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PILOTED FLIGHT SIMULATOR STUDY OF LOW-LEVEL WIND SHEAR.(U)

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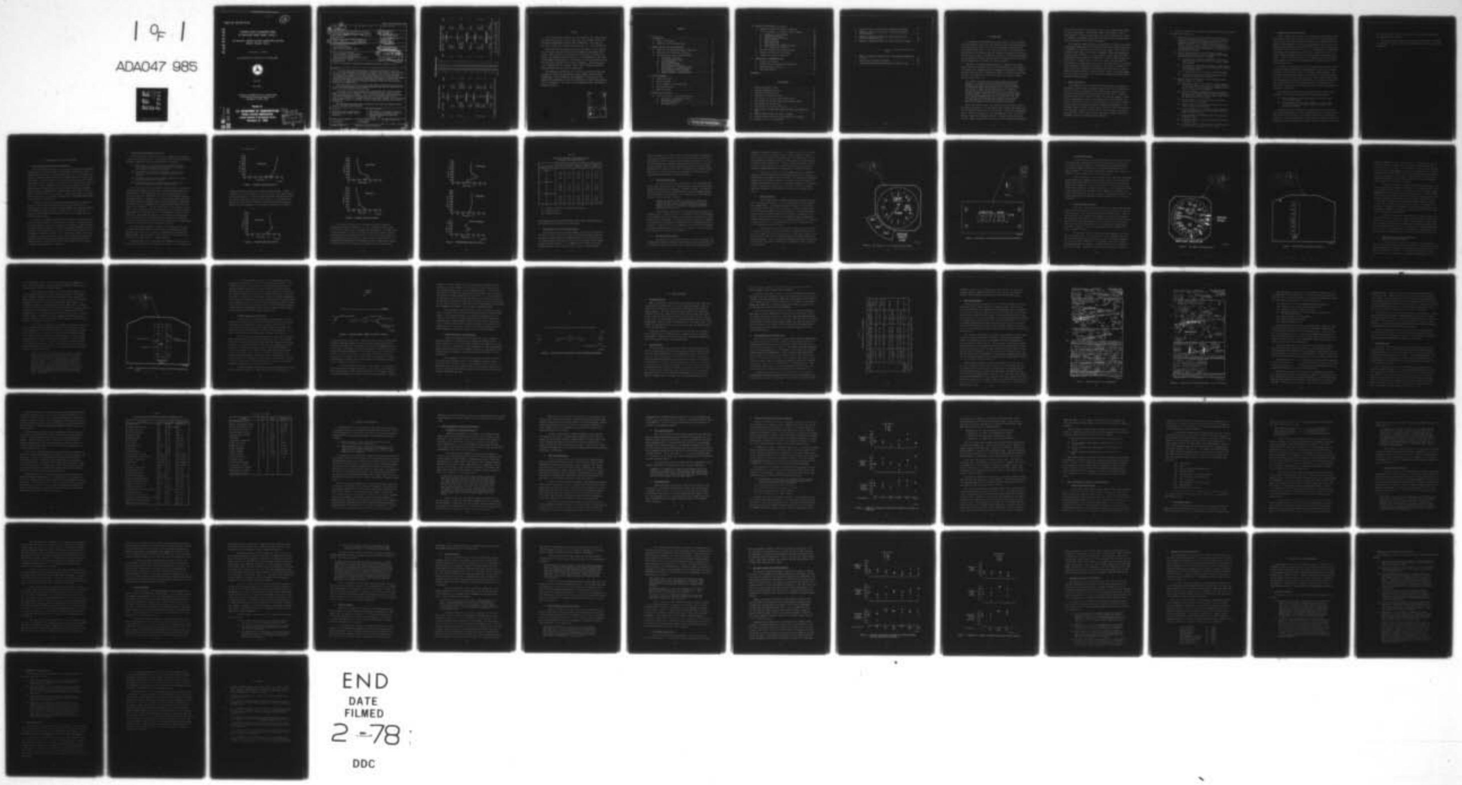

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PILOTED FLIGHT SIMULATOR STUDY OF LOW-LEVEL WIND SHEAR, PHASE 1

ALL-WEATHER LANDING SYSTEMS, ENGINEERING SERVICES SUPPORT PROJECT, TASK 2

W. B. Gartner, A. C. McTee

SRI INTERNATIONAL, MENLO PARK, CALIFORNIA 94025

May 1977

Interim Report

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Phase 1 of All Weather Landing System Engineering Services Support, Task 2

16. Abstract

A piloted flight simulation study was conducted to evaluate the need for improved cockpit displays and procedures for aiding airline pilots in anticipating and coping with the effects of low-level wind shear. The principal objectives of the study were to determine pilot and aircraft response to the shear encounter under "baseline" conditions, using existing cockpit displays and approach management procedures, and then to evaluate the improvement that might be realized from various ways of augmenting the information available to the pilot for wind-shear detection and flight control.

The basic evaluation plan called for eight highly experienced airline pilots to fly the simulated approach and landing sequences under baseline conditions, and then to fly them using each aiding concept.

The results of the study indicated that pilots would not be able to successfully cope with the more severe frontal and thunderstorm shears using existing flight instruments and procedures. All of the aiding concepts evaluated provided some useful information for alerting the pilot to a potential shear and for indicating the effects of the shear during the encounter. However, pilot preferences were strongly in favor of a display of ground speed integrated with the airspeed indicator.

SRI and Bunker-Ramo Corporation accomplished this work with Douglas Aircraft Company as simulation subcontractor.

17. Key Words Wind shear, cockpit displays, all weather landing systems, flight simulation	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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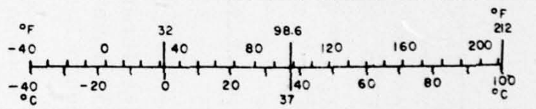
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This interim report documents the first phase of the flight simulation study conducted as a part of Task 2 of the All-Weather Landing Systems Engineering Support contract (DOT FA75WA-3650). The study was carried out under the technical direction of Mr. W. J. Cox, FAA ARD-743.

The DC-10 simulation facility used for this phase of the investigation was leased from the Douglas Aircraft Company at Long Beach, California. Data collection was carried out from 19 April to 14 May 1976. Douglas also provided technical services in the development of the simulation computer programs and in the conduct of the data collection activities under the direction of Mr. Warren A. Stephens. The contributions of Mr. Stephens, Mr. Art Torosian, and Mr. John D. McDonnell warrant special mention and are sincerely appreciated.

The important contributions of the airline and FAA pilots who participated in this study also warrant special mention and are hereby acknowledged. Their cooperation and commitment to the goals of this project were remarkable in view of the difficulty of their task as evaluators, the demands on their time, and the midnight-to-dawn scheduling of simulator sessions.

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I INTRODUCTION

The simulation study documented in this report is the first phase of an investigation of the need for improved cockpit aids and procedures to assure the safe conduct of terminal area operations under adverse environmental conditions. At the direction of FAA, this initial study was concerned with potential aircraft operating problems in the presence of low-level wind shear, and emphasis was placed on the timely identification of promising concepts and techniques for aiding pilots in anticipating and coping with the effects of a shear encounter.

Wind shear is generally characterized as a change in wind speed and/or direction occurring over a very short distance in the atmosphere. An encounter with complex and rapidly changing wind conditions close to the ground can represent a significant hazard to low-level flight operations, as indicated by the following excerpt from a recent aircraft accident report (Ref. 1):

> "The captain of Flying Tiger 161 stated that during his approach...he experienced severe changes of wind direction, turbulence, and down drafts between the OM and the airport. He observed airspeed fluctuations of 15 to 30 kn and at 300 feet he had to apply almost maximum thrust to arrest his descent and to strive to maintain 140 kn on his inertial navigation system groundspeed indicator. The aircraft began to drift rapidly to the left, and he eventually had to apply 25° to 30° of heading correction to overcome the drift. He believed that the conditions were so severe that he would not have been able to abandon the approach after he had applied near maximum thrust, and therefore he landed."

About eight minutes after this incident occurred, another captain initiated an approach to the same runway, under similar and perhaps more severe wind-shear conditions, and the aircraft crashed into the approach lights. One of the findings of the investigation of this accident was that the flight crew's apparent failure to recognize and correct the aircraft's high descent rate at the low end of the approach was probably due to their reliance on degraded external visual reference rather than on flight instruments. This accident report noted, however, that in this instance "...adverse winds might have been too severe for a successful approach and landing even had they relied upon and responded rapidly to the indications of the flight instruments."

The foregoing comments indicate the potential severity of the operational hazard represented by the low-level wind-shear encounter and serve to highlight the central concern of the present study. That concern is focused on the flight crew's ability to manage terminal area operations in the presence of shear--i.e., their ability to make timely decisions regarding the continuation of an approach or takeoff flight sequence and their ability to apply effective corrective action when unacceptable instabilities in flight-path control occur. The investigation is centered on the adequacy of information available to the pilot in command, from either his flight instruments or external visual reference, for anticipating the shear encounter, assessing adverse effects on airspeed management and flight-path control, and successfully coping with these effects during the shear encounter.

A. Phase 1 Objectives

In this phase of the investigation, SRI was tasked to develop and implement a piloted flight simulator evaluation of a set of airborne systems and techniques designated by FAA as potentially effective aids to pilots for detecting and coping with low-level wind shear. Guidelines provided by FAA for the conduct of Phase 1 stressed the urgency of carrying out a comprehensive survey of potential pilot aiding concepts that would include both near-term, readily implemented systems and techniques, and some systems requiring considerable engineering development. The principal intent of Phase 1 testing was to provide an early determination of the potential operational effectiveness of the candidate systems and techniques that could be used to guide subsequent in-depth study and development of the most promising aiding concepts.

Accordingly, Phase 1 data collection activities were directed toward three specific objectives:

(1) Determine pilot and aircraft responses to low-level wind shear under baseline conditions--i.e., while conducting precision ILS approach and landing operations in a jet transport airplane that is representative of those in current airline use, with flight crews following established normal operating procedure, and in situations where no alerting information is available to the crew prior to the wind-shear encounter.

(2) Explore differences in pilot and aircraft response to shear under alternative aircraft guidance, control mode, and environmental conditions, to include:

  (a) A conventional non-precision approach using Visual Approach Slope Indicator (VASI) for vertical flight-path guidance.

  (b) A non-precision approach incorporating a DME-defined visual descent point (VDP) for initiating the close-in final approach segment.

  (c) A coupled approach to Category II weather minimums.

  (d) A takeoff and departure climb-out using both full thrust and reduced-thrust procedures.

(3) Conduct screening evaluations of eight candidate pilot aiding concepts, to include:

  (a) Wind-shear advisories to the pilot, based on ground sensor system data, indicating the expected direction and severity of shear conditions at designated altitudes or segments of the approach.

  (b) A modified approach management technique stressing the use of off-nominal flight situation indications and providing a display of ground speed versus vertical speed for the 3° glide path.

  (c) The availability of INS wind speed and direction readouts during the approach.

  (d) A panel display of ground speed integrated with the conventional airspeed indicator.

  (e) A panel display of the difference between the along-track wind component on the surface and at the aircraft's present altitude.

  (f) A panel display of flight-path angle and potential flight-path angle.

  (g) A head-up display of flight-path angle and potential flight-path angle.

  (h) A head-up flight-path angle display incorporating the wind difference indicator (Item 3-e above).

B. Overview of the Evaluation Plan

Phase 1 testing was conducted at the Douglas Aircraft Company Flight Crew Training Center in Long Beach, using the DC-10 training simulator. This facility is an FAA-certified DC-10 operational training device providing a full complement of controls and instruments for all flight crew member positions and representing all flight guidance and control modes available on the aircraft in service use. The simulator is equipped with a six-degree-of-freedom motion system and is coupled with a Vital III computer generated imaging system for representing the external visual scene. A more detailed description of the facility and of the modifications required to represent the candidate pilot aiding concepts is presented in Section II.

The basic evaluation plan called for eight highly experienced pilots to fly the simulated operational flight sequences, first under baseline conditions and then using each of the candidate aiding concepts. Four different wind profiles were applied to represent the demands imposed on the pilot by the low-level shear situation. Wind conditions represented in the simulation were defined by NASA MSFC under a separate contract to FAA, and their derivation is described in Ref. 2. Detailed plots of wind speeds, direction, and turbulence levels used in the simulation are presented in Section II.

Data collection procedures were designed to provide two kinds of measures of the relative effectiveness of the aiding concepts:

(1) Pilot evaluations of the operational utility and limitations of each concept.

(2) Objective measures of aircraft response to shear, based on flight situation parameters reflecting approach stability and outcomes.

Assessments of pilot acceptance and workload were also a part of the evaluation plan and were used to explore additional factors that may affect the full utilization of the aiding concepts in the operational situation. These assessments were based on pilot responses to structured debriefing interviews conducted after each simulator session and as each pilot completed the overall run schedule. Data collection procedures are described in Section III.

Study results are presented and discussed in Section IV. The report is concluded, in Section V, with an outline of the conclusions and recommendations.

II DESCRIPTION OF THE TEST CONDITIONS

A. Basic Aircraft and Environmental Simulation

The DC-10 Training Simulator leased from the Douglas Aircraft Company provided all of the basic simulation capabilities required for Phase 1 testing, and was modified, as subsequently explained, to incorporate wind shear and turbulence models and the test displays used for the pilot aiding concepts. The DC-10 simulator is an FAA certified flight crew training facility that has been used for airline initial and recurrent training since 1971. It has a complete three-station crew compartment, and the flight controls, flight guidance system, flight instruments, navigation and communications equipment, and aircraft subsystems conform in all respects to the DC-10-10 series aircraft. Flight control modes in the simulator included all of the manual, autopilot, and autothrottle modes found on the aircraft in service use.

Simulator response characteristics, handling qualities, and performance were based on the aerodynamic model for the DC-10-10, with a 350,000-lb gross weight represented for the approach and landing sequences, and a 400,000-lb gross weight on the takeoff runs. The simulator is mounted on a six-degree-of-freedom motion base and is coupled with the Vital III visual system.

Vital III is a computer-generated imaging system using colored light points to depict airport and surrounding city features. Shaded surfaces are also generated to represent runway texture, markings, numerals, horizon glow, and other features. The runway environment depicted for Phase 1 testing was an approach over the city to runway 24 right and 25 left at Los Angeles International Airport (LAX). The system could be set up for an approach to either runway end, on a selective basis, provided a simulation of the VASI lights, a "Black Hole" effect achieved by deleting foreground lights, and visibility conditions ranging from clear down to a runway visual range (RVR) of 1600 feet.

B. Wind-Shear and Turbulence Conditions

The four wind-shear profiles used in the simulation were supplied by FAA for the Phase 1 tests. They represent low-level wind shears that might be produced by four basic meteorological conditions:

(1) Wind conditions in a highly mixed atmospheric boundary layer wherein temperature stratification is consistent with adiabatic distribution (9.8°/km).

(2) The condition of low-level temperature inversion overlaid by fairly strong winds immediately above the inversion.

(3) Fast-moving frontal zones producing significant turning of the wind vector with altitude.

(4) Thunderstorm cold air outflow producing abrupt changes in both horizontal and vertical wind velocities.

For convenience, the shear profiles associated with each of these conditions will hereafter be referred to as the "neutral" profile (or shear profile 1), the "inversion" profile (or shear profile 2), the "frontal" profile (or shear profile 3), and the "thunderstorm" profile (or shear profile 4), respectively. In the simulation these shear profiles were defined by tabulated values of the along-track, cross-track, and vertical velocity components for various altitude levels from the surface up to 1500 feet. The tables were stored in the simulation computer as north-south and east-west components so as to give the required along-track and cross-track values for the approach to runways 24R and 25L at LAX. Wind velocity components in the tables were transformed into the aircraft axis system where they were summed with turbulence values, and the results were applied to the calculation of aircraft angle of attack, side slip angle, and longitudinal velocity.

The wind profiles supplied for Phase 1 testing were defined as a function only of altitude above ground level. No variations in these profiles were included as a function of horizontal position along the approach path. Thus, no change in wind direction or velocities would occur if the aircraft flew at a constant altitude.

Tabulated values of the along-track wind component versus altitude for the neutral shear profile are plotted in Figure 1. This profile was

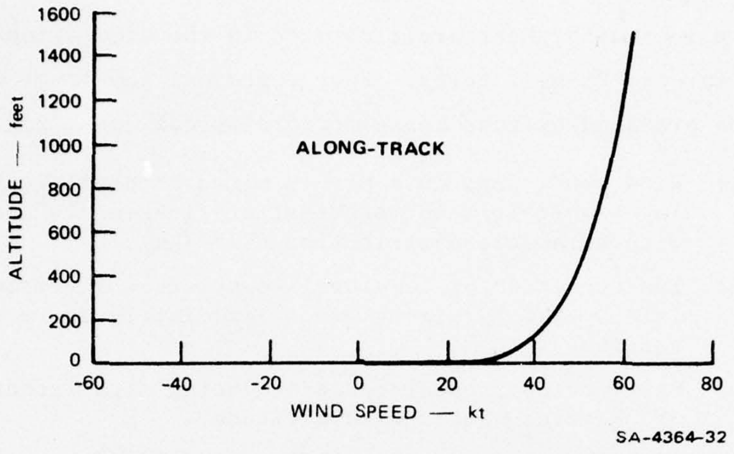

FIGURE 1 NEUTRAL WIND-SHEAR PROFILE

applied with no variation of wind direction with altitude. Figure 2 is a similar plot for the inversion profile, which was also applied with no cross-track component. Along-track and cross-track components defining the frontal shear profile are plotted in Figure 3. The thunderstorm profile was the only shear condition with a significant vertical component; all three components of this profile are plotted in Figure 4.

