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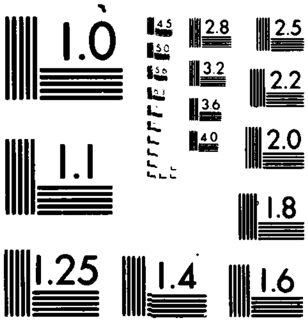

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REPORT NO. FAA-RD-80-103

WIND SHEAR SYSTEMS IMPLEMENTATION BENEFIT/COST STUDY

AUGUST 1980

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16. Abstract

Since July 1973 there have been eight U.S. air carrier accidents attributed to encounters with strong low-level wind shears during terminal flight operations. The FAA research and development effort has taken a threefold approach to the wind shear problem: (1) developing and implementing improved forecasting techniques and procedures for predicting and reporting low-level wind shear in the terminal area; (2) placing wind shear detection equipment on the ground and transmitting information to the pilot; and (3) installing equipment aboard the aircraft that would provide the pilot with wind shear information in "real time".

The results of the latter effort, i.e., airborne wind shear systems and techniques are evaluated as to their relative benefits and costs both to the user and to the FAA. Ground speed is a major input variable to many of the candidate airborne wind shear systems. Eight techniques for providing ground speed are evaluated and cost comparisons are documented. Also evaluated are three self contained wind shear systems that do not rely on ground speed as a reference and a head-up display for displaying wind shear data.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

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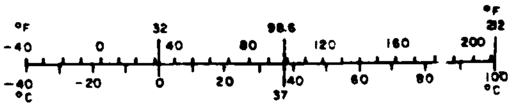
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

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



CONTENTS

PARAGRAPH TITLE PAGE

1.0 Executive Summary 1-1
2.0 Background and Status of the Wind Shear Program 2-1
2.1 Background 2-1
2.2 FAA Research and Development 2-1
2.3 Cost/Benefit Study Requirement 2-2
3.0 Conclusions and Recommendations 3-1
4.0 Candidate Airborne Wind Shear Systems 4-1
4.1 Introduction 4-1
4.2 Manned Flight Simulation Program 4-1
4.3 System Descriptions 4-6
5.0 Benefit Analysis 5-1
5.1 Benefit Summary 5-1
5.2 Basis for Determining Benefits 5-1
5.3 Wind Shear on Take-off 5-4
6.0 Cost Analysis 6-1

APPENDICES

A Wind Shear Scenario A-1
B Sources and Basis of Cost Data B-1
C Ground Equipment Installation Phasing C-1
D Cost Computations D-1
E Program/Project Year Discount Factors E-1
F Air Carrier Airports with ILS F-1

1.0 EXECUTIVE SUMMARY

The FAA has established an engineering and development program to:

- Examine hazards to air carrier aircraft caused by encounters with strong low-level wind shears during terminal area flight operations.
- Develop solutions to the wind shear problem.
- Integrate these solutions into the National Airspace System.

The FAA effort has taken a threefold approach:

- Develop and implement improved forecasting techniques and procedures for predicting and reporting low-level wind shear in the terminal area.
- Placing wind shear detection equipment on the ground and transmitting information to the pilot.
- Placing equipment in the aircraft that would provide wind shear information to the pilot in real time.

The ground system phase has already been completed and the Low Level Wind Shear Alert System (LLWSAS) is currently being installed at 60 major airports in the United States.

The airborne portion of the FAA's wind shear program identified several alternative systems or techniques that would assist the pilot in coping with the low-level wind shear problem. This Benefit/Cost Study evaluates those systems or techniques that are considered by the FAA to be viable alternatives. Primary emphasis is placed on cost evaluations inasmuch as the benefits of the three primary techniques (i.e., Airspeed/Groundspeed, Acceleration Margin and Modified Flight Director) have been analyzed and documented in prior FAA studies.[1]

An analysis of the costs of alternative viable airborne wind shear systems/techniques reveals that the least expensive equipment that will provide an independent source of groundspeed is a two-beam Doppler (approximately three thousand dollars to each user in quantity production). The accuracy of this system, however, has not been verified and may be less than the desired standards (yet to be developed). The second least expensive equipment is the ILS Doppler invented by Mr. Forrest Yetter ($4500 minimum to each user plus

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[1] References 1-4.

$9.69 million of FAA costs to modify 603 ground ILS Localizers). This system is less subject to multipath errors than other systems that cooperate with a ground station. The third least expensive system ($7,000 to each user) is Safe Flight Instrument Corporation's self contained wind shear system. This is a reactive system which does not rely on groundspeed. The fourth least expensive system (i.e., GE's CORAN at $10,000 for each user) requires no ground station and is thus not subject to multipath. This system is being tested by the FAA at FAATC and should possess the desired accuracy.

This study provides the costs of:

- Eight methods (including the above three) of obtaining groundspeed.
- Modified Flight Director
- Acceleration Margin
- Head-up display
- Safe Flight System
- SFENA system
- Smiths Industries System

Also the study provides a brief description of each alternative evaluated, and a very general discussion summarizing the benefits to be derived. With respect to benefits, those systems which predict or anticipate a wind shear are considered more safe than those that react to wind shear. This evaluation is based on the fact that most turbojeet aircraft do not possess a sufficient acceleration capability in normal approach configuration to maintain safe flight through severe wind shears. Predictive and anticipatory systems permit the pilot to adjust his approach speed, as required, whereas reactive systems do not. Accordingly, the three self contained Wind Shear Systems currently being marketed by avionics manufacturers are considered to have lower relative benefits than the airspeed/groundspeed and other viable wind shear system/techniques being considered by the FAA.

2.0 BACKGROUND AND STATUS OF THE WIND SHEAR PROGRAM

2.1 BACKGROUND

Since July 1973 there have been eight U. S. air carrier accidents attributed to encounters with strong low-level wind shears during terminal area flight operations. Additionally, during the year 1964 through 1975, there were 23 transport category airplane accidents that occurred during takeoff or approach, in which the involvement of a low-level wind shear was a distinct possibility.

In May 1977 the FAA adopted an amendment to Part 121 of the Federal Aviation Regulations which required air carriers to adopt an approved system for obtaining forecasts and reports of adverse weather conditions, including low altitude wind shear, that may affect safety of flight on each route to be flown and at each airport to be used. The FAA also issued Advisory Circular No. 00-50A, Low Level Wind Shear, to provide guidance in recognizing meteorological conditions that produce wind shear phenomena.

In addition, the FAA has established an engineering and development program for the purpose of examining the hazards associated with wind shear, developing solutions to the wind shear problem, and integrating those solutions into the National Airspace System.

2.2 FAA RESEARCH AND DEVELOPMENT

The FAA research and development effort has taken a threefold approach to the wind shear problem. One approach was to develop and implement improved forecasting techniques and procedures for predicting and reporting low-level wind shear in the terminal area. A second approach has explored the feasibility of placing wind shear detection equipment on the ground and transmitting information to the pilot. The approach considered in this report has tried to determine whether equipment could be installed aboard the aircraft that would provide the pilot with wind shear information in "real time".

Research into the use of ground-based equipment has involved various arrays of anemometers, radar detectors, acoustic devices and laser sensors.

The LLWSAS was selected from the ground-base techniques and is being installed at 60 major airports within the United States. This system will provide a warning transmitted to the pilot by an air traffic controller, whenever the surface wind vector difference between any remote anemometers (usually installed in approach and departure corridors) and the centerfield anemometer exceeds 15 knots (7.7 mps). This system is particularly effective in detecting wind shear caused by thunderstorm gust fronts at the surface.

The second part of the FAA research and development approach to the wind shear problem concentrated on the airborne systems. The FAA, through a series of simulator experiments has identified a number of airborne systems that may prove effective in warning a pilot of the existence of wind shear. Also, the avionics industry has developed several systems which they are advocating as aids to the pilot in coping with severe low-level wind shear.

2.3 COST/BENEFIT STUDY REQUIREMENT

One task of contract DOT-FA79WA-4279 in support of the FAA's wind shear system implementation plan is a Benefit/Cost Study of alternative techniques for solving the wind shear problem. Inasmuch as a decision has previously been made to implement the LLWSAS at 60 major airports, no further analysis is required with respect to ground-based warning systems. The current FAA wind shear Research and Development activity is concerned with airborne systems. Therefore, this study analyzes the benefits and costs of those candidate systems currently being considered by the FAA.

3.0 CONCLUSIONS AND RECOMMENDATIONS

All airborne techniques currently being evaluated will increase safety if adequate safeguards are provided to preclude pilots from flying into hazardous wind shear conditions that they would otherwise have avoided if a minimum alert had been provided.

The relative ranking (least costly to most costly) of the airborne system (techniques) is:

1. Airspeed/Groundspeed with Miles Phoenix groundspeed
2. Airspeed/Groundspeed with Yetter groundspeed
3. Safe Flight Wind Shear System
4. Airspeed/Groundspeed with CORAN groundspeed
5. Airspeed/Groundspeed with Modified DME
6. SFENA Avionics
7. Smiths Industries Avionics
8. Airspeed/Groundspeed with Marlow (Luneberg Lens) groundspeed
9. Airspeed/Groundspeed with Inertial groundspeed
10. Airspeed/Groundspeed with Doppler groundspeed
11. Airspeed/Groundspeed with Precision DME groundspeed

Other systems or techniques such as the head-up displays and data from previous airborne measurements are not true systems but enhancements to other systems and cannot be evaluated separately.

It is concluded that viable cost alternatives are available for aiding the pilot in coping with hazardous wind shear conditions on the final approach. The least costly alternative for obtaining groundspeed data (i.e. the Miles Phoenix two beam Doppler) has not been tested to verify that it possesses the required accuracy.

Recommendations:

- Use a self contained airborne wind shear rather than a cooperative air/ground system. Self contained systems are least expensive, do not have multipath, and can be implemented more rapidly (i.e. do not have to wait for FAA to secure funds for ground equipment).

- Investigate accuracy of the low-cost Miles Phoenix Doppler if cost of the FAA sponsored G.E. CORAN is not within the acceptable cost range.
- Utilize Yetter groundspeed as most cost effective method contingent upon FAA implementing appropriate ground facilities.
- Utilize G. E. CORAN groundspeed as most cost effective method if Yetter system ground facilities are not implemented.

4.0 CANDIDATE AIRBORNE WIND SHEAR SYSTEMS

4.1 INTRODUCTION

The FAA conducted a series of piloted flight simulations (June 1975 to July 1979) to evaluate and refine pilot aided concepts for solving the wind shear problem. Results of these simulations[1] demonstrate the three most promising candidate wind shear systems to be: (1) Airspeed/Groundspeed Procedure, (2) Modified Flight Director, and (3) Acceleration Margin.

A fourth pilot aided system which has a potential for providing visual cues to the pilot of the wind shear hazard is Head-Up Display (HUD).

Also, three equipment manufacturers[2] have developed avionic systems to assist the pilot in coping with wind shear.

An eighth concept suggested more recently is a system which would provide landing aircraft with wind data from previous airborne measurements.

A summary of the previous FAA flight simulation experiments which provide a basis for defining the most promising wind shear systems is provided in paragraph 4.2 below followed in paragraph 4.3 by a brief description and status of the eight candidate systems, identified above.

4.2 MANNED FLIGHT SIMULATION PROGRAM

A series of manned flight simulation experiments was conducted to identify and refine the most effective pilot-aiding concepts. The experiments were grouped into four phases of simulations using both training and engineering

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[1] References 1,2,3, 4 and 7.

[2] Safe Flight Instrument Corporation, the French Avionics Firm SFENA, and Britain's Smiths Industries

development simulators and modelling short-haul, medium-haul and wide-body jet transport aircraft in current airline operations. The simulators were all equipped with six-degrees-of-freedom movement, visual systems with variable weather and visibility, and a full complement of controls for all flight crew positions. Each was capable of simulating all flight guidance and control modes available on the aircraft in service use.

a. Phase I

Phase I of the simulation effort was a controlled screening of candidate systems and techniques. The most effective were selected for in-depth analysis and further refinement. The bulk of these experiments were conducted in a DC-10 training simulator at the Douglas Aircraft Company Flight Crew Training Center in Long Beach, California. In this phase of the simulation effort, pilot performance data and subjective pilot opinions were recorded on highly experienced pilots, most of whom held DC-10 pilot qualifications. The pilots were subjected to various flight scenarios and wind shear conditions while being aided by several discrete concepts. Examples are:

(1) Wind Shear Advisories based on ground-based sensor data;

(2) Panel display of groundspeed versus vertical speed for a 3° glide slope;

(3) Panel display of wind shear and direction (from INS*);

(4) Panel display of groundspeed integrated with conventional airspeed indicator (ΔV);

(5) Panel and simulated head-up display of difference between along-track wind component at surface and aircraft altitude (ΔW);

(6) Panel and simulated head-up display of flight path angle and potential flight path angle;

(7) Panel display of angle-of-attack; and

(8) Panel display of rate-of-airspeed change.

