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AIRBORNE AIDS FOR COPING WITH LOW-LEVEL WIND SHEAR. (U)

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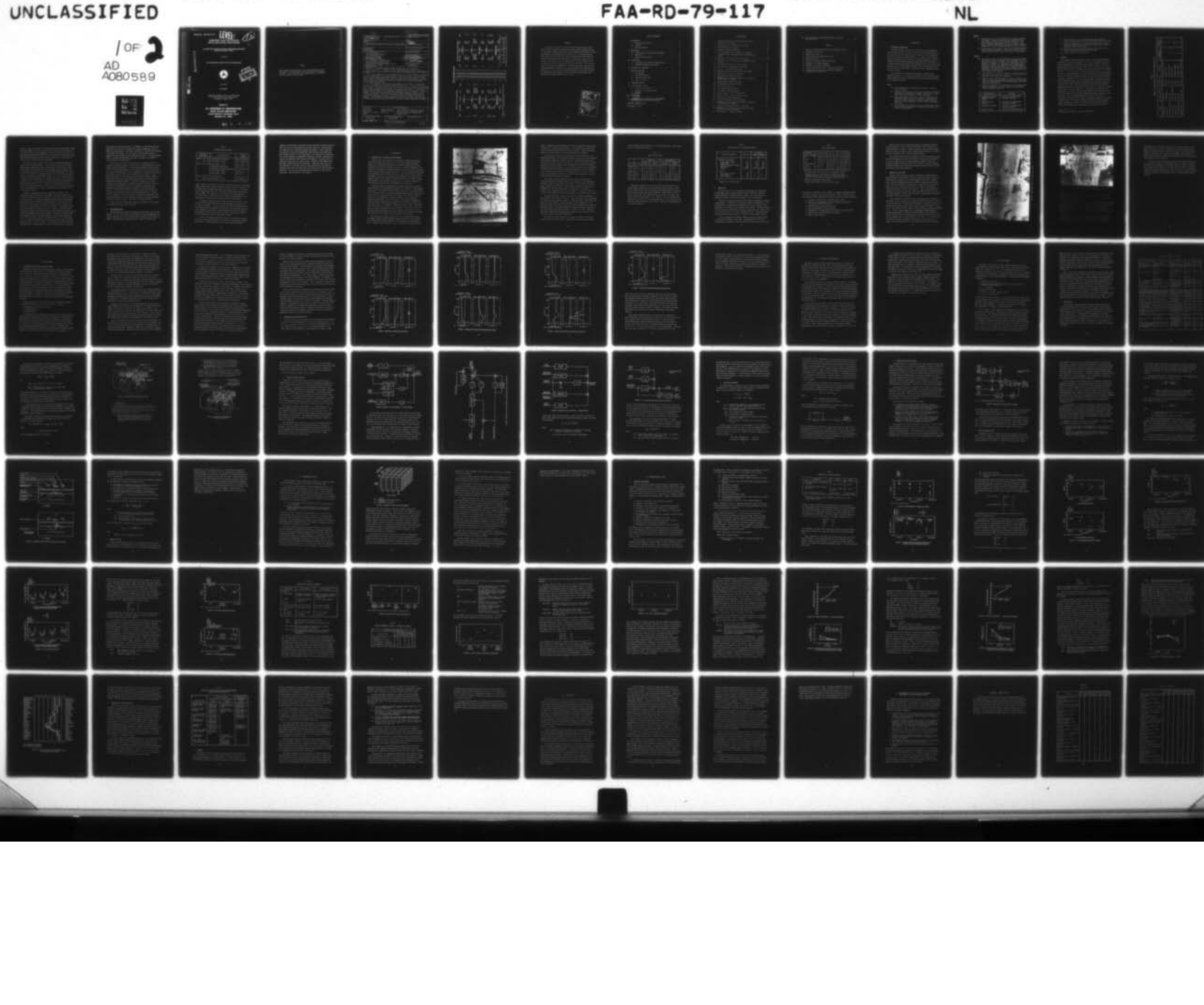

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Report No. FAA-RD-79-117

LEVEL II

AIRBORNE AIDS FOR COPING WITH LOW-LEVEL WIND SHEAR

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

W.H. Foy

SRI INTERNATIONAL, MENLO PARK, CALIFORNIA 94025

July 1979

Final Report

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

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Technical Report Documentation Page

1. Report No. 18 FAA-RD 79-117	2. Government Accession No.	3. Recipient's Catalog No. 11
4. Title and Subtitle 6 AIRBORNE AIDS FOR COPING WITH LOW-LEVEL WIND SHEAR.		5. Report Date Jul[redacted]79
		6. Performing Organization Code
7. Author(s) 10 W. H./Foy		8. Performing Organization Report No. SRI Project 4364
9. Performing Organization Name and Address SRI International Aviation Systems Laboratory 333 Ravenswood Avenue Menlo Park, CA 94025		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 15 DOT-FA75WA-3650
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered 9 Final Report. June[redacted]975-Jul[redacted]979
		14. Sponsoring Agency Code FAA/ARD-740

15. Supplementary Notes

Prepared on ALL-WEATHER LANDING SYSTEMS, Engineering Services Support, Project 4364, Task 2. Work done by SRI, Bunker Ramo Corp., Collins Div. of Rockwell International, Douglas Aircraft, NASA Ames Research Center, and Boeing Co.

16. Abstract

This report summarizes the development and test of airborne displays, instrumentation and procedures for aiding an airline jet-transport pilot to cope with wind shear on approach-and-landing and on takeoff. The task involved analysis of wind-shear effects, development of wind models including shear and turbulence, specification of displays and instrument models, and conduct of six large-scale piloted flight-simulation exercises.

A set of candidate standard wind-shear models was developed. The beneficial effects of training in a moving-base simulator were noted. In tests on both wide-bodied (DC-10) and nonwide-bodied (B-727) airplanes, and both precision and localizer-only approach, conventional instrumentation was found inadequate for coping with wind shear. Many instruments and techniques, including head-up displays, were tested. Ground speed was found to be an important additional item of information. A system, "MFD/ΔA," consisting of acceleration and ground speed augmented flight director, acceleration-margin criterion for advising go-around, and minimum-height-loss go-around pitch steering, was found to solve the wind-shear problem on approach and landing. Test procedures and requirements for device qualification were developed. No instrumentation was found that aided in coping with severe wind shear on takeoff.

17. Key Words	18. Distribution Statement
Wind fields, Wind shear, Approach and landing, Takeoff, Flight simulation, Airborne instrumentation	This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	98	

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METRIC CONVERSION FACTORS

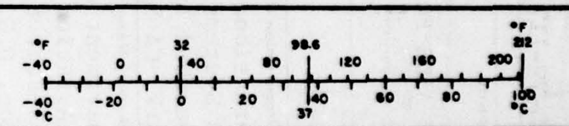
Approximate Conversions to Metric Measures

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

*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

The purpose of Task 2 of the All-Weather Landing Systems (AWLS) project was to develop and implement a manned flight-simulation program to investigate terminal flight operations, emphasizing wind-shear effects, and determine the operational and technical role of head-up displays. This final report describes the results obtained by the AWLS team--SRI International, Bunker Ramo Corporation, and Collins Avionics Group of Rockwell International--on the capabilities of certain aiding concepts to assist the pilot in coping with low-level wind shear. The aids were based on airborne instrumentation. The aiding systems tested included approach-management techniques, go-around decision aids, techniques for assisting the pilot during the go-around maneuver, and head-up displays. The sponsoring organizations were FAA Wind Shear Program Office and ARD-740; the Technical Monitor was W. J. Cox.

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I INTRODUCTION

A. Program and Objectives

The FAA Wind-Shear Program has the objectives of examining the hazards associated with low-level wind shear, developing solutions to the wind-shear problem, implementing the solutions, and integrating them into the National Airspace System. In support of this program, potential solutions in the category of airborne equipment were investigated by the All-Weather Landing Systems (AWLS) team under Task 2 of a contract from the FAA Approach and Landing Division. The Task 2 team consisted of SRI, Bunker Ramo Corporation (BR), and Collins Avionics Group of Rockwell International. The AWLS contract Statement of Work for Task 2 follows.

The Contractor shall develop and implement a manned flight-simulation program to: investigate terminal flight operations, emphasizing wind-shear effects, and determine the operational and technical role of head-up displays.

Phase 1

(a) Review related prior developments and studies. Analyze existing systems.

(b) Identify potential benefits, basic requirements, and inherent advantages or disadvantages for HUD as they relate to wind-shear effects on terminal-area flight operations.

(c) Prepare and submit for approval a plan for simulation test experiments which provides an evaluation of the potential utility of flight procedures, displays (head-up and head-down) and control techniques to aid the pilot in wind-shear encounters.

(d) After approval of the Phase 1 Plan by the Contracting Officer, lease the required simulator and supporting facilities, and conduct the experiments.

Phase 2

(e) Upon approval by the Contracting Officer, prepare and submit for approval a plan for simulation-test experiments which will examine in detail those potential solutions to wind-shear encounters identified as a result of Phase 1. (The Phase 2 simulation experiments may include head-up displayed information if found to provide promising results in Phase 1.)

(f) After approval of the Phase 2 Plan by the Contracting Officer, lease the required simulator, supporting facilities, and required display aiding devices, and conduct the experiments.

Phase 3

(g) Upon approval of the Contracting Officer, prepare and submit for approval a Plan for simulation-test experiment which will provide an evaluation of a HUD. These experiments should be designed to evaluate, as completely as simulation state-of-the-art will permit, the advantages and/or disadvantages of head-up displays as they relate to low visibility landing operations. The Plan should include specifications for a HUD including a description on the manner in which the HUD will be installed in the simulator.

(h) After approval of the Phase 3 Plan by the Contracting Officer, lease the required simulator, supporting facilities, and required HUD, and conduct the experiments.

(i) Analyze the data from experiments. Potential benefits, advantages, and/or disadvantages of procedures and instrumentation, including HUD, shall be identified together with their appropriate explanations.

(j) Develop a comparison of effectiveness of the following wind-shear aiding concepts for wide-bodied and nonwide-bodied turbojet transport airplanes.

System/Concept	Maneuver
Airspeed/Ground Speed Concept of Speed Control	Precision and Nonprecision Instrument Approach
Modified Flight Director	Precision and Nonprecision Instrument Approach
Acceleration Margin	Precision and Nonprecision Instrument Approach
Angle of Attack	Take-off and Missed Approach

(k) Determine effects on the Airspeed/Ground Speed concept of using a landing runway with not less than 5000' density altitude.

(l) Determine suitability of the Modified Flight Director using a synthesized glide slope established with range rate, altitude change rate and initialization.

(m) Develop test procedures and performance requirements for airborne wind-shear aiding device qualification.

(n) Prepare and submit a final report.

B. Approach

In accordance with the Statement of Work, the investigations were concerned with airline transport jet aircraft. The approach was to give primary consideration to the lowest-cost candidate aiding concepts to ensure that any potential solution would be cost effective. The project task included the test of airplane control laws, the analysis of airplane responses to wind shears, the development of wind models, the determination of the hazards presented by various wind fields, and the development and test of various instruments intended to aid the pilot in coping with wind shear. The majority of the effort was spent on a series of piloted flight simulation tests. Table 1 summarizes these simulation exercises that have been sponsored under the FAA Wind-Shear Program. Except for the 1978 DC-10 trial, these tests formally treated only the precision-approach problem--i.e., approach and landing with full Instrument Landing System (ILS). The first exercise,[1*] conducted by the AWLS team, was exploratory in nature; a DC-10 training simulator was supplied and supported by Douglas Aircraft Company, McDonnell-Douglas Corporation, under subcontract. The FAA Simulation Branch, ARD-540, did a similar exploratory study with a B-737 model in the Flight Simulator for Advanced Aircraft (FSAA) at the National Aeronautics and Space Administration's (NASA) Ames Research Center. The aiding techniques showing the most promise and potential cost effectiveness were tested in our Phase 2

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*References are listed at the end of this report.

Table 1

SUMMARY OF WIND-SHEAR PILOTED FLIGHT-SIMULATION TESTS

Period	Test Conductor	Aircraft	Simulator	Number of Wind Profiles	Number of Pilots
Apr-May 1976	SRI, BR	DC-10	Douglas, Training	4	8
July 1976	FAA ARD-540	B-737	NASA, FSAA	3	11
Nov 1976-Jan 1977	SRI, BR	DC-10	Douglas, MBDFS	4	16
July-Aug 1977	SRI, BR, ARD-540	B-727	NASA, FSAA	12	7
Sept-Oct 1977	SRI, BR	DC-10	Douglas, MBDFS	8	8+26
Nov 1978-Jan 1979	SRI, BR	DC-10	Douglas, MBDFS	15	20
May-June 1979	SRI, BR, FAA	B-727	Boeing, M-Cab, HUD	10	12

exercise[2] with a DC-10 model in the Douglas Moving-Base Development Flight Simulator (MBDFS). In July and August 1977, a ground-speed display and the modified (acceleration-augmented) flight director were tested in an experiment conducted by FAA ARD-540, SRI, and BR with a B-727 model in the FSAA at NASA Ames Research Center, using a large set of wind profiles. A report on the results has been published.[3]

In Autumn of 1977, a Phase 3 test of DC-10 aiding techniques was conducted in the Douglas MBDFS. This involved a set of wind profiles significantly expanded over those used in earlier DC-10 tests. Eight pilots took part in initial trials of candidate aiding techniques, and an especially large group (26) of subject pilots participated in a "Full Trial" of the three most promising systems. In these trials an aiding "system" incorporated ground-speed information, flight-steering guidance, a thrust-control function, and an automatic warning (or advisory) that a go-around should be initiated. The overall performance was marginal; it would have been adequate if the subject pilots had always chosen to honor the go-around advisories. However, the rate of nuisance alarms on the go-around warning was too high. Improvement of the go-around decision aids was needed.[4]

The Phase 4 simulation exercise, conducted in November 1978-January 1979, again at Douglas in the MBDFS, involved validation tests of systems developed from the techniques that had shown the most promise in previous tests. Two approach-and-landing situations were simulated, using manual control assisted by flight director. The first was a precision (full ILS) approach in Category I visibility to an 11,500-foot runway at 5,300-foot altitude, 95° air temperature. The systems tested were MFD/ΔA (modified steering and thrust commands on flight director, acceleration margin for go-around advisory, and modified go-around steering command) and GNS/RED (dual-pointer display of airspeed and ground speed with compatible thrust command, alphanumeric microcomputer display for go-around, and modified go-around steering command). The second situation was a nonprecision approach (localizer only) with 400-foot ceiling, 5,000-foot RVR, to the same runway. The systems tested were MFD/ΔA and GNS/MF/R (same as GNS/RED except for modified flight director steering), both using a synthetic glide path. Performance of both aiding systems was better than baseline (conventional) approach management, and the MFD/ΔA was good enough to constitute a solution to the wind-shear problem on approach and landing. In a third test, takeoff trials were run against five wind profiles by the three project pilots. No good airborne means of coping with wind shear was found. A report on the Phase 4 DC-10 results is in publication.[5]

The last major activity of this task was a simulation exercise conducted in May-June 1979 by the AWLS team at Boeing Commercial Airplane Company, Renton, Washington. A piloted flight-simulator study was run in a B-727 fixed-based simulator to evaluate the potential contribution of a head-up display (HUD) to pilot management of an approach and landing when various types of low-level wind shear are encountered. Twelve experienced subject pilots flew simulated approach scenarios under both VMC and IMC conditions, using experimental HUD formats derived from a Boeing HUD development program. A baseline condition for the HUD evaluation was established by having the same pilots fly the approach scenarios using standard B-727 panel instruments, augmented with a ground-speed management technique developed in previous wind-shear studies. The test HUD formats were generally regarded as helpful for both detecting wind-shear effects and providing guidance for control actions. However, test results showed no substantial improvement over baseline performance in either approach outcomes or approach management during the shear encounters. This report[6] is being published.

Table 2 shows the relationship between the phases of the Statement of Work and the various task activities.

C. Task Organization

The FAA Wind-Shear Program is under the supervision of Mr. H. Guice Tinsley. Lt. Col. Larry Wood, USAF and FAA, is the program manager for airborne systems. Mr. W. Joe Cox was the FAA technical officer for this effort. The AWLS project supervisor was Mr. Dean F. Babcock (SRI).

Table 2

SUBTASKS AND ACTIVITIES

Statement of Work Items	Task Activities	Period of Work
Phase 1 (a), (b)	Preliminary HUD studies	June 75-Feb 76
(c), (d)	DC-10 Phase 1 Tests	Dec 75-July 76
Phase 2 (e), (f)	DC-10 Phase 2 tests	Aug 76-Feb 77
	Wind-model development	Mar-July 77
	Wind-shear hazard determination	June 77-Jan 78
	B-727 tests at NASA	Apr-Aug 77
	DC-10 Phase 3 tests	Apr-Nov 77
Phase 3 (g)-(i)	B-727 HUD tests	Jan-July 79
(j)-(m)	DC-10 Phase 4 tests	Apr 78-Mar 79

Task 2, Phase 1, was led by Mr. Walter B. Gartner (SRI) and in subsequent phases was led by Dr. Wade H. Foy (SRI) with Mr. Gartner's support. On the AWLS team, the Bunker Ramo (BR) effort was led by Dr. A. C. McTee; he was supported by Capt. W. O. Nice and, after November 1976, by Col. Don M. Condra. The supervisor of the work at Collins-Rockwell was Mr. James Foster. At SRI, Mr. David W. Ellis was responsible for the development of the wind-shear models and hazard determination.

The Douglas simulation support effort for the DC-10 Phase 1 tests was led by Mr. Warren Stephens; on subsequent phases the leader was Mr. John D. McDonnell. In the B-727 tests at NASA Ames Research Center the supervisor of the responsible section was Mr. Jack Cayot, FAA; the B-727 simulation was based on an approach-and-landing model developed at Boeing by a team led by Mr. Dave J. Clymer. The Boeing effort on the B-727 HUD tests was led by Mr. Wayne D. Smith.

In each of the flight simulation exercises the FAA made a general selection of the aiding concepts to be tested and selected the simulation facility. SRI wrote detailed test plans, developed detailed simulator specifications, developed with BR assistance detailed specifications for the test instrumentation and data collection, and negotiated the subcontract for simulation support when needed. Collins developed the modified (acceleration-augmented) flight director algorithms that were tested in several of the experiments. The simulation subcontractor (or facility manager) programmed the simulation computer, installed the special instrumentation and operated the simulator. The FAA, with BR assistance, recruited the subject pilots. BR and the FAA handled pilot briefing, familiarization, and debriefing. During the test runs, BR was responsible on the AWLS team for test direction and furnished the observer pilots, who also played the first-officer role; SRI and Collins monitored. The test data were analyzed and evaluated by SRI with BR assistance. SRI produced the test reports.

II SIMULATORS

A. Douglas DC-10, Training and Development

Phase 1 tests were conducted at the Douglas Flight-Crew Training Center, Long Beach, California, using the DC-10 training simulator, modified 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. The simulator is mounted on a six-degree-of-freedom motion base and is coupled with the Vital III visual system, 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, and 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 1,600 feet.

The DC-10 tests, Phases 2-4, were run on the Douglas Moving Base Development Flight Simulator (MBDFS), shown in Figure 1, which consists of a modified DC-10 cockpit mounted on a six-degree-of-freedom moving base. A Redifon Visual system was used to represent the external visual

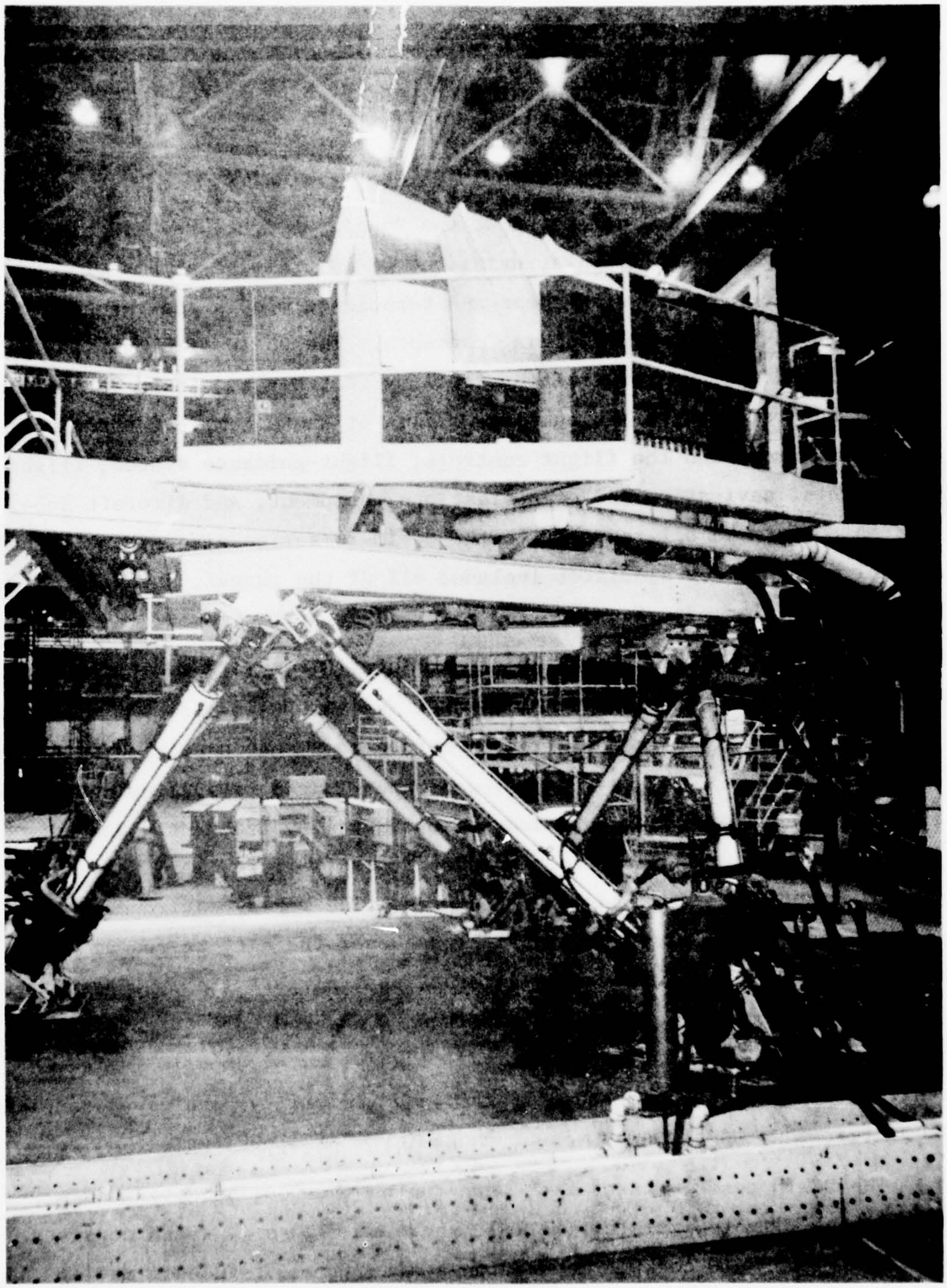


FIGURE 1 DOUGLAS MOVING-BASE DEVELOPMENT FLIGHT SIMULATOR

scene. Programs for data acquisition and DC-10 equations of motion were mechanized on a Sigma-5 hybrid computer. The simulation was modified to include specified wind-shear and turbulence models. Cockpit instrument panels were reconfigured to include the experimental displays.

