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and Space Administration

Scientific and Technical
Information Branch

SUMMARY

A piloted simulation study has been undertaken to determine the feasibility and potential benefits of utilizing a forward-looking display to provide information that would enable aircraft to reduce their in-trail separation, and hence increase runway capacity, through the application of multiple glide-path approach techniques. This portion of the study was an initial exploration into a concept in which traffic information was added to a head-up display (HUD) format to allow the pilot to monitor the traffic situation and to self-space on a lead aircraft during a single glide-path approach task.

The tests were conducted in a motion-base cockpit simulator configured as a current-generation transport aircraft. The dynamic effects of the vortices generated by the lead aircraft were also included in the simulation. An electronic display, which was provided in the front windscreen location of the simulator, presented an out-the-window color scene of the simulated terrain combined with computer-generated symbology used to represent information that might be presented in a HUD. The information included typical aircraft-guidance information and the current and past positions of the lead aircraft. Additionally, the displayed information provided self-separation cues which allowed the pilot to maintain separation on the lead aircraft while performing an instrument approach to landing. Separation-performance data and pilot subjective ratings and comments were obtained during approaches where the separation cues were provided by either an air traffic controller or the displayed symbology.

The results of this study indicate that the display concept could provide sufficient information to the pilot for traffic monitoring and self-separation. A major result of this study was that an increase in situational awareness, relative to conventional instrument flight, was provided to the pilot by the displayed traffic information. Additionally, the test results showed that a reduction of interarrival-time dispersion relative to a controller providing separation cues is possible by using the displayed information for self-separation.

INTRODUCTION

In general, airports operate at a much higher efficiency during visual flight conditions as compared with instrument meteorological conditions. This increased efficiency can be attributed, in part, to reduced in-trail separation (below the standard imposed for wake-vortex consideration) that is routinely used by pilots during visual approaches. This ability to utilize a reduced separation is made possible by the pilot's knowledge of his flight path and of the path of the lead aircraft, and also by the adjustment of his own path (based on his knowledge of wake-vortex behavior) relative to the lead aircraft.

Two primary techniques that, in conjunction, may allow airports operating under instrument conditions to achieve nearly the same level of capacity as that realized under visual conditions are multiple glide-path approach methods and the reduction of the interarrival separation intervals currently required between aircraft. Aircraft interarrival separation, although a direct function of airport capacity, is presently dictated by wake-vortex considerations (through vortex-dissipation times). The multiple glide-path approach method offers the potential to reduce interarrival separation through the avoidance of wake vortices, rather than through their dissipation. By providing the trailing aircraft either a higher or laterally offset (upwind or closely spaced parallel runway) approach path, reduced-separation approaches might be possible with minimum vortex hazard.

Although the multiple glide-path approach method is not a new idea, its implementation has not been initiated because of several possible operational problems associated with it, the primary ones being: interference of the navigation signal, lack of adequate missed-approach guidance, communication interference and delay (delayed go-around instructions, especially critical with reduced separation), and pilot willingness to accept reduced-separation standards (both laterally and longitudinally). The introduction of the Microwave Landing System (MLS) may reduce or alleviate the navigation-signal interference problem since a microwave system is not as subject to refraction as a conventional instrument landing system (ILS). Additionally, MLS has the potential for resolving many of the missed-approach restrictions via precision-departure guidance. By providing information that would enable the pilot to be responsible for self-separation, the problems associated with communication interference and pilot acceptance could probably be minimized to a level such that reduced-separation, multiple glide-path approaches would be operationally feasible. In seeking methods to improve airport capacity, therefore, the question arises as to whether an electronic display, presenting the data-linked position of surrounding aircraft traffic, could provide information which would enable the pilot to be responsible for self-separation under instrument conditions to allow for the practical implementation of reduced-separation, multiple glide-path approaches.

A research effort has been undertaken to address this question and to determine the feasibility of this concept. The study specifically addressed in this paper was an initial effort in this area. The primary objective of this study was to determine whether information could be satisfactorily provided on a forward-looking, head-up display (HUD) format that would permit the pilot to monitor and maintain a prespecified in-trail separation interval, to monitor adherence of the preceding aircraft with respect to its designated glide path, to detect unanticipated actions by the preceding aircraft, and to monitor runway occupancy. The operational task was an ILS approach to landing while following a single lead aircraft on the same approach path. During this study, each of three pilots flew 33 approaches with data being taken in the form of quantitative measurements and pilot questionnaires.

SYMBOLS AND ABBREVIATIONS

AGS	aircraft-guidance symbol
ATC	Air Traffic Control
HUD	head-up display
IAS	indicated airspeed
IAT	interarrival time
IFR	Instrument Flight Rules
ILS	instrument landing system

IMC	instrument meteorological conditions
rms	root mean square or quadratic mean
SELF	pilot responsible for separation maintenance
TOGA	takeoff and go-around
ΔT	deviation from nominal time spacing
V_{ref}	nominal final approach speed, knots

RESEARCH SYSTEM

Simulator Description

This study employed the Langley Visual/Motion Simulator (fig. 1), which is a part-task, six-degree-of-freedom, motion-base simulator capable of presenting

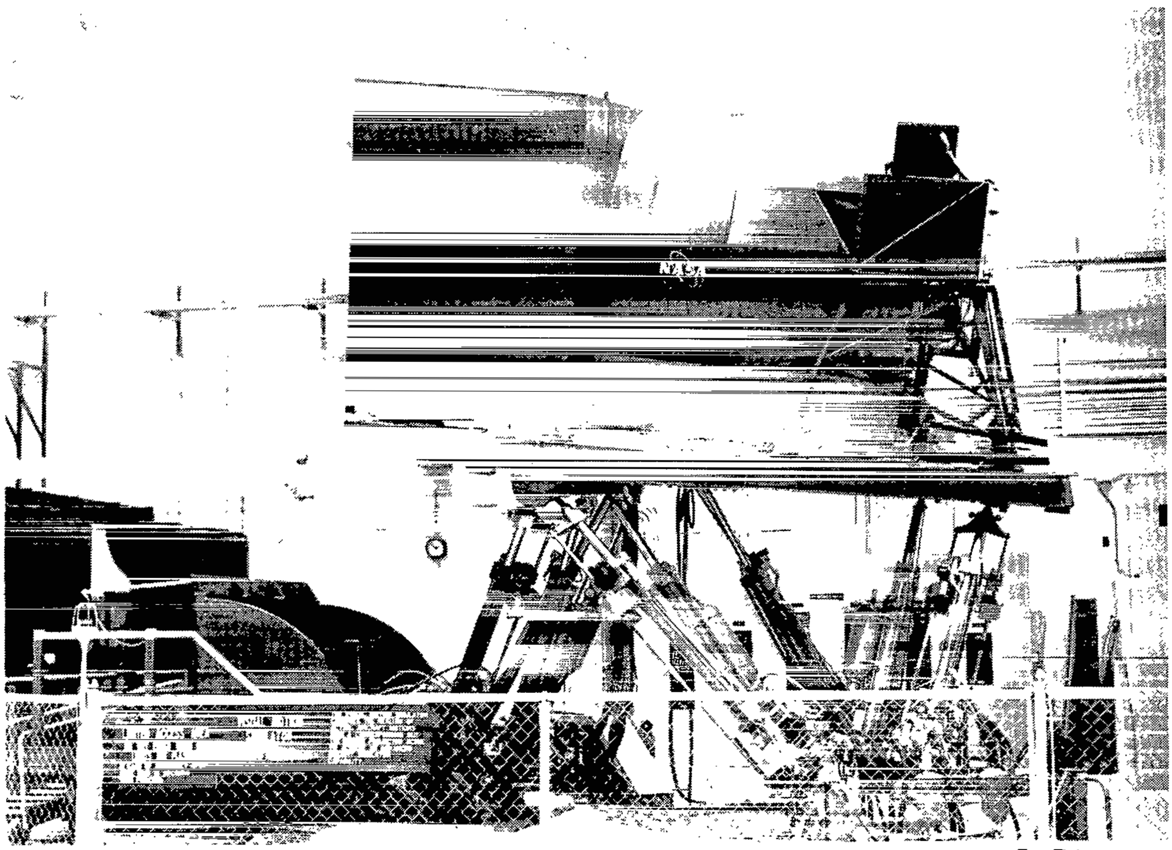

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Figure 1.- The Langley Visual/Motion Simulator.

realistic acceleration and attitude cues to the pilot. Audio cues for aerodynamic buffeting and engine noise were also provided. The aircraft dynamics modeled were those of a Boeing 737 and included nonlinear aerodynamic data and atmospheric effects. Conventional electromechanical navigation instruments, which included a horizontal-situation indicator, a flight director, and distance-measuring equipment (DME), were provided in the cockpit. Neither an autopilot nor a stability augmentation system was provided to the pilot. In addition, no attempt was made to duplicate any specific aircraft cockpit configuration or control-wheel force-feel characteristics. This simulator is further described in reference 1.

Additions to the aircraft force and moment equations caused by the vortex flow fields were made based on a strip-theory technique described in reference 2. The vortices generated by this method were for an aircraft in the normal landing configuration (wing leading- and trailing-edge flaps deployed, all landing flaps at 30°, landing gear down, a lift coefficient of 1.40, and a velocity of 140 knots) at a weight of 509 914 lb (fig. 2). After generation, the vortices descended at a rate of

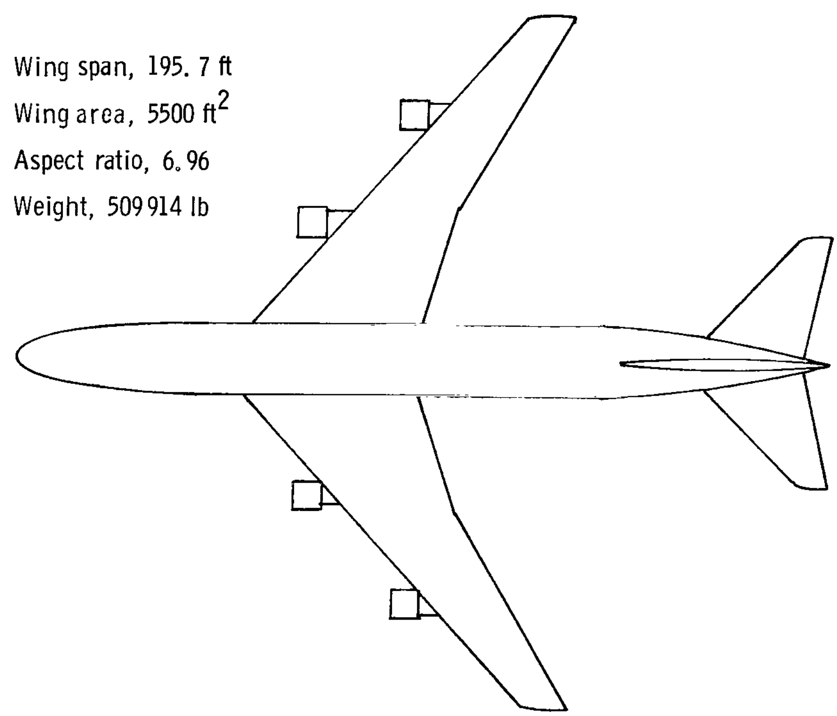


Figure 2.- Drawing of vortex-generating aircraft used in this simulation investigation.