*INS - Inertial Navigation System

The results of those experiments indicated that groundspeed/airspeed comparison (ΔV) ranked as the best aiding concept by pilot opinions and by the comparison of recorded landing performance. The second best aiding concept was found to be the along-track wind component comparisons (ΔW), either head-up or head-down, particularly when presented on a head-up display. There was also an indication that the head-up displayed flight path angle has some merit. As a continuation of Phase I, the top ranking aiding concepts were reexamined in the Flight Simulator for Advanced Aircraft (FSAA) at NASA/Ames Research Center using a Boeing 737 model. The results of that simulator experiment verified the findings from the previous Phase I simulation efforts.

b. Phase II

The Phase II simulation experiments were conducted in the Moving Base Development Flight Simulator (MBDFS) at the Douglas Aircraft Company facility using the DC-10 model. These experiments provided an in-depth evaluation of improved ΔV, ΔW, and flight path angle (both air and ground derived) displays. This activity also evaluated a modified flight director system (MFD) developed by Collins Radio.

The results of the more detailed evaluations in the Phase II simulations confirmed that the groundspeed/airspeed comparison (ΔV) provides significant aid to the pilot and the along-track wind component comparison (ΔW) provides some aid to the pilot in detecting and coping with wind shear. In addition, it was also shown that the modified control laws (algorithms) for flight director/thrust commands also significantly increased the pilots ability to handle wind shear encounters. Pilot acceptance of each of these concepts was high.

Phase III flight simulation experiments were conducted at both the NASA FSAA, using a Boeing 727 model, and at the Douglas MBDFS, using a DC-10 model. The purpose of this series of experiments was to evaluate several different methods of displaying the ΔV concept in the cockpit, to optimize the MFD control laws/algorithms for wind shear and to investigate the potential of two concepts to aid the pilot in making the missed approach or go-around decision. The go-around aids evaluated were:

(1) Panel display of energy rate (a comparison between actual total energy rate of change and desired rate of change for a 3° glide slope).

(2) Warning indication based on acceleration margin (a comparison between aircraft acceleration capability and the acceleration that will be required to overcome the shear (ΔA).

c. Phase III

The Phase III simulation results again demonstrated that the ΔV and MFD concepts were effective in providing the pilot the information required to successfully negotiate hazardous wind shear conditions. The ΔV concept was successful in all the methods in which it was presented: groundspeed displayed on a digital readout; groundspeed displayed as a second needle on a conventional airspeed indicator (round dial); airspeed and groundspeed integrated into a special velocity indicator (vertical scale); or airspeed/groundspeed, command displayed on the fast-slow indicator. In addition, it was shown that the ΔA concept provided timely go-round information for those severe shears that approached or exceeded the performance capability of the aircraft.

The energy rate concept was shown to provide some aid to the pilot in making a go-around decision, but suffered from one serious drawback which is common to several of the unsuccessful concepts (such as angle-of-attack, airspeed rate of change, and flight path angle) which were tested in the earlier simulations. Although all of these concepts provide a positive indication of a shear condition and the severity thereof, the indication is not presented until the shear environment is encountered. In other words, the pilot is given an indication that he has entered a hazardous condition that he did not want to enter. On the other hand, those successful concepts which use groundspeed were shown to be predictive in nature in that they provide an indication to the pilot of the shear condition which lies ahead of the aircraft so that the pilot may take timely action.

d. Phase IV

Phase IV flight simulation experiments were conducted at the Dougl MBDFS, using a DC-10 model. The purpose of these experiments were to validate the ΔA, ΔV and MFD concepts under worse case conditions (high gross weight, high temperature, high altitude, low ceilings and low visibilities) and to evaluate the applicable concepts during non-precision approach and missed approach conditions. An existing airspeed indicator was modified to present an analog display of airspeed, groundspeed and the acceleration margin calculation all on the same instrument. This allowed the presentation of wind shear information within the normal T-Scan of the pilot. The ΔV, and MFD concepts were again proven to be successful, even under marginal performance and weather conditions, in aiding the pilot to safely traverse those shears which were within the performance capability of the aircraft and to detect and avoid those shears which approached or exceeded that capability.

4.3 SYSTEM DESCRIPTIONS

A brief description, status of development, and projected availability of each of the eight candidate systems is provided in this section.

a. Airspeed/Groundspeed Comparison (ΔV).

(1) The basic concept which has proven most successful in manned simulation experiments for a wide range of shear conditions on approach is the groundspeed/airspeed comparison. Basically, it is a simple procedure whereby the pilot computes a minimum desired groundspeed by subtracting the headwind component of the runway wind from the approach true airspeed. He then flys a normal approach using indicated airspeed, except that he does not allow the groundspeed to fall below the predetermined value. The procedure automatically causes the pilot to add additional airspeed to compensate for any airspeed loss that will occur when the shear condition is reached. As such, it is a predictive procedure so that if the amount of correction needed exceeds the known performance capability of the aircraft, the pilot is given the indication to perform a missed approach prior to penetrating the shear conditions.

(2) Status of Development

Airspeed is already available on all aircraft as a primary flight instrument. Groundspeed is discussed in paragraph i below following the individual system descriptions in as much as it is used in several different systems.

b. Modified Flight Director

(1) Description

Modern Flight Directors are highly damped for passenger comfort and are not responsive enough for highly dynamic shear conditions.

By providing the pilot with a selectable second set of control laws algorithms which are quicker, more active, and based upon inputs derived from groundspeed acceleration augmentation and tighter coupling to the glidepath, the ability to traverse wind shear conditions is greatly increased.

(2) Status of Development

Under Task 5, Project 4364, All-Weather Landing Systems, Engineering Support Services,[1] designs were developed for fully automatic control, for flight director coupled to a full ILS, and for flight director for non-precision approaches. Control laws were designed for four aircraft: CV-880, DC-10, B-727, and the Gulfstream I. The designs were tested by piloted simulations and in the case of the Gulfstream, carried to implementation in flight hardware. Design, fabrication, installation, and checkout of the modifications required to implement the MFD algorithms to the flight director of the FAA Grumman Gulfstream I, based at NAFEC, began in November 1978 and were completed on 15 June 1979. The NAFEC Gulfstream I and its modified flight director were returned to NAFEC in June 1979 flight tests.

(3) Projected Availability

Modifications to existing aircraft could be accomplished in six months or less. New systems could be a production line item.

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[1] FAA-RD-79- , "Inertially Augmented Approach Couplers", Final Report, June 1979.

(4) Cost

Modification of existing systems: \$11K

Replacement plug in flight directors: \$6K X 2 = \$12K

c. Acceleration Margin (ΔA)

(1) Description

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 headed positive (knots)

TAS = True airspeed of airplane (knots)

GNS = Ground speed of airplane (knots)

WD = Wind difference (knots)--difference between along-track wind at present position and on the runway

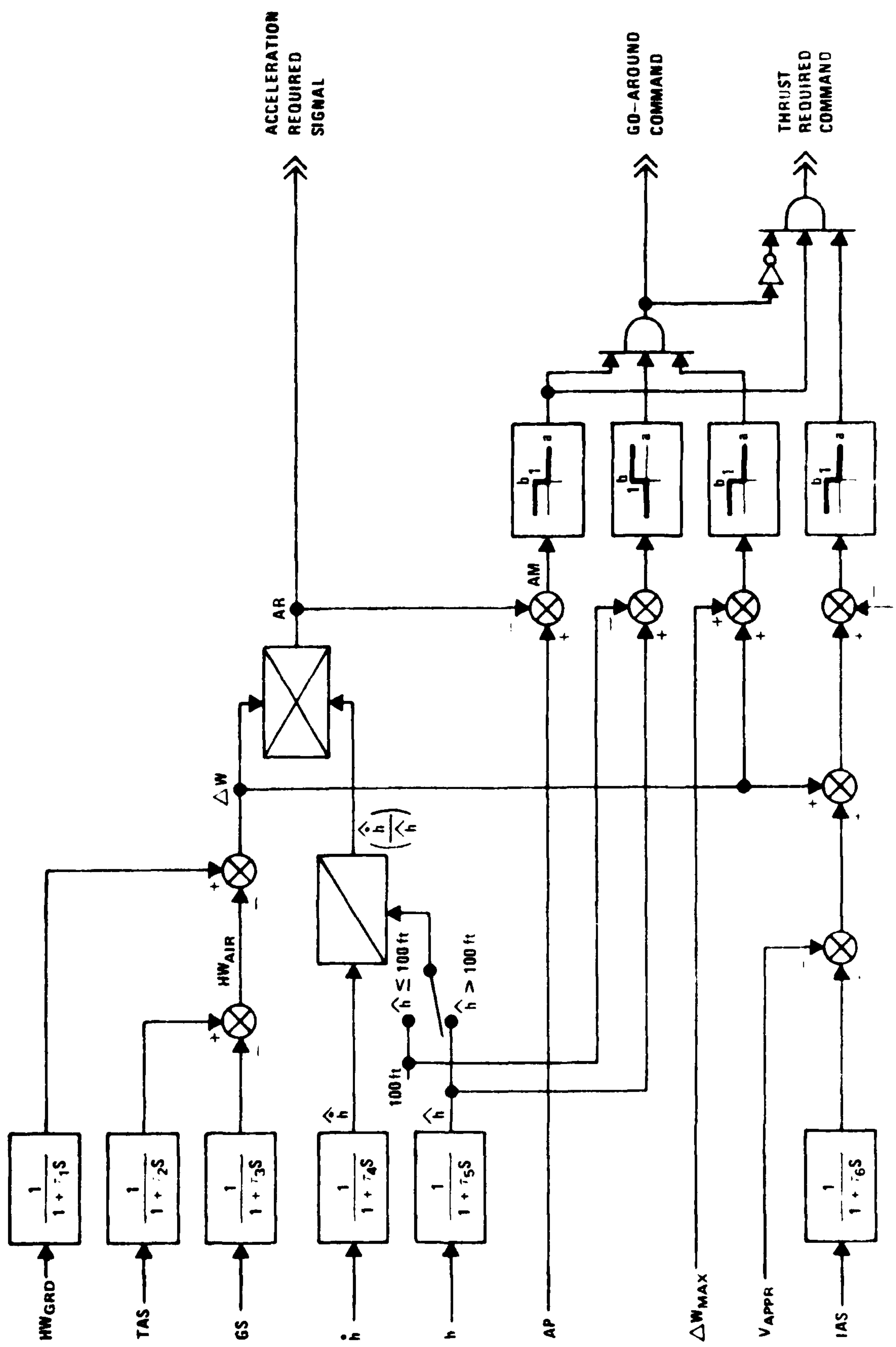
H = Altitude of airplane CG above ground, positive up (feet)

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

Figure 4-1 illustrates a typical system. For those aircraft currently having inertial navigators, groundspeed may be derived from the current on board equipment. For other aircraft, an alternative means of determining groundspeed must be provided.

(2) Status of Development

The acceleration margin algorithm was validated during Phase III simulations. During Phase IV, the algorithm was augmented to inhibit the


HW_GRD
TAS
GS
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ΔW_MAX
V_APPR
IAS
1/(1 + τ1S)
1/(1 + τ2S)
1/(1 + τ3S)
1/(1 + τ4S)
1/(1 + τ5S)
1/(1 + τ6S)
HW_AIR
ΔW
AR
AM
ĥ
ĥ ≤ 100 ft
ĥ > 100 ft
100 ft
ḣ/ĥ
a
b
1
ACCELERATION REQUIRED SIGNAL
GO-AROUND COMMAND
THRUST REQUIRED COMMAND

go-around advisory if the wind difference is less than 25 knots or no more than 8 knots greater than the airspeed pad. These inhibit values were determined Empirically to lower the criterion for advising a go-around so as to reduce nuisance alarms. A external source of ground speed, altitude, altitude rate and runway winds is required to compute acceleration margin.

(3) Projected Availability

This is a simulation tool at present but could be converted to production hardware based on algorithms used in the DC-10 trainer.

(4) Cost

Computer. For aircraft not equipped with a suitable computer an airborne computer will cost approximately $1,000.

Ground Speed. The cost of ground speed is discussed in paragraph i.

Display. An analog display will usually be a part of an integrated airspeed/groundspeed/acceleration margin display. A separate analog accleration margin display would cost $ 2,000. The cost of a go-around light includes a computer activated digital switch and a panel light plus the cost of installation. Installation cost is estimated at $25-$50.

f. Head-Up Display

(1) Description

(a) U.S. Developments[1]

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-7. 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.

