same time. This is the case with the decelerating technique at V_{DEC} approach speed. 5) With the decelerating technique, the penalties in difficulty of control and landing distance caused by either excess speed or steep angles are very slight. In the experiment, typical landing distances varied from a little over 600 ft at $\gamma = 3°$ to a little under 1000 ft at $\gamma = 18°$. 6) In VFR conditions, as the approach path angle is steepened, the difficulty of the landing gradually increases. Larger rates of descent, higher flare point and increased flare normal acceleration are the contributing factors. Under IFR conditions, these factors would probably severely limit the minimum ceilings that would be operational.

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Flight Evaluation of Three-Dimensional Area Navigation for Jet Transport Noise Abatement

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NASA, working with American Airlines, has completed the first phase of research to evaluate the operational feasibility of two-segment approaches for noise abatement. For these tests, area navigation was used to establish the upper glide slope and an ILS was used to establish the lower. The flight director was modified to provide command information during the entire approach. Twenty-eight pilots representing the airlines, professional pilot associations, FAA, and NASA participated. With an ILS approach for comparison, the procedure gave a noise reduction of 18 EPNdb at the outer marker and 8 EPNdb 1.1 naut miles from touchdown.

Introduction

THE NASA Ames Research Center, in conjunction with American Airlines, has completed the first phase of research to evaluate the operational feasibility of two-segment approaches for use as a noise abatement procedure. Using this technique, the aircraft approaches on a steeper than normal glide slope and then makes a transition to the standard approach path in time to stabilize prior to the landing. By keeping the aircraft higher above the ground and reducing the engine power during landing, the two-segment approach pattern lessens the community noise near airports.

The effectiveness of the two-segment approach as a noise abatement technique has already been demonstrated by both the FAA and NASA.[1-5] However, these studies have all been conducted using experimental equipment and crew procedures which are not typical of those used in air carrier service. A program was therefore formulated with American Airlines to correct this situation. A principal objective of this study was to evaluate the operational feasibility of using three dimensional area navigation equipment for two-segment approaches. The flight director steering computer was modified to include a two-segment approach mode that used the area navigation system and standard Instrument Landing System (ILS), to provide a continuous flight director signal during the entire approach. Two major aims of the program were 1) to develop crew procedures that make use of this equipment and are representative of those that might be used in air carrier service and 2) to demonstrate the equipment and procedures to a broad sample of pilots representing the airlines, professional pilot associations, and FAA.

In this paper, the equipment and evaluation procedures used by American Airlines are discussed. In addition, the pilot and onboard observer evaluations are summarized and data are presented which indicate the precision with which the aircraft was able to follow the two-segment glide slope, the precision with which the two-segment glide slope was established, and the noise reduction that was achieved as a result of flying the two-segment approach.

Equipment Description

A Boeing 720-023B, equipped with Pratt and Whitney Aircraft JT3D-3/3B fan jet engines, was used for the evaluation. This is a 109-passenger version of the standard Boeing 720 model. The maximum takeoff gross weight is 221,000 lb and maximum landing gross weight is 175,000 lb. The normal American Airlines cockpit configuration was maintained with the exceptions that the existing Collins FD 105 flight director and steering computer on the captain's side was replaced by a Collins FD 108 flight director and steering computer, a Butler National three-dimensional area navigation system and the associated display were installed, and a Lear-Siegler barometric al-

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timeter with a fine and coarse synchro was installed to provide the altitude input into the area navigation system.

Equipment Mechanization

It was concluded in Ref. 5 that before the two-segment approach will be operationally acceptable it will be necessary to provide a two-segment flight director mode and some degree of automation to relieve the pilot workload. Without a two-segment flight director mode the pilot will not be able to consistently make the transition from level flight to the upper glide slope without an overshoot. Flight director steering is also needed to make the transition from the upper glide slope to the normal glide slope without an undershoot. An undershoot of the normal glide slope is considered particularly undesirable because additional power is required to get the aircraft back on the approach path. In this case the noise perceived on the ground in the region of the transition is actually increased.