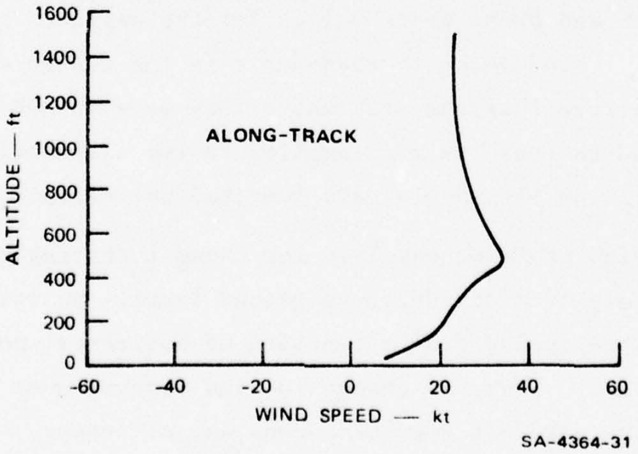

FIGURE 2 INVERSION WIND-SHEAR PROFILE

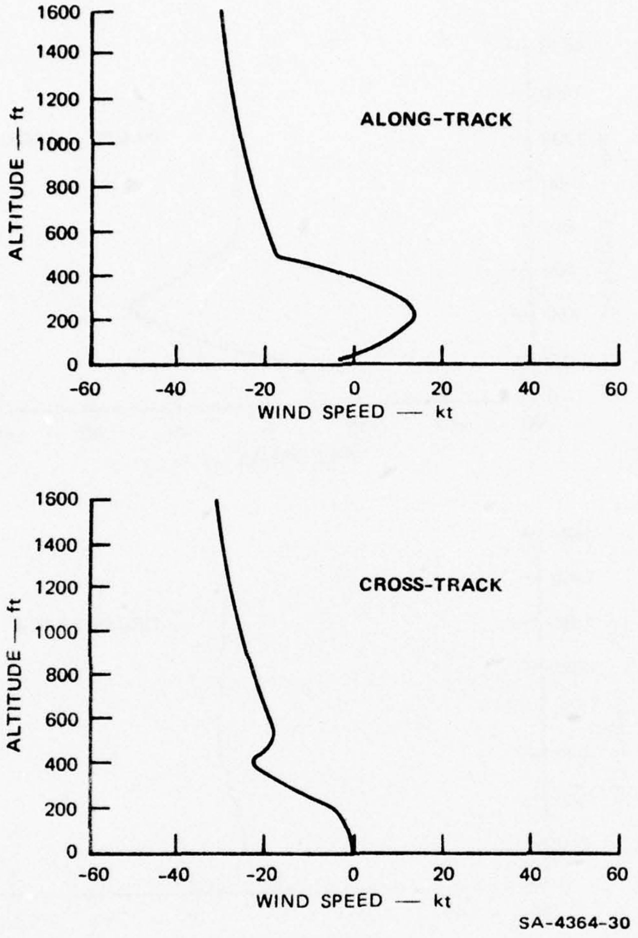

FIGURE 3 FRONTAL WIND-SHEAR PROFILE

To enhance the realism of the simulated wind-shear conditions, turbulence was added to Profiles 1, 2, and 4 (turbulence levels associated with the frontal shear were considered negligible). The values used in the simulation are listed in Table 1 for each of the shear profiles. Table entries are the turbulence levels, in knots, for each component of the designated wind-shear profile, expressed as standard deviations (σ). Turbulence was represented in the simulator using a random number generator with conversion to a Gaussian distribution using a table look-up.

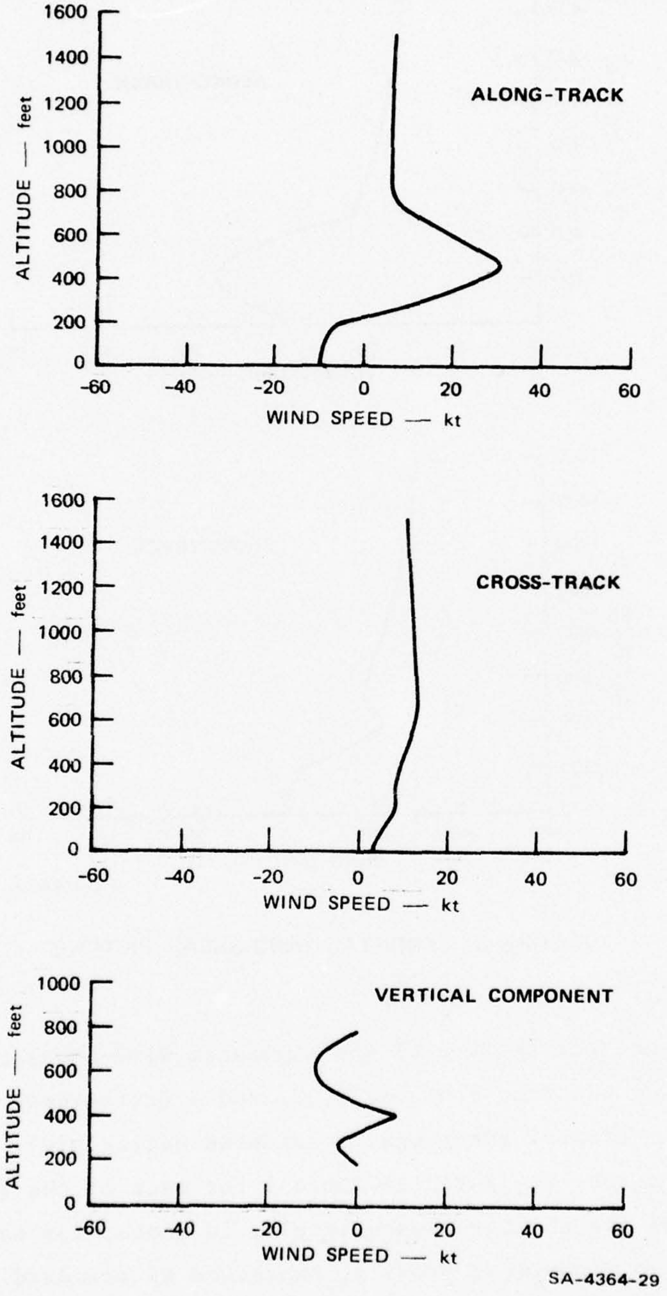

FIGURE 4 THUNDERSTORM WIND-SHEAR PROFILE

Table 1

VALUES OF TURBULENCE REPRESENTED IN THE SIMULATED WIND-SHEAR PROFILES

Shear Profile*	Altitude 32 ft	Altitude 100 ft	Altitude 200 ft	Altitude 400 ft	Altitude 600 ft
1: Neutral					
σ_u	7.68	5.55	4.54	3.71	3.30
σ_v	6.14	4.73	4.03	3.43	3.12
σ_w	3.98	3.47	3.19	2.92	2.79
2: Inversion					
σ_u	0.88	1.63	3.61	0.50	0.25
σ_v	0.88	1.63	3.61	0.50	0.25
σ_w	0.10	0.15	0.25	0.09	0.06
4: Thunderstorm					
σ_u	3.50	4.05	4.43	4.85	5.11
σ_v	2.80	3.46	3.95	4.50	4.86
σ_w	2.53	3.53	4.35	5.36	6.05

*σ_u = Standard deviation of longitudinal velocity.
σ_v = Lateral velocity.
σ_w = Vertical velocity.

The Gaussian output was passed through a first-order lag with a filter time constant of 0.5 second on all three axes.

C. Representation of Pilot Aiding Concepts

The eight pilot aiding concepts adopted for screening evaluation in the Phase 1 test exercise were construed as alternative ways either of alerting the flight crew to an imminent exposure to significant shear, or of more directly indicating the effects of the shear on the airplane during the shear encounter. It is important to note that none of the candidate aiding concepts were intended to replace existing cockpit flight instruments; they were viewed as alternative ways of augmenting existing instruments that would continue to be available to the crew. For purposes of Phase 1 testing, these concepts were defined in terms of the new or different information available to the pilot (i.e., not currently available from existing cockpit instruments), the display mode adopted for the simulator tests, and the procedures to be used by evaluation pilots. Brief descriptions of the manner in which each aiding concept was represented in the simulator follow.

1. Wind-Shear Advisories

The content, format, and language used in the wind-shear advisories were developed by FAA. These advisory formats were preliminary and were developed only for purposes of Phase 1 testing. The general intent was to provide a brief description of the wind changes expected at various points in the approach, as illustrated by the following message for the frontal shear condition:

> "30 knot tailwind at 1500 feet shifting to 13 knot headwind at 250 feet. Expect abrupt 26 knot positive shear between 450 and 250 feet, followed by 10 knot decreasing headwind to surface. 25 knot left crosswind at 400 feet, diminishing at touchdown."

Shear advisory messages for the scheduled wind condition were presented to the evaluation pilot on a 3-by-5-inch card at the beginning of the approach and he was allowed as much time as he needed to read and assimilate the information. Pilots were briefed to report their initial go/no-go decision regarding the continuation of the approach and then to continue in either case so that the approach outcome could be documented. Subsequent approach management decisions or changes in control technique were carried out at the pilot's discretion.

2. VSI Ground Speed Placard

The intent of this aiding concept was to provide the pilot with a simple and inexpensive readout of ground speed, using an available cockpit instrument, and thereby permit him to monitor the along-track wind component throughout the approach. The display consisted of a placard attached to the Vertical Speed Indicator (VSI) as shown in Figure 5. The scaling of the ground speed placard and its alignment with the VSI scale produced a nomograph relating vertical speed to ground speed for a nominal 3-degree glide slope. As long as the pilot was able to maintain this glide path angle, he could use the VSI needle for a direct reading of ground speed that was independent of indicated airspeed.

Pilots were briefed to fly the approach using the primary instruments for flight-path control and attempt to detect the shear by monitoring and interpreting the VSI placard. The technique of combining ground speed with indicated airspeed to estimate the along-track wind component was explained. However, no approach management or flight-path control techniques for coping with shear based on the use of ground speed were suggested or prescribed for use during the evaluation run series.

3. INS Wind Readout

This aiding concept is simply the conventional wind speed and direction readout available on aircraft equipped with inertial navigation systems (INS). For purposes of Phase 1 testing, it was assumed that current limitations on the availability of INS wind computations at low indicated airspeeds could be eliminated by system design refinements and that the wind readout would be available throughout the approach. The test display used for the simulation was a six-character numeric readout located on the center pedestal, forward of the throttles, as shown in Figure 6. A computational lag time of 5 seconds was used for the simulated wind data readout.

Pilots were briefed to include this readout in their scan and to attempt to estimate current wind effects by combining INS winds with the latest report of surface wind conditions. They were reminded of the wind direction readout in true rather than magnetic heading, and of the 5-second lag time. Again, no specific techniques for using this information for shear detection or modification of approach control technique were prescribed.

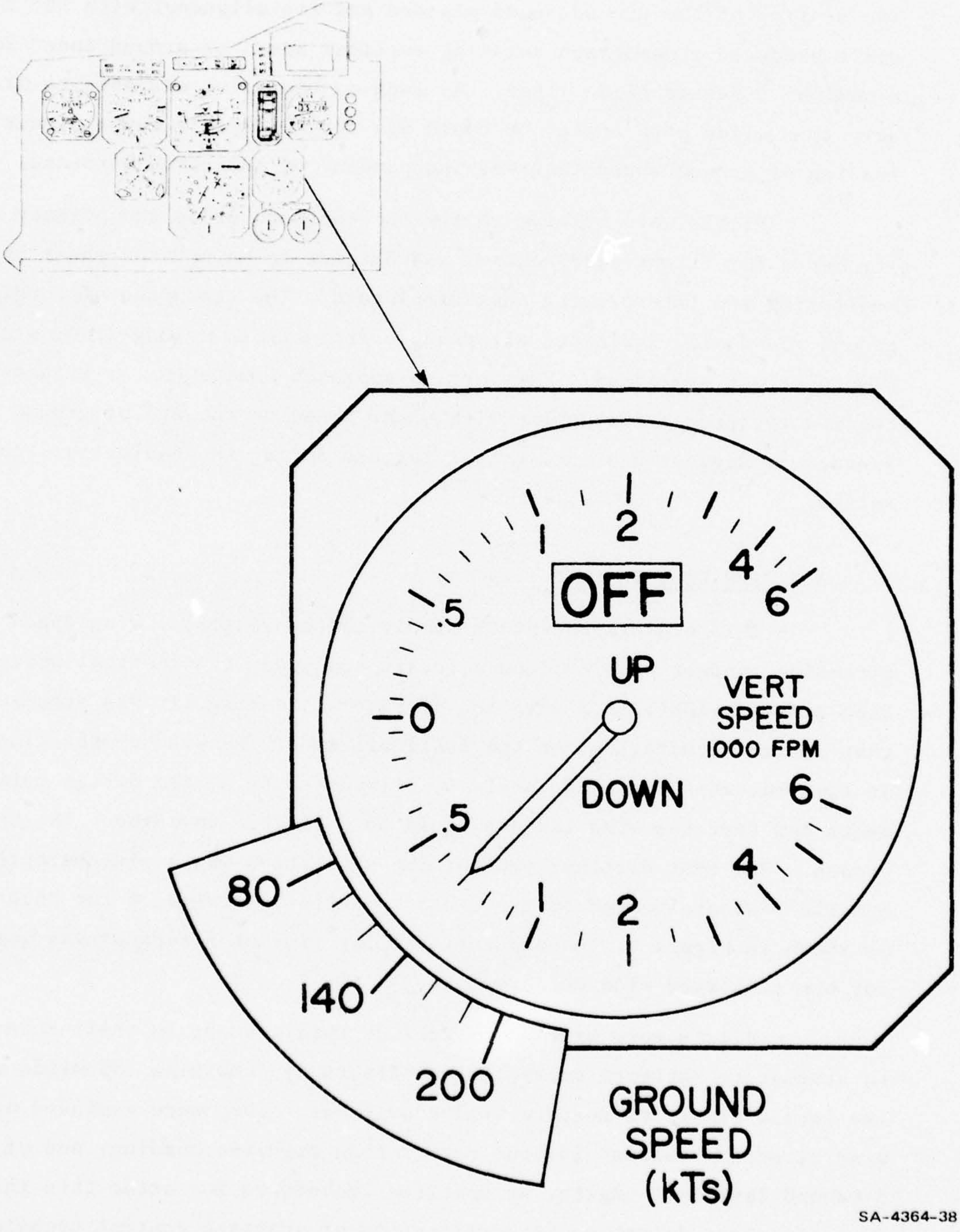

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FIGURE 5 TEST DISPLAY OF THE VSI GROUND SPEED PLACARD

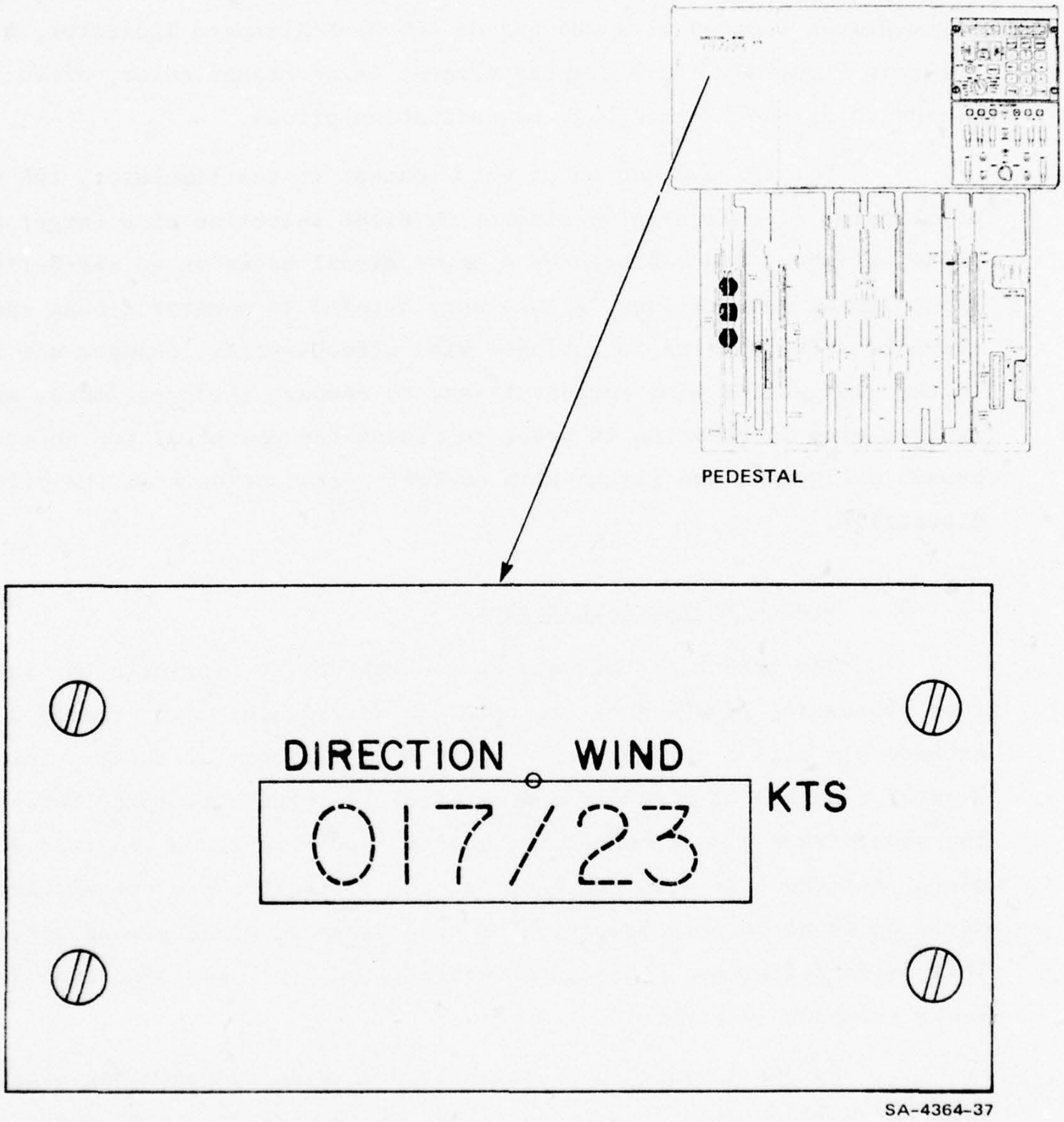

FIGURE 6 TEST DISPLAY OF INS WIND SPEED AND DIRECTION READOUT

4. Ground Speed Display

In this concept, ground speed information is presented in close association with indicated airspeed to facilitate pilot monitoring of the along-track wind component. Ground speed was displayed using the servo-driven command airspeed bug on the Mach/Airspeed Indicator, as shown in Figure 7. This display element is an orange color, often referred to as the "salmon bug" by evaluation pilots.