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[1] Reference 7 p. 47-52

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 4-2. 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 enter of the reference [illegible] "[illegible]," 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. 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

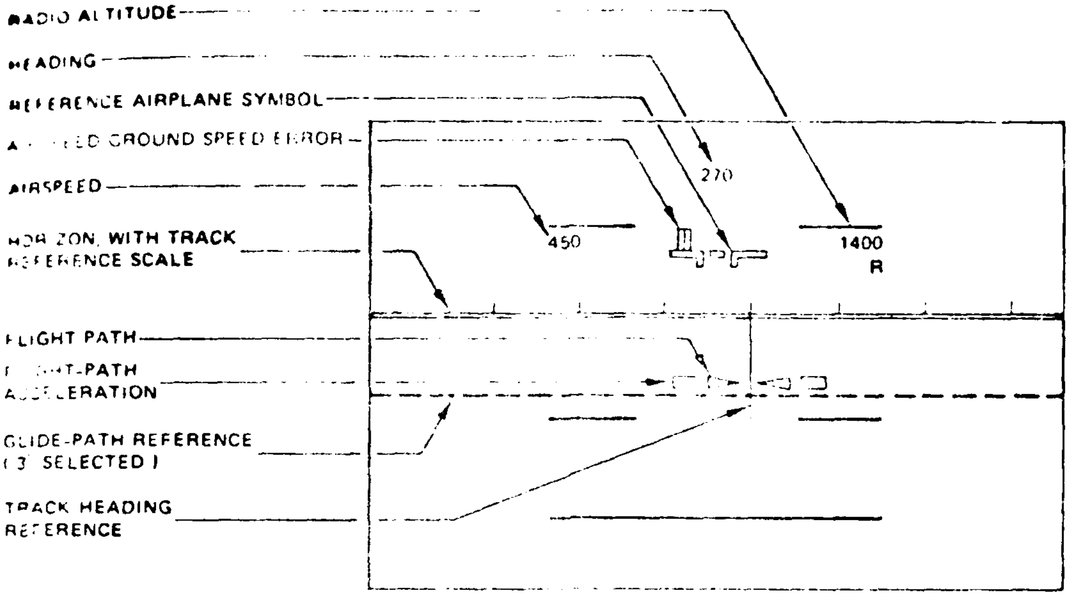
W_{XS} = Tabulated value of the head wind component (W_X) on the surface for the selected wind profile in ft/s.

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

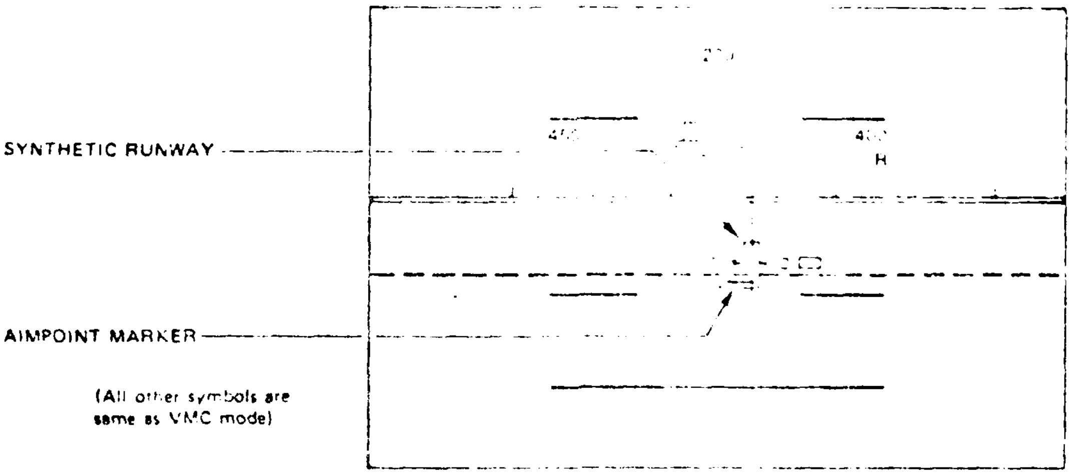
$$\gamma_{pot-A} = \gamma_A + \left(\frac{\Delta TAS/sec}{g} \right) 57.3 \quad ,$$

where

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



(a) VMC MODE



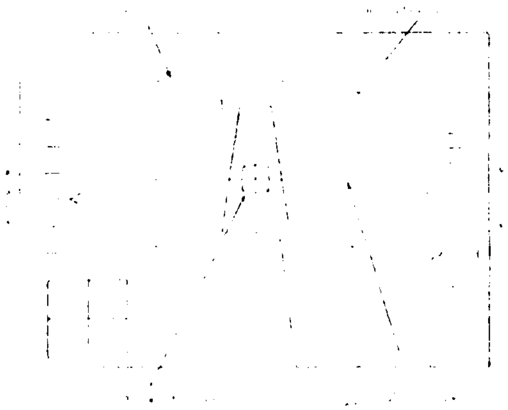
(b) IMC MODE

FIGURE 4-2 SYMBOLOGY SELECTED FOR THE INERTIAL HUD (IHUD)

The CAA Development

Britain's Civil Aviation Authority (CAA) in conjunction with British Aerospace at Filton is examining ways for alerting the pilot sooner of hazardous wind shear conditions. The company's design and development simulater, set up to represent a BAC one-eleven cockpit was used in tests completed in March 1979. The aim of the trials was to assess the feasibility of presenting wind shear information on a HUD. About 59 airline pilots took part in the trials, each of them flying 17 different approaches in the simulator. Some of the approaches were manual and some automatic, with various weather conditions. Several of them included windshear, the model of this being a downburst cell to one side of the runway centreline. Full conclusions from the tests have not yet been published, but pilots who adapted to the HUD quickly (or who had previous HUD experience) seemed to find the aid useful when flying approaches through wind shear.

The HUD used in British Airways tests is illustrated below. Aircraft is on the glidepath at decision height. Potential flight path and touchdown point are coincident and raw ILS data are at bottom left. Speed and altitude data are also shown.



(2) Status of Development.

In the United States, the FAA is currently evaluating the use of head-up displays for wind shear as a part of their Head-up Display Evaluation program.

In Britain, British Aerospace has examined ways of using the HUD for Wind Shear alert HUD, per se, is not currently available in production aircraft.

(3) Projected Availability.

It is likely that current airliners will utilize other wind shear systems described herein. However, the next generation of airliners will probably rely on HUD.

(4) Cost.

HUD is a display of wind shear data rather than a system. For aircraft initially designed with HUD, there will be no increase in cost for the display itself for wind shear applications. For add-on systems similar to the one being installed in the DC-9-80, a complete add-on set for one pilot is projected to cost $75-100K exclusive of the cost of certification.

e. Safe Flight Instrument Corporation Wind Shear System.

(1) Description

The Safe Flight Instrument Corporation, which pioneered the mass production of pre-stall warning indicators for aircraft, has developed a wind shear monitor system which will be tested soon by the FAA. This system does not utilize a direct measurement of ground speed. Instead, it uses inputs of airspeed, angle of attack, and pitch attitude; these inputs are processed along with the outputs from a vertical and a longitudinal accelerometer, to detect the rate of change of headwind, and the angular displacement of the aircraft due to downdraft. Signals representing these two quantities are summed to form the total wind shear output signal, which is displayed on the very simple indicator shown in Figure 4-3.

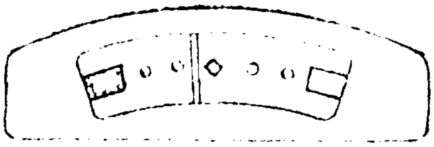


Figure 4-3. Safe Flight Wind Shear Indicator

The indicator displays, in units of acceleration (g's), the total energy loss due to the wind shear. At a preselected threshold, it actuates an alert. As illustrated in Figure 4-4, the horizontal component is derived by subtracting inertial acceleration from airspeed rate. Airspeed rate is

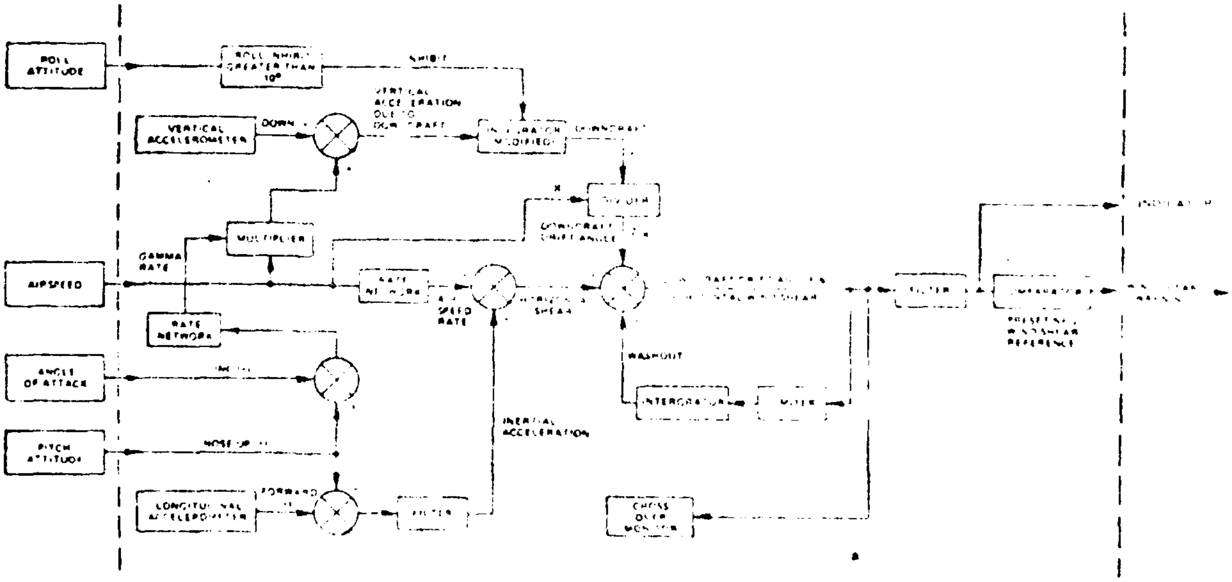


Figure 4-4. Safe Flight Instrument Corporation
Wind Shear System Description

obtained by taking the airspeed signal and passing it through a high pass filter. The inertial acceleration signal is obtained from an accelerometer built into the wind shear computer. The accelerometer signal is summed with a pitch attitude signal to cancel the gravity component of the accelerometer. A wash-out circuit is also employed to cancel errors due to prolonged acceleration. This inertial acceleration signal is summed with the airspeed rate signal producing the horizontal shear signal.

The vertical component is obtained from a vertical accelerometer in the computer. The vertical accelerometer signal is negatively summed with a gamma rate signal (amplified by the airspeed signal) to cancel the effects on the vertical accelerometer due to changes in aircraft flight path. This sum is integrated then divided by the airspeed, thereby obtaining a draft angle. This signal is equivalent to the Downdraft Drift Angle of the flight path.

The Downdraft Drift Angle of the flight path is then combined with the horizontal shear signal and forms the total wind shear output signal. This signal is fed to an indicator and a comparator. At a pre-set level, a warning output is activated.

The wind shear indicator displays, in units of acceleration (g's), the sum of the Downdraft Drift Angle and the rate of change of head wind component. The wind shear alarm threshold is set to trip at a sustained horizontal shear, or a sustained Downdraft Drift Angle, or any combination of Downdraft Drift Angle and horizontal shear that would total an equivalent signal level.

A unique feature in the wind shear system is a cross-over monitor network. This circuit senses zero cross-overs of the combined wind shear warning signal and compares them against a time reference. By doing this, the computer is continually checking the validity of its wind shear computation. If the wind shear signal does not go through a band around zero, at least once every 25 seconds, the computer will provide a flag alerting the pilot that the system is inoperative.

(2) Status of Development

Has previously been developed and tested in NASA- Ames B-727 simulator. Currently undergoing flight tests at NAFEC.

(3) Availability

Currently available.

(4) Cost

$7K with indicator shown in Figure 4-3; $7,800 with both voice warning and indicator.

f. Smiths Industries Wind Shear System

(1) Description

In England, British Airways is developing a wind shear system which measures the rate of change of total energy (kinetic plus potential energy) of the aircraft. In this system, energy rate is derived from two outputs from the aircraft's air data computer, those which drive the airspeed indicator and the vertical speed indicator (VSI). The information is presented on an extra pointer on the VSI as shown in Figure 4-5. The normal function of the VSI remains unchanged.

The Vertical Speed Indicator (Figure 4-5) is arranged so that a second concentric pointer (1) is added indicating Energy Rate to the same scale (2) as Vertical Speed. The original Vertical Speed needle (3) is unchanged.