6 ft/sec until they reached a point 600 ft below their generation point, at which time they ceased to descend. To simulate ground effect, vortices that came within 60 ft of the ground were held at that altitude and were spread outward at a rate of 6 ft/sec. The lower than nominal descent rate (with nominal being approximately 7 to 8 ft/sec) and the lower than nominal maximum-descent position (with nominal being approximately 900 ft below the generation point) were used to provide worse than normal vortex conditions by keeping the vortices closer to the flight path of the generating aircraft.

The visual landing display system (VLDS), shown in figure 3, provides the pilot with an out-the-window color scene of the simulated terrain. The system utilizes a

L-75-7496

Figure 3.-Visual landing display system at the Langley Research Center.

60-ft by 24-ft three dimensionally scaled terrain model, including a large commercial airport, that is traversed in three axes by a gantry carrying a closed-circuit color-television camera. Gantry movements account for aircraft spatial position, whereas the television-probe optics-system motions account for heading, pitch, and bank of the aircraft. Additionally, the capability exists to simulate IMC flight with this system by the employment of a controllable skyplate in its optical probe. Camera and gantry motions are commanded by the aircraft-simulation computer program, and the resulting scene is routed to the window screen of the simulator.

Primary Display Hardware

The primary pilot display for this study employed an out-the-window virtual-image system of the beam-splitter, reflective-mirror type. The system, located nominally 50 in. from the pilot's eye, presented a nominal 48° width by 36° height field of view of a 525-line raster video system and provided a 46° by 26° instantaneous field of view. The system supplies a color picture of unity magnification with a resolution on the order of 9 min of arc. The forward-looking, HUD-type presentation for this study was obtained by mixing the video signal from the VLDS camera with the video output from a graphic system by Adage, Inc., which generated the HUD symbology.

Controller's Station

A simplified air traffic controller's station was used in a portion of this study. This station employed a 20-in. monochromatic cathode-ray tube for the controller's scope. The display format for this device (fig. 4) was generated by the same graphics system that generated the HUD symbology. In addition to the scope, a direct two-way telephonic link was provided from this station to the cockpit to simulate the ground-air radio link.

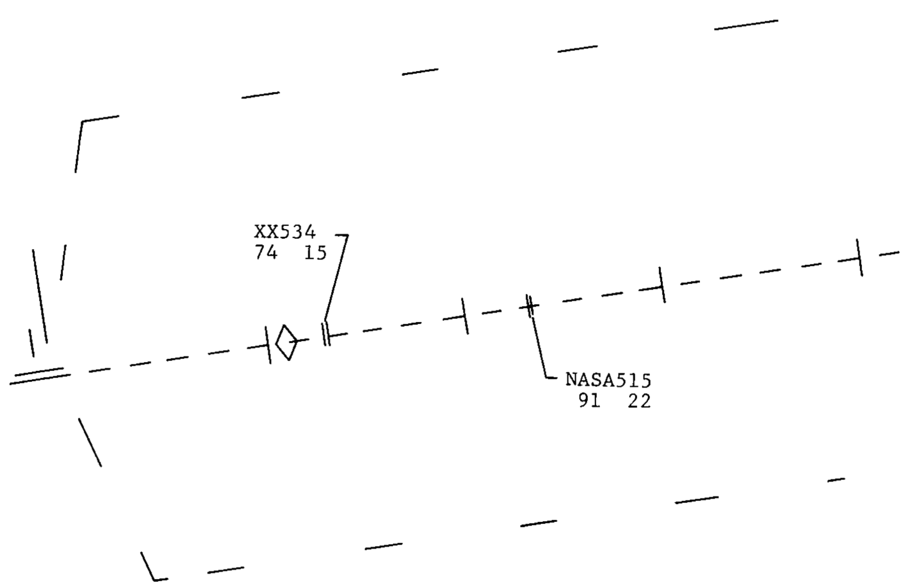


Figure 4.- Typical scene as presented on the approach controller's display.

Traffic-Generation Technique

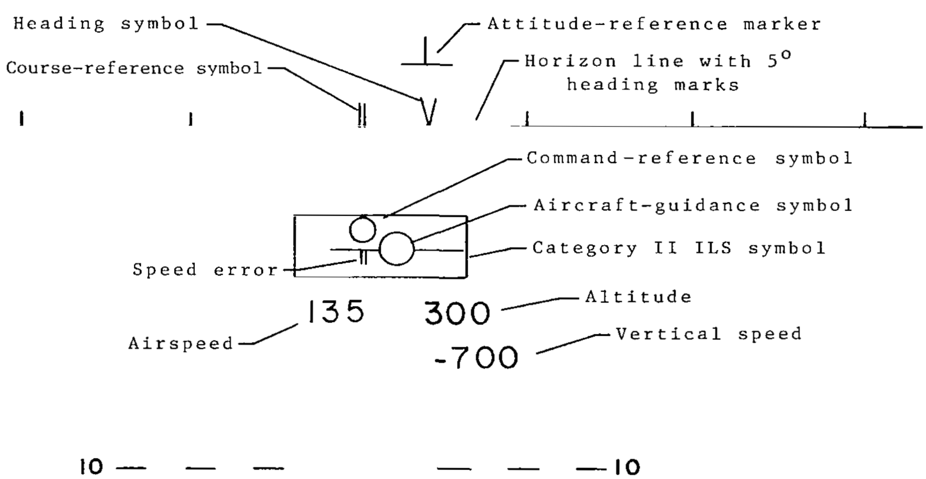
The displayed traffic was generated from data previously recorded by using the Langley Flight Simulation Computing Subsystems. Specifically, the traffic data were created by using a piloted simulation capability, wherein flights were made along a path that was prescribed by the test scenario. The data from these individual flights were recorded and then, by time correlating, were used as the parameters for the lead aircraft.

EXPERIMENTAL DESIGN

Basic-Display Format

The basic-display format, excluding the traffic information, was the ILS approach portion of the HUD format developed for the McDonnell Douglas DC-9-80 (known as the Super 80) (refs. 3 to 5). Information on this display was made available by the Douglas Aircraft Company, who developed the concept, and Sundstrand Data Control, Inc., who designed and built the HUD equipment. This format was essentially command oriented in that of the three guidance-related symbols (command reference, aircraft guidance, and category II ILS "window"), only the command-reference symbol moved conformally with the external view.

The components of this format, shown in figure 5 for an arbitrary situation, were as follows: The attitude reference marker, which was a nonmoving symbol, was used in conjunction with the horizon line to indicate pitch attitude and heading. The horizon line and its associated pitch scales moved conformally with the pitch and



The conditions shown are as follows:

- 2° pitch attitude
- 2° right drift-correction angle
- 135-knot airspeed
- 300-ft altitude
- 700-ft/min descent
- Within the category II ILS limits (slightly low and to right)
- 3 knots slow
- Pitch-up and roll-left command

Figure 5.- Basic-display format.

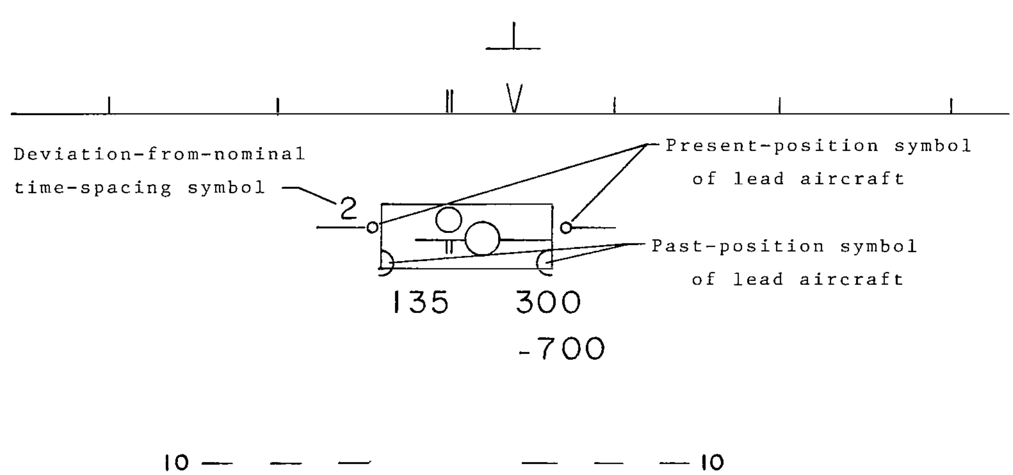
roll attitudes of the aircraft. Additionally, these scales translated in the roll axis to indicate the drift-correction angle ("crab" angle) of the aircraft. This angle was determined by comparing the course reference symbol, which was fixed to the horizon line, with the heading symbol, which moved in pitch and roll with the horizon line but did not translate with heading. The command-reference symbol was always under the course-reference symbol and would overlay the aiming point on the runway. The aircraft-guidance symbol (AGS) could conceptually be thought of as the position projection of the aircraft being flown. The movement of this symbol, which combines the desired glide-slope angle, the ILS error, and various aircraft position and attitude parameters, is such that by overlaying the command-reference symbol with this symbol, a smooth transition to the glide path will occur and be maintained. The category II ILS window symbol provided a measure of deviation from the nominal glide path and was referenced to the AGS; however, the scaling was not unity and the location of the window symbol was not conformal with the outside view unless the aircraft was flying exactly along the nominal approach path.

It should be noted that the guidance symbology was oriented toward category II ILS approaches. In addition to these attitude- and path-guidance symbols, a speed-error symbol was also provided. This symbol grew vertically as a function of speed error where a 3-knots-fast indication would show the symbol being above the "wing" line of the AGS and its length being equal to the radius of the center circle of the guidance symbol. The error signal to drive this symbol came from the flight-director algorithm of the aircraft.

The display format was software windowed to provide a 30° wide by 20° high field of view.