For the evaluation of this concept in the simulator, the normal positioning of this display element by pilot selection of a target approach airspeed was replaced by a drive signal based on an air-derived ground speed computation. Pilots were briefed to monitor ground speed/airspeed relationships to estimate wind effects--i.e., changes and trends in the along-track wind component--and to compare these estimates with surface wind information in order to assess the potential for shear. Approach management and flight-path control technique were at the pilot's discretion.

5. Wind Difference Indicator

The intent of this aiding concept was to eliminate the information processing required of the pilot in determining wind effects and to provide him with a more direct display of the potential shear. This indicator consists of a panel mounted display of the difference between the along-track wind component at ground level, based on reported surface winds, and the same wind component at the aircraft's present altitude, based on an airborne computation of true airspeed minus ground speed. This "wind difference" (hereafter abbreviated "ΔW") was displayed in knots as shown in Figure 8.

ΔW was computed by subtracting the wind component at altitude from the surface wind. Positive values of ΔW were displayed above the zero (no difference) index and indicated a greater head-wind component (or lesser tail-wind component) on the surface relative to the winds presently affecting the airplane. Negative values of ΔW, displayed below the zero index, indicated a lower head-wind component (or greater

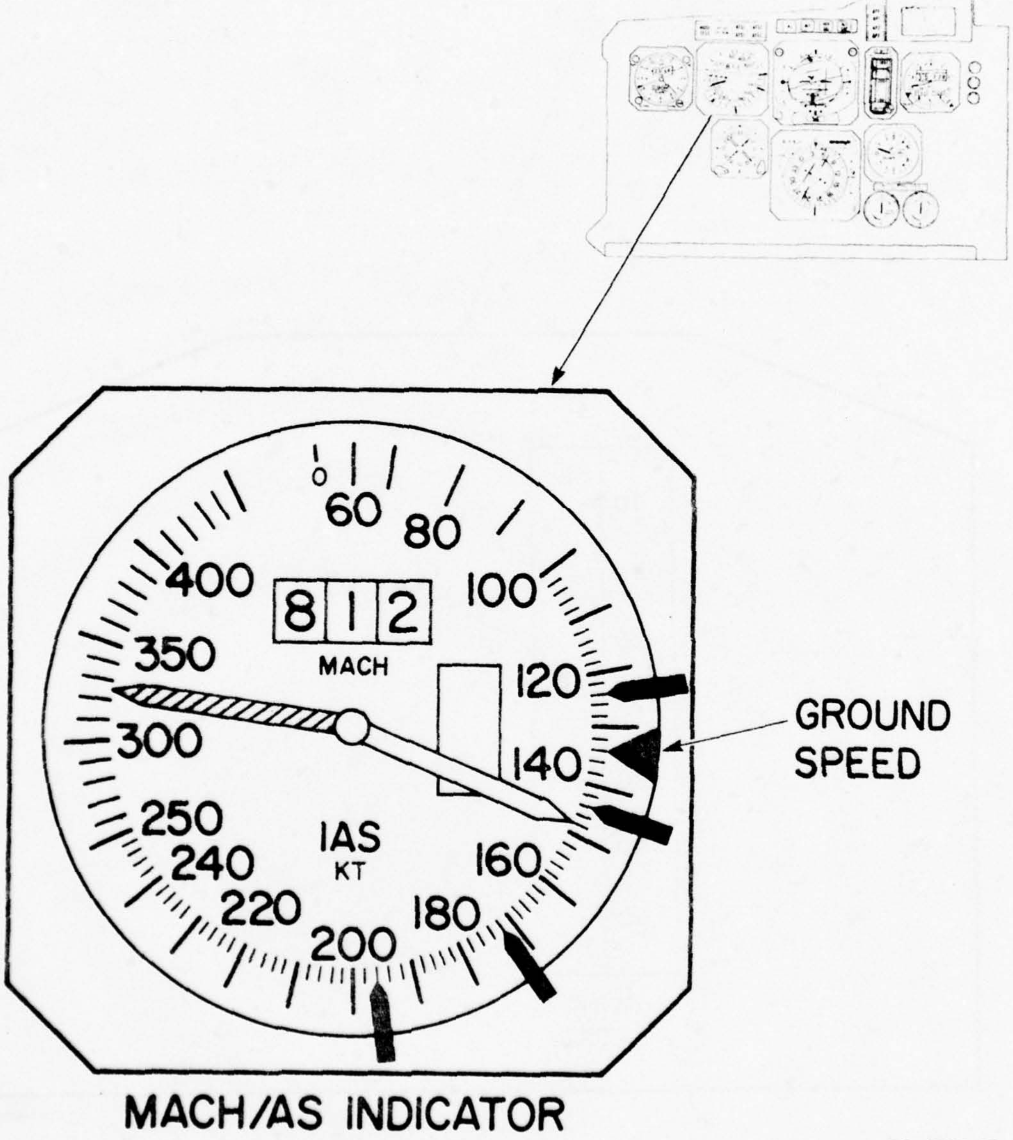

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FIGURE 7 TEST DISPLAY OF GROUND SPEED

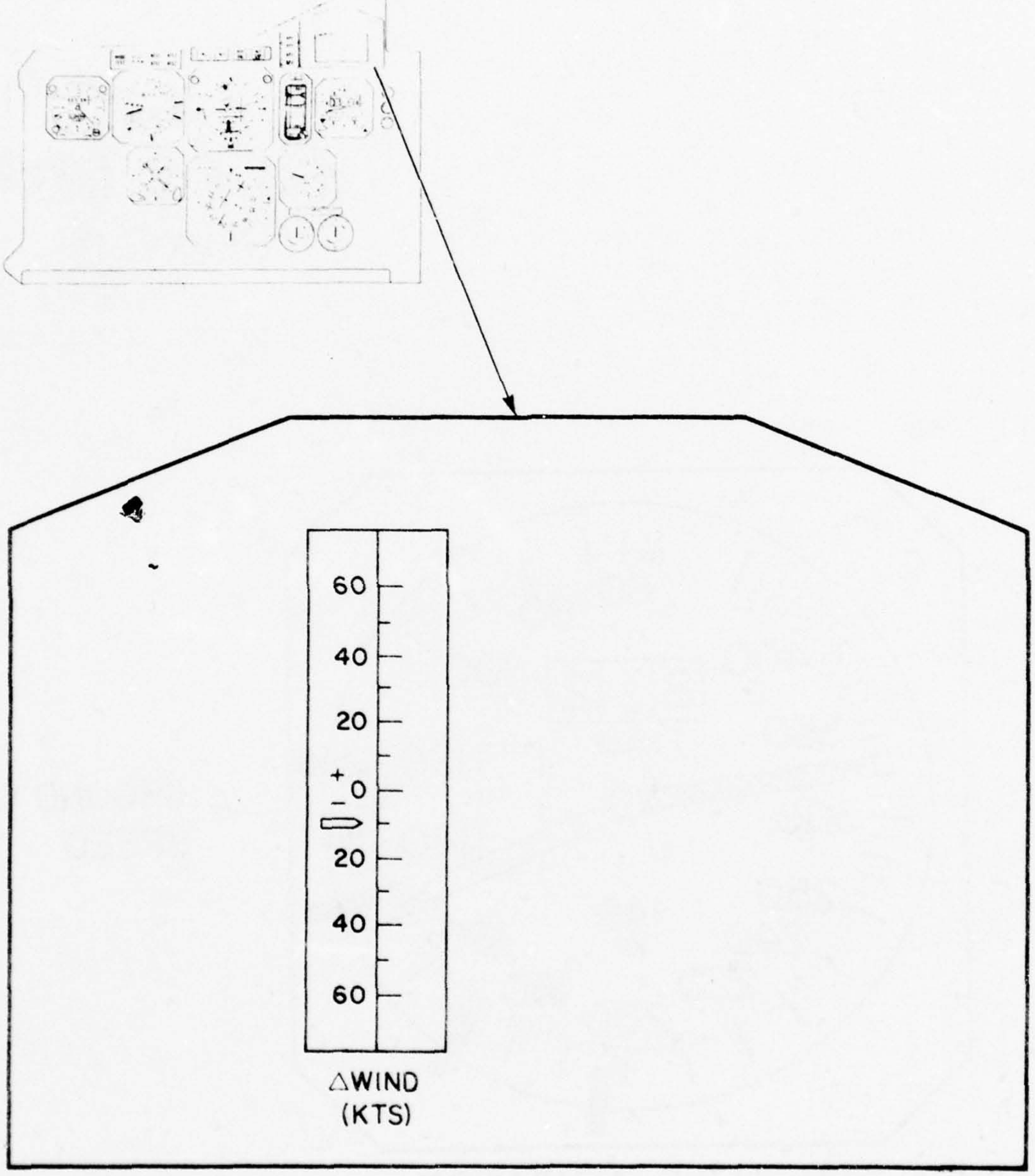

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FIGURE 8 TEST DISPLAY OF THE WIND DIFFERENCE tail-wind component) on the surface and were thus intended to alert the pilot to a decrease from the present head-wind component some time before arrival at the runway. It is important to note that this indicator could only show the difference in the two wind components; the displayed value would therefore change only as the actual wind velocities changed, either on the ground or at altitude. Indicated values of ΔW would not change with changes in airspeed and neither of the two wind components being compared to provide ΔW is displayed.

Pilots were briefed to monitor ΔW and to notice changes in the indicated value as the approach progressed. It was suggested that negative readings would indicate a corresponding net loss in airspeed somewhere between the aircraft's present position and the surface; reversals in the wind velocity profile below the aircraft's present altitude could produce an increase in airspeed first and then the indicated decrease. It was further suggested that pilots add a "pad" to their previously selected target approach speed to match the amount of any negative ΔW reading. For example, if the approach bug speed was 140 knots and the ΔW indicator reading was -20 knots, the pilot would fly 160 knots, modifying this speed pad as ΔW changed.

Pilots were briefed to interpret positive values of ΔW as indications that they were flying into an "increasing energy" situation and could expect a net increase in airspeed. The suggested airspeed management technique with positive ΔW readings was to maintain bug speed with no extra additives and monitor ΔW for changes as the approach progressed. At the low end of the approach the pilot might, at his discretion, estimate potential touchdown speeds to be excessive and elect to go-around.

6. Panel Display of Flight-Path Angle and Potential Flight-Path Angle

Flight-path angle is generally understood as the aircraft's angle of climb or descent relative to the horizon. In this study, flight-path angle was derived from the relationship between pitch attitude and angle of attack and is therefore an air-mass-referenced angle or air velocity vector; it corresponds to a ground-referenced angle, such as the 3-degree glide slope, only when the along-track wind component is zero. In this discussion, ground-referenced flight-path angles will be referred to as "climb" and "descent" angles.

This distinction is important to the intended application of the flight-path angle display to the wind-shear problem. Flight-path angle (hereafter abbreviated as FPA) was displayed on an indicator located above the altimeter, as shown in Figure 9. Pilots were briefed to monitor FPA relative to a fixed reference angle (black marker set at -3 degrees in Figure 5) representing a 3-degree glide slope. As long as the pilot was maintaining the glide slope (by reference to primary flight instruments), the FPA reading could be used to estimate wind effects. Readings above the reference angle marker indicated a relatively shallow FPA and, hence, a headwind; relatively steeper FPA readings (below the marker) indicated a tailwind condition. Rapid changes in the FPA reading provided an indication of wind shear.

The concept of a "potential flight path" was derived from early work on improved flight management displays for the SST and from more recent developments in the head-up display of vertical guidance information. Gannett (Ref. 3) has characterized potential flight-path angle (hereafter abbreviated as PFPA) as a display element "...that responds to acceleration of the aircraft along the flight path as influenced by changes in thrust or drag." After flying this kind of display element on the Thompson-CSF head-up display systems (CV-91 and TC-121), another pilot has provided a concise description of PFPA that fits the concept adopted in this study (Ref. 4):

> "This is the path the aircraft would fly when in equilibrium, and it is presented in such a way that its relationship to the velocity vector is a measure of the excess, or deficiency, of thrust. When the speed is stabilized, the potential path is coincident with the actual path, or velocity vector. If thrust exceeds drag, the potential path rises above the velocity vector and results either in acceleration (reducing angle of attack) if the velocity vector is held constant, or in the velocity vector moving up (with pitch attitude) if angle of attack is held constant. The potential path is the primary reference for thrust management."

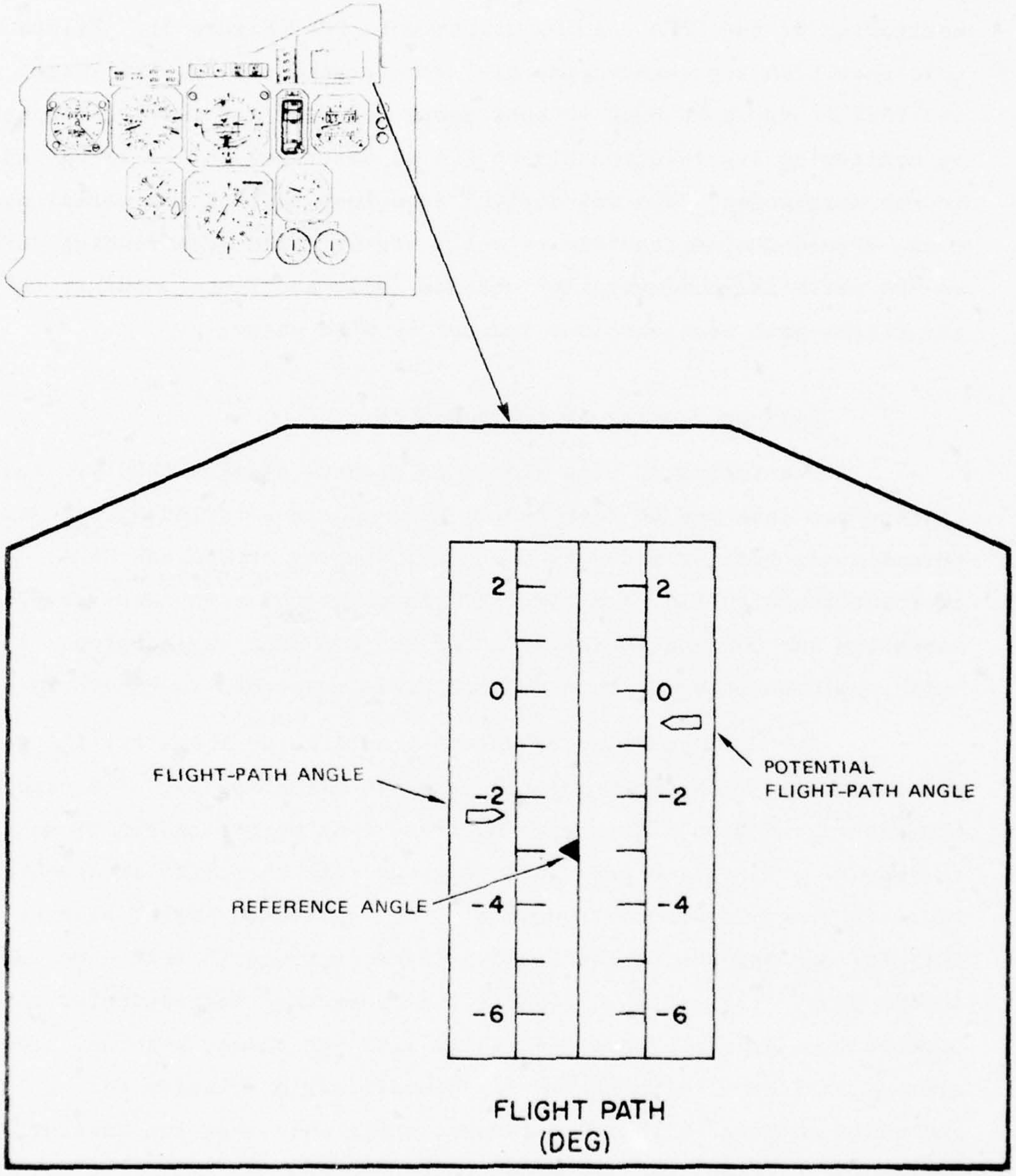

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FIGURE 9 TEST DISPLAY OF FLIGHT-PATH ANGLE AND POTENTIAL FLIGHT-PATH ANGLE

For a more complete discussion of the PFPA concept and its mathematical derivation, the reader is referred to Wanner (Ref. 5) and Klopfstein (Ref. 6). In the present study, PFPA was displayed on a separate indicator adjacent to the FPA indicator to facilitate pilot monitoring of the PFPA reading relative to FPA (Figure 5). Pilots were told that PFPA represented inertial accelerations along the flight path and that it could be used to anticipate the need for throttle adjustments by monitoring its relationship to FPA as described in the foregoing quote. In the simulation, PFPA was derived from longitudinal and normal accelerations resolved along the air velocity vector. The PFPA reading relative to FPA reflected configuration changes (gear and flaps), thrust changes, and flight-path accelerations induced by wind shear.