The modified DC-10 cockpit contained Captain, First Officer, and Instructor stations. The Instructor station, located aft of the Captain's station, was equipped for selection of test conditions and control of mission start, reset, and position freeze. Subject pilots flew simulated approach or takeoff sequences from the Captain's station with the basic configuration shown in Figure 2. All flight controls, flight instruments, guidance systems, and aircraft subsystems necessary for the performance of the studies were provided at the Captain and First Officer stations. Except for experimental displays, installed cockpit equipment conformed with standard DC-10 aircraft equipment.

The Sigma-5 provides program control of data collection and of simulated aerodynamic response, winds, and turbulence, with appropriate parameter values obtained from lookup tables. Wind profiles and turbulence conditions represented in the simulation were noted during each simulator run, and were shown together with aircraft variables of interest on a multichannel strip-chart recorder; at the end of each run a "quick look" summary was provided by output on the computer line printer.

The external visual scene was generated by a Redifon rigid-model system with a scale factor of 750 to 1. The visual scene was represented by a 620-line color television image, and was displayed by high-resolution monitors viewed through a special Douglas Aircraft assymmetric lens. The Captain and First Officer stations were each equipped with a separate monitor and lens. The visual system had a maximum approach distance of 2.25 miles and an eye-altitude range of 725 feet to 15 feet. Approach and strobe lighting were realistically simulated under variable ceiling and runway visual range (RVR) conditions.

The simulator had six degrees of freedom, provided by a six-jack (Franklin Institute) motion base. Motion was controlled from a ground control station located adjacent to the cockpit/platform. Motion capability is summarized in Table 3.

Table 3

MBDFS MOTION LIMITS

Axis	Excursion	Velocity: Payload 20,000 lb	Velocity: Payload 3,600 lb	Acceleration: Payload 20,000 lb	Acceleration: Payload 3,000 lb
Heave	±42 in.	±39 in./s	±40.5 in./s	±1.65 g	±1.65 g
Sway	±67.5 in.	±67 in./s	±72.3 in./s	±1.43 g	±2.25 g
Surge	±65 in.	±71 in./s	±71.6 in./s	±1.50 g	±2.6 g
Roll	±30.7°	±35.6°/s	±36.2°/s	±7.8 rad/s^2	±7.8 rad/s^2
Pitch	±33.3°	±33.6°/s	±32.0°/s	±7.8 rad/s^2	±7.8 rad/s^2
Yaw	±38.7°	±36.3°/s	±40.3°/s	±7.9 rad/s^2	±7.8 rad/s^2

Equations of motion for the DC-10 series aircraft provided continuous flight simulation over the low-speed flight envelope. Table lookup functions were used for nonlinear aerodynamic data such as lift, drag, rolling, yawing, and pitching moments. Ground effects on aerodynamic coefficients were simulated over the entire flap range. Nonlinear lateral control spoilers were included. Control surfaces were simulated as either first- or second-order systems, with dead zones and position limits included for all surfaces. Basic DC-10 characteristics are listed in Table 4.

Table 4

CHARACTERISTICS OF SIMULATED AIRCRAFT

Aircraft Parameters	DC-10-10	B-727-200	
		NASA	Boeing
Approach and Landing			
Gross weight (klbs)	350	140	140
Flaps (deg)	50	30	40
Center of Gravity (% MAC)	20	25	20
V_{ref} (knots)	136	127	124
Engines	CF6-6D	JT8D-7	JT8D-9
Takeoff			
Gross Weight (klbs)	375*	--	--
Flaps (deg)	22	--	--
V_2 + 10 (knots)	158	--	--

*Phases 1 and 3 had 400 klbs.

B. NASA B-727

The 1977 test of a B-727 airplane in wind shear was conducted at the NASA Ames Research Center, Moffett Field, California, using the Flight Simulator for Advanced Aircraft (FSAA). The cockpit was configured as a Boeing 727-200 for this phase of the test program.

The FSAA is a general-purpose aircraft simulator designed to provide a high degree of flexibility in satisfying research requirements. It is equipped with a six-degree-of-freedom motion base and a visual flight attachment for representing the external visual scene. Aircraft equations of motion and data acquisition programs are implemented on a Sigma 8 computer located nearby in a central computing facility. Simulator motion capabilities are listed in Table 5. Range of lateral motion is wide.

A full, six-degree-of-freedom, nonlinear equation workup was used to obtain B-727 dynamics on the FSAA. Representative B-727 flight instruments were installed on the captain's instrument panel and modified

Table 5

FSAA MOTION LIMITS

Parameter / Axis	Displacement*	Velocity†	Acceleration‡
Roll	±0.663 rad	±1.75 rad/s	±2.09 rad/s^2
Pitch	±0.349 rad	±1.01 rad/s	±2.62 rad/s^2
Yaw	±0.436 rad	±0.90 rad/s	±1.68 rad/s^2
Longitudinal	±3.45 ft	±7.0 ft/s	±8.0 ft/s^2
Lateral	±40.0 ft	±28.6 ft/s	±8.0 ft/s^2 §
Vertical	±4.2 ft	±8.6 ft/s	±12.0 ft/s^2

*Maximum displacement allowed by the parabolic limiter.

†Maximum velocity reached under a maximum acceleration starting from rest at one end of the available travel and driving into the parabolic limiter at the other end.

‡Maximum instantaneous acceleration.

§Track rubber damage is likely at these values.

as required to include the test concepts. A complete mathematical model of the B-727 dynamics was supplied by Boeing. Table 4 has basic data. This nonlinear model included such details and features as the following:

- Accuracy of model for all airspeeds down to stall
- Variations in aerodynamic forces and moments as functions of α,β, and control deflection
- Ground effects, varying with altitude
- Lateral/longitudinal coupling effects
- Aerodynamic force and moment variations with flap deflection
- Control wheel force/displacement functions
- JT8D-7 engine dynamics.

Subject pilots flew the simulated approach and landing sequences from the Captain's station, using the instrument panel and control configuration shown in Figure 3. Centered around a Collins FD-109 flight-director system, the panel included a Mach/airspeed indicator, barometric and radar altimeters, and a vertical-speed indicator.

The external visual scene was displayed on color TV monitors located at both the Captain's and the First Officer's stations in the simulator. The terrain model used for this experiment was scaled at 600:1 and included an airport with an 8,000 by 200-ft runway. Approach lighting, including strobes, was realistically represented under variable ceiling and runway visual-range conditions.

C. Boeing B-727 with HUD

The B-727 HUD evaluation study was conducted at Boeing's Renton Flight Simulation Center (RFSC) using the fixed-base "M-cab" and associated simulation computers and visual-simulation facilities. Subject pilots flew the simulated approach and landing sequences from the left seat of the M-cab (Captain's station) and a project pilot occupied the right seat on all training and data runs to conduct the simulation sessions and play the role of First Officer. The cab was configured to represent the control systems and flight instruments available in the B-727-200 airplane. Figure 4 shows the panel configurations and controls available at both pilot stations.

A Pilot Display Unit (PDU), leased from Sundstrand, was fitted to the subject pilot's station in the overhead installation shown in Figure 4 for the presentation of experimental HUD formats. The PDU is fitted to an adjustable tray and the solid optical block can be stowed when it is not in use. This unit provides a green, cursive display in a format determined by x-, y-, and z-input signals from a programmable symbol generator. A Sundstrand-developed Solid Optical Path HUD (SOPH) system was used to project a reflectively collimated image and provide a wide field of view. For the nominal pilot viewing distance of 6.25 inches, the instantaneous horizontal field was 30 degrees with both eyes scanning from left to right, and the binocular field of view with both eyes looking straight

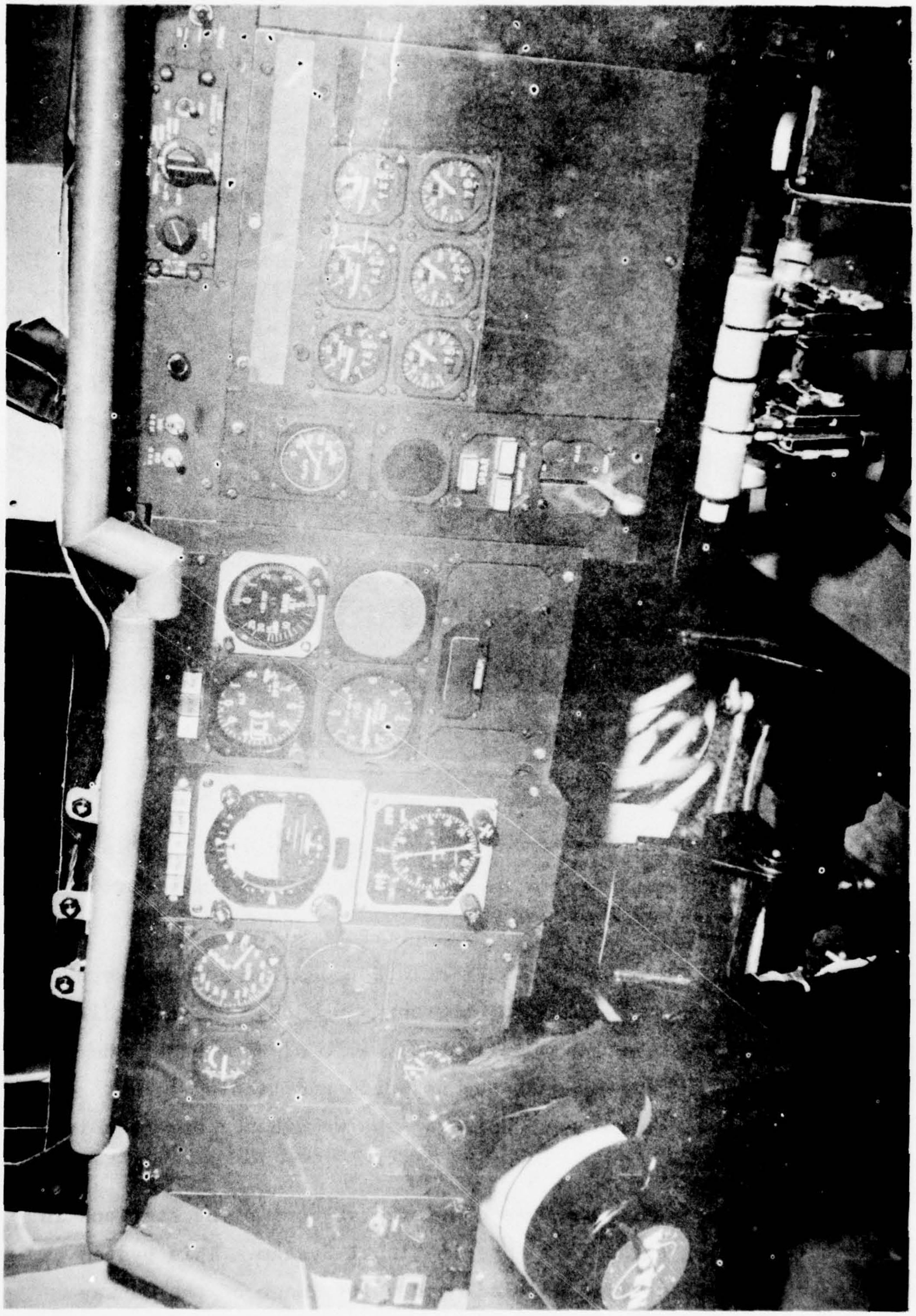


FIGURE 3 CONFIGURATION OF THE FSAA-PILOT'S STATION

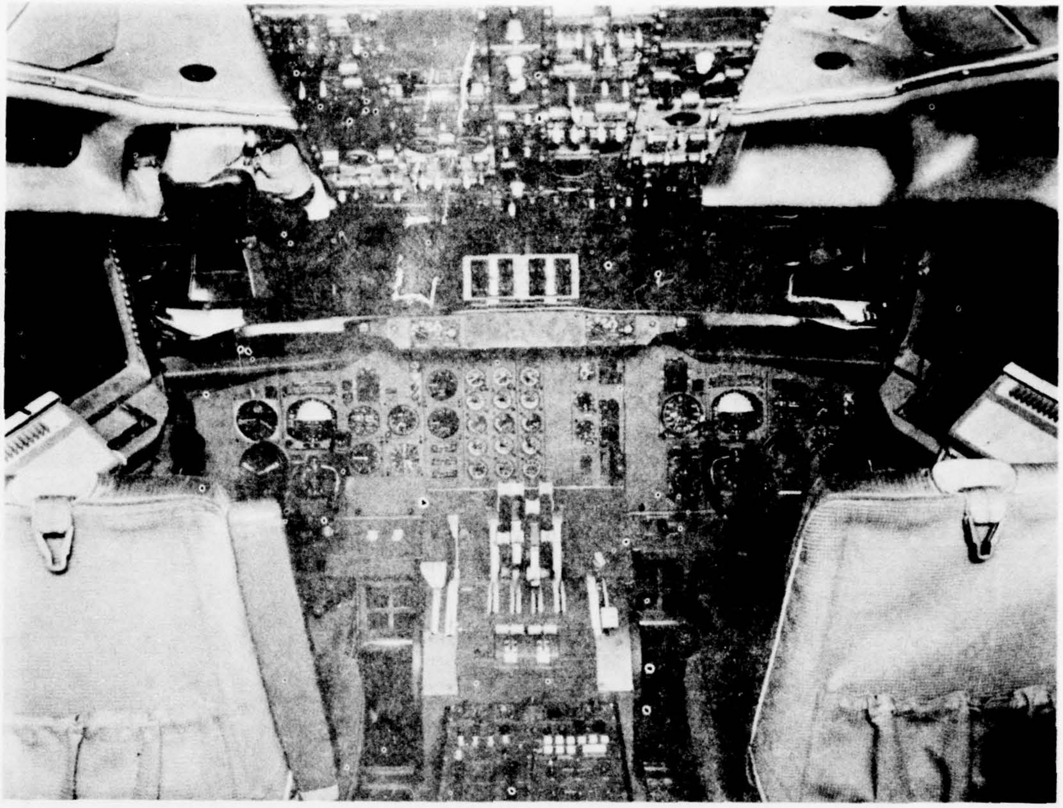


FIGURE 4 M-CAB B-727 PILOTS STATION

ahead is 16 degrees. The instantaneous vertical field of view is 15 degrees; with +1 and -0.6 inches of head movement, the total vertical field of view is 26 degrees.

The aircraft model used in the simulation was the Boeing-proprietary 727 Standard Simulation Model (SSM) currently used for 727 control-system studies. This model provided a full aerodynamic simulation of the B-727-200 with JT8D-9 engines for the approach and landing flight envelope (Table 4). Performance computations were based on a sea-level standard day.

The external visual scene was displayed at both pilot stations in the cab using Boeing's Phase II Interim-Visual System. This system provides an infinity collimated black and white image of the runway environment on two TV monitors mounted above the glare shield in the windscreen frame. The image is derived from a terrain model scaled at 1000:1 and represents a 200 × 10,000 foot runway. Approach and runway lighting, including strobe lights, were available and variations in runway visual range were simulated by adjusting the contrast and brightness controls on the TV monitors.

The aircraft model, wind models, display drive-signal computations, real-time data recording, and programmed choice of simulation scenario selections were implemented on the Harris computer system. An operator was available in the computer room during all test sessions to monitor simulator operations and selection of test conditions. Test HUD display formats and symbology were generated using the Boeing ADDS-900 Symbol Generator.

III WIND MODELS

A. Development and Severity Classification[7]

Wind shear encountered during approach and landing or during takeoff and climbout may result from one or a combination of different causes. Wind disturbances caused by topographical features such as buildings, trees, mountains, or valleys can manifest themselves as wind shear. Wind shear may be generated by the wake and vortex systems of other aircraft. Wind shear also may be due to meteorological factors arising from local weather phenomena or atmospheric conditions. Although wind shears caused by topography and wake turbulences may be severe and certainly impose constraints on terminal area operations, they are somewhat predictable. On the other hand, the really hazardous aspect of wind shears arising from meteorological conditions is that they are often neither predictable nor easy to detect. Moreover, the effects of a wind field will be highly dependent on the aircraft flight path and timing of the wind-shear encounter.

Three broad classes of wind conditions are now commonly recognized as significant producers of low-level wind shear. They are:

- Atmospheric boundary layer effects
- Frontal systems
- Thunderstorms.

In developing useful numerical models of winds associated with these conditions, SRI reviewed the literature and consulted a large number of meteorologists. Wind data came from tower measurements, accident reconstructions, and meteorological math models; the data for each situation were converted to a three-dimensional wind field programmed as functions of altitude and longitudinal position. A number of different wind profiles was produced from each wind field by varying the runway position relative to each wind field and, where applicable, by varying the parameters of the wind model. Care was taken to maintain realism. Some wind profiles for approach and landing, for example, were thunderstorm models constructed during the investigations of actual accidents. A useful and challenging profile for takeoff was constructed by taking a thunderstorm model and translating the storm center horizontally with respect to the simulated runway until the winds encountered presented hazardous conditions. Turbulence models, based on Dryden spectra, were developed for each situation, with the intensity and scale length for each of three components programmed as functions of altitude.

The method used for severity classification relied on a fast-time computer model that incorporated horizontal, vertical, and pitching motion (3 degrees of freedom) and used aircraft models flown with a pitch controller to maintain a reference airspeed. The model yielded consistent and reliable results that agreed substantially with piloted simulator results providing more comprehensive simulations.

The computer modeling techniques proved to be a valuable supplement to piloted simulator tests. In addition to providing comparisons of wind profile severity and data for case studies on the effects of wind shear, automated fast-time computer modeling enabled evaluation and refinement of techniques for coping with wind shear before the techniques were committed to costly piloted simulator tests.

Generally, the severity of wind-shear encounters was found to be highly dependent on the position and alignment of the approach path with respect to the wind field and on the timing of the encounter. The effects of wind shear on aircraft were dependent on aircraft configuration, engine response, control systems, and control technique. Prediction of the outcome when an aircraft encounters low-level wind shear in a complex wind field is thus difficult from knowledge of the wind field alone.

The aircraft models tested were affected by the vertical wind component as well as by wind shear in the longitudinal wind component. Yet for all wind profiles derived from measured data, the maximum shear (23 knots per 100 feet) was comparable in magnitude for vertical and longitudinal wind components. Shearing vertical winds were often accompanied by shearing longitudinal winds. In the high-severity wind profiles, the two wind components combined adversely to produce complex wind shear possessing greater hazards; in the low-severity wind profiles, no shear in the vertical component was present. Higher severity profiles were also found to contain reversals in wind shear direction.

The height and strength of the encounter is important to the successful detection and avoidance of severe wind shear. Wind shears occurring at low altitudes (from 100 to 300 feet) do not allow much time for detection and recovery. Severe wind shears occurring at higher altitudes may force a long landing because of overshoot during recovery; however, they allow additional time for the pilot to execute a go-around.

Severe wind shear was also found to be hazardous on takeoff. The hazards of wind shear encountered on takeoff are different in some respects from those encountered on approach and landing. For example, the departure path is steeper, and the effects are more localized. Because of the steeper path and higher airspeeds, the time of exposure to potentially hazardous shear is lessened. Measurement and prediction of potentially hazardous wind shear may be easier over the shorter time frame. On the other hand, on takeoff there is generally less reserve thrust available for recovering from a loss of airspeed induced by wind shear.

Of three broad classes of wind conditions (atmospheric boundary layer effects, frontal systems, and thunderstorms) the most severe wind-shear encounters occurred in wind fields produced by thunderstorms. Such wind fields are of complex form in which the wind profiles encountered by the aircraft vary greatly with distance. Large wind shears in both vertical and longitudinal wind components were found and they often occurred simultaneously. Reversals in wind-shear direction were common. In spite of the fact that a given wind field contained hazardous wind profiles, about 80 percent of the flights through the wind field at various glide path positions resulted in safe passage; i.e., their outcome was not adversely affected. The timing and positioning of the wind-shear encounters were hazardous to the aircraft in a comparatively small percentage of flights. The situation is complicated further because a thunderstorm system may contain several storm cells traveling at a rate sufficient to produce entirely different wind profiles to each aircraft in a landing sequence.

Wind profiles from frontal systems varied considerably in relative severity, but were generally lower in potential severity than wind profiles from thunderstorms. Less wind shear in the vertical wind component of frontal wind profiles was found, since frontal systems lack the downflow region found in thunderstorms. The frontal wind fields varied less with distance, were less dynamic and more predictable than wind fields attributed to thunderstorms. It is noted, however, that frontal systems are potentially very hazardous to aircraft operations. For example, a frontal profile may have moderate, sustained rates of shear with reversals accompanied by little or no turbulence. Thus, a moderate or high severity wind profile may not be detected until it is too late to avoid or recover from the effects of wind shear.

Wind profiles arising from atmospheric boundary-layer effects tested in this project ranked low in relative severity. The unstable, stable, and neutral categories of boundary layer winds contained no vertical wind component and no low-altitude reversals in wind shear direction. When constant surface friction velocity and surface roughness were assumed, the wind fields varied only as a function of altitude. The most hazardous category of boundary layer wind is the very stable case (low-level jet), which is characterized by potentially high shear rates and low-level reversals in wind shear direction. Although the low-level jet wind profiles tested ranked low-to-moderate in relative severity, potentially dangerous low-level jet winds are possible.