Traffic-Display Format

The traffic-display format (fig. 6) was identical to the basic-display format with the addition of three symbols: the present-position symbol of the lead



The conditions shown are as follows:

- Leader is slightly high on the ILS.
- Leader was slightly low on the ILS.
- 2-sec slow separation error

Figure 6.- Traffic-display format.

aircraft, the past-position symbol of the lead aircraft, and the numeric symbol for deviation from nominal time spacing. The general concept in the formulation of these symbols was to provide the pilot with adequate information so that he could: (1) assess the potential danger stemming from the vortices generated by the lead aircraft, (2) modify his approach profile for vortex avoidance, and (3) adjust his speed to provide for adequate in-trail separation. With this in mind, it was determined that the lateral deviation of the lead aircraft relative to the glide path was of no concern to the follower as long as the lead aircraft remained within nominal ILS limits. For this reason, and while the within-limits condition was met, the lateral position of the lead aircraft was not shown to the follower. The rationale and implementation for each of the symbols are given in the following discussion.

Present-position symbol of lead aircraft.- The primary purpose of the present-position symbol of the lead aircraft ($L_{present}$), which was represented by a left and right "wing," was to provide information to the pilot on how accurately the lead aircraft was following the intended path. This information was important since it was used as the major factor in determining if a missed-approach procedure was required (because of some unusual maneuver on the part of the lead aircraft). This symbol was driven vertically as a function of the ILS glide-slope error of the lead aircraft in the same manner as the ILS box except that, unlike the basic display where the ILS box was driven relative to the AGS, the $L_{present}$ symbol was driven relative to the ILS box. The vertical position was "frozen" once the lead aircraft descended below a 100-ft altitude.

Two lateral motions were also possible with the $L_{present}$ symbol, and these were also based relative to the ILS box. The first motion was a function of the closure rate on the lead aircraft, wherein each half of the symbol (the "wings") moved either toward the other (indicating an increase in separation) or farther apart (indicating a decrease in separation). The motion was scaled such that a 20-knot closure rate would reflect as a gap between the circular ends of the symbol and the ILS-box edge equal to one-quarter of the width of the ILS box. This closure-rate indication was also limited to 20 knots. The other lateral motion that this symbol would exhibit was a function of the lateral ILS error of the lead aircraft and would occur only when the error was greater than approximately 1/2°. At this time, the symbol would move laterally as a function of ILS localizer error with the "wing" opposite the direction of motion being blanked to reduce display clutter. That is, if the lead aircraft were deviating to the right, the right "wing" would move to the right and the left "wing" would be blanked. This feature was important during the last portion of the approach in that the pilot could tell whether or not the lead aircraft was exiting the runway.

Past-position symbol of lead aircraft.- The primary purpose of the past-position symbol of the lead aircraft (L_{past}), which was represented by a left and a right half-circle, was to provide some general information as to where the vortices generated by the lead aircraft were relative to the following aircraft (referred to as ownship). The implementation of this symbol was simply a "playback" of the position of the stored $L_{present}$ symbol relative to the ILS box. That is, if ownship were positioned at 10 n.mi. from the runway, the L_{past} symbol indicated the position of the lead aircraft when he also was 10 n.mi. from the runway. Since vortices normally descend after generation, the top of each half-circle of the L_{past} symbol was placed on the display at the position that was previously occupied by the circular ends of the "wings" of the $L_{present}$ symbol, thus implying this descending condition. Unlike the $L_{present}$ symbol that "froze" when the lead aircraft descended below 100 ft in altitude, the L_{past} symbol remained active until ownship landed.

Deviation-from-nominal time-spacing symbol.- The numeric symbol denoting a deviation from nominal time spacing (ΔT) was designed to aid the pilot in maintaining the in-trail separation and was an indication, in seconds, of his separation error. The symbol ΔT is defined as follows:

$$\Delta T = \frac{\Delta R - T_N V_F}{V_{F,nom}}$$

where ΔR is the in-trail separation, V_F is the ground speed of ownship, $V_{F,nom}$ is the nominal final approach speed (V_{ref}) of ownship (the final speed that ownship should decelerate to and which is a value selected before the approach begins), and T_N is defined as

$$T_N = T_{desired} + \frac{R_L}{V_L}\left(1 - \frac{V_{L,nom}}{V_{F,nom}}\right)$$

where R_L is the range to the runway of the lead aircraft, $T_{desired}$ is the desired (and preselected) separation time and is calculated as $\Delta R/V_{F,nom}$ at $R_L = 0$, and $V_{L,nom}$ is the assumed nominal approach speed of the lead aircraft. The term $\frac{R_L}{V_L}\left(1 - \frac{V_{L,nom}}{V_{F,nom}}\right)$ is used to compensate for dissimilar approach speeds. Any error generating from a miscalculation in nominal approach speeds, which is usually based on aircraft type, will diminish as the lead aircraft approaches the runway. For similar final approach speeds, ΔT reduces to

$$\Delta T = \frac{\Delta R - T_{desired} V_F}{V_{F,nom}}$$

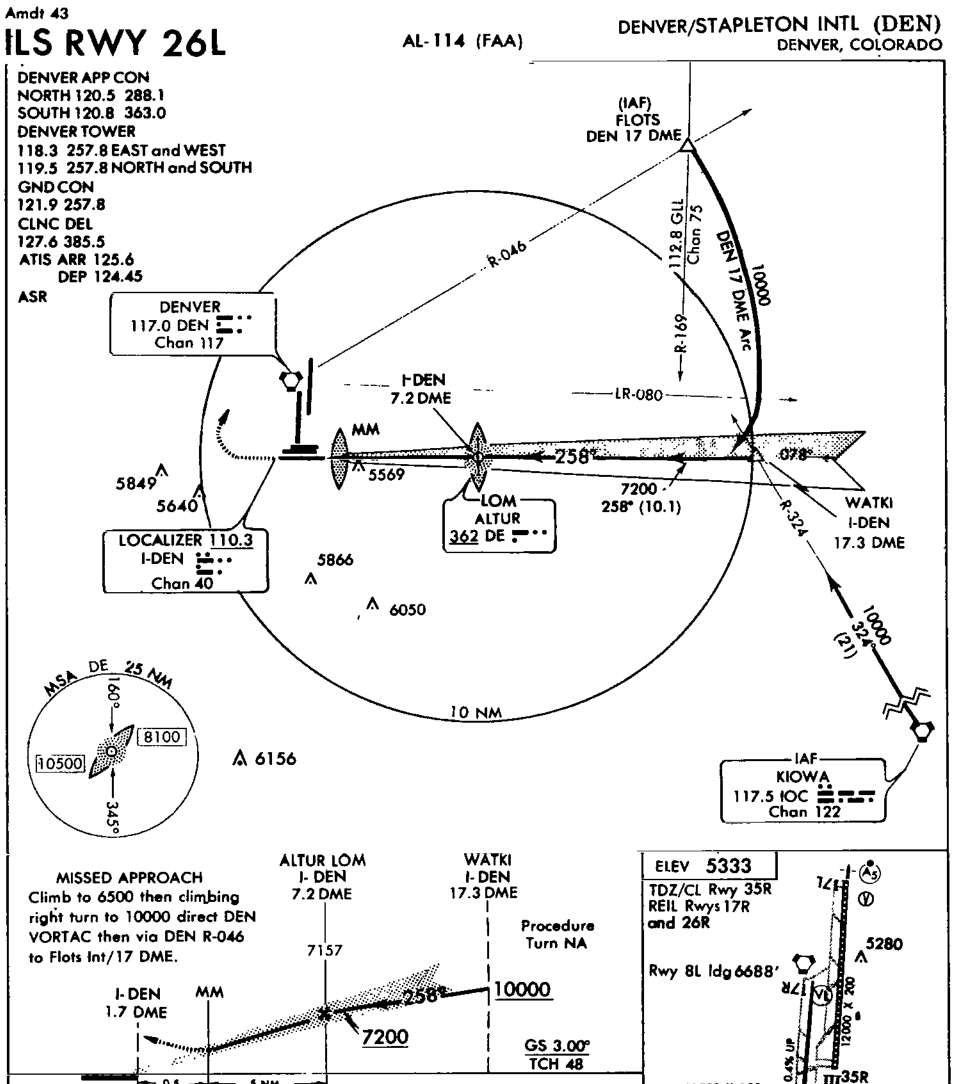
In addition to the ΔT symbol, which was always over the left side of the AGS, a numeric display of ΔR, displayed in tenths of nautical miles, was shown over the right side of the AGS at any time that ΔR became less than 2 n.mi. It should be noted that most of the concepts for the traffic-display format, noted previously, were obtained under a contract to Dynasyst, Inc., of Princeton, New Jersey.

One additional modification was implemented in the traffic-display format in an attempt to reduce pilot workload due to the in-trail separation task. This modification involved driving the speed-error symbol on the basic format with a speed-error term obtained from the ΔT equation. Since a zero ΔT is the quantity actually desired, we set ΔT equal to zero and solve for V_F, which is actually, then, the desired V_F (that is, $V_{F,desired}$) for ΔT equal to zero. Then, speed error is

$$\text{Speed error} = V_F - V_{F,desired}$$

Task Description

The basic piloting task in this study was a manual-instrument approach and landing (fig. 7) while following the vortex-generating lead aircraft in weather



CATEGORY	A	B	C	D
S-ILS 26L	5533/24 200 (200-½)			
S-LOC 26L	5780/24 447 (500-½)		5780/40 447 (500-¾)	5780/50 447 (500-1)
CIRCLING	5880-1 547 (600-1)		5880-1½ 547 (600-1½)	5900-2 567 (600-2)
SIDESTEP RWY 26R	5780-1 458 (500-1)		5780-1½ 458 (500-1½)	5780-2 458 (500-2)

FAF to MAP 5.5NM					
Knots	60	90	120	150	180
Min:Sec	5:30	3:40	2:45	2:12	1:50

Figure 7.- Sample approach chart. Decision height was reduced to 150 ft for this study.

conditions simulating a 150-ft ceiling and calm air. The approach was to runway 26L at the Stapleton International Airport, Denver, Colorado. Under all test conditions, the pilots were provided with the basic-display format which was utilized as the primary display for the approach task. For consistency, a standard pilot-briefing form (see appendix A) was used in briefing each pilot before each simulation session. In addition, a questionnaire on the description of initial conditions and performance variables to be measured was given to the test subjects prior to participating in the test. (See appendix B.) The test subjects were further instructed to fly the simulator in a manner they deemed acceptable for airline-type operations and to avoid radical maneuvers. Besides being professional pilots, the test subjects had attended an airline training school and were experienced in flying Boeing aircraft. During the test runs, the test engineer acted as the copilot in regard to lowering the flaps and other such tasks as directed by the evaluation pilot. The test engineer did not offer comments on the simulated situation during the sessions.

During this study, the means for providing the in-trail separation was divided into two categories, ATC and SELF. Under ATC separation, the pilot was provided only with the basic-display format and he received his separation instructions, in the form of speed commands, from a pseudo approach control that employed a simulated ATC approach controller's radar scope. The approach controller was instructed to control the separation of ownship such that: (1) ownship was never closer than 3 n.mi. from the lead aircraft, and (2) ownship was as close as possible to 3 n.mi. as the lead aircraft crossed the runway threshold. Under SELF, the separation criterion was subdivided into three $T_{desired}$ times: 90, 60, and 45 sec. The basis for these times was taken from references 6 and 7. Additionally, the 90-sec time, coupled with a final approach speed of 120 knots, would equate to a separation distance of 3 n.mi., thus allowing a general comparison of data obtained with this separation criterion with data obtained under ATC separation. The 45-sec interval was the smallest time used (and also, therefore, the smallest separation) since this time borders on the current minimum possible runway occupancy time (ref. 7).

Traffic Profiles

The traffic scenario utilized in this study was that of a single lead aircraft which was flying the ILS approach to runway 26L at the Stapleton International Airport, Denver, Colorado. Four different profiles for the lead aircraft were used and are described in the following discussion.

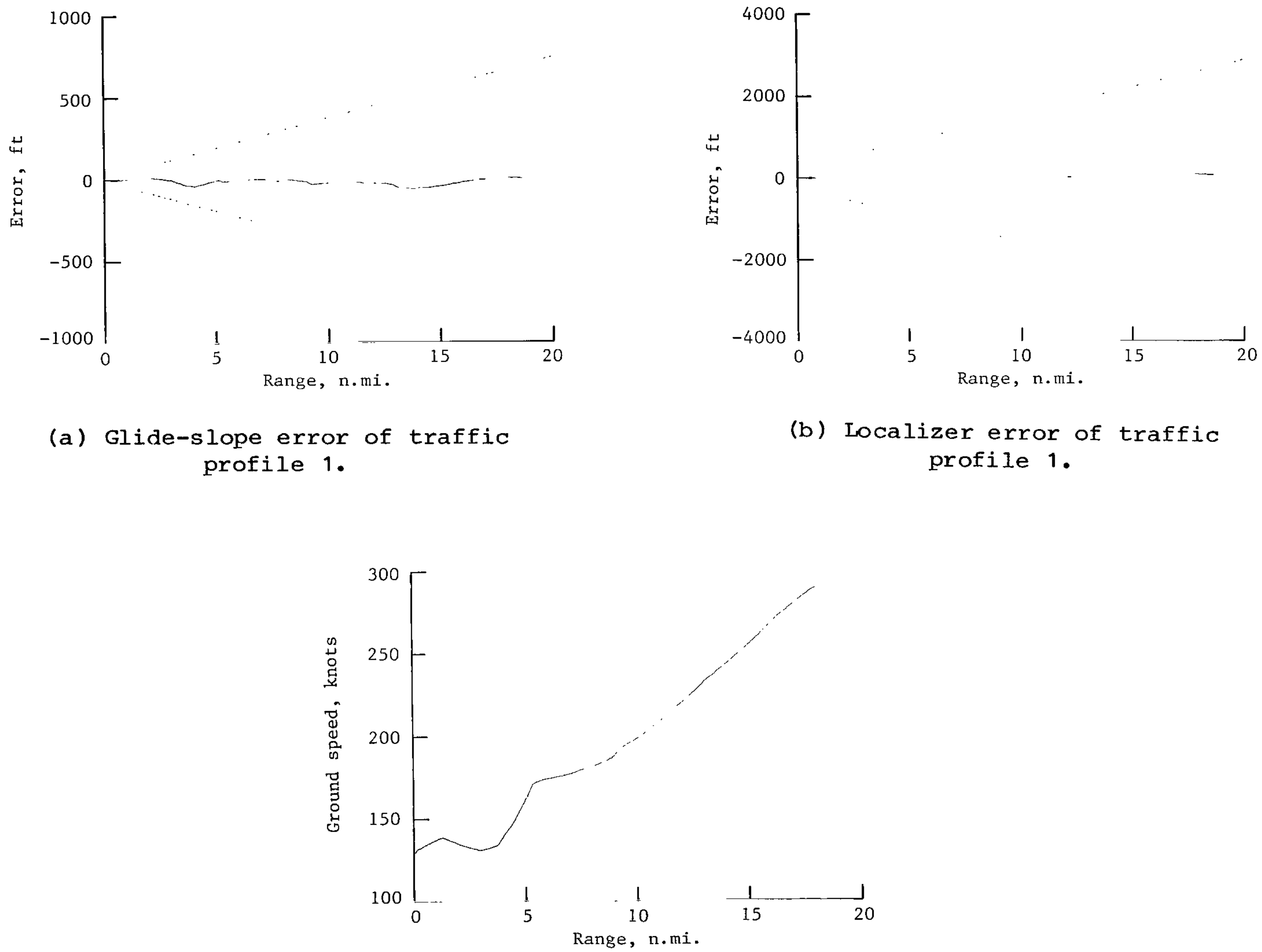
Profile 1.- The first traffic profile was that of an aircraft with $V_{ref} = 120$ knots (the same as that of ownship). This aircraft flew an almost idle-thrust descent while carefully maintaining the ILS path, landed, and exited the runway in a normal but expeditious manner. This profile was considered the baseline profile.

Profile 2.- The second traffic profile was exactly the same as that of profile 1 except that the lead aircraft did not exit the runway. This profile was chosen to determine if the ownship could detect this type of blunder.

Profile 3.- The third traffic profile was very similar to that of profile 1 except that when the lead aircraft reached a 150-ft altitude, it executed a missed approach (go-around). This profile, along with profile 2, constituted the two blunder scenarios used in this study.

Profile 4.- The fourth traffic profile was that of an aircraft with V_{ref} = 140 knots (20 knots higher than ownship), representing an aircraft in the heavy class. Except for the higher approach speeds, this profile was similar to that of profile 1.

The glide-slope error, localizer error, and ground-speed profile plots for profiles 1 and 4 are shown in figure 8.

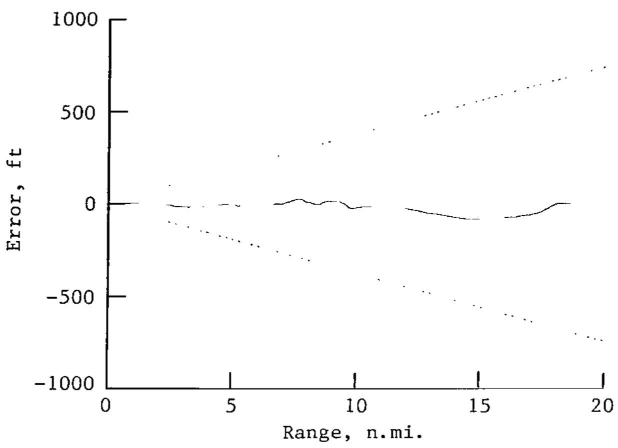


(a) Glide-slope error of traffic profile 1.

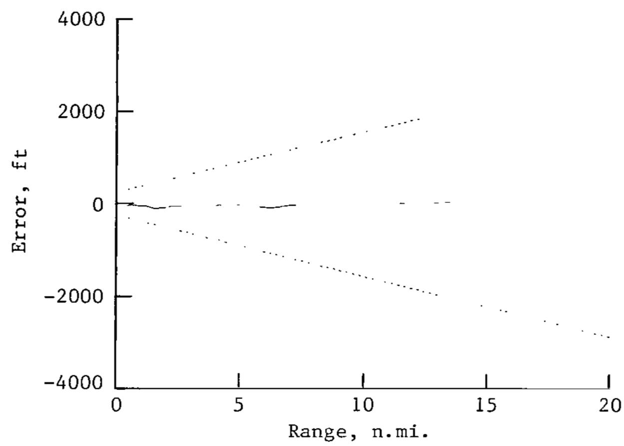
(b) Localizer error of traffic profile 1.

(c) Ground speed of traffic profile 1.

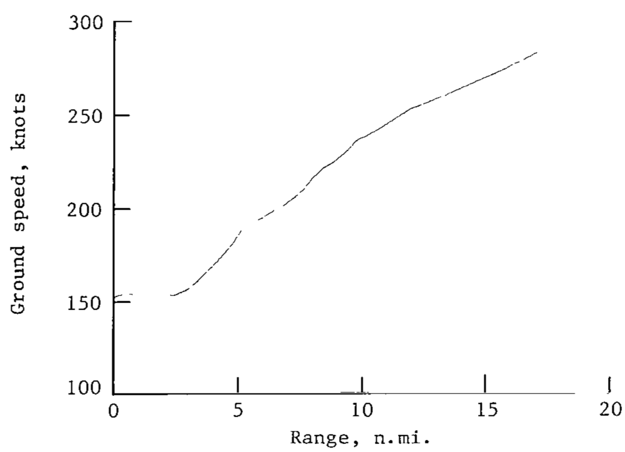
Figure 8.- Flight-path performance of traffic profiles 1 and 4. Dashed lines indicate category II ILS window edges.



(d) Glide-slope error of traffic profile 4.



(e) Localizer error of traffic profile 4.



(f) Ground speed of traffic profile 4.

Figure 8.- Concluded.

TEST CONDITIONS

A total of 99 simulated instrument approaches were flown by three professional pilots to obtain data, with each pilot flying 33 approaches. Both the test and the test matrices (shown in table I) were divided into two major sections. The first section employed a standard separation (3 n.mi. or 90 sec) and was used primarily to determine the differences, if any, between the ATC-controller criterion and the SELF criterion. The second section was aimed at determining the acceptability, from a pilot-workload standpoint, of reduced in-trail separation approaches.

Sufficient training was given both prior to the initial simulation data sessions and before each individual session of the first test section to minimize the learning effects. Except for the two blunder cases, the pilots were trained in all situations shown in the test matrices.

The initial conditions for the lead aircraft were as follows: on the ILS path, approximately 15 n.mi. from the runway threshold, and at an IAS of 250 knots. The initial conditions for ownship were as follows: on the ILS path, at an IAS of 250 knots, and at a distance behind the lead aircraft such that ΔT was approximately zero.

It should be noted that for the SELF 45-sec separation task, $V_{L,nom}$ was set to the same value as $V_{F,nom}$ when the actual $V_{L,nom}$ was 140 knots. This was done because the initial in-trail separation would be less than 0.7 n.mi. if $V_{L,nom} = 140$ knots were used.

RESULTS AND DISCUSSION

The results of this study are divided into three areas of discussion. The first section discusses the general results of the study. The second section discusses the standard-separation task (3 n.mi. or 90 sec), in which the SELF- and ATC-separation data are compared. The third section is an analysis of the SELF reduced-separation interval with the 90-sec separation interval used as a basis for comparison. The data from the blunder scenarios were not used in the analysis of the quantitative data.

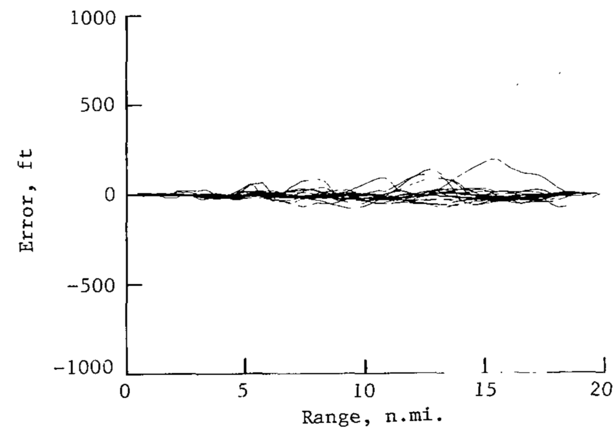
General

Situational awareness.- An increase in situational awareness was provided to the pilot by the addition of the traffic symbology to the display. The consensus of the pilot commentary relating to the traffic symbology was that it "provided a better feel for the situation relative to normal IFR." A noteworthy point relating to this pilot consensus was that the only go-around executed by an evaluation pilot during a nonblunder scenario occurred during an ATC-separation approach. The conditions leading to this occurrence were ownship within normal ILS limits and just prior to crossing the runway threshold, no traffic information on the display (ATC separation), and a slight pilot-induced roll oscillation. At this time, the evaluation pilot believed that he had descended below the glide path of the lead aircraft and that the roll oscillation was due to ownship encountering the vortex of the lead aircraft. The evaluation pilot then decided that to attempt landing at this time would be unsafe and, therefore, he initiated a go-around maneuver.

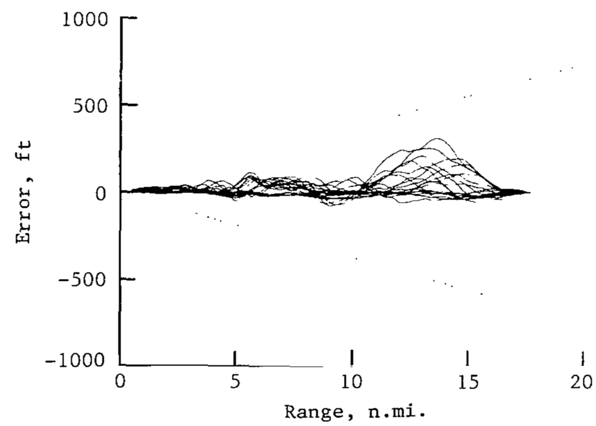
Blunder scenarios.- During six of the SELF data runs, blunder scenarios were introduced in which the lead aircraft either executed a missed approach while on a short final approach or failed to exit the runway after landing. All blunder scenarios were correctly identified by the pilots with the proper corrective action: a go-around maneuver, being initiated before a critical situation could develop. The lead aircraft executing a missed approach was first indicated to the evaluation pilot by the $L_{present}$ symbol moving steadily toward and then above the ILS-box symbol. As the $L_{present}$ symbol continued to stay above the ILS box, and before the L_{past} symbol began to move upward, the pilots always began a go-around maneuver. The occupied-runway blunder became apparent to the evaluation pilot as he approached the runway after the lead aircraft landed by the $L_{present}$ symbol moving neither right nor left, indicating that the lead aircraft was not turning off the runway. The pilots normally waited until the decision height symbol enunciated, and if the lead aircraft was then still on the runway, they would execute a go-around maneuver.

Vortex encounters.- At no time during the 99 data runs did a vortex upset occur. This result was obtained primarily by the pilot being able to monitor and track the glide slope precisely and by the fact that the lead aircraft was also, in general, precisely tracking the glide path. With the reduced-separation cases, however, a greater possibility existed for a vortex encounter, since ownship was potentially closer to the vortices. The fact that an encounter did not occur may, in part, be attributed to the pilot's having knowledge of the past position of the lead aircraft and thus being able to stay above that position, thereby reducing the likelihood of an encounter.

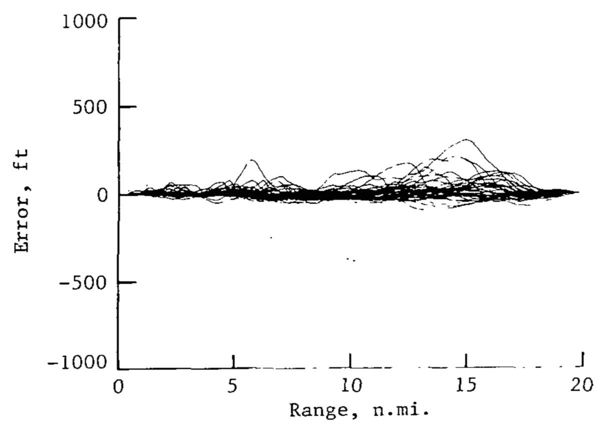
Glide-slope tracking.- The glide-slope tracking error (fig. 9) appears to have a somewhat sinusoidal characteristic. This characteristic can be partially attributed



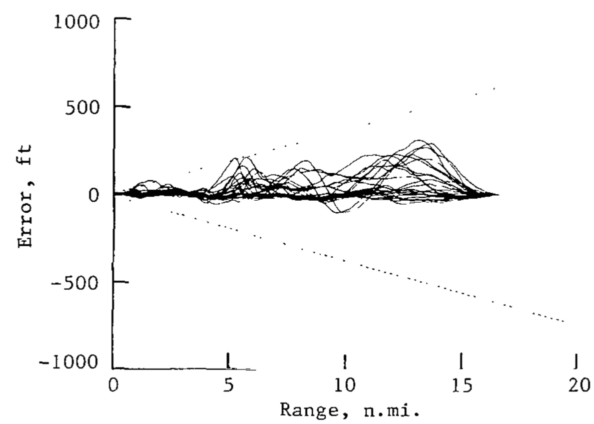
(a) Glide-slope error during ATC separation.



(b) Glide-slope error during 60-sec self-separation.



Glide-slope error during 90-sec self-separation.



(d) Glide-slope error during 45-sec self-separation.

Figure 9.- Glide-slope tracking performance. Dashed lines indicate glide-slope window edges.

to deployment of the aircraft flaps, which are lowered in steps throughout the approach and produce a pitch-attitude change and an increase in lift (for a given speed and angle of attack). Therefore, if ownship were on the glide slope and at the proper pitch attitude required to maintain that flight path prior to flap deployment, the pilot would have to make an immediate and continuous pitch-attitude correction upon and during a flap change in order to compensate for this attitude change and keep the aircraft on the proper flight path. The control technique used by some pilots in this study, however, was to allow the aircraft to begin to trim at the new attitude brought about by a flap change, with a resulting divergence from the glide slope, before initiating a correction to bring the aircraft back to the proper flight path. The reason given for the use of this technique was that it minimized the glide-slope tracking task and reduced the possibility of overcontrolling the aircraft while remaining within acceptable glide-slope limits.

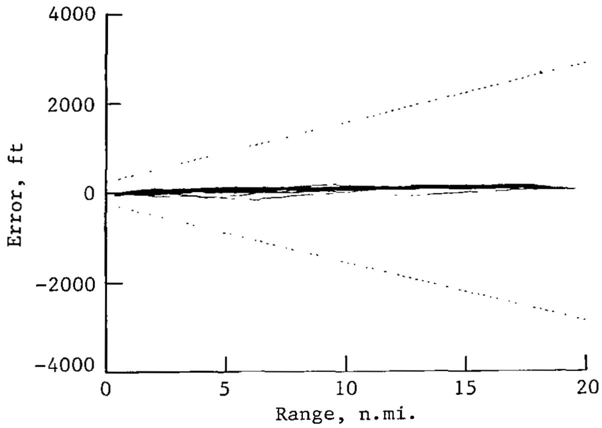
Approach speeds.- No statistical difference was noted in the quantitative-data analysis at the 95-percent confidence level between ownship following traffic profile 1 (with V_{ref} = 120 knots) and traffic profile 4 (with V_{ref} = 140 knots).

Closure-rate indication.- The consensus of the pilot commentary was that the indication of closure rate, provided by the motion of the $L_{present}$ symbol, was not consciously used.

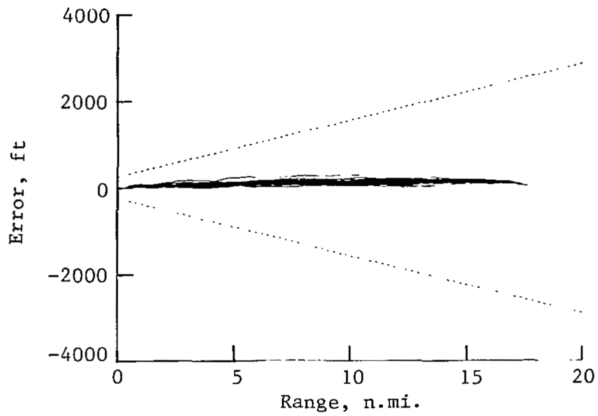
Speed error.- The pilots indicated that by driving the speed-error symbol (when employing self-separation) as a function of ΔT, separation maintenance using the speed-error symbol was easier than using the ΔT symbol since speed-error tracking is a normal piloting task.

Standard Separation

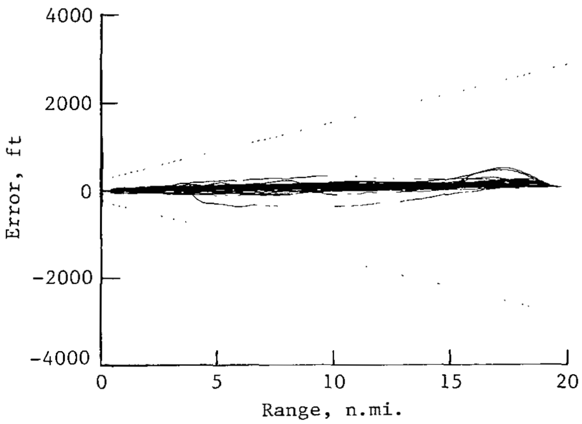
General performance.- No statistically significant difference in the localizer tracking error (fig. 10) was noted between ATC separation and self-separation with a mean and rms of 0.044° and 0.078°, respectively, for ATC and similarly of 0.044° and 0.101° for SELF. The glide-slope tracking error (fig. 9), unlike the localizer error, showed a statistically significant difference at the 99-percent confidence level with a mean and rms of -0.009° and 0.030°, respectively, for ATC separation and similarly 0.002° and 0.043° for SELF. With the traffic symbology present on the display, this statistically significant difference between the two separation methods was not unexpected since the pilot commentary indicated that all pilots intentionally flew either at or slightly above the flight path of the lead aircraft by using the L_{past} symbol of the lead aircraft as a reference. Although this significant difference did occur in the glide-slope data, it is questionable, however, if the difference would have any real effect from an operational standpoint. Since a mean glide-slope error of -0.009° is less than an error of 3 percent relative to the category II ILS boundary of ±0.35°, and similarly since an error of 0.002° is less than 1 percent, it is doubtful that this difference would have any effect on a real-world operation. What could make an operational difference, however, would be the lead aircraft flying an unusually high or erratic vertical path, since ownship always tried to remain above the lead aircraft.