7. Head-Up Display of FPA and PFPA

The inclusion of a simulated head-up display (HUD) in Phase 1 testing was intended to represent a head-up presentation of the same information as that provided by the panel display of FPA and PFPA. In coordination with FAA, a minimum HUD format considered necessary for assessing the head-up presentation of FPA and PFPA was adopted. A schematic representation of this HUD format is presented in Figure 10.

The HUD symbology shown was generated by the Vital III system and integrated with the simulated external visual scene. The display elements are composed of orange colored light points spaced close enough to appear as lines and generated brighter than the light points used to represent the airport environments. The "Reference Angle" element (circle) corresponds to the fixed 3-degree glide-path reference index in the panel display; in the HUD, it is located 3 degrees below the horizon line and is aligned laterally with the runway heading. The FPA element indicates the computed flight-path angle relative to the horizon and would coincide with the reference angle only when the aircraft was descending (through the air mass) at -3 degrees.

A basic HUD format consisting of an aircraft symbol and horizon line for attitude reference, a depressed sight line to indicate the

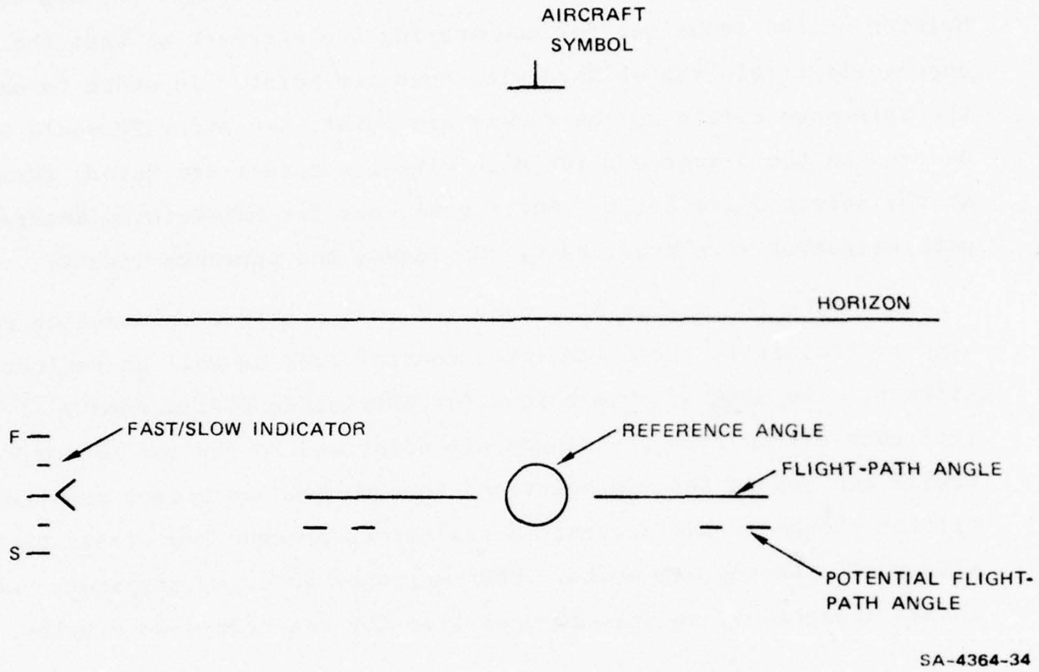

FIGURE 10 HEAD-UP DISPLAY FORMAT FOR PHASE 1 TESTING

desired glide-slope angle, and a flight-path marker that shows the actual vertical flight-path angle of the aircraft was suggested more than 20 years ago by the work of Calvert (Ref. 7) and Lane and Cummings (Ref. 8). In the Phase 1 HUD format, a fast-slow indicator was added to this basic format for airspeed management, and the PFPA element was included as an extension of the FPA information. The dashed bars representing PFPA blend with the FPA marker when inertial speed is stabilized, rise above the FPA marker to indicate acceleration along the flight path, and drop below to indicate deceleration.

Pilots were briefed on the use of the HUD for the detection of wind effects and for flight-path control. Wind effects were indicated, as in the panel display of FPA, by the position of the FPA marker relative to the reference angle circle while the pilot was maintaining a 3-degree glide path. The HUD format in Figure 10 provides flight-path control guidance only when external viewing conditions allow the pilot to see the intended touchdown point on the runway (aim point). Pilots were briefed on the technique for maneuvering the aircraft so that the reference angle circle was aligned with this aim point. In order to maintain the reference circle on the runway aim point, the aircraft would have to descend on the 3-degree glide path with its actual trajectory terminating at the selected aim point. Additional cues for maintaining lateral flight-path alignment were provided by the runway and approach lights.

The FPA marker also provided roll attitude information and was used to facilitate the flight-path control task as well as indicate wind effects. The suggested technique for correcting displacements of the reference circle from the runway aim point was to fly the FPA marker toward and beyond the aim point and then to hold an offset position until the change in the aircraft's trajectory brought the circle back in alignment with the aim point. PFPA was used as an anticipatory cue for thrust management, as described earlier for the head-down display.

8. Head-Up Display of Wind Difference

This pilot aiding concept was simply the basic flight-path angle HUD format just described with an additional display element. As shown in Figure 11, the Wind Difference Indicator was added to the right side of the HUD. It provided the same information on differences between surface winds and winds at the aircraft's position as that described for the panel mounted instrument, and pilots were briefed to use it in the same manner.

The availability of this indicator head-up allowed the pilots to monitor wind differences deeper in the approach, beyond the point where they would typically transition to external visual reference. It also permitted them to cross-check changes in ΔW with wind effects indicated by the FPA and PFPA display elements, which were not available when the panel ΔW display was used.

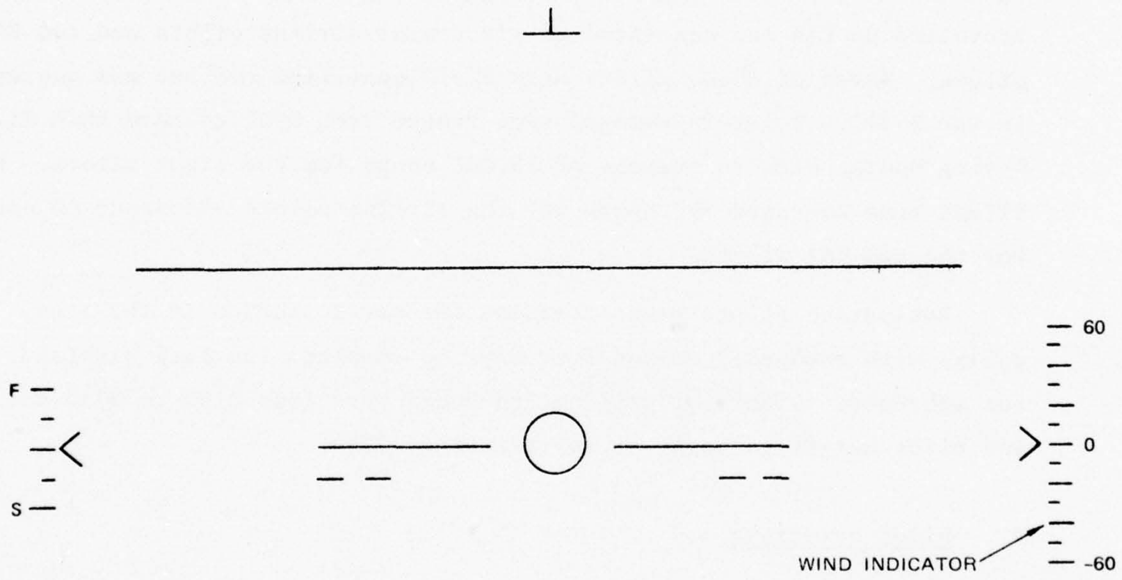

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FIGURE 11 HEAD-UP DISPLAY INCLUDING THE WIND DIFFERENCE INDICATOR

III STUDY PROCEDURES

A. Evaluation Pilots

Phase 1 simulation exercises were designed primarily to expose experienced airline and FAA pilots to the test wind-shear profiles and to obtain their assessments of the potential usefulness of the candidate aiding concepts. The eight pilots who participated in the study were recruited by FAA and consisted of six senior airline pilots and two FAA pilots. Seven of these pilots were DC-10 qualified and one was current in the B-747. Pilot-in-command time ranged from 8000 to more than 21,000 flying hours, with an average of 15,000 hours for the eight pilots. DC-10 flight time averaged 760 hours for the airline pilots and about 60 hours for the two FAA pilots.

Evaluation pilots were scheduled for participation in the study in pairs, with each pair taking four days to complete the full simulator run schedule. Simulator utilization hours were from 0130 to 0730 daily, and pilot briefings began at approximately 0030.

B. Pilot Briefings

Similar briefings were given to all pilots who participated in the study. A comprehensive initial briefing was given to each pair of subjects when they reported for the first morning's flying. This initial briefing lasted approximately one hour and was designed to provide all necessary background information on the study and describe the simulator and procedures to be used. The briefing did not describe the number or the characteristics of the shear profiles to be used. However, an audio-visual presentation developed by Douglas to introduce pilots to the general characteristic of wind shear was included as part of the briefing. This slide show, entitled "The Hostile Environment," was presented to provide a common frame of reference for the subsequent discussions of wind shear and to remind the pilots of the basic indicators of wind shear available from existing flight instruments.

The initial briefings served as an overall introduction to the program and to the test personnel. They were conducted by the Test Director, a project pilot who occupied the right seat to role-play as first officer, and a Douglas simulator engineer who manned the instructor's station to manage run conditions. On some occasions other project personnel from FAA and SRI were present for these briefings.

More detailed briefings, specific to each of the aiding concepts, were given to pilots individually just prior to the run series in which that aiding concept was presented. These briefings were typically quite short and were presented by the Test Director. HUD briefings, especially for the pilot's initial session using the HUD, were given in considerable detail and tended to be longer. This was considered necessary because the pilots were generally unfamiliar with HUD, and none had seen the simulated HUD before.

C. Pilot Exposure to Test Conditions

The relatively large number of aiding concept and shear combinations argued for varying the order of exposure to test conditions in order to preclude any bias due to learning or fatigue effects that might carry over from one run condition to another. Accordingly, each pair of pilots flew the aiding concept in a different order. All pilots flew simulator familiarization (two approaches), initial baseline (eight approaches), and training effect (two approaches) runs on their first day, in that order. After this initial baseline series, however, the order of conditions was varied. Table 2 illustrates a typical scheduling of simulator sessions for one pair of evaluation pilots. The presentation of shear profiles was also varied for each aiding concept to control for carryover effects and to minimize pilot learning of the shear profiles.

The HUD sessions were treated as a block because of the special briefings and training approaches required for familiarization with the display characteristics. Accordingly, the schedule was arranged so that

Table 2

TYPICAL WEEKLY SIMULATOR SCHEDULE

Pilot	Monday	Tuesday	Wednesday	Thursday	Friday
A	*(2) Familiarization	(4) Training	(4) ΔW HUD	(4) Coupled	(4) Shear Advisory
	(4) Baseline	(4) NP/BH HUD	(4) Panel FPA	(4) VSI Ground	(4) INS Wind
B	(2) Familiarization	(4) Training	(4) ΔW HUD	(4) Coupled	(4) Shear Advisory
	(4) Baseline	(4) NP/BH HUD	(4) Panel FPA	(4) VSI Ground speed	(4) INS Wind
A	(4) Baseline	(2) Training	(4) NP/VDP	(4) ΔW Panel	(4) Takeoff
	(2) Training effects	(4) Cat-I HUD	(4) NP/VASI	(4) DME Ground speed	
B	(4) Baseline	(2) Training	(4) NP/VDP	(4) ΔW Panel	(4) Takeoff
	(2) Training effects	(4) Cat-I HUD	(4) NP/VASI	(4) DME Ground speed	
Approach Total	24	28	32	32	24

*Numbers in parentheses represent number of approaches flown.

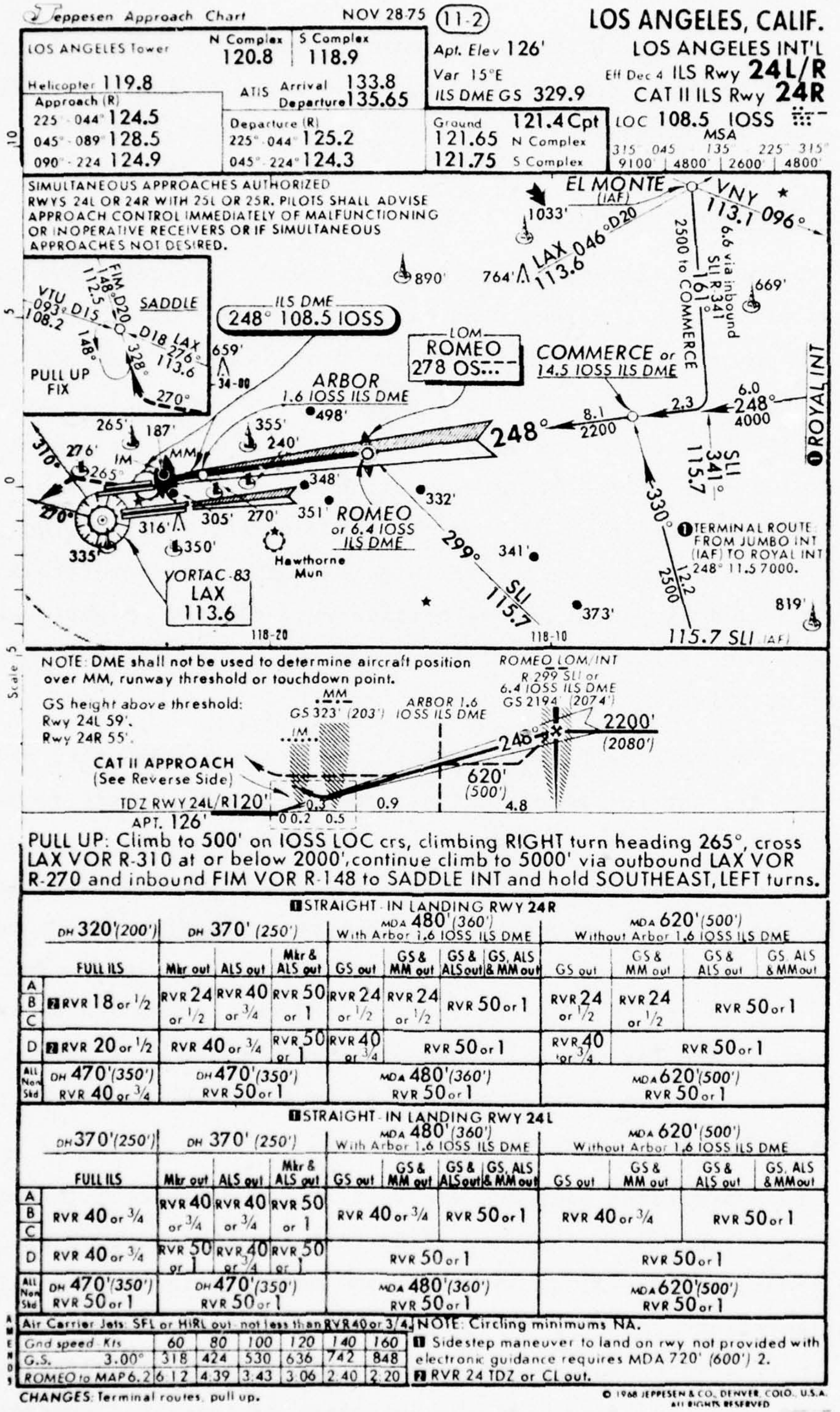
the HUD was taken up at the beginning of a day and most of the HUD approaches could be completed during that day's flying. The "HUD day," however, was scheduled on different week days for each pilot pair.

D. Data Run Procedures

Before initiating an approach, the first officer provided the evaluation pilot with a flight condition or "weather" card. This card was placed on the console and showed the weather conditions for the approach to be flown, the aircraft landing weight, and the applicable speed requirements for the weight and flap setting. The information on this card was used each time by the evaluation pilot to set up his approach and to choose his approach target speed based on the reported surface winds. The surface winds presented were correlated with the shear profile being flown. Surface wind direction and velocities were changed slightly at times to prevent the evaluation pilot from becoming too familiar with the associated shear profiles.

The approaches flown during this study were conducted as nearly like routine air carrier operations as possible. Pilots were requested to manage their approaches just as they would on the line, including the go-around decision when necessary. The Los Angeles International Airport (LAX) was selected as one with which most evaluation pilots were familiar, and standard approach charts for this airport were used, with only slight modifications to incorporate the VASI and the Visual Descent Point. The approach plate for the ILS approach to runway 24R is reproduced in Figure 12. Non-precision approaches were flown using the approach plate for runway 25L, modified as shown in Figure 13.

Each simulated approach was initiated 9 miles from the airport at the initial approach altitude (2200 feet for 24R and 1900 feet for 25L). The simulator was set up on course and heading, in the initial approach configuration (gear up, 22 degree flap setting) at 175 knots airspeed, and in trim with appropriate power settings. All checklists were assumed to have been completed with the exception of the final landing check list. Flight directors, course selectors, radios, and altimeters were all pre-set by the first officer. The approach was started when the evaluation pilot advised he was ready.



Jeppesen Approach Chart NOV 28-75 (11-2)

LOS ANGELES, CALIF.
LOS ANGELES INT'L
Eff Dec 4 ILS Rwy **24L/R**
CAT II ILS Rwy **24R**
LOC 108.5 IOSS

LOS ANGELES Tower N Complex 120.8 S Complex 118.9
Helicopter 119.8
ATIS Arrival 133.8 Departure 135.65
Approach (R)
225°-044° 124.5
045°-089° 128.5
090°-224 124.9
Departure (R)
225°-044° 125.2
045°-224° 124.3
Apt. Elev 126'
Var 15°E
ILS DME GS 329.9
Ground 121.4 Cpt
121.65 N Complex
121.75 S Complex

MSA 315°–045°	045°–135°	135°–225°	225°–315°
9100'	4800'	2600'	4800'

SIMULTANEOUS APPROACHES AUTHORIZED RWYS 24L OR 24R WITH 25L OR 25R. PILOTS SHALL ADVISE APPROACH CONTROL IMMEDIATELY OF MALFUNCTIONING OR INOPERATIVE RECEIVERS OR IF SIMULTANEOUS APPROACHES NOT DESIRED.

[1] TERMINAL ROUTE: FROM JUMBO INT (IAF) TO ROYAL INT 248° 11.5 7000.

NOTE: DME shall not be used to determine aircraft position over MM, runway threshold or touchdown point.

GS height above threshold:
Rwy 24L 59'.
Rwy 24R 55'.

PULL UP: Climb to 500' on IOSS LOC crs, climbing RIGHT turn heading 265°, cross LAX VOR R-310 at or below 2000', continue climb to 5000' via outbound LAX VOR R-270 and inbound FIM VOR R-148 to SADDLE INT and hold SOUTHEAST, LEFT turns.

[1] STRAIGHT-IN LANDING RWY 24R

	DH 320'(200')	DH 370' (250')			MDA 480'(360') With Arbor 1.6 IOSS ILS DME				MDA 620'(500') Without Arbor 1.6 IOSS ILS DME			
	FULL ILS	Mkr out	ALS out	Mkr & ALS out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out
A B C	[2] RVR 18 or 1/2	RVR 24 or 1/2	RVR 40 or 3/4	RVR 50 or 1	RVR 24 or 1/2	RVR 24 or 1/2	RVR 50 or 1		RVR 24 or 1/2	RVR 24 or 1/2	RVR 50 or 1	
D	[2] RVR 20 or 1/2	RVR 40 or 3/4		RVR 50 or 1	RVR 40 or 3/4	RVR 50 or 1			RVR 40 or 3/4	RVR 50 or 1		
All Non Std	DH 470'(350') RVR 40 or 3/4	DH 470'(350') RVR 50 or 1			MDA 480'(360') RVR 50 or 1				MDA 620'(500') RVR 50 or 1			

[1] STRAIGHT-IN LANDING RWY 24L

	DH 370'(250')	DH 370' (250')			MDA 480'(360') With Arbor 1.6 IOSS ILS DME				MDA 620'(500') Without Arbor 1.6 IOSS ILS DME			
	FULL ILS	Mkr out	ALS out	Mkr & ALS out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out
A B C	RVR 40 or 3/4	RVR 40 or 3/4	RVR 40 or 3/4	RVR 50 or 1	RVR 40 or 3/4		RVR 50 or 1		RVR 40 or 3/4		RVR 50 or 1	
D	RVR 40 or 3/4	RVR 50 or 1	RVR 40 or 3/4	RVR 50 or 1	RVR 50 or 1				RVR 50 or 1			
All Non Std	DH 470'(350') RVR 50 or 1	DH 470'(350') RVR 50 or 1			MDA 480'(360') RVR 50 or 1				MDA 620'(500') RVR 50 or 1			

Air Carrier Jets: SFL or HIRL out not less than RVR 40 or 3/4.

Gnd speed-Kts	60	80	100	120	140	160
G.S. 3.00°	318	424	530	636	742	848
ROMEO to MAP 6.2	6:12	4:39	3:43	3:06	2:40	2:20

NOTE: Circling minimums NA.

[1] Sidestep maneuver to land on rwy not provided with electronic guidance requires MDA 720' (600') 2.

[2] RVR 24 TDZ or CL out.

CHANGES: Terminal routes, pull up.

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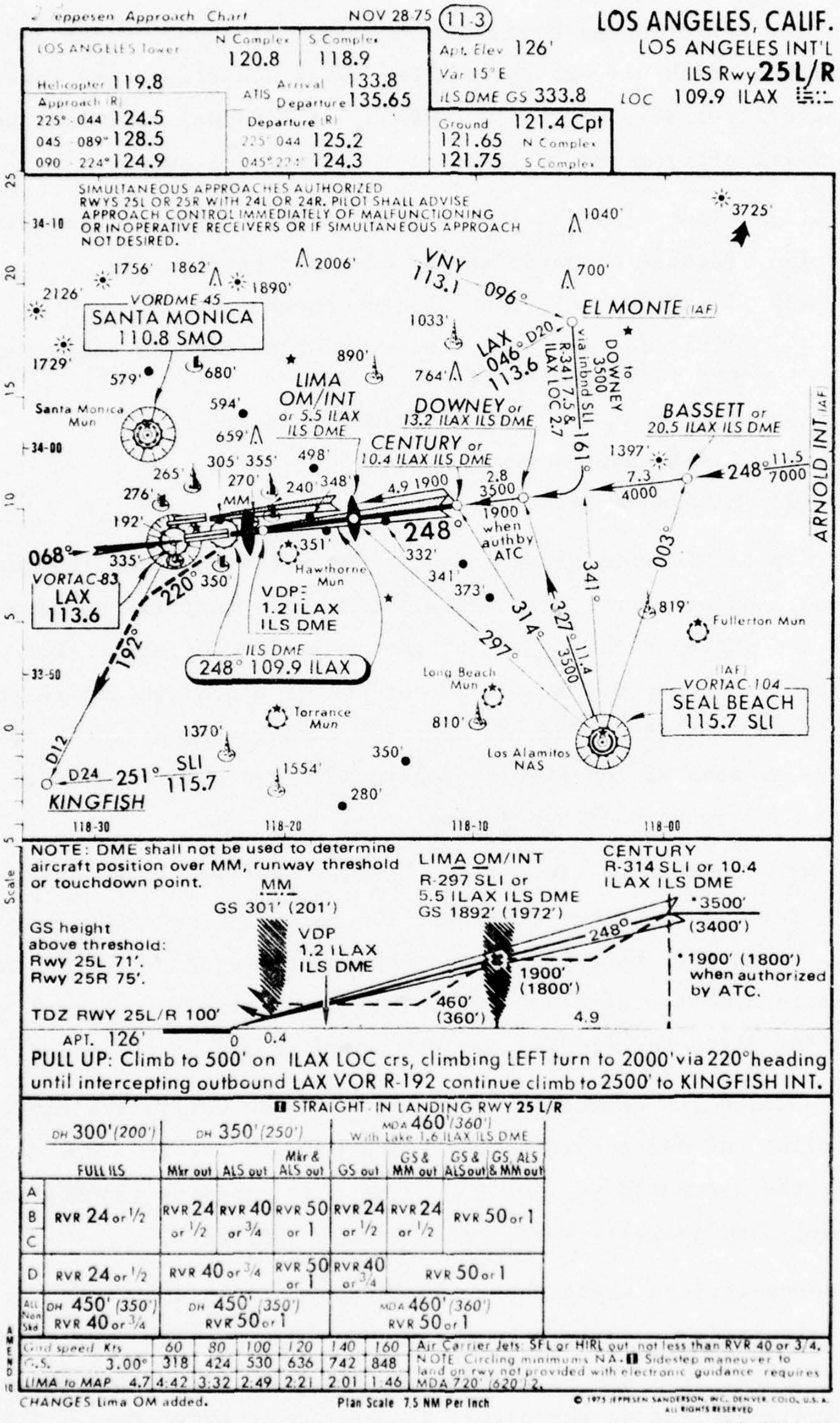
FIGURE 12 APPROACH PLATE FOR ILS APPROACHES



Jeppesen Approach Chart NOV 28-75 (11-3)

LOS ANGELES, CALIF.
LOS ANGELES INT'L
ILS Rwy **25L/R**
LOC 109.9 ILAX

LOS ANGELES Tower	N Complex 120.8	S Complex 118.9
Helicopter 119.8	ATIS Arrival 133.8	ATIS Departure 135.65
Approach (R)	Departure (R)	Ground 121.4 Cpt
225°-044 124.5	225°-044 125.2	121.65 N Complex
045-089° 128.5	045°-224° 124.3	121.75 S Complex
090-224° 124.9		

Apt. Elev 126'
Var 15°E
ILS DME GS 333.8

SIMULTANEOUS APPROACHES AUTHORIZED RWYS 25L OR 25R WITH 24L OR 24R. PILOT SHALL ADVISE APPROACH CONTROL IMMEDIATELY OF MALFUNCTIONING OR INOPERATIVE RECEIVERS OR IF SIMULTANEOUS APPROACH NOT DESIRED.

NOTE: DME shall not be used to determine aircraft position over MM, runway threshold or touchdown point.

GS height above threshold:
Rwy 25L 71'.
Rwy 25R 75'.

PULL UP: Climb to 500' on ILAX LOC crs, climbing LEFT turn to 2000' via 220° heading until intercepting outbound LAX VOR R-192 continue climb to 2500' to KINGFISH INT.

▮ STRAIGHT-IN LANDING RWY **25 L/R**

	DH 300' (200')	DH 350' (250')			MDA 460' (360') With Lake 1.6 ILAX ILS DME			
	FULL ILS	Mkr out	ALS out	Mkr & ALS out	GS out	GS & MM out	GS & ALS out	GS, ALS & MM out
A B C	RVR 24 or 1/2	RVR 24 or 1/2	RVR 40 or 3/4	RVR 50 or 1	RVR 24 or 1/2	RVR 24 or 1/2	RVR 50 or 1	
D	RVR 24 or 1/2	RVR 40 or 3/4		RVR 50 or 1	RVR 40 or 3/4	RVR 50 or 1		
All Non Skd	DH 450' (350') RVR 40 or 3/4	DH 450' (350') RVR 50 or 1			MDA 460' (360') RVR 50 or 1			

Gnd speed Kts	60	80	100	120	140	160
G.S. 3.00°	318	424	530	636	742	848
LIMA to MAP 4.7	4:42	3:32	2:49	2:21	2:01	1:46

Air Carrier Jets: SFL or HIRL out not less than RVR 40 or 3/4.
NOTE Circling minimums NA. ▮ Sidestep maneuver to land on rwy not provided with electronic guidance requires MDA 720' (620') 2.

AMEND 10

CHANGES Lima OM added.

Plan Scale 7.5 NM Per Inch

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FIGURE 13 APPROACH PLATE FOR NON-PRECISION APPROACHES (modified)

The approach was conducted by each individual evaluation pilot in accordance with his own procedures. Gear and flaps were lowered by the first officer at the pilot's command. All normal call-outs were made by the first officer and included at least the following:

(1) Glide slope active (or approaching non-precision fix
(2) Passage of outer marker or non-precision fix
(3) Completion of final landing check list
(4) Altitude, airspeed, and rate of descent as requested by the individual pilot
(5) Approaching and reaching minimums
(6) Lights and runway sightings
(7) Missed approach points.

Each evaluation pilot made his own decision about landing or going around, and all first officer call-outs were modified as requested to meet the stated requirements of the individual pilots. After each landing the simulator was frozen at nose wheel touchdown and reset back to the initial position for the next run. On go-arounds, the simulator was frozen as soon as the aircraft was stabilized with a positive rate of climb, and reset was then accomplished.

Most approaches flown in the study were ILS approaches to runway 24R under Cat-I weather minimums (300-foot ceiling, 2400-foot RVR). These approaches were flown manually by reference to the flight director, and autothrottles were not used. The transition to external visual reference for flare and landing was below 300 ft and at the pilot's discretion.

Coupled ILS approaches were flown in the Cat-II visibility conditions. Autopilot and autothrottles were used down to the 100-foot decision height where the automatic systems were disengaged and the landing maneuver was accomplished manually by external visual reference.

Nonprecision approaches were localizer-only approaches to runway 25L, simulating a failure in the glide-slope system. The approach plate was slightly modified by eliminating the LAKE fix at 1.6 NM on the ILAX DME and substituting the visual descent point (VDP) fix at 1.2 NM on the ILAX DME. The MDA was also changed to allow descent to 460 feet MSL immediately after leaving the outer marker, instead of maintaining 620 feet MSL to LAKE. Approach procedures for the non-precision approaches were similar to those already described for initial simulator positioning, configuration, and airspeed. On these approaches, the first officer called out approaching and passing fixes, and MDA, in addition to the normal altitude/airspeed call-outs. The initiation of the descent and the descent rate were at the discretion of the pilot in command.

Four takeoffs were also included in the master run schedule. A simulated aircraft gross weight of 400,000 pounds was used for these runs, and both maximum thrust and reduced thrust takeoffs were made. Only two of the test shear profiles were considered appropriate for the takeoff sequences. The frontal and thunderstorm profiles were used to represent a head-wind shearout during the departure climbout.

On the takeoff runs, the first officer called out airspeeds and actuated gear and flaps as directed by the pilot in command. Callouts of V_1, V_2, and V_R were normally requested. Takeoff runs were terminated when an altitude of approximately 1200 feet was reached.

E. Data Collection

Two distinct kinds of data were collected during the study: (1) pilot-generated data, including comments, opinions, and aiding concept ratings provided by each evaluation pilot, and (2) quantitative flight situation data recorded on magnetic tape and strip chart recorders. The two sources of data complement each other. Pilot assessments of the effectiveness of the aiding concepts were contrasted with objective records of approach outcomes.

Pilot generated data were obtained following each simulator run and in debriefing sessions. Pilot comments during and immediately after each approach were recorded on the first officer's inflight data card. This card was also used to record the evaluation pilot's rating on his performance and work load on each approach. These ratings were using a scale of one (best) to seven (worst). It was expected that pilot comments and ratings recorded immediately following the approach would be free of influence by other approaches or test conditions.

Pilot debriefings were conducted following each session in the simulator, for each pilot, and at the end of the week's participation for each pair of pilots jointly. The session debriefings were normally conducted by the Test Director alone, although other team members or official visitors sometimes observed. The debriefings were loosely structured to allow the pilots a maximum opportunity for comment without being led toward an answer.

End-of-the-week debriefings were usually more crowded, with all of the regular test team plus both pilots and ordinarily several visitors present. Structure again was kept quite loose to allow maximum free comment. Pilots were asked to make "best" and "second best" choices from the aiding concepts they had seen during the week. All pilot debriefing comments were recorded on cassette tapes for subsequent transcription and detailed study.

At the initial program briefing, each evaluation pilot completed an experience history form, primarily to evaluate his total and recent DC-10 experience. Each was also asked whether he had had prior experience with head-up display, flight-path angle, ground speed, or inertially sensed wind displays. Following his week's flying, each pilot was given a 27-item questionnaire to complete and return. The questionnaire was used to obtain comparative judgments of aiding concepts and to ask for opinions as to how the concepts might be improved.