B. Candidate Standard Wind Models[7]

Over the course of our work more than 21 wind models were developed and used in various combinations in the piloted simulation tests. Of these the seven shown in Figure 5 were chosen and recommended to the FAA as candidate standard wind profiles for system qualification. The figure shows the wind components as encountered on an ideal 3° glide

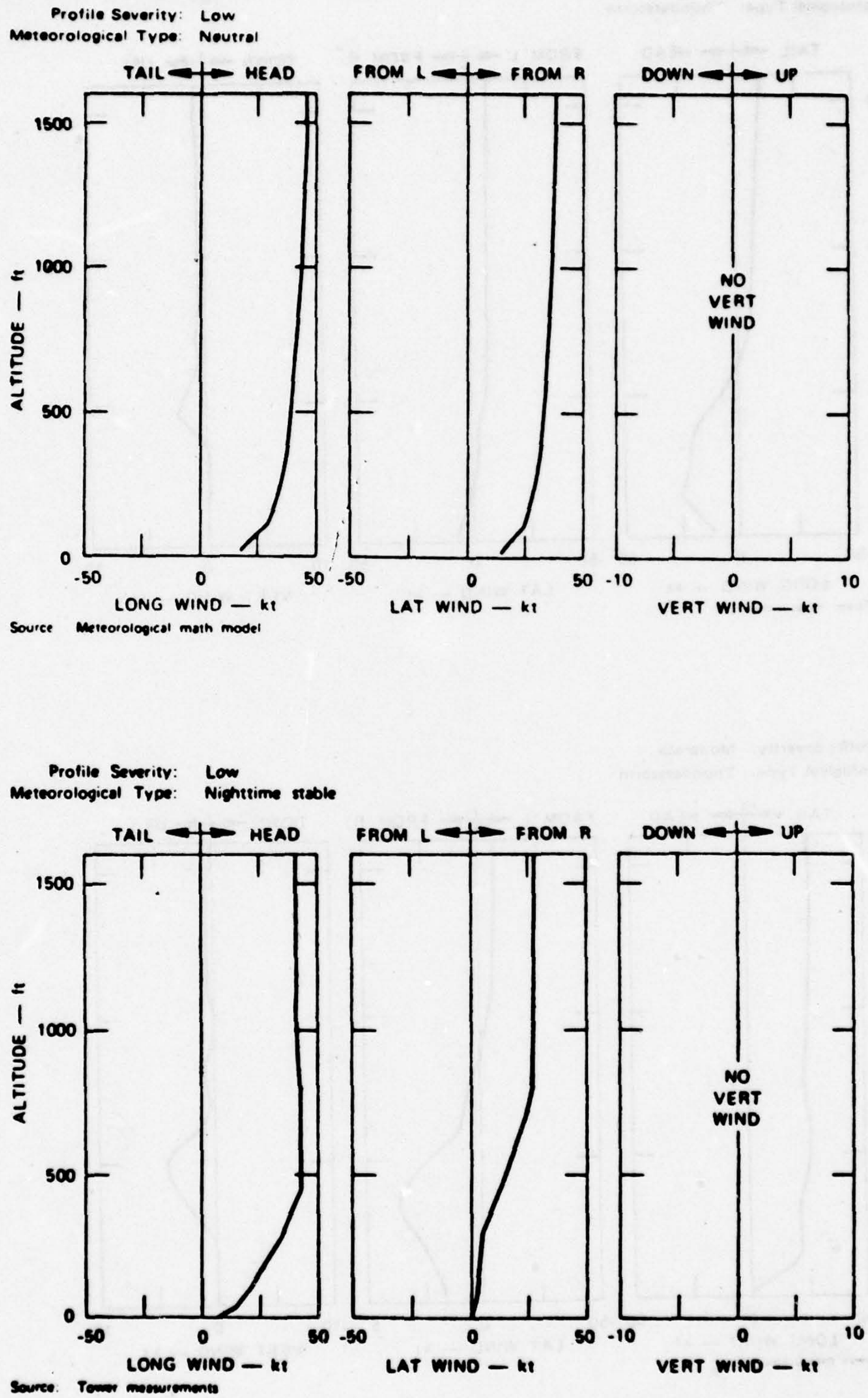
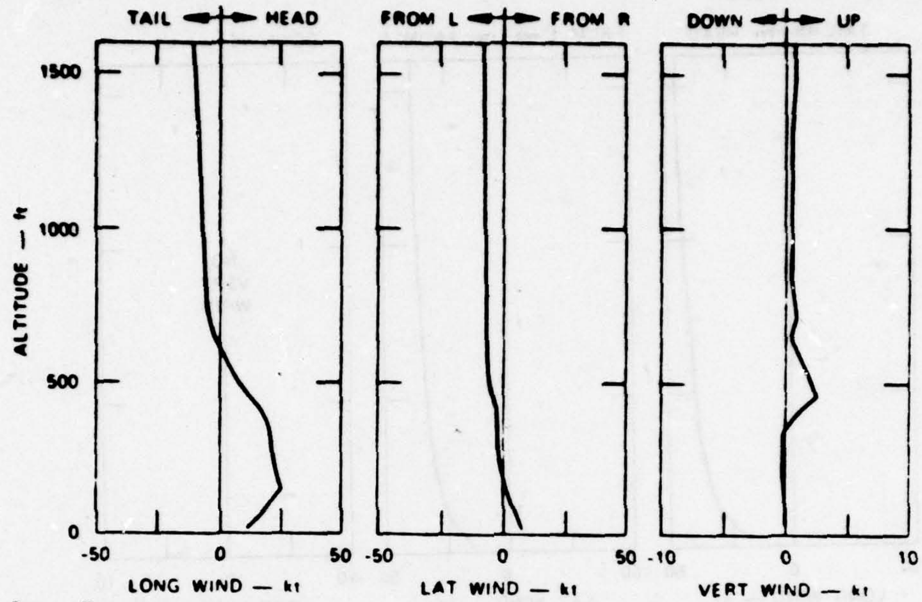


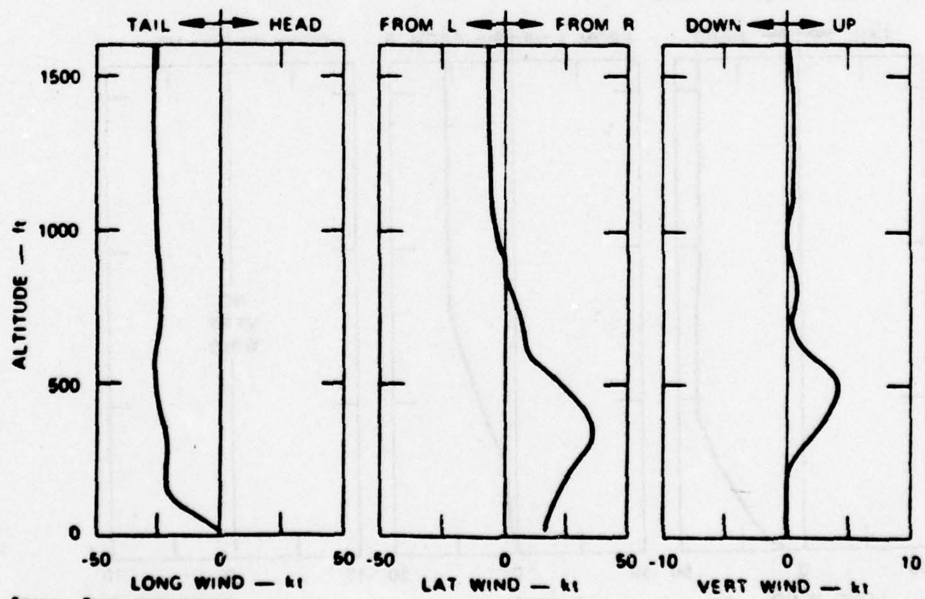
FIGURE 5 CANDIDATE STANDARD WIND SHEARS

Profile Severity: Moderate
Meteorological Type: Thunderstorm



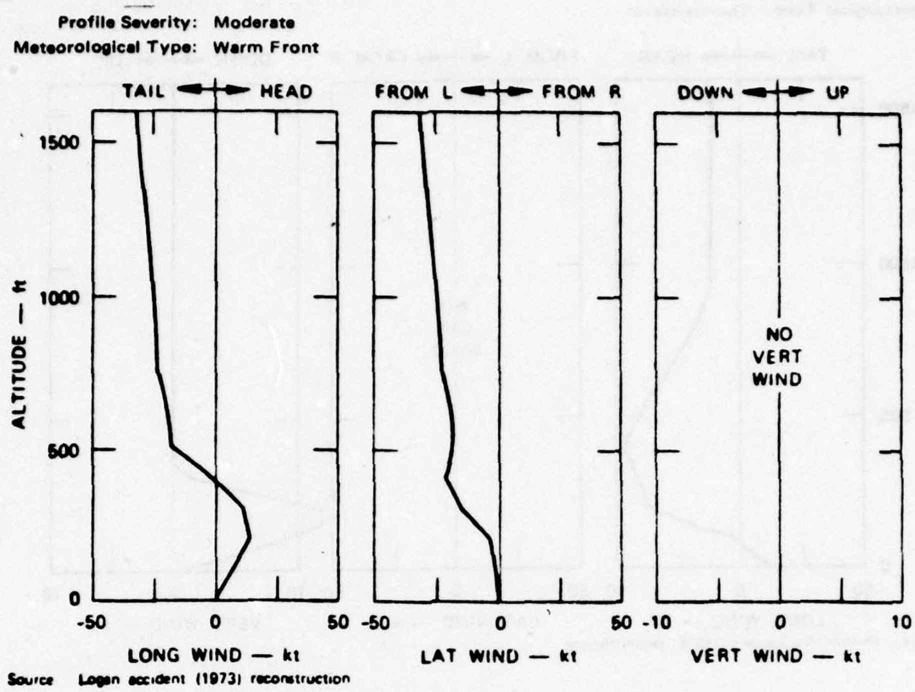
Source: Tower measurements

Profile Severity: Moderate
Meteorological Type: Thunderstorm



Source: Tower measurements

FIGURE 5 CANDIDATE STANDARD WIND SHEARS (CONTINUED)



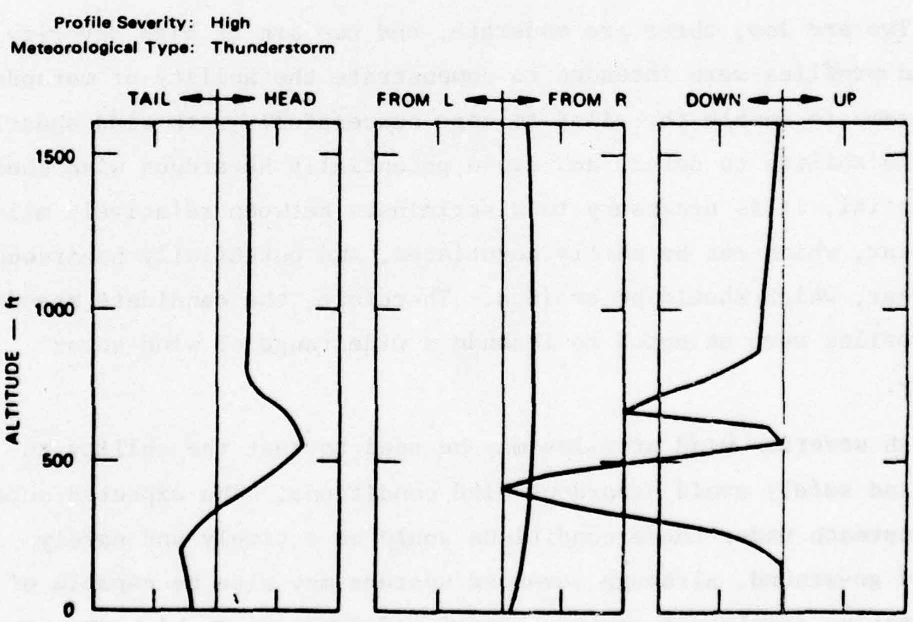


FIGURE 5 CANDIDATE STANDARD WIND SHEARS (CONTINUED)

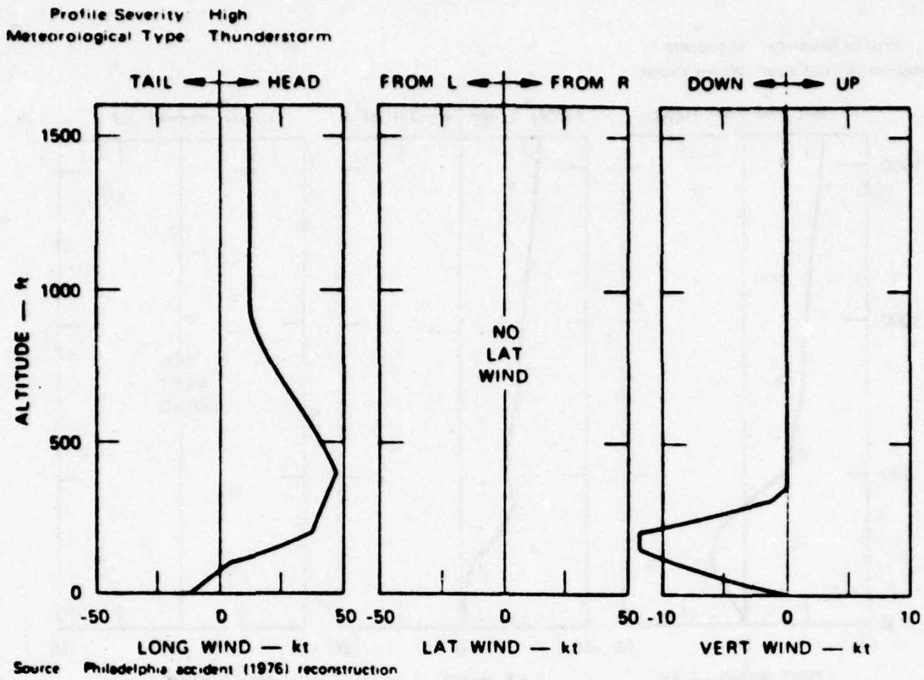


FIGURE 5 CANDIDATE STANDARD WIND SHEARS (CONCLUDED)

path. Two are low, three are moderate, and two are of high severity. The wind profiles were intended to demonstrate the ability of methods and systems to enable the pilot to cope successfully with wind shear. Since the ability to detect and avoid potentially hazardous wind shear is essential, it is necessary to discriminate between relatively mild wind shear, which can be safely negotiated, and potentially hazardous wind shear, which should be avoided. Therefore, the candidate standard wind profiles were selected to include a wide range of wind shear severity.

High severity wind profiles may be used to test the ability to detect and safely avoid hazardous wind conditions. The expected outcome of an approach under these conditions would be a timely and safely executed go-around, although advanced systems may also be capable of demonstrating consistent, safely negotiated landings in high-severity wind profiles. Low-severity wind profiles are relatively mild. Although some wind shear is present, it lies within the capabilities of the aircraft models tested, and can be safely negotiated. In most instances, the expected outcome of an approach in low-severity wind profiles would be a safe landing. Moderate-severity wind profiles probably represent the most dangerous wind-shear conditions for the pilot because they will tempt him to land, when the most prudent choice might be to execute a go-around. The successful outcome of the approach would be either a safe landing or a well-executed go-around.

IV TRAINING AND PROCEDURES

The need to make the flight-simulation exercises as realistic as possible was recognized from the start. The simulators were of high quality and great pains were taken to have them faithfully reproduce the responses of the actual airplanes. The wind profiles represented actual meteorological conditions. Great efforts were made to recruit subject pilots who were highly experienced and particularly knowledgeable of airline operations. A list of the pilots who contributed their efforts to the tests is given in the Appendix.

Wind variation in space is a common weather phenomenon. Coincidence of short-term high-intensity wind variation and low-level flight operations is fortunately not so common. In fact, encounters with high-severity low-level wind shear such as the conditions at Kennedy (1975) and Philadelphia (1976) airports (Figure 5) are extremely rare in the operational experience of line pilots. None of the subject pilots had experienced such conditions in an actual flight environment. The fact that these conditions produced accidents shows that the occurrence is frequent enough to be of concern in aviation safety.

Because low-level wind shear of high or even moderate severity is seldom encountered, normal experience on airline flight operations does not provide adequate pilot training in handling it. Further, as we note in Section V, many airline aircraft do not have instrumentation that enables a direct computation of the wind vector for approach and landing or for takeoff, and so wind shear when it happens is often not recognized as such. This emphasizes the importance of including wind shear in pilot training programs. We found that a high quality six-degree-of-freedom moving base simulator like the Douglas MBDFS made a very effective training vehicle. Just a dozen approaches or so were enough to enhance significantly a pilot's ability to recognize wind shear and to cope with it.

A standard piloting technique in turbulent air is to increase the nominal approach airspeed by 10 or 20 knots. This method of applying an "airspeed pad" is useful in providing some wind shear protection when encountering a headwind-loss shear, which is one of the more hazardous types of wind shear. The pad must be used with caution, of course. The shear type may be hard to recognize, particularly with standard aircraft instrumentation. An airspeed pad on landing, especially if a tailwind-loss shear is encountered, may lead to a high-speed touchdown with danger of overrun if the runway is short and/or wet.

Another useful procedure is to have the copilot monitor the instruments and call out certain altitudes, airspeed readings, and unusual conditions. These procedures are standardized by some airlines. Our simulation exercises showed that a crew's ability to cope with wind shear can be improved by judicious use of callouts. For example, having the copilot monitor vertical speed closely and call out any sink rates greater than some 1200 ft/min (750 ft/min was nominal for the DC-10 in the simulated configuration on a 3° glidepath) was effective in giving warning that the airplane was heading into trouble.

V AIDS AND DISPLAYS

The search for effective low-cost airborne solutions to the low-level wind-shear problem ran the gamut from the simple device to rather complicated combinations of aids. In considering these aids, it is important to recognize that the pilot had available an array of "standard" or "conventional" instruments, information displays, and procedures that formed the basis for his flight management. In the DC-10 the instruments consisted of:

- airspeed (AS) indicator
- flight director with attitude-director indicator (ADI) and fast-slow command bug (F/S)
- radio altimeter
- barometric altimeter
- horizontal situation indicator (HSI)
- vertical speed indicator.

The same array was used in the B-727, except that in the B-727 NASA tests the F/S command was not available. These displays with the corresponding algorithms (drive signals) and procedures constituted the "baseline" system of flight management. The aiding instrumentation or procedures were additions to or changes in this baseline set.

At the outset it was recognized that implementation of an effective aid is not a simple matter. Approach and landing and takeoff are demanding operations. The provision of additional information, even though potentially useful in coping with wind shear, may easily have the effect of distracting the pilot so much that overall performance deteriorates. If an additional display is located outside the pilot's normal instrument scan pattern, there is a good chance that it will be ignored. It is not enough simply to give the pilot more information; he also needs to know what it implies about the airplane's state and what control actions are needed to respond to changes in the indicator. Quantitites such as angle of attack, rate of change of energy, and aircraft acceleration that are sensitive to wind-shear effects are also sensitive to turbulence; therefore, such quantities must be filtered carefully to avoid the undesirable fluctuations caused by turbulence, but also to respond quickly enough to wind changes caused by shear. The effective aiding information, as it developed, was of the type that could be integrated into the standard instruments and displayed in a way that was easy and natural to read and use.

Most of the aiding information was displayed on the instrument panel; the major exceptions were the DC-10 Phase 1 and B-727 HUD tests in which head-up displays were implemented. Table 6 summarizes the instruments, algorithms, and procedures that were formally tested and evaluated during the course of Task 2. The list includes wind-shear warnings, aids for control of airplane speed and/or attitude, and techniques for advising the pilot to break off an approach and initiate a go-around (G/A). In addition, some informal trials were run on an angle-of-attack display and a display of rate of change of airspeed.[3] The number of different potential aids prohibits a description of each one in this summary report; Table 6 gives references where technical details can be found. Instead, we shall describe the systems that were shown to be most effective.

A. Ground Speed

In an approach supported by the instrument landing system (ILS), the localizer supplies lateral position and the glide slope supplies angular position in a vertical plane. The standard airborne instrumentation supplies vertical velocity, airspeed, and, usually, accelerations in the airplane axes. A missing piece of information is aircraft velocity with respect to the ground along the approach path. Without this ground speed (GNS) instrumentation it is easy to see that the pilot cannot compute longitudinal wind at the aircraft. GNS information, therefore, was basic to most of the successful techniques for coping with wind shear.

Table 6

CONCEPTS TESTED FOR AIDING IN WIND SHEAR

New Aid or Procedure	Purpose	How Displayed	Tested In	References
Wind-shear advisory	Advance warning	Audio message	DC-10 Ph. 1	1
Wind readout	Warning	Digital, on pedestal	DC-10 Ph. 1	1
Wind difference (ground minus air)	Warning	Analog, above altimeter	DC-10 Ph. 1	1
	Speed control	AS command, digital, F/S command	DC-10 Ph. 2	2
Ground speed (GNS)	Warning	Bug on AS indicator	DC-10 Ph. 1	1
	Warning	Digital, under AS indicator	DC-10 Ph. 2	2
	Speed control	Analog, on V_{mo} needle	DC-10 Ph. 2; B-727 NASA	2,3
	Speed control	Digital, over ADI	DC-10 Ph. 3	4
GNS plus GNS-based speed command	Speed control	GNS on V_{mo} needle, command on F/S	DC-10 Ph. 3,4; B-727 HUD	4-6
Approximate GNS	Warning	Placard on vertical speed indicator	DC-10 Ph. 1	1
Flight-path angle (FPA) plus potential FPA, air-mass	Warning, pitch, speed	Analog, above altimeter	DC-10 Ph. 1	1
FPA, ground referenced	Warning, pitch control	Analog, scale on ADI	DC-10 Ph. 2	2
FPA, hybrid ground/air	Warning, pitch control	Analog, scale on ADI	DC-10 Ph. 2	2
Modified flight director (MFD)	Pitch and roll control	ADI command bars	DC-10 Ph. 2; B-727 NASA	2,3,8
MFD plus F/S with GNS	Pitch, roll, speed	ADI command, F/S command	DC-10 Ph. 3,4	4,5,8
MFD plus F/S without GNS	Pitch, roll, speed	ADI command, F/S command	DC-10 Ph. 3	4,8
Head-up display (HUD) with air-mass FPA	Warning; pitch, roll, speed	Synthesized onto visual scene	DC-10 Ph. 1	1
HUD with ground-referenced FPA	Warning; pitch, roll, speed	Solid optical-block pilot-display unit	B-727 HUD	6
HUD with hybrid ground/air FPA	Warning; pitch, roll, speed	Solid optical-block pilot-display unit	B-727 HUD	6
Modified procedure for deciding to go-around (G/A)	G/A advisory	Pilot-monitored standard instruments	DC-10 Ph. 3	4
Acceleration margin	G/A advisory	Warning light	DC-10 Ph. 3	4
	G/A advisory	Analog, beside ADI plus warning light	DC-10 Ph. 4	5
Energy rate	G/A advisory	Analog, under AS indicator, plus warning light	DC-10 Ph. 3	4
Microprocessor-driven run-evaluation display	Warning, G/A advisory	Digital, above altimeter	DC-10 Ph. 4	5
Modified algorithm for G/A guidance	Pitch control on G/A	ADI command bar	DC-10 Ph. 4	5

We found that a particularly useful aid in wind shear is to replace the conventional airspeed-error thrust management with a technique designed to maintain both airspeed and ground speed (GNS). Given the pilot's selected approach speed, V_{app}, in terms of indicated airspeed, we calculate a reference ground speed, GNS_{ref}, as follows:

$$GNS_{ref} = TV_{app} - WX_{gnd} \quad ,$$

where

$TV_{app} = V_{app}$ converted to true airspeed (knots),

WX_{gnd} = Wind component at ground along runway, with headwind positive (knots).