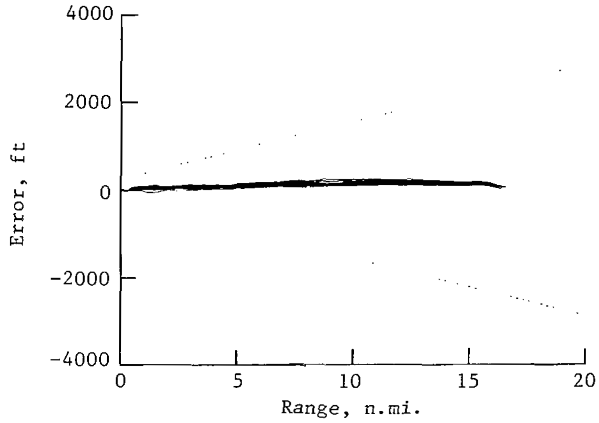
(a) Localizer error during ATC separation.



(b) Localizer error during 60-sec self-separation.



(c) Localizer error during 90-sec self-separation.

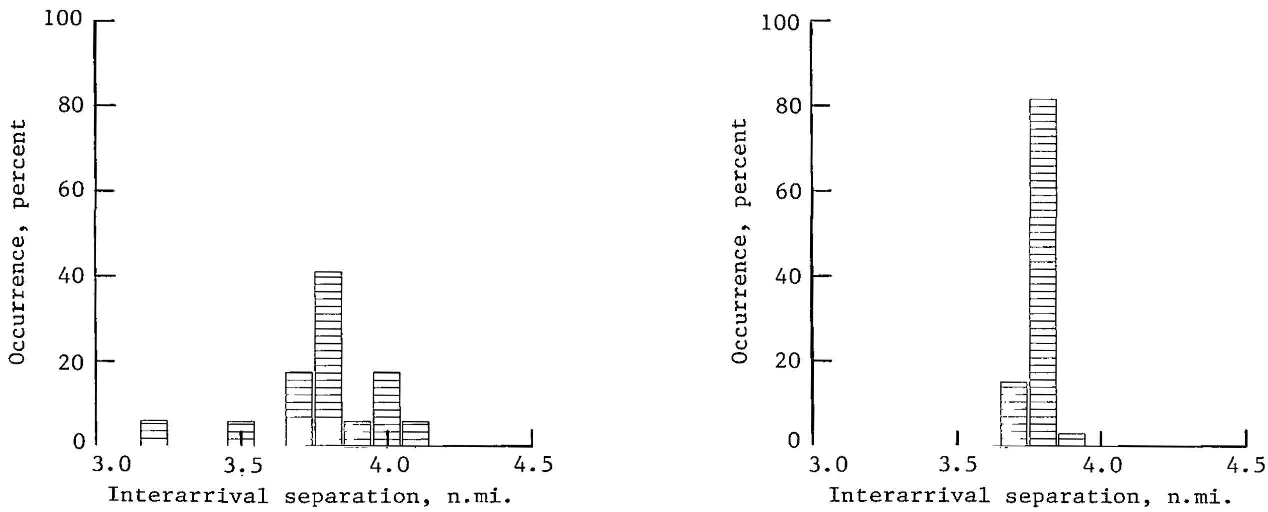


(d) Localizer error during 45-sec self-separation.

Figure 10.- Localizer tracking performance. Dashed lines indicate localizer window edges.

Separation and workload.- It is of interest to note that mean values for interarrival separation (the separation as the leader crosses the runway threshold) for both the ATC and SELF were 3.8 n.mi. (table II and fig. 11). Although the mean values were the same, however, the deviation values of the interarrival separation were 0.20 n.mi. for ATC separation and 0.04 n.mi. for self-separation. Pilot-workload ratings, obtained from the pilot questionnaire, are shown in table III(a). For the SELF 90-sec separation, the task of maintaining the in-trail separation was considered very easy overall with a low level of additional workload associated with it. This task was considered somewhat more difficult if the lead aircraft had a higher V_{ref}, as can be seen in table III(a) by the ratings being shifted more toward the difficult side of the rating scale.

The qualitative data also noted a major increase in throttle activity for SELF relative to ATC separation. The quantitative data, however, show an average of 21 throttle movements prior to the lead aircraft crossing the threshold for the self-separation task compared with 18 movements for the ATC task (table II). This differ-



(a) ATC separation.

(b) 90-sec self-separation.

Figure 11.- Normalized values of interarrival-separation results.

ence was not significant at the 90-percent confidence level. The average throttle movements, from the initiation of the run until landing, were 29 for the SELF task and 25 for the ATC task. Similarly, this difference was not significant at the 90-percent confidence level.

Although the interarrival separation intervals are important, of more significance to airport capacity is the runway delivery accuracy, which is measured in terms of the time interval between the lead aircraft crossing the runway threshold and the trailing aircraft arriving at the runway threshold. This time interval, referred to as interarrival time (IAT), is frequently used as a parameter in defining arrival capacity for a particular runway. Additionally, the less that IAT varies from the mean IAT, the shorter the mean IAT can be for an equivalent level of missed approaches. Figure 12 illustrates this effect of IAT dispersion on runway arrival

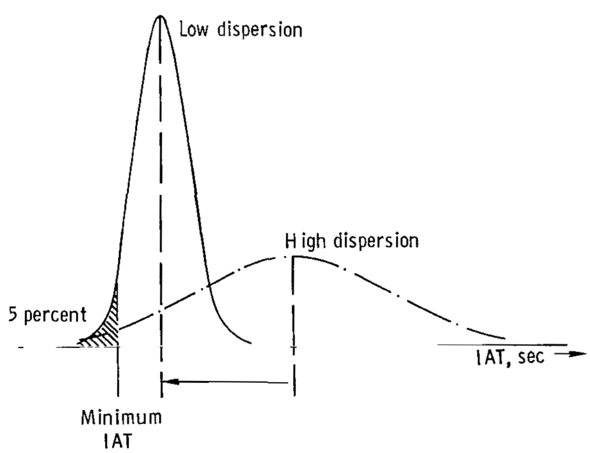


Figure 12.- Illustration of effect on mean IAT resulting from lower IAT dispersion.

capacity. As shown, for a given minimum allowable IAT, the mean IAT of a distribution with a low dispersion can be less than the mean of a distribution with a higher dispersion. Since a shorter mean IAT results in an increase in arrival capacity, it is desirable to minimize the dispersion of IAT (ref. 7). As shown, for a given minimum allowable IAT, the mean IAT of a distribution of times with a low dispersion can be less than the mean of a distribution with a higher dispersion. Previous studies (ref. 8) have shown the deviation of the IAT for ATC operations to be approximately 18 sec. IAT deviation values obtained in this study for ATC separation and SELF were 5 sec and 2 sec, respectively.

From an overall performance and workload standpoint, then, it would appear that a reduction in IAT dispersion relative to ATC separation can be obtained with the use of this self-separation concept with only a small increase in pilot workload. The fact that a significant workload increase due to the self-separation task did not occur is indicated by the pilot-questionnaire results and by the similar localizer mean tracking errors associated with the ATC- and self-separation tasks.

Reduced Separation

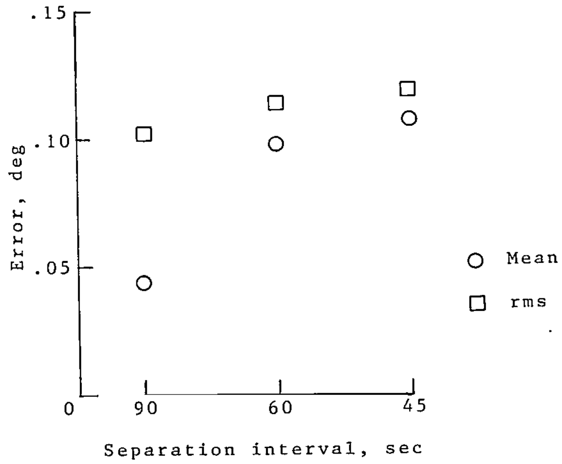
For this section of analysis, the SELF 90-sec separation interval is used as the basis of comparison for the SELF 60-sec and 45-sec intervals.

General performance.- Unlike the localizer tracking performance for the standard-separation analysis, for the reduced-separation intervals there is a significant difference in the localizer performance between the three separation intervals at the 99-percent confidence level. As previously stated, the mean and rms performances were 0.044° and 0.101°, respectively, for the 90-sec separation interval. The mean and rms values for the 60-sec interval were 0.098° and 0.113°, respectively, and for the 45-sec interval they were 0.107° and 0.117°, respectively (fig. 13). As can be seen, a slight but consistent degradation in localizer tracking performance occurs as the separation interval is reduced.

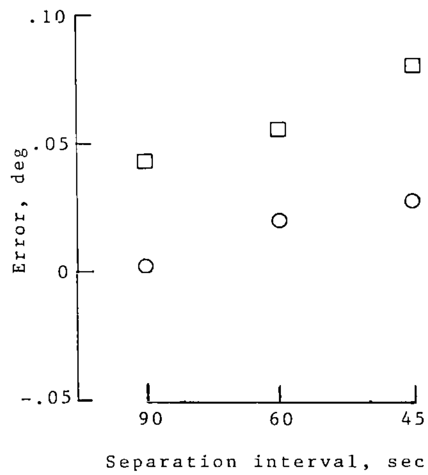
It should be noted, however, that with a localizer window of ±1.25° (fig. 10), even a mean error of 0.107° results in an error of less than 9 percent relative to the window. Additionally, as the separation interval is reduced, the vertical position of ownship moves closer to the vortex flow fields, which appear to the pilot as wind gusts that are ranging in intensity levels from unnoticeable to slight as the vertical positions move closer. Since the vortex flow fields interact with the aircraft aerodynamics, an increase in the flow-field strength could result in an increase in the ILS-path tracking error with a corresponding increase in pilot workload.

