by RNP-0.3 (5650'?)

-Bruce

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