The aiding technique is to adjust the throttles so that the indicated airspeed is at or above V_{app} <u>and</u> the ground speed is at or above GNS_{ref}. The effect, when flying with a strong headwind that will disappear at the ground, is to require an airspeed higher than normal (V_{app}) as protection against the shear-out of the head wind.

In one display tested, this technique was implemented on the usual round-dial airspeed indicator by driving a second needle, the V_{mo} pointer, to read GNS. Colored "bugs" were positioned on the edge to indicate V_{app} and GNS_{ref}. This implementation with a dual-needle indicator in the DC-10 simulator is shown in Figure 6.

The display of GNS was supplemented in some tests by the addition of a GNS-based speed command on the flight director Fast/Slow (F/S) indicator. The algorithm was:

$$F/S = \text{minimum of } (V_a - V_{app}) \text{ and } (GNS - GNS_{ref}) \quad ,$$

where

$$V_a = \text{indicated airspeed (knots)}$$

The F/S command was limited to ±20 knots.

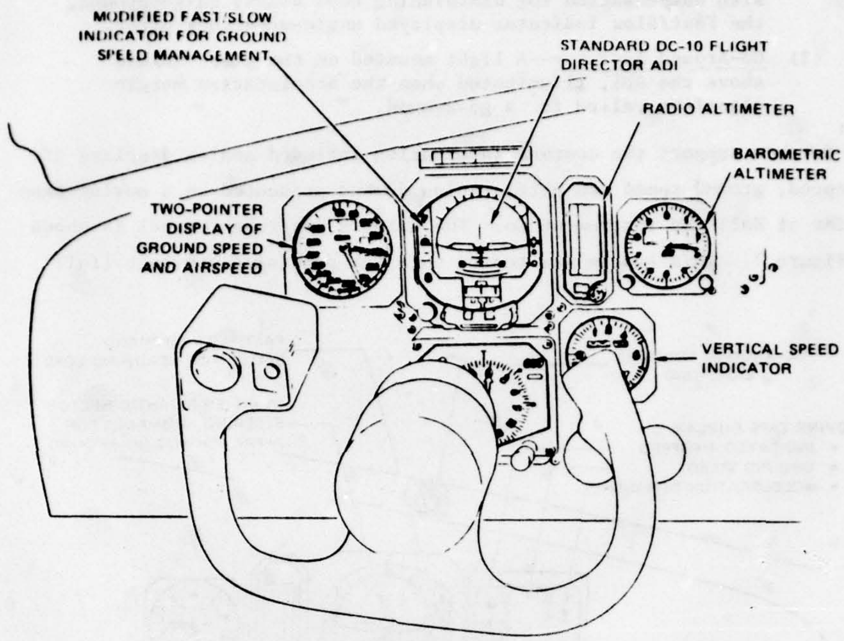


FIGURE 6 DC-10 INSTRUMENT PANEL CONFIGURATION WITH GNS

B. <u>The MFD/ΔA System</u>

The development and trial of various potential aids culminated in the DC-10 Phase 4 test in the system we designated "MFD/ΔA." This system's performance was good enough for it to be considered a solution to the wind-shear problem on approach and landing.[5] This aiding system contains the following combination of command information:

(1) <u>MFD</u>--Pitch and roll flight-director steering commands were based on the Collins acceleration-augmented control laws for ILS tracking; in the go-around mode (TOGA button depressed), a modified pitch-steering command was provided based on the SRI minimum height loss go-around guidance computation.

(2) Thrust Command--The flight director Fast/Slow indicator provided speed commands based on the Collins algorithm with compensation for diminishing head winds; on go-around, the Fast/Slow indicator displayed angle-of-attack error.

(3) Go-Around Advisory--A light mounted on the glare shield above the ADI, illuminated when the acceleration margin algorithm called for a go-around.

Raw data to support the command information included analog displays of airspeed, ground speed and acceleration demand presented on a moving-tape device of Kollsman Instrument Co. The pilot's instrument panel is shown in Figure 7. This system was tested both for precision approach (full

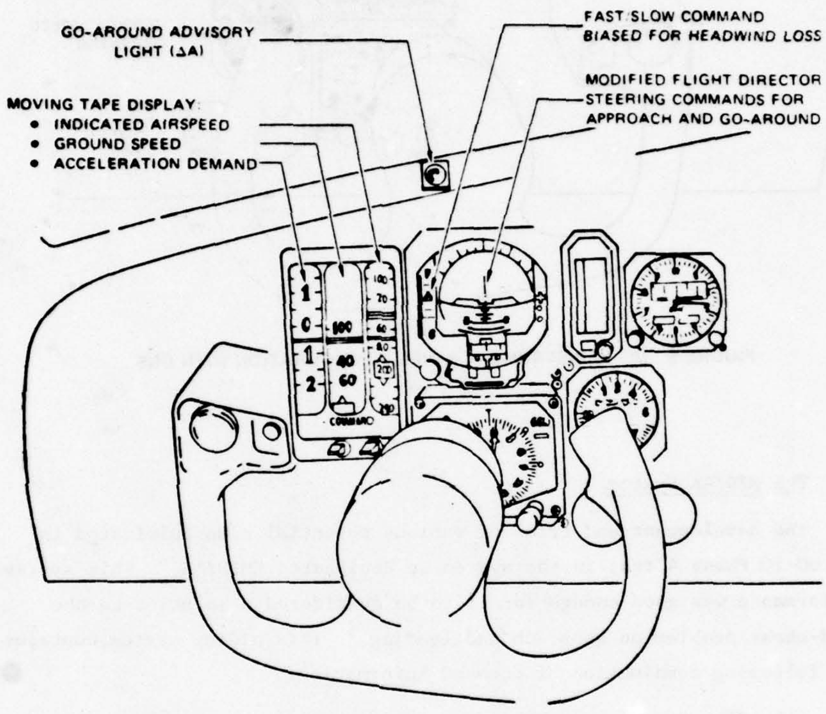


FIGURE 7 INSTRUMENT PANEL CONFIGURATION FOR THE MFD/ΔA TEST SYSTEM

ILS) and nonprecision approach (localizer only). In the nonprecision approach case it was assumed that aircraft longitudinal displacement could be obtained by integrating GNS, and a glidepath deviation signal was computed from a synthesized glidepath using altitude and displacement.

Let us describe the MFD/ΔA system elements.

1. <u>Modified Flight Director</u>

Under Task 5 of this AWLS contract, Collins developed improved flight-director control laws that incorporate acceleration augmentation to aid in coping with wind shear on approach and landing; the work has been reported.[8] In comparison with the standard or "baseline" flight-director commands, these modified steering-control laws exhibit quickened responses to changing wind and other transients. The modified flight director also had a modified speed command, driving the fast/slow "bug," that used acceleration augmentation and wind-shear compensation to improve speed control. To illustrate the techniques, simplified block diagrams of the MFD longitudinal and lateral controls are given in Figures 8 and 9, and a similar diagram of the MFD speed control is given in Figure 10.

When used on a nonprecision approach, the flight-director pitch-steering command requires a substitute for glide-slope deviation. Note that the MFD longitudinal control, Figure 8, has altitude error as a basic input. On precision approach this signal was obtained from glide-slope deviation and altitude. On nonprecision approach, the altitude error signal was computed by using a synthetic glide path. Figure 11 shows this algorithm.

With the MFD the pilot's task was to steer the simulated airplane so as to follow the flight director steering commands as closely as possible. Thus, this part of the experimental task was the same in concept as conventional approach management by flight-director reference. When the MFD was used, both the pilot's and the copilot's flight directors were driven by the MFD signals.

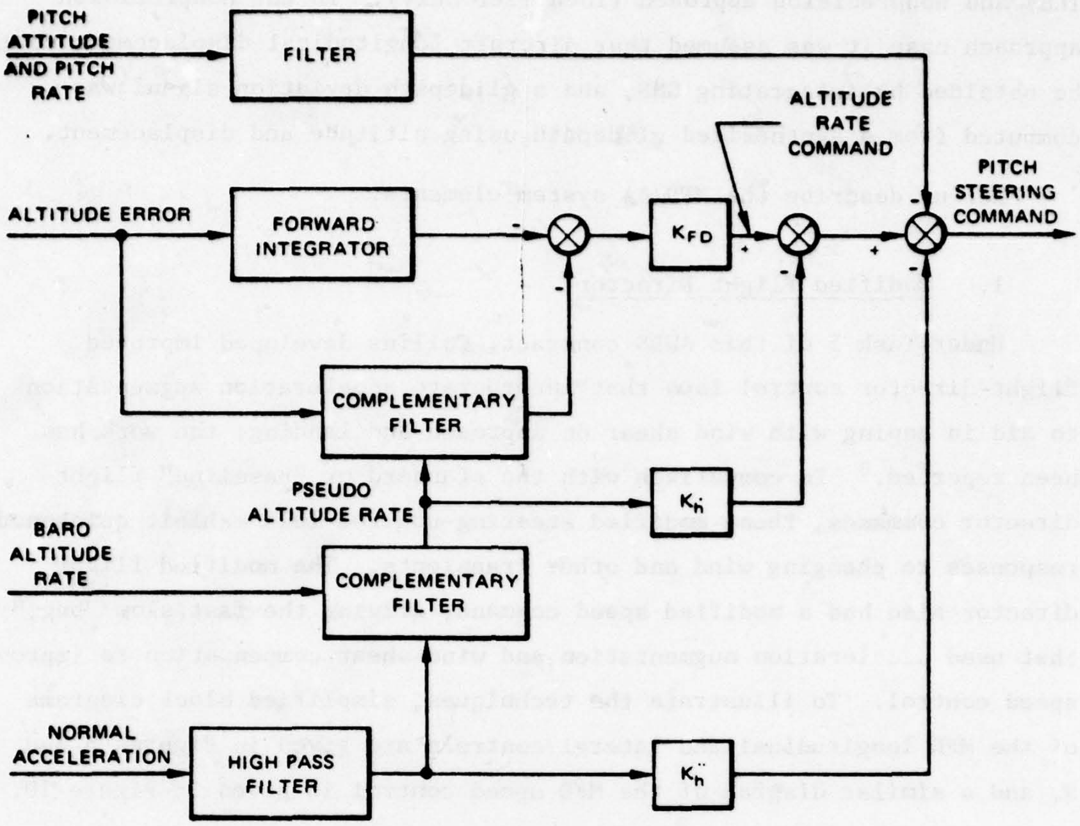


FIGURE 8 MODIFIED FLIGHT DIRECTOR — PITCH STEERING

For approach and landing, the pilot's speed control task was aided by supplying a speed-error indication on the fast/slow scale of the flight director. The pilot moved the throttles to keep the F/S indicator showing zero error, in the conventional way. The dynamic effects of the simulated wind shears produced speed errors greater than 10 knots, however, so the conventional ±10-knot scale was changed to read ±20 knots.

A basic assumption of the system was that a measurement of ground speed (GNS) would be available in the airplane simulated. From this assumption it was an easy step, in developing the synthetic glideslope for non-precision approach, to assume also that a measurement of initial position could be made. Examples of possible sources are a distance-measuring equipment (DME) reading, or the point of crossing the center

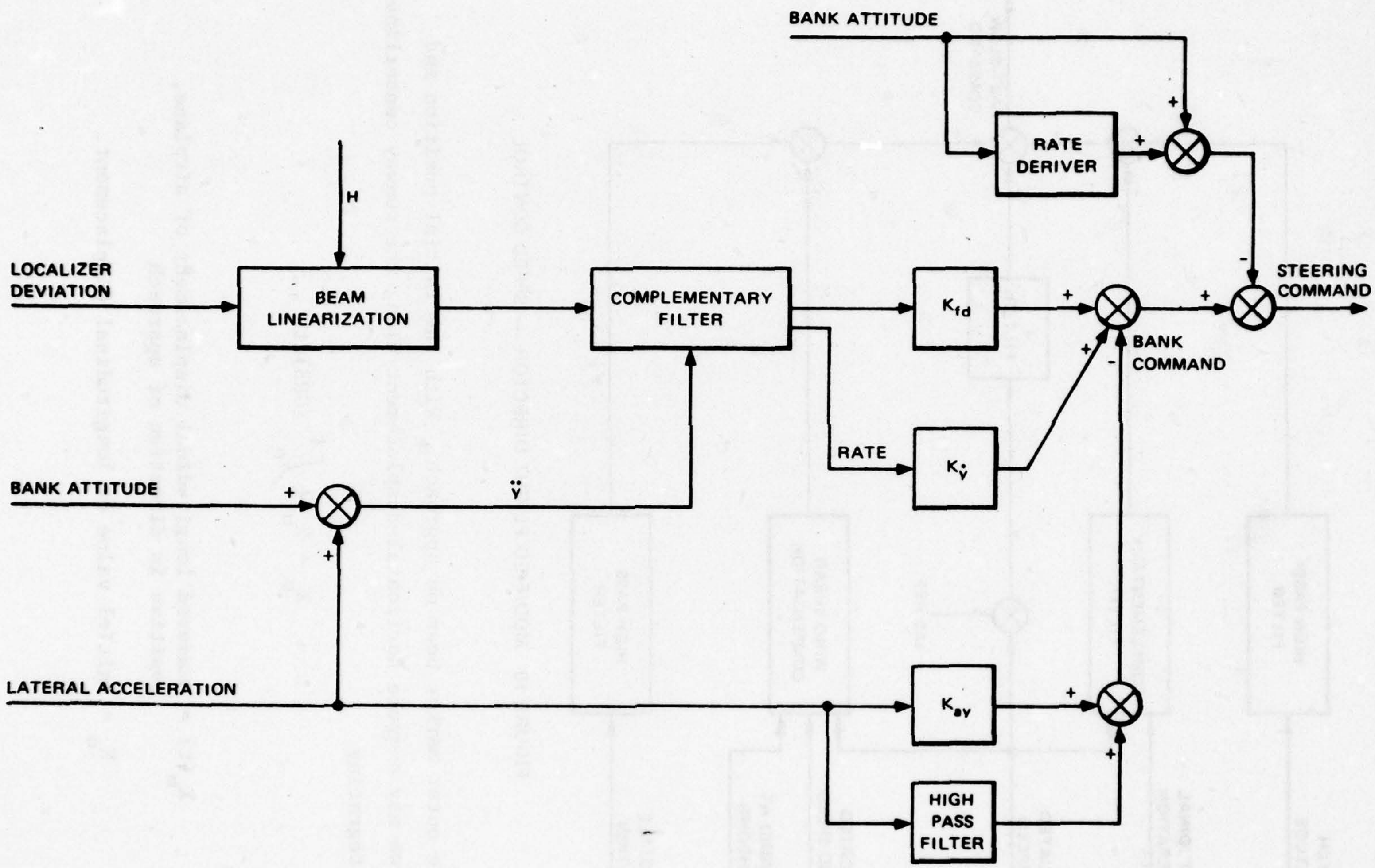


FIGURE 9 SIMPLIFIED LATERAL-CONTROL LAW FOR MODIFIED FLIGHT DIRECTOR

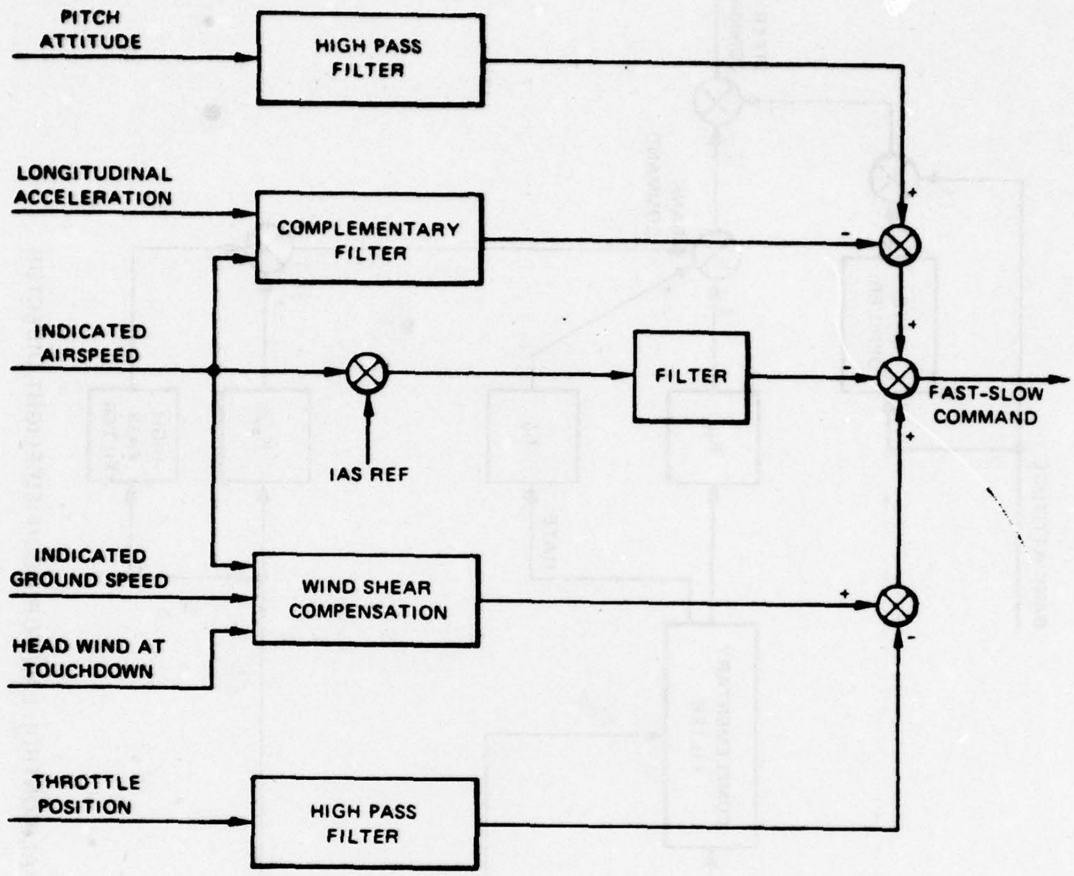


FIGURE 10 MODIFIED FLIGHT DIRECTOR — SPEED CONTROL

of the outer marker beam on approach. With the initial position and GNS, we may compute horizontal displacement along the runway centerline by integrating

$$X_m = X_o + \int_o^t (GNS)dt \quad ,$$

where

$X_m(t)$ = Measured longitudinal displacement of airplane, positive in direction of approach

X_o = Initial value of longitudinal displacement.

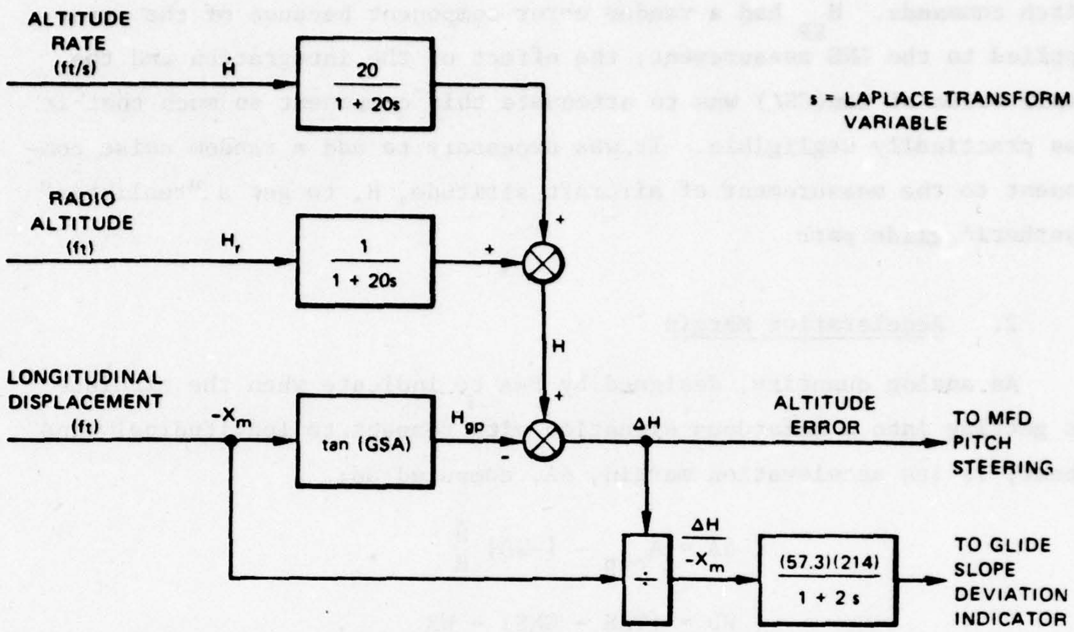


FIGURE 11 ALTITUDE ERROR FROM SYNTHETIC GLIDE PATH

An error in initialization would appear as a constant bias error in X_m. We took a value of ±600 feet, corresponding to a single-reading DME bias, as the initialization error. On each simulator run the particular value of the X-bias error was dependent on the wind profile, being selected to cause the most difficulty. For instance, an error of +600 feet was applied to runs on a wind profile where a head wind loss was expected.

The measurement of X and the standard measurement of airplane altitude above ground from a radio altimeter, for instance, were combined to synthesize a reference glide path on nonprecision approach. Assuming that X = 0 at the glide path intercept point on the runway, we computed:

$$H_{gp} = -X_m \tan(GSA) \quad ,$$

where

H_{gp} = Height above ground, positive up (feet), of the glide path at longitudinal displacement X_m

GSA = Glide path angle (degrees) above horizontal, nominally 3°.

The altitude error of the airplane then was $H - H_{gp}$, which gave vertical deviation from the synthesized glide path and was used for flight director pitch commands. H_{gp} had a random error component because of the error applied to the GNS measurement; the effect of the integration and the small value of tan(GSA) was to attenuate this component so much that it was practically negligible. It was necessary to add a random noise component to the measurement of aircraft altitude, H, to get a "realistic" synthetic glide path.

2. <u>Acceleration Margin</u>

An analog quantity, designed by FAA to indicate when the airplane is getting into a hazardous situation with respect to longitudinal wind shear, is its acceleration margin, ΔA, computed as:

$$\Delta A = A_{cap} - [-WD]\frac{\dot{H}}{H} ,$$

$$WD = (TAS - GNS) - WX_{gnd} ,$$

where

A_{cap} = Acceleration capability of the airplane in level flight in approach configuration (knots/s).

WX_{gnd} = Wind component at ground along runway, with head wind positive (knots).

TAS = True airspeed of airplane (knots).

GNS = Ground speed of airplane (knots).

H = Altitude of airplane center of gravity above ground, positive up (feet).

$\dot{H}$ = Rate of change of altitude with time, positive up (feet/s).

In this, A_{cap} is a constant for the approach and will depend on the selected approach speed, the flap setting, the maximum engine thrust available, the drag, the aircraft weight, and the air density. For instance, values for the DC-10 at 350 klb, 50° flaps, nominal approach speed, gear down, are:

Sea level, standard day	1.67 kt/s,
9,000 feet, standard day	1.00 kt/s.