The glide-slope tracking error, like the localizer data, showed a significant difference at the 99-percent confidence level for the three separation intervals with the performance degrading as the separation interval was reduced. The mean and rms error values were 0.002° and 0.043° for the 90-sec interval, 0.020° and 0.055° for the 60-sec interval, and 0.027° and 0.079° for the 45-sec interval, respectively. As can be seen, a consistent degradation occurred as the separation interval was reduced. It should be noted, however, that even the worst performance exhibited was considered operationally acceptable.

Separation and workload.- As stated previously, a key factor to airport capacity is the dispersion of the IAT relative to some mean IAT. The deviation values



(a) Localizer error.



(b) Glide-slope error.

Figure 13.- ILS tracking error during self-separation.

obtained in this study for the 90-, 60-, and 45-sec separation intervals were 1.87, 1.22, and 2.10 sec, respectively. If 90, 60, and 45 sec are assumed to be the minimum calculated IAT's and a nominal violation (go-around) rate of 5 percent of these minimums is acceptable, then the calculated mean IAT's using the aforementioned values would be 93.1, 62.0, and 48.5 sec, respectively. The theoretical runway capacity, in landings per hour, would then be 38.7, 58.1, and 74.3 for the minimum 90-, 60-, and 45-sec calculated IAT tasks, respectively.

From a pilot-workload basis, the workload associated with the self-separation task was considered acceptable for all three separation intervals (table III). The overall separation-workload rating for the 90-sec interval was "very easy," the rating for the 60-sec interval was again "very easy," and the rating for the 45-sec interval was "easy." The self-separation task, therefore, became somewhat more difficult as the separation interval was reduced. Additionally, as was seen in the standard-separation analysis, the self-separation task was considered somewhat more difficult if the lead aircraft had a higher V_{ref}.

In general, then, it would seem that self-separation, with theoretical IAT's as close as 45 sec, is possible from both a performance and pilot-workload standpoint. Although ILS tracking performance did degrade and pilot workload did increase as the separation interval was reduced, the path-tracking performance and workload were within operationally acceptable limits.

CONCLUDING REMARKS

A piloted simulation study was undertaken to determine the feasibility and potential benefits of utilizing a forward-looking, head-up display (HUD) format to provide information to a pilot to enable him to be responsible for his own separation behind a vortex-generating lead aircraft during an instrument approach.

An increase in situational awareness, relative to conventional instrument flight, was provided to the pilot by the addition of the traffic symbology to the display. For all approaches where the maneuvering of the lead aircraft would have caused a potentially hazardous condition to occur, the pilots properly identified the condition and initiated an appropriate corrective action.

At a self-separation interval of 90 sec, a reduction in interarrival-time dispersion, relative to Air Traffic Control separation, was observed with only a small increase in pilot workload. Interarrival times as close as 45 sec were possible, with associated pilot workload and path-tracking performance remaining within acceptable limits.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
March 15, 1984

APPENDIX A

PILOT BRIEFING

You are the captain of a 737 on a revenue flight. You are expected to comply with all normal ATC speed restrictions and fly the aircraft within its normal performance envelope.

ATC: You will/will not be cleared to land, depending on runway-occupancy conditions. ATC will attempt to have you at a 3-n.mi. separation as the lead aircraft crosses the threshold. Speed reductions may be issued.

HUD: You are cleared for the approach and landing (normal ATC procedures in effect) with the exception of traffic separation and runway occupancy. You are responsible for these. The separation/spacing algorithms are set up so that you will have a 90-sec (3 n.mi. at 120 knots) separation as the lead aircraft crosses the threshold.

Fly as though it were a real operation. NOTE:

(1) V_{ref} = 120 knots

(2) Flaps: 0°, 10°, 20°, 25°, 30°, and 40°

(3) Would advise starting with gear down, flaps 0°

(4) The speed brakes are operational.

(5) The TOGA switch is operational.

(6) Without the traffic symbology, the speed bug provides a nominal (linear) deceleration profile to 120 knots at 2 n.mi.

(7) Lead aircraft with V_{ref} = 140 knots are to be considered in the HEAVY class.

Reduced separation: All the above apply except that the separation algorithm is set up so that you will have either a 60- or 45-sec separation as the lead aircraft crosses the threshold.

APPENDIX B

PILOT QUESTIONNAIRE

I. SPACING (skip if controller used):

(1) Did the lead aircraft behave as expected (no unusual maneuvers)?

☐ Yes ☐ No

If no, what did it do and what were your actions?

(2) Was there any concern with respect to maintaining a safe separation interval?

☐ Yes ☐ No

If yes, what was (or caused) the concern?

(3) Did the self-spacing task add an unacceptable level of workload?

☐ Yes ☐ No

If yes, state how and any recommendations that may cure some.

(4) Rate the self-separation task:

No problem	Very easy	Easy	Not easy	Difficult	Very difficult	Impossible

II. VORTEX:

(1) Was the vortex ever encountered?

☐ Yes ☐ No

If yes, how severe was the encounter and how did it affect the approach?

(2) Was any technique used to avoid the vortex?

☐ Yes ☐ No

If yes, what?

III. GENERAL:

(1) Was the displayed information adequate for safe separation?

☐ Yes ☐ No ☐ N/A

If no, explain.

(2) Did you accurately maintain the prescribed separation?

☐ Yes ☐ No ☐ N/A

If no, why not?

(3) Was the display easy to use?

☐ Yes ☐ No

Comments:

(4) Was the displayed information easy to interpret?

☐ Yes ☐ No

Comments:

(5) At any time did you have the feeling you were being "led down the primrose path?"

☐ Yes ☐ No

If yes, why?

(6) Any general comments?

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8. Sinha, A. N.; and Haines, A. L.: Longitudinal Separation Standards on Final Approach for Future ATC Environments. MTR-6979, Mitre Corp., Oct. 1975.

TABLE I.- TEST MATRICES

(a) Standard separation

Pilot	Test sequence made under in-trail separation -					
	ATC	SELF	ATC	SELF	ATC	SELF
1	2	[a]3	2	[a]3	2	[b]3
2	2	[a]3	2	[b]3	2	[a]3
3	[a]2	[a]3	[a]2	[b]3	[a]2	[a]3

(b) Reduced separation (90, 60, or 45 sec)

Pilot	Test sequence made with separation interval of -								
	90 sec	60 sec	45 sec	90 sec	60 sec	45 sec	90 sec	60 sec	45 sec
1	1	2	[a]3	1	2	[b]3	1	2	[a]3
2	1	2	[a]3	1	2	[a]3	1	2	[b]3
3	1	2	[b]3	1	2	[a]3	1	2	[a]3

[a]One of the set is of a dissimilar speed profile (profile 4).
[b]One of the set is a blunder (profile 2 or 3).

TABLE II.- STATISTICAL ANALYSIS

[The notation 1-st signifies first]

---------------------- Separation (n.mi.) ------------------

ATC Separation

Pilot 1	samples	6	mean	3.7	deviation	0.22	range	0.57	minimum	3.3	maximum	3.8
Pilot 2	samples	6	mean	4.0	deviation	0.10	range	0.25	minimum	3.8	maximum	4.1
Pilot 3	samples	5	mean	3.9	deviation	0.16	range	0.40	minimum	3.7	maximum	4.1
Totals	samples	17	mean	3.8	deviation	0.20	range	0.86	minimum	3.3	maximum	4.1

SELF Separation -- 90 Sec

Pilot 1	samples	11	mean	3.8	deviation	0.03	range	0.10	minimum	3.8	maximum	3.9
Pilot 2	samples	11	mean	3.8	deviation	0.03	range	0.12	minimum	3.8	maximum	3.9
Pilot 3	samples	11	mean	3.9	deviation	0.02	range	0.09	minimum	3.8	maximum	3.9
Totals	samples	33	mean	3.8	deviation	0.04	range	0.13	minimum	3.8	maximum	3.9

ANALYSIS of VARIANCE (ATC and SELF, 90 Sec data)

cell means for 1-st dependent variable -- Separation

							marginal
pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3	
control =	ATC	SELF	ATC	SELF	ATC	SELF	
separation	3.64833	3.79636	3.91333	3.76909	3.82600	3.81636	3.79400
count	6	11	6	11	5	11	50

standard deviations for 1-st dependent variable - Separation

pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3
control =	ATC	SELF	ATC	SELF	ATC	SELF
separation	0.22257	0.03264	0.10191	0.03300	0.16196	0.02501

ANALYSIS of VARIANCE for 1-st dependent variable - Separation

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	643.18916	1	643.18916	65458.99	0.0000
pilots	0.12450	2	0.06225	6.34	0.0038
control	0.00004	1	0.00004	0.00	0.9479
interaction	0.16614	2	0.08307	8.45	0.0008
error	0.43234	44	0.00983		

SELF Separation -- 60 Sec

Pilot 1	samples	6	mean	2.4	deviation	0.02	range	0.05	minimum	2.4	maximum	2.5
Pilot 2	samples	6	mean	2.4	deviation	0.04	range	0.10	minimum	2.4	maximum	2.4
Pilot 3	samples	6	mean	2.4	deviation	0.00	range	0.01	minimum	2.4	maximum	2.4
Totals	samples	18	mean	2.4	deviation	0.03	range	0.10	minimum	2.4	maximum	2.5

SELF Separation -- 45 Sec

Pilot 1	samples	8	mean	1.9	deviation	0.14	range	0.32	minimum	1.8	maximum	2.1
Pilot 2	samples	8	mean	1.9	deviation	0.18	range	0.45	minimum	1.7	maximum	2.2
Pilot 3	samples	8	mean	1.9	deviation	0.14	range	0.30	minimum	1.8	maximum	2.1
Totals	samples	24	mean	1.9	deviation	0.14	range	0.45	minimum	1.7	maximum	2.2

TABLE II.- Continued

--------------------- Theoretical IAT (sec) ---------------------

ATC Separation

Pilot 1	samples	6	mean	92.4	deviation	4.17	range	11.99	minimum	87.5	maximum	99.5
Pilot 2	samples	6	mean	93.9	deviation	2.30	range	5.71	minimum	90.1	maximum	95.8
Pilot 3	samples	5	mean	91.8	deviation	5.25	range	13.11	minimum	86.5	maximum	99.6
Totals	samples	17	mean	92.7	deviation	3.84	range	13.11	minimum	86.5	maximum	99.6

SELF Separation -- 90 Sec

Pilot 1	samples	11	mean	90.5	deviation	1.29	range	4.09	minimum	89.1	maximum	93.2
Pilot 2	samples	11	mean	90.3	deviation	0.91	range	3.22	minimum	88.3	maximum	91.5
Pilot 3	samples	11	mean	89.6	deviation	1.42	range	4.83	minimum	85.9	maximum	90.7
Totals	samples	33	mean	90.1	deviation	1.24	range	7.29	minimum	85.9	maximum	93.2

