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Low-Altitude Wind Shear and Its Hazard to Aviation

Committee on Low-Altitude Wind Shear and Its Hazard to Aviation, Aeronautics and Space Engineering Board, Atmospheric Sciences and Climate Board, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Low-Altitude Wind Shear and Its Hazard to Aviation

Report of the
Committee on Low-Altitude Wind Shear and Its Hazard to Aviation

A Joint Study
Commission on Engineering and Technical Systems
Aeronautics and Space Engineering Board
Commission on Physical Sciences, Mathematics, and Resources
Atmospheric Sciences and Climate Board
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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September 29, 1983

Dr. Frank Press
Chairman,
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Dr. Press:

It is my privilege to submit the report of the Committee on Low-Altitude Wind Shear and Its Hazard to Aviation, which was established under the terms of an agreement between the National Academy of Sciences and the Federal Aviation Administration (FAA). The task of the committee was to review the state of knowledge of low-altitude wind shear, to study the hazards of low-altitude wind variability, and to recommend actions to reduce the hazards of wind-shear encounters and improve flight safety. This work was directed by the terms of Public Law 97-369, signed December 18, 1982.

The committee's principal finding confirmed that low-altitude wind variability (or wind shear) presents an infrequent but highly significant hazard to aircraft while landing or taking off, and that when significant wind shears may be present, pilots should delay takeoffs or landings or divert to alternate airports.

In the near term, risks can be reduced by improving and automating the Low-Level Wind Shear Alert System (LLWSAS) and by its installation at all major airports. Ground personnel must be better trained in the utilization of LLWSAS data and in the use of wind-shear warnings derived from forecasts of weather conditions that are conducive to generating wind shear. Voluntary reports of wind-shear encounters or alerts by pilots to air traffic control personnel along with weather advisories remain the only sources of wind-shear information for those airports that lack LLWSAS installations.

The committee found that the education and training of most pilots with respect to wind shear and its hazards are inadequate and that the risk posed by wind shear can be reduced very soon by an education campaign directed at all classes of pilots.

Better information is required concerning the response to wind shear of aircraft of various categories and sizes and of the effects of piloting techniques and guidance and control systems. This information could provide the basis for improved pilot training to cope with wind-shear encounters. It should be possible to design better guidance and control aids to improve a pilot's ability to avoid an accident in the event of an inadvertent wind-shear encounter.

Utilization of a highly automated Doppler radar derived from the NEXRAD system and optimized for wind-shear detection and located in an airport's terminal area would provide greatly enhanced wind-shear detection capability and pilot warning of potential wind-shear hazards. This would require related development of procedures for analyzing and displaying observations and communicating warnings to ground controllers and flight crews.

Research in a number of areas is required to help reduce the hazards of low-altitude wind shear. Meteorological research is needed to understand more fully all forms of wind shear and to lead to better, more timely forecasts. Data derived from LLWSAS operations should be recorded and analyzed, and an additional field research program directed to measurements of wind-shear phenomena should be undertaken at a humid southeastern location, to supplement research done in the semi-wet north-central midwestern United States and high, dry midwestern plains.

Research is also needed to determine the effects of heavy rain, which often accompanies wind shear, on aircraft aerodynamic characteristics. Research on airborne wind-shear detection systems should be continued, in view of the benefits that could be provided by a small-sized, lightweight, airborne wind-shear detector.

There appears to be no single solution to all hazards caused by wind shear. To help ensure that all feasible steps are undertaken to minimize its risks, however, it is recommended that the FAA establish an integrated program to maintain a sustained effort for coping with all aspects of low-altitude wind shear in aircraft operations and to minimize its hazards to flight safety.

Sincerely,

John W. Townsend

John W. Townsend
Chairman

JWT/1ds

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Preface

On July 9, 1982, Pan American World Airways Flight 759 crashed shortly after taking off from New Orleans International Airport. One-hundred forty-five persons on board the airplane and eight persons on the ground died. The crash was attributed by the National Transportation Safety Board to strong low-altitude wind shears produced by isolated yet heavy thunderstorms in the vicinity of the airport.

One month later, the Subcommittees on Investigations and Oversight and on Transportation, Aviation, and Materials of the U.S. House of Representative's Committee on Science and Technology held joint hearings on weather problems affecting aviation. The hearings addressed the current technical capability to detect hazardous weather phenomena, such as wind shear, and the extent of its hazard to aircraft takeoff and landing operations. Subsequent to these hearings, P.L. 97-369 was passed in December 1982 requiring the Federal Aviation Administration (FAA) to contract with the National Academy of Sciences (NAS) “to study the state of knowledge, alternative approaches and the consequences of wind-shear alert and severe weather condition standards relating to takeoff and landing clearances for commercial and general aviation aircraft.” The law also specified that the study be completed within 6 months.

Under the terms of an agreement between NAS and the FAA signed on March 17, 1983, the study was also to review what is known about low-altitude wind shear and wind variability, how it is detected and measured, and how warnings are communicated to pilots and air traffic controllers. Furthermore, the study was to address the adequacy of pilot training on what to do when wind shear is encountered and to evaluate the implications for aircraft design, construction, and flight operations.

To conduct the study, NAS created an ad hoc Committee for the Study of Low-Altitude Wind Shear and Its Hazard to Aviation. The committee was established under the National Research Council's Commission on Engineering and Technical Systems (CETS) and Commission on Physical

Sciences, Mathematics, and Resources (CPSMR). The committee was divided into two panels. First, the Panel on Low-Altitude Wind Variability, was to review the state of knowledge on low-altitude wind shear, including detection, measurement, and prediction. The panel was also asked to recommend changes and improvements in wind-shear warning techniques and procedures as well as required research and development relating to wind shear. A second Panel on Aircraft Performance and Operations was asked to review hazards of low-altitude wind shear to commercial and general aviation operations. This panel was to consider the diversity of aircraft design and performance characteristics, air traffic control procedures, and pilot training and practices. The panel was also asked to recommend changes to improve flight safety in the event of encounters with hazardous wind shears, including research and development.

The committee's charge was accomplished by means of three meetings of the full committee and of each of its two panels in Washington, D.C., from April through July 1983. In addition, each panel met separately in May. The Panel on Low-Altitude Wind Variability met at the National Center for Atmospheric Research in Boulder, Colorado, and the Panel on Aircraft Peformance and Operations met at the National Aeronautics and Space Administration's (NASA) Langley Research Center in Hampton, Virginia.

Throughout its work, the committee received generous cooperation from the FAA, NASA, the National Transportation Safety Board, the U.S. Air Force, the National Oceanic and Atmospheric Administration, and the National Center for Atmospheric Research.

Low-Altitude Wind Shear and Its Hazard to Aviation

Executive Summary

Congressional concern over the crash of Pan American World Airways Flight 759, a Boeing 727, minutes after takeoff from the New Orleans International Airport on July 9, 1982, resulted in legislation passed in December 1982 providing that the FAA enter into an agreement with NAS to study and assess the hazards of low-altitude wind shear on takeoff and landing aircraft operations. To accomplish this task the NRC established the Committee on Low-Altitude Wind Shear and Its Hazard to Aviation, consisting of two panels: the Panel on Low-Altitude Wind Variability and the Panel on Aircraft Performance and Operations.

The committee's principal finding confirmed that low-altitude wind variability (or wind shear) presents an infrequent but highly significant hazard to aircraft landing or taking off. Fortunately, most severe types of wind shear are relatively infrequent, generally short lived, and affect only local areas. Some wind shears have been understood by meteorologists for a number of years. These include those found in gust fronts, warm and cold air-mass fronts, mountain waves, low-level jet streams, gravity waves, terrain-induced turbulence, and sea-breeze fronts. Most are predictable, sometimes hours in advance. The more-skilled pilots recognize the potential presence of these shears and the dangers they pose.

Scientists have recently begun to recognize the importance of storm downdrafts that are unusually small in horizontal cross sections and that are of short duration. Such downdrafts have been called microbursts. These often severe but localized events present the greatest danger to aircraft operations. Wind shear that resulted from the strongest microbursts actually measured in the summer of 1982 Joint Airport Weather Studies (JAWS) in Denver could not have been penetrated safely if encountered below 300-500 feet of altitude by an aircraft* during takeoff or landing.

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*In this report the term aircraft includes commercial transports and general aviation aircraft, helicopters and airships.

Adding to the seriousness of the situation, microbursts are highly transient, existing for only a matter of minutes; thus, prediction and detection are difficult. On the positive side, because of their small size and short duration, an aircraft encountering a microburst near a runway is a relatively rare event.

Near-Term Actions

Information and Education

The committee found that the risks posed by all forms of wind shear can be reduced. This can be accomplished almost immediately by an urgent information and education campaign aimed at all aircraft pilots, including general aviation. Such a program should include warnings to avoid encountering wind shear if possible as well as the best advice available on piloting techniques to minimize risk when a shear is inadvertently encountered at low altitude. As part of this campaign, the FAA should revise and update its 1979 advisory circular on wind shear (AC 00-50A) to incorporate new information.

Low-Level Wind Shear Alert System

Beyond this first step, risks can be reduced by improving and automating the existing Low-Level Wind Shear Alert System (LLWSAS). This system of ground-level wind sensors currently installed at 59 airports should be upgraded and the improved system should eventually be deployed at all high-traffic density airports with terminal automation systems (153 airports) where there is likelihood of the occurrence of dangerous wind shears. LLWSAS data need to be better interpreted and disseminated quickly to air traffic controllers and pilots. Also, radar observations currently unused as well as pilot reports (PIREPs) should similarly be made available to controllers and pilots in a format that can be easily understood, and pilots and ground personnel should be better trained in their use.

Pilot Training

Steps also should be taken in the near term to improve our understanding of how an aircraft responds to wind shear under various piloting techniques and guidance and control systems. These studies should consider the effect of aircraft type. The information gained could lead to recommendations for improved training of pilots to cope with wind-shear encounters.

Medium-Term Actions

Airborne Alert of Wind-Shear Encounters

In the medium term, it should be possible to design better guidance and control aids in the cockpit for business and transport aircraft based on existing (but not widely used) sensing and display systems.

These systems will not warn pilots of a wind-shear event ahead of their aircraft but will improve their ability to recover from a wind-shear encounter and to avoid an accident when a shear is inadvertently encountered.

Long-Term Actions

Terminal Doppler Radar

There is no single solution to all hazards caused by wind shear. Utilization of a highly automated, ground-based terminal Doppler radar offers considerable hope. A radar system, currently being considered, could use subsystems from the NEXRAD Project, a joint effort of NOAA, DoD, and the FAA. The terminal radars would be located at or near major airports. They would do much to detect all forms of wind shear and would provide adequate warning to pilots.

Airborne Remote Detectors

Since it is not realistic to assume that all airports might be equipped with Doppler radar, there is a need for airborne detectors that could see ahead of an aircraft and give advance warning of the presence of wind shear. Some systems offer promise, but much further research and development is required to yield a small-sized, lightweight, economical airborne detector.

Time Phasing

By their nature, actions to reduce wind-shear hazards must be time phased. It should be possible to conduct an education and training campaign in 1 to 2 years. Improvements to the present system will probably take 3 to 5 years to implement. It will probably take 5 to 7 years to develop and deploy terminal Doppler radars at airports. Research on airborne remote sensors can be accelerated immediately, but it is unlikely to yield operational benefits in less than 7 to 10 years.

Research Needs

Meteorology

A number of areas require further research to reduce the hazards of low-altitude wind shear. From a meteorological standpoint, more work is needed to fully understand all forms of wind shear. This should lead to better and more timely forecasts of the phenomena. This effort should include field studies of low-altitude wind shear, particularly those associated with convective clouds and thunderstorms. To help in this understanding, LLWSAS data should be recorded at all sites and analyzed, and existing data from previous research programs should be reexamined. At an appropriate time, another major field research program, such as JAWS, should be carried out in the humid southeastern United States to complement that done in the dry midwestern plains.

To improve the timeliness and effectiveness of present and future warning systems, research is needed on the automation of observations and their display and dissemination to users. An important component of this program would be an operational test project at a major airport that has a high likelihood of wind shear.

Aircraft Performance and Operations

With respect to aircraft performance and operations, additional analyses and simulation studies are needed on the control of both transport and general aviation aircraft in wind shear. Research is also needed on the effects of heavy rain, which often accompanies wind shear, on all aircraft. Simplified mathematical models of wind shear are needed for use in simulators, which are used to develop aircraft systems and to train pilots. Research is also essential on airborne detectors and on guidance and control systems and their cockpit displays. Work is needed on longer-range airborne warning systems, such as those based on Doppler radar or lidar, that can detect wind shear well ahead of an aircraft.

Pilots should be informed on how best to fly their aircraft to escape an accidentally encountered wind shear. Simple instruments, such as angle-of-attack indicators, energy-rate sensors, or vertical-acceleration meters, which could be added to existing aircraft, should be studied as aids in coping with a severe wind-shear encounter.

The committee has concluded that wind shear represents a hazard to all aircraft, ranging from small general aviation aircraft to swept-wing jet transports. Much more analysis is needed to bound the problem for the many types of aircraft that exist and their instrumentation. Moreover, general aviation pilots are typically less well trained than air transport pilots, and general aviation pilots have little or no access to advanced training simulators. They often operate from smaller and less well instrumented airports. The most practical and immediate solution appears to be an extensive education program to warn general aviation pilots of the hazards associated with low-altitude wind shear and to teach both avoidance and escape procedures.

Finally, the committee recommends that the FAA establish an integrated and sustained program for coping with all aspects of wind shear--meteorological, technological, operational, and educational.

RECOMMENDATIONS

Specific recommendations are presented below under four broad categories: general, detection and prediction, aircraft performance and operations, and research. The numbering of the recommendations does not signify priority.

General

1. Need For an Integrated Wind-Shear Program

To provide for the safety of the flying public, the FAA and the aviation industry should address the many facets of the low-altitude wind-shear problem as a whole. The FAA should develop and implement a coherent and sustained program for coping with the educational, meteorological, technological, and operational aspects of low-altitude wind-shear hazards.

2. Wind-Shear Education Program

The FAA and the industry should prepare and disseminate as widely as possible updated and authoritative information on wind shear. Informational materials should stress avoidance of wind shear and should describe flight control techniques for recovery from encounters. The information should encompass all of types of aircraft, with appropriate guidance for each class. It should include recommendations on the most effective means of training pilots.

The FAA should revise and update its 1979 advisory circular (AC 00-50A) on wind shear and the Airman's Information Manual (AIM) to present the latest information, including detection techniques, alerting and warning procedures, effects of wind shear on aircraft performance, and procedures for recovery from wind-shear encounters.

3. Pilot/Controller Communications

The FAA should promote the use of standardized terminology and improved communications between flight crews and control towers. A standardized system of pilot reports (PIREPs) should be developed for reporting low-altitude wind-shear encounters. PIREPs should be mandatory and should include a report of the location, severity, and nature of the shear encountered--in consistent, standardized terminology. Controllers should communicate such reports to all flight crews in the vicinity. In addition, techniques for the direct broadcast to pilots of wind-shear data from LLWSAS or other sensors should be investigated.

4. Wind-Shear Detection System Development

The FAA should select a site to test direct and remote-sensing techniques in a complete system for detecting low-altitude wind shear and for providing information to pilots and controllers and to test the use of the information in the air traffic control system. The test site should be at a major airport where wind shear conditions are relatively frequent.

Detection and Prediction

5. The Low-Level Wind Shear Alert System (LLWSAS)

LLWSAS is the only system available in the near term for detecting low-altitude wind shear on an operational basis and every effort should be made to assess and improve its performance. Opportunities include, but are not limited to, better signal processing, reduced spacing between and increased number of sensors, improved sensor response and improved wind-display techniques and criteria for issuing wind-shear warnings, and the possible use of ground-based pressure sensors to augment LLWSAS information. An improved LLWSAS system is being developed for installation at New Orleans International Airport. This upgraded system, to be operationally tested in early 1984, should provide the basis for modification of current LLWSAS installations and for improved system performance for future installations. Depending on the New Orleans test results, the FAA should modify existing LLWSAS systems and install improved systems at all high-traffic density airports with terminal automation systems (153 airports) where there is likelihood of the occurrence of dangerous wind shears.

6. Record and Analyze LLWSAS Data

LLWSAS wind measurements should be recorded and analyzed to evaluate the system's performance and to learn more about the climatic properties of low-altitude wind shear. This should be done at all airports equipped with LLWSAS.

7. Use of Available Radar Data

The existing network of weather radars, operated by the NWS, should be used more effectively to judge the likelihood of wind-shear conditions. These radars detect rain showers, thunderstorms, and phenomena often associated with wind shear. Information from weather radars should be made available to air traffic controllers in a timely and easily understandable fashion.

8. Next Generation Weather Radar (NEXRAD)

The next generation Doppler weather radar system (NEXRAD) should be developed and installed with all possible speed. This long-range radar system will serve many national needs related to severe-weather detection, forecasting, and warning. For aviation the NEXRAD system can be used to detect and monitor weather situations along flight routes and, if located at or near some airports, to detect low-altitude wind shear or its precursors. Moreover, the Doppler radar will advance the rate of development of radar techniques for the detection of low-altitude wind shear and the development of dedicated Doppler terminal radars.

9. Airport Terminal Weather Radar

The FAA should take immediate action to develop a pulsed Doppler radar system that can be used to observe weather conditions at and around airport terminals. This terminal radar system should be able to operate with a high degree of automation and to provide information on low-altitude wind shear, turbulence, and rainfall intensity. Such a radar must be capable of supplying information updated each minute and must have such features as ground-clutter cancellation and adequate spatial resolution.

10. Use of Airport Terminal Weather Radar Observations

For terminal Doppler radar to be most useful to traffic controllers and pilots, a concerted effort should be devoted to developing procedures for analyzing, displaying, and using its observations.

11. Airborne Remote Sensors

Research should continue on the use of airborne Doppler lidars and microwave Doppler radars as a means for detecting low-altitude wind shear.

Aircraft Performance and Operations

12. Wind-Shear Effects on Flight Characteristics

The FAA should sponsor analytical and simulator investigations to determine:

- The wind-shear penetration and recovery capabilities of transport aircraft, based on various onboard detection, guidance, and control systems.
- The effects of wind shear on various typical categories of general aviation aircraft and helicopters so that authoritative information on their response characteristics and piloting techniques in wind shear can be provided.

13. Aircraft Operating Procedures

The FAA should ensure that air carriers and other commercial operators instruct flight crews on what to do if they inadvertently encounter a low-altitude wind shear during takeoff or landing. In addition, the FAA should encourage operators of jet aircraft to incorporate in their manuals the operating procedures recommended in its advisory circular on wind shear. Aircraft manufacturers should recommend configuration-change sequences (gear, flaps, power, spoilers, etc.) that provide the highest probability for recovery from a wind shear encounter. Pilots should be taught to exceed the normal maximum thrust limits and to go to emergency thrust when necessary.

14. Guidance and Control Aids

Onboard sensors and guidance aids should be evaluated in a systematic manner to determine their merits for future development and for possible retrofit in existing aircraft. These include flight director modifications, ground speed/airspeed flight management systems, vertical-acceleration sensors, and energy-rate sensors. Angle-of-attack indicators should be added to the cockpit instrumentation of transport aircraft for use in maneuvering through wind shears. Angle of attack should be provided either as a separate variable or as an input to other command displays. Sensors should provide flight crews with a voice warning of a hazardous wind shear.

15. Standardization of Wind-Shear Models

The FAA should sponsor a program to develop and define standardized models of wind shear based on the latest meteorological data. These models are required for design and certification of aircraft subsystems and for use in training simulators. The FAA should include other government agencies, aircraft manufacturers, commercial operators, and any other interested parties in the program.

16. Certification of Onboard Systems

The FAA should update its certification requirements for airborne wind-shear alerting, flight guidance, and automatic control systems.

17. Wind-Shear Simulation Training

The FAA and the industry should cooperate to investigate new and innovative ways to make available the best possible simulation training for wind shear to the largest possible number of pilots, including general aviation pilots.

Research

18. Effects of Heavy Rain

Investigations should continue on how heavy rain affects the low-speed aerodynamic characteristics of aircraft. Particular attention should be paid to the possible adverse effects of heavy rain on aircraft lift, performance, and controllability, including its effects on wind-shear detection and flight sensor systems.

19. The Nature of Low-Altitude Wind Shear

More must be learned about the various kinds of wind shear and the meteorological conditions that cause or are associated with them. This knowledge is needed to reduce the hazards represented by low-altitude wind shear. Research should include additional field observations and the construction of theoretical models over the relevant scales--from about 1,000 feet to 10-20 miles and from minutes to hours.

The existing body of data obtained by various research programs should be reexamined and augmented, at an appropriate time, by a field program in the humid southeastern United States. Analyses of the data obtained from the JAWS Project should be used to plan any new field investigation. Basic research into the origins of strong thunderstorm downdrafts and possible forecast methods should be an important component of any new program.

1

Introduction

Low-altitude wind variability, or wind shear,* has long been recognized as a potential hazard to aircraft landing and taking off. Although wind shear can result from a number of basically different meteorological conditions, pilots have been trained to avoid thunderstorms in particular because of often associated severe wind variability and turbulence near the ground and aloft.

It has recently been recognized that small, short-lived downdrafts, called microbursts, are serious hazards to aircraft during landings and takeoffs. In some microbursts the air carried downward strikes the ground and spreads out in a shallow layer--sometimes only a few hundred feet in thickness. The parent cloud from which the microburst descends is a convective one but one that has not necessarily grown to thunderstorm size and strength.

Thunderstorm outflow and accompanying downdrafts, some of the scale and intensity that have recently been named microbursts and downbursts, were identified by the Thunderstorm Project nearly 40 years ago (Byers and Braham, 1949). Such outflows and downdrafts were newly emphasized as the cause of some serious accidents after a quantitative analysis of the winds encountered by Eastern Airlines Flight 66 while landing at John F. Kennedy International Airport on June 24, 1975. Analysis of the flight recorder data from another aircraft operating in the immediate vicinity provided a wind model considered to be very similar to that encountered by EAL Flight 66.

A detailed map of the wind-shear patterns at the time of the crash was constructed from an analysis of available data, including meteorological satellite photographs and surface weather observations and measurements (Fujita, 1976; Lewellen et al., 1976). The analysis provided valuable insight into the characteristics of violent downburst

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*Unless specified otherwise in this report, wind shear is the difference of wind velocity at two points divided by the distance between the two points.

cells within thunderstorms, the need to detect their presence as early as possible, and the need for immediate communication of warnings to air traffic controllers and flight crews in the vicinity.

INCIDENT/ACCIDENT RECORDS

In 1977 the FAA conducted a study of NTSB reports on aircraft accidents and incidents related to low-altitude wind shear that occurred from 1964 through 1975 (Shrager, 1977). More than 59,000 reports were reviewed, covering all classes of civil aircraft and flight operations. About one-third of the accidents or incidents, more than 19,000, occurred during terminal area operations. Only 25 accidents or incidents involving large aircraft (more than 12,500 pounds) were identified in which low-altitude wind shear could have been a contributing factor. Of these 25 cases, 23 occurred during approach or landing and only 2 during takeoff.

Table 1 lists 27 U.S. aircraft accidents or incidents that occurred from 1964 to 1982 and that are attributed to low-altitude wind shear. The list includes most of the 25 cases identified by the FAA. Some were omitted because, on further examination, they could not be attributed to wind shear. The table does include wind-shear-related accidents or incidents that have occurred since 1976, including 2 during 1982.

In 1981 general aviation aircraft numbered more than 200,000 and flew more than 40 million hours (compared with 3,973 aircraft and 8 million flight hours for air carriers). General aviation operations accounted for 662 fatal accidents from all causes, with 1,265 fatalities (FAA, 1981). Informal accident cause/factor statistics from the NTSB for 1981 indicate that weather caused or was a related factor in 40 percent (289 cases) of the U.S. general aviation accidents. Of these, wind shear was reportedly the cause of one fatal accident and was a factor in two. It should be noted that the NTSB generally investigates only those general aviation accidents that result in a fatality, and not all of those attributed to weather were analyzed by trained meteorologists. Low-altitude wind variability may have been a factor in some of these.

In 1975, NASA, in cooperation with the FAA, instituted the Aviation Safety Reporting System (ASRS), whereby safety-related incidents involving aircraft operations are submitted voluntarily and treated anonymously, with the expectation that potential flight safety problems may be identified and corrective action suggested. A total of 26 reports have been indexed as wind shear related out of nearly 21,600 reports received since May 1, 1978. Of these, 17 appear to involve wind shear as a primary factor.

A recent study (Anderson and Clark, 1981) of the effects of wind shear on aircraft operations and flight safety in Australia, including an extensive survey of pilots, concluded that wind shear was a causal or contributory factor in numerous aircraft accidents in Australia and elsewhere and that inadequate knowledge of wind structure and of the resulting effects on aircraft operations constitutes a flight safety hazard. Furthermore, the term wind shear is subject to various interpretations among pilots, and specific definitions are often misunderstood. Pilot judgments as to the aircraft types most susceptible to wind shear were not readily explicable in terms of aircraft size, landing speed, or wing loading. The use of standard terminology and improved training for pilots and air traffic controllers was recommended, along with research on optimal piloting techniques during wind-shear encounters.

In the United Kingdom the Royal Aircraft Establishment has undertaken a program to extract wind-shear data from records obtained from 10 Boeing 747 aircraft operated throughout the world by British Airways. (Haynes, 1980; Woodfield and Woods, 1981). This is a continuing effort to obtain wind information on strong wind-shear events during approach and landing. Time histories of wind velocities and aircraft reactions to interesting events are identified and analyzed. The results may lead to statistics on the probabilities of encountering wind shears and criteria for testing and evaluating autopilots and onboard wind-shear detection systems.

The rarity and lack of a reliable statistical data base on wind-shear-related accidents, shear encounters, or even the frequency of occurrence of potentially hazardous wind shears does not diminish the importance or severity of the safety problem. The potentially catastrophic consequences of an encounter during takeoff or approach and landing require that wind shear always be taken into account as a primary safety consideration when weather conditions are such that strong wind shears may be present. The widespread lack of appreciation among pilots, traffic controllers, and aircraft operations personnel of the seriousness of the possible safety hazards has exacerbated the problem.

Reports by the NTSB of investigations of air carrier accidents at least partly attributable to wind shear have resulted in a series of specific safety recommendations by the NTSB to the FAA. These recommendations are routinely considered and acted on by the FAA and followed up by the NTSB. Together with other FAA activities, these have contributed to a compendium of FAA actions with respect to wind shear. The NTSB's report of the investigation of the Pan American World Airways Flight 759 accident that occurred on July 9, 1982, contained 14 recommendations for priority and longer-term action intended to improve safety in wind-shear weather conditions (NTSB, 1983).

TABLE 1 Aircraft Accidents and Incidents Related to Low-Altitude Wind Shear (1964-1982)

No	Year & Date	Time (LST)	Location	Airline Flt No (Aircraft type)	T/O or LDG (Runway)	Fat/Inj	Wind Shear Experienced	Weather Systems and References( )
1	1964 MAR 01	1129	Lake Tahoe NV	Paradise 901A (L-1049)	•LDG ---	85/0	During climbout after a missed approach	Strong mountain lee wave during snowstorm (1) (3) (9)
2	1964 JUL 01	2134	JFK New York NY	AA 64 (B-720B)	•LDG 31R	0/0	Windshift from headwind to crosswind	Thunderstorm with a sharp pressure rise(1)
3	1965 MAR 17	1858	Kansas City MO	TWA 407 (B-727)	•LDG 36	0/0	Wind direction change on final, 310°-21kts to 280°-22kts	Unstable moist air(1)
4	1968 JUN 08	1351	Salt Lake Cty UT	UAL 8327 (B-727)	•LDG 34L	0/1	260°-13kts at 1351 to 280°-12kts at 1354	Heavy thunderstorm with suspected gust front(1)
5	1970 JUL 20	1136	Naha AB Okinawa	FLY TIG 45 (DC-8)	•LDG 18	4/0	10kts tailwind near threshold	Heavy rainshower one mile in diameter(1)
6	1970 DEC 10	1926	St Thomas VI	Carib-Atl (CV-640)	•LDG 09	NA	Landing in 080°-20kts wind	Lee side flow in rainshower (1)
7	1971 JAN 04	1832	LGA New York NY	FAA N-7 (DC-3)	•LDG 04	0/2	Tail wind changed into headwind.	Frontal Shear(1) (9)
8	1972 MAY 18	1421	Ft Lauderdale FL	EAL 346 (DC-9)	•LDG 09L	0/3	180°-10kts at 1418 to 130°-12kts at 1426	Heavy thunderstorm(1)
9	1972 JUL 26	1406	New Orleans LA	NA 32 (B-727)	•LDG 28	0/0	IAS dropped 162 to 122kts	Intense rainstorm and thunderstorm(1)
10	1972 DEC 12	2256	JFK New York NY	TWA 669 (B-707)	•LDG 04R	0/0	42kts tailwind at 1500'to 5kts headwind at the surface	Frontal shear(10); Fog and drizzle (1) (9)
11	1973 MAR 03	1250	Wichita KS	TWA 315 (B-727)	• LDG 19R	0/0	100°-10kts at 1240:00 to 170°-10 kts to 070°-10kts at 1249:10	Thunderstorm(1)
12	1973 JUN 15	1403	ORD Chicago IL	Airlift 105 (DC-8)	•LDG 22R	0/0	Estimated downdraft 50fps at 3000', 13fps at 500' AGL	Heavy rainstorm(1)
13	1973 JUL 23	1643	St Louis MO	OZ 809 (FH-227B)	•LDG 30L	38/6	Up- and downdrafts	Outflow shear(4); Thunderstorm, sharp pressure rise(1)
14	1973 NOV 27	1851	Chattanooga TN	DL 516 (DC-9)	•LDG 20	0/42	Low-altitude wind shear	Outflow shear(4); Thunderstorm outflow (1) (9)
15	1973 DEC 17	1543	Boston MA	Iberia 933 (DC-10)	•LDG 33L	0/16	200°-24kts at 500', 260°-12kts at 200', 315°-08kts at surface	Frontal shear(4); Rain and fog(1) (9)

16	1974 JAN 30	2341	Pago Pago SAMOA	PAA 806 (B-707)	•LDG 05	96/5	Decreasing headwind and/or downdraft during the final 4 seconds	Outflow shear(4); Heavy rainshower (1) (9)
17	1975 JUN 24	1457	JFK New York NY	EAL 902 (L-1011)	• LDG 22L	--	8kts headwind to 6kts tailwind with 20fps downdraft	Small downburst or microburst (5); Strong thunderstorm (1) (9)
18	1975 JUN 24	1505	JFK New York NY	EAL 66 (B-727)	•LDG 22L	112/12	14kts headwind to 1kt headwind with 21fps downdraft	Small downburst or microburst (5); outflow shear(4); Strong thunderstrom (1) (9)
19	1975 AUG 07	1511	Denver CO	CO 426 (B-727)	•T/O 35L	0/15	IAS decreased 158 to 116kts in 5 seconds	Small downburst or microburst (6); Outflow shear(4); Thunderstorm (1) (9)
20	1975 NOV 12	2002	Raleigh NC	EAL 576 (B-727)	•LDG 23	0/1	10° windshift, gust up to 2ikts	3 inch per hour rain fall rate(1) (9)
21	1975 DEC 31	1056	Greer SC	EAL (DC-9)	•LDG 03	0/0	200° change in wind direction	Light rain and fog(1)
22	1976 JUN 23	1612	Philadelphia PA	AL 121 (DC-9)	•LDG 27R	0/87	65kts headwind to 20kts tailwind	Microburst(7); Outflow shear (4); Fast-moving thunderstorm (1) (9)
23	1976 DEC 12	2326	Cape May NJ	Atl Cty 977 (DHC-6)	•LDG 19	3/7	Gust to 50kts	Frontal shear(1) (9)
24	1977 JUN 03	1258	Tucson AZ	CO 63 (B-727)	•T/O 21	0/0	30kts headwind to 30kts tailwind	Microburst(7); Outflow shear (4); Downdraft in thunderstorm (9)
25	1979 AUG 22	1412	Atlanta GA	EAL 693 (B727)	• LDG 27L	--	strong downdraft and headwind	Microburst(8); Thunderstorm rainshower(9)
26	1982 JUL 09	1509	New Orleans LA	PAA 759 (B-727)	•T/O 10	153/9	Headwind tailwind and downdraft shear	Microburst with heavy rain(9)
27	1982 JUL 28	1521	LGA New York NY	TWA 524 (B-727)	•LDG 22	--	Severe wind shear at 20-100' AGL	Strong thunderstorm with gusty winds(2)
	TOTAL: •24 Accidents; • 3 Incidents; 491 Fatalities / 206 Injuries							

Sources: (1) Shrager, 1977; (2) NTSB letter to FAA, March 25, 1983; (3) Wuttele, 1970; (4) FAA Wind Shear Program, Dec. 1982; (5) Fujita and Byers, 1977; (6) Fujita and Caracena, 1977; (7) Fujita, 1978; (8) Fujita, 1980; (9) NTSB Accident/ Incident Reports; (10) Sowa, Private Communication.

FAA WIND-SHEAR PROGRAM ACTIVITIES

In 1971 the FAA initiated a program to work on the problem of wind shear in coordination with other organizations working in the field. Several areas of investigation were addressed, including wind-shear forecasting techniques and means of detecting the presence of wind shear with both ground-based and airborne instrumentation.

A multiphased research and development program was undertaken to investigate and develop cockpit displays, instrumentation, and operational procedures for assisting a pilot in the event of a wind-shear encounter. The project involved development of wind-shear models and evaluation of cockpit instrumentation, various cockpit instrument panel display configurations, and flight-path management systems in moving-base simulations of the flight of various large transport airplanes in wind shear. The results have been published in a series of reports (e.g., Foy, 1979).

In 1976 a wind-shear detection system called the Low-Level Wind Shear Alert System (LLWSAS) was developed (Goff, 1980), and installations are now in operational use at 59 major airports (see Table 2). Also, the FAA published an advisory circular (AC 00-50), entitled Low Level Wind Shear, dated April 18, 1976, intended to provide guidance for recognizing the possibilities of hazardous wind-shear situations and piloting techniques for recovery from wind-shear encounters.

Detailed research on the nature and characteristics of downbursts, sponsored by the FAA together with the NWS, NSF, and NASA has been undertaken. Project NIMROD conducted by the University of Chicago in the north-central midwestern United States during 1978-1979 and the JAWS Project in the Denver area during the summer of 1982 have provided extensive new knowledge on the meteorological characteristics of wind shear required for more realistic computer modeling of wind-shear fields for flight simulation, instrument design and development, and system certification.

In May 1977 the FAA amended Part 121 of the Federal Aviation Regulations [FAR 121.601 (b)] to require air carriers to adopt an approved system for obtaining weather forecasts and reports of adverse weather conditions, including low-altitude wind shear, at each airport used in their operations. In support of this rule, FAA inspectors were directed to ensure that the air carriers provided pilot training for adverse weather operations, applying the information on wind-shear hazards contained in the FAA's Advisory Circular AC 00-50.

In 1979 the FAA published an updated advisory circular (AC 00-50A, dated 1/23/79) and developed a pilot training film to provide detailed information, guidance, and training to cope with wind shear during takeoff or landing operations, based on newly acquired data. In May 1979 the FAA issued an advance notice of proposed rulemaking (NPRM 79-11) to invite public discussion and to solicit comments as to the

TABLE 2 Location of Low-Level Wind Shear Alert System (LLWSAS) Installations

IN OPERATION (59 UNITS)

Albuquerque, NM
Atlanta, GA
Baltimore, MD
Birmingham, AL
Boston, MA
Buffalo, NY
Charlotte, NC
Chicago (O'Hare), ILL
Cincinnati, OH
Cleveland (Hopkins), OH
Columbus, OH
Dallas/Ft. Worth, TX
Dayton, OH
Denver, CO
Des Moines, IA
Detroit (Metro.), MI
Ft. Lauderdale (Int.), FL
Houston (Int.), TX
Houston, TX
Indianapolis (Int.), IN
Jackson, MS
Jacksonville, FL
Kansas City (Int.), MO
Knoxville, TN
Las Vegas, NV
Little Rock, AR
Los Angeles, CA
Louisville, KY
Memphis (Int.), TN
Miami, FL
Milwaukee, WI
Minneapolis (Int.), MN
Mobile, AL
Nashville, TN
New Orleans, LA
New York (Kennedy) NY
New York (LaGuardia) NY
Newark (Int.), NJ
Norfolk, VA
Oklahoma City, OK
Omaha, NE
Orlando (Int.), FL
Philadelphia (Int.), PA
Phoenix, AZ
Pittsburgh (Int.), PA
Raleigh-Durham, NC
Roanoke, VA
Rochester, NY
St. Louis (Int.), MO
Salt Lake City, UT
San Antonio, TX
San Juan, PR
Sarasota, FL
Tampa, FL
Tulsa, OK
Washington (Dulles), VA
Washington, (National), VA
W. Palm Beach, FL
Wichita, KS

TO BE INSTALLED (51 UNITS)

Albany, NY
Asheville, NC
Augusta, GA
Austin, TX
Baton Rouge, LA
Billings, MT
Bristol, TN
Cedar Rapids, LA
Charleston, SC
Charleston, WV
Chattanooga, TN
Colo Spgs, CO
Columbia, SC
Columbus, GA
Dallas-Love, TX
Daytona Beach, FL
El Paso, TX
Fayetteville, NC
Fort Smith, AR
Fort Myers, FL
Grand Rapids, MI
Green Bay, WI
Greensboro, NC
Greer, SC
Honolulu Oahu, HI
Huntsville, AL
Lansing, MI
Lexington, KY
Lincoln, NE
Lubbock, TX
Madison, WI
Midland, TX
Moline, IL
Monroe, LA
Montgomery, AL
Pensacola, FL
Peoria, IL
Richmond, VA
Rochester, MN
San Francisco, CA
Savannah, FA
Shreveport, LA
Sioux City, LA
Sioux Falls, SD
Springfield (Capitol), IL
Springfield, MO
Syracuse, NY
Tallahassee, FL
Toledo, OH
Tuscon, AZ
Windsor Locks, CT

Source: FAA. 1983

need to amend FAR 121 to require large air carrier aircraft to utilize wind-shear detection equipment or to take other actions to provide practical, effective, and reliable detection of hazardous wind shears. No regulatory action has yet been taken directly in response to this proposal. In this connection, however, the FAA has prepared an advisory circular presenting criteria for operational approval of airborne wind-shear alerting and flight guidance systems and wind-shear detection and avoidance systems.

These proposed criteria, including presently available mathematical models of a variety of wind-shear and turbulence fields, are intended to permit FAA acceptance of concepts designed to enable pilots to recognize the presence of wind shear, to optimize their reactions, and to fully utilize the performance capabilities of their aircraft to cope with a wind-shear hazard that may be encountered. The circular provides that the wind-shear models will be updated as new data become available. This advisory circular is currently under review, preparatory to its adoption.

Air traffic control procedures used by the FAA relative to wind shear include the use of meteorological forecasts, surface and upper-air weather and weather radar observations, voluntary pilot reports (PIREPs) of wind-shear encounters, and LLWSAS.

2

Low-Altitude Wind Shear

THE NATURE OF LOW-ALTITUDE WIND SHEAR

Wind variability is a perennial and inescapable problem for aviation. Meteorological circulations or terrain-induced airflows can on occasion induce large and rapidly changing variations in air velocity over small distances. These variations produce correspondingly sudden changes in the relative flow of air over an aircraft's wings and other lifting surfaces, with attendant changes in an aircraft's flight path. Thus, small-scale wind variations and turbulence can pose hazards to aviation, particularly when they occur in the lowest few hundred feet of the atmosphere, the zone that aircraft must penetrate while landing or taking off. To eliminate--or at least appreciably reduce--the hazards posed by low-altitude wind variability, it is necessary to understand the sources of wind changes and the risks they represent. It is also necessary to know how to detect, measure, and predict them and how to communicate useful information on wind variability to air traffic controllers and pilots in a timely fashion.

The wind changes not only with distance but also with time. As a result, the term wind variability is sometimes used when considering low-altitude flight hazards. Technically speaking, wind shear is the local variation, at a particular time, of wind velocity with distance. It is measured by dividing the velocity difference at two points by the distance between them. Strong wind variations over horizontal distances of 1 to 10 miles can cause particular difficulties for aircraft. Most often, in this report, we refer to wind variations as wind shears. In circumstances where time variations are important, they will be identified.

The three-dimensional airflow in the lower atmosphere, and the associated wind shears and turbulence, vary from place to place by season and by meteorological conditions. Based on experience, rough estimates can be made of the degree of hazard, frequency of occurrence, and difficulty of detection of various types of wind shear.

Atmospheric turbulence is generally defined statistically in terms of scale and intensity. Its effects are seen in an aircraft's ride and handling qualities and are taken into account in aerodynamic, flight control, and structural design criteria. However, patchy small-scale turbulence need not be present at low altitudes within layers of air with strong wind shear (Lee and Beckwith, 1981).

The most serious effects of wind shear are those that cause an aircraft to lose lift and altitude. This is particularly hazardous when an aircraft is close to the ground, either landing or taking off, when an aircraft unexpectedly flies from a region of headwinds into a region of strong tailwinds, and especially if the transition occurs in a strong downdraft. Turbulence and heavy rain, when occurring in association with wind shear, can contribute to flight hazards and increase the chances of an accident. The following paragraphs describe the types of wind-shear situations and the risks each poses to aviation.

Convective Outflows

Thunderstorms and other convective clouds are critically important sources of low-altitude wind variability. Many produce strong downdrafts that transport air downward, which then spreads out rapidly over the ground. The size and strength of the downdraft depend on the properties of the thunderstorm and on the humidity and temperature structure of the atmosphere. As shown in Figure 1, thunderstorms occur most frequently in Florida, along the Gulf of Mexico coast, and over the central parts of the United States. Whenever there is a thunderstorm or precipitating convective clouds, hazardous low-altitude wind shear can be present. Some experts believe, however, that strong downdrafts and associated flight hazards are more likely when the thunderstorm cloud bases are high and the surface humidities are low.

Microbursts. Following the crash of Eastern Airlines Flight 66 at New York City's Kennedy Airport on June 24, 1975, the term downburst came into use to describe a strong downdraft that induces an outburst of damaging winds on or near the ground. Subsequently, studies of the EAL crash and of Continental Flight 426 at Denver on August 7, 1975, and Allegheny Flight 121 at Philadelphia on June 23, 1976, concluded that each of these accidents was related to downburst-induced wind shear (Fujita and Byers, 1977; Fujita and Caracena, 1977).

Results of the above studies indicated that the downbursts that contributed to these accidents were of small size and short life, and the term microbursts has been used to describe them. Microbursts are small downbursts, less than 2.5 miles in outflow size, with the peak winds lasting only 2 to 5 minutes. Some microbursts reach the ground, while others dissipate in mid-air and are not detected by ground-based anemometers. A critical point is that microbursts can come from convective clouds that are not accompanied by lightning.

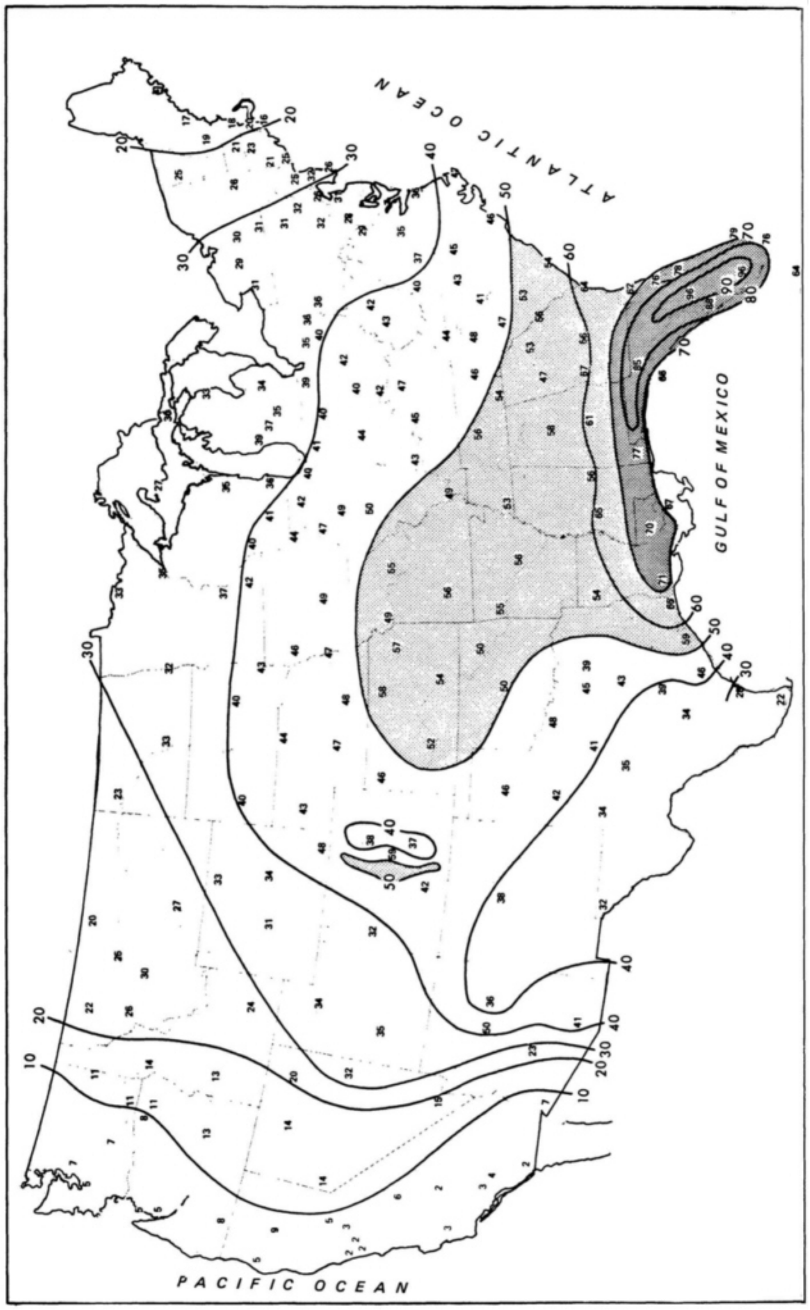

FIGURE 1 Mean Number of Days per Year with Thunderstorms; 1951-1975. (Source: Court and Griffiths, 1982).

The most recent wind-shear-related accident, the crash of Pan American Airlines Flight 759 in New Orleans, was reported by the NTSB (1983) to be a result of microburst-induced wind shear.

Climatology of Microbursts . Data on which to base averages of the frequency and intensity of microbursts are very limited. During a 43-day period in May and June 1978, ground-based anemometers associated with NCAR's portable automated mesonet (PAM) were deployed as part of the NIMROD Project near Chicago. PAM automatically measures wind speed and direction, dry- and wet-bulb temperatures, and pressure and rainfall at 27 surface stations (wind measurement is at 12 feet above the ground). Fifty microbursts were detected, 32 with rain (wet microbursts) and 18 without rain (dry microbursts) (see Table 3). Wind shear is apparently not related to rainfall intensity.

TABLE 3 Frequency of Microbursts Detected by PAM

	NIMROD	JAWS
Number of operational days	43	86
Number of microburst days	11	49
Number of wet microbursts*	32	31
Number of dry microbursts**	18	155
Total number of microbursts	50	186
Number per operational day	1.2	2.2
Number per microburst day	4.6	3.8

*Equal to or greater than 0.01 inches of rain during the period of peak winds.

**Less than 0.01 inches of rain between both the onset of high winds and the end of the microburst winds including the calm period if any.

The PAM deployed in the Joint Airport Weather Studies (JAWS) Project near Denver detected 186 microbursts on 49 days of an 86-day observation period from May to August 1982 (Fujita and Wakimoto, 1983). This amounts to 2.2 per day, nearly twice the rate found in the NIMROD Project. Of the total 186 microbursts, 155 were dry and only 31 were wet. Most were not associated with active cumulonimbus clouds but rather occurred under streaks of evaporating precipitation (virga) from dissipating cumulonimbus or dissipating cumulus congestus clouds. Because of their association with convective clouds, microbursts tend to occur most often between noon and midnight, but, as shown in Figure 2, the diurnal pattern differed at the NIMROD and JAWS locations.

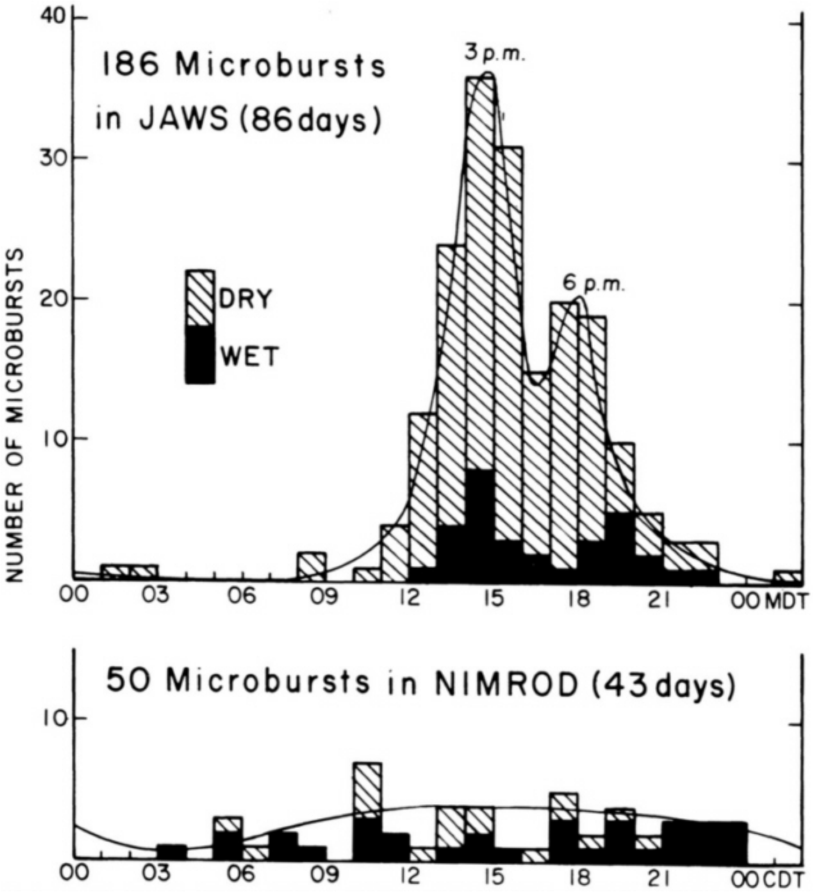

FIGURE 2 Diurnal Variation of Surface Microbursts of All Intensities Measured at the 27 PAM Stations. (Source: Fujita and Wakimoto, 1983).

Aircraft passing through the center of a microburst will experience a change in wind velocity that can be specified as the vector difference of the headwind and the tailwind along the flight path. The maximum wind difference of the JAWS microbursts, measured by ground-based anemometers, exceeded 95 knots on one occasion (see Figure 3).

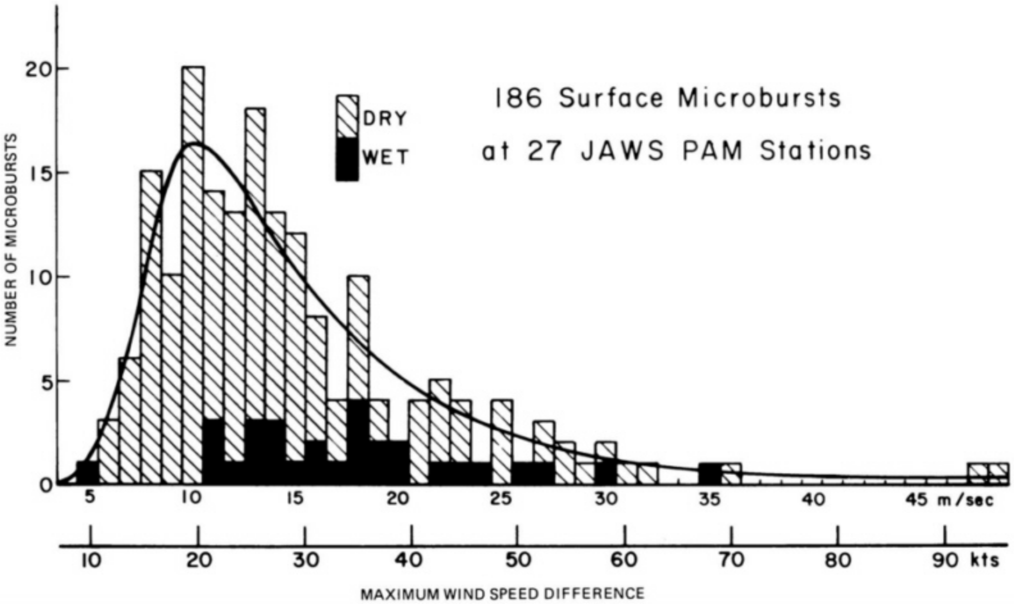

FIGURE 3 Frequency of Surface Microbursts as a Function of the Maximum Wind-Speed Difference Measured at the 27 PAM Stations. (Source: Fujita and Wakimoto, 1983).

The JAWS Project used Doppler radar primarily to observe microbursts. With three wind-measuring Doppler radar systems, three-dimensional pictures of microbursts were obtained. Figure 4 shows the horizontal and vertical velocity profiles of a particularly strong microburst. The classical profile of headwind, downdraft, and tailwind are clearly seen in this figure.

Because the Doppler radars were used to concentrate on specific cases of interest and because they were not operated continuously, their data cannot be used to establish a microburst climatology. Nevertheless, the Doppler radars detected and observed 75 microbursts on 33 of the 86 operational days (McCarthy et al., 1983).

The Doppler radar data allowed for an examination of the time history of JAWS microbursts observed near Denver. Figure 5 shows the percentage of microbursts that reached maximum velocity differential as a function of time from the detection of the initial velocity divergence near the ground. Approximately half of those observed reached maximum intensity within 5 minutes, and nearly all reached maximum velocity within 10 minutes. This figure dramatically illustrates the extremely short duration of these events.

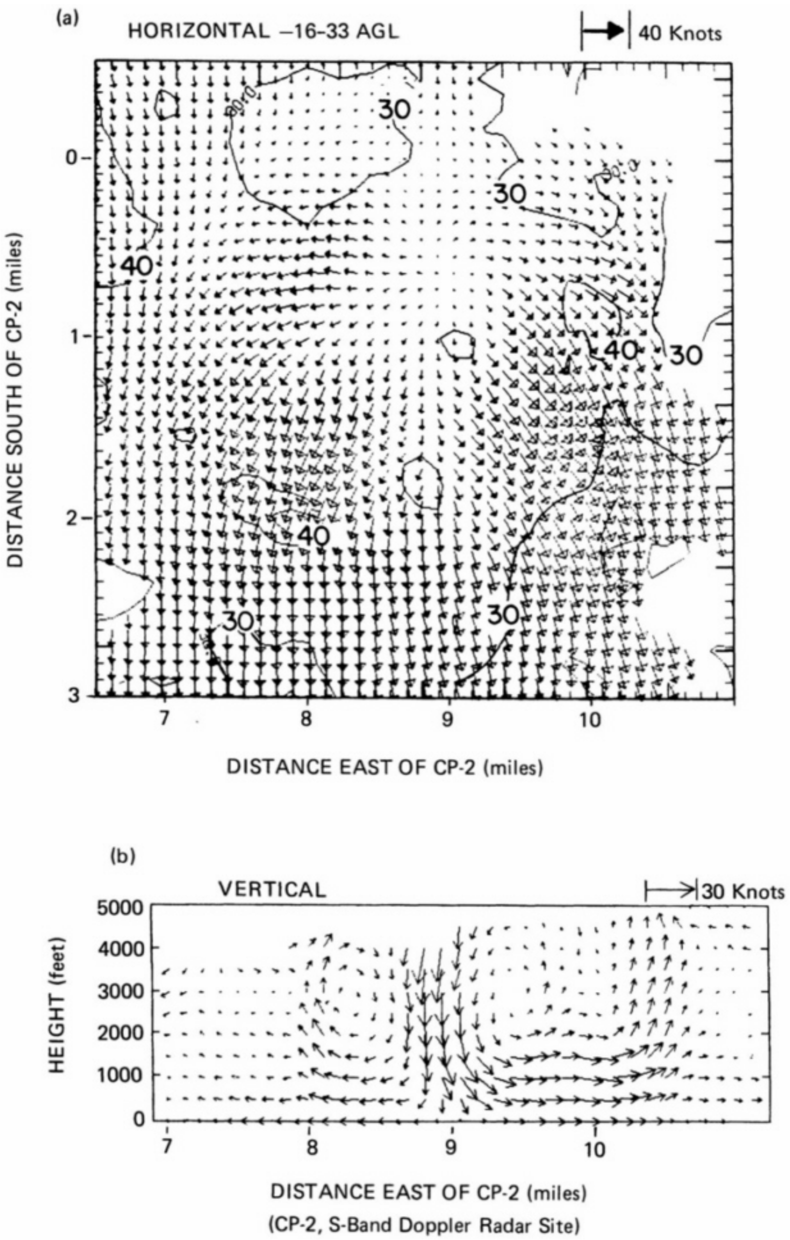

FIGURE 4 Velocity Fields With Respect to the Ground, Based on a Dual Doppler Analysis for a Microburst Occurring at 1452 MDT on July 14, 1982. Contours Are Radar Reflectivity Factors (dBZ_e). (Source: Wilson and Roberts, 1983).

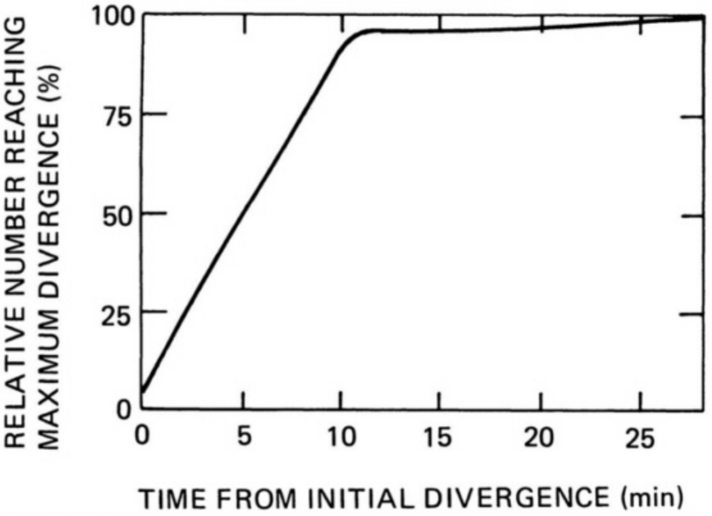

FIGURE 5 Percent of Microbursts Reaching Maximum Velocity Differential as a Function of Time from Initial Divergence. (Source: Wilson and Roberts, 1983).

Gust Fronts

A gust front is the leading edge of a mass of cool air that has recently descended from a thunderstorm or convective cloud. There is a large amount of literature on this subject, which was examined for the Thunderstorm Project (Byers and Braham, 1949) and has since been much studied at the NSSL and by many researchers (Brandes, 1977; Charba, 1974; Goff, 1976, 1977; Sasaki and Baxter, 1982). As shown in Figure 6, the cool air near the gust front, which may be up to 1 mile in depth, is characterized by strong turbulent winds. The cool air sinks, while the warm air rises. The depth of the gust front, the associated wind shear and turbulence, and its speed of advance over the ground depend on the nature of the parent cloud and the wind distribution through the layer in which the cloud is imbedded.

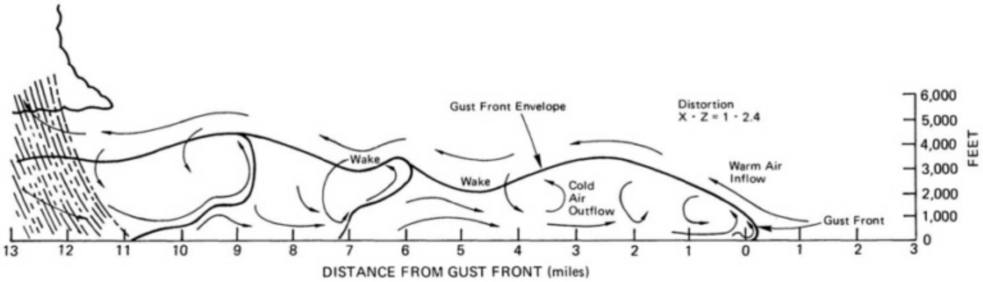

FIGURE 6 Squall Line Thunderstorm Outflow (schematic). (Source: Goff, 1980).

the winds are light and change little with height, the gust front is almost symmetrical around the storm that produced it. By the time the storm has dissipated, the gust front may have moved tens of miles away from the parent storm and weakened substantially.

When there is strong vertical wind shear through the atmosphere and a severe long-lasting convective storm, the associated gust front tends to be maintained at the leading edge of the parent storm. The pattern of its advance can be very asymmetric with strong outward-blowing winds in those sectors coinciding in direction with the strongest winds aloft in the cloud layer.

Gust fronts, as they sweep over the ground, can usually be detected by radar, by a sufficiently dense network of ground-based anemometers (such as LLWSAS), and by microbarographs. Once detected, it is possible--largely through extrapolation--to predict their position anywhere from a few minutes to perhaps one-half hour in advance. Also, radar echoes often indicate the presence of deep convective clouds and the possibility of a gust front.

Gravity and/or Solitary Waves

As a gust front moves away from its parent storm, the temperature contrast across it is gradually reduced. The resulting circulation, when it exists in a shallow surface layer capped by a temperature inversion, can persist as a strong clear-air circulation that usually moves at speeds of 15 to 40 knots over long distances. Known variously as gravity waves or solitary waves, these motions are caused not only by gust fronts but also by downslope winds and by sea-breeze fronts. Solitary waves occur most often during the night and early morning. Over northern Australia, where they have been studied extensively, they occur throughout the year but are most frequent during the late winter and early spring (August to November). Corresponding climatic information for the United States is almost totally lacking. In vertical cross section, a typical solitary wave can have a horizontal dimension of several hundred feet to 6 miles with a 15-knot updraft at the leading section and a downdraft of similar strength on the trailing part. Because of the relatively long-lasting nature of solitary waves, their distinctive wind shifts, and associated pressure patterns at the ground, it should be possible to detect, track, and predict their arrival over an airport, given a surface-observing network of sufficient density.

Sea-Breeze Fronts

A sea breeze is a local wind that blows from sea to land. It is caused by the temperature differences that occur daily between the sea surface and the adjacent land. It usually occurs on relatively calm, sunny summer days. Often, the onset of a sea breeze occurs suddenly as a sea-breeze front, separating the cool air from the warm air, moves inland. Sea-breeze fronts cause a sudden change in wind velocity, from near calm to a brisk cool breeze. At the onset, the sea breeze flows across the coastline, but as time goes on it turns to its right (in the northern hemisphere) and has a component along the coastline.

Wind shear associated with sea breezes can prove to be a hazard at airports that are located along coastlines, such as Logan International Airport in Boston and the John F. Kennedy International Airport in New York City. For example, the occurrence of thunderstorm downdrafts and outflows when a sea breeze could have been expected caused some confusion about the wind velocity over the approach to runway 22 at Kennedy Airport when EAL Flight 66 crashed on June 24, 1975.

In some areas, sea breezes occur regularly during the summer and can be predicted with a fair degree of accuracy. Ground-based anemometers and airborne detectors should be able to detect wind shears, so that pilots can take appropriate action.

Air-Mass Fronts

Separate air masses do not mix readily when they come into contact if they have different temperatures and humidities. Instead, the colder, more dense air mass passes under the warmer, less-dense air mass. The zone of transition between the two air masses is called a front. When the cold air advances, forcing the warm air to retreat and pass over the wedge of cold air, it is called a cold front. When the warm air advances, the frontal boundary moves toward the cold air and a warm front is said to exist.

All fronts have some degree of wind shear across the zone of transition between the air masses, but the narrower the zone the stronger the wind shear is likely to be. When the transition zone is perhaps 300 or more feet deep, the wind-velocity change with height is gradual and turbulence is weak or nonexistent. Nevertheless, an aircraft taking off or landing through such a zone experiences changes in wind velocity.

There usually is a sharp change of wind velocity across fronts. Figure 7 shows a cross section of a warm front just south of O'Hare International Airport in Chicago. The data were recorded aboard an instrumented Boeing 747 during its approach to O'Hare's runway 32L (Sowa, 1974). The effective tailwind-to-headwind change was 22 knots in this case. Had this landing been attempted on runway 04R (oriented 80° clockwise), the wind variability would have been 59 knots. The front had an extremely narrow transition zone and was approximately 300 feet thick. The change of wind velocity was abrupt and had moderate, or more severe, turbulence associated with it.

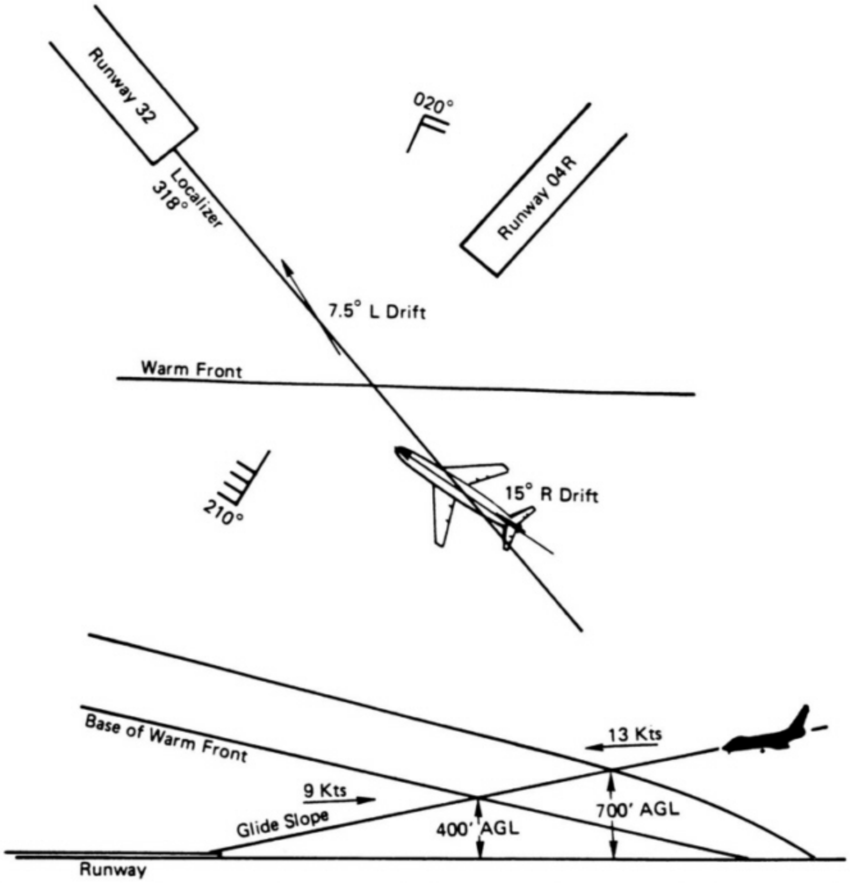

FIGURE 7 Wind Shear Across a Warm Front During a Landing Approach. (Source: Sowa, 1974)

The following pilot report is typical of a flight through a frontal zone with high wind variability. It was recorded at the Madison, Wisconsin, airport.

> Have report on wind shear forecast for Madison. Took off on Runway 18 on 0233Z. Hit base of front at 1500 ft. Rate of climb pegged with excessive pitch-up, and moderate turbulence lasted through 5000 ft. (Sowa, 1974)

One U.S. air carrier has been forecasting low-altitude wind variability associated with frontal conditions since 1962 (Sowa, 1974). The forecasts give wind direction and speed on either side of the front, tell whether the front has an abrupt or gradual transition zone, and give the intensity of turbulence, if any. This technique is now used by many airlines. The NWS provides forecasts for low-altitude wind variability for warm and cold fronts, low-altitude jet and nocturnal inversions, cold surface inversions, friction-surface slowing, inversions, and sea-breeze fronts.

Weather forecasters cannot now specify the altitude of the base of the layer of strong wind shear beyond 4 hours. Techniques need further refinement to improve such forecasts.

Frontal conditions and the accompanying wind shears occur in all parts of the United States, but they are most frequent over the middle latitudes during the colder months of the year. While Hawaii averages about two shears per winter, the central and northeast portions of the United States average four to five per month during the fall, winter, and spring. The southern states and those east of the Rocky Mountains average one significant frontal passage per month during the same seasons.

Terrain-Induced Wind Shear

Mountain terrain can cause significant low-altitude wind variability, depending on the nature of the large-scale wind field. Airports located close to mountains, near breaks in mountain ranges (known as gorges), or on hills with sharp dropoffs near the ends of runways are subject to steady-state winds that break down into chaotic gusts that are constantly changing. The presence of turbulence, often severe, can compound the problem of operating aircraft in or out of these airports.

The following is a typical pilot report of this condition. It came from a Boeing 707 airplane that had just taken off from the Anchorage, Alaska, airport:

> Take-off on Runway 06R. Light turbulence right after lift-off. At 500 ft, turbulence changed to what I can only describe as massive bursts. The aircraft pitched, yawed, and slipped. The cockpit became a capsule of ricocheting manuals, log books, and debris. Aileron control was stop-to-stop, air-speed changes of plus or minus 50 knots. I made a slow left turn, established a slow climb attitude and, at 4000 ft, the shearing action subsided and turbulence became moderate.*

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*Sowa, 1977, Copyright American Institute of Aeronautics and Astronautics

Because of the pulsing nature of terrain-induced winds, another aircraft on the same approach several minutes later might encounter winds much different from those described above.

This type of low-altitude wind variability may or may not have clouds or precipitation associated with it. The synoptic weather patterns that cause terrain-induced wind shear and turbulence are known and their occurrence can be predicted, but it still is not possible to adequately predict precise wind values at specific altitudes and locations (Sowa, 1977). Wind shear induced by terrain occurs most often in late fall, winter, and early spring. It may happen only three to four times per season in some places but as often as 20 days per month in places where the terrain and the prevailing weather patterns are favorable.

Mountain Waves

Mountains induce high-amplitude undulations or waves in air currents flowing over them (Lilly, 1978; Lilly and Zipser, 1972). They are associated with strong shears and turbulence, and their influence can extend from near the ground to very high altitudes. Mountain waves are typified by descending air over the lee side of the mountain range. The descending air has acquired distinctive names in various parts of the world--“Santa Ana” in the Los Angeles Basin; “chinook” along the Rocky Mountains of western Canada and the United States; and “foehn” in Switzerland, Norway, and Sweden.

These strong, gusty winds at the earth's surface produce low-altitude wind shear and turbulence at airports located in the lee of mountains. It is not unusual to have gust velocities double that of the steady-wind values. In extreme cases these gust velocities can exceed 100 knots. Under certain meteorological conditions, a strong temperature inversion existing near the ground restricts the downslope winds from reaching the surface. Instead, the air glides along the top of the inversion, producing wind shear and turbulence about 300 to 1,500 feet above the ground.

Mountain waves can be predicted. It is not possible, however, to precisely forecast the steady-state wind velocity, the gust factor, or the turbulence intensity of such winds. These have been observed during every month of the year in Alaska and in the western mountainous regions of the United States and Canada. Mountain waves are most frequent in the fall, winter, and spring. In an average year, to the lee of the Rocky Mountains, in Montana and southern Canada, there are 15 wave days a month. In Colorado and the more southern states there is an annual average of 7 wave days a month. The mountains in the eastern United States usually do not produce strong downslope winds because their lee slopes are not particularly steep.

Low-Level Jet Streams

The strength of the wind near the ground is tightly linked to diurnal processes in the lower atmosphere. During daytime the earth's surface is heated by the sun, and the planetary boundary layer is marked by vertical air motions. This process causes the frictional influence of the ground on the wind to be transmitted through a deep layer of air. Thus, wind velocities near the ground tend to be relatively high in the form of a concentrated current called a low-level jet stream. The formation of such a jet stream depends also on the distributions of heating and cooling and their daily variations over sloping terrains (see, for example, McNider and Pielke, 1981). Figure 8 shows a low-level jet stream observed at the NSSL in Norman, Oklahoma.

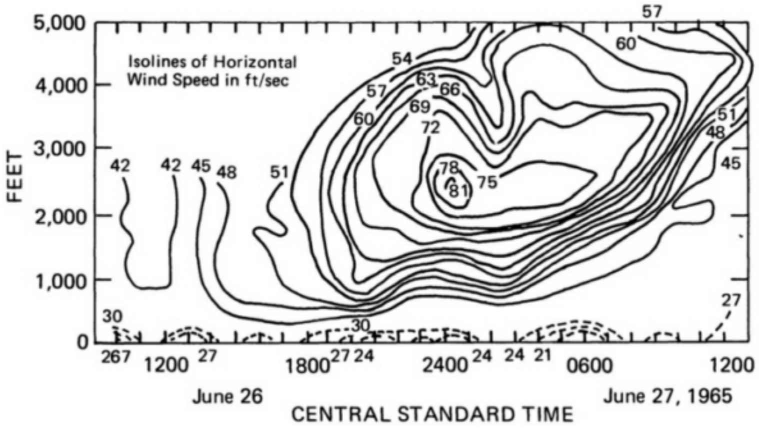

FIGURE 8 Low-Altitude Jet Stream Near Norman, Oklahoma, Observed by Means of Doppler Radar. (Source: Lhermitte, 1966).

In a typical low-altitude jet stream situated over an airport, the wind at the surface tends to be light and to come from the same direction as the stronger flow immediately above the airport. Consequently, an aircraft that is landing will typically approach the runway into the jet stream wind. As the aircraft descends below the jet stream, headwinds decrease, often substantially, as the aircraft nears touchdown. The sudden loss of headwind can be a serious problem if the pilot is unaware of the situation. In a typical low-altitude jet stream situation, as described above, the event occurs often in clear air but at night when the visual perspective of the pilot may be inhibited.

Tornadoes

No discussion of low-altitude wind shear would be complete without at least a mention of tornadoes and other high-speed atmospheric vortices, such as waterspouts and dust devils. Most often dust devils, of the type commonly seen over desert areas during the hot, dry summer months, are too small to pose serious risks.

Because of the very strong wind shears that characterize them, tornadoes should always be avoided. Most of the time they can be seen by pilots flying below the bases of the parent thunderstorms. An appropriate radar should be capable of detecting existing and incipient tornadoes in sufficient time to allow pilots to fly around them.

GROUND-BASED SENSING OF LOW-ALTITUDE WIND SHEAR

Low-Level Wind Shear Alert System

Following several airline crashes during the mid-1970s, the FAA developed the Low-Level Wind Shear Alert System (LLWSAS) (Goff, 1980). Initiated by NOAA's NSSL, the system consists of an array of wind-velocity measuring instruments located on the ground at or near an airport.*

LLWSAS typically consists of a centerfield wind sensor and 5 outlying sensors normally about 2 miles from the center site, located on the basis of meteorological factors, terrain considerations, logistical constraints, and to favor the Instrument Landing System (ILS). The sensors have propeller vanes on standards that rise about 10 to 60 feet above the ground as necessary to obtain clear airflow above terrain or other obstructions. Each site is polled once every 10 seconds. The centerfield site is considered a reference site, for which a 2-minute running average of wind velocity is maintained.

LLWSAS is controlled by a central miniprocessor (usually located in the control tower), which maintains the 2-minute running average of the centerfield wind. This information is continuously displayed in the tower, is used by controllers, and is relayed to pilots.

In addition, once every 10 seconds, the miniprocessor compares the 10-second wind at outlying sites to the 2-minute average at the center site. A vector difference computation is made and, if a 15-knot threshold is reached or exceeded, an alert is given to tower

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*The FAA estimates the cost of the present LLWSAS system to be approximately $200,000 for each airport installation.

controllers. The computer normally displays only the centerfield average wind velocity, plus a gust factor,* if appropriate. But if the wind shear threshold is exceeded, the wind velocity at the appropriate peripheral anemometer also is displayed. Controllers may, however, choose to display any or all sectors at one time.

The wind-shear calculation is designed to detect the sudden onset of a gust front at an outlying site by comparing the wind discrepancy at the outlying site with that at the centerfield site. The centerfield site, because of its long averaging period, cannot effectively detect wind shears.

LLWSAS has been installed at 59 airports and is scheduled to be installed at 51 others by 1985 (Table 2). LLWSAS data were recorded during the JAWS Project at Stapleton International Airport in Denver in 1982 but are not usually recorded at other times or at other airports. LLWSAS is the only operational means currently in use for detecting wind shear. Nevertheless, the system has several limitations. These include the following:

- The system cannot measure winds above the sensors on the ground. This may not be a big problem for gust fronts or sea breezes, but it limits the detection of wind shear that may not be present at the surface.
- There are temporal and spatial resolution limitations that may present serious problems for detecting the smallest-scale events. Although LLWSAS sensors are located an average of about 2 miles between the centerfield and remote sites, the effective wind-shear resolution is near 4 miles because of the long averaging period at the centerfield site. Likewise, the temporal resolution is compromised by the long averaging at the centerfield site; a brief high-wind encounter at centerfield would probably not be identified. This effectively eliminates the centerfield site as a high-resolution wind-shear sensor.
- Surface wind events outside of the perimeter of the anemometer field would not be detected.
- Vertical wind motions are not sensed directly; only horizontal ones are detected, and these, of course, may have been initiated by downdrafts.
- Sensors do not directly measure wind along flight paths and are thus susceptible to reporting events that may not reflect wind shear or lack of one on an airplane's flight path.

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*A gust factor is also calculated and displayed for the centerfield site, this factor being the difference between the peak and mean values of the wind velocity during the 2-minute averaging period.

During an 86-day observation period of the JAWS Project, the LLWSAS data at Stapleton International Airport were recorded. Figure 9 shows that there were nearly 4,000 triggering wind-shear events (defined as a 10-second sample with a vector wind-velocity difference equal to or greater than 15 knots, between any remote site and the centerfield site). Once a trigger occurs, the wind-shear warning light remains on for three consecutive samples, or about 30 seconds or longer if another stronger shear occurs. Hence, multiple triggers may be seen as a single LLWSAS alarm.

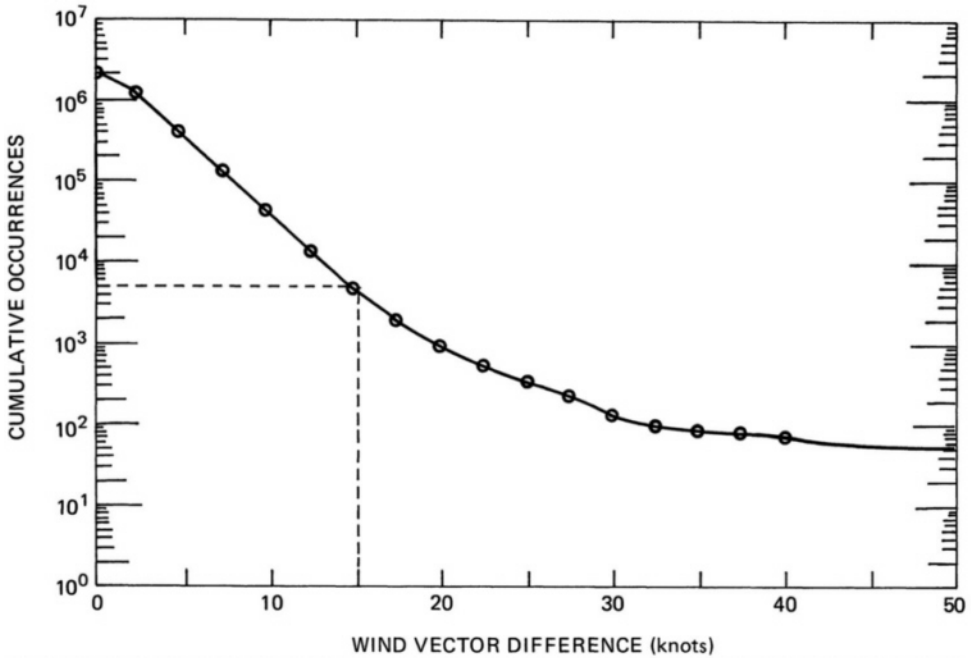

FIGURE 9 Cumulative Occurrences of Triggering Wind-Shear Events for All LLWSAS Remote Stations During JAWS. (Source: McCarthy et al., 1983).

During the JAWS Project, 466 alarms were detected by LLWSAS, distributed by day as shown on the right side of Figure 10. In comparison, Fujita (private communication) tallied the number of microburst events that occurred during the same period within 8 miles of Stapleton Airport detected by the NCAR's PAM* system, as shown on

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*PAM (portable automated mesonet) automatically measures the speed and direction of the wind at each of its sensors 12 feet above the ground. Because the sensors were located over a wide area during the JAWS Project, PAM was able to measure the wind speed and direction on opposite sides of microbursts occurring within its field and thus provide evidence of the existence of the microburst.

the left side of Figure 10. Notice that although the microburst frequency was high on certain days, comparison with the LLWSAS identification of comparable wind-shear events indicates an erratic correlation. For example, on some days, notably July 14, 15, and 18, both counts seem comparable. However, on other days, particularly May 19 and June 29 when a number of microbursts occurred, there was no clear identification of a wind-shear event on the LLWSAS. On yet another type of day, the LLWSAS shows many wind-shear alerts with no corresponding microburst indications, as seen on June 5, 22, and 30; July 8; and August 1 and 7. An examination of this latter set of days by Bedard et al. (1983) indicates that a number of LLWSAS alarms were associated with weak gustiness situations that barely reached the 15-knot vector difference threshold. It must be clearly understood that the microburst daily frequency statistics shown on the left side of Figure 10 do not include other wind-shear events, such as gust fronts. Consequently, the data presented here illustrate only the inadequacy of the LLWSAS as a microburst detector.

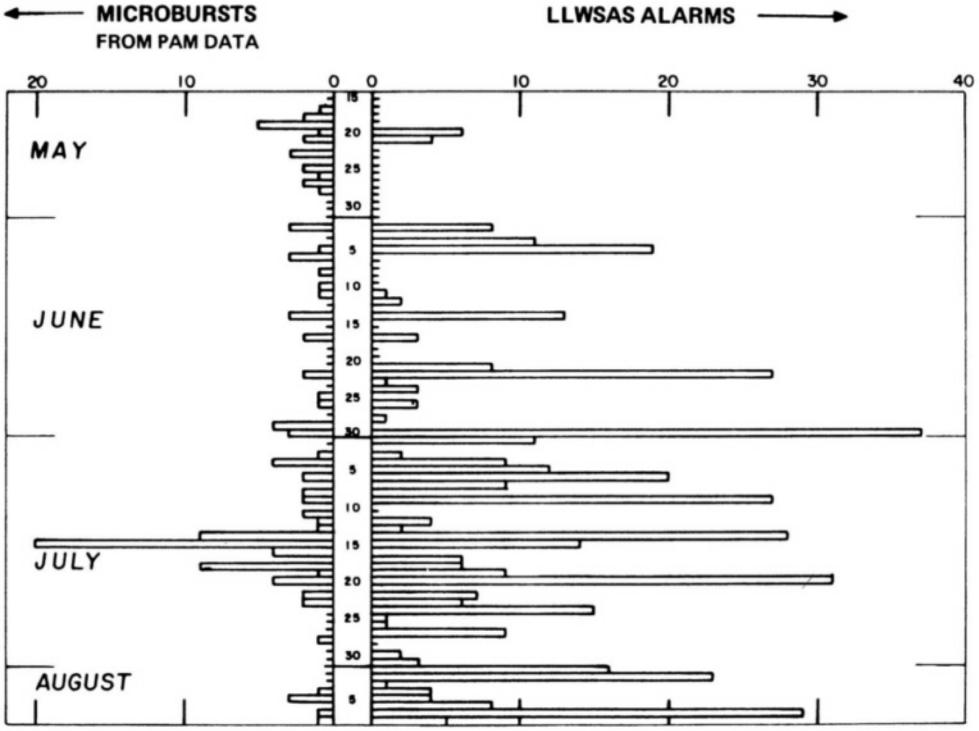

FIGURE 10 Daily Frequency of Microbursts within Eight Miles of the Stapleton Runways and the Daily Count of LLWSAS Alarms During JAWS. (Source: Fujita, private communication).

From the JAWS LLWSAS analysis and from a more generic study of the system, it is concluded that the LLWSAS system, as presently configured with large sensor spacing, performs adequately as a detector of larger-scale wind-shear phenomena occurring near the earth's surface, such as fronts, thunderstorm gust fronts, sea breezes, certain orographic situations, and some larger-scale downbursts. LLWSAS will also detect the wind shear caused by a microburst if it occurs in the vicinity of the sensors. However, there is substantial evidence that because of the small horizontal scale of microbursts the present operational LLWSAS system does not detect some microbursts that occur between or beyond the sensors. Furthermore, the system detects wind-shear events that, on careful inspection, are found not to represent a hazard to aircraft. The JAWS analysis makes it clear that substantial improvements to the LLWSAS, such as increasing the sensor density and improving individual sensor responsiveness, would significantly enhance the LLWSAS's capability to detect a broader range of hazardous low-altitude wind-shear events near the earth's surface. An improved LLWSAS system is being developed for installation at New Orleans International Airport. This upgraded system, to be operationally tested in early 1984, should provide the basis for modification of current LLWSAS installations and for improved system performance for future installations.

Pressure Sensors

It has long been known that active thunderstorms sometimes cause the atmosphere to undergo distinctive pressure changes related to the vertical motions of the air in the storms. Also, as the cool outrushing air in the gust front moves away from the storm that produced it, a “pressure jump” is commonly seen in association with wind shifts associated with the gust front.

Several tests have been conducted on a system of sensors designed to detect changes in atmospheric pressure. At Dulles International Airport, outside Washington, D.C., a network of microbarographs was coupled with ground-based anemometers to detect low-altitude wind shear. The microbarographs were found to give warnings up to 3 minutes (see Figure 11) earlier than would anemometers alone (Bedard et al., 1979).

A 3-month test at the Hartsfield International Airport in Atlanta showed that pressure and wind sensors could be successfully integrated into a single system. During this brief test, the downdraft air in several small microbursts impacted the ground between the sensors, and the resulting gust fronts passed over the sensor array without triggering the pressure sensors. The Atlanta investigations did not adequately test the effectiveness of a combined wind-pressure sensor system for the detection of low-altitude wind shear.

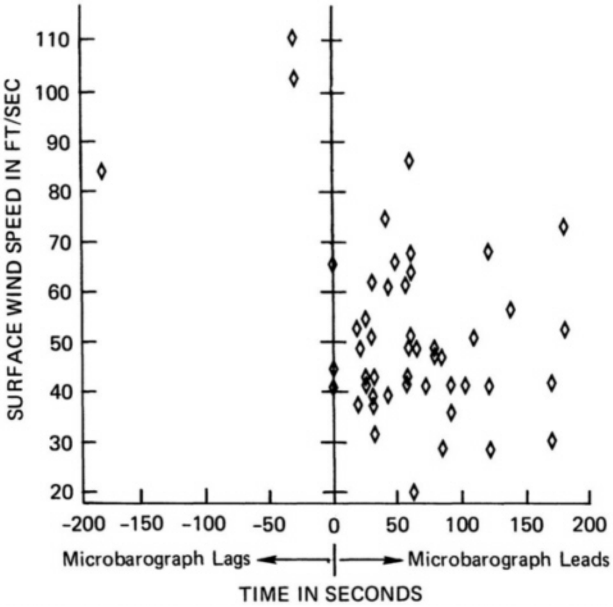

FIGURE 11 Relative Arrival Times of Pressure Jumps and Gust Surges. (Source: Bedard et al., 1979).

Ground-Based Microwave Radar

Rain showers and thunderstorms, common sources of hazardous low-altitude wind shear, are routinely detected by conventional radars of the type operated by the NWS and the FAA. The radar echo intensity and its dimensions, shape, and motion can be used to judge the likelihood of wind shear, although not with great certainty. For traffic controllers to use such information, the data must be displayed to them in an appropriate and timely fashion. When mature, intense thunderstorms with heavy precipitation, which causes strong radar echoes, occur over or near an airport, hazardous low-altitude wind shear and turbulence are likely to be present. In such cases, suspension of takeoffs and landings should be considered. Air traffic controllers do not have direct access to the information from the network of weather radars operated by the NWS, but they do receive weather advisories from the NWS.

It needs to be reiterated, however, that hazardous low-altitude wind shear often occurs without precipitation. The absence of a radar echo over an airport does not mean that wind shear does not exist. Nor does the presence of an echo guarantee that wind shear is present.

Microwave Doppler Radar

Pulsed Doppler radar can effectively detect low-altitude wind variability (see Figure 4). Research at the NSSL, the NCAR, and the University of Chicago (JAWS Project), as well as field experiments, have demonstrated that an appropriately designed, pulsed Doppler radar can detect tornadoes, downbursts, microbursts, gust fronts, solitary waves, and sea-breeze fronts. It can also identify the boundaries between distinct air masses (e.g., Wilson et al., 1980).

Wind shear has been observed by Doppler radar in many regions of the United States and during all seasons. Highly sensitive research radars have detected echoes from clear (to the human eye) air as well as from precipitation. Clear-air echoes are commonly detected in moist atmospheric boundary layers in spring, summer, and autumn but are rare in cold, dry, winter air.

These discrepancies are usually explained in terms of differences in the refractive index inhomogeneities of air, quantities that depend on the distributions of temperature and water vapor in the air. Moreover, insects sometimes produce clear-air echoes, especially during warm months. Since most wind shears, particularly those associated with convective storms, occur during the warm months, the wintertime clear-air performance limitation does not appear to be a major problem.

A Doppler radar measures directly the velocity of the wind toward or away from the radar (parallel to the radar beam). As a consequence, cross-beam velocities are not measured directly and vertical velocities cannot be measured directly, except when the antenna is pointing vertically. In research programs, several Doppler radars have been used together to examine the same scattering volume from different aspects. From such spatially independent measurements, it is possible to reconstruct a complete three-dimensional vector wind field. Figure 4 shows an analysis of a microburst based on the use of multiple Doppler radars. Because of their cost, multiple Doppler radar systems are unlikely to become operational at airports in the foreseeable future.

Much has been done with single Doppler radar to deal with the problem of wind shear. In the case of features possessing certain symmetries, such as small-scale cyclones and some microbursts, the Doppler velocity “signature” is sufficiently independent of viewing angle to allow operators to infer the cross-beam components from the spatial pattern of the radial velocity alone. Shears associated with gusts and other frontal systems can be measured accurately using the gradients of radial velocity in the vicinity of the front along with contiguous radial velocity measurements on both sides of the front. Thus, a single Doppler radar located away from an airport can effectively detect and quantify many hazardous phenomena over the airport.

But most microbursts are not symmetrical, because air descending toward the earth's surface carries the velocity characteristics of winds aloft. In such cases an off-airport radar might easily miss a hazardous case or overestimate its actual threat. In these cases it would be best to have airport radar with beams parallel or nearly parallel to the runways.

Alternatively, it is important that the space over the airport be carefully monitored, since precursors of microbursts on and near the ground are most likely to be found through the examination of Doppler signatures aloft. These can most effectively be monitored from an off-airport site.

Next Generation Radar (NEXRAD)

The FAA, NOAA, and DoD are working together to develop an advanced pulsed Doppler weather radar. Referred to as the next generation radar, or NEXRAD, it will address the common need among the principal government users of meteorological data for information on the current location, severity, and movement of such weather phenomena as tornadoes, severe thunderstorms, heavy precipitation, tropical cyclones, hail, high wind shears, and severe turbulence. Each NEXRAD installation will provide weather information for ranges exceeding 200 miles and heights of 60,000 feet at a rate of once every 3.5 minutes. Because of the large number of meteorological phenomena, the size of the coverage volume, and the magnitude of the resultant data rate, NEXRAD, whether manned or unmanned, will rely heavily on automation to perform the required observations and to communicate the results to users.

Several factors make the NEXRAD system an unlikely choice to measure low-altitude wind shear over airport terminals. One serious consideration is the minimum scan update time of 3.5 minutes for the NEXRAD network. Such a rate is too slow to optimally detect microbursts. Radar siting criteria also makes NEXRAD's use unlikely in terminal areas. NEXRAD will require an unobstructed view for 200 miles. In addition, the height of the NEXRAD antenna and tower will force some NEXRAD systems to be located sufficiently far away from some airports as to eliminate any possibility for low-altitude coverage of the terminal area.

However, because NEXRAD can outperform and suppress ground clutter better than the radars used in research to detect microbursts, a stand-alone NEXRAD devoted strictly to an airport's terminal area might be useful. However, this would be difficult to accomplish because of frequency overcrowding. NEXRAD uses a 2700- to 2900-MHz frequency band, which is used by many other radar systems in many areas of the continental United States. NEXRAD's frequency will require additional design or operational measures to be employed in some areas. Adding approximately 100 NEXRAD systems for terminal use would, therefore, appear impractical.

A Terminal Radar for Wind-Shear Detection

The FAA has proposed that an unmanned Doppler radar be dedicated to the effective detection of low-altitude wind shear and the reduction of hazards to aviation. The committee concludes that the concept of a terminal radar can be justified and that FAA should aggressively support its development. But such a program must not interfere with the development of NEXRAD. To effectively reduce flight hazards over airports, radar observations are necessary over and in the vicinity of airports. Information from a terminal radar and other sources must be communicated to both pilots and air traffic controllers in a timely, concise, reliable, and easily understood manner.

If a Doppler weather radar is to serve airport terminal operations, it must detect and warn of the most serious aviation hazards with a high reliability. An analysis of wind-shear-related accidents shows that the turbulent airflows associated with convective clouds and thunderstorms represent major hazards. The design of a Doppler radar system must take into account the nature of microbursts, specifically their small dimensions, short durations, and the fact that the strongest winds may be at altitudes of a few hundred feet. Furthermore, such a radar should also be able to detect the other types of shears described earlier.

A terminal radar must be able to measure low-altitude wind shear. It must be able to encompass a wide range of velocities and radar reflectivities in both clear and cloudy air, to eliminate or greatly reduce ground clutter, and to observe phenomena located very near the ground. It will also need a resolution capability of approximately 500 feet to enable it to identify a downdraft and an antenna that scans the airspace surrounding the terminal every 1 to 2 minutes. Although the scan strategy depends on the location of the radar relative to the airport, scans at approximately 6 to 8 elevation angles are necessary to properly monitor the airspace.

Since each Doppler radar scan produces three fields of data--reflectivity, mean velocity, and spectrum variance--the average time available to scan and analyze one field varies from 2.5 to 6.7 seconds. Microbursts, downbursts, and gust fronts can be reliably detected in research programs using manual techniques and highly skilled observers. There is considerable uncertainty, however, that it would be possible in day-to-day operations to extract and communicate wind-shear information in a timely fashion using manual detection techniques at the very high scan rates that appear to be necessary.

A high degree of automation is needed if a terminal radar is to be effective given the very short lifetimes of some microbursts and the even shorter time available for making decisions. At present, however, there are no automated techniques for detecting low-altitude wind shear. For an unmanned Doppler weather radar to be viable, a systematic study must be made of algorithms needed to detect wind shear for representative climatically different areas of the country.

System Design Considerations. Ground clutter presents a significant problem to using data from radars used to observe meteorological targets near the ground. All available measures will be needed to mitigate clutter in an airport's vicinity. The combination of a low sidelobe antenna design and electronic cancellation should be able to reduce clutter by at least 40 dB compared with existing research radars.

A microwave Doppler radar operating at a 10-centimeter wavelength proposed for NEXRAD can effectively measure wind shear around an airport. What is not known is whether a 10-centimeter wavelength is best for Doppler radars used at airport terminals. A 10-centimeter wavelength is needed for NEXRAD in order to “see through” severe storms and heavy precipitation to measure reflectivity at long ranges. This is not necessary for terminal radars that need to detect signals out to distances of only 20-30 miles.

A narrow beam (approximately 1°) requires an antenna about 25 feet in diameter at a 10-centimeter wavelength. The antenna diameter needed for a fixed beamwidth is directly proportional to wavelength. Therefore, a 1° beamwidth at 5- or 3-centimeter wavelengths can be achieved with antenna diameters of 13 and 8 feet, respectively. A small antenna costs less and is more easily sited on a busy airport than a large one. On the other hand, a larger antenna and shorter wavelength would provide a narrower beam and improved ground-clutter rejection.

There is a strong possibility that the signal-to-ground clutter ratio can be increased further by using shorter wavelengths. This is true when the objects that scatter the radar beam are water droplets or insects in the clear air. In this case the power backscattered by small particles is inversely proportional to the fourth power of wavelength, while the ground-clutter return is only weakly dependent on wavelength.

In determining the most appropriate wavelength for detecting low-altitude wind shear, it is necessary to consider inhomogeneities in the atmosphere that may be caused by water vapor and temperature variations, because observing dry microbursts depends on detecting such radar targets.

Range and Velocity Ambiguities. Because there is very little time to make decisions, the processing and signaling scheme must eliminate range and velocity ambiguities for airport radars. Many techniques address this problem, but none will be described in detail here. Shorter wavelengths tend to make this problem more severe; however, the relatively short range of the radar somewhat counteracts this effect. Therefore, range and velocity ambiguity considerations alone should not rule out the use of 5- or 3-centimeter wavelengths.

Siting of Doppler Radar Antenna. Ideally, a Doppler radar antenna should be located such that it can measure wind velocities along the takeoff and departure corridors, including curved approach paths that will be permitted by the microwave landing system (MLS) in the near future. For a variety of reasons, such a goal is virtually impossible to achieve because major airports usually have a number of runways with different orientations. Airport buildings complicate this problem. The question is further complicated by the nature of wind shear. Some experts have concluded that radar antenna should be installed on airport grounds, while others think it would be best to have it off the airport. Studies are needed at each airport where a terminal weather radar is to be installed to ascertain the best location for the antenna.

Remote Sensing by Means of FM-CW Radar

Some experts have suggested that a frequency-modulated, continuous-wave (FM-CW) Doppler radar might be used instead of a pulsed Doppler radar to detect low-altitude wind shear. FM-CW Doppler radar has many of the characteristics of the pulsed Doppler radars described in the preceding section. For the same average power, antenna aperture, and bandwidth, both types have the same sensitivity and resolution. The key difference between them is that a pulsed Doppler radar transmits high-power, low duty-cycle pulses, while an FM-CW Doppler radar transmits a low-power, full duty-cycle signal with linear frequency modulation. Because of this, an FM-CW Doppler radar can transmit high average power over a broad signal bandwidth and therefore achieve high sensitivity and resolution at short ranges. The high resolution contributes to significant ground-clutter rejection. Wind measurements have been made at ranges as short as 40 feet. An FM-CW clear-air radar might also locate wingtip vortices, another type of low-altitude wind variability that is potentially hazardous to small aircraft. Research should be continued on the use of FM-CW radar for wind shear and turbulence detection.

Longer-Wavelength Profiling Radar

Vertically pointing Doppler radars can measure a vertical profile of the wind above the radar throughout the troposphere when operating at long wavelengths of 1-10 meters. The measurements can be made at a rapid rate. These radars can measure winds above the earth's boundary layer better than microwave systems because of the nature of clear-air turbulence. On the other hand, a VHF or UHF band radar cannot effectively detect microbursts because the beam is not easily scanned and the beamwidth will tend to be wide. With adequate clutter cancellation, however, such a radar could be a superb tool for measuring vertical shear of the horizontal wind in all parts of the country and during all seasons. The NWS is investigating the use of VHF or UHF wind profilers to supplement its rawinsonde network. Such systems, if equipped with ground-clutter cancellers designed to measure the lowest 3,000 feet of the atmosphere, should yield useful data on the vertical shear of the horizontal wind at or near airports. It does not appear, however, that such systems are necessary components of a low-altitude wind-shear detection system.

Doppler Lidar

Lidar (light detection and ranging) is the optical equivalent of microwave radar. A suitably designed pulsed Doppler lidar operating at a wavelength of about 10 micrometers can measure winds in optically clear air during all seasons by detecting the backscattered power from small atmospheric particles. The principal advantage of lidar is its ability to make clear-air measurements that are virtually free from ground-clutter contamination. A disadvantage is that the laser signal can be absorbed by rain, clouds, and fog, which can strongly attenuate the signal over ranges of 1 to 2 miles. Doppler lidar should be investigated as a technique for detecting wind shear, especially in the western United States, where many clear-air microbursts occur. In the JAWS Project, an infrared Doppler lidar detected and measured some microbursts more clearly than did the radar.

Acoustic Sounding

Doppler acoustic sounders can measure profiles of the horizontal wind in the boundary layer. The beams cannot be steered easily, however, and the signals can be severely contaminated by natural and man-made audio noise. Using such a system at airports is, therefore, most appropriate for detecting areawide wind shear, such as that associated with low-level jet streams. Such sounders are already in use at the Hong Kong and Calgary, Canada, airports.

AIRBORNE REMOTE SENSING OF WIND SHEAR

Microwave Doppler Radar

An airborne Doppler radar would be an effective tool for detecting and warning of hazardous wind shears if it had capabilities equivalent to those available in ground-based systems. Unfortunately, because of size, space, and power limitations, the Doppler radars now under development for airborne commercial use appear to be insufficiently sensitive and provide inadequate spatial resolution to address the low-altitude wind-shear problem.

Some airborne Doppler radars used in research programs where space is not a problem (e.g., that operated by NOAA on its Lockheed P-3 aircraft and NASA on its Skyvan aircraft) offer capabilities similar to those of ground-based systems. It is beyond the scope of this study to determine whether a suitable airborne system can be developed. However, a thorough study should be conducted to determine the feasibility of such a development. If the results are positive, a prototype radar should be developed and tested. Such a prototype might have to use a wavelength between 1.5 and 3 centimeters, a flat plate antenna to achieve very low antenna sidelobes, a ground-clutter canceller, and substantial transmitter power (probably between 25 and 100 kilowatts of peak power).

Doppler Lidar

The British Royal Aircraft Establishment and the Royal Signals and Radar Establishment have collaborated to develop an airborne continuous-wave (CW) Doppler lidar that is flown on a small jet aircraft (HS 125) and was tested during the JAWS Project. The system is focused to measure the wind at a range of approximately 1000 feet ahead of the aircraft. The system has been flown reliably for extended periods of time, is rugged and lightweight, and requires minimal maintenance and calibrations. Pulsed lidar technology should be explored to see if a practical system can be developed to sense wind shear an order of magnitude farther ahead, say to 2 miles.

The CW system can measure velocities accurately but only in the region of focus. Combined with the true airspeed measurement on the aircraft, the system can warn of impending shear about 4 seconds in advance of an encounter during approach or departure. These short CW lidar warnings are not unambiguous because of the lack of spatially contiguous data but are certainly of value if for no other purpose than to alert pilots when to abort landings. On takeoff, a warning after the aircraft is airborne may be of little value. As with other optical systems, airborne lidar is severely attenuated by clouds and precipitation. Such systems deserve careful scrutiny for use by the aviation industry but at the present time remain in the research category.

Passive Infrared Radiometry

NASA has been conducting test flights with a passive IR radiometer. Devices of this type detect the IR radiation emitted by gases and particles and thus detect temperature differences in the field of view. Gust fronts are accompanied by a decrease in temperature, and according to NASA an IR radiometer can give as much as a 70-second warning of the arrival of a gust front. An IR radiometer is inexpensive, small, lightweight, and easily installed and flown on aircraft.

Unfortunately, there is little correlation between measured temperature differences and the occurrence of wind shear caused by microbursts. In some instances, temperature increases; in others, it decreases; and in yet others, no temperature change occurs. Even for gust fronts there is no strong correlation between the degree of temperature change and the intensity of the wind shear resulting from it. The IR radar beam can also be absorbed in clouds, fog, and rain, causing ambiguous interpretations. Thus, IR radiometry cannot be recommended as a primary sensor for wind shear, but it deserves additional research.

INTERPRETATION AND COMMUNICATION TO AIR TRAFFIC CONTROLLERS AND PILOTS

The previous sections have described various types of wind shear and a variety of sensing techniques be used to detect them. Equally if not more important to the overall aviation system is the need to successfully interpret and effectively communicate wind-shear data to air traffic controllers and pilots. The detection of low-altitude wind shear requires application of sophisticated technology. Unless this technology produces a useful product, its ultimate value will fall short of expectations. A useful product is one that is easily interpreted without ambiguity, provides definitive and quantitative information on hazards, and does not have a large number of false alarms. Any detection system must meet these criteria or its usefulness will be limited at best. An effective warning system has several essential elements: (1) sensing, (2) computation, (3) display, (4) interpretation, and (5) dissemination.

Microbursts impose particularly severe requirements on such systems because of their short lifetimes and small size. All too frequently, plans for detection and warning systems place too much emphasis on basic sensors and too little on the other ingredients, which are equally important. Indeed, if any of the links is missing, the system will be ineffective. For example, a Doppler radar is a sensor, an essential ingredient for detecting wind shears.

Computation is also essential and in a Doppler radar system would provide the signal and data processor to compute the fields of velocity and various other derived information. In our era of high-speed integrated circuits and rapidly advancing technology in computers, computation is the strongest link in this chain. Today's computational systems are fast, inexpensive, and accessible. The principal question is what computations are necessary to accomplish the desired result.

Display and interpretation do not necessarily occur in that order. Automated systems perform the interpretation in machines and then display the result. Interpretation by humans requires, first, that the data fields be displayed in a fashion suitable for viewing. Rapid and reliable interpretation is the most challenging task in a microburst detection and warning system. Automation is highly desirable because machines are fast, vigilant, and promise low operational costs. Unfortunately, machines are far inferior to humans in pattern recognition, which is crucial to an effective system. Machines also do only what they are programmed to do.

An effective detection and warning system must make the best use of machines and people. Machines must be used for rapid real-time calculations and image interpretation. Display of hazardous situations must be provided in relatively simple and unambiguous formats for controllers and other users. Meteorologists in Center Weather Service Units (CWSUs) should also be able to view the data fields from which automated interpretations have been made in order to resolve uncertainties that surely will occur in real time. With such a process, false alarms will be minimized while retaining a high probability for accurate detection of hazardous conditions.

Dissemination is the last link. Dissemination of information in various forms is obviously involved throughout the chain, but most important are the links from controllers to pilots or from machines to controllers and pilots. Techniques exist to transmit virtually limitless data to users, but this capability alone is no more than a tool. Effective dissemination will occur only if technologists, meteorologists, controllers, and pilots work together to design the final products that are to be disseminated. Air traffic controllers and pilots are very busy and cannot be burdened with excessive data. Neither can they afford to work with data that are insufficient for them to take effective corrective action in real time. The system must provide just enough and no more.

There also will be a good deal of training needed. Users must be well schooled in what the phenomenon is, what the system is trying to do, why it was designed as it was, and what its limitations are. It is only through a strong education program for all operations and flight staff that a system will realize its full potential.

In summary, the system's developers must give serious attention to the interpretation and communication of information needed by the user. In fact, this link is as important and as difficult as the development of basic sensors.

WIND-SHEAR PREDICTION

The discussion to this point has concentrated on the nature of low-altitude wind shear and its detection. It should be clear, given the highly localized and transitory nature of most wind shears and the speed with which they develop, that effective monitoring techniques must play a significant role in providing for aircraft safety. It is also important to develop the capability to forecast weather conditions and systems that are conducive to generating wind shear. Such forecasts can in turn be used to develop a corresponding hierarchy of wind-shear alerts. Forecasting strategies need to be developed using techniques that identify precursor conditions to microbursts, rather than the more rigorous techniques of numerical weather prediction.

As noted earlier, some types of low-altitude wind shear (e.g., shears caused by fronts, low-level jet streams, and sea breezes) can be accurately predicted hours in advance, but this is not the case with other types of shear. The hazardous shears caused by the downdrafts associated with convective clouds cannot yet be predicted successfully by either numerical or operational techniques. However, in the latter area, some researchers have made limited progress in using characteristic signatures of radiosonde temperature and humidity profiles to identify days with a high potential for the occurrence of microbursts (e.g., Caracena et al., 1983). Others have developed a model of downburst formation that, if verified, could provide some basis for shorter-term microburst predictions (Emanuel, 1981).

The primary objective of operational prediction is to make possible the warning of conditions conducive to generating microbursts or severe downdrafts, modeled after the severe thunderstorm or tornado watch currently produced by the NWS. Such a wind-shear watch would provide controllers and pilots with an early indication that conditions are prevalent for hazardous low-altitude wind shears. Because such conditions are relatively rare, such a watch would be unusual and would heighten awareness in the several hours before a possible encounter. Finally, the watch concept could be implemented by the NWS.

NATIONAL WEATHER SERVICE INTERACTION WITH THE FEDERAL AVIATION ADMINISTRATION

The NWS provides a wide variety of forecast services, including those provided to the FAA and to aviation community. It has often been stated that the ability to forecast any meteorological phenomenon is directly related to the ability to observe it. Development of an adequate capability to observe low-altitude wind shear still requires a lot of work.

Thunderstorms present the greatest danger to aircraft. Along with the usual hazards to aircraft, thunderstorms also produce low-altitude wind surges or gust fronts that move out ahead of the storm. Downbursts and microbursts are closely associated with the gust fronts but on a smaller temporal and spatial scale. Radar and satellite pictures are used mainly to detect thunderstorms. Unfortunately, we are not yet able to observe with any degree of consistency which thunderstorm cells have significant low-altitude wind shear associated with them.

Meteorologists can predict wind shear associated with cold and warm fronts and with low-level jet streams with greater accuracy than those induced by convective activity. However, the low frequency and wide spacing of upper-air observations inhibits the meteorological monitoring of the parameters that cause the events. The turbulence portion of the Aviation Area Forecast indicates the likelihood of low-altitude wind shear. The forecast is prepared three times each day by the National Aviation Weather Advisory Unit in Kansas. In addition, 52 Weather Service Forecast offices issue, at the same frequency, 498 site-specific terminal forecasts, including the likelihood of low-altitude wind shear. These aviation/weather notices are transmitted to FAA and NWS offices as well as to those in the aviation community having the appropriate communications equipment.

Progress has been slow in the development of techniques for forecasting low-altitude wind shear associated with convective clouds and thunderstorms. Thunderstorms are assumed to have the potential for creating low-altitude wind shear, but only on some days do convective clouds cause hazardous wind shears. Recent research at the NOAA's ERLs indicates some skill in forecasting low-altitude wind shear caused by convective clouds.

Potential hazards can also be identified by certain precipitation radar echoes or satellite cloud images known to be associated with low-altitude wind shear. These short-duration (less than 2 hours) features are useful in specifying areas where hazards exist, but they do not yield the type of specific indications of low-altitude wind shear needed to plan flights.

The National Severe Storms Forecast Center in Kansas City issues daily forecasts of thunderstorms that may approach severe limits. Severe-thunderstorm watches are then issued as necessary. However, as recent investigations in the JAWS Project and analyses of the Pan American Airlines crash in New Orleans have shown, accidents can occur in storms that are not considered severe.

Dissemination of Weather Advisories

While disseminating forecasts of the more persistent nonconvective wind shears can be handled adequately, it is the convective low-altitude shears that pose the greatest danger to aircraft. An estimated 90 percent of significant operational low-altitude wind shears are convectively induced (NWS, 1982). These instances are frequently dealt with after the fact. While weather forecasts and in-flight advisories admonish that forecasts of thunderstorms imply the existence of low-altitude wind shears, pilot reports (PIREPs) are the most effective warnings of the actual existence of shear. In fact, until more definitive airborne and remote-sensing systems are instituted, PIREPs may be the single most important safety item in identifying most hazards to aircraft operations. Thus, aircraft encounters with severe low-altitude wind shear should be reported in a timely and accurate manner. Current reporting procedures are cumbersome and time-consuming, particularly considering how much pilots have to do during takeoff or landing.

Compounding the problem, many PIREPs are not disseminated beyond the air traffic controller receiving them. There are several weaknesses in the pilot reporting system that must be improved before pilots can depend on being consistently advised by other pilots of the existence of low-altitude wind variations.

The NWS and the FAA currently have several arrangements for communicating and disseminating weather information within the National Airspace System. These arrangements need to be examined and improved. One shortcoming is that most information is communicated via telephone. The FAA is currently developing equipment that will enable meteorologists at its CWSUs to transmit weather messages automatically to towers and control facilities within any center's area of responsibility.

3

Aircraft Performance and Operations

This chapter discusses the performance and flight characteristics of airplanes as distinguished from other forms of aircraft, such as helicopters and airships. Most of the analysis cannot be generalized and may not apply to aircraft other than airplanes. Although the hazards of wind shear to helicopters could be large, there are insufficient statistics to determine the extent of the problem. Similarly, the frequency of airship operations is so low that it does not merit special attention at this time.

WIND-SHEAR WARNINGS

Operational information on wind shear originates from meteorological forecasts, pilot reports (PIREPs), and/or detection by Low-Level Wind Shear Alerting Systems (LLWSAS) at those airports that have such equipment (currently 59). Meteorological forecasts are the least useful for predicting downbursts because of their short lifetime and random occurrence and location. These forecasts, at best, warn flight crews and controllers of conditions conducive to generating downbursts and wind-shear activity. This information, despite its lack of small-scale detail, alerts pilots to the possibility of a wind shear encounter, reducing their recognition and reaction times. Forecasts and PIREPs of encounters are the only sources of wind shear information for the thousands of airports that lack LLWSAS.

Pilots are not required to submit reports of wind-shear encounters. PIREPs are voluntary weather reports, broadcast by pilots to towers, departure control, approach control, flight service stations, or to an air-route traffic control center to warn of encountered or observed weather phenomena. The Airman's Information Manual (AIM) tells pilots when and how to report wind shears and other hazardous-weather information. Published quarterly by the FAA, it provides flight crews with basic flight information and air traffic control (ATC) procedures for use in the National Airspace System. In particular, AIM's Section 523 urges pilots to report wind shear encounters and specifies a particular format to ensure that enough information is furnished to make the report useful. Excerpts from the AIM, Section 523, are contained in Appendix A of this volume.

The FAA Air Traffic Controller's Handbook contains instructions for the use of PIREPs and LLWSAS information, including the issuance of wind shear advisories to pilots. The instructions contained in Section 7, are minimal. Under Section 6 the subject of wind-shear advisories is dealt with at some length for those airports that are equipped with LLWSAS. The handbook notes that “LLWSAS is designed to detect possible low-altitude wind shear conditions around the periphery of the airport and that it does not detect wind shear beyond that limitation.”

The FAA Facility Operation and Administration Handbook (paragraph 1222, dated September 2, 1982) gives the facility chief the option of using the centerfield wind information: “if operationally feasible, facility chiefs may elect to designate wind information derived from remote sensors located near runway thresholds as the wind to be issued to arriving aircraft rather than from the centerfield source, except that the centerfield source will be used during outages of the remote sensor/s.” Such procedures as described above require the local facility chief to issue a letter to airmen explaining to arriving aircraft the origin of wind information, if it is obtained from a peripheral, sensor. However, controllers are not required to specify the source of remote-wind data used when issuing these data to arriving aircraft, except when an alert occurs.

The training material of the Controller Training Academy at Oklahoma City does not incorporate the best-available information on wind shear. Wind shear is treated under the heading “Turbulence” and comprises, perhaps, three pages of text. Additional, more up-to-date information should be included and given more emphasis in training materials.

In response to NTSB Safety Recommendations issued March 25, 1983 (NTSB, 1983), which addressed the need for improvements in the LLWSAS system and procedures for its use, the FAA is in the process of amending its handbook for controllers. Similarly, the FAA plans to emphasize in the AIM the importance of pilots reporting wind-shear occurrences promptly. The FAA is preparing additional material for pilots and controllers in the form of advisory circulars and bulletins.

At busy airports, controllers must communicate vital LLWSAS data and other weather information while occupied with their primary task of guiding aircraft and ensuring traffic separation. Not only is it difficult to interpose weather information, in the fast-paced flow of traffic directives, it is also important that the wind shear information be transmitted promptly and clearly without the likelihood for misinterpretation.

If not given in a standardized format, PIREP can exacerbate the difficulty of the controllers' task. A recent FAA staff study of the FAA weather program in October 1982 (unpublished) recognized the problem of handling and distributing PIREPs and recommended revising the current procedures to improve their proper processing and distribution.

This situation calls for an alternative means of transmitting critical information accurately and directly to pilots. During 1977 the FAA conducted a study of how to best provide pilots with information on potentially hazardous weather conditions. Among other things, the FAA looked at the cost of a system that would allow a meteorologist at the Center Weather Service Unit (CWSU) to tape a hazardous weather advisory covering the center's geographic area of responsibility. CWSU meteorologists at the ATC center either now have or could acquire all the information they need to prepare a transcribed broadcast of reported or predicted low-altitude wind shears and of any other hazardous weather occurring in or forecasted for the geographical boundaries of the center, including air carrier terminals and other airports. In the proposed system, meteorologists would update the taped advisory as required, which would be continuously broadcasted on a discrete frequency. The FAA reported on March 23, 1978 that such a system would require four discrete frequencies in the 25-kilohertz range and 66 transmitters to adequately cover the continental airspace for all aircraft operating above 18,000 feet. The cost of such a system was estimated to be $1 million.

As noted earlier, the FAA is developing equipment that will enable meteorologists at their CWSUs to transmit automatically weather messages to towers and control facilities. However, in the near term, pending completion of an automatic data up-link, perhaps the proposed system or some variation, is worthy of another look.

In summary, all equipment and procedures now in place can be improved and refined to make warnings of possible wind-shear hazards more effective. It is essential that the aviation system exploit these capabilities to the utmost while more advanced warning systems, such as NEXRAD, terminal radars, airborne radars, and other airborne detection/warning concepts, are being developed.

COCKPIT PROCEDURES AND TRAINING

FAA Regulations

The Federal Aviation Regulations (FAR) applicable to air carriers and certain other categories of operators require these operators to develop and use approved procedures to advise pilots of severe weather conditions, including possible thunderstorms and frontal systems that may cause low-altitude wind-shear conditions at departure and destination airports; flight procedures for operating in potentially hazardous weather conditions; approved airman training programs covering all aspects of normal and emergency operations; and manuals including “instructions and information necessary to allow the personnel concerned to perform their duties and responsibilities with a high degree of safety.” [FAR 121.135(a)(1)]. This is in accordance with the Federal Aviation Act of 1958 [Sec. 601(b)], which prescribes that: “the Administrator shall give full consideration to the duty resting upon air carriers to perform their services with the highest possible degree of safety in the public interest.”

The airplane flight manual required for airplane type certification by the FAA need not include a discussion of wind-shear effects on the airplane. The flight operations manual for each airplane used by an airline, however, is required to include a detailed discussion of piloting procedures to be followed in the event of a wind-shear encounter during takeoff or landing. In addition, air carriers are required to include procedures for coping with wind shear as part of their FAA-approved training programs. These operational and training programs are monitored in the field by FAA operations inspectors, who have the responsibility to evaluate the adequacy of the air carriers' training programs and line operations.

The FAA issued Advisory Circular AC 00-50A, entitled Low Level Wind Shear, on January 13, 1979. It is the primary source of FAA guidance to pilots for recognizing the more significant meteorological phenomena that may cause wind-shear hazards. It also contains procedures for pilots to use in detecting the presence of wind shears and for flying airplanes safely in the event of an encounter. Since its publication in 1979, much more has been learned about the characteristics and hazards of wind shear, especially from Projects NIMROD and JAWS. Advisory Circular AC 00-50A should be revised and updated to include new information. In particular, the FAA should describe the structure of downbursts and enhance the discussion of airplane performance and piloting techniques in wind-shear conditions.

Operating Procedures

Airline flight operations manuals were reviewed by the committee as to the procedures specified for use by airline flight crews in the event of low-altitude wind-shear encounters. All of the instructions appear to be based on the recommendations in FAA Advisory Circular AC 00-50A, and on recommendations developed by the Boeing Company, and published in the January 1977 and January 1979 issues of Boeing Airliner magazine (Higgins and Roosme, 1977; Higgins and Patterson, 1979). But there is considerable variance among airlines in the extent of coverage and in details on flight operations procedures. Some manuals provide very extensive instructions, while others are far less complete. Additional emphasis needs to be placed on the potential severity of and hazards from downbursts and strong wind shears and the importance of early recognition of and immediate reaction to them. In addition, the manuals should discuss flying at high angles of attack or at stick-shaker speed* and the need for timely PIREPs phrased in standard terminology. It is noted that some airlines include material relevant to wind shear in their training manuals rather than in their flight operations manuals. In these cases, the training materials and flight operations manual materials are complementary.

Airline flight operations manuals are organized differently from one company to another, as are their methods of presenting procedures for dealing with wind shears. Typically, all procedures related to takeoff and initial climb appear in one section of the manual and all procedures applicable to approach and landing appear in another.

One major airline presents extensive material on wind shear in its flight operations manual. It includes the following warnings in the part of the manual dealing with takeoff (normal operations):

> If significant wind shear is suspected, consider the alternatives of taking off in a different direction or delaying the takeoff until conditions are more favorable. If shear is suspected, use full takeoff thrust; do not use reduced thrust. If the takeoff is not obstacle limited, a speed in excess of V_2+10** may be used for the initial climb to provide additional protection from decreasing headwinds or downdrafts. If significant wind shear or downdrafts are encountered at low altitude after takeoff and airspeed has decreased to below normal climb speed, apply go-around thrust and adjust pitch attitude to climb out at the existing airspeed. Do not lower the nose in an attempt to regain speed until reaching a safe altitude. If ground contact is imminent, use the procedure for avoiding imminent ground contact.

A similar warning appears in the section of the flight operations manual dealing with landing (normal operations):

> If wind shear is encountered on final approach, do not hesitate to go around if the approach profile and airspeed cannot be restabilized. It cannot be emphasized too strongly that a go-around is often the professional pilot's best course of action. If ground contact is imminent, use the procedure for avoiding imminent ground contact.

The emergency section of the same manual contains the following:

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*The “stick shaker” is a device that vibrates the control column to provide stall warning prior to reaching stall angle of attack.

**V_2 is defined as the engine-out takeoff safety speed. Normal all-engine initial-climb target speeds vary from V_2+10 to V_2 +20 knots, depending on the model.

AVOIDING IMMINENT GROUND CONTACT

In the event of imminent contact with the ground, such as during an extreme wind shear or downdraft encounter or unintentional flight toward terrain, it may be necessary to use all available airplane energy by trading airspeed for altitude to avoid or soften impact.

Simultaneously increase pitch attitude and apply thrust, if necessary, to the limit of forward throttle movement. The initial rotation should be accomplished sharply, and pitch attitude should then be adjusted to achieve a rate of airspeed decay sufficient to arrest the descent and to climb. Maintain these conditions until reaching a safe height or until the stick shaker activates, whichever occurs first. If the stick shaker activates, lower the nose sufficiently to stop further airspeed decay, maintain attitude and thrust, and continue climb with the stick shaker activated. When safe conditions are achieved, initiate recovery of airspeed. Be aware that in almost all cases, pitch attitudes in excess of 20 degrees will be required in this maneuver. Rate of airspeed decay should not be so great as to decelerate significantly below stick shaker speed.

There are some potential problems with a pullup to stick shaker speed that should be considered:

- If the pullup is accomplished too soon (significantly prior to imminent ground contact) climb rate is actually decreased, since climb rate at stick-shaker speed is less than at V_2, V_2 + 10, or V_{prog}.*
- If the pullup is accomplished too soon, and ground contact still occurs, there is no airspeed cushion to use for a “flare” to soften impact.
- If airspeed decay rate during the pullup is too great, speed will decrease through the stick-shaker speed, and the airplane could stall.
- When at stick-shaker speed, any turbulence or additional shear could cause the airplane to stall.
- It is possible that the effects of heavy rain could cause an increase in the airplane's stall speed. This could cause the airplane to stall before reaching stick-shaker speed.

Nevertheless, if ground contact is indeed imminent, this maneuver represents a “last chance” effort to avoid or soften contact with terrain. Early recognition of the flight

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*V_{prog}. refers to a preselected or commanded speed, which may be entered into a flight director or autothrottle.

> condition, either through GPWS [Ground Proximity Warning System] alert or crew awareness of the possibility of wind shear, should allow use of the normal go-around procedure which would avoid the necessity of using the extreme measures described above.
>
> Any time engine limits are exceeded in these circumstances, the possibility of severe engine damage exists and a landing at the nearest suitable airport may be required.

This discussion of operating procedures during a wind-shear encounter is among the most comprehensive treatments found in manuals used by airlines operating under Part 121 of the FAR. It does not appear that similarly detailed procedures are common among the Part 135 commuter and air taxi or the general aviation communities.

No U.S. aircraft operators--airline, commuter/air taxi, or general aviation--are known to have established operational limitations governing the takeoff and landing decision by the pilot-in-command based solely on reported low-altitude wind-shear levels. LLWSAS information is generally treated as advisory in nature. It is clear that the 15-knot vector difference threshold that triggers an LLWSAS alert is not regarded as a serious operational hazard except in the case of a takeoff limited by runway length or by obstacles in the departure flight path. Airline operating policies and procedures typically require pilots to assess all relevant factors in deciding whether to take off or to continue an approach to landing in the event of a potential wind-shear exposure. The wind-shear level indicated by LLWSAS is only one of many factors to be considered.

Training Programs

A review of airline training programs reveals that, as required by the FAA, FAR 121 air carriers train flight crews on the nature of wind shear and operational procedures required to cope with its potential threat. But the exact nature and timing of the training vary widely from airline to airline. All airlines appear to cover the subject extensively in ground training. As with operations manuals, the material is based largely on excerpts from the FAA's advisory circular, Boeing Airliner articles, and the technical literature.

The FAA has a similar wind-shear ground training requirement in FAR 135, for operators subject to those regulations. However, the committee was unable to assess the scope of coverage of wind-shear hazards in ground training programs of FAR 135 operators. There is no specific requirement for wind-shear training for general aviation pilots other than the very general “aeronautical knowledge” requirement in FAR 61, applicable to issuance of pilot certificates and ratings.

The FAA has no specific requirement for flight training of pilots on procedures to be followed in the event of an inadvertent wind-shear encounter. The FARs applicable to training have evolved from a premise that all necessary flight training--for all classes of operators--can be conducted in flight in an airplane. Requirements in the FARs governing use of simulators to conduct flight training are permissive. Simulators may be substituted for airplane training, but there is no requirement for simulator training for any class of carrier, not even for air carriers operating under FAR 121.

Inflight training for wind-shear encounters is not feasible. In view of the random and rare occurrences of wind shear in nature and because of the threat posed to flight safety by exposure to severe wind shears at low altitude, air carriers operating under Part 121 conduct such flight training in simulators. These devices are more economical to operate than airplanes and provide superior training capability for a range of abnormal and emergency training problems, including severe wind-shear encounters. However, only those few “advanced” simulators approved under FAA's Phase II and Phase III criteria in Appendix H of FAR 121 are required to incorporate “representative three-dimensional wind-shear dynamics based on airplane-related data.”

FAR 135 operators typically conduct a much smaller amount of flight training in simulators. Also, relatively little flight training in simulators is conducted within the general aviation community, although corporate and other operators of sophisticated multiengine turbojets use simulators extensively for training.

It is unlikely that simulators will become universally available for flight training in the foreseeable future--not even for air carriers operating under FAR 121. Their use is limited in part by the FAA requirements that simulators meet demanding technical specifications (FAR 121.407; FAR 121, Appendix H; FAR 135.335; Advisory Circular AC 120-40). Many aircraft, including older transport-category types, have never had an adequate simulator data package developed to enable a simulator to be programmed such that it can meet applicable criteria for FAA approval.

The FAA has fostered and regulated simulator training since the introduction several decades ago of regulations governing the use of simulators in air carrier training programs. As simulators have been improved, the FAA has systematically recognized and credited their use in pilot training, checking, and certification programs. Advisory Circular AC 120-40, Airplane Simulator and Visual System Evaluation, contains criteria for the approval of simulators. However, these criteria are conservative in the sense that they require simulators with capabilities that make them very complex and expensive to obtain and to operate, in order to be approved as a training device for pilots operating under FAR 121 and 135. The FAA does not specifically recognize simulators as a substitute for airplane training of general aviation pilots, although the FAA has granted several exemptions for this purpose.

Wind-Shear Modeling for Training Simulators

Advanced simulators currently used for pilot training and checking are required to be capable of full-mission, pilot-in-the-loop simulation. They are required to have appropriate visual display and actual cockpit force-feel systems, including instrumentation, recording systems, and appropriate dynamic modeling of the wind shear conditions to be encountered.

Accurate portrayal of downbursts and wind-shear conditions and related aircraft responses in a simulator with motion base and visual displays presents a complex computer modeling problem. It requires extensive and expensive computation capabilities, available only in costly advanced simulators with large memory capacities, fast computation capabilities, and real-time cockpit controls and displays and response times necessary for the realistic portrayal of wind-shear encounters.

Results of recent wind-shear measurements in the JAWS Project indicated that the wind-shear models now being used by the airline industry for training, for airborne control and display system development, and for certification purposes do not accurately portray actual wind-shear situations. Most models in use today are based on data developed for the FAA during 1976-1979 (Foy, 1979).

The most accurate portrayal of wind-shear fields are the four-dimensional, time-varying models based on JAWS data being proposed by NASA's Langley Research Center. These models are of interest and importance in research. However, their use of time dependence greatly increases computational requirements, which can easily exceed the capabilities of the computers used in simulators.

It is possible to use a somewhat simplified representation of wind shears for some purposes without significantly compromising the results. In these cases, very real benefits in time and effort plus substantial savings in costs can be achieved. The increasing complexity and costs associated with the latest developments in computer modeling and simulation may make it prohibitively expensive for many potential users and may serve to stifle the application of new technology and safety advances. Studies should be undertaken to determine when simplified wind-shear models are acceptable for purposes of system design, evaluation and certification, and for training in simulators.

The FAA has proposed procedures for approving airborne wind shear systems (Draft Advisory Circular AC 120-XX, Approval of Airborne Wind Shear Detection Systems). This proposed advisory circular describes wind fields considered acceptable for various specific applications. They were developed from accident reconstructions, meteorological data, and other sources. The FAA plans to update these wind field definitions as new information from JAWS and other studies becomes available. The new definitions should include “severe” wind profiles that may exceed the performance capability of a specific airplane.

Development of these new wind-shear models will take a considerable period of time and much effort. It is essential that industry standards for implementation and use of the resulting models be established to minimize different interpretations of the data. This should be undertaken as a joint government-industry effort. The FAA should publish the results for use in simulator training as well as for evaluation and approval of airborne systems. If possible, these wind-field models should be standardized for specific applications to ensure consistency among users. Particularly promising is a simple empirical model that defines a three-dimensional wind field that may be adapted for use in simulator applications to represent thunderstorm outflow phenomena of the type associated with recent aircraft accidents. This model is being developed at NASA's Ames Research Center.

PERFORMANCE IN WIND SHEAR

Airplane Response to Wind Shear

Airplanes generate the aerodynamic forces that make flight possible by means of airspeed, which is the velocity of an airplane relative to the surrounding air mass. Thus, a change in velocity of the surrounding air, or a wind shear, will cause a change in the aerodynamic forces on an airplane. However, all airplanes have some degree of speed stability and, as a consequence, once they have been disturbed by a wind shear, they will try to return to their original velocity relative to that of the new air mass. This process may take a half a minute or more depending on the airplane and the size of the wind shear (assuming the pilot takes no corrective actions).

When an airplane encounters a wind shear, there will be changes in components of wind along each of the airplane's axes of motion. The longitudinal axis runs along the center of the fuselage and the wind component along this axis is a headwind or tailwind. The vertical axis has its associated up- or downdrafts, and the lateral axis has its associated crosswinds from the left or right. Each of these wind components will produce a different response based on the airplane's aerodynamic configuration. A brief description of how an airplane responds to each of these wind shears along individual axes will contribute to an understanding of the wind-shear problem. The airplane's response to each of these wind-shear components assumes no corrective action by the pilot and that the wind is steady before the plane enters and after it leaves the shear field. In actuality, wind-shear components exist in three dimensions, and the net effect of flying through such a wind field imposes disturbances in all six degrees of freedom of the aircraft. Much of the ensuing discussion centers on the control-fixed response. The closed-loop (piloted) responses will, of course, be very different and will represent actual cases that must be studied.

Longitudinal Wind Shear. A longitudinal wind shear that increases an airplane's airspeed can arise either from an increase in a headwind or a decrease in a tailwind. In either case, an increased airspeed caused by a shear will cause an increase in lift and drag. The airplane pitches up and climbs, while its pitch stability causes it to reduce its angle of attack and decrease its lift as it starts to recover to its original trim condition. In the free-response case, after several oscillations, the airplane will restablize at its original airspeed on a flight path that is parallel but displaced above its original one, and its new speed relative to the ground will have decreased by the magnitude of the wind shear. A reduction in engine thrust is required to regain the original inertial flight path.

A decreasing tailwind and an increasing headwind both provide an apparent increase in airplane performance. However, the two cases present different problems to the pilot attempting to fly a glideslope since the decreasing tailwind case, with its higher ground speed, requires less power to follow the proper approach path. The opposite situation for a longitudinal wind shear occurs when there is an increasing tailwind or decreasing headwind. In this case, airspeed decreases and lift and drag are reduced. The airplane pitches down and descends, while the airplane's pitch stability causes it to increase its angle of attack to recover lift. Eventually, the airplane will restabilize at its trimmed airspeed on a flight path parallel to the original one but displaced below it and at a higher ground speed than before the wind-shear encounter. The shear has caused a reduction in altitude, which has been converted into increased ground speed at the original airspeed. To restore the altitude loss, energy must be added to the airplane in the form of increased engine thrust.

Updrafts. An updraft disturbs an airplane by increasing its angle of attack. This increased angle of attack increases lift and drag, which cause the airplane to climb and decelerate. The increased lift causes the airplane to pitch nose-down to reduce the angle of attack and to recover its original value. Again, after several oscillations, the airplane will return to its original angle of attack and airspeed relative to the air mass, but it will be climbing relative to its original inertial flight path.

The opposite situation, a downdraft, decreases an airplane's angle of attack, thus reducing lift and causing it to sink. The decrease in lift causes a decrease in drag and a nose-up pitch to restore angle of attack. Eventually, the airplane will settle out at the original airspeed and angle of attack but will descend inertially within the air mass.

Updrafts impart energy to an airplane making it climb; downdrafts absorb energy, making it sink. Pilots must reduce power in updrafts and increase power in downdrafts to restore the energy balance of the airplane.

Lateral Wind Shear. Crosswinds and lateral wind shears act on an airplane by generating side forces plus yawing and rolling moments. The initial response is to “weathervane” into the wind and to roll with the upwind wing rising. In a steady crosswind the airplane, which may or may not be enhanced by a stability augmentation system, will eventually stabilize with the wings approximately level and flying into the wind on a new heading. Basically, lateral wind shears do not cause large changes in altitude or airspeed. However, if large bank angles develop or if large lateral control spoiler deflections are used, a small loss of lift and rate of descent will be generated. During the landing approach, lateral wind changes will increase a pilot's workload by making the directional tracking task more difficult. However, while taking off or during go-around, precise heading control is not required, and some amount of drift from the runway centerline is acceptable.

In summary, longitudinal and vertical wind shears can add energy to or subtract energy from an airplane. This must be compensated for by the use of throttles and by the appropriate application of longitudinal control by the pilot. Lateral shears do not affect an airplane's energy state as significantly, but they do make flying a precise approach path more difficult, thus adding to a pilot's workload.

Pilot's Control in Wind Shear. Having discussed the response of an airplane to wind shears in the absence of pilot control, some discussion of pilot actions required to counter wind shear is relevant. The most exacting period of a flight is the landing approach because the pilot must fly an inertially fixed flight path to a point on the runway. It is in this context that pilot actions will be discussed.

A decreasing headwind or increasing tailwind shear causes a loss in airspeed and a tendency for an airplane to sink below the glide slope. To counter this, the pilot must increase the airplane's angle of attack at the rate of about 1 degree of angle of attack for each 3 to 4 knots of speed lost. Additional pitch attitude is required since the angle of descent increases and the airspeed decreases. Simultaneously with the required pitch-attitude increase, power must be increased to return the airplane to the glide slope, to overcome the increased drag, and to accelerate back to the intended approach speed or to initiate a go-around if the pilot sees fit. In a strong wind shