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To Closely Spaced Parallel Runways**

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NASA RESEARCH FOR INSTRUMENT APPROACHES TO CLOSELY SPACED PARALLEL RUNWAYS

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ABSTRACT

Within the NASA Aviation Systems Capacity Program, the Terminal Area Productivity (TAP) Project is addressing airport capacity enhancements during instrument meteorological conditions (IMC). The Airborne Information for Lateral Spacing (AILS) research within TAP has focused on an airborne centered approach for independent instrument approaches to closely spaced parallel runways using Differential Global Positioning System (DGPS) and Automatic Dependent Surveillance-Broadcast (ADS-B) technologies. NASA Langley Research Center (LaRC), working in partnership with Honeywell, Inc., completed an AILS simulation study, flight test, and demonstration in 1999 examining normal approaches and potential collision scenarios to runways with separation distances of 3,400 and 2,500 feet. The results of the flight test and demonstration validate the simulation study.

ACRONYMS AND ABBREVIATIONS

| | |
|--------|--|
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| AILS | Airborne Information for Lateral Spacing |
| CSPA | Closely Spaced Parallel Approach |
| DGPS | Differential Global Positioning System |
| EADI | Electronic Attitude Director Indicator |
| EEM | Emergency Escape Maneuver |
| IFD | Integrated Flight Deck |
| ILS | Instrument Landing System |
| IMC | Instrument Meteorological Conditions |
| LaRC | Langley Research Center |
| MANOVA | Multivariate Analysis of Variance |

| | |
|----------|--|
| MSP | Minneapolis-St. Paul |
| NASA | National Aeronautics & Space Administration |
| ND | Navigation Display |
| PRM | Precision Runway Monitor |
| RA | Resolution Advisory |
| RTO | Rejected Take Off |
| SLS-2000 | Honeywell Satellite Landing System-2000 |
| TA | Traffic Advisory |
| TAP | Terminal Area Productivity |
| TCAS | Traffic Alert And Collision Avoidance System |
| TLX | Task Load Index |
| WFF | Wallops Flight Facility |

INTRODUCTION

Currently, a number of U. S. airports experience a significant arrival capacity decrease during instrument conditions due to the loss of simultaneous operations to closely spaced parallel runways. Today, the minimum parallel runway separation for independent instrument approaches is 4,300 feet unless a Precision Runway Monitor (PRM) is used to enable approaches to runways as close as 3,400 feet.¹

NASA's Aviation System Capacity Program is addressing airport capacity enhancements during instrument meteorological conditions (IMC) within the Terminal Area Productivity (TAP) Project. Within TAP, the Airborne Information for Lateral Spacing (AILS) research has focused on the development of an airborne centered approach for independent instrument approaches to parallel runways as close as 2,500 feet using Differential Global Positioning System (DGPS) and Automatic Dependent Surveillance-Broadcast (ADS-B) technologies. The AILS concept employs DGPS based precision instrument approaches in conjunction with an ADS-B data link between participating aircraft to exchange state vector information and process algorithms for flight technical error and collision threat alerting.

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NASA Langley Research Center (LaRC), working in partnership with Honeywell, completed an AILS simulation study in 1999 examining normal and potential collision scenarios utilizing sixteen airline pilot test subjects, each paired with a research pilot serving as first officer. Autocoupled and manual approaches to runways with centerline separation distances of 3,400 feet and 2,500 feet were studied with intrusion miss distances (distance of closest encounter), pilot reaction times and pilot acceptability as the critical factors. The results of the study supported the AILS concept. Specifically, miss distances during all runs were greater than 1,000 feet, the pilot reaction times were within acceptable norms, and the AILS procedures were rated as acceptable by all test subjects. The simulation study results were validated in a follow-on flight test at the NASA Wallops Flight Facility and in a demonstration at the Minneapolis - St. Paul International Airport (MSP) using the NASA B-757 and Honeywell G-IV aircraft. Each aircraft was equipped with AILS/Traffic Alert and Collision Avoidance System (TCAS), Mode-S/ADS-B, and DGPS hardware for the flight test and demonstration. For the flight test, six of the airline pilot test subjects from the simulation study flew a subset of the potential collision scenarios investigated in the simulation study and achieved the critical objective of simulation study validation with very similar results. Additionally, the MSP demonstration provided the opportunity to validate the AILS concept in revenue airport airspace and to provide industry and government insight into the AILS concept.