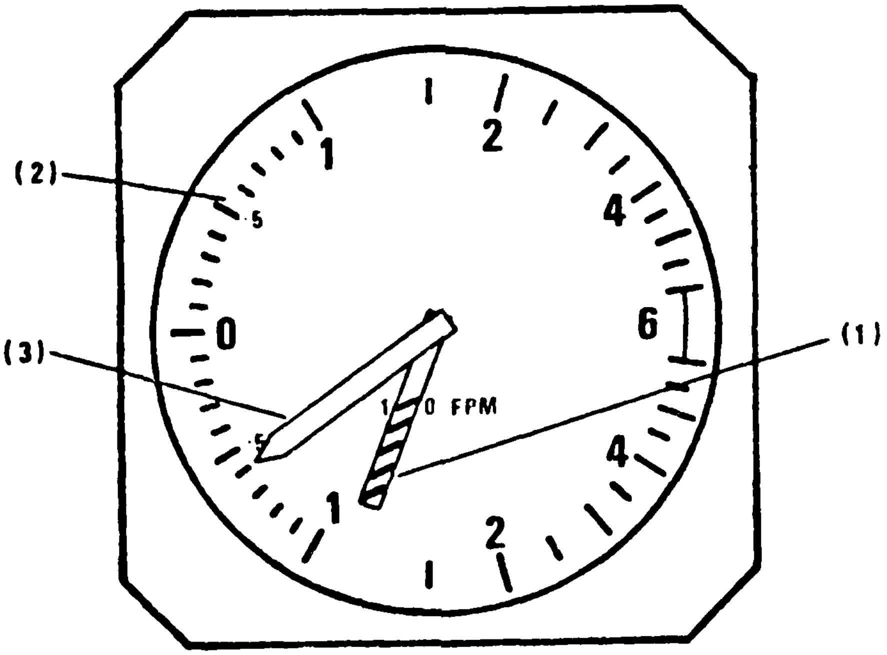


Figure 4-5

Energy Rate is derived as follows:

Total Energy = Potential Energy + Kinetic Energy

$$= mgh + \tfrac{1}{2}mv^2 \qquad \ldots (1)$$

Energy Ht = Total Energy/Unit Mass

$$= h + v^2/2g \qquad \ldots (2)$$

$$\text{Energy Rate} = {}^{dh}/_{dt} + {}^{v}/_{g} \cdot {}^{dv}/_{dt}$$

$$= \dot{h} + {}^{v}/_{g} \cdot \dot{v} \qquad \ldots (3)$$

Where h = height, v = airspeed

i.e.

Energy Rate = Vertical Speed + Kinetic Rate ft/time

Energy Rate has units of distance/time, and can be computed in ft/min and indicated to the same scale as Vertical Speed.

In speed - stabilised flight the $\dot{v}$ term of equation (3) is by definition zero, i.e. Kinetic Rate is zero and Energy Rate is equal to Vertical Speed. The Energy Rate pointer (1) of (FIG. 1) is therefore hidden under the Vertical Speed pointer (3) during speed-stabilised flight. The Energy Rate pointer may be thought of as indicating the potential Vertical Speed. Hence in (FIG. 1) the actual Rate of Descent is [illegible] ft/min, but the potential Rate of Descent (i.e. Energy Rate) is 12[illegible] ft/min.

Movement of the Energy Rate pointer may be either pilot or atmosphere-induced.

PILOT ACTIONS	ATMOSPHERE
Throttle Stick Configuration Change	Windshear

(2) Status of Development

Simulations were accomplished in April 1979 with satisfactory results in a simulated aircraft representative of a BAC 1-11 500 at 80,000 lb. with mid c.g. It was recommended that the L1011-1 simulator be modified to provide more and more realistic wind shear test and that flight tests be conducted of the two-pointer VSI in an L1011-1 aircraft to permit airborne evaluation.

(3) Availability

This system could be available subsequent to flight evaluations.

g. SFENA Wind Shear System

(1) Description

A system somewhat similar to the British Smiths Industries wind shear system described in paragraph f above,has been developed by the French avionics firm SFENA. However, details on its operating principles are considered proprietary by the manufacturers, and are not available at this time. The FAA plans to test one of these systems during the next phase of the wind shear program.

The system comes in two models depending on whether or not the airplane possesses a intertial navigator. The system consists of 2 indicators (one for pilot and one for co-pilot) which replace the vertical speed indicators and a computer to compute energy rate.

(2) Status of Development

The SFENA system was simulated in the NASA Ames B-727 simulators in 1979. A complete operating system is scheduled for installation in NAFEC's B-727 in early 1980 for evaluation.

(3) Availability

SFENA's Washington representative * estimates that the system could be available by the end of 1980 if there were a demand.

(4) Cost

Accelerometer package with two indicators which replace the vertical speed indicators: $12-15K.

h. Data From Previous Airborne Measurements

(1) Description

A ground derived hazard evaluation and warning system utilizing data from previous airborne measurements is illustrated by Figure 4-6. Its concepts include:

- Acquiring and processing atmospheric disturbance data from other aircraft on final approach, to more accurately assess the environment
- Providing more sophisticated computer capability than available in airborne systems, since ground facilities cost normally is less constrained than airborne equipment cost
- Providing a hazard evaluation service to aircraft that are not equipped for total autonomous evaluations
- Inserting a human controller into the hazard evaluation process, with both raw data and hazard evaluation displays, to monitor and/or supplement the automatic system.

This system would require an air/ground data link to provide the ground station with air derived airspeed, groundspeed, and altitude.

---

[1] Dr. Roger Phaneus (SFENA Consultant) (202) 296-7650

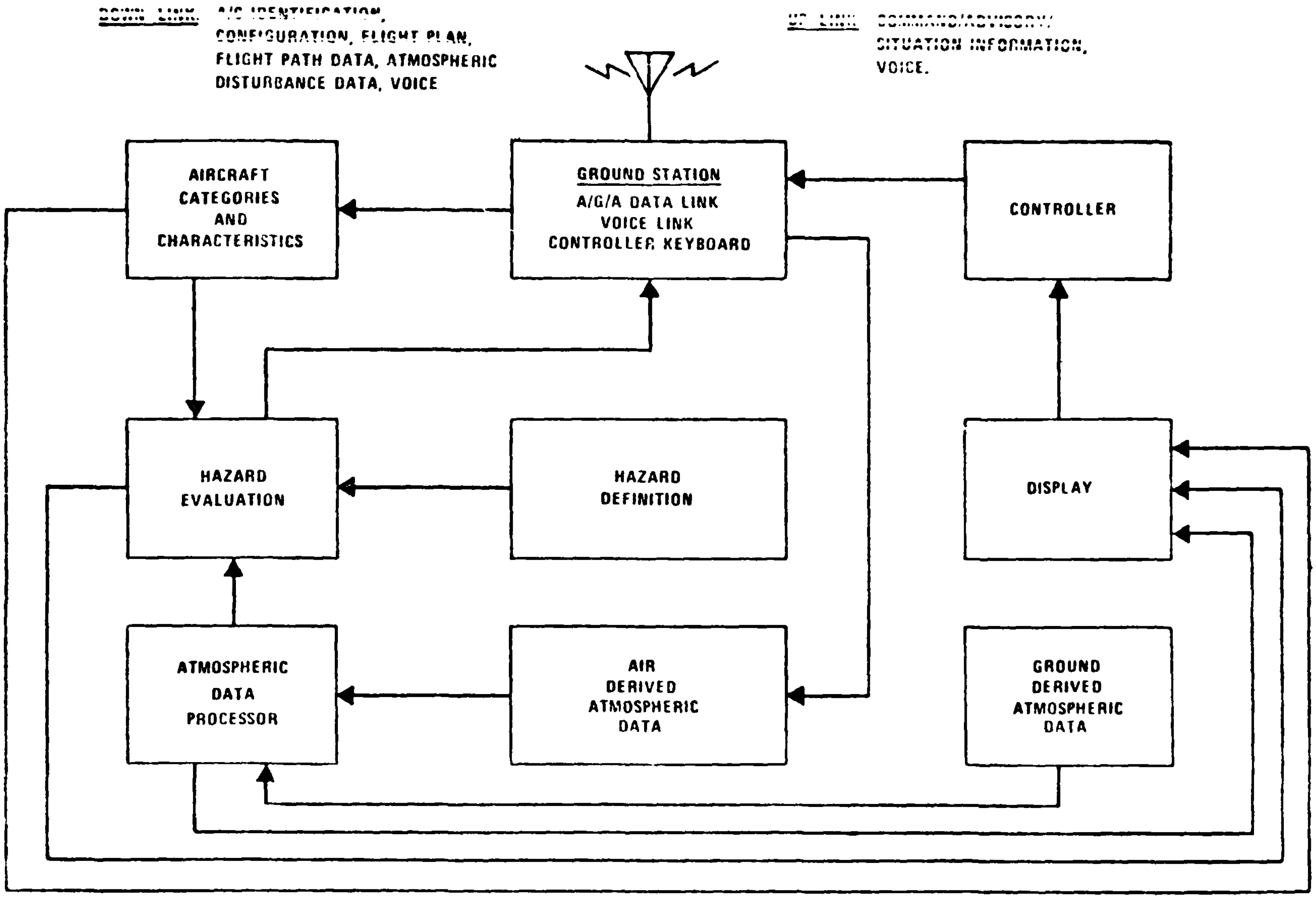


Figure 4-6. Ground Derived Hazard Evaluation and Warning System

(2) Status of Development

Conceptual. Has not been simulated as a part of the FAA's pilot simulation program.

(3) Availability.

Three to five years.

(4) Cost

Engineering estimates for this conceptual system are:

(a) Airborne user

$300-$500 per participating aircraft to modify DABS to downlink airspeed, groundspeed, and altitude plus cost of a groundspeed source.

(b) Ground Costs (per installation)

Computer -- $1500

Display --- $1000

(c) Data Links

No-costs. Downlink would be by DABS; uplink by voice from controller to landing aircraft.

i. Groundspeed

As indicated in the previous system descriptions, groundspeed, or (approximately the same) slant range rate to the glide path intercept point on the runway, is a missing state variable needed to determine longitudinal wind at the airplane.

(1) Inertial Navigators.

A source of groundspeed is available on those aircraft which possess an Inertial Navigation System (INS) or a Doppler navigator but it must be instrumented and displayed. A significant part of the FAA effort has been devoted to the job of coming up with a system, much less expensive than the Inertial or Doppler navigator, which would provide an updated readout of groundspeed at least once every five seconds and preferably about two and to displaying groundspeed/airspeed in a manner most easily understood.

(2) DME Groundspeed

Off-the-shelf groundspeed indicators based on DME are not satisfactory for measuring groundspeed for use in a wind shear system without improvement.

One such improvement, developed and tested by the FAA reduced DME averaging times to less than 5 seconds by using an accelerometer with Kalman filtering, with a resulting accuracy of ±1.5 knots.

In a concurrent program Sierra Research developed a precision range tracker which is an add-on to the airborne DME equipment, and which provides a groundspeed readout with a 5-second averaging accuracy of ± 1.5 knots, or a 3-second averaging accuracy under ± 3 knots.

As discussed in Chapter V, however, DME accuracy in a multipath environment is not satisfactory for groundspeed measurement.

(a) Projected Availability.

Improvements to the airborne DME are development items and would require 12-18 months lead time to be available in production quantities. Installation of ground DME transponder would be the pacing item as they would require normal F & E budgeting planning and would probably have to be phased over 5-10 years.

(b) Cost.

The cost of improving a new product DME is estimated to be $500 per unit additional cost. The cost of an add-on box to an installed DME such as the Collin 860-E would be $2000 if the ground transponder is located at least 4000 feet beyond threshold and not more than 720 feet off runway centerline. If ground transponders are not located within these limits, an additional $1800 cost will be required to provide offset computational capability to the airborne DME.

Each required new ground DME transponder will cost $45K. Generally, a ground transponder will be required for each runway end. However, on long runways, a centerfield DME could serve both runway ends. (See Appendix F for siting constraints).

(3) Luneberg Lens.

Another concept for obtaining groundspeed employs the airborne weather radar, plus a special reflector (Luneberg lens) which would be installed on the surface of the airport. The special coded reflector shifts the frequency of the returned signal which is then processed in the aircraft to provide a groundspeed readout. Developed by Stanford Research Institute and Marlow Industries, the concept would require modification to the airborne weather radar and the installation of coded rotating Luneberg Lens at each ground installation.

(a) Projected Availability.

The concept has been tested at speeds up to 55 miles per hour and found to be technically feasible. Airborne tests would be required to validate the concept, at approach landing speeds. Projected availability would be approximately two years after funds are made available for the production and installation of the ground installations.

(b) Cost.

The cost to the airborne user to modify an RDR 1-E Bendix airborne radar, the one used in the Marlow Industries developments, will be $10-12K. The cost to the government of installing a Luneberg lens will be $17K per installation. Siting limitations for the Luneberg lens should be similar to the DME limitation, i.e., the greater the distance the lens is located off runway centerline, the greater the groundspeed error.

(4) ILS Doppler (Yetter Groundspeed Invention).

The FAA has developed and tested an ILS Doppler which superimposes a sine-wave subcarrier tone on the signal of a conventional ILS localizer. Special circuitry added to the airborne receiver picks off the tone signal and provides a groundspeed readout with very little averaging time.

(a) Status of Development

Brassboard model successfully flight tested. However, 603 ground ILS localizers would have to be modified to assure full utilization. (See Appendix F).

(b) Projected Availability

3-5 years.

(c) Cost.

Each airborne processor is expected to cost $4,500 and each ground installation $8K. Both the airborne and ground elements require a very precise clock. $4K of the above costs of the ground element is for an atomic clock. The Navy is currently funding a development program to reduce the costs of atomic clocks. If the objectives of the Navy's program are realized, the cost of the atomic clock could drop to one half of its current cost of $4K. The proposed clock for airborne users is the quartz clock at a cost of $500. This clock, however, would have to be periodically updated.

(5) CORAN

General Electric's Aircraft Equipment Division has developed an add-on to an off-the-shelf radar altimeter. This installation, which is called CORAN (Correlation of Radar Altimetering for Navigation), includes two receiving antennas mounted a specified distance fore and aft of the radar altimeter antenna, which transmits pulses in its normal manner. The radar echos returned from the ground and received at the two receiving antennas are correlated. As the distance between the antennas is known, the groundspeed can be calculated.

(a) Projected Availability.

A system has been produced by the FAA for test in the NAFEC Gulfstream aircraft. General Electric has invested considerable company development funds to meet the anticipated need for a competitive groundspeed

(b) Cost.

The current prototype costs $50K plus considerable G.E. funds. G.E.'s target price is $10-15K. The lower range would provide groundspeed only whereas the upper range would provide both groundspeed and radar altimetry.

(6) Doppler Velocity Sensors.

Marconi Avionics, England, has developed a low cost doppler velocity sensor, Model AD660DVS which is currently being installed on the new Boeing 737 Airliners. According to Marconi, the AD660DVS can be installed in large or small aircraft as a cost effective means of obtaining groundspeed for fuel management, wind shear, etc.

A similar doppler velocity sensor currently utilized for helicopter has been developed by Decca Corp.

(a) Status of Development.

Doppler velocity sensors are current off the shelf hardware.

(b) Projected Availability.

No delay.

(c) Cost.

Marconi Avionics has quoted a price of $25K for the AD660DVS groundspeed sensor. The Decca Corp. helicopter model will cost about $20K.

j. Displays

Several methods have been tried for displaying groundspeed. One is a digital readout directly below the airspeed indicator or directly above the ADI. Another is a separate pointer on the airspeed indicator; this has the advantage of showing the relationship between airspeed and groundspeed, plus the capability of using a separate "bug" on the rim to show G_{ref}. Other methods of showing groundspeed include a vertical scale, side-by-side with a vertical scale for the airspeed.

(1) Cost.

Off the shelf displays are not available for concurrently displaying airspeed and groundspeed but no development effort is required to produce such an instrument. The cost is expected to vary from the insignficant cost of a simple two-way selector switch up to $2K to replace the airspeed indicators with two needles/tapes or digital displays [illegible] speed.

5.0 BENEFIT ANALYSIS

5.1 BENEFIT SUMMARY

Table 5-1 summarizes the relative benefits of competing wind shear techniques. Systems that provide the most predictive data are placed highest on the list (techniques 1-5). Similarly techniques that provide the easiest pilot interpretation of wind shear data are placed highest on the list. Reactive systems (Systems 6-8) are less effective than predictive systems inasmuch as most large turbojet aircraft do not have sufficient energy on an approach at normal approach speed to recover from the most severe wind shear encounters by reactive procedures.

TABLE 5-1. RELATIVE BENEFITS OF COMPETING WINDSHEAR TECHNIQUES/SYSTEMS

RANK	TECHNIQUE
1	Airspeed/Groundspeed, Accel. Marg., Mod. Flt. Dir. & Head-Up Display
2	Airspeed/Groundspeed, Accel. Marg., Mod. Flt. Dir. & Special Displays
3	Airspeed/Groundspeed, Accel. Marg. & Modified Flight Director
4	Airspeed/Groundspeed and Acceleration Margin
5	Airspeed/Groundspeed
6	Safe Flight Instrument Corp W/S System (1)
7	SFENA Wind Shear System (1)
8	Smiths Industries Wind Shear System(1)

(1) The last three reactive systems rank equally below the airspeed/groundspeed technique.

5.2 BASIS FOR DETERMINING BENEFITS

The objectives of implementing an airborne wind shear system or technique are to:

- Warn pilots of potential hazardous wind shear encounters.
- Provide pilots with in flight wind shear detection and aircraft control guidance for coping with wind shear encounters.

More basically the objective is increased safety.

All techniques evaluated during the Low-Level Wind Shear Simulation[1] increase safety. So do the commercial systems being developed.[2] It cannot be concluded, however, that the more sophisticated wind shear systems are the safest. The safest system may be the system which prevents the pilot from flying into an unsafe condition.

No recent accidents have been attributed to wind shear. Therefore, the technique of making pilots aware of the hazards associated with wind shear may be the safest of all techniques. Similarly, providing pilots with a system for flying through a hazardous condition may be the least safe unless accompanied by extensive training and special restrictions to landing.

With respect to the safety of airspeed/groundspeed, the modified flight director, and the acceleration margin, the results of the Phase 4 piloted flight simulation study of Low-Level Wind Shear are documented in Reference 4. The Phase 4 simulations compared three systems: (1) baseline (unmodified DC-10), (2) Groundspeed (with a special run evaluation display) and (3) a combination airspeed/groundspeed display together with modified flight director and acceleration margin. The simulations did not attempt to evaluate the modified flight director and acceleration margin as separate wind shear systems. It is believed that this is the correct approach and that the acceleration margin and modified flight directors are options that can be added at additional cost to a baseline airspeed/groundspeed system (technique) for coping with the wind shear hazard. Although Reference 4 recommends a combination of Airspeed/Groundspeed, Acceleration Margin, and the Modified Flight Director, it provides sufficent data to show that an Airspeed/Groundspeed system (technique) provides an increase in performance over a baseline technique (no aids) in several of the wind shear profiles.

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[1] References 1-4

[2] Safe Flight Instrument Corporation, The French Avionics Firm SFENA, and Britian's Smiths Industries.

The greatest variable in analyzing relative system benefits is groundspeed accuracy and reliability. However, for a wind shear system containing a given groundspeed source, it can be stated that the pilot will be able to cope with wind shear better if he also has an acceleration margin display; still better if he has a modified flight director; and best of all if he has both an acceleration margin display and a modified flight director. A still further improvement could be obtained through better displays, one of which is the head-up display.

5.2 ANALYSIS OF GROUNDSPEED MEASURING TECHNIQUES

The relative ranking of eight airborne techniques for measuring groundspeed are provided in Table 5-2.

TABLE 5-2. RELATIVE RANKING OF AIRBORNE TECHNIQUES FOR MEASURING GROUNDSPEED

Relative Ranking	Technique	Ground Station	Accuracy	
			Benign Environment	Multipath Environment
1 (1)	INERTIAL	NONE	GOOD	GOOD
2 (1)	CONVENTIONAL DOPPLER (3-4 Beam)	NONE	GOOD	GOOD
3	PRECISION DME	PDME TRANSPONDER	GOOD	GOOD
4	YETTER ONE-WAY DOPPLER	PRECISION CLOCK ON ILS LOCALIZER	GOOD	GOOD
5	CORAN	NONE	GOOD	GOOD
6	MILES PHOENIX DOPPLER (2 Beam)	NONE	FAIR	FAIR
7	MOD. NAV. DME WITH PREDICTIVE FILTER	DME TRANSPONDER	GOOD	POOR
8	MARLOW RADAR RANGE RATE (2)	ROTATING LUNEBERG LENS	GOOD	FAIR

(1) Rank equally as a source of groundspeed.
(2) Ranked lowest due to technical risk. Has not been flight tested. Will be moved to No. 7 if technical feasibility is demonstrated at approach airspeed.

The techniques evaluated are: DME with predictive filter[1], precision (MLS) DME, one way Doppler (Yetter Invention), Radar Range Rate (Marlow Industries rotating Luneberg Lens), inertial, airborne Doppler (3 or more beams), airborne Doppler (Miles Phoenix 2 beam), and G.E.'s CORAN.
Of these, the first four require cooperating ground stations; the latter four are self contained. All four techniques which require a cooperating ground station suffer some degradation when operating in a multipath environment.[2] Therefore operational benefits of these techniques, all other factors equal, could be less than the five techniques that do not require a ground station. The Marlow Radar Range Rate is ranked lowest due to the technical risk. Accuracy has not been demonstrated in an aircraft. The inertial and 3 beam doppler techniques all possess the accuracy required for satisfactory groundspeed measurement. An engineering model of CORAN with the required groundspeed accuracy has been procured by the FAA for testing at NAFEC. It is ranked below the previous techniques due to the nonavailability of test data. The Miles Phoenix 2 beam Doppler theoretically possesses accuracy better than systems subject to multipath errors but less than the other four self contained techniques discussed above. However these systems have satisfactory accuracy in a benign environment. Accuracy test data of the Miles Phoenix two beam Doppler is not available.

5.3 WIND SHEAR ON TAKE-OFF

It should be noted that all systems or techniques for coping with wind shear are landing aids. The only safe technique for coping with wind shear on take-off is to delay take-off until the hazardous situation passes.

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[1] Reference 8 concludes that the non-modified navigational DME has unacceptable accuracy. A predictive filter modification is required to provide the navigational DME with suitable accuracy for measuring range rate.

[2] Reference 10, Figure 1

6.0 COST ANALYSIS

Table 6-1 presents engineering estimates for the various component elements of alternative techniques for coping with Low Level Wind Shear on landing. Rationale for these estimates is contained in Appendix B.

Four scenarios are costed. All scenarios are based on a turbojet fleet of 2500 aircraft landing at 603 runways. The assumptions for each scenario are contained in Appendix A. The assumptions vary the user/FAA costs and sophistication of displays. All scenarios assume that FAA ground system costs would be phased over a 5 year period (FY 1983-1988). The full operational date of those systems requiring ground transmitters would be 1990.

Investment costs in current dollars for the four scenarios are presented in Tables 6-2 through 6-5. Operational costs are presented in Table 6.6.

On a simple cost basis, the relative (least costly to most costly) ranking of techniques are:

- Airspeed/Groundspeed with Miles Phoenix groundspeed
- Airspeed/Groundspeed with Yetter groundspeed
- Safe Flight Wind Shear System
- Airspeed/Groundspeed with CORAN groundspeed
- Airspeed/Groundspeed with Modified DME groundspeed
- SFENA Avionics
- Smiths Industries Avionics
- Airspeed/Groundspeed with Marlow (Luneburg Lens) groundspeed
- Airspeed/Groundspeed with inertial groundspeed
- Airspeed/Groundspeed with Doppler groundspeed
- Airspeed/Groundspeed with precision DME groundspeed
- Head-Up Display

TABLE 6-1. WIND SHEAR SYSTEM COMPONENT COSTS (X $1000)

	SYSTEM	WIND SHEAR AVIONICS	GROUNDSPEED AVIONICS	GROUNDSPEED SURFACE	COMPUTER	DISPLAY	UNIT OPERATING COST/YEAR
1.	AIRSPEED/GROUNDSPEED WITH INERTIAL NAV	NR	NR	NR	NR	0-2	0
	WITH INERTIAL GROUND SPEED SYSTEM	NR	20	NR	NR	0-2	.75
	WITH DOPPLER GROUNDSPEED	NR	20-25	NR	NR	0-2	.80
	WITH YETTER GROUNDSPEED	NR	4.5	8	NR	0-2	.34/.6
	WITH MARLOW GROUNDSPEED	NR	10-12	17	NR	0-2	.41/1.2
	WITH GE CORAN	NR	10-15	NR	NR	0-2	.45
	WITH MILES PHOENIX GROUNDSPEED	NR	3	NR	NR	0-2	.11
	WITH MODIFIED NAV DME GROUNDSPEED	NR	2-3.8	46 (1)	NR	0-2	.11/.45
	WITH PRECISION DME GROUNDSPEED	NR	9.1	91	NR	0-2	.34/.45
2.	MODIFIED FLIGHT DIRECTOR	5-6	(2)	NR	NR	NR	.19
3.	ACCELERATION MARGIN	NR	(2)	NR	0-2	0-2	0
4.	HEAD-UP DISPLAY	(3)	(3)	(3)	NR	75-100	3.2
5.	SAFE FLIGHT SYSTEM	7	NR	NR	NR	NR	.25
6.	SFENA SYSTEM	12-15(4)	NR	NR	NR	NR	.49
7.	SMITHS INDUSTRIES	12-15(4)	NR	NR	NR	NR	.49
8.	PREVIOUS MEASUREMENTS	0.5	(3)	0.5	(3)	NR	.02/.01

(1) Not required if suitable DME Ground Transponder is installed
(2) Requires a source of GS (3) Data may be obtained from any WS sensor
(4) Replaces 2 VS indicators valued at $2500 each

TABLE 6-2.