A comprehensive set of flight situation parameters and events was recorded on digital magnetic tape, at a sampling rate of 5 samples per second, for subsequent quantitative analysis. These parameters are listed in Table 3. In addition, a digital printer triggered by main gear touchdown printed the values of several parameters describing touchdown performance, and an 8-channel strip chart recorder was used for quick-look monitoring of performance during the approach.

Table 3

FLIGHT SIMULATION PARAMETERS RECORDED ON MAGNETIC TAPE

Parameter	Unit	Range	Resolution
Elapsed time	sec	0-600	0.2 sec
Longitudinal position	ft	-20K to 50K	1 ft
Lateral position	ft	± 2K	1 ft
Vertical position	ft	0-2K	1ft
Heading error	deg	± 30	0.1 deg
Sideslip angle	deg	± 10	0.1 deg
Pitch angle	deg	± 30	0.1 deg
Roll Angle	deg	± 30	0.1 deg
Vertical speed	ft/sec	± 50	1 ft/sec
Airspeed	kt	0-300	1 kt
Ground speed	kt	0-250	1 kt
Cross-track velocity	ft/sec	± 25	0.1 ft/sec
Longitudinal acceleration	ft/sec^2	± 5	0.1 ft/sec^2
Normal acceleration	ft/sec^2	± 30	0.1 ft/sec^2
Pitch rate	deg/sec	± 10	0.1 deg/sec
Roll rate	deg/sec	± 10	0.1 deg/sec
Elevator deflection	deg	± 64	0.1 deg
Rudder deflection	deg	± 64	0.1 deg
Aeleron deflection	deg	± 64	0.1 deg
Pitch acceleration	rad/sec^2	± 3	0.1 rad/sec^2
Control column position	inches	± 8.97	0.1 inch
Control wheel position	deg	± 90	0.1 deg
Rudder pedal position	inches	± 4.24	0.1 inch
Throttle position	deg	0-256	0.1 deg
Horizontal stabilizer position	deg	-5 to +15	0.1 deg
Flap position	deg	0-50	1 deg
Flight-path angle (air)	deg	± 10	0.1 deg
Potential flight-path angle (air)	deg	± 10	0.1 deg
Wind speed (along track)	kt	± 60	0.1 kt
Wind speed (cross track)	kt	± 40	0.1 kt

Table 3 (concluded)

Parameter	Unit	Range	Resolution
Wind speed (vertical	kt	± 20	0.1 kt
Pitch steering bar signal	deg	± 10	0.1 deg
Bank steering bar signal	deg	± 25	0.1 deg
Localizer deviation	mV	± 15	0.1 mV
Glide-slope deviation	mV	± 15	0.1 mV
Airspeed bug setting	kt	0-200	1 kt
RPM (N_1)	%	0-100	1%
Altimeter (barometric)	ft	0-2K	1 ft
Angle of attack	deg	0-20	1 deg
DME 1 distance	nm	0-10	0.1 nm
DME 2 distance	nm	0-10	0.1 nm
VOR 1 bearing	deg	0-360	0.1 deg
VOR 2 bearing	deg	0-360	0.1 deg
Wind differential	kt	± 60	1 kt
Marker beacon			
Autopilot disengage			
Left gear touchdown			
Autothrottle disengage			
Right gear touchdown			
Go-around initiate			

IV RESULTS AND DISCUSSION

Implementation of the test procedures described in the preceding section generated pilot evaluations and flight situation data on a total of 512 simulator runs. These data were reduced to derive two principal indicators of the relative effectiveness of alternative pilot aiding concepts:

(1) Pilot assessments of the potential operational utility and limitations of each of the aids.

(2) Approach outcomes--i.e., objective determinations of the effectiveness of approach management and flight-path control based on aircraft state parameters at 100 feet (Inner Marker) and at touchdown.

The screening of candidate pilot aiding concepts was based primarily on contrasts with baseline conditions, and data reflecting pilot reactions and performance under these conditions are presented first. As indicated earlier, the term "baseline" is used to refer to the fact that no augmentation of existing cockpit instrumentation or flight crew procedures is available to the pilot; within the context of this study, such conditions may therefore be construed as "unaided". The subsequent discussion of the outcomes of the screening evaluations will examine contrasts between different aiding concepts as well as their relationship to baseline conditions.

Phase 1 testing was carried out as an exploratory study, covering a diverse set of operational conditions and of incompletely developed aiding concepts. Within the time and resource constraints imposed on this phase of the program, a fully controlled experimental evaluation of each aiding concept and alternative operational context was not feasible and was not attempted. Accordingly, relatively greater emphasis was placed on pilot assessments of the potential usefulness of the candidate aiding concepts, and quantitative data reflecting differences between aiding concepts were not analyzed for statistical significance. Quantitative data were recorded primarily to provide a basis for detailed analyses of pilot and aircraft responses to the different wind-shear conditions following a case study approach for a particular set of run conditions.

A. Pilot Assessments of Baseline Performance

1. Simulation of Wind-Shear Profiles

Immediately following their exposure to the simulated wind shears under baseline conditions, pilots were asked to express their reactions to the realism and severity of the shears and to comment on their ability to detect them. They were also asked to critique the overall simulation (i.e., aircraft response, visual scene, turbulence, etc.), especially in regard to any features they felt might degrade their performance or ability to assess the shears.

The simulated shear conditions were generally regarded as "realistic but rarely encountered," with most of the reservations about realism referred to shear profile 4 (thunderstorm shear). With only one exception, the pilots stated that they had never encountered wind-shear effects as great as those represented in the simulation. Nevertheless, even the more severe shears were accepted as reasonable, and pilots were impressed with the potential training value of exposure to them in the simulator. As one pilot put it:

> "I think it's educational to see some of those excessive or high shears in there, because I think very few pilots have ever been exposed to those kind of shears...what I'm saying is I think you have to train on some of these things in the simulator - more than we have in the past...they talk about it, but until the guy has gone down there and witnessed his speed bouncing around and the high sink and landed short a few times, it doesn't make much of an impression...it makes a much greater impression when you bounce the thing off the approach lights and see that that could happen in the real world."

Pilot reactions to the simulated turbulence conditions were not so positive. Six of the eight pilots commented that the turbulence was not realistic. Some felt that the airspeed indicator movements were too abrupt ("too jerky") and that for such indications the motion system did not produce an appropriate level or rate of cab movement.

Most of the pilots reported that their first and clearest indication of the shear was a change in airspeed, with one pilot adding simultaneous displacement from the glide slope to the airspeed change. Vertical speed was mentioned by two of the pilots as a secondary indication of shear, saying it was less frequently used because it is outside of the primary instrument scan pattern.

In their critique of the overall simulation, pilot comments were generally favorable. The most common complaint was that roll response was too sensitive (control loading seemed to be much lighter than in the aircraft) and some of the pilots felt that the simulator's response to pitch and throttle inputs was too slow. Only one of the pilots felt that discrepancies in the simulator's handling qualities were adversely affecting his performance.

2. VASI and VDP Procedure

Six of the eight pilots flew the night visual approach using VASI as an aid for glide-path control. All of them felt that the VASI simulation was the best that they had seen in a simulator, but some of them noted that it was too "sensitive" in that red-white color changes occurred too abruptly. Comments on the usefulness of VASI for detecting the shear were favorable in all instances. The pilots felt that departures from the 3-degree glide slope were easily detected and that this gave them a clear and timely indication of the shear effects.

Pilots felt that the VASI as simulated could provide trend information as well as discrete position, and were able to fly specific light combinations (red over two whites, or two reds over one white) as desired. Reports indicated that the pilots were able to detect developing shears by observing the VASI color changes, and to go around on the "3 red" indication. Their general opinion was probably effectively summarized by the pilot who said, "Some guidance is better than no guidance."

All pilots who flew the VDP procedure recognized the value of a clear indication of when to initiate the final descent on a non-precision approach, but the consensus was that the procedure did not provide any assistance for detecting or coping with wind shear. Two of the pilots recognized that the DME information might be useful in determining wind effects (e.g., by noting its rate of change or the DME position on arrival at the MDA), but the availability of the VDP fix, per se, could not be related to the wind-shear problem.

3. The Coupled Approach

The six pilots who flew the coupled approach in simulated Category II weather were generally relieved to have the autopilot and autothrottle systems cope with the shears. They all believed that the automatics performed very well in delivering the aircraft to an acceptable position for the manual takeover at the 100-foot decision point. They also felt that the reduced workload and the time available to concentrate on the approach management task enabled them to do a better job of detecting shear effects. As one pilot put it: "...there's no question about it, I think you can do a much better job of flying any kind of turbulence or shear using the coupler."

One of the more perceptive pilots noted the importance of autothrottle performance in producing this level of pilot confidence:

> "A good set of autothrottles with the acceleration term is essential if you intend to use the couplers in negotiating turbulence and shear conditions...I think without that you would not be able to use them...I think this is a way to go, but I stress that the throttles must have the right smarts."

4. The Takeoff Runs

Pilot debriefings on this test condition were focused on the usefulness of the simulated PIREPS (pilot reports) provided just prior to takeoff. Most of the pilots (5 out of 6) felt that these reports helped them to anticipate the airspeed changes during climbout. None felt that management of the shear encounter during climbout was particularly challenging with all engines operating, even in the reduced thrust condition.

B. Approach Outcomes for Baseline Conditions

Figure 14 presents an overview of approach outcomes for the alternative baseline test conditions. Three components of the approach outcome are represented in these data plots. The plot at the top of Figure 14 shows the proportion of go-arounds flown under each baseline condition (number of go-arounds relative to the total number of approaches attempted). The next plot down is based on a count of within-limits approach outcomes derived from data on aircraft position and tracking tendencies at a glide slope height of 100 feet. The plot at the bottom of the figure is based on a count of within-limits landings derived from touchdown data.

An approach was counted as "within limits" if, at the range corresponding to a glide-slope height of 100 feet, the aircraft was within ±75 feet of the extended runway centerline, tracking so as to remain within these limits, and within ±28 feet of the glide slope (two dots). The data points are the number of within-limits approaches relative to the total number of completed approaches; this means that the approaches resulting in go-arounds were not included in the derivation of these proportions.

The data points for landings are based on the same subsets of completed approaches as those used for the approach outcomes, and are also shown here as proportions. Landings were counted as within limits when touchdown paramaters satisfied the following conditions:

(1) Wheel contact occurred within the touchdown zone (threshold to 3000 feet down the runway) and with the midpoint of the aircraft within ±50 feet of the centerline.

(2) Rate of descent was 10 ft/sec or less.

(3) Lateral velocity was less than 14.5 ft/sec.

(4) Pitch attitude was less than 13 degrees.

(5) Roll attitude was less than 9 degrees.

Separate data plots are provided in Figure 14 for the pilot's first (ILS-1) and second (ILS-2) exposure to the four wind-shear conditions on the manually flown precision approach runs. Outcomes of the two replications of the precision approach for shear profiles 2 and 3 are plotted next (TRNG) to indicate training effects. The last three plots are for

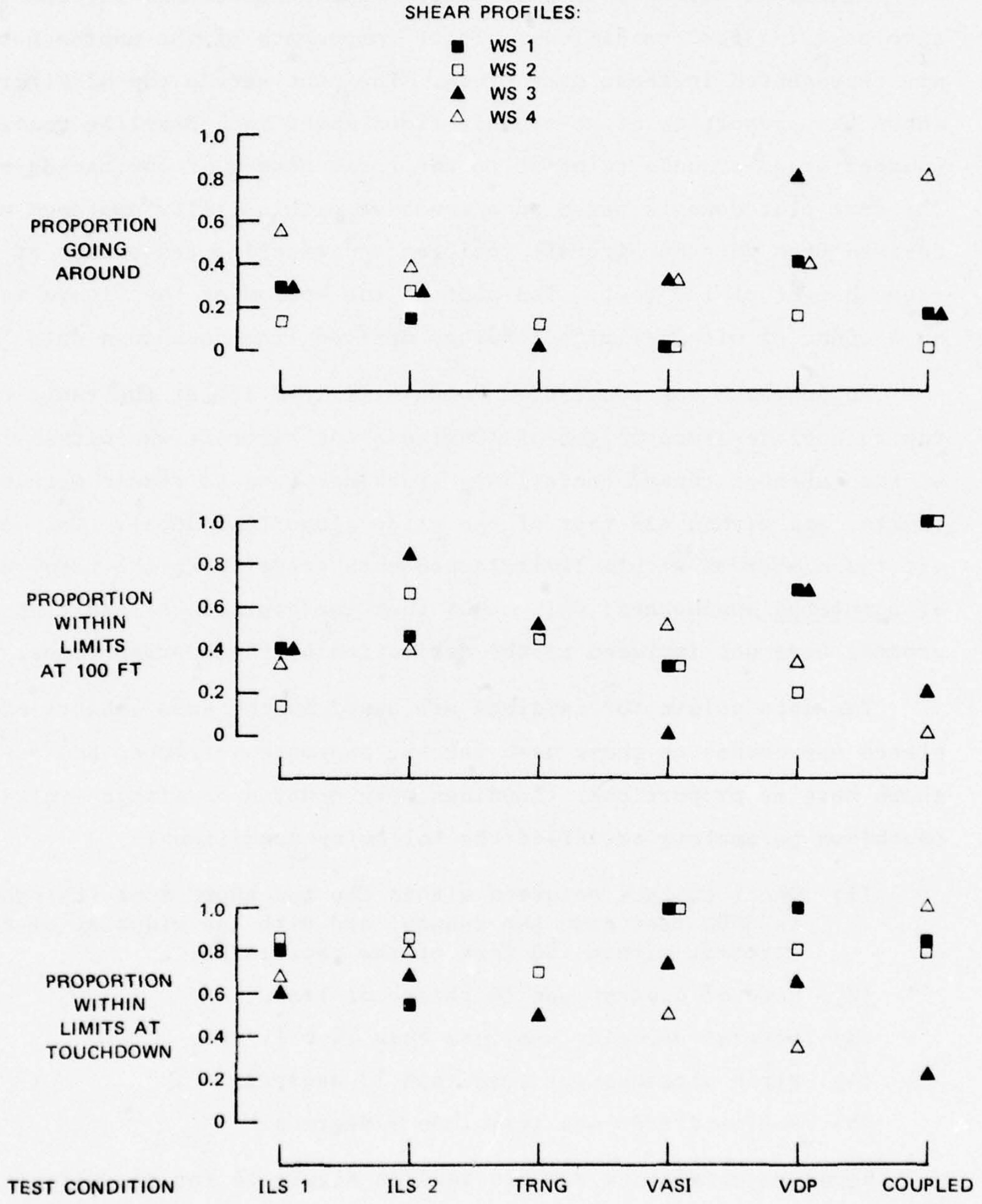

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FIGURE 14 SUMMARY OF APPROACH OUTCOMES FOR ALTERNATIVE BASELINE TEST CONDITIONS the non-precision approaches using VASI, the VDP procedure, and the coupled approach to the Category II decision height. Data points in each plot are coded to distinguish the effects of the different wind-shear conditions using the following symbols:

■ Represents the neutral boundary layer shear (WS-1)
□ Represents the night time inversion shear (WS-2)
▲ Represents the frontal/directional shear (WS-3)
△ Represents the thunderstorm gust front shear (WS-4)

The data indicate some training effect across initial baseline run series (ILS and TRNG) with a slight trend toward fewer go-arounds and a higher proportion of within-limits approaches to 100 feet. However, no training effect is apparent in the touchdown plots. Approach performance on the extended baseline series (VASI, VDP, COUPLED) show the relatively greater effects of differences in test conditions and shear profiles.

On the VASI approaches for shear profiles 1 and 2, there were no go-arounds, and all touchdowns were within limits. However, this result is probably due to the unrestricted visibility condition on this run series rather than to the guidance provided by the VASI. Notice that performance on the more severe profiles (3 and 4) is at about the same level as initial baseline.

The spread on VDP runs is due in part to the smaller number of runs completed for this condition (5 rather than 8). Approach outcomes appear to be somewhat better than initial baseline for shear profiles 1 and 2, and about the same or worse for shears 3 and 4.

The expected improvement in approach outcomes for the coupled condition was obtained only for shear profiles 1 and 2. There were comparatively few go-arounds (1 out of 6) on the frontal shear (WS-3); however, data for both the approach to 100 feet and the landings for the coupled approaches show consistently poorer performance than initial baseline for this shear. The proportion of go-arounds for the thunderstorm shear (WS-4) was 4 out of 5, somewhat higher than initial baseline conditions. This result may be due in part to the combination of the severe down-draft associated with this shear and the very low visibility condition

(1600 feet RVR). The 1.0 proportion of within-limits touchdowns for this condition may be misleading, since it is based on only one completed approach.

When the number of within-limits landings is related to the total number of approaches attempted, the overall proportions of within-limits touchdowns across wind-shear conditions are as follows:

(1) For the ILS approach (ILS 1 and 2), it is 31 out of 60, or 52%.

(2) For the non-precision approach using VASI, it is 17 out of 24 or 71%.

(3) For the non-precision VDP approach, it is 10 out of 21 or 48%.

(4) For the coupled ILS approach, it is 11 out of 22 or 50%.