THE AILS SYSTEM

The fundamental principle governing the AILS system is the transfer of lateral separation responsibility to the flight deck during parallel approaches, while still making sure that the paired aircraft remain in their assigned airspace on the approach. The primary components that have made this capability possible are navigation using DGPS, data link using ADS-B, AILS alerts hosted in the TCAS box, and operational procedures.² The technologies involved are not new, but working in concert they provide the unique capability of allowing pilots to detect and avoid possible encroaching traffic while flying closely spaced parallel instrument approaches.

The AILS system relies on ADS-B communications to broadcast highly accurate information between paired aircraft. A Mode-S transponder was used to communicate the mode of the system. The aircraft was considered "equipped" if it had the AILS configuration and "armed" if it was successfully exchanging AILS-specific ADS-B

messages. In addition to this data link between aircraft, each aircraft flew a DGPS, ILS look-alike precision approach. A one-way link between the ground station and the aircraft provided the approach data (latitude, longitude, glide slope angle, runway slew angle, etc.) that the AILS algorithms used to make its calculations. The alerts, coupled with a precise set of procedures for an EEM, made the AILS system complete. Throughout the design of the AILS system, considerable emphasis was placed on a cost-effective implementation to existing aircraft fleets and new aircraft alike.³

Displays and Alerts

The EADI and ND displays were modified to host AILS alert messages and symbols. The primary purpose of the alerts was for flight path management where accurate navigation was required to keep each aircraft on its respective course. Intrusion alerts were generated for situations where the parallel traffic strayed from its course and approached the path of the ownship in a threatening manner. Table 1 describes all the alerts and what was annunciated on the AILS displays in each instance.

| Alert State | Level | Description | |
|-------------|----------|--------------|-------------------|
| | | Annunciation | Ownship State |
| localizer | advisory | LOCALIZER | Off by 1 dot |
| localizer | caution | LOCALIZER | Off by 2 dots |
| path | caution | PATH | Off path |
| path | warning | CLIMB TURN | Off path |
| traffic | caution | TRAFFIC | Intruder off path |
| traffic | warning | CLIMB TURN | Intruder off path |

Table 1. AILS Alert Table

The EADI and ND displays used to support the AILS concept were derived from adding AILS specific display information symbols. An example of the two AILS displays is shown in Figure 1. The EADI was modified to display text messages signaling the alert state (see Table 1). The ND with the existing TCAS symbol set was modified for AILS as well. Ground track vectors were added to TCAS traffic symbology. This feature proved valuable just before an EEM when the adjacent aircraft was threatening the ownship. The ND was also enhanced with a 2 NM range scale option

in order to give pilots a better perception of how close the adjacent aircraft was to the ownship.

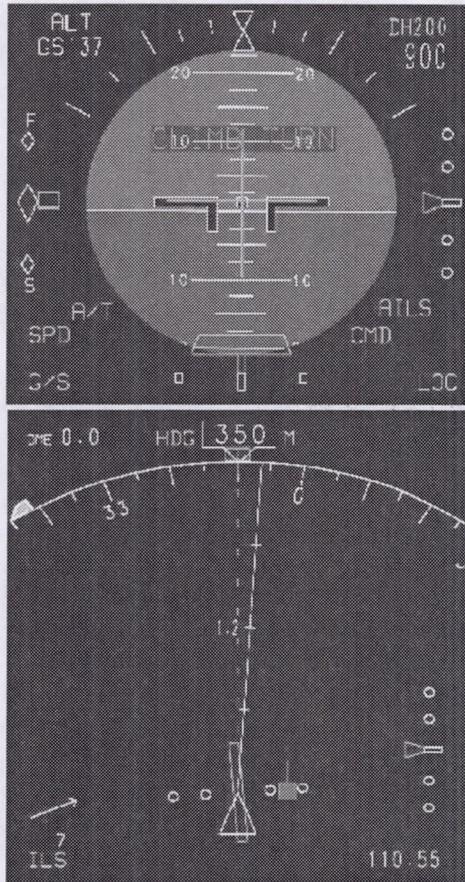


Figure 1. EADI and ND showing AILS symbology

Another valuable addition to the ND was an escape heading bug which was automatically set on the compass rose at the AILS procedural escape heading of 45 degrees from the approach heading and in the direction away from the parallel traffic and runway.⁴ This bug was automatically set when the AILS algorithms were activated, which occurred when the two AILS equipped aircraft did an electronic “hand shake” for pairing at approximately 10 NM from the runway threshold.