WIND SHEAR INVESTMENT COSTS, SCENARIO I

CURRENT DOLLARS (X $1,000,000)

DATA SOURCE	FAA COSTS (630 Runways)	USER COSTS (2500 TURBOJET FLEET)			
		AIRSPEED/ GROUNDSPEED	MODIFIED FLIGHT DIR (1)	ACCELERATION MARGIN(1)	OTHER
INERTIAL GROUNDSPEED	0	$43.48	$15.00 (2)	$2.13	
DOPPLER GROUNDSPEED	0	48.02	15.00	2.13	
YETTER GROUNDSPEED	$4.82	9.69	15.00	2.13	
MARLOW GROUNDSPEED	10.25	23.55	15.00	2.13	
GE CORAN GROUNDSPEED	0	21.42	15.00	2.13	
MILES PHOENIX G.S.	0	7.02	15.00	2.13	
MOD. NAV. DEM G.S.	23.87	4.90	15.00	2.13	
PRECISION DME G.S.	47.32	19.41	15.00	2.13	
SAFE FLIGHT AVIONICS	0				$17.50
SFENA AVIONICS	0				30.00 (4)
SMITHS INDUSTRIES AVIONICS	0				30.00 (4)
HEAD-UP DISPLAY	0				(3)
PREVIOUS MEASUREMENTS	0.20				1.25 (1)

(1) Not a stand alone cost. Requires Groundspeed.

(2) Will be double this cost if 2 MFD's are req'd

(3) Not in this Scenario

(4) Replaces 2 Vertical Speed indicators

TABLE 6-3.
WIND SHEAR INVESTMENT COSTS, SCENARIO 2
CURRENT DOLLARS (X $1,000,000)

DATA SOURCE	FAA COSTS (603 RUNWAYS)	USER COST (2500 TURBOJET FLEET)			
		AIRSPEED/ GROUNDSPEED	MODIFIED FLIGHT. DIR (1)	ACCELERATION MARGIN (1)	OTHER
INERTIAL GROUNDSPEED	0	$43.48	$15.00 (4)	$2.13	
DOPPLER GROUNDSPEED	0	48.02	15.00	2.13	
YETTER GROUNDSPEED	$4.82	9.69	15.00	2.13	
MARLOW GROUNDSPEED	10.25	23.55	15.00	2.13	
GE CORAN GROUNDSPEED	0	21.42	15.00	2.13	
MILES PHOENIX G.S.	0	7.02	15.00	2.13	
MOD. NAV. DME G.S.	23.05	8.14	15.00	2.13	
PRECISION DME G.S.	47.32	19.41	15.00	2.13	
SAFE FLIGHT AVIONICS	0				$17.50
SFENA AVIONICS	0				30.00 (4)
SMITHS INDUSTRIES AVIONICS	0				30.00 (4)
HEAD-UP DISPLAY	0				(3)
PREVIOUS MEASUREMENTS	0.20				1/25 (1)

(1) Not a stand alone cost.
Requires Groundspeed.
(2) Will be done this
cost if 2 MFD's are req'd
(3) Not in this Scenario
(4) Replaces 2 Verified Speed Indicators

TABLE 6-4.
WIND SHEAR INVESTMENT COSTS, SCENARIO 3
CURRENT DOLLARS (X $1,000,000)

DATA SOURCE	FAA COST (603 RUNWAYS)	USER COSTS (2500 TURBOJET FLEET)			
		AIRSPEED/ GROUNDSPEED	MODIFIED FLIGHT DIR (1)	ACCELERATION MARGIN (1)	OTHER
INERTIAL GROUNDSPEED	0	$44.73	$15.00 (4)	$5.88	
DOPPLER GROUNDSPEED	0	49.27	15.00	5.88	
YETTER GROUNDSPEED	$ 4.82	10.94	15.00	5.88	
MARLOW GROUNDSPEED	10.25	24.80	15.00	5.88	
GE CORAN GROUNDSPEED	0	22.67	15.00	5.88	
MILES PHOENIX G.S.	0	8.28	15.00	5.88	
MOD. NAV. DME G.S.	23.87	6.15	15.00	5.88	
PRECISION DME G.S.	47.32	20.66	15.00	5.88	
SAFE FLIGHT AVIONICS	0				$17.50
SFENA AVIONICS	0				[illegible] (2)
SMITH INDUSTRIES AVIONICS	0				30.00 (2)
HEAD-UP DISPLAY	0				(3)
PREVIOUS MEASUREMENTS	0.20				[illegible] (1)

(1) Not a stand alone cost. Requires Groundspeed.
(2) Will be double this cost if 2 MFD's are req'd
(3) Not in this Scenario
(4) Replaces 2 Vertical Speed Indications

TABLE 6-5

WIND SHEAR INVESTMENT COSTS, SCENARIO 4

CURRENT DOLLARS (X $1,000,000)

DATA SOURCE	FAA COSTS (603 Runways)	USER COSTS (2500 TURBOJET FLEET)			
		AIRSPEED/ GROUNDSPEED	MODIFIED FLIGHT DIR (1)	ACCELERATION MARGIN (1)	OTHER
INERTIAL GROUNDSPEED	0	$43.48	$15.00	$2.13	
DOPPLER GROUNDSPEED	0	48.02	15.00	2.13	
YETTER GROUNDSPEED	$ 4.82	9.69	15.00	2.13	
MARLOW GROUNDSPEED	10.25	23.55	15.00	2.13	
GE CORAN GROUNDSPEED	0	21.42	15.00	2.13	
MILES PHOENIX G.S.	0	7.02	15.00	2.13	
MOD.NAV. DME G.S.	23.87	4.90	15.00	2.13	
PRECISION DME G.S.	47.32	19.41	15.00	2.13	
SAFE FLIGHT AVIONICS	0				$17.50
SFENA AVOPMOCS	0				30.00 -(3)
SMITHS INDUSTRIES AVIONICS	0				30.00 - (3)
HEAD-UP DISPLAY	0				217.50
PREVIOUS MEASUREMENTS	0.20				[illegible].25 (1)

(1) Not a stand alone cost.
Requires Groundspeed.
(2) Will be double this
cost if 2 MFD's are req'd
(3) Replaces 2 vertical Speed Indicators

TABLE 6-6. WIND SHEAR OPERATIONAL COSTS

SCENARIO 1, DISCOUNTED DOLLARS (PRESENT VALUE X $1,000,000)

	INERTIAL		YETTER		MARLOW		GE	MILES	MOD NAV DME		PDME		SAFE		
	GS ONLY	DOPPLER	USER	FAA	USER	FAA	CORAN	PHOENIX	USER	FAA	USER	FAA	FLIGHT	SFENA	SMITHS
1983	1.26	1.34	.56	0	.69	0	.76	.18	.18	0	.57	0	.49	.82	.82
1984	1.15	1.22	.51	.003	.63	.006	.69	.17	.17	.02	.52	.02	.45	.75	.75
1985	1.04	1.11	.46	.007	.57	.014	.63	.15	.15	.05	.47	.05	.41	.68	.68
1986	.94	1.01	.43	.011	.52	.022	.57	.14	.14	.08	.43	.08	.37	.62	.62
1987	.86	.92	[illegible]	.014	.47	.028	.52	.13	.13	.10	.39	.10	.34	.56	.56
1988	.78	.83	.35	.016	.43	.032	.47	.11	.11	.12	.35	.12	.31	.51	.51
1989	.72	.76	.32	.016	.39	.032	.43	.10	.10	.12	.32	.12	.28	.47	.47
1990	.64	.69	.29	.015	.35	.030	.39	.09	.09	.11	.29	.11	.25	.42	.42
1991	.59	.63	.26	.013	.32	.026	.35	.08	.08	.10	.27	.10	.23	.38	.38
1992	[illegible]	.57	.24	.012	.29	.024	.32	.08	.08	.09	.24	.09	.21	.35	.35
1993	[illegible]	.52	.22	.011	.27	.022	.29	.07	.07	.08	.22	.08	.19	.32	.32
1994	.41	.47	.20	.010	.24	.020	.26	.06	.06	.08	.20	.08	.17	.29	.29
1995	[illegible]	.43	.18	.009	.22	.018	.23	.06	.06	.07	.18	.07	.16	.26	.26
1996	.36	.39	.16	.009	.20	.017	.21	.05	.05	.06	.16	.06	.14	[illegible]	.24
1997	[illegible]	.35	.15	.008	.18	.016	.19	.05	.05	.06	.15	.06	.13	.22	.22
1998	.28	.33	.13	.007	.17	.014	.18	.04	.04	.05	.14	.05	.12	.20	.20
15 Yr Totals															
Air Carriers	10.79	11.58	4.85		5.94		6.49	1.56	1.56		4.9		4.25	7.09	[illegible]
FAA				[illegible]		[illegible]				1.19		1.19			

NOTE: Scenario 2, 3, and 4 O & M not computed but 2 & 3 are essentially the same and option 4 (Head-up Display) will add 15 year discount costs of $71.2M

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APPENDIX A

WIND SHEAR SCENARIOS

SCENARIO 1

The Commercial Turbojet Fleet consists of 2500 aircraft. 367 of this fleet have inertial navigators. The remaining 2133 have no readily available airborne source of groundspeed information.

The commercial Fleet operates from certain runways on which ILS landing aids are currently installed or planned (see Appendix F).

Airborne Wind Shear systems fall into two general categories: (1) self contained airborne systems and (2) airborne systems that are dependent upon a ground-based source of data. Ground data for the latter system are provided for 603 ILS runways (Appendix F).

Ground DME transponders are located more than 4000 feet beyond runway threshold and less than 720 feet from runway centerline.

Displays consist of a single needle or digital display for groundspeed and a go-around light display for acceleration margin.

Ground systems (FAA costs) are funded equally over a 5 year period beginning in FY 1983 and ending in FY 1987 as follows: 120 systems, 1983; 120 systems, 1984; 120 systems, 1985; 120 systems, 1986; and 123 systems, 1987.

SCENARIO 2

Same as Scenario I except all DME equipped aircraft are able to compute groundspeed from ground transponders located more than 720 feet off runway centerline. Under this scenario, 18 fewer ground transponders are required.

SCENARIO 3

Same as Scenario I except a moving tape display compares airspeed and groundspeed and the real value of acceleration margin is used in lieu of a go-around light.

SCENARIO 4

Same as Scenario I except a single pilot head-up display is used.

APPENDIX B

SOURCES AND BASIS OF COST DATA

1. Inertial Navigators

A listing of inertially equipped aircraft is contained in Table B-1.

TABLE B-1. U.S. AIR CARRIER FLEET EQUIPPED W/INS*

Airline	DC-10	747	L1011	A300
American	28	11		
Braniff		3		
Continental		15		
Flying Tiger		6		
National	16			
Northwest	22	21		
TransWorld		11	30	
Pan American		43		
United	37	18		
Western	9			
Delta			28	
Eastern			34	7
Seaboard	1	3		
World	3	4		
Air Canada		6	7	
CP Air		4		
Total 367	116	145	99	7

* This data was obtained from the May 1979 issue of Air Transport World and from Mr. Frank White of ATA.

Those aircraft equipped with the Delco Caroussel 4 inertial navigator or equivalent have groundspeed continuously displayed on the Horizontal Situation Indicator (HSI). TWA has 21 aircraft so equipped.

The Flying Tiger B-747 possess fewer HSI displays than Delco Carroussel 4 (see TWA above) but have been modified to display "goundspeed" on the "miles to next check point" display at any time groundspeed drops below 200.

The USAF has inertial navigators on all their C-5A and C-141 fleet. Groundspeed is displayed on the inertial navigator console.

Costs of obtaining groundspeed from an inertial navigator is a display cost and not a source cost according to current users of the system. Groundspeed is available as a binary coded signal on an external source or display.

Data was obtained from:

Lt. Col. L. Wood FAA ARD 312 (202) 426-9350

Maj. Tim Hatch USAF Military Airlift Cmd. (618) 256-3610

Capt. Bill Sonnemann Staff Flt. V.P. TWA (212) 557-3862

Capt. Jack Bliss Flying Tigers (213) 831-1813

2. Inertial Ground Speed

The estimated cost of an inertial ground speed system, designed to provide ground speed only, will cost approximately $20K. This cost is based on an estimate by Mr. Joe Cox, FAA Consultant.

3. Doppler Ground Speed

The cost of a Marconi AD660DVS is estimated to be $25K, with delivery in June 1981. This quote was made by Mr. John Carter of the Marconi Atlanta Georgia Office, (404) 394-7800.