Because the two-segment approach is straight-in, the ILS localizer can be used for lateral guidance during the entire descent. The existing lateral flight director and autopilot modes can therefore, be used without any changes.

In order to provide the pilot a continuous vertical steering signal on the flight director during the two-segment approach, it was necessary to add a new mode to the flight director steering computer. The system mechanization was based on results presented in Refs. 4 and 5 and is illustrated in Fig. 1. The upper glide slope was defined by a three-dimensional area navigation waypoint and the angle of the upper segment. Both the coordinates of the waypoint and the upper segment angle are inserted into the navigation computer. The ILS glide slope was used for the lower segment. The flight director steering computer was mechanized so that upon selecting the two-segment approach mode, the system was armed to automatically capture the upper glide slope in a conventional manner. The capture was activated upon sensing a prespecified deviation of the aircraft below the upper glide slope. After capturing the upper glide slope the flight director continued to provide command information using the sensed deviation of the aircraft from the upper glide slope for guidance. A trip signal from the radio altimeter at 1000 ft alt was used to automatically arm the flight director for the ILS capture. This assured that the ILS capture was not activated by a false lobe of the ILS glide slope. The ILS glide slope deviation was then monitored within the flight director computer and upon sensing a prespecified glide slope deviation, the vertical guidance automatically switched from the three-dimensional area navigation signal to the ILS glide slope signal and an above beam ILS glide slope capture was activated.

The attitude director indicator (ADI) glide slope scale displayed the aircraft's position with respect to the upper glide slope prior to the ILS capture (200 ft per dot where each dot corresponds to 0.30 in.) and displayed the aircraft's position with respect to ILS glide slope after the ILS capture (0.35° per dot). The position of the aircraft

Table 1 Project participants

Program management	American Airlines, NASA, FAA
Onboard data recording and navigation data analysis	Battelle Columbus Labs.
Noise measurements and data reduction	Hydrospace Research Corp.
Ground radar measurements	Bell Aerospace Corp.

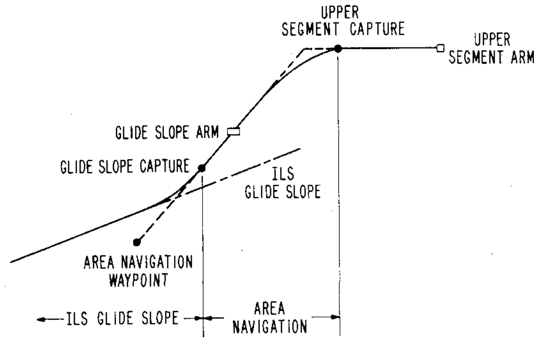

Fig. 1 System mechanization in vertical plane.

with respect to the ILS glide slope was displayed on the course deviation indicator (CDI) glide slope scale during the entire approach.

Progress display lights were used to annunciate the key events during the approach. These lights are located just above and to the right of the ADI. The upper light showed amber when the flight director was armed to capture the localizer and turned green at the localizer capture. The third light from the top showed amber when the flight director was armed to capture the upper glide slope and turned green at the upper glide slope capture. The lower light turned amber at 1000 ft alt when the trip signal from radio altimeter armed the flight director for the ILS glide slope capture and then turned green at the ILS capture. (The second light from the top was used to annunciate when the flight director was in the enroute area navigation mode and was not used during the approach.)

Flight Test Program

The flight test was conducted at Stockton Metropolitan Airport, Stockton, Calif. The aircraft served as the command post from which the project was managed. The airborne navigation and guidance signals were recorded on board the aircraft. A high precision ground radar was used to measure the aircraft position. The ground noise caused by the over-flying aircraft was measured at 6 sites underneath the approach path and at three side line locations. Communication existed between the aircraft, the tower, and the radar. The radar also had communication with the noise measurement stations. A list of project functions and the responsible organizations are listed in Table 1.