AILS Procedures

To ensure that the cockpit crew was prepared for the AILS approach and its responsibilities while conducting the approach, some additional procedures were developed for the AILS approaches. A special AILS briefing was conducted by the pilot flying prior to entering the AILS portion of the approach. This briefing included the AILS landing runway, the direction of the emergency escape turn, and the EEM

altitude and heading. For example, “This will be an AILS approach to runway 35R. In the event of an EEM, I will make a climbing right turn to a heading of 036 degrees and will climb to 3,200 feet.” The pilot flying then announced when the green AILS heading bug and the green “AILS” on the EADI were in view. These symbols remained on the display throughout the AILS approach. These annunciations indicated that the normal TCAS RA and TA alerts were inhibited for the other AILS aircraft and the AILS alerts were operational. At this point, strict compliance with the flight path was required, and compliance with warning and caution alerts was mandatory.

Some airlines, but not all, require their pilots to keep their hands and feet on the controls during autocoupled approaches in order to guard the controls and throttles. When the AILS “path” or “traffic” alerts were annunciated, the AILS procedures required the pilots to simply keep their hands and feet on the controls so that they were prepared to disconnect the autothrottle and autopilot and follow the EEM procedure in case a “Climb Turn” warning followed.

Emergency Escape Maneuver Procedures

Although the probability of an EEM is very low, if it is ever needed, however, it must be accomplished quickly and precisely. The receipt of a “CLIMB TURN” warning indicates imminent danger of a mid-air collision.⁵ In order to execute an EEM (i.e., upon receipt of a “CLIMB TURN” warning,) the pilot should disconnect the auto-throttle, if engaged, select go-around thrust, and turn to the 45-degree escape heading.

The EEM is different from and should not be confused with a normal go-around. There was no flight director guidance for the EEM and the test subject pilots who participated in the AILS experiments were advised not to follow the flight director or the approach raw data since they were still referencing the normal approach.

PHASE ONE: PARAMETRIC ANALYSIS

After the AILS algorithms were developed, Honeywell conducted a computer-based parametric analysis to evaluate the performance of the alerting system and determine time thresholds for triggering the alerts⁶. Honeywell researchers simulated over 150,000 scenarios with two aircraft on parallel approaches where one crossed the other’s path, alerts were generated and EEMs were performed. A safety buffer was designed to reserve 900 feet on both sides, and 2500 feet in front and behind each aircraft. None of the scenarios used in this analysis generated a false alert. Therefore, when

the intruder followed a "normal" trajectory no alerts were issued, and when the intruder intruded, the appropriate alerts were issued.

Honeywell determined alert probabilities including the probability of a successful alert, the probability of an unnecessary/nuisance alert (different from a false alert), and the probability of a collision given an alert. Also defined by this parametric analysis was the average miss distance after an alert to measure how well the alerting system kept the aircraft separated. These values, along with findings from previous AILS studies provided a baseline for the 1999 AILS simulator study.^{7,8,9}

PHASE TWO: SIMULATION STUDY

The goal of the simulator phase of the study was to validate through experimentation that a pilot's response to an AILS alert was not affected by operational variations such as the flight control mode used by the pilot during the approach, the runway separation or the geometry of the intruder's path. The experiment was designed with two independent variables, runway separation (2,500 and 3,400 feet) and flight control mode (autocoupled and manual), and three dependent measures, reaction time, miss distance (distance of closest encounter) and subjective workload. The subjects were required to fly the EEM in the manual mode.

| Mode | Runway Spacing | | | | | | | | | | | |
|--------|----------------|---|---|---|---|---|---------|---|---|---|---|---|
| | 2500 ft | | | | | | 3400 ft | | | | | |
| | Scenarios | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 |
| Auto | X | X | X | X | X | X | X | X | X | X | X | X |
| Manual | X | X | X | X | X | X | X | X | X | X | X | X |

Table 2. AILS Run Matrix

The experiment was a full factorial experiment with randomized blocks. The blocks were by both runway spacing and control mode. To counteract learning, each of the six encounter scenarios was masked to look different to the subjects while preserving the characteristic of the geometry.

Methods and Procedures

The subject pool consisted of 16 Boeing 757 type rated pilots currently employed by commercial airlines.