The cost of a Decca of the type currently used in rotary wing aircraft is estimated to be $20K. This cost was quoted by Mr. Hird of the Decca Washington Office: 587-1161.

4. Yetter Ground Speed

A breadboard Yetter ground speed system has been built and is undergoing testing. Production costs are estimated by Mr. Yetter as follows:

Ground costs to modulate 5 KHz signal (at each ILS site)

Electronics	$4000
Rubidium Clock	$4000

Airborne Costs (each airplane)

Quartz Clock (has to be periodically updated)	$ 500
Rubidium Clock (alternative to quartz clock)	4000
Electronics	4000

5. Marlow (Lunebuerg Lens) Ground Speed

Costs of $10-12 to modify the airborne radar and $17 K for each runway end were obtained from Mr. Ray Marlow (214) 494-2521 based on an installed quantity of 200-400 airborne systems and 700 ground systems.

6. G. E. CORAN Radio Altimetry Ground Speed

Costs were obtained from G. E. Utica, N. Y. CORAN Representative, Mr. Eisenberg, 315-797-1000, Ext. 7792. The prototype CORAN being tested by NAFEC. cost the government $50K. The 50K, however, was not the real cost inasmuch as most of the development was funded by G.E. G. E.'s target price for production units is $10-15K. The top price would include radar altimetry data plus ground speed - the lower price would be an instrument for ground speed only.

7. Miles Phoenix Doppler Ground Speed

The estimate of $3000 for a production quantity beam Decca Doppler was provided by Mr. Harvey Schwartz (602) 994-8770. The unit is 7½" X 14' X 2" in size and could be mounted in the wheel well and thus presents no special installation problems.

8. Navigation DME Ground Speed

Cost estimates were obtained from Sierra Research Corp. TR-1798, 28 Jan. 1978. The cost estimate of $500 is for a new product DME, $2000 is for an add-on box to present DME for uncorrected ground transponder offset and $3800 is for an add-on box to compute along track velocity from an offset ground transponder where one ground transponder serves more than one runway. Airborne receivers that do not have an offset ground transponder computational capability cannot measure ground speed from ground DME sites more than 720 feet off runway centerline.

Also the ground transponder must be more than 4000 feet beyond threshold. This means that most airports would require the installation of a $46K ground DME transponder on each landing runway not currently equipped. The $46K includes the approximate current cost to the FAA but does not include maintenance and spares. Costs of future production buys would have to be adjusted for inflation.

9. Precision DME Groundspeed

Costs of $91,000 for a precision DME transponder and $9,100 for an airborne receiver are based on the cost estimates contained in the U.S. Microwave Landing System proposal to ICAO as inflated at 10% per year.

10. Modified Flight Director

Cost data for the modified flight director was obtained from Collins Cedar Rapids, Iowa, who developed the flight director utilized in the FAA's wind shear tests. Estimated prices are based on a modified flight director similar to those simulated during the FAA/SRI wind shear program as follows:

a) The flight director system to be modified will include two multi axis flight director boxes similar to the Collins 562A-5F5. The modification cost for each of these boxes will be approximately $4,000.

b) FAA performance requirements will result in modification of all three axes of flight control. This requirement will result in the addition of at least one accelerometer in each axis at approximately $1,000 each.

c) New replacement flight directors will be plug replaceable units, except for the accelerometer input wiring. These flight directors will be approximately $6,000 each.

d) Installation costs do not include the possible requirement for a wind shear discrete drive for an instrument panel display.

Collins cautioned that actual costs cannot be projected until performance factors are established.

11. Acceleration Margin

Acceleration margin is a computed analog quantity designed to indicate when the airplane is getting into a hazardous situation with respect to longitudinal wind shear. Aircraft with computers can accomplish this function if properly programmed and provided the following inputs:

Acceleration capability of the airplane

Wind component at ground along the runway

True airspeed of airplane

Ground speed of airplane

Altitude

Rate of change of altitude

Aircraft, which do not possess an airborne computer would have to procure a single general purpose avionic computer at a cost of $1K

12. Head-up Display

The cost of installing a head-up display for one pilot in the DC-9-80 is estimated to be $75-100 K exclusive of certification.

Source: Jack McDonnel, (213) 593-5616

13. Size of Commercial Turbojet Fleet

Fleet consists of 2500 aircraft. Of these 367 have inertial navigation (see Appendix B-1). 2133 would require a source of groundspeed for windshear.

Source: Mr. Daniel R. Keenan AFS- 240 426-8096.

14. Maintenance and Operating Costs.

Maintenance costs of avionics are roughly 1 to 1½ cents per flying hour per $1,000 of acquisition cost. By assuming the costs of the investment shown in a given table and assuming 2500 flying hours per year the maintenance cost is computed.

15. Initial Spare Units (avionics)

In practice major air carriers stock spare avionic units at airports around the country. In practice the number of spare units is 1/3 to 1/2 the number installed in the aircraft.

16. Doucmentation and Training (Avionics)

If one assumes that the cost of special documentation, training two technicians, and procurement of special test equipment is $25,000 and the airline has 250 airplanes, the prorated unit cost is $100 per aircraft.

17. ILS Runways

All airports served by turbojet aircraft are authorized ILS. Of the current and planned 844 ILS (AAF-120 report dated June 12, 1979) 603 are at CONUS airports served by air carrier aircraft. According to the FAA Terminal Area Forecast the remaining ILS runways have no current or projected air carrier operations.

18. DME Requirements

Of the 603 ILS runways 11 are currently equipped with DME. For DME groundspeed computation 519 ground transponders would be required (DME located more than 4000 feet beyond threshold and less than 720 feet off runway centerline).

19. Yetter Invention Requirements

Of the 603 ILS runways 603 ILSs would require modification for the Yetter Groundspeed.

20. Lunenberg Lens Requirement

Of the 603 ILS runways all would require Lunenberg Lens for the Marlow Groundspeed Technique.

21. Safe Flight Instrument Corporation Wind Shear System

Cost information was obtained from Randy Green (914) 946-9500, of Safe Flight.

22. SFENA Wind Shear System

Cost information was obtained from Dr. Roger Phaneuf, SFENA consultant and Washington contact. Telephone (202) 296-7650.

23. Smiths Industries Wind Shear System

Cost is estimated to be competitive with SFENA which uses same principles.

APPENDIX C

Ground Equipment Installation

Phasing

	Scenario 1, 3, 4	Scenario 2
1983	0	0
1984	60	60
1985	180	180
1986	300	300
1987	420	420
1988	540	540
1989	603	585
1990	603	585
1991	603	585
1992	603	585
1993	603	585
1994	603	585
1995	603	585
1996	603	585
1997	603	585
1998	603	585

APPENDIX D

COST COMPUTATIONS

Scenario I	(X$1,000,000)
1. Inertial	
Groundspeed	
2133 acft X Inertial G S Source @$20,000	$42.66
2133 acft X displays @ $250	0.53
367 acft have inertial navigaters X displays @$250	0.09
	$43.28
2. Doppler Groundspeed	
2133 acft X $22,500	$47.98
367 acft X displays @ $250	0.09
	$48.02
3. Yetter Groundspeed	
2133 acft X $4,500	$ 9.60
367 acft X displays @250	0.09
	$ 9.69
FAA Costs:	
603 ILS X $8,000	$ 4.82
4. Marlow Groundspeed	
2133 acft X $11,000 (average)	$23.46
367 acft X display @250	0.09
Total User Costs	$23.55
FAA Costs	
603 ILS runways X $17,000	$10.25

APPENDIX D COST COMPUTATIONS (Continued)

5. G.F. Coran	
2133 acft X $10,000	$21.33
367 acft X displays @$250	0.09
	$21.42
6. Miles Phoenix Groundspeed	
2133 acft X $3,000	$ 6.40
2133 Displays @$250	0.53
367 inertial acft displays @$250	0.09
	$ 7.02
7. Modified Navigation	
DME Groundspeed	
2133 acft X $2,000	$ 4.27
2500 acft X displays @$250	0.63
Total user cost	$ 4.90
FAA Costs	
519 New DME Transponders @$46,000	$23.87
8. Precision DME Groundspeed	
2133 acft X $9,100	$19.41
2500 displays @ $250	0.63
Total User Cost	[illegible]
FAA Costs	
(519 +11) runways @ $91,000	$48.23
9. Safe Flight System	
2500 X $7,000	$17.50
10. SFENA System	
2500 X $12,000	$30.00

APPENDIX D COST COMPUTATIONS (Continued)

11. Smith Industries	
2500 X $12,000	[illegible]
12. Previous Measurements	
2500 acft X $500 (User	$ 1.25
396 Airports X $500 (FAA)	$ 0.20
13. Modified Flight Director	
2500 X $6K	$15,000
14. Acceleration Margin	
2133 X $1K	[illegible]
Scenario 2:	
Same as Scenario 1 except DME Groundspeed:	
2133 acft X $3800	[illegible]
2500 acft X displays @ $250	0.63M
Total user costs	8.[illegible]M
FAA Costs	
501 New DME Transponders @ $46,000	[illegible]
Scenario 3:	
Same as Scenario 1 except displays:	
2500 acft X $2000	[illegible]
Scenario 4:	
Same as Scerine 1 except displays	
2500 acft X $[illegible]*	[illegible]

*Average of the [illegible] 10 [illegible]

APPENDIX E

Program/Project Year Discount Factors

PRESENT VALUE OF $1 (Single Amount - To be used when cash-flows accrue in different amounts each year).

Project Year	Calender Year	10%
1	1981	0.954
2	1982	0.867
3	1983	0.788
4	1984	0.717
5	1985	0.652
6	1986	0.592
7	1987	0.538
8	1988	0.489
9	1989	0.445
10	1990	0.405
11	1991	0.368
12	1992	0.334
13	1993	0.304
14	1994	0.276
15	1995	0.251
16	1996	0.228
17	1997	0.208
18	1998	0.189
19	1999	0.172
20	2000	0.156

Factors are based on continuous compounding of interest at the stated effective rate per annum, assuming uniform cash flows throughout stated one-year periods. These factors are equivalent to an arithmetic average of beginning and end of the year compound amount factors found in standard present value tables.

APPENDIX F

AIR CARRIER AIRPORTS WITH ILS

State/Airport	Commissioned/Rwy	ILS Planned 80/81	[illegible] * Scenario 1	[illegible] * Scenario 2
Alabama				
Anniston	05		1	1
Birmingham	05,23		1	1
Dothan	31		1	1
Huntsville	18R,36L		1	1
Mobile	14,32		2	2
Montgomery	09,27		1	[illegible]
Muscle Shods	29		1	[illegible]
Tuscullosa	04		1	1
Arizona				
Chandler		UNK	1	1
Flagstaff		21	1	1
Grand Canyon		03	1	1
Phoenix	08R		1	1
Tuscon	11L		1	[illegible]
Ryan		UNK	1	1
Yuma	21R		1	1
Arkansas				
Fayetteville	16		1	1
Ft. Smith	25	07	1	1
Harrison		36	1	1
Hot Springs	05		1	1
Little Rock	04,22		2	2
Texarkana	22		1	1
California				
Arcata-Eureka	31		1	1
Bakersfield	30R		1	1
Burbank	07		1	1
Chico	13L		1	1
Crescent City	11		1	1
Fresno	29R		1	1
Long Beach	30		1	1
Los Angeles (Intl)	07R, 06R (DME), 07L (DME), 24L 24R (DME), 25L (DME), 25R 06L		0	[illegible]
Marysville		UNK	1	1
Modesto	28R		1	1
Monterey	10	28	2	2
Oakland	11, 27R, 29		3	2
Ontari	07,25		1	1
Red Bluff		33	1	1
Redding	34		1	1

* Scenario 1. DME 4000 Ft from threshold and less than 720 Ft from Centerline
Scenario 2: DME 4000 Ft from threshold and greater than 720 ft. from centerline.
(Requires airborne computer)