The term TAS - GNS is approximately the longitudinal wind velocity at the airplane, head wind positive, so WD is the wind difference or estimated wind shear, the change in wind between airplane present position and the ground; a decreasing head wind is a positive difference. The magnitude of $H/\dot{H}$ is the expected time in seconds to reach the ground, and $\dot{H}$ will be negative for descent. Thus, the term $[-WD]\dot{H}/H$ is the expected acceleration demand due to longitudinal wind shear, with a decreasing head wind for a descending aircraft giving a positive demand. If the demand equals or exceeds A_{cap}, ΔA becomes zero or negative and the situation is potentially hazardous.

Preliminary trials[4] showed that the condition $\Delta A \leq 0$, if used as a criterion for advising a go-around, produced too many nuisance alarms. It was necessary to augment the algorithm. We computed the difference, DA, between the wind change and the airspeed pad by:

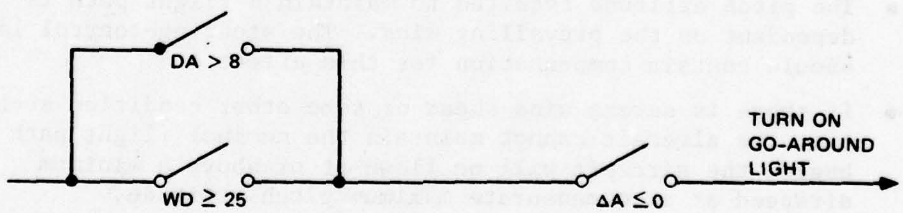
$$DA = WD - (IAS - V_{app}) ,$$

where

IAS = Indicated airspeed (knots)

V_{app} = Selected approach speed (knots).

Then we implemented a go-around advisory, closing the "switches" when the indicated condition is "true," as follows:



Thus, a go-around was advised, and a yellow "go-around ΔA" light on the instrument panel was lit, if $\Delta A \leq 0$ AND if [$WD \geq 25$ knots OR $DA > 8$ knots]. The effect is to inhibit the go-around advisory if either the wind difference (decreasing head wind) is less than 25 knots or the wind difference is no more than 8 knots greater than the airspeed pad. The particular values 8 and 25 knots were chosen empirically.

3. Modified Go-Around Guidance

Situations will occur on approach and landing, especially with wind shear of high severity, for which the appropriate action is to abort the approach and make a "go-around." In the simulated airplane the pilot initiated the maneuver by pressing the TOGA button and saying "go-around." He advanced the throttles to give full (102%) engine rpm and steered on the flight-director commands while the copilot activated the lever to raise the landing gear and moved the flap lever to 22°. The standard or "baseline" DC-10 go-around steering and F/S signals for the flight director are derived from heading, angle of attack, indicated airspeed, and longitudinal acceleration. They provide a smooth pitch-up maneuver.

An alternative method was designed in an attempt to minimize the loss of altitude during the go-around. This modified go-around guidance, developed by SRI, was intended to provide a pitch steering control law for use in wind shear. The control law was designed specifically for the simulator validation tests, and would require additions and modifications if used in a production aircraft.

The rationale of the design is as follows:

- The dominating requirement during go-around is terrain avoidance and obstacle clearance. After the initial pitch-up maneuver, it is assumed that flying a nominal positive flight-path angle will result in a safe go-around.
- The pitch attitude required to maintain a flight path is dependent on the prevailing wind. The steering-control law should contain compensation for this effect.
- If there is severe wind shear or some other condition such that the aircraft cannot maintain the nominal flight path angle, the aircraft will be flown at or above a minimum airspeed at a commensurate maximum pitch attitude.

The design is described schematically in Figure 12. Vertical-speed $\dot{H}$ and ground-speed GNS inputs were used to compute flight-path angle γ. Flight-path angle and angle of attack α then go into the computation of the pitch steering signal Δ. This signal and the pitch rate term $\dot{\theta}$ for damping are the controlling terms as long as airspeed remains high. When airspeed drops to or below the stall value, the minimum function chooses

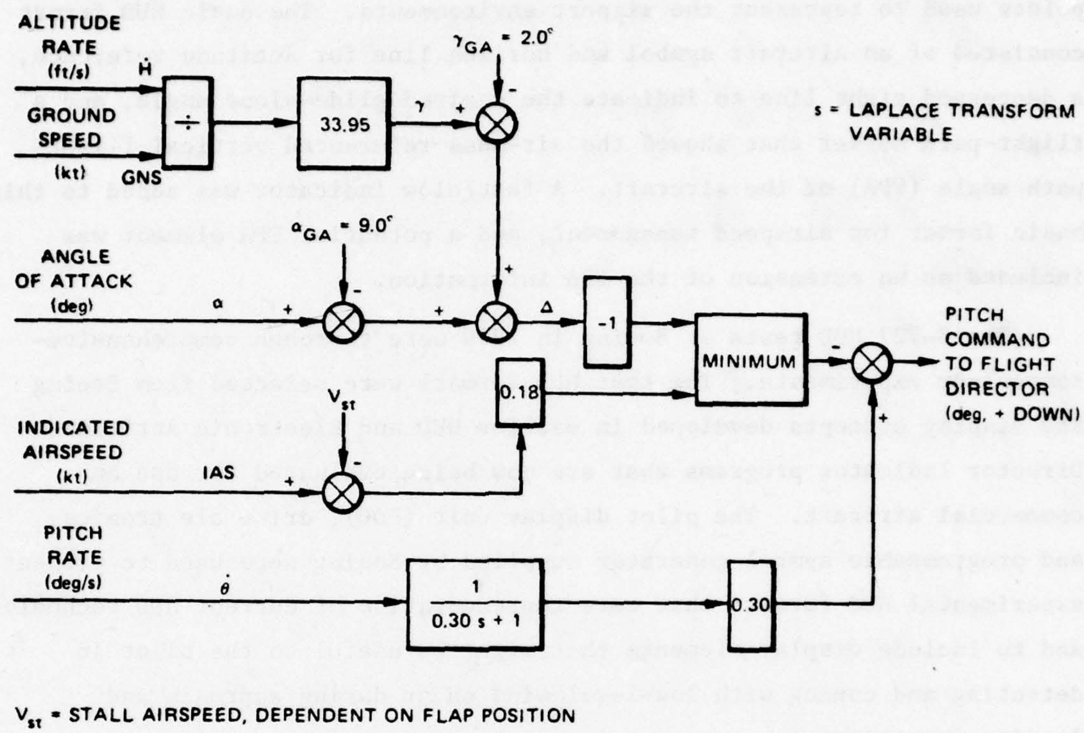


FIGURE 12 MODIFIED GO-AROUND PITCH STEERING

the IAS-V_{st} input, which results in a pitch-down command to gain airspeed. The reference flight path angle, γ_{GA}, and angle of attack, α_{GA}, were chosen empirically to give a good DC-10 go-around maneuver.

With the modified go-around method the pilot advanced throttles to give full thrust immediately after pushing TOGA. He was then not using the F/S indicator on the flight director for the thrust control. Therefore, to provide additional information, the F/S signal was modified so that the F/S displayed an approximation to angle of attack error.

C. Head-up Display (HUD)

Exploratory trials of a HUD in wind shear were made in the DC-10 Phase 1 tests at Douglas. The HUD symbology was generated by the Vital III system and integrated with the simulated external visual scene. The display elements were 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 basic HUD format consisted of an aircraft symbol and horizon line for attitude reference, a depressed sight line to indicate the desired glide-slope angle, and a flight-path marker that showed the air-mass referenced vertical flight-path angle (FPA) of the aircraft. A fast/slow indicator was added to this basic format for airspeed management, and a potential FPA element was included as an extension of the FPA information.

The B-727 HUD tests at Boeing in 1979 were thorough comprehensive-comparison experiments. The test HUD formats were selected from Boeing R&D display concepts developed in earlier HUD and Electronic Attitude-Director Indicator programs that are now being evaluated for use on commercial aircraft. The pilot display unit (PDU), drive electronics, and programmable symbol generator supplied by Boeing were used to present experimental HUD formats that were representative of current HUD technology and to include display elements that might be useful to the pilot in detecting and coping with low-level wind shear during approach and landing operations.

The key elements of the Boeing HUD formats of interest for wind-shear application were the display of flight-path angle and the vertical guidance provided by a glide-path reference marker and synthetic runway. The potential value of displaying "flight-path acceleration" for more effective thrust management during shear encounters was also of interest. Accordingly, these display elements were emphasized in the HUD formats selected for the wind-shear tests.

Following a preliminary checkout in the simulator, two basic versions of the HUD were selected by the FAA for testing:

- An inertial HUD (IHUD), distinguished by the use of ground-referenced quantities in the computation of flight-path display elements.
- A noninertial HUD (NHUD) with display-element computations based on the assumption that only standard instrumentation would be available on the aircraft.

The test HUD formats were further distinguished by adapting a VMC mode for use when adequate external visual reference to the runway was available, and an IMC mode that added a synthetic runway symbol to the HUD format as a substitute for the actual runway when visibility was obscured.

The selected IHUD format is shown in Figure 13. The computation of inertial flight-path angle, (γ_I) in degrees, was:

$$\gamma_I = \left[\mathrm{Tan}^{-1}\left(\frac{\dot{h}}{GNS}\right)\right] 57.3 \quad ,$$

where:

$\dot{h}$ = Vertical velocity of the aircraft at the aircraft center of gravity in ft/s in the inertial frame,

GNS = Ground speed, derived from the longitudinal velocity at the aircraft center of gravity in ft/s.

Flight-Path Acceleration, or "potential flight-path angle" (γ_{pot}) was also computed in degrees, using

$$\gamma_{pot} = \gamma_I + \left(\frac{a_x}{g}\right) 57.3 \quad ,$$

where:

a_x = Longitudinal acceleration at the aircraft center of gravity in ft/s^2

g = The gravitational constant (32 ft/s^2).

The IHUD was also distinguished by the computation of the lateral component of the flight-path marker to display the effects of drift angle. The lateral displacement of the center of this symbol from the center of the reference airplane symbol was derived from "heading error," i.e., aircraft heading minus runway heading in degrees, with negative values indicating that aircraft heading was to the left of the runway heading.

The final distinguishing feature of the IHUD was that the airspeed error symbol on the left wing of the reference airplane symbol was driven by the ground-speed management algorithm described in Section V-A.

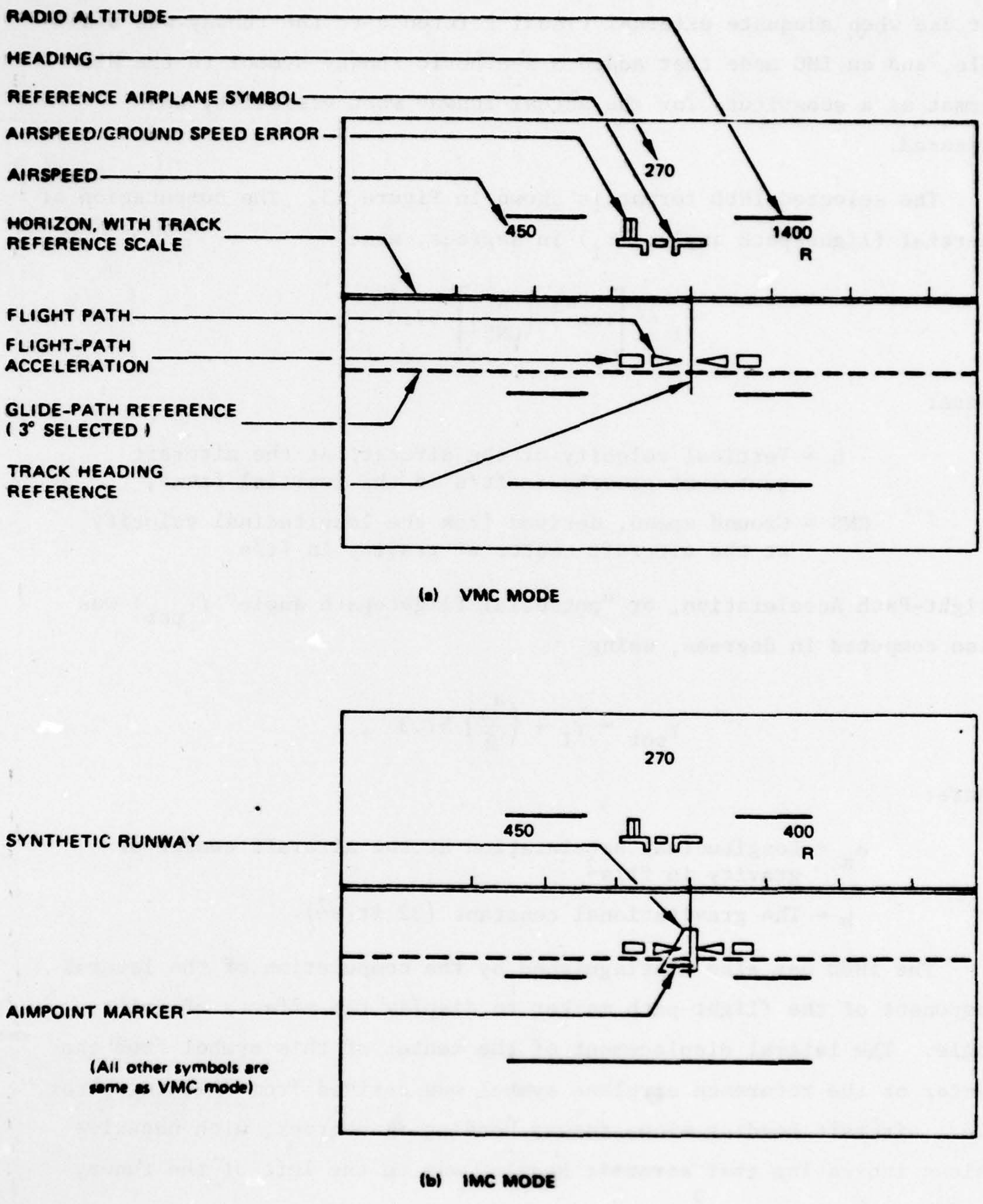


FIGURE 13 SYMBOLOGY SELECTED FOR THE INERTIAL HUD (IHUD)

It combined a selected ground-speed reference (GNS_{ref}) with the selected target-approach speed (V_{app}) as reference values for the display of speed error on the approach.

As noted earlier, the NHUD did not differ from the IHUD in appearance. The distinguishing features of the NHUD were that:

- The display of airspeed error was referenced to V_{APP} and did not include the ground-speed management feature.
- The computation of flight-path angle was air-mass referenced.
- The flight-path symbol did not indicate drift angle (it remained centered on the track-heading reference symbol).
- The computation of flight-path acceleration was also air-mass referenced.
- Barometric altitude was displayed rather than radio altitude.

The computation for air-mass flight-path angle (γ_A) was:

$$\gamma_A = \left[\mathrm{Tan}^{-1} \left(\frac{\dot{h}}{TAS - W_{XS}} \right) \right] 57.3 \quad ,$$

where:

$\dot{h}$ = Vertical speed at the aircraft center of gravity in ft/s, derived from barometric-altitude rate

TAS = True airspeed in ft/s

W_{XS} = Tabulated value of the head wind component (W_X) on the surface for the selected wind profile in ft/s.

Air-mass flight-path acceleration (γ_{pot-A}) was computed using

$$\gamma_{pot-A} = \gamma_A + \left(\frac{\Delta TAS/sec}{g} \right) 57.3 \quad ,$$

where

$\Delta TAS/sec$ = rate of change of TAS, ft/s^2.

D. Angle of Attack

Serious consideration was given to the display and use of aircraft angle of attack, α, information as an aid in coping with wind shear, and an α display was tried informally in one of the piloted flight-simulation exercises.[3] It was recognized that an α instrument poses difficult design problems. For instance, the raw α signal must be smoothed to keep the turbulence from making it unreadable, but the smoothing cannot be so great that response to wind shear is slowed. Another problem is that the display scale should show the airplane trim position and stall point, but these are functions of airplane configuration and airspeed. Because of the design and computational difficulties, we concluded that the best use of α would have it incorporated in the drive signals of the flight director steering bars and F/S command. This was done, for example, in the modified G/A guidance (Section V-B-3) algorithm, and it proved to be effective.

VI EXPERIMENTAL DESIGN

The DC-10 Phase 1 test in 1976 was an exploratory flight-simulation exercise intended to screen a large number of potential aids.

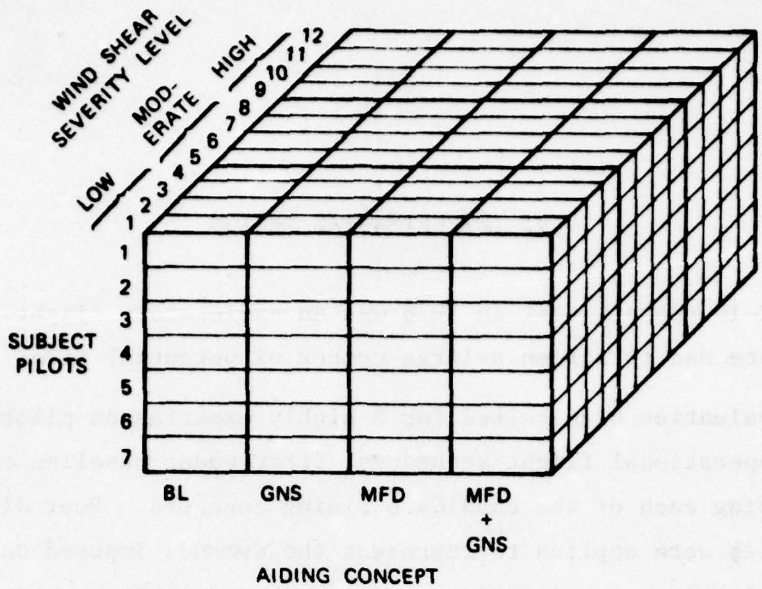
The evaluation plan called for 8 highly experienced pilots to fly simulated operational flight sequences, first under baseline conditions and then using each of the candidate aiding concepts. Four different wind profiles were applied to represent the demands imposed on the pilot by the low-level shear situation on approach and landing. 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 might 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.

The other approach-and-landing simulation exercises were formally designed experiments intended to provide direct performance comparison of two or more flight-management techniques and/or absolute measures of technique performance. In the B-727 NASA test, for example, a four-by-three factorial design, with repeated measures on both factors, was used to structure the experimental evaluation of the aiding concepts. The overall plan of the experiment is schematized in Figure 14; it called for each of the 7 subject pilots to fly four data runs under each combination of aiding concept and wind shear severity condition. The four levels of



BL = BASELINE
GNS = GROUND SPEED BASED SPEED CONTROL (2-NEEDLE)
MFD = MODIFIED FLIGHT DIRECTOR

FIGURE 14 DESIGN OF THE B-727 NASA EXPERIMENT

aiding concept and three levels of wind-shear severity defined the independent variables of interest. Data runs were flown against a total of 12 different wind profiles, which were sorted into the three severity levels. Four wind profiles were assigned to each level of severity and subject pilots were exposed to the same 12 profiles using each aiding concept; baseline (BL) was construed as one level of aiding. The order of pilot exposure to the four levels of aiding was partially counter-balanced across pilots to preclude any systematic bias in the data caused by motivation, fatigue, or learning effects that might carry over from one simulator session to another, and the order of exposure to the different wind profiles was randomized.

The experimental design provided data on a total of 384 approach sequences (runs), with 28 data runs for each unique combination of aiding concept and shear severity level. A single session in the simulator consisted of the 12-run series flown by each pilot using one of the four aids plus three additional runs for pilot familiarization and training.

Each pilot was thus assigned to four sessions in the simulator to complete the full run schedule.

In all the flight simulation experiments some of the familiarization runs were made with wind profiles that had shear; these training profiles were not included in the test set.

As in most studies of this kind, the principal sources of variation in approach performance data were expected to be differences among pilots and the effects of individual wind-shear conditions. The evaluation plans controlled for these factors by using the same pilots on all combinations of display and visibility conditions (repeated measures design) and by using the same wind profiles on each set of test data runs.

In a typical simulation test, each subject pilot was given a standardized project orientation briefing at the beginning of the first day. This initial briefing covered the objectives of the study, the role of the subject pilot, the general procedures to be followed, and the scheduling of simulator sessions. Immediately prior to each scheduled session, pilots were individually briefed on the assigned aiding concept and the procedures to be followed in the simulator. The overview of pilot procedures in the briefing outline for each aiding concept also served to define the experimental task. On all sessions except the baseline run series, the presession briefing stressed the importance of following the prescribed approach-management procedure as an element of the aiding concept being evaluated. Pilots were reminded of the fact that it was the aiding concept, and not their individual skills and proficiency per se, that was the focus of the evaluation.

Debriefing sessions were conducted immediately following each simulator session to allow pilots to comment on their experiences and to record their critique of the aiding concepts.

The basic intent of the studies of takeoff and climbout was to obtain data by flight simulation on the effects of the low-level wind-shear encounter, and to make informal evaluations of the performance differences of various aids and control procedures. These were exploratory investigations, so no formal experimental designs were used. The runs were made with the project pilots (DC-10 Phase 4) or with invited subject pilots on a time-available basis (DC-10 Phases 1 and 3).

VII EFFECTIVENESS OF AIDS

A. Approach and Landing

Even in a carefully designed formal experiment, measurement of the performance or effectiveness of a candidate aiding concept is not a simple matter. Comprehensive data were recorded on each test run in our flight simulation exercises and the subject pilots were debriefed in detail so we could consider and analyze any of a wide choice of possible performance measures. On the approach and landing tests, examples of useful measures are:

- Inverse of deviations from the desired glidepath.
- Avoidance of airspeed loss.
- Avoidance of go-arounds (G/A) on low-severity wind shears.
- Avoidance of false (nuisance) alarms on G/A advisories.
- At the end of the approach, is the airplane in an acceptable position-velocity "window?"
- At touchdown, is the airplane in a acceptable position-velocity-attitude "window?"
- Inverse of workload as estimated by the pilot.
- Inverse of workload as estimated from control activity.
- Subjective pilot evaluation of usefulness.
- Acceptability of the aiding concept for airline operations.

We examined various combinations of these measures on the different tests, choosing those that seemed most appropriate to the test situation. The detailed results are given in the interim reports on the simulation tests. In this section, only the most significant and decisive results will be cited.

The DC-10 Phase 1 tests[1] were an exploratory screening of the several candidate aids intended to guide subsequent in-depth study and development of the most promising concepts. Both precision and nonprecision approaches were made, and the pilots made a G/A whenever they considered it appropriate. Based on subjective assessments of usefulness, the aids were rank ordered as follows ("1" is most useful, "10" is least):

(1) Ground speed (GNS) on airspeed (AS) indicator.

(2) Visual Approach Slope Indicator (VASI) on runway for visual approach.

(3) HUD with air-mass flight-path angle (FPA) and wind difference display.

(4) Wind readout, digital.

(5) HUD with air-mass FPA.

(6) Wind difference, analog.