A random mix of captains and first officers participated. The subjects were trained individually and a training script was used to achieve consistency. The subjects were given a 50-minute classroom briefing on how to interpret and respond to the AILS alerts, then a hands-on session was conducted in the NASA Integrated Flight Deck (IFD) simulator. The IFD is a fixed-based simulator, which closely replicates the B-757 cockpit. At the end of the classroom briefing, a simple quiz was given to determine how much the subjects understood about AILS and its procedures. Deficiencies evident through a less-than-perfect score were corrected before the subject moved on to the simulator-flying phase of the experiment. As part of the simulator training, the pilots were given the opportunity to fly several AILS approaches. The first time was for familiarization (no alerts were issued.) During the second approach, they were exposed to a wind shear alert. Their performance during this run served as a baseline indicating how they performed in an emergency situation that was similar to one that would trigger an AILS alert. The remaining runs emphasized how the EEM should be executed as well as reinforcing the meaning of the AILS alerts.

One day after the subjects were trained, they returned for the data collection phase of the experiment. Each pilot flew the simulator from the left seat accompanied by a research first officer in the right seat. The paired aircraft, the intruder, was a simulated AILS-equipped aircraft. Each run began with both aircraft on the final approach approximately 14 miles from the runway threshold. The subjects were expected to approach the runway as they normally would for landing, conforming to normal instructions from the ATC unless an alert was issued.¹⁰ Each subject completed 24 runs which included 20 runs where the parallel traffic turned off-course toward the test subject's aircraft. These intrusion scenarios therefore represented a worse case situation where the intruding aircraft failed to respond to its alerts and subsequently caused the ownship to execute the EEM.^{11,12} The six intrusion scenarios were:

- (1) intruder faster than ownship and passing ahead
- (2) intruder faster than ownship passing behind
- (3) intruder faster than ownship on a collision path
- (4) intruder slower than ownship and passing ahead
- (5) intruder slower than ownship and passing behind
- (6) intruder slower than ownship on a collision path

The pilots' perceived workload was measured by administering the NASA Task Load Index (TLX) survey each time they changed flight control modes and at the end of the experiment. A structured questionnaire was also given at the end of the experiment.

PHASE THREE: FLIGHT TEST

The primary purpose of the flight experiment was to validate the experimental data findings obtained in the simulator. To this end, a subset of the simulator study runs was performed in flight. The flight test was conducted at NASA Wallops Flight Facility (WFF) using the NASA B-757 as the ownship and the Honeywell G-IV as the intruder. The six pilot test subjects who participated in the flight test were B-757 type-rated captains who were selected from the 16 simulator subject population. Each subject flew a total of 6 intrusion scenarios in the flight test, a subset of the number they had flown in the simulator. The intrusion scenarios were:

- (1) intruder slower than ownship and passing behind
- (2) intruder faster than ownship passing behind
- (3) intruder faster than ownship on a collision path

Figure 2 shows one of the flight trajectories flown by ownship and the intruder. Note the points at which the caution and warning alerts were triggered and the predicted closest point of approach (CPA).

Runway 35 at WFF was selected based on the desirability to operate south of the airport. In addition to the existing Runway 35, two additional "pseudo" parallel runways were created, one representing the 2,500 feet lateral separation, the other 3,400 feet. The aircraft were "staged" for each approach to achieve the desired initialization point of the encounter and at the desired speed and to closely replicate the intrusion scenarios of the simulator study.

DGPS course guidance was provided by Honeywell's version of a GPS Landing System, a Satellite Landing System (SLS-2000), which uses Differential GPS for guidance. Each final approach course was offset 2 degrees outboard from the extended runway centerline to alleviate the problem of overlapping azimuth courses. The extended centerline of the runway and the final approach course intersected 0.44nm (2,676 ft) from the runway threshold. The glide slope was 3 degrees for all approaches.