Approach Procedures

During the first week of the flight test, the NASA and American Airlines project pilots developed an approach procedure that they considered to be operationally feasible. The upper segment glide slope, the flap setting, and the approach velocities were all defined. The two-segment approach procedure that appeared reasonable at the conclusion of these studies consisted of a 6° upper segment that was initiated at 3000 ft above field elevation and with a flare to the ILS at about 550 ft (see Results Sec.). Prior to beginning the two-segment approach (i.e., before the airplane reached a point 8 naut miles from the runway threshold) the pilot would tune the appropriate navigation receivers, acquire the localizer, and arm the flight director for the capture of the 6° slope. At the 8 naut miles point he would lower the flaps to 20° and establish an airspeed equal to V_{ref} + 30 knots (reference velocity V_{ref} is equal to 1.3 the stall velocity) with approximately 3400 lb/hr fuel flow per engine. At the 7 naut miles point, he would lower the flaps to 30° and establish an airspeed equal to V_{ref} + 20 knots. When the glide slope displacement indicator showed proximity to the upper segment, the pilot would lower the gear and set the flaps at 40° and then 50°.

Table 2 Noise abatement two-segment approaches evaluation pilots

Date	Name	Title	Company or agency represented
	Capt. B. Wohl	Project pilot	American Air Lines (AA)
	Mr. F. Drinkwater III	Project pilot	NASA/Ames Research Center (ARC)
	Capt. B. Ehman	Base superintendent of flying-SF	AA
8/18/71	Mr. G. Cooper[a]	Branch chief/flight operations	NASA/ARC
	Mr. G. Hardy[a]	Research pilot	NASA/ARC
8/23/71	Mr. F. Fulton	Research pilot	NASA/Flight Research Center (FRC)
8/24/71	Mr. J. Dydek[a]	Air carrier inspector/FAA-SW region	FAA
	Mr. M. Russell[a]	Flight standards/FAA-Washington	FAA
8/25/71	Capt. McCormick	Chairman Air Traffic Control Comm.	Allied Pilots Association
	Capt. A. Cleaver[a]	Line pilot	Eastern Air Lines (EAL)
	Capt. Slayden[a]	Line pilot	EAL
8/26/71	Capt. T. Foxworth	ALPA representative for noise abatement committee	Airline Pilots Assoc. (ALPA)
8/27/71	Capt. C. Rogers	720 Flight manager	Continental Air Lines (CAL)
8/31/71	Capt. Benninghoff	Assistant vice pres. flying training and flying procedures	AA
	Capt. A. Resser[a]	Director-flying engineering	AA
	Capt. S. Saint[a]	Retired captain-AA	Consultant/Com.
9/1/71	Capt. D. Thompson	Chief pilot - 720	Western Air Lines (WA)
9/2/71	Capt. E. Ernest	Line pilot	United Air Lines (UAL)
	Capt. R. Roberts[a]	720 Flight Manager	UAL
	Capt. Parshall[a]	ALPA safety representative	UAL
	Capt. P. Learned[a]	Manager of flight operations	UAL
9/3/71	Capt. A. Weidman	Manager-flight standards	WA
9/8/71	Capt. Roitsch	Dir. of flight operations tech. ser.	Pan American World Airways (PAA)
	Capt. P. Soderlind	Vice pres. of operations	North Western Air Lines (NWA)
	Capt. R. Van Tuyle[a]	Retired captain UA	R. Dixon Speas
	Capt. Dixon	General manager - flying	Trans World Air Lines (TWA)
9/9/71	Mr. R. Innis[a]	Research pilot	NASA/ARC
	Mr. R. Gerdes[a]	Research pilot	NASA/ARC

[a]These pilots were able to fly a few two-segment approaches but did not participate as full-fledged subjects.