(7) Wind shear advisory.

(8) FPA plus potential FPA, analog.

(9) Visual-approach procedure based on visual descent point (VDP) for initiation of descent.

(10) Approximate GNS, placard on vertical-speed indicator.

Based on approach outcomes, it appeared that pilots could not cope successfully with the more severe wind shears using conventional (baseline) flight instruments and procedures.

The next simulation tests, DC-10 Phase 2, involved three distinct formal comparison experiments.[2] In all three the situation was a Category I precision approach with 300-foot ceiling. Three wind shear profiles and one no-shear condition were used. The pilots were asked to continue each approach down to the 100-ft altitude point, even if they thought a G/A should be made, to provide a quantity of data on approach outcomes. The window defining an acceptable or "in-limits" approach outcome is given in Table 7. Experiment 1 compared with baseline three speed-management aids based on GNS:

GNS-1--Analog GNS on V_{mo} needle on AS indicator

GNS-2--GNS on digital readout

ΔW--Wind difference as AS command plus digital readout plus F/S command

Table 7

WINDOW* FOR IN-LIMITS APPROACH

Parameter	DC-10	B-727
Vertical offset from glideslope less than	± 28 ft (2 dots)	± 28 ft
Lateral offset from localizer less than	± 75 ft (runway width)	± 75 ft
Rate of descent less than	1500 ft/min	1500 ft/min

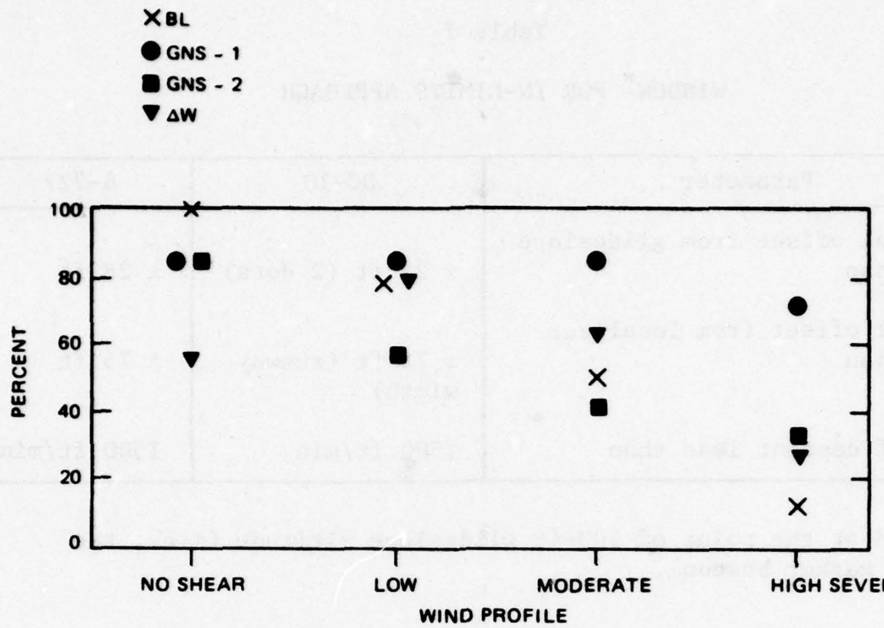
*Placed at the point of 100-ft glideslope altitude (i.e., the inner marker beacon).

Figure 15 shows the percent of the approaches that were in-limits at the inner marker; GNS-1, the two needle display, was the best performer by a significant margin. More insight is provided by Figure 16, which shows that all three aids were effective in avoiding airspeed loss on the high-severity wind shear. The pilot average acceptance ratings, on a scale of 1 (not at all confident) to 5 (highly confident) were:

Baseline	3.0
GNS-1	3.9
GNS-2	3.5
ΔW	3.1

This experiment confirmed that conventional (baseline) approach management was not effective in coping with moderate and high-severity wind shear.

Next, experiment 2 tested FPA, displayed on analog tape on the ADI, against baseline. This was motivated by the idea that while FPA was judged to perform poorly in Phase 1, the concept had enough theoretical appeal to be tried on an accessible integrated display. Two FPA algorithms were tested:



NOTE: Proportion within limits at 100 ft

FIGURE 15 GNS EXPERIMENT APPROACH OUTCOMES

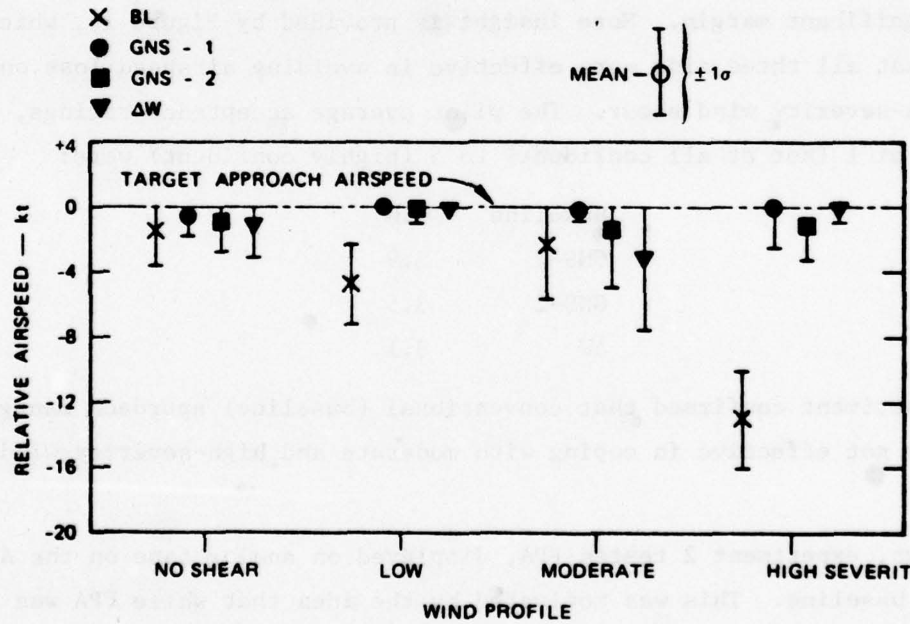


FIGURE 16 MAXIMUM DROP IN INDICATED AIRSPEED OVER THE 800- TO 100-FOOT APPROACH SEGMENT

γ_{GM}: Ground referenced FPA,

γ_H: Hybrid FPA, computed from altitude rate divided by true airspeed.

Two procedures were tested, one with the pilot flying by flight director and monitoring FPA, and the second with the pilot using raw localizer and glideslope deviations with FPA for path-rate information. Results are shown in Figure 17; the only significant differences are where the FPA aid performed worse than baseline. The airspeed losses were not significantly different for these cases, and the pilot acceptance ratings were:

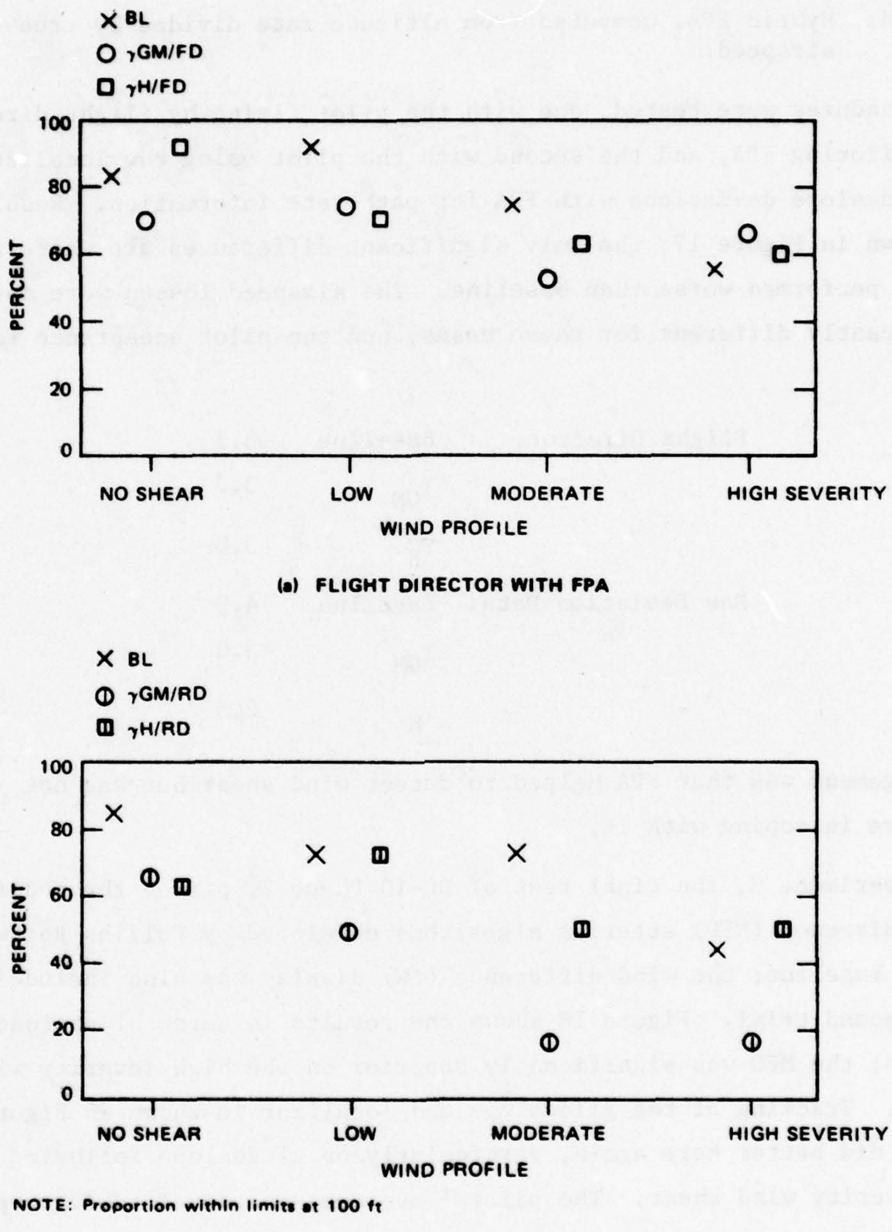
Flight Director:	Baseline	3.1
	γ_{GM}	3.3
	γ_H	3.0
Raw Deviation Data:	Baseline	4.0
	γ_{GM}	3.0
	γ_H	2.5

The judgement was that FPA helped to detect wind shear but was not effective in coping with it.

Experiment 3, the final test of DC-10 Phase 2, pitted the modified flight director (MFD) steering algorithms developed by Collins-Rockwell against baseline; the wind difference (ΔW) display was also included, for a second trial. Figure 18 shows the results in terms of approach outcomes; the MFD was significantly superior on the high-severity wind profile. Tracking of the glideslope and localizer is shown in Figure 19; the MFD did better here again, particularly on glideslope following with high-severity wind shear. The pilots' average acceptance ratings were:

Baseline:	3.0
MFD:	3.6
ΔW:	3.6
MFD + ΔW:	4.1

It was concluded that the MFD held real promise as an aid in wind shear.

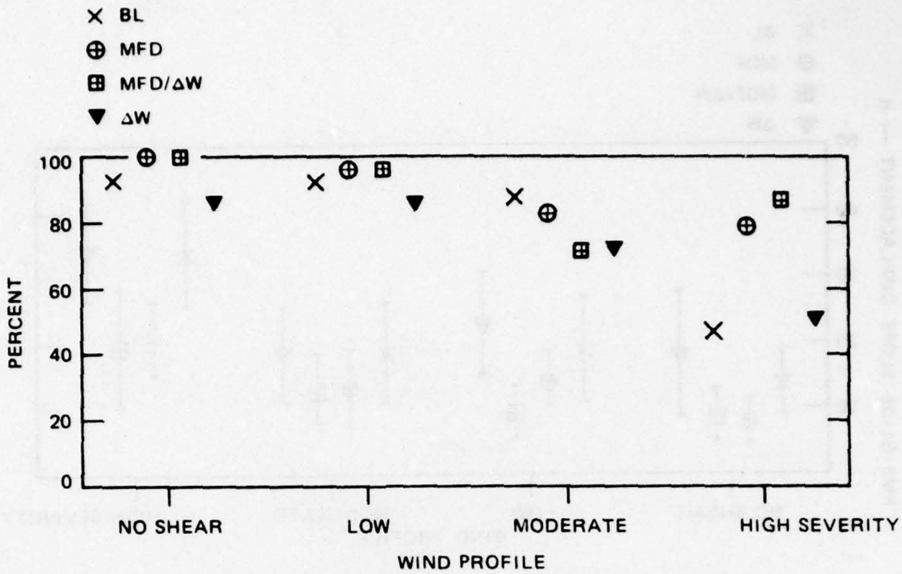


(a) FLIGHT DIRECTOR WITH FPA

NOTE: Proportion within limits at 100 ft

(b) RAW DEVIATION DATA PLUS FPA

FIGURE 17 FPA EXPERIMENT APPROACH OUTCOMES

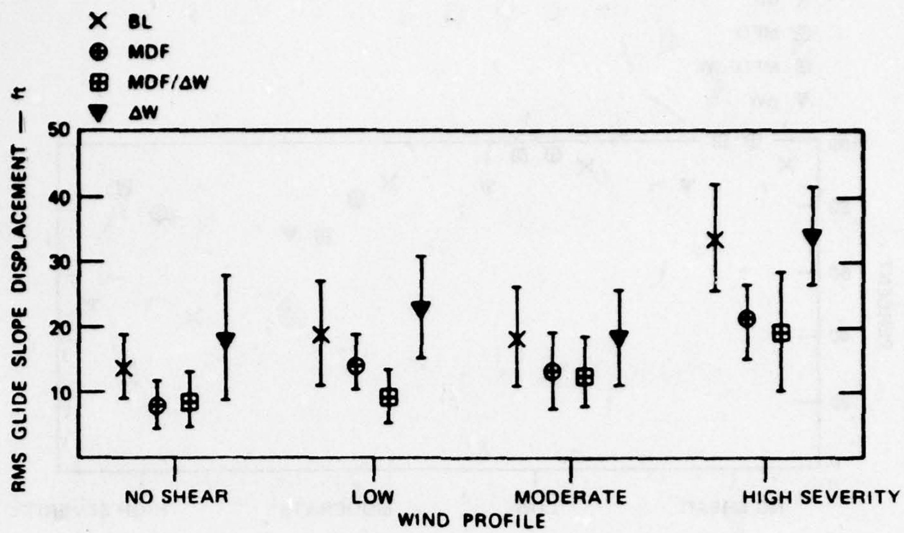


NOTE: Proportion within limits at 100 ft

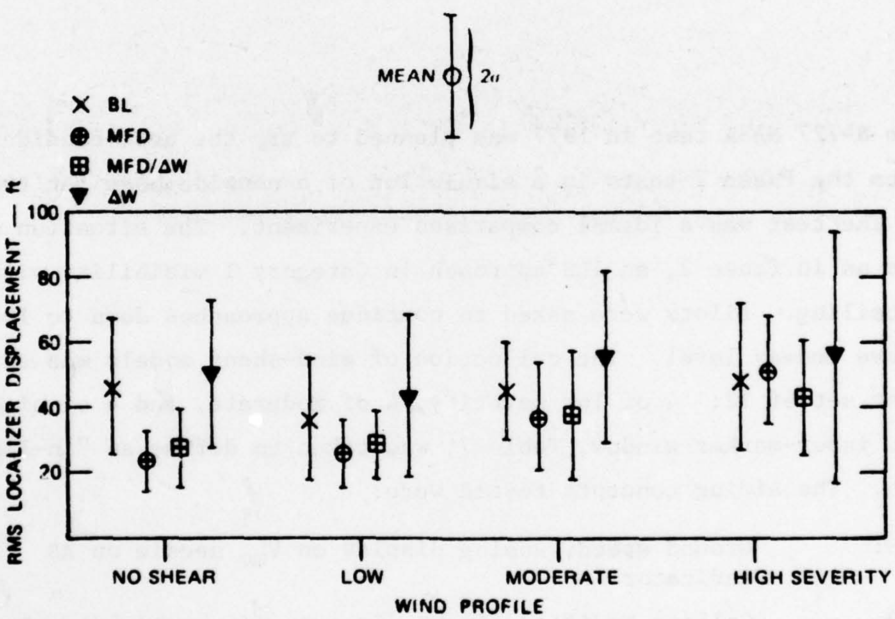
FIGURE 18 MFD EXPERIMENT APPROACH OUTCOMES

The B-727 NASA test in 1977 was planned to try the best candidate aids from the Phase 2 tests in a simulation of a nonwide-body jet transport.[3] The test was a formal comparison experiment. The situation was the same as in Phase 2, an ILS approach in Category I visibility with 300-ft ceiling. Pilots were asked to continue approaches down to 100 feet above runway level. The collection of wind-shear models was expanded to a test set of 12: 4 of low severity, 4 of moderate, and 4 of high. The same inner-marker window, Table 7, was taken to define an "in-limits" approach. The aiding concepts tested were:

GNS:	Ground speed, analog display on V_{mo} needle on AS indicator
MFD:	Collins modified flight-director pitch and lateral-steering algorithms
MFD + GNS:	Combination of GNS and MFD



(a) MEAN VARIATION IN GLIDE SLOPE TRACKING OVER THE 800- TO 100-FOOT APPROACH SEGMENT



(b) MEAN VARIATION IN LOCALIZER TRACKING OVER THE 800- TO 100-FOOT APPROACH SEGMENT

FIGURE 19 PATH TRACKING ACCURACY

Results in terms of approach outcomes are shown in Figure 20. The aids, on this showing, did not perform significantly better than the baseline method. The most notable result, however, is that the baseline "in-limits" percentage on high-severity wind shear was higher than in the DC-10 Phase 2 tests (Figures 15, 17, 18). This is explained by Figure 21, which shows the airspeed data; baseline has no large loss of airspeed on the high-severity profiles (compare with the loss shown in Figure 16) indicating that the B-727 pilots used airspeed pads to help cope with the winds. The pilot average acceptance ratings (again, "1" = not at all confident, "5" = highly confident) for this test were:

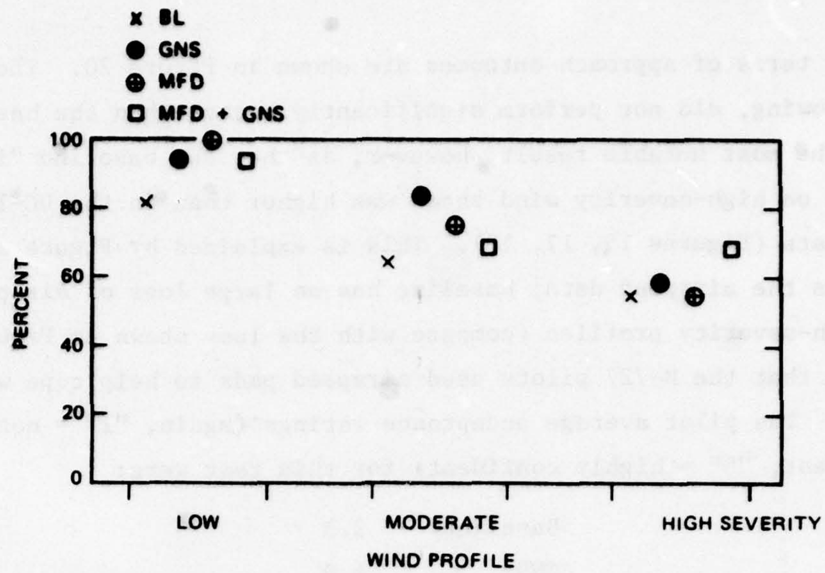
Baseline:	3.3
GNS:	4.0
MFD:	3.7
MFD + GNS:	4.1

It was concluded that airspeed pads, the GNS technique, and the MFD were all helpful B-727 aids. The pilots judged that the GNS and MFD aids represent clear improvements over baseline.

In the autumn of 1977 we conducted the DC-10 Phase 3 flight-simulation tests to evaluate the capabilities of improved GNS displays, improved MFD algorithms, and candidate G/A decision aids to provide solutions to wind-shear encounters on approach and landing. The situation simulated was an ILS approach in Category I visibility with 150-ft ceiling. Runway was 150 by 7,000 ft. The pilots were asked to execute a G/A when and if they considered it to be appropriate. When the approach was continued to touchdown, it was judged to be an "in-limits" landing if the aircraft state was inside the touchdown window defined in Table 8; the limits were derived from the DC-10 airplane configuration. Comparatively brief initial trials (4 pilots; 6 wind-shear profiles, 3 moderate and 3 high severity) were conducted to try out various panel GNS displays and two versions of the MFD integrated with speed command (developed by Collins).

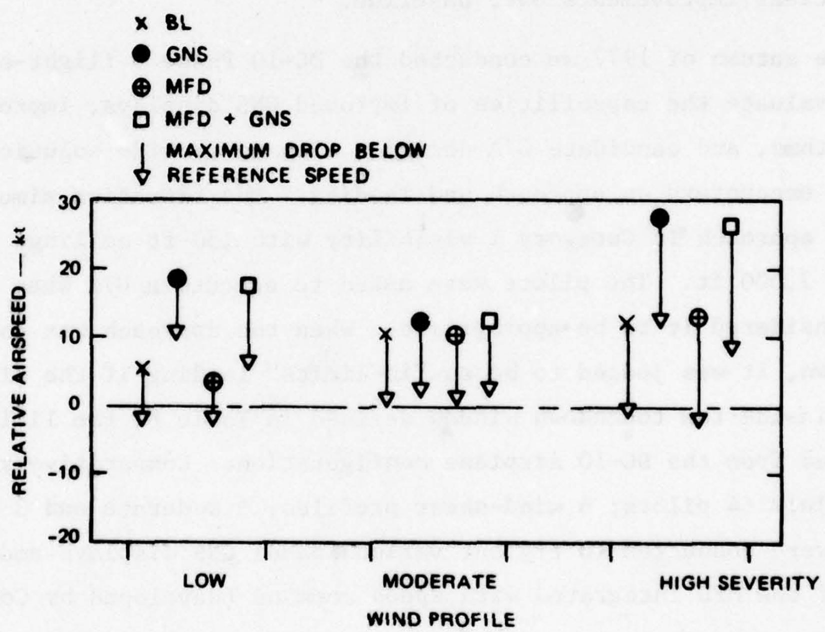
GNS-3: GNS, analog, on the V_{mo} needle of the AS indicator plus command on the F/S

GNS-4: GNS-based command on the F/S.



NOTE: Proportion within limits at 100 ft

FIGURE 20 B-727 NASA APPROACH OUTCOMES



NOTE: Proportion within limits at 100 ft

FIGURE 21 B-727 NASA AIRSPEED MANAGEMENT

Table 8

WINDOWS FOR IN-LIMITS TOUCHDOWN

Parameters	DC-10 Phase 3	DC-10 Phase 4
Position		
Longitudinal	Between threshold and 3,000 ft of runway	Between threshold and point where stopping roll would run over end
Lateral	± 50 ft from runway centerline	± 50 ft from centerline
Velocity		
Rate of descent	Less than 11 ft/sec	Less than 14 ft/sec
Lateral speed	Less than 15 ft/sec	Less than 15 ft/sec
Attitude		
Pitch angle	+ 1 to + 13 degree	0 to + 13 degree
Roll angle	± 9 degree	± 9 degree

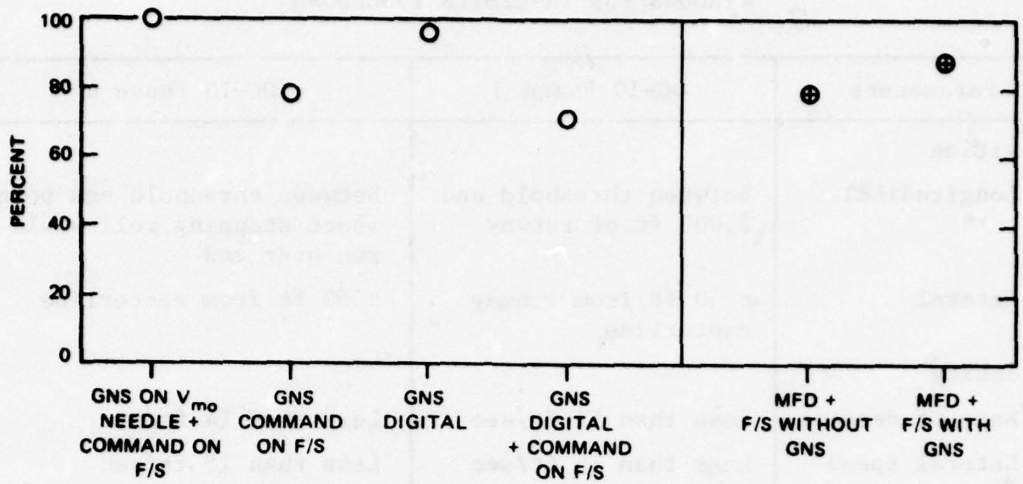
GNS-5: Digital display of GNS above the ADI.

GNS-6: GNS, digital, above the ADI plus command on the F/A.

MFD + F/S without GNS: Modified flight director steering plus airspeed-based F/S command.

MFD + F/S with GNS: Modified flight director steering plus F/S command with diminishing head-wind shear compensation

The results, in terms of the percent of the 24 total approaches with each aid that did not end in an out-of-limits impact with the ground, are shown in Figure 22. The GNS-3 method was best and the MFD with GNS information did better than without. The pilot preferences favored GNS-3 and GNS-6. Various go-around (G/A) decision aids were compared in another brief initial trial (4 pilots, 6 wind profiles as before). We recognized that a G/A advisory technique should incur a performance penalty for nuisance alarms, and so we set up the approach-and-landing performance scoring scheme[5] shown in Table 9. When averaged over all test runs, the best possible score is +10, the worst score is -10, and



NOTE: Proportion of approaches that were in-limits touchdowns or successful go-arounds

FIGURE 22 PHASE 3 INITIAL TRIALS: GNS AND MFD

Table 9

SYSTEM PERFORMANCE SCORING: APPROACH AND LANDING

Points Given for Each Run			
Result of Run	Wind Profile Severity		
	Low	Moderate	High
Touchdown in limits	+10	+10	+10
Touchdown out of limits	-10	-10	-10
G/A attempted, successful	-5	+2	+10
G/A attempted, unsuccessful	-10	-10	-10

the score is reduced for G/A's on wind shears of low and moderate severity.

The G/A decision aids tested were:

BL:	Baseline instruments and G/A decided per conventional practice.
Modified BL Procedure:	BL instruments, decide G/A if rate of descent is greater than 1,250 ft/min and glideslope deviation is lower than 1.75 dots.
ENR:	Energy-rate analog display, on panel, with warning light (developed by Douglas).
MFD + F/S with GNS + ENR:	Modified flight director and F/S with ENR for G/A decision.
ΔA:	Acceleration margin criterion for G/A advisory, warning light (developed by FAA).
GNS-3 + ΔA:	GNS displayed on V_{mo} needle + command on F/S + ΔA for G/A decision.

The performance score results are shown in Figure 23. The aiding concepts are clearly superior to the baseline methods, and the

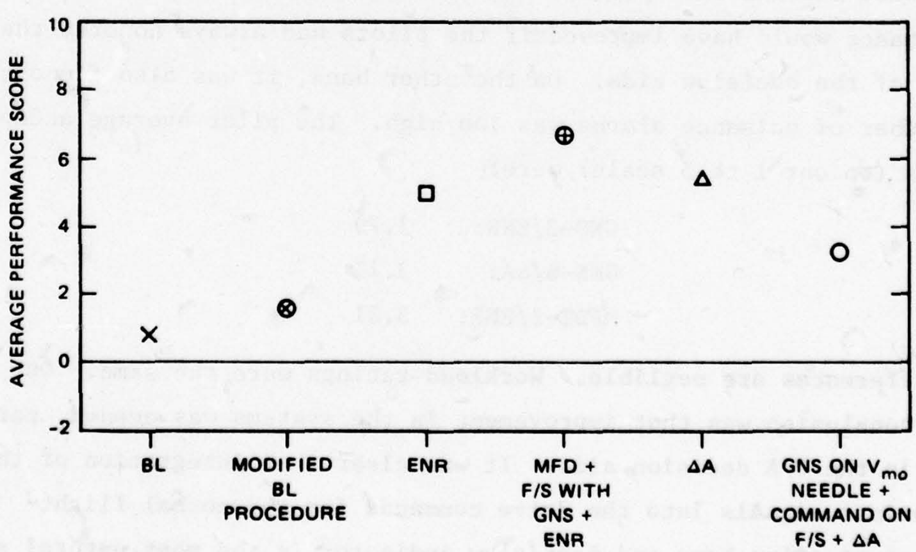


FIGURE 23 INITIAL TRIALS: GO-AROUND DECISION AIDS

performance of the energy rate and acceleration-margin devices was comparable.

The major effort of Phase 3 was a full trial[4] of candidate systems for coping with wind shear in which we had 26 subject pilots, a notably large number. The situation was the ILS approach, Category I, as before, and pilots made a G/A if they thought it appropriate. Of eight wind-shear profiles used, 4 were for training runs with the aiding systems and 4 were for test (2 moderate and 2 of high severity). Each system tested included accelerated augmented flight-director steering and/or improved speed management plus a G/A decision aid:

GNS-3/ENR:	Analog GNS displayed on the V_{mo} needle + command on the F/S plus energy-rate indicator and warning light.
GNS-6/ΔA:	Digital GNS above the ADI plus command on the F/S plus acceleration-margin warning light.
MFDT-2/ENR:	Modified flight director plus F/S command with GNS plus energy rate.

Results of the 104 runs with each system, in terms of average performance (Table 9) scores, are shown in Figure 24. There was no significant difference between the systems. A detailed analysis indicated that the performance would have improved if the pilots had always honored the G/A advice of the decision aids. On the other hand, it was also found that the number of nuisance alarms was too high. The pilot average acceptance ratings (on our 1 to 5 scale) were:

GNS-3/ENR:	3.79
GNS-6/ΔA:	3.77
MFDT-2/ENR:	3.81

The differences are neglible. Workload ratings were the same. Our major conclusion was that improvement in the systems was needed, particularly in the G/A decision aids. It was clear that integration of the appropriate signals into the drive commands for the normal flight-director steering bars and fast/slow indicator is the most natural and effective way to aid the pilot in approach management. It was noted that the pilot should have backup information to verify the aircraft state

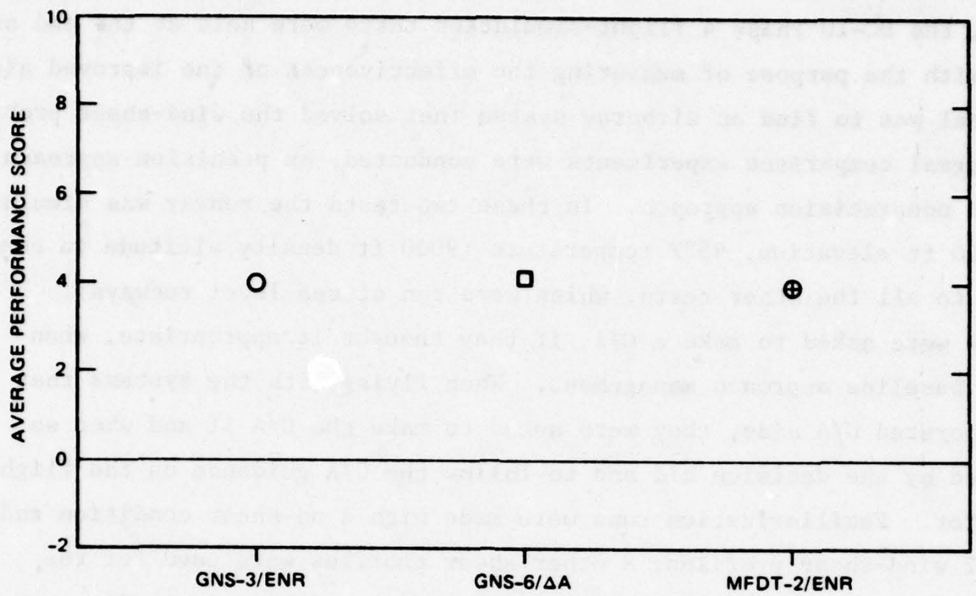


FIGURE 24 FULL TRIAL: SYSTEM PERFORMANCE

and to provide some assurance that the fast/slow command was appropriate. Backup information is particularly important in support of any go-around decision aid or advisory. The subject pilots expressed strong opposition to having only the warning light without some information to show why the light had turned on. It was noted that pilots in actual operations would be reluctant to accept and act on a go-around advisory when the other displays seemed to indicate that the approach was within acceptable limits. When cross-checks of the conventional instruments did confirm the go-around warning, it was often too late to execute a successful missed-approach. Therefore, a go-around advisory or wind-shear warning should not only be issued in an on-off fashion, but also should be supported by a display of the reason for the warning and an analog display of information that would enable the pilot to see a trend toward a hazardous state. The instruments in conventional use (baseline) do not supply all the information needed.

After a considerable amount of development work on the aiding concepts, the DC-10 Phase 4 flight-simulation tests were held at the end of 1978 with the purpose of measuring the effectiveness of the improved aids.[5] The goal was to find an airborne system that solved the wind-shear problem. Two formal comparison experiments were conducted, on precision approach and on nonprecision approach. In these two tests the runway was simulated at 5300 ft elevation, 95°F temperature (9000 ft density altitude in contrast to all the other tests, which were run at sea level runways). Pilots were asked to make a G/A, if they thought it appropriate, when using baseline approach management. When flying with the systems that incorporated G/A aids, they were asked to make the G/A if and when so advised by the decision aid and to follow the G/A guidance on the flight director. Familiarization runs were made with a no-shear condition and with 2 wind-shear profiles; 8 other shear profiles were used for the test, of which 5 were selected for each session with a given pilot and system: 2 low-severity shear, 1 moderate, and 2 high.

The Phase 4 precision-approach experiment simulated an ILS approach in Category I visibility, 150-ft ceiling, to a runway 150 by 11,500 ft. Ten subject pilots tested each of 3 systems:

BL:	Baseline (conventional) approach management.
MFD/ΔA:	Modified flight director plus F/S with GNS plus acceleration margin plus modified algorithm for G/A guidance (system described in Section V.B).
GNS/RED:	GNS, analog, on V_{mo} needle plus command on F/S plus run evaluation (microprocessor) display plus modified algorithm for G/A guidance.

Note that, as compared with the Phase 3 instrumentation, the acceleration margin (ΔA) algorithm was improved to provide greater inhibition of nuisance alarms, and an integrated analog display of ΔA-GNS-AS was supplied for the MFD/ΔA system. The results in terms of performance scoring (Table 9) are shown in Figure 25. The MFD/ΔA performance is much better than baseline, better than GNS/RED, and reasonably close to the expected top level (8.0) corresponding to the score that would be obtained in a comparable flight-simulation test with no wind shear.[5] Another significant factor, avoidance of airspeed loss, is shown in Figure 26; the MFD/ΔA system is nearly ideal on this measure. The

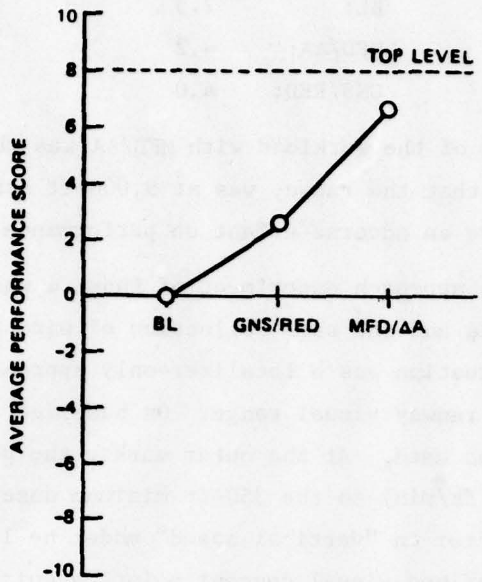


FIGURE 25 SYSTEM PERFORMANCE — PRECISION APPROACH

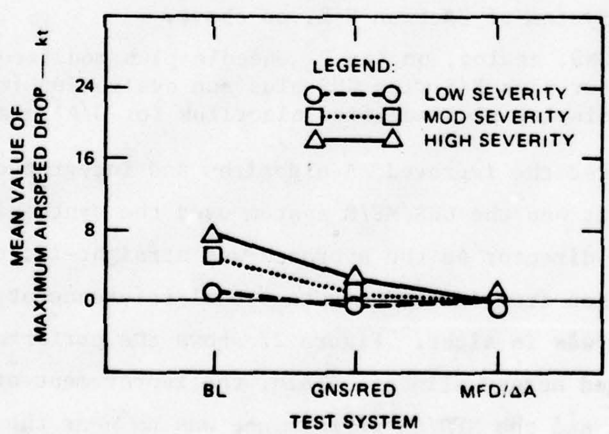


FIGURE 26 MAXIMUM DROP IN AIRSPEED OVER THE 500- TO 100-FOOT PRECISION APPROACH SEGMENT

pilot average ratings of acceptability (1 = no wind-shear solution, 5 = acceptable solution) were:

BL:	2.5
MFD/ΔA:	4.2
GNS/RED:	4.0

Subjective evaluation of the workload with MFD/ΔA was that it was not excessive. The fact that the runway was at 9,000-ft density altitude did not appear to have an adverse effect on performance.

The nonprecision approach experiment of Phase 4 was conducted with 10 more subject pilots and the same collection of wind profiles to the same runway. The situation was a localizer-only approach with 400-ft ceiling and 5,000-ft runway visual range. On baseline runs a 3-step approach procedure was used. At the outer marker the pilot made a steep descent (about 1,000 ft/min) to the 350-ft minimum descent altitude (MDA) with the flight director in "vertical speed" mode; he leveled off at MDA, proceeded to a DME-defined visual descent point, acquired the approach lights and runway visually, and completed the approach by visual reference. The systems tested were:

BL:	Baseline.
MFD/ΔA:	System of Section V-B, as above.
GNS/MF/R:	GNS, analog, on the V_{mo} needle plus modified flight director plus F/S with GNS plus run evaluation (microprocessor) display plus modified algorithm for G/A guidance.

MFD/ΔA incorporated the improved ΔA algorithm and integrated display, as above. Both it and the GNS/MF/R system used the synthesized 3° glidepath with flight director so the approach was straight-in; the pilot made the transition from instruments to visual reference at his option after the runway was in sight. Figure 27 shows the performance scoring (Table 9) averaged across pilots. Again, the improvement of MFD/ΔA over BL was striking, and the MFD/ΔA performance was up near the expected top level. The same good results for the aiding systems in terms of avoiding airspeed loss are shown in Figure 28. The pilot average ratings of acceptability (scale 1 to 5) were:

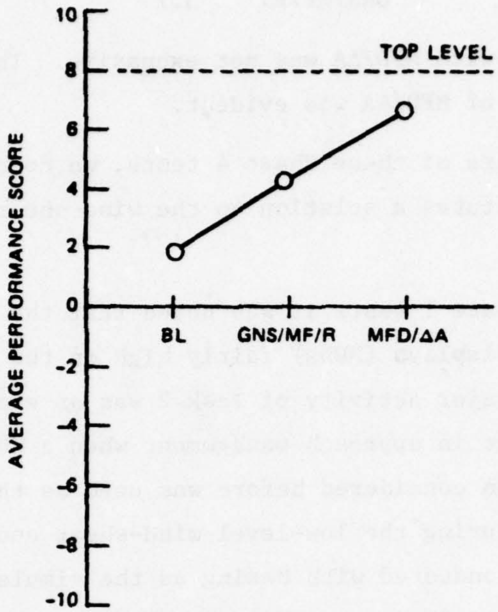


FIGURE 27 SYSTEM PERFORMANCE — NONPRECISION APPROACH

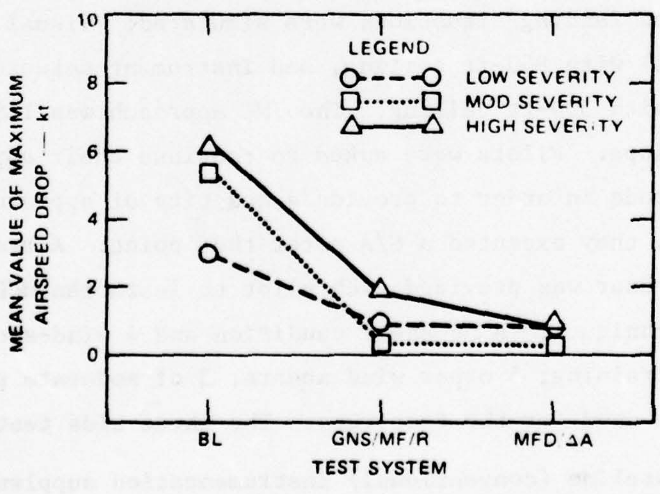


FIGURE 28 MAXIMUM DROP IN AIRSPEED OVER THE 500- TO 100-FOOT NONPRECISION APPROACH SEGMENT

BL:	2.2
MFD/ΔA	3.8
GNS/MF/R:	3.7

Again, the workload with MFD/ΔA was not excessive. The superiority in overall performance of MFD/ΔA was evident.

Given the results of these Phase 4 tests, we concluded that the MFD/ΔA system constitutes a solution to the wind-shear problem on approach and landing.

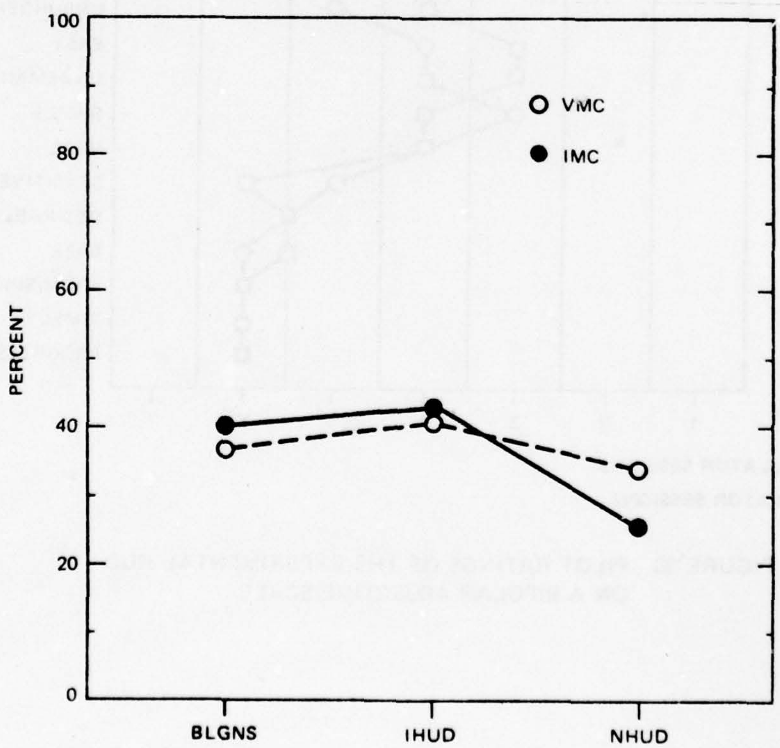
In the DC-10 Phase 1 tests it was noted that the evaluation pilots ranked the head-up displays (HUDs) fairly high on the list of candidate methods. The last major activity of Task 2 was an evaluation of the potential improvement in approach management when a HUD rather than the panel instrumentation considered before was used as the primary flight-control instrument during the low-level wind-shear encounter. This B-727 HUD test was conducted with Boeing as the simulation subcontractor (Section II-C) using a Boeing-supplied R&D HUD that featured extra-wide vertical and lateral fields of view. The two HUD versions (same hardware, different drive algorithms) tested are discussed in Section V-C. The test was a formal comparison experiment with 12 subject pilots. Two approach and landing situations were simulated: visual meteorological conditions (VMC) with 850-ft ceiling, and instrument meteorological conditions (IMC) with 300-ft ceiling. The IMC approach was ILS-supported with 3° glideslope. Pilots were asked to continue their approaches down to 100-ft altitude in order to provide a quantity of approach outcomes; if appropriate, they executed a G/A after that point. A training session of at least an hour was provided each pilot to learn the HUD symbology and control techniques. A no-shear condition and 4 wind-shear profiles were used for training; 5 other wind shears, 3 of moderate severity and 2 of high, were used for the test runs. The three aids tested were:

BLGNS: Baseline (conventional) instrumentation supplemented by GNS, analog, on the V_{mo} plus command on F/S (Section V-A).

IHUD: HUD with ground-referenced drive signals for flight-path angle and other variables.

NHUD: HUD without GNS; flight-path angle approximated by hybrid air-mass and ground referenced information.

Remark that the two HUD versions were being tested against a panel display, BLGNS, that had been found to work well in wind shear in the previous simulation tests. The window of Table 7 defined an "in-limits" approach at the inner marker. Results in terms of approach outcomes are shown in Figure 29. Performance of BLGNS and IHUD were not significantly different, while the NHUD did less well, particularly on the VMC case. In terms of avoidance of airspeed loss, the three systems showed comparable results. Pilot subjective evaluation of workload and measures of the control activity also showed no appreciable differences. A semantic-differential questionnaire on the usefulness of this type of HUD was given the pilots, with the average results shown in Figure 30. In general, pilot acceptance of the HUD concept was positive. However, they found use of the HUD to be difficult and demanding, and the symbology to be complex and overly sensitive to control inputs and disturbances.