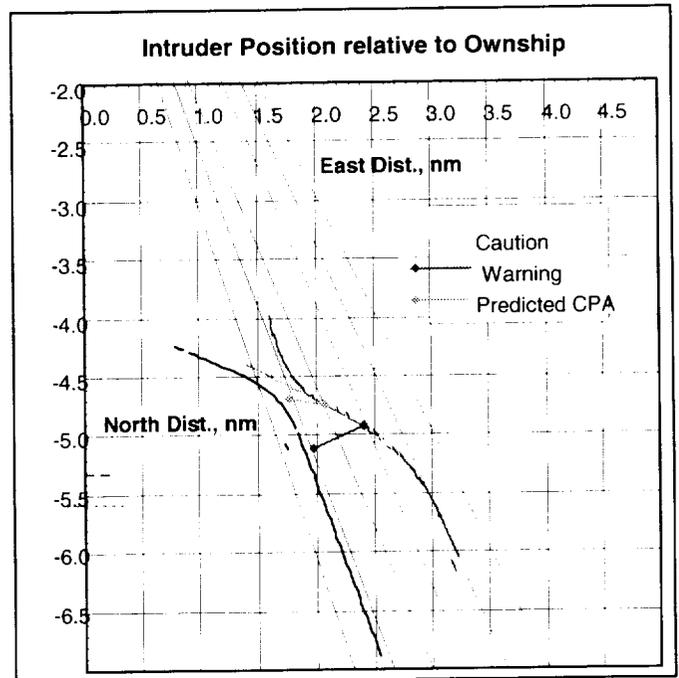


Figure 2. Intruder Position relative to Ownship

SUMMARY OF SIMULATION AND FLIGHT RESULTS

Statistical analyses were done using the MINITAB™ version 13 statistics package. Multivariate analysis of variance (MANOVA) was used to test the effect of the factors, flight control mode, runway separation, scenario, aircraft speeds, and interaction effects of these combined factors on both the reaction time and miss distance. T-tests were conducted to test that the mean reaction time would be less than 2 seconds (a design goal) and that the mean miss distance would be equal to 1,200 ft (also a design goal). In addition, a χ^2 test of the variance was conducted for a miss distance of $1,200 \pm 500$ ft.¹³ These tests not only considered the individual responses, but also the correlation and co-variances between and within the factors and responses. Although the flight data set was not meant to be a statistically valid sample, the trends acquired in flight followed those of the simulator and therefore met the intent of validating the findings from the simulator.

| Source | Degrees of freedom | Sequential sum of squares | Adjusted sum of squares | Adjusted mean square | F | P-value |
|-------------------|--------------------|---------------------------|-------------------------|----------------------|-------|---------------------|
| Control mode | 1 | 3.919 | 3.9088 | 3.9088 | 20.07 | 0.0000 [†] |
| Runway separation | 1 | 0.1594 | 0.1594 | 0.1594 | 0.82 | 0.366 |
| Error | 313 | 60.9515 | 60.9515 | 0.1947 | | |
| Total | 315 | 65.0299 | | | | |

Table 3a. MANOVA of Simulator Reaction Times

| Source | Degrees of freedom | Sequential sum of squares | Adjusted sum of squares | Adjusted mean square | F | P-value |
|-------------------|--------------------|---------------------------|-------------------------|----------------------|------|---------|
| Control mode | 1 | 237938 | 241913 | 241913 | 1.05 | 0.306 |
| Runway separation | 1 | 413047 | 413047 | 413047 | 1.79 | 0.181 |
| Error | 313 | 72073323 | 72073323 | 230266 | | |
| Total | 315 | 72724308 | | | | |

Table 3b. MANOVA of Simulator Miss Distances

Test of Reaction Time Hypotheses

The statistical analyses presented here were based on the assumption that the scenarios had no effect on the reaction time and miss distance and that only the effects of flight control mode and runway separations were being investigated. The null hypotheses, H_{0i} , and the alternate hypotheses, H_{ai} were tested for each case.

- H_{01} : Mean RT_A = Mean RT_M
- H_{02} : Mean RT_{25} = Mean RT_{34}
- H_{a1} : Mean $RT_A \neq$ Mean RT_M
- H_{a2} : Mean $RT_{25} \neq$ Mean RT_{34}

As shown in the MANOVA Table 3a above, the first null hypothesis was rejected with a P-value of 0.0000. This means that based on the experimental results, at a significance level of $\alpha = 0.05$, there was a significant difference between the mean reaction time in the autopilot mode (RT_A) and the mean reaction time in the manual mode (RT_M). We failed to reject the second null hypothesis. This means that based on the experimental results, there was not a significant difference between the mean reaction time when approaching runways that were 2,500 feet apart (RT_{25}) and the mean reaction time when approaching runways that were 3,400 feet apart (RT_{34}).

In other words, the flight control mode indeed had a statistically significant effect on the reaction time. As explained later in the questionnaire section, the test subjects did not validate this fact, possibly because the difference was too small for human perception. The

runway separations, on the other hand, did not have a significant effect on the recorded reaction times.

Test of Miss Distance Hypotheses

To investigate whether the miss distances were affected by the flight control mode or the runway separation, null hypotheses H_{03} and H_{04} and alternate hypotheses H_{a3} and H_{a4} were tested.