The glide slope capture command on the flight director occurred when a 300 ft vertical deviation from the 6° slope is detected. The pilot would then maintain an airspeed of V_{ref} + 20 knots on the 6° slope with approximately 1500 lb/hr of fuel flow. The radio altimeter automatically armed the flight director at 1000 ft alt for the ILS capture and the ILS capture occurred at 0.7° above the ILS centerline. The pilot would then use the pitch command guidance to make the transition to the normal ILS glide slope and reduce the airspeed to V_{ref} + 10 knots with about 3000 lb/hr fuel flow. The additional 10 knots carried on the upper segment was bled off during the transition to the ILS glide slope to allow the pilot to make a smooth transition with a gradual build up in thrust.

Pilot Evaluations

The remainder of the flight test period was used to expose a broad sample of pilots to the two-segment approach. Each guest pilot was first given a thorough preflight briefing by the American Airlines project pilot on the two-segment flight procedures and cockpit equipment to be evaluated. The briefing typically took from between 2 to 3 hr and occurred the day prior to the flight evaluation.

The usual flight program was to have each subject pilot fly from the left-hand seat and perform five two-segment approaches for familiarization, and five two-segment approaches and two standard ILS approaches for data. During the first two familiarization approaches the autopilot was coupled to the localizer and the project pilot controlled the throttles from the co-pilot seat. These first two approaches would have also been coupled to the autopilot vertically if this capability had existed. However the autopilot was not modified to fly the two-segment glide slope so the evaluation pilot controlled the vertical path by using the pitch trim wheel on the autopilot console. The third approach was flown completely manual with the evaluation pilot controlling his own power. The fourth approach was identical to the third approach except under simulated IFR conditions. The fifth approach was again flown identical to the third approach but this time the pilot abused the approach by flying through the upper glide slope in order to evaluate the procedure and command guidance. The five two-segment data approaches were flown in the same manner as the first two familiarization approaches and the ILS approaches were flown coupled to the autopilot with the evaluation pilot controlling his own power.

Twenty-eight pilots participated in the flight program although about half of them did not fly the full set of approaches described above. A list of all pilots who partici-

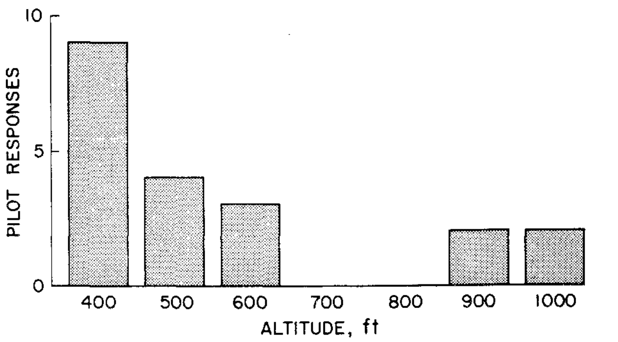

Fig. 2 Pilot assessment of acceptable ILS intercept altitude.

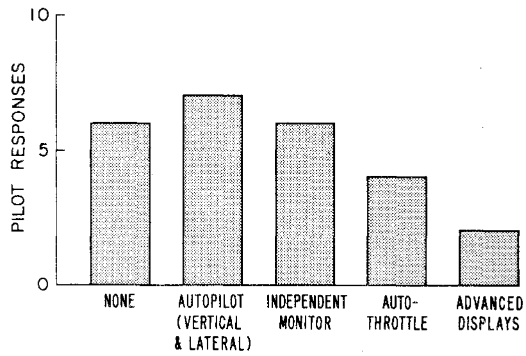

Fig. 3 Pilot assessment of additional instrumentation required.

pated and their level of participation is included in Table 2.

After each flight, a debriefing was held to obtain the subject pilots reaction to the approach procedure and to define areas which would require further refinement. The evaluation pilots were also given a questionnaire to fill out at their convenience. Twenty of the pilots who participated returned the completed questionnaire. In general, the responses to the questionnaire indicated that the evaluation pilots considered the two-segment approach feasible. However, concern was expressed over the general acceptance of the procedure until the equipment can be proven to be sufficiently reliable and not prone to inducing pilot errors during routine operations.