NOTE: Proportion of runs in-limits at 100-ft window

FIGURE 29 B-727 HUD TEST: APPROACH OUTCOMES

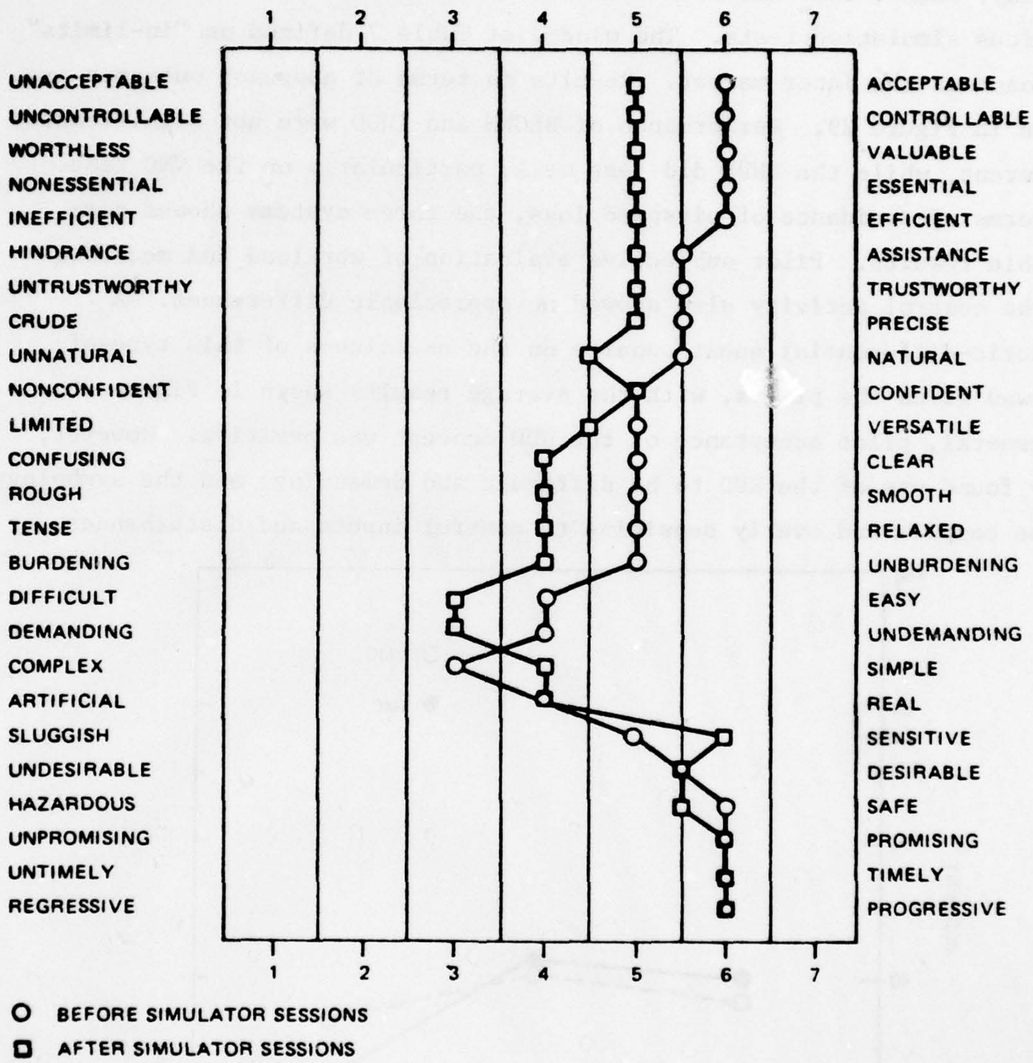


FIGURE 30 PILOT RATINGS OF THE EXPERIMENTAL HUD ON A BIPOLAR ADJECTIVE SCALE

The most unacceptable features of the test HUD formats were the guidance provided for lateral flight-path control, especially on the NHUD, and the limitations in horizontal field of view when high drift angles were required. We concluded that in wind shear the HUD without GNS information performed more poorly, but the HUD with GNS did as well as the panel display. The HUD concept had promise, but needed further development.

B. Comparison of Aiding Concepts

Note that the successful system, MFD/ΔA, consists of four functional elements: a programmed speed pad when anticipating a head-wind loss (provided by the fast/slow algorithm and thrust-control procedure based on ground speed), tight path control (provided by the modified flight director steering), a go-around decision aid (provided by the acceleration margin computation), and a minimum height-loss guidance aid for go-around (provided by the modified go-around steering command on the flight director). Even with all the simulator tests and analytical work that have been done, it is not easy to assess the relative merit of the individual functional elements. However, there were tests[4] of the speed control and MFD without the go-around aids, and the performance (while better than baseline) was not found to be adequate. It appears that both good flight-path control and an effective G/A aid are necessary elements of a successful system.

The effectiveness of various individual aids can be compared directly because several formal experiments were conducted to make such tests. The most useful way, overall, is to compare the performance of each aiding concept to conventional (baseline) approach-and-landing management. Table 10 summarizes these comparisons in general terms, considering all useful measures (approach outcomes, touchdown outcomes, path following, speed control, workload, and acceptability). In the table, the simulation tests from which the conclusions are drawn are shown.

Table 10

IMPROVEMENT OVER BASELINE IN APPROACH MANAGEMENT
EXPECTED WITH VARIOUS AIDS

Aiding Concept	Precision Approach: Wide-Body DC-10	Precision Approach: Nonwide-Body B-727	Non-Precision Approach: Wide-Body DC-10
AS/GNS concept of speed control	DC-10, Ph. 2, Significant improvement	B-727, NASA, Probable improvement	DC-10, Ph. 4, Contributed to improvement
Modified flight director	DC-10, Ph. 2, Significant improvement	B-727, NASA Probable improvement	DC-10, Ph. 4, Contributed to improvement
Acceleration margin for G/A advisory	DC-10, Ph. 3, Significant improvement		DC-10, Ph. 4, Contributed to improvement
Energy rate for G/A advisory	DC-10, Ph. 3, Significant improvement		
Modified G/A guidance	DC-10, Ph. 4, Contributed to improvement		DC-10, Ph. 4, Contributed to improvement
Flight Path Angle (panel display)	DC-10, Ph. 2, No improvement		
IHUD (ground referenced)		B-727, HUD, Probable improvement	
NHUD (hybrid air/ ground reference)		B-727, HUD, No probable improvement	

C. <u>Takeoffs</u>

Exploratory trials of takeoffs in wind shear were run in the DC-10 Phase 1 and Phase 3 tests to gain insight into the problem and make preliminary assessments of possible aids.[1,4] Further studies with computer models[7] showed that the hazard on takeoff is at least as dangerous as that on landing and the range of possibly effective control actions in response to shear is much more limited. On a takeoff on which a head-wind loss or a downdraft or both occur (either can lead to the airplane sinking below the desired flight path) the appropriate response is to advance the throttles to full thrust (they may already be there) and to steer in pitch so as to minimize the loss of altitude. In effect, the airplane should be controlled to get maximum available lift. There are realistic wind profiles in which even this operation at the limit of airplane capability is not enough to prevent ground contact.

The most comprehensive set of takeoff simulation trials was conducted in the DC-10 Phase 4 exercises.[5] The simulation scenario adopted was designed to represent a normal, full-thrust takeoff. Air density and temperature conditions represented in the simulation were set for a sea-level field elevation and a standard day. The runway was 150 by 10,400 feet and there were no visibility restrictions.

Five wind profiles were developed especially for the takeoff tests. Four were thunderstorm wind fields characterized by a substantial head-wind shearout during the first 500 feet of the climbout. On three of these thunderstorm shears the head-wind shearout was accompanied by a downdraft in excess of 10 knots. The fifth wind profile represented a frontal shear, with a milder head-wind shearout occurring in combination with a downdraft of less than 5 knots.

Takeoff sequences were initiated from brake release with the aircraft on the runway centerline. The pilot advanced the throttles to takeoff position where they were trimmed for a 102% N_1 setting by the "First Officer" (FO) in the right seat. The FO called out V_1 (130 knots) and V_R (136 knots), and the pilot executed a normal rotation and climbout following the test procedure to be described.

All takeoff sequences were flown using the instrument panel configuration shown in Figure 7 for the MFD/ΔA test system. However, the only element of this test system considered appropriate to the takeoff situation was the modified flight-director pitch-steering commands developed for go-around guidance (see description in Section V-B-3). The standard DC-10 pitch steering command for takeoff, which attempts to stabilize the climbout at V_2 + 10 (158 knots) and incorporates a minimum angle of attack reference, was used as a baseline comparison system.

To obtain additional information on possible control strategies for coping with the shear encounter on takeoff, two variations on the use of the modified flight director and two variations of the baseline procedure were tested. The four resulting test situations were defined as follows:

(1) Follow standard DC-10 pitch steering command immediately after rotation; this was BL.

(2) Pitch up to 15° at rotation and thereafter attempt to establish and maintain V_2 + 10 by reference to the airspeed indicator, with no pitch-steering command available; hereafter referred to as "no flight director" (NOFD).

(3) Follow the modified pitch-steering command immediately after rotation; hereafter referred to as "MPD at lift-off" (MPD).

(4) Use BL procedure for rotation and initial climb and switch to MPD when shear effects are encountered; hereafter referred to as "MPD option" (MPD opt).

The three pilots flew four 5-run test series, one for each of the alternative climbout control strategies. The evaluation of takeoff outcomes was thus based on a total of 60 data runs, and contrasts between alternative control strategies were based on 15 runs using each technique.

Each session consisted of a brief training series on the selected control technique and then one data run for each of the five wind profiles. In all instances when severe shear effects were encountered, the throttles were advanced to an overboost condition of 113% of N_1.

The outcomes of the takeoff attempts through the five test shear conditions were remarkably consistent for the three pilots and, for the most part, showed little difference across the four control strategies.

Encounters with the combined head-wind shearout and low-level downdraft were extremely hazardous for both BL and the test systems. Crashes were recorded on all of the test runs under these conditions. On another profile the severest portion of the downdraft was encountered above 500 feet and, terrain permitting, this shear might be survivable. However, a 500-foot loss of altitude was typical for this shear condition. Encounters with the milder thunderstorm profile with no downdraft and with the frontal shear were comparatively benign; none of the pilots had any difficulty climbing through these conditions using any of the four control strategies.

The overall picture given by the takeoff outcome data was that individual wind-shear effects were dominant and that none of the aiding techniques tested could cope effectively with the combined effects of a head-wind shearout and downdraft during the first 500 feet of the climb-out.

VIII CONCLUSIONS

Task 2 consisted of a series of piloted flight-simulation tests supported by analytical and experimental studies of airplane response to wind shear and the meteorological phenomena that produce low-level shear. Approach-and-landing tests were run under different conditions of visibility, with different levels of approach instrumentation (full ILS and localizer only), and with both wide-body and nonwide-body jet transports. The simulation experiments were run with a significantly large number of experienced pilots and the simulators were of good quality. While the data on the subject were sparse, the project team was convinced that for both training and tests on wind-shear effects a moving-based simulator with faithful aerodynamic response is greatly to be preferred over fixed-base or simulator motion of less than six degrees of freedom.

A major conclusion, over all the tests, was that conventional (baseline) approach-management techniques, based on attempts to maintain a stabilized indicated airspeed from glide-slope capture to the flare, are not effective in coping with the more severe (e.g., frontal and thunderstorm) wind-shear encounters. The percentage of acceptable approach outcomes under these conditions was generally less than 50%.

The development effort that led up to the DC-10 Phase 3 tests emphasized approach management, considering both acceleration augmentation and use of ground-speed information. The results showed that ground speed is particularly important; it was needed in all three systems selected for the Full Trial. The systems differed in their steering algorithms (baseline DC-10 or Collins acceleration augmentation) and their speed commands (ground-speed error or Collins modification with head-wind shear compensation) but their performance was comparable. This suggests that several potential solutions to the wind-shear problem are available.

In the DC-10 Phase 4 tests the systems were augmented with new displays, more effective go-around decision aids, and minimum height-loss go-around guidance. This produced the MFD/ΔA system. Results for both the precision and nonprecision approach demonstrated a substantial and operationally significant increase in the safe management of low-level shear encounters when the pilot-aiding features of the MFD/ΔA system were available. This system produced within-limit touchdowns or successfully executed go-arounds on all of the more hazardous high-severity shear encounters for the precision approach. On the nonprecision approach this level of performance was achieved on all but one of the high-severity shear encounters. Over all levels tested of wind-shear severity, and for both precision and nonprecision approaches, the MFD/ΔA performance showed a major improvement over baseline as well as coming close enough to the expected top level of performance (which corresponds to the simulator results with no shear). The MFD/ΔA system performed well enough and ranked high enough in acceptability to be recommended as a solution to the wind-shear problem on approach and landing. We do not mean to imply, of course, that MFD/ΔA is the only solution nor even that it is the most economical solution. We can only say that it is the system that has been found to work, and that the line of development taken (starting with minimal changes to the airplane instrumentation and introducing more complexity only when needed for improved performance) implies that it should be reasonably cost effective.

It was found that pilot workload, reflected by pilot judgements of the level of mental and physical effort involved in managing the wind-shear encounter, was not significantly increased over baseline when any of the aiding concepts were used. The most noticeable effects on workload are associated with the severity level of the shears. We also concluded that with sufficient training and familiarization, pilots will accept an approach-management technique calling for deliberate variation in command airspeed to cope effectively with the low-level shear environment.

The aiding systems that showed a significant performance improvement over baseline in wind shear required instrumentation of certain aircraft variables and wind components that are not available in many current aircraft. Certain other required quantities that are available in some aircraft but not in others are not measured currently to the necessary accuracy or with the required response time. Wind shear is a dynamic phenomenon, so the smoothing (or averaging) time of an instrument must be chosen carefully to respond quickly enough without being so fast that it is overexcited by turbulence. Of the quantities that are usually not available or not measured adequately, the most important are ground speed, altitude above the runway, and altitude rate. Specifications for these measurements were developed and reported.[5]

The test results support a firm requirement for accurate knowledge of the winds on the runway; the along-runway component is needed by algorithms such as the acceleration margin, and the cross-wind component is needed to enable the pilot to anticipate his lateral-control action. On approach-and-landing the wind readings are needed in the touchdown zone; on takeoff they should be read at both the near and far ends of the runway. Because the winds can change rapidly in wind-shear situations such as thunderstorms, the data should be transmitted to the pilot with as little delay as possible.

Most of the pilots participating in the B-727 HUD study felt that the head-up display provided very good information for detecting significant wind-shear effects on the approach. In some instances, the HUD provided dramatic indications of wind effects, such as the flight-path symbol dropping out of the bottom of the display when strong downdrafts were encountered, and the loss of lateral guidance information in high cross-wind conditions. But in too many instances, as indicated by the test results, this information became available too late for corrective action to be effective, or the guidance provided for control action was not adequate.

The tests showed that there are realistic wind-shear conditions that, occurring on takeoff, exceed the aerodynamic and thrust capability of the airplane. An attempt to make a normal takeoff in such a situation, even when aided by a minimum-height-loss pitch-steering algorithm, cannot be retrieved by pilot action. The most appropriate recourses we have found are either not to attempt to take off at all, to take off in a different direction, or else to prolong the takeoff roll so that rotation will lift the airplane off with 20 knots or more of excess airspeed. Either action, in practice, requires advance notice (that is, prior to starting the takeoff roll) of the wind-shear condition.

IX RECOMMENDED TEST PROCEDURES AND PERFORMANCE REQUIREMENTS FOR DEVICE QUALIFICATION

Perhaps the most important thing to come out of the series of wind-shear tests and experiments was the design of a practical and effective experimental procedure for testing proposed aiding systems for approach and landing. The procedure is that used in the precision approach and nonprecision approach experiments of the DC-10 Phase 4 tests, and includes the following components:

- A collection of realistic three-dimensional wind models of three levels of severity. The wind field includes both shear and turbulence (when appropriate) and is programmed as functions of altitude and displacement.
- An airplane simulator of good quality with a good visual-scene generator. In these turbulent and dynamic wind conditions, simulator motion is needed for fidelity and for providing the pilot realistic cues. The airplane simulated is close to the upper limit of the normal range of landing weight.
- Participation of some 8 to 10 subject pilots, preferably with experience in airline operations; the experiment is run with a repeated-measures design (each pilot is compared against himself) to control for differences in pilot proficiency.
- Presentation of wind profiles and aiding systems to the subject pilots is counterbalanced and randomized to compensate for learning and fatigue.
- The training or familiarization runs include some wind profiles with shear, but do not include the test profiles.
- A performance scoring method like that defined in Table 9 is adopted.

We recommend that a test of this type be prescribed for the qualification of any candidate aiding system. The MFD/ΔA has, of course, passed the test. To be considered successful, a candidate system should be required to show both a significant improvement (for example, a mean score difference of at least 4.5 using Table 9) over conventional or baseline approach management, and an adequate absolute level of performance (for instance, a mean score of 6.0 or more).

APPENDIX: SUBJECT PILOTS

The pilots who acted as subjects in the flight-simulation tests are listed in Table A-1. They were recruited by the FAA with the assistance of the Air Transport Association and the Airline Pilots Association, and they contributed their services without remuneration from the project. Notable was the participation of many sectors of the aviation community: FAA, U.S. Air Force, Douglas, Boeing, Lockheed, and ten airlines. The professional excellence and efforts of these pilots, and the support of their sponsoring organizations, were greatly appreciated.

Table A-1

PILOT LIST

Pilot	DC-10 Ph. 1	DC-10 Ph. 2	B-727 NASA	DC-10 Ph. 3	DC-10 Ph. 4	B-727 HUD
Alexander, Don D., FAA Flight Test				x		
Andre, George, Trans World Airlines						x
Armstrong, Don, FAA, AWE-160						x
Attebery, O. E., American Airlines		x				
Booth, R. K., Continental Airlines				x		
Brown, Jack L., United Airlines					x	
Brown, William A., Pan American Airlines	x	x		x	x	
Brown, William R., ALPA/ Delta Airlines						x
Browning, William A., USAF 4950 TW					x	
Carlton, Wilfred M., Western Airlines				x		
Carpenter, S. M., USAF, MAC		x				
Carter, D. L., Western Airlines				x		
Cavanaugh, Dale, United Airlines						x
Cloud, D. E., American Airlines					x	
Cokeley, Ralph C., Lockheed Corp.		x		x	x	
Connor, Bill, Delta Airlines				x		
Connors, Paul C., USAF, 4950 TW					x	
Cusanelli, H. H., American Airlines				x		
Daniel, Terry A., USAF				x		

Table A-1 (Continued)

Pilot	DC-10 Ph. 1	DC-10 Ph. 2	B-727 NASA	DC-10 Ph. 3	DC-10 Ph. 4	B-727 HUD
Davenport, Richard A., FAA, ANW-270						x
DeBolt, Don, Northwest Airlines					x	
Doyle, John D., Northwest Airlines			x			
Dummer, Thomas M., Northwest Airlines			x			
Erdman, Ken, FAA, Test Pilot				x		
Estridge, W. W., American Airlines		x				
Frederickson, Jerry T., Northwest Airlines				x	x	
French, E. Craig, USAF, 3MAS		x		x		
Gannett, James R., Boeing Company		x		x	x	
Gorman, Ed, Continental Airlines				x		
Gough, Richard M., FAA, AFS-160						x
Hanna, Ron, American Airlines				x	x	x
Hazelhurst, G. A., American Airlines		x				
Hof, George A., Jr., American Airlines				x		
Imrich, Thomas, FAA, AFS-203					x	
Jehlik, R. R., Continental Airlines		x				
Johnson, E. W., FAA		x		x		
Knickerbocker, H. H., Douglas Co.				x		
Lahr, Ray, United Airlines, ALPA		x		x	x	
Laughlin, W. S., Continental Airlines	x	x				

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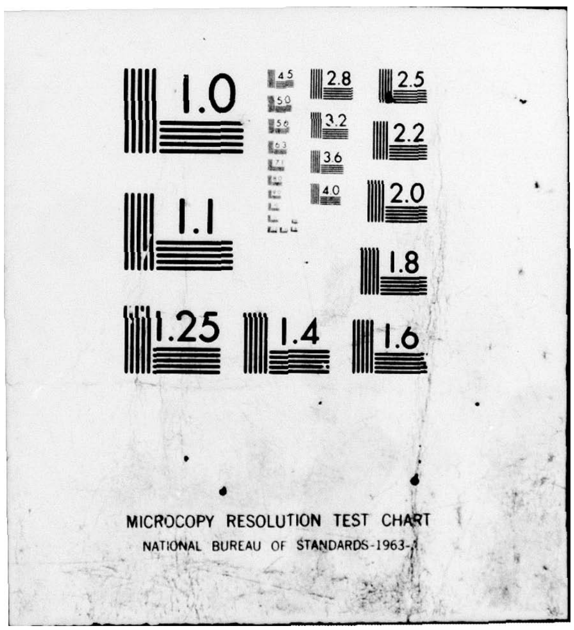
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table A-1 (Continued)

Pilot	DC-10 Ph. 1	DC-10 Ph. 2	B-727 NASA	DC-10 Ph. 3	DC-10 Ph. 4	B-727 HUD
LeBel, James R., Western Airlines				x		
Levendoski, R. J., FAA, AFS-203					x	x
Melvin, William W., ALPA/ Delta Airlines						x
Menard, J. L., FAA	x					
Miller, Russell J., United Airlines			x			
Miller, S. S., United Airlines		x			x	
Milton, Dean, FAA, ANW-216						x
Mullins, Joe J., Continental Airlines				x		
Nelsen, R. O., Continental Airlines					x	
Nelson, Philip G., USAF, IFC				x		
Norman, R. E., Jr., National/ ALPA	x	x		x	x	x
Pease, Donald J., Boeing Company						x
Quigley, W. Steve, USAF, MAC				x		
Rathert, Paul F., Western Airlines				x		
Reeser, A. M., American Airlines	x					
Reichardt, R. W., Continental Airlines	x	x		x		
Richards, B. M., Continental Airlines					x	
Riggs, Donald E., Flying Tiger Lines				x		
Ryalls, Fred, ALPA/United Airlines			x			
Ryan, John J., FAA, NAFEC						x

Table A-1 (Concluded)

Pilot	DC-10 Ph. 1	DC-10 Ph. 2	B-727 NASA	DC-10 Ph. 3	DC-10 Ph. 4	B-727 HUD
Sample, Robert, FAA, AGS-160			x			
Saucke, L. C., American Airlines	x					
Sende, John E., United Airlines			x			
Shimon, Ivan H., American Airlines					x	
Smith, J. E., FAA	x					
Sonneman, W. R., Trans World Airlines				x	x	
Spreen, Les, American Airlines				x		
Thompson, Ted, USAF, AFISC				x		
Tymczyszyn, Joe, Jr., FAA Flight Standards				x		
Vietor, C. W., American Airlines		x				
Whallon, Leon C., FAA, AWE-270				x		x
Wiebracht, W. David, Douglas Co.					x	
Weinstein, Warren, American Airlines				x		
Witter, Gordon L., American Airlines				x		

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