- H_{03} : Mean MD_A = Mean MD_M
- H_{04} : Mean MD_{25} = Mean MD_{34}
- H_{a3} : Mean $MD_A \neq$ Mean MD_M
- H_{a4} : Mean $MD_{25} \neq$ Mean MD_{34}

Based on a significance level of $\alpha = 0.05$, we failed to reject both the third and fourth null hypotheses. The results of the MANOVA are shown in Table 3b. This means that based on the experimental results, there is neither a significant difference between the miss distance while flying an autopilot approach then switching to flying the EEM in the manual mode (MD_A) versus flying the entire approach in the manual mode (MD_M). There was not a significant difference between the mean miss distance when the runways were 2,500 feet apart (MD_{25}) versus the mean miss distance when the runways were 3,400 feet apart (MD_{34}).

Subjective Questionnaire

The questionnaire was administered after the pilots completed all runs. It consisted of 12 questions addressing issues such as the AILS operational

feasibility, the EEM and other procedures, the displays and alerts, and the flight control modes used while flying the AILS approaches. These questions were designed to serve as validation for the quantitative responses.

Approximately 44% of test subject pilots did not prefer a particular flight control mode for the AILS approach, but of those who had a preference more preferred the autopilot mode. A total of 55% of the respondents did not think the autopilot slowed their response to the EEM. However, according to actual reaction time data from the simulator, subjects responded slower when flying an autopilot approach. The difference was 0.3 seconds, which proved to be too low for human perception.

A confirmatory factor analysis was performed on the subjective questionnaire to verify its effectiveness in addressing the different factors. Factor analysis was based on the correlation between the recorded responses to the questions. In general, most of the responses to the questionnaire were in favor of AILS. Questions about alerts and EEM factored out as expected (i.e., validated the quantitative results obtained from the simulator). Correlation coefficients between the question addressing the AILS operational feasibility and the average recorded values of the reaction time in the auto-coupled mode resulted in a positive correlation of 0.41 and miss distance in manual mode resulted in a negative correlation of - 0.52 which implied that whenever the subjects stated that AILS is "very practical" they scored larger reaction times, and smaller miss distances. This discrepancy may be attributed to the way the questions were posed to the pilot test subjects.

DEMONSTRATION FLIGHTS

As a way of testing the AILS concept in an active airport environment where parallel runway operations are conducted, the MSP airport was chosen for the AILS demonstration flights. Of the three intrusion scenarios that were tested at WFF, the scenario where the intruder was slower than the ownship and passing behind was flown to demonstrate to industry and government that two aircraft on parallel runways at 3,400 feet apart can safely perform an approach to landing in IMC.

Unlike the isolated airspace at Wallops, MSP is encapsulated by Class B airspace.¹⁴ The air traffic controllers at MSP provided ATC services as well as staging assistance to the AILS aircraft. Due to the precision required in the staging process, assistance was provided from a ground facility. The MSP controllers assisted in staging the aircraft by providing heading and

speed guidance. NASA pilots in the B-757 and Honeywell pilots in the G-IV flew the demonstration runs.

CONCLUSION

The AILS system was successfully developed, tested in simulation and flight, and demonstrated in an operational environment at MSP. Each phase of this multi-phased project brought researchers closer to realizing the feasibility of the AILS concept. Important questions regarding an onboard separation capability were answered in the research. The robustness of the study was enhanced by taking the users into consideration and accounting for their performance while operating the system.

It is now known that pilots will respond to the AILS alerts in approximately 1 second whether the distance between the runways is 3,400 feet or 2,500 feet. Although statistical variations (0.3 seconds) were seen in mean pilot response time when the approach was flown in the autopilot mode versus when flown in the manual mode, the difference was not operationally significant.

The distance the aircraft closed on each other before they broke out of the approach was not affected by flight control mode or runway separation. This is because the AILS algorithms were modeled on time thresholds that were built into the system.^{15,16} Specifically, the mean miss distance found in the simulator was 2,236 feet with a standard deviation of 479 feet. In flight, the mean miss distance was 1,860 feet, within the range of the value obtained in the simulator.

Pilot acceptability of the AILS concept was outstanding. They appreciated the clarity of the alerts and the simplicity of the operational procedures. By using existing guidance, navigation and control technologies, AILS has demonstrated the feasibility to perform instrument approaches to closely spaced parallel runways.

ACKNOWLEDGMENTS

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