ANALYSIS of VARIANCE (ATC and SELF, 90 Sec data)

cell means for 1-st dependent variable -- theoretical IAT

pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3	marginal
control =	ATC	SELF	ATC	SELF	ATC	SELF	
IAT	92.34000	90.42000	93.82167	90 21545	91.78600	89.56636	90.96240
count	6	11	6	11	5	11	50

standard deviations for 1-st dependent variable - theoretical IAT

pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3
control =	ATC	SELF	ATC	SELF	ATC	SELF
IAT	4.17040	1.28871	2.29594	0.91296	5.25020	1.42247

ANALYSIS of VARIANCE for 1-st dependent variable - theoretical IAT

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	372760.87614	1	372760.87614	61028.05	0.0000
pilots	13.14219	2	6.57110	1.08	0.3498
control	74.43382	1	74.43382	12.19	0.0011
interaction	6.22311	2	3.11156	0.51	0.6043
error	268.75313	44	6.10803		

SELF Separation -- 60 Sec

Pilot 1	samples	6	mean	60.0	deviation	0.83	range	2.42	minimum	58.4	maximum	60.8
Pilot 2	samples	6	mean	59.6	deviation	0.91	range	2.54	minimum	58.5	maximum	61.1
Pilot 3	samples	6	mean	60.0	deviation	0.25	range	0.69	minimum	59.6	maximum	60.3
Totals	samples	18	mean	59.8	deviation	0.71	range	2.67	minimum	58.4	maximum	61.1

SELF Separation -- 45 Sec

Pilot 1	samples	8	mean	45.0	deviation	0.35	range	0.96	minimum	44.6	maximum	45.6
Pilot 2	samples	8	mean	44.6	deviation	1.30	range	3.49	minimum	42.7	maximum	46.2
Pilot 3	samples	8	mean	45.0	deviation	0.16	range	0.49	minimum	44.8	maximum	45.3
Totals	samples	24	mean	44.9	deviation	0.77	range	3.49	minimum	42.7	maximum	46.2

TABLE II.- Continued

---------------------- Actual IAT (sec) ---------------------

ATC Separation

Pilot 1	samples	6	mean	96.1	deviation	5.94	range	15.47	minimum	86.0	maximum	101.4
Pilot 2	samples	6	mean	101.7	deviation	2.76	range	6.15	minimum	98.4	maximum	104.6
Pilot 3	samples	5	mean	100.3	deviation	4.39	range	11.01	minimum	96.3	maximum	107.3
Totals	samples	17	mean	99.3	deviation	4.94	range	21.33	minimum	86.0	maximum	107.3

SELF Separation -- 90 Sec

Pilot 1	samples	11	mean	98.2	deviation	1.76	range	5.72	minimum	95.2	maximum	101.0
Pilot 2	samples	11	mean	96.2	deviation	1.50	range	3.75	minimum	94.4	maximum	98.2
Pilot 3	samples	11	mean	99.1	deviation	0.97	range	3.54	minimum	96.6	maximum	100.1
Totals	samples	33	mean	97.8	deviation	1.87	range	6.52	minimum	94.4	maximum	101.0

ANALYSIS of VARIANCE (ATC and SELF, 90 Sec data)

cell means for 1-st dependent variable - actual IAT

							marginal
pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3	
control =	ATC	SELF	ATC	SELF	ATC	SELF	
IAT	96.10333	98.15000	101.63333	96.16091	100.23600	99.08182	98.29840
count	6	11	6	11	5	11	50

standard deviations for 1-st dependent variable - actual IAT

pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3
control =	ATC	SELF	ATC	SELF	ATC	SELF
IAT	5.94164	1.76191	2.75648	1.50402	4.39492	0.96523

ANALYSIS of VARIANCE for 1-st dependent variable - actual IAT

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	433854.50985	1	433854.50985	53811.71	-.0000
pilots	50.19204	2	25.09602	3.11	0.0544
control	26.02266	1	26.02266	3.23	0.0793
interaction	110.49150	2	55.24575	6.85	0.0026
error	354.74804	44	8.06246		

SELF Separation -- 60 Sec

Pilot 1	samples	6	mean	62.9	deviation	1.04	range	2.70	minimum	61.8	maximum	64.5
Pilot 2	samples	6	mean	61.6	deviation	0.62	range	1.70	minimum	60.8	maximum	62.5
Pilot 3	samples	6	mean	64.0	deviation	0.34	range	0.83	minimum	63.6	maximum	64.4
Totals	samples	18	mean	263.8	deviation	1.22	range	3.63	minimum	60.8	maximum	64.5

SELF Separation -- 45 Sec

Pilot 1	samples	8	mean	47.6	deviation	1.47	range	4.92	minimum	45.9	maximum	50.8
Pilot 2	samples	8	mean	47.3	deviation	2.47	range	7.12	minimum	44.2	maximum	51.3
Pilot 3	samples	8	mean	49.0	deviation	2.09	range	5.02	minimum	47.5	maximum	52.6
Totals	samples	24	mean	48.0	deviation	2.10	range	8.41	minimum	44.2	maximum	52.6

TABLE II.- Concluded

--------------------- Throttle (movements) ---------------------

ATC Separation

Pilot 1	samples 2	average activity 3 (9)	maximum 4 (12)
Pilot 2	samples 2	average activity 19 (27)	maximum 24 (29)
Pilot 3	samples 5	average activity 24 (31)	maximum 29 (38)
Totals	samples 9	average activity 18 (25)	maximum 29 (38)

SELF Separation -- 90 Sec

Pilot 1	samples 5	average activity 20 (27)	maximum 32 (41)
Pilot 2	samples 6	average activity 15 (21)	maximum 24 (38)
Pilot 3	samples 11	average activity 25 (34)	maximum 44 (57)
Totals	samples 22	average activity 21 (29)	maximum 44 (57)

ANALYSIS of VARIANCE (ATC and SELF, 90 Sec data)

cell means for 1-st dependent variable - throttle movements

							marginal
pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3	
control =	ATC	SELF	ATC	SELF	ATC	SELF	
throttle	1.16667	9.36364	6.50000	8.54545	24.00000	25.27273	12.82000
count	6	11	6	11	5	11	50

standard deviations for 1-st dependent variable - throttle movements

pilots =	Pilot1	Pilot1	Pilot2	Pilot2	Pilot3	Pilot3
control =	ATC	SELF	ATC	SELF	ATC	SELF
throttle	1.83485	11.90187	10.46422	8 97066	6.00000	9.18794

ANALYSIS of VARIANCE for 1-st dependent variable - throttle movements

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	6950.21645	1	6950.21645	81.04	0.0000
pilots	3211.25322	2	1605.62661	18.72	0.0000
control	164.50216	1	164.50216	1.92	0.1731
interaction	108.74568	2	54.37284	0.63	0.5353
error	3773.78788	44	85.76791		

SELF Separation -- 60 Sec

Pilot 1	samples 6	average activity 25 (30)	maximum 34 (41)
Pilot 2	samples 6	average activity 18 (22)	maximum 30 (33)
Pilot 3	samples 6	average activity 25 (33)	maximum 32 (41)
Totals	samples 18	average activity 22 (28)	maximum 34 (41)

SELF Separation -- 45 Sec

Pilot 1	samples 8	average activity 27 (33)	maximum 47 (52)
Pilot 2	samples 8	average activity 20 (27)	maximum 28 (33)
Pilot 3	samples 8	average activity 29 (38)	maximum 41 (57)
Totals	samples 24	average activity 26 (33)	maximum 47 (57)

TABLE III.- SUMMARY OF PILOT-WORKLOAD RATINGS FOR SELF-SEPARATION TASK

(a) 90-sec separation interval[a]

Pilot	No problem		Very easy		Easy		Not easy		Difficult		Very difficult		Impossible	
1	5	2	2	1	2									
	7		3		2									
2			2		4	1	3	2						
			2		5		5							
3	2		6		1	2		1						
	2		6		3		1							
All pilots	7	2	10	1	7	3	3	3						
	9		11		10		6							

[a]Explanation of pilot-workload ratings is given as follows:

Data-block format

Lead aircraft with same V_{ref}	Lead aircraft with faster V_{ref}
1	3
Total: 4	

TABLE III.- Continued

(b) 60-sec separation interval

Pilot	No problem	Very easy	Easy	Not easy	Difficult	Very difficult	Impossible
1		6					
2		1	4	1			
3		5	1				
All pilots		12	5	1			

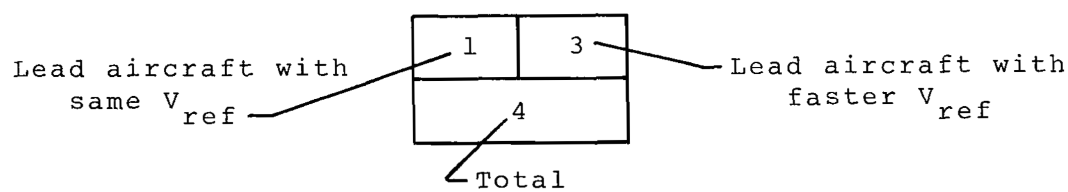
TABLE III.- Concluded

(c) 45-sec separation interval[a]

Pilot	No problem		Very easy		Easy		Not easy		Difficult		Very difficult		Impossible	
1			5		2	2								
			5		4									
2			1		5		1	2						
			1		5		3							
3	1		1		4		2	1						
	1		1		4		3							
All pilots	1		7		11	2	3	3						
	1		7		13		6							

[a]Explanation of pilot-workload ratings is given as follows:

Data-block format



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16. Abstract

A piloted simulation study has been undertaken to determine the feasibility and potential benefits of utilizing a forward-looking display to provide information that would enable aircraft to reduce their in-trail separation, and hence increase runway capacity, through the application of multiple glide-path approach techniques. This portion of the study was an initial exploration into a concept in which traffic information was added to a head-up display (HUD) format to allow the pilot to monitor the traffic situation and to self-space on a lead aircraft during a single glide-path approach task. The tests were conducted in a motion-base cockpit simulator configured as a current-generation transport aircraft and include the dynamic effects of the vortices generated by the lead aircraft. The information provided on the HUD included typical aircraft-guidance information and the current and past positions of the lead aircraft. Additionally, the displayed information provided self-separation cues which allowed the pilot to maintain separation on the lead aircraft. Performance measurements and pilot subjective ratings and comments were obtained during approaches where the separation cues were provided by either an air traffic controller or the displayed symbology. The results of this study indicate that the display concept could provide sufficient information to the pilot for traffic monitoring and self-separation. Additionally, an increase in situational awareness, relative to conventional instrument flight, was provided to the pilot by the displayed traffic information.

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