The responses to the following two key questions are summarized in Figs. 2 and 3: 1) All things considered, what altitude do you feel is most compatible for transitioning to the ILS glide slope? 2) What additional flight instrumentation or aircraft systems do you feel are needed to fly two-segment approaches (other than provided in this evaluation)?

It is shown in Fig. 2 that all but four of the evaluation pilots considered an ILS intercept altitude of 600 ft to be acceptable and several considered 500 ft intercept altitude to be acceptable. The pilots' responses to the second question are divided into five categories: 1) no additional instrumentation would be required, 2) autopilot coupling would be required, 3) some sort of independent monitor would be required to assure a transition from the upper glide slope, 4) autothrottle would be necessary, and 5) an advanced instrumentation such as a multifunction display or a heads up display would be required. It is shown in Fig. 3 that some of the twenty pilots who responded felt that more than one type of added instrumentation would be required.

Observer Evaluations

A number of persons were invited to participate as onboard observers during the flight evaluation. They were debriefed along with the pilots and were also given questionnaires to fill out. Most of the observers indicated that except for the change in engine tone at the ILS glide slope intercept, they were not able to make a distinction between the two-segment and standard ILS approaches. None of the observers have expressed anxiety because of the increased rate of descent.

Results

The airborne and radar tracking data were reduced for ten typical two-segment approaches and three ILS approaches to determine the accuracy with which the navigation system was able to establish the upper segment and the precision with which the aircraft was able to follow the two-segment approach path. The nominal profile, defined by the coordinates inserted in the navigation computer and the ILS geometry, will serve as a basis of comparison when discussing the accuracy with which the two-segment glide slope was actually established by the area navigation system and ILS during the flight evaluations.

The nominal profile is defined in Fig. 4. The area navigation waypoint was located at the field elevation, 0.655 naut miles from the touchdown point. The waypoint coordinates were referenced to the Stockton VORTAC which is located about 4 naut miles prior to the touchdown point and about 1 mile to the left of the approach path. The upper segment intercepts the ILS glide slope, which is set at 2.5°, at 297 ft alt and intercepts the ILS capture line, which is 0.7° above the ILS glide slope, at 473 ft alt.

In Fig. 5, the nominal two-segment glide slope is compared with the two-segment glide slopes established by the three-dimensional area navigation system and ILS. The two-segment glide slopes established by the area navigation system and ILS were computed by summing the radar indicated vertical position of the aircraft with the onboard computed deviation of the aircraft below the two-segment glide slope. The nominal two-segment glide slope is shown by the solid line. A two-segment glide slope computed for a typical run is given by the symbols. The symbols illustrate the upper glide slope down to about 580 ft alt at which point the aircraft intercepts the ILS capture line. From that point to touchdown, the symbols illustrate the lower or ILS glide slope. The shaded area represents the envelope of upper glide slopes established by the three-dimensional area navigation system. For these runs, the capture occurred between 500 and 600 ft alt. The average capture occurred at 550 ft alt or about 80 ft above the nominal capture point.

The aircraft position with respect to the two-segment glide slope (as established by the three-dimensional area navigation system and ILS) is illustrated in the upper part of Fig. 6. Two graphs are presented in order to show the aircraft's position with respect to the upper and lower glide slopes respectively. The solid line in each graph

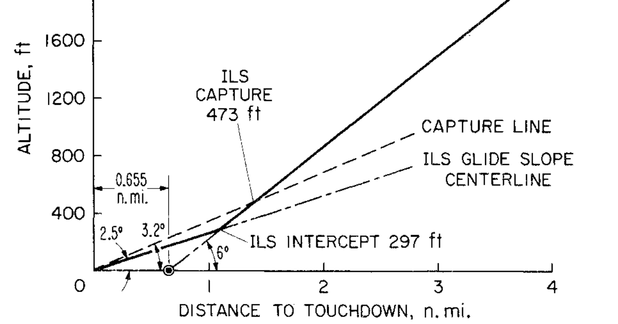

Fig. 4 Vertical two-segment glide slope.