Comparisons among the alternative baseline conditions are confounded by differences in weather conditions and guidance represented in the simulation. Moreover, the interpretation of these results must be tempered by a consideration of the small number of approaches on which they are based. However, the data indicate that considerable augmentation of baseline capability will be required if pilots are to cope successfully with the kinds of low-level wind-shear conditions represented in this study.

C. Pilot Assessments of Candidate Aiding Concepts

1. Ranking of Aiding Concepts

In the general debriefing sessions conducted after their exposure to the full set of candidate aiding concepts, the evaluation pilots were asked to make "best" and "second best" choices. Six of the eight pilots selected the Ground Speed display as their first choice, and two preferred the Wind Difference Indicator. There was considerably less consensus in their selections of the second-best aiding concept, with four pilots choosing some version of the Wind Difference Indicator, three preferring the INS Wind Readout, and one reluctantly stating that the Shear Advisories would be his second choice. Preferences expressed for the Wind Difference

Indicator, as either a first or second choice, were accompanied in all instances by the qualification that the panel mounted test display was unacceptable due to its location out of the normal instrument scan and to difficulties in reading the display.

The completed questionnaires received some time after the run series from five of the eight pilots tended to confirm the rankings of Ground Speed and the Wind Difference Indicator as the most useful aiding concepts. The questionnaire also called for a rank ordering of the other aiding concepts, including VASI and the VDP procedure. There was very little agreement among the five responding pilots regarding the particular ranking of each concept. For example, the INS Wind Readout was ranked from first to ninth, Shear advisories were rated from third to tenth, and the Head-up Display was rated from third to ninth. However, the pattern of choices could be reduced to the following rank ordering:

1st	Ground Speed
2nd	VASI
3rd	Head-up Display of Wind Difference
4th	INS Wind Readout
5th	Head-up Display of Flight Path Angle
6th	Panel Display of Wind Difference
7th	Shear Advisories
8th	Panel Display of Flight Path Angle
9th	VDP Procedure
10th	VSI-Ground Speed Placard.

Pilot critiques of each aiding concept, based on post-session debriefings and on the observations of test personnel, are summarized and discussed below.

2. Ground Speed Display

The rationale most often given for the first-place ranking of this aiding concept was that it was easy to read and interpret. They liked the convenient location, clearly within the normal instrument scan during the approach, and its close association with indicated airspeed. One pilot summed it up this way:

> "The ground speed, especially on the airspeed indicator where it's so in the field of scan all the time, makes you very aware of what the wind is and how it's changing and what to expect from a shear standpoint, based on what's being reported on the ground."

Some of the pilots reported that they used the ground speed display to compute the existing head-wind/tail-wind component, and there were some complaints about this computational workload. It seemed obvious that there were large differences in the understanding of how ground speed was to be used. In the words of one pilot, "You told us what it was going to do, but not how I'm supposed to react to it from a pilot's standpoint." The comment is well taken; unless the subject pilot was already somewhat familiar with a concept, the four approaches devoted to that concept probably did not give him time to develop his own notion as to how best to use it. Even if we had been able to brief on specific use techniques, the opportunity for learning or rehearsing them would be very limited within the four approaches.

The general consensus was that having ground speed displayed on the airspeed indicator was helpful and a preferred location, but that adding a second bug, of a different color, would be better than preempting the command bug. It was also suggested by one pilot that the Mach limit needle ("barber pole") could be used to display ground speed, since the Mach limit is of no importance during approach and landing. Another pilot suggested that the ground speed display might be combined in some fashion with the slow-fast indicator; his reason for suggesting this was that the airspeed bug was not part of his scan on short final--below about 500 feet.

One of the pilots who did not see this concept as especially helpful commented that the use of the airspeed command bug for ground speed actually disrupted his normal scan, and that this would require him to set up a whole new scan procedure, which would take more time than was available during the study. He was also concerned about the potential for confusing the ground speed bug with command airspeed. His contention was:

> "...you'll have to change the format. It's totally unacceptable to have it above the airspeed indicator. When it's at either end of the indication then it's out of your scan because it's not within the range of airspeeds you're using on the approach--you have to hunt for it, and then you've lost the flight director. Conversely, when it is close to approach airspeed indications, you have a tendency to go after it... it moves and unconsciously you add or subtract power, pull the nose up or down to chase after it. No matter where it was, it was creating problems."

Crew coordination and callouts were also frequently mentioned in connection with the ground speed display. Apparently, it would be acceptable to some pilots to have the first officer or flight engineer calling out ground speeds, winds, or drift components. The callouts were suggested as a means of reducing the pilot's workload, especially in mental computation.

3. Wind Difference Indicator

Pilot assessments of the Wind Difference Indicator were mixed, ranging between the opinion of one pilot that it was "very effective and would reduce operational workload" to that of other pilots who said it "wasn't worth a damn" and "actually degraded performance." The pilots who rated this concept high said they liked it because it gave them some anticipation of the shear--a feeling for what lay ahead of them on the approach--and because it was the only aiding concept in the set that could be clearly related to a pilot action for coping with the shear. As they said it:

> "The reason I feel we are both commenting on the wind meter and the airspeed is that they're the only ones that are giving us information as to what's going to happen to us and what we're suppose to do before it happens. The rest of the stuff is after the fact...It doesn't do any good to anticipate a shear because you don't care, you know the shear's there...You want to know what you're supposed to do to get through it, and these are the only things that helped us."

What the pilots were supposed to do, of course, if they adopted the procedure suggested in the briefings, was to "pad" their previously selected approach airspeed by the full amount of any negative reading of the Wind Difference Indicator. Most of the pilots did experiment with this speed pad but in most instances did not add as much airspeed as the wind meter called for. Some of the pilots were uncertain about when in the approach to apply (or remove) the airspeed pad and they seemed reluctant to believe that excess airspeed would in fact bleed off prior to touchdown. Quoting one pilot: "The readings were sometimes hard to believe, but they turned out to be true."

We had anticipated that pilots would have some difficulty with the Wind Difference concept because the indicator does not respond directly to control inputs, but only to the external wind environment. A change on the meter is thus seen only when a change occurs in winds on the surface or at the aircraft's position. Contrary to our expectations, however, pilots reported no difficulty in this aspect of meter usage.

The location of the wind meter on the panel in the area above the altimeter was a problem mentioned by nearly every one of the evaluators. The pilot's normal instrument scan does not include this area and they felt that some training would be necessary before they would be able to scan it routinely. The test display used for this concept was also small and poorly lighted and therefore hard to read. The most common suggestions for improving the concept centered on revamping the display and locating it nearer the radar altimeter or airspeed indicator--i.e., on either side of the ADI. Two pilots felt that the positive-negative sense of the display should be reversed, so that negative readings would be above zero and mean that power should be added to achieve a corresponding increase in airspeed.

The wind difference information was, of course, displayed head-up as well as head-down. Pilot comments indicate that the head-up display was almost unanimously preferred, although this may have been a "halo effect" that carried over from the generally positive evaluations of the HUD concept. Unquestionably, the Wind Difference Indicator was much easier to see in the HUD, and this may also have contributed to the comparatively high ranking of the HUD when the wind information was included. Interestingly, when pilots were asked in the questionnaire whether the wind meter was better for detecting or for coping with wind shear, most of the responses indicated that the head-down meter was better for detecting shear, while the HUD with wind meter was better for coping with shear.

A frequently reported advantage for the wind meter was that it eliminated the mental computations associated with estimating wind effects when parameters such as INS wind or ground speed are used. The pilots in this evaluation were very sensitive to any requirement for mental computations during the approach, with this sensitivity most often manifested in reports of increased workload. Opinions as to the effect of the wind meter on operational workload were almost evenly divided between increase and decrease. Location and display format were cited as reasons for the expected increase in workload.

4. Head-up Displays

Pilot reactions to the head-up displays were more complex and varied than for any of the other aiding concepts. Their overall reaction was probably best expressed by the pilot who commented that "...on the first couple of runs I was kind of in the dark, but then we started gluing each individual piece together and I think it makes more sense--at this point I think it will definitely have some value if we can sort it all out." This pilot was referring to the separate elements of the basic display format, but the reaction applies more generally to the many unresolved issues associated with the head-up display (HUD) concept and its application to the wind-shear problem.

The most enthusiastic advocate of the HUD concept was a pilot who had a remarkable ability to screen out the more troublesome features of the concept and to use only those elements of the display that he found helpful. He felt that the reference flight-path angle element (the circle), together with airspeed, were excellent aids for detecting and coping with the low-level shear, especially for the transition from instruments to visual reference. However, this pilot deliberately excluded the flight-path angle and potential flight-path angle elements from his scan on his initial exposures to the HUD and included them later only because he felt an evaluation of these elements was expected.

The other evaluators did not attempt to "sort it all out" in this manner and generally attempted to use the full HUD from the outset. Their assessments of the potential usefulness of the HUD were generally positive, but all of them had some kind of complaint about what was presented, how it was displayed, and/or how to use the display. Only one of the eight pilots felt that the HUD, as it was represented in the simulation was "not acceptable at all." His criticisms of HUD ranged from a conviction that the display elements dynamics did not match the response of the aircraft to his control inputs, to a rejection of the display content and format as "incomplete" (no ILS information) and "primitive" (relative to an operational system he had flown).

There was a definite trend toward more positive acceptance of the HUD with increasing exposure across the three sessions in which it was used. Pilot comments following the first session were more often noncommittal (e.g., "It's a new concept...I found it very interesting"; "It was less difficult to fly than I anticipated") and only two of the eight pilots felt they had adequate time to evaluate the concept. After the second sessions, the comments were more in terms of specific ways the HUD was helpful and four of the pilots felt the time for evaluation was adequate. Finally, after the third exposure, terms like "outstanding," "highly successful," "certainly an advantage," and "very useful" appeared in the pilot comments.

The HUD features cited most often as limiting its operational usefulness were:

(1) The lateral displacement of the 3-degree flight-path reference circle in a strong cross-wind situation.

(2) The excessive activity and instability of the flight-path angle and potential flight-path angle elements, especially in turbulence.

(3) The apparent lack of coherence in the overall display configuration--i.e., the tendency for the display elements to move apart or in seemingly unrelated ways, during the shear encounter.

(4) The lack of a clear and easily used pitch (or angle of attack) reference; the aircraft symbol was unanimously considered to be too far away to be useful.

The most positive comments relating to the head-up display of flight-path angle were those associated with the IFR-VFR transition condition. One pilot stated that:

> "...what I had then was excellent--very, very good. I couldn't speak enough for having that airspeed presentation there with the circle, in that order of priority, and then the flight path angle bars...The minute that airspeed started to move, to decay, and it was not responding to my throttle response, and then when I looked over and saw that the predicted glide path angle circle was moving towards me, I knew, there was no doubt in my mind, that the present aircraft configuration was not going to resolve it...So I have to apply different techniques--flap retraction, go-around low. No doubt I had cues that I normally would not have got in that timely a fashion."

Pilot assessments of the potential flight-path angle bars were generally negative, probably because of the unfamiliarity of the information provided and of the excessive activity of this display element relative to the flight-path angle bar. However, most of the pilots did think that they provided anticipatory information for managing airspeed. This display element was the one pilots most often ignored or felt they needed much more experience with for a proper evaluation.

5. <u>INS Wind Readout</u>

Seven of the eight pilots commented that the INS Wind Readout alerted them to the shear condition by providing information they could compare with the surface wind report. All of them were familiar with the potential usefulness of this concept and thought the availability of current information on the winds presently affecting the airplane would help them manage the approach.

As we anticipated, the negative comments were directed to the difficulty in including this information in the normal instrument scan during an approach and to the mental workload required to monitor and detect significant changes in wind effects. The almost unanimous position taken on the resolution of these problems was to assign the INS monitoring task to the First Officer, and have him call out significant wind changes and/or potential shear conditions.

6. Shear Advisories

Seven of the eight pilots felt that the wind-shear advisory messages would help them to anticipate the occurrence of significant low-level shear and that it would be desirable to have this information prior to starting the approach. Most of the pilots stated that they would modify their usual approach management procedures on the basis of the shear advisory; however, only three of eight pilots actually indicated that they would not proceed after reading an advisory. In the four instances where pilots did elect to go-around on reading the advisory, we requested that they attempt the approach for data; three of these approaches resulted in short landings (in the approach lights) and one in a go-around.

The principal difficulty with advisories represented in this study, according to seven of the eight pilots, was that the structure of the messages was too complex and the language was not sufficiently clear. In the words of one evaluator:

> "The criticism is that it needs to have a format change in that there is too much verbiage in it and it's not structured... You're talking about 'positive and negative' and 'head wind-tail wind' all in the same report and format. That is definitely a very negative value...It's too lengthy and voluminous to be a good memory item."

In one way or another, most of the pilots put in a plea for both brevity and for some way of organizing the information by approach segment or altitudes so that they could get a clearer picture of what to expect and where in the approach it would happen. The suggestion of two of the pilots was to describe the wind shear <u>effect</u>--i.e., an expected change in airspeed, rather than the changes in wind velocity or direction; "I would say that if you gave the wind and where the shear takes place and say expect a 15-knot change of airspeed--or drop in airspeed--that would be a big help." Most of the pilots felt that they would need some sort of reminder of reported shear conditions as the approach proceeded.

The general recommendation was to have the First Officer call out the expected changes to alert the pilot flying the approach, but there was little agreement on when and how this might be accomplished.

One of the pilots had a high regard for the shear advisory information but was suspicious of actually getting it in the operational situation:

> "They were magic, right on target. They were practically equivalent to a display, but of course in the real world you wouldn't see this because no one could update the rapidly changing condition on the approach to give you that kind of information...I felt that to try to apply the advisories directly to the flight could lead into a trap. You would be in anticipation of something that wasn't really going to happen or it might actually be the reverse."

Two of the pilots mentioned an unexpected effect the advisories might have on the pilot's anticipation of shear: that it might make them too apprehensive and over-react to the actual shear encounter. One of them said he would sometimes imagine the severity of the shear to be greater than it actually turned out to be. The other pilot reported that his apprehension led him to try to out-guess the shear rather than follow what his instruments were telling him, and that this resulted in an unnecessary go-around.

7. Panel Display of Flight-Path Angle

Pilots were unanimous in their rejection of this concept, primarily on the basis of its poor location and the difficulties they had in both reading the instrument and appreciating the relevance or usefulness of the information it provided. All of the eight pilots complained about the deficiencies in how the information was presented, with one pilot expressing it most succinctly:

> "The damned presentation is too small to be of any good. You've got to get it on a bigger gauge and a bigger needle and maybe then it could show you that...I'm not sure that even then it would tell you much down when you get out of 400 or 500 feet, and where it gets iffy whether you're going to make the runway or not with shear."

The latter part of this pilot's statement is important because it points up the fact that even with the display problems resolved, pilots might not find the information particularly useful. It was the on-site Test Director's impression that the panel display of flight-path angle was not used by at least half of the pilots; perhaps the poor presentation allowed them to evade the more troublesome task of attempting to understand and use the information. Positive assessments of the operational usefulness of flight-path angle information tended to be vague and, in almost all instances to be qualified by the assertion that some other instrument did a better job of providing the same information. The following quotes are typical:

> "The information is useful and interesting when you initiate the approach and as long as conditions are relatively steady state it does give you an indication that is useful...I personally don't see any advantage of this over a ground speed display."
>
> "I think it provided a clue to me of whether I had a tail or head wind because that's about all it did for me. I could detect the same thing basically on the IVSI."
>
> "It was very easy to recognize head wind and tail wind with relation to the pointer. But that was basically about the only value I was able to get out of it."

Four of the eight pilots simply rejected the concept, saying "...it was just something I was trying to do because it was there and you guys asked me to do it...I wouldn't use it, I wouldn't even look at it or use it at all." "I don't like it; I wouldn't want it and have no use for it." "Can I use four letter words? I didn't care for the instrument." More significant than the common complaints about the out-of-scan location and poor readability of the display were the comments of two of the pilots that attempts to use the display on the low end of the approach would degrade their control of the aircraft by reference to primary instruments or external visual reference.

8. VSI Ground Speed Placard

Most of the pilots were intrigued with this device and felt that it had some merit in alerting them to wind shear whenever they could keep the approach reasonably stable on the 3-degree glide path. They all commented on the difficulty of including the VSI in their scan and of attempting to interpret the ground speed reading when the VSI needle was bouncing around in turbulence. Some of them felt they could do about as well using other instrument indications, and none of the pilots felt strongly about adopting this concept.

D. Approach Outcomes Using Aiding Concepts

An overview of approach outcomes is presented in Figures 15 and 16 for each of the candidate pilot aiding concepts just discussed. The data plots are the proportion of go-arounds and within-limits approaches, and were derived following the procedure described earlier for baseline conditions (see Section IV-B). Data points are again coded to show the differential effects of the four wind-shear conditions. The first test condition in each figure (BL) represents baseline systems performance on the pilot's second exposure to the shears (ILS 2 in Figure 14), and was included here to facilitate the contrast with performance using the aiding concepts.

Figure 15 presents the approach outcome summaries for the shear advisory (ADV) and the aiding concepts representing alternative ways of augmenting existing panel instruments. All of these "head-down" concepts were evaluated under the same set of test conditions--i.e., full ILS guidance, manual control using flight director, Category 1 weather (2400 feet RVR), and the same runway environment. Also, the data points shown for each test shear are all based on eight runs, one for each evaluation pilot.