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DML Seen	DME Seen
California (Continued)				
Sacramento (Metro)	16,34		1	1
San Deigo (Lind.)	09 (DME)	27	1	1
San Francisco	19L, 28L	10R	2	2
Tracy		UNK	1	1
San Jose (Muni.)	30L		1	1
Colorado				
Arapahoe	34		1	1
Colorado Spgs.	17R	35	1	1
Denver (Stapleton)	08R, 36L (DME), 35L, 35R	17L	2	2
Durango		02	1	1
Grand Junction	11		1	1
Pueblo	07L, 25R		1	1
Connecticut				
New Haven	02		1	1
Windsor Locks	06, 24, 33		2	1
Delaware				
Wilmington	01		1	1
District of Columbia				
Washington (Dulles)	01L, 01R, 12, 19L, 19R		4	3
Washington(Nat'l)	18, 36		1	1
Florida				
Daytona Beach	06L		1	1
Ft. Myers	05		1	1
Ft. Lauderdale	09L	09R, 27R	2	2
Gainsville	28		1	1
Jacksonville	07,13,25		2	2
Miami (Intl.)	09L, 09R, 27L, 27R	12, 30	4	3
Orlando (Intl.)	36L, 36R	18R	2	2
Orlando (Herndon)	07		1	1
Panama City	14		1	1
Pensacola	16		1	1
Sarasota	31	13	1	1
St. Petersburg	17		1	1
Tampa	18L, 36L	18R	2	1
Tallahassee		27	1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Sign	DME User
Georgia				
Atlanta (Hartsfield)	09L, 09R, 08, 26, 27L	27R	2	2
Augusta (Bush)	35, 17		1	1
Columbus	05		1	1
Macon	05		1	1
Savannah	09	18, 27	2	1
Valdosta	35		1	1
Idaho				
Boise	10R		1	1
Idaho Falls	20		1	1
Lewiston	26		1	1
Pocatello	21		1	1
Twin Falls	25		1	1
Illinois				
Bloomington	29		1	1
Carbondale	18		1	1
Champaign	31		1	1
Chicago (Midway)	04R, 13R, 31L		3	3
Chicago (O'Hare)	04L, 04R, 09L, 09R, 14L, 14R (DME) 22L, 22R, 27L, 27R, 32L, 32R		6	4
Decatur	06		1	1
Marion	20		1	1
Moline		27	1	1
Mt. Vernon	23		1	1
Peoria	30	12	2	2
Quincy	03		1	1
Rockford	36		1	1
Springfield	04	22	1	1
Indiana				
Bloomington	35		1	1
Evansville	22	04	1	1
Ft. Wayne	04, 31		1	1
Gary	30		1	1
Indianapolis (Muni.)	04L, 22R, 31	13	1	1
South Bend	27	09	2	2
Iowa				
Ames		31	1	1
Burlington	36		1	1
Cedar Rapids	08	27	2	2
Des Moines	12L, 30R		1	1
Dubugul	31		1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Seen	DME Seen
Iowa (Continued)				
Davenport		14	1	1
Fort Dodge	06		1	1
Mason City	35		1	1
Sioux City	31	13	1	1
Waterloo	12,30		1	1
Kansas				
Garden City		35	1	1
Goodland	30		1	1
Great Bend	35		1	1
Hutchinson	13		1	1
Hays		34	1	1
Johnson Co.		35	1	1
Liberal		35	1	1
Manhattan		03	1	1
McFairfax		35	1	1
Salina	35		1	1
Topeka	13, 31		1	1
Witchita	01R, 19R		2	2
Kentucky				
Covington (Grtr. Cin.)	09R, 18, 27L, 36		2	1
Lexington	04	22	2	2
London		15	1	1
Louisville (Stand)	01, 19, 29		2	2
Paducah	04		1	1
Louisiana				
Alexandria (Esler)	26		1	1
Baton Rouge	13, 22		1	1
Monroe	04	22	2	2
New Orlans (Moisnt)	01, 10	28	2	2
Shreveport (Grtr.)	13, 31		2	2
Maine				
Augusta	17		1	1
Bangor	33	15	1	1
Portland	11	29	2	2
Maryland				
Baltimore	10, 15R, 28		1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Scen	DME Scen
Massachussetts				
Boston	04R, 15R, 27, 33L	22L	2	1
Hyannis	24	15	1	1
Martha's Vineyard	24		1	1
Nantuckett	24	33	1	1
New Bedford	05	23	2	2
Michigan				
Alpena	36		1	1
Battle Creek	22		1	1
Benton Harbor	27		1	1
Detroit City	15, 33		2	2
Detroit (Willow Run)	15R	23L	2	2
Detroit (Metro)	03L, 03R, 21L, 21R, 27		2	1
Escanaba	09		1	1
Flint	09	27	2	2
Grand Rapids	08R, 26L		2	2
Houghton (Hancock)	31		1	1
Iron Mountain	01		1	1
Ironwood		27	1	1
Kalamazoo	35	17	2	2
Lansing	09, 27		2	2
Marquette	08		1	1
Manistee		27	1	1
Menominee		14	1	1
Muskagon	32	23	2	2
Pellston	32		1	1
Saginaw	05	23	1	1
Travise City	28	36	1	1
Minnesota				
Bemidji		31	1	1
Brainerd		22	1	1
Duluth	09, 27		1	1
Hibbing	31		1	1
International Falls	31		1	1
Mpl. St. Paul	04, 11R, 22, 29L (DME), 29R		2	1
Rochester	13, 31		2	2
Thief Rvr. Falls	31		1	1
Mississippi				
Columbus	18		1	1
Greenville	17L		1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Scen	DME Scen
Mississippi (Continued)				
Greenwood		18	1	1
Gulfport	13		1	1
Jackson (Thompson)	15L, 33L		1	1
Meridian	01	19	1	1
Tupelo		18	1	1
Missouri				
Cape Girardeau	10		1	1
Columbia	02		1	1
Ft. Leonard Wood		14	1	1
Joplin	13	35	1	1
Kansas City (Intl)	01, 09, 19		2	1
Kansas City (Mid Cont)		27	1	1
St. Louis (Lambert	06, 12R, 24, 30L		3	2
Montana				
Billings	09	27	1	1
Butte		15	1	1
Bozeman	12		1	1
Great Falls	03, 34		1	1
Helena	26		1	1
Kalispell	01		1	1
Missoula	11		1	1
W. Yellowstone	01		1	1
Nebraska				
Grand Island	35		1	1
Hastings		14	1	1
Lincoln	35L	17R	1	1
Norfolk		01	1	1
North Platte		29	1	1
Omaha	14R, 32L		1	1
Scottsbluff	30		1	1
Nevada				
Carson City		UNK	1	1
Elko		23	1	1
Ely		18	1	1
Las Vegas	25		1	1
Reno	16 (DME)		0	0
New Hampshire				
Keene	02		1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Scen	DME Scen
New Hampshire (Continued)				
Lebanon	07	18	1	1
Manchester	35		1	
New Jersey				
Atlantic City (NAFEC)	13		1	1
Millville	10		1	
Newark	04L,04R		1	
Titerboro	06		1	1
Trenton	06		1	1
New Mexico				
Albuquerque	08		1	
Gallup		06	1	
Roswell	21		1	
Silver City		26	1	
New York				
Albany	01, 19		2	
Binghamton	16, 34		2	
Buffalo	05, 23		1	1
Elmira	24	06	1	
Islip	06, 24		2	
Ithica	32		1	1
New York (JFK)	04L, 04R (DME) 13L 22L, 22R, 31L, 31R		4	2
New York (Laguardia)	13, 04, 22	31	3	3
Niagra Falls	28R		1	1
Syracuse	10, 14, 28	32	2	1
White Plains	16	34	2	2
Utica	15, 33		2	2
North Carolina				
Asheville	16, 34		2	
Charlotte	36L, 05	18R, 36R	2	2
Fayetteville	03		1	1
Greensboro	14, 23	05	3	3
Hickory				
Jacksonville	05		1	1
Kingston	04		1	1
New Bern		04	1	1
Raleigh	05, 23		2	2
Rocky Mount	04		1	1
Wilmington	34		1	1
Winston Salem	33		1	1

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Seen	DME Seen
North Dakota				
Bismarak	31		1	1
Fargo	35	17	1	1
Grand Forks	35		1	1
Jamestown	30		1	1
Minot	31		1	1
Ohio				
Akron (Canton)	01,23, 19		2	2
Cleveland (Hop)	05R (DME) 23R, 28L	18R, 36L	3	2
Cleveland (LRF)	24R		1	1
Columbus	03		1	1
Columbus (Post)	10L, 10R, 28L		3	1
Dayton (Gen)		20	1	1
Dayton (Main)	06L, 18, 24L, 24R,		3	2
Toledo	25		1	1
Toledo (Express)	07		1	1
Youngstown	14, 32		2	2
Oklahoma				
Enid	35		1	1
Lawton		35	1	1
McAlister		01	1	1
Oklahoma City (WR)	17L, 17R, 35R		3	1
Ponce City		17	1	1
Tulsa	17L, 35R	17R, 35L	3	3
Oregon				
Eugene	16		1	1
Kalmath Falls	32		1	1
Medford	14		1	1
North Bend	04		1	1
Pendleton	25R		1	1
Portland	10L		1	1
Portland (Intl)	10R, 20, 28R		1	1
Redmond	22		1	1
Pennsylvania				
Allentown	06, 13		1	1
Bradford	32	14	2	2
Erie	06, 24		2	2
Middletown	13		1	1
Meadville		25	1	1
Newcastle		04	1	1
Philadelphia (Intl)	09R, 27L, 27R	17	2	2

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Seen	DME Seen
Pennsylvania (Continued)				
Pittsburg	32		1	1
Pittsbugr (Gtr)	10L, 28L	10R, 28R, 32	3	2
Reedsville	06		1	1
Wilkes-Barre	04	22	2	2
Williamsport	27		1	1
Rhode Island				
Providence	23L, 05R, 34		3	2
South Carolina				
Anderson		05	1	1
Charleston	15	33	1	1
Columbia	11, 29		2	2
Florence	09		1	1
Greer	03	21	2	2
Greenville	36		1	[illegible]
Myrtle Beach	23		1	1
South Dakota				
Aberdeen	31		1	1
Huron	12		1	1
Pierre	31		1	1
Rapid City	32		1	1
Sioux Falls	03	21	1	1
Watertown	35		1	1
Yankton		31	1	1
Tennessee				
Bristol	22	04	2	2
Chattanooga	02,20		2	2
Clarksville		34	1	1
Jackson	02		1	1
Knoxville	04L, 22R		2	1
Memphis (Intl)	09, 17L, 17R, 35L, 35R	27	[illegible]	[illegible]
Nashville	02L, 31	20R	[illegible]	[illegible]
Texas				
Abilene	35R		1	[illegible]
Amarillo	04		1	1
Austin	12R, 30L		1	1
Beaumont	11		1	1
Brownsville	13R		1	1
Corpus Christi	13, 35		2	2
Dallas (Love)	13L, 31L		1	1
Dallas/FTW	17L, 17R, 31R, 31L, 35R		3	3

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Seen	DME Seen
Texas (Continued)			1	1
El Paso	22	32	1	1
Houston (Inter Cont)			1	1
Houston (Hobby)	03		2	2
Houston (Intl)	08, 14, 26, 32	01	1	1
Killeen			1	1
Laredo	17C		1	1
Longview	13	26	1	1
Lubbock	17R		1	1
McAllen	13		1	1
Midland	10		1	1
San Angelo	03		2	2
San Antonio	03R, 12R, 30L		1	1
Temple	15		1	1
Tyler	13		1	1
Victoria	12L			
Utah		20	1	1
Cedar City		16R	2	2
Salt Lake City	16L, 34L			
Vermont			1	1
Barre Montpelier	17		1	1
Burlington	15			
Virginia			1	1
Charlottesville	03	12	1	1
Danville			1	1
Hot Springs	24		1	1
Lynchburg	03		1	1
Newport News	06		1	1
Norfolk	05, 23(DME)		1	1
Richmond	06, 15, 33		2	2
Roanoke	05, 33		1	1
Staunton	04			
Washington			1	1
Pasco	21R		1	1
Seattle (Boeing)	13R	34L	1	1
Seattle (SEA-TAC)	16R, 34R	18	1	1
Richland			1	1
Spokane	03, 21		1	1
Yakima	27			

APPENDIX (Continued)

State/Airport	Commissioned/Rwy	ILS Planned 80/81	DME Scen	DME Scen
West Virginia				
Beckley	10, 19		2	2
Bluefield	22		1	1
Charleston	23(DME)		0	0
Clarksburg	21		1	1
Huntington	12	30	2	2
Lewisburg	08		1	1
Morgantown	18		1	1
Parkersburg	03		1	1
Wheeling	03		1	1
Wisconsin				
Appleton	03		1	1
Eau Claire	22		1	1
Green Bay	06R	24L, 36	2	2
Jonesville	04		1	1
LaCrosse	18	13	2	2
Madison	36, 18		1	1
Milwaukee	01L, 07R, 19R, 25L		2	2
Manistee	27		1	1
Mosonee	08		1	1
Oshkosh	36		1	1
Rhinelander		09	1	1
Wyoming				
Casper	03, 07		1	1
Cheyenne	26		1	1
Jackson	36		1	1
Rock Springs	25		1	1
Sheridan	31		1	1

Total Airports with 1 or more ILS	346
Total Airports with ILS Planned for 1980-81	50
Total ILS equipped/Planned Airports with ILS	396
Total ILS Runways	603
Total runways with DME, AT, ILS, LOC,	11
Additional DMEs Required (Scenario 1)	519
Additional DMEs Required (Scenario 2)	501

LME