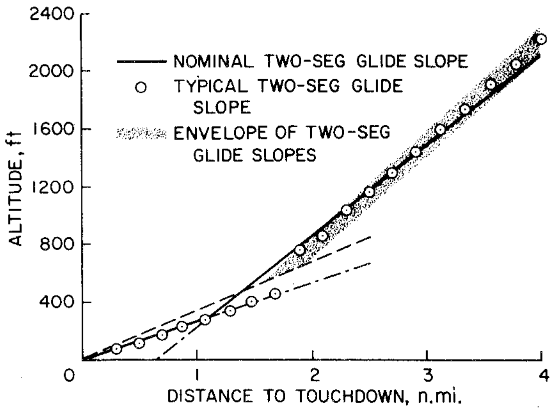

Fig. 5 RNAV/ILS established two-segment glide slope.

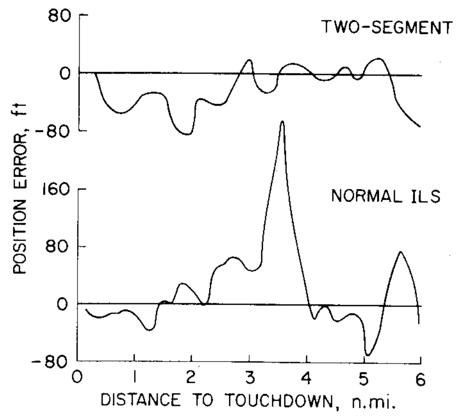

Fig. 7 Comparison of ILS and two-segment lateral position errors.

shows the aircraft position error during a typical approach. In the graph on the right, it is seen that between 5 and 6 naut miles from touchdown the aircraft is in the process of making the transition from level flight to the upper segment and is still below the upper glide slope. It is also seen that the aircraft, in this approach, overshoots the upper glide slope during the transition by a maximum of 30 ft at 4 naut miles from touchdown. The shaded area between 4 and 4.75 naut miles from touchdown shows the scatter in the position error for all the runs analyzed over this region of the trajectory where the capture overshoot (if any) should occur. The maximum overshoot for the runs analyzed was about 40 ft and in many cases the transition was made without any overshoot. After capturing the upper glide slope, the aircraft was able to track to within 30 ft. In all the approaches analyzed, the aircraft position error on the upper segment was within 75 ft. The graph on the right shows the ILS capture. Between 1.5 and 1.0 naut miles from touchdown the aircraft is in the process of making the transition from the upper segment to the ILS glide slope and is still above the ILS glide slope. In this approach, the aircraft makes the transition without sinking below the ILS glide slope. An undershoot is observed at 0.5 naut miles from touchdown but this undershoot is considered to be a normal tracking error and not an error caused by the transition. The shaded area between 1.0 and 0.75 naut miles from touchdown shows the scatter in the position error for all the runs analyzed over this region of the trajectory where the ILS undershoot due to the transition should occur. In all cases analyzed, the undershoot has been less than 8 ft and in most cases there has not been any undershoot.

The lower plot in Fig. 6 illustrates the aircraft position with respect to the ILS glide slope during an ILS approach and is presented for comparison with the two-segment approach. A sufficient amount of data has not yet been reduced to make a meaningful statistical comparison of the aircraft position errors measured during a two-segment approach with the position error measured during an ILS approach. However, it appears that the position errors on the upper glide slope during the two-segment approach are somewhat greater than the position errors measured during the ILS approaches at comparable distances from touchdown. After the ILS capture, the aircraft position errors measured during the two-segment approach and ILS approach appear comparable.

The aircraft's position with respect to the ILS localizer during a typical two-segment and an ILS approach is shown in Fig. 7. Again a sufficient amount of data has not been reduced at this time to make a significant statistical comparison between the two types of approaches. However, from an examination of the limited data available, it appears as though the two-segment approach does not cause a degradation in the lateral position errors. The spike in the position error during the ILS approach is not considered significant considering the scaling of the plot.

On August 19, 1971, the American Airlines project pilot made six two-segment approaches and six standard ILS approaches with the aircraft near maximum landing weight in order to measure the noise reduction associated with this particular two-segment approach. These data have been reduced to effective perceived noise level in accordance with the appendices of FAR Part 36-noise Standards[6] and are plotted as a function of the distance from the threshold in Fig. 8. The symbol is the effective perceived noise in decibels (EPNdb) averaged over the six runs analyzed and the spread in EPNdb obtained for the individual runs is superimposed. The numbers along the top of the plot locate the noise measurement sites. These data show a noise reduction of approximately 18 EPNdb

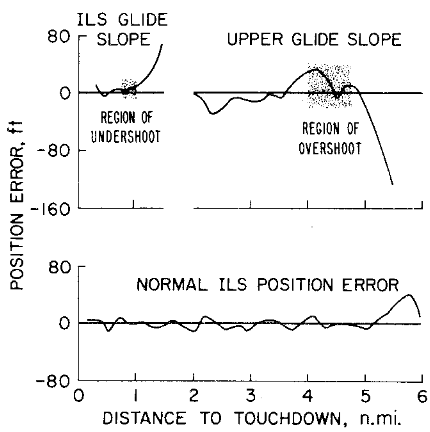

Fig. 6 Comparison of ILS and two-segment vertical position errors.

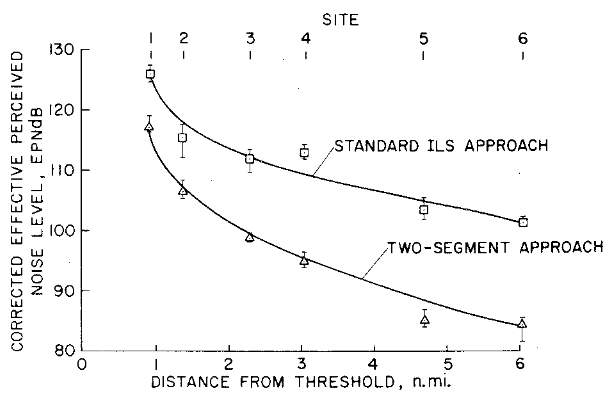

Fig. 8 Comparison of noise measured during two-segment approach and standard ILS approach.

at the outermost sites and 8 EPNdb at the first site which was located about 1 naut miles from the threshold. This amount of noise reduction is comparable to that achieved during the BOEING 707-80 two-segment approach flight test program.[4] There appears to be some small improvement at the inner site due to the smoother application in power that resulted because of the additional 10 knots air speed carried on the upper segment and bled off during the ILS transition.

Concluding Remarks

The first phase of research aimed at determining the operational feasibility of the two-segment approach as a noise abating technique, has been completed. A total of twenty-eight pilots representing the airlines, professional pilot associations, NASA, and the FAA participated. In general, the evaluation pilots considered the procedures to be operationally feasible. However, there was concern expressed over the general acceptance of the procedure until the equipment can be proven sufficiently reliable and not prone to inducing pilot errors.

Although the program was not aimed at passenger evaluation of the procedure the onboard observers who participated did not express any special concern or discomfort during the two-segment approaches.

The area navigation system used for these tests was capable of establishing an upper glide slope using the VOR and DME signals from the Stockton VORTAC. The effect of other VORTAC locations on the accuracy with which the upper glide slope can be established was not considered as a part of these tests.

The flight director and raw data displays provided the pilot with adequate information for making a smooth two-segment approach. The upper segment capture was consistently made with less than a 40 ft overshoot. Having captured the upper glide slope, the pilots were able to follow it to within a 75 ft vertical deviation. The transition to the ILS glide slope was also smooth and resulted in a maximum undershoot of 8 ft, and, in most cases, the transition was accomplished without any undershoot.

Based on the noise measurements a noise reduction of 18 EPNdb at the outer site and 8 EPNdb at a site located about 1 naut mile from touchdown was achieved compared to an ILS approach.

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