Approach outcome summaries for the Head-up Display (HUD) aiding concept are presented separately in Figure 16 to call attention to the fact that test conditions for evaluating this concept were not the same as those just cited. It will be recalled from the discussion of study procedures in Section III that all eight pilots were exposed to the HUD in the same order. On the first run series, the basic HUD (no wind difference information) was used as the primary reference for flight-path

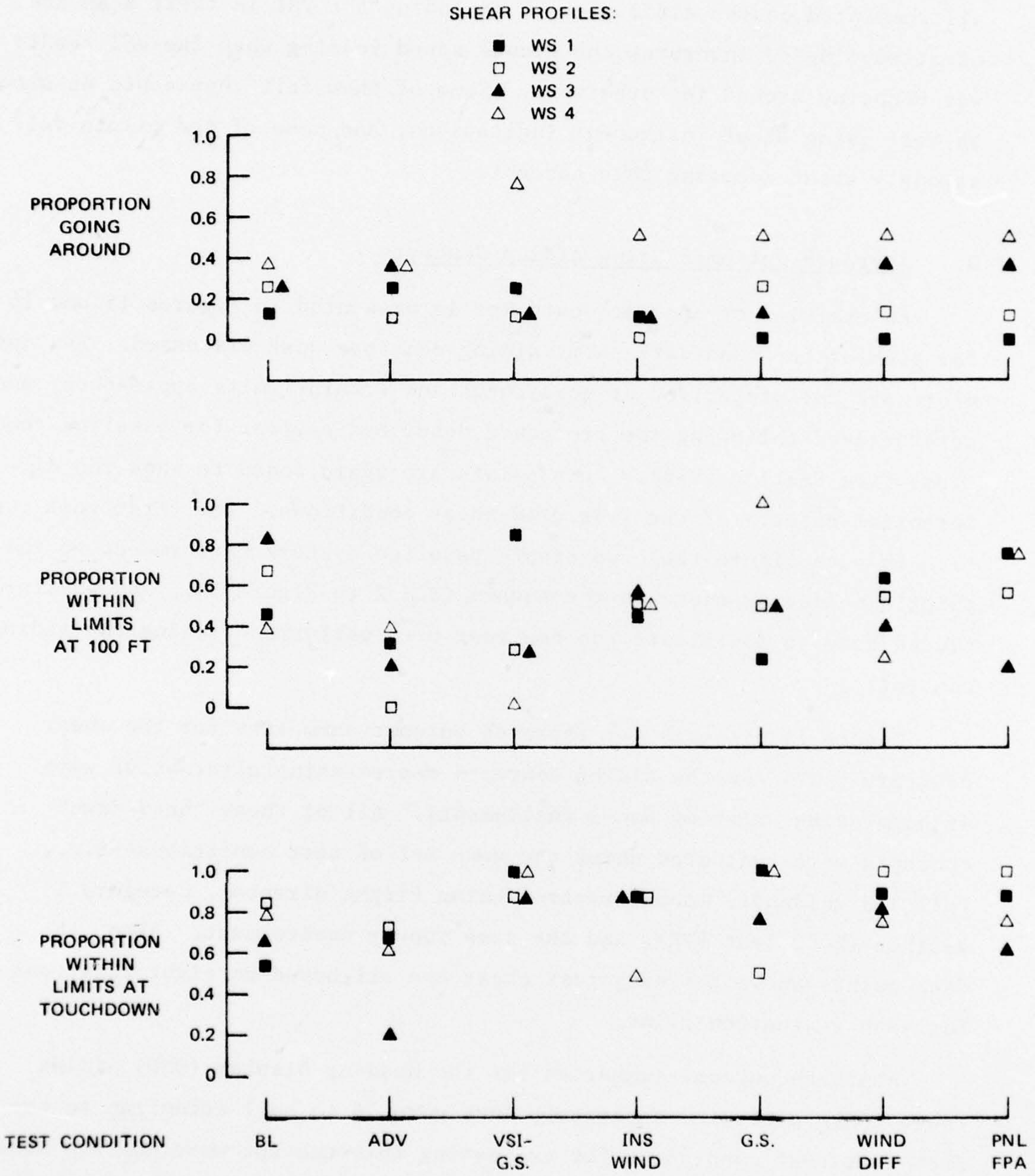

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FIGURE 15 SUMMARY OF APPROACH OUTCOMES FOR SHEAR ADVISORIES AND HEAD-DOWN DISPLAY CONCEPTS

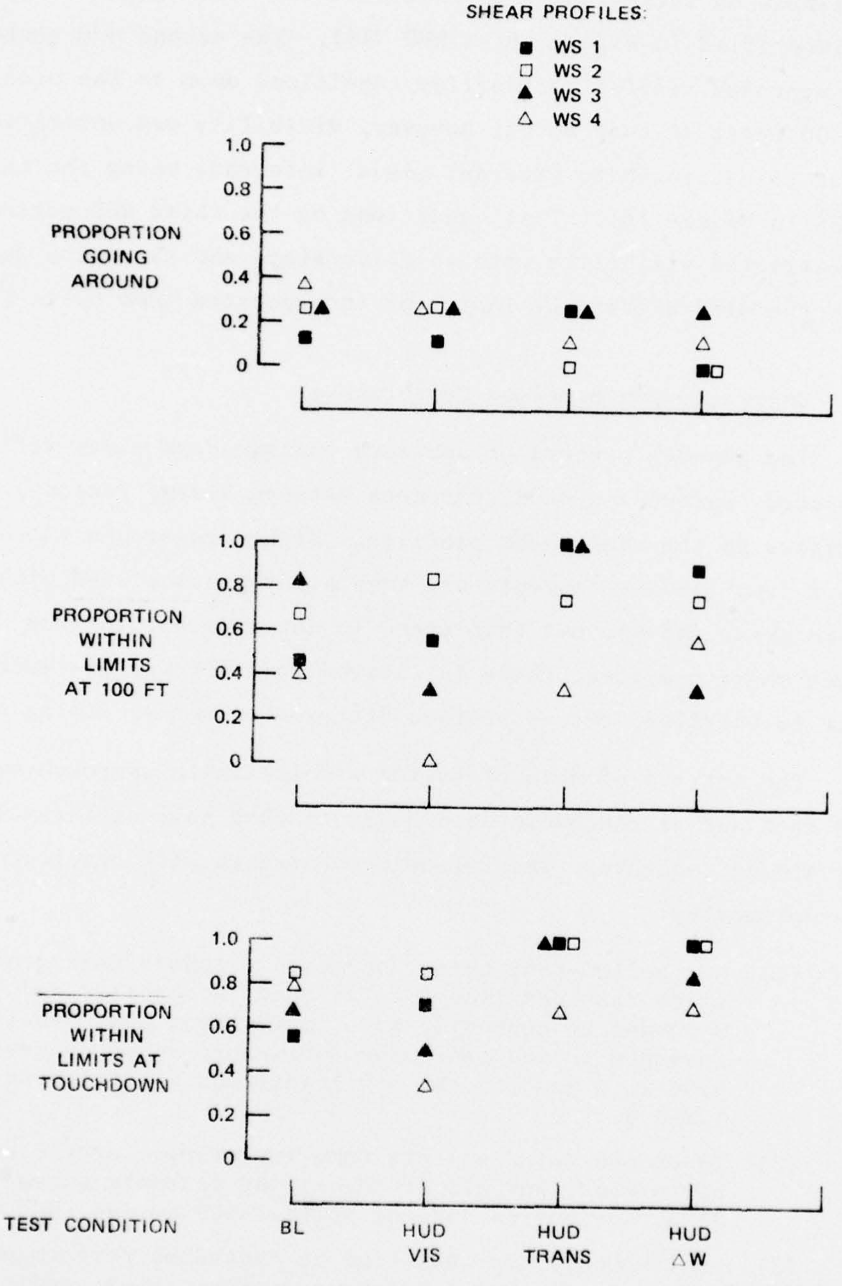

FIGURE 16 SUMMARY OF APPROACH OUTCOMES FOR HEAD-UP DISPLAY CONCEPTS

control throughout a night visual approach; no glide-slope guidance was available on these runs and visibility was unrestricted. (This condition is identified in Figure 16 as HUD VIS). The second HUD series was an ILS approach similar to baseline conditions down to the breakout altitude of 400 feet; at that point, however, visibility was unrestricted and the pilot transitioned to external visual reference using the basic HUD (HUD TRANS in Figure 16). Test conditions on the third HUD series were again unrestricted visibility with no glide slope and the pilot used the HUD with the Wind Difference Indicator incorporated (HUD ΔW in Figure 16).

E. Contrast with Baseline Performance

The general pattern of approach outcome data plots reflects the expected confounding of differences between aiding concepts with differences in the wind shear profiles. Higher go-around rates for the "head down" aiding concepts are consistently associated with the thunderstorm shear (WS-4), but this trend is not apparent for the HUD. For the other shear profiles, there is a trend toward lower go-around rates relative to baseline, but no obvious differences across aiding concepts.

The pattern of data plots for within-limits approach outcomes at 100 feet and at touchdown does begin to show some differential effects for aiding concepts. The following contrasts with baseline performance are noteworthy:

(1) At the 100-foot point, approach outcomes were generally worse than baseline for the Shear Advisories and VSI-Groundspeed concepts; some improvement over baseline performance is indicated for the Ground-Speed concept on profile 4 and for the HUD transition condition on shears 1 and 3.

(2) Touchdown data indicate some improvement over baseline performance for all of the aiding concepts except the Shear Advisories and the initial HUD series (HUD VIS).

(3) Improvements over baseline in touchdown performance appear to be most consistent (across shear conditions) and of greater magnitude for the VSI-Ground-Speed and HUD transition concepts, in that order.

(4) Touchdown performance was generally better than approach outcomes at 100 feet and less variable across shears; this indicates that pilots were often able to convert an out-of-limits approach to a within-limits touchdown.

F. Contrast with Pilot Assessments

The correspondence between approach outcomes and pilot ratings of the most helpful aiding concepts is quite good for the pilot's first and second choices. Performance using the top-rated Ground Speed display was not as good as the lowest rated VSI Ground Speed placard; considered together, however, these data plots indicate the potential effectiveness of providing ground-speed information to the pilot. A comparatively high proportion of within-limits landings is also indicated for the Wind Difference Indicator, especially when the head-up version is considered. High pilot ratings for VASI are also supported by the data plots shown earlier in Figure 14.

It is also of interest to note that the performance using the low-rated Shear Advisories was generally poorer than baseline. However, approach outcomes for the rejected panel display of flight-path angle (PNL FPA in Figure 15) were about the same as baseline. This result is consistent with the pilot reports that, for the most part, they did not use the head-down flight-path angle information.

The relative effectiveness of the candidate pilot aiding concepts can be summarized by considering the same over-all ratios of within-limits touchdowns as those used in Section IV-B to contrast alternative baseline conditions. These ratios relate the number of within-limits approach outcomes to the total number of approaches attempted across all four shear conditions. The number of within-limits landings recorded for the second baseline series (ILS-2) and for each of the candidate aiding concepts are as follows (corresponding percentages, shown in parentheses, are based on a total of 32 runs under each condition):

Baseline (ILS-2)	17	(53%)
Shear Advisory	13	(41%)
VSI-Ground Speed	20	(63%)
INS Wind Readout	21	(66%)
Ground Speed	21	(66%)
Wind Difference Indicator	21	(66%)
Panel Flight Path Angle	20	(63%)
HUD (Visual Approach)	15	(47%)
HUD (transition)	21	(66%)
HUD (Wind difference)	26	(81%)

V CONCLUSIONS AND RECOMMENDATIONS

The principal intent of this exploratory study, as stated in the introduction, was to provide an early determination of the need for improved cockpit aids and procedures for coping with low-level wind shear and to provide guidelines for the subsequent development and testing of promising pilot aiding concepts. Summary statements concerning the need for improvement and the outcome of the survey evaluation of candidate aiding concepts are given below as the conclusions of this phase of the investigation. Guidelines for subsequent evaluation and testing of these aiding concepts are then presented as recommendations for Phase 2.

A. Need for Improvement

Conclusions relating to the need for improved pilot aiding are as follows:

(1) Approach outcomes under baseline conditions indicate that pilots will not be able to cope successfully with the more severe low-level wind shears using existing flight instruments and procedures. Only 52% of the manually flown precision ILS approaches resulted in within-limits landings, and performance was slightly worse for the coupled approach and non-precision approach using the VDP procedure. Performance was somewhat better on the VFR approach using VASI (71% within-limits landings).

(2) Pilots are generally unfamiliar with the potential hazard of severe low-level shear. None of the evaluation pilots in this study, with pilot-in-command time averaging about 15,000 hours, had experienced shear conditions as severe as those represented in the simulation. It is also instructive, in this regard, to note that the availability of wind-shear advisories, alerting the pilots to the presence of substantial changes in wind speed and direction on the approach, did not produce any improvement in either approach outcomes (they were slightly worse) or approach management.

B. Outcomes of the Aiding Concept Evaluation

The following are the conclusions regarding evaluation of the aiding concepts:

(1) Based on pilot assessments, the most promising aiding concept was the display of ground speed in close association with the airspeed indicator.

(2) Pilots also expressed a high regard for the Wind Difference Indicator, especially when this information was presented in the head-up display.

(3) The availability of some form of vertical flight-path guidance and airspeed management information in the HUD was considered to be very helpful by most of the pilots. However, flight-path angle and potential flight-path angle, as represented in the HUD simulation, were generally regarded as unacceptable because of excessive activity of the display elements in turbulence and shear and because of the difficulties of interpreting the information provided.

(4) The panel display of flight-path angle and potential flight-path angle was generally regarded as useless, primarily because of discrepancies in the location and readability of the display but also because of difficulties in interpreting the information and applying it to the wind-shear problem.

(5) Wind-shear advisory messages were assessed as a sound operational concept (pilots wanted them provided in the operational situation), but they were considered to be too complex and unclear to be useful. Changes in format and language were strongly recommended.

(6) Approach outcome data generally supported the pilot assessments. However, differences in performance across aiding concepts did not appear to be significant except for the comparatively poor performance with the shear advisories and initial runs using the HUD.

(7) All of the aiding concepts examined provided some information that the pilots could use to anticipate wind shear and/or to detect the effects of the shear during the encounter. However, with only one exception (the Wind Difference Indicator), no explicit guidance was provided to the pilots for using the information for planning the approach, assessing the progress of the approach, or taking corrective actions. Pilots reported little difficulty in understanding the basic concepts, but they did not have time to develop a method of using the information displayed to do a better job of coping with wind shear.

C. Recommendations for Phase 2

The following are the recommendations for further development of the aiding concepts in Phase 2:

(1) Continue the development and testing of panel displays of ground speed and wind difference as the most promising near-term aiding concepts.

(2) Further development of the flight-path angle and potential flight-path angle should be carried out analytically and with simulation to resolve the problem of the excessive activity and incorrect readings in turbulence and vertical wind shear.

(3) Develop explicit pilot procedures for using any aiding concept selected for Phase 2 evaluation before additional simulator testing is scheduled.

(4) Continue the development of wind shear advisories as a "hazard alert" message that will be available to pilots whenever weather conditions in the vicinity of the approach or takeoff flight path are anticipated; revisions to the format and language should be oriented toward alerting the pilot to the location of significant shear (position and altitude) and expected effects (e.g., magnitude of airspeed loss) rather than a description of the wind velocity profile.

D. Concluding Remarks

One of the more significant observations of Phase 1 testing was that the evaluation pilots did not expect shears of the difficulty or intensity of those used in the program. As one team member said, "Shears of this magnitude are not only not *expected*, they are not generally *imagined*."

It is therefore recommended that airline training programs incorporate exposure to severe shears, and that this exposure include shears of such nature and intensity as to dictate a go-around decision. The rationale for this recommendation is twofold: (1) Airline pilots should be aware of the intensity and aerodynamic effects that characterize severe shear environments, and (2) the training process should emphasize the fact that a decision to go-around is appropriate in the presence of some shears.

It is further recommended that airline training programs specifically treat aerodynamic effects of shear. We heard a number of evaluation pilots complain of sluggish response to throttle inputs in the simulator; we feel that the shear effects may have been responsible for the "sluggish" acceleration. The pilot may have been unable to distinguish between these aerodynamic effects of the shear environment and the response of the simulator thrust computation itself.

Crew coordination is an important factor that was not fully explored in this study. Evaluation pilots often expressed the desire to have the first officer relay display information, such as speeds, altitudes, winds, errors, and so forth. Clearly, such callouts require planning and coordination, both to ensure a reliable and timely flow of information to the pilot flying and to ensure that at least one pilot still has sufficient time head-up to permit visual detection of cues and/or other aircraft. However, simply shifting part of the instrument scan to the first officer may not be an optimal way of unburdening the pilot flying when low-level shear occurs in the range of altitudes at which the crew is "going visual"--i.e., looking for or flying with reference to outside visual cues. The onset of a shear is more detectable on instruments than by unaided visual reference, and it therefore seems necessary that crew procedures be designed to ensure that one pilot is always on instruments for earliest detection of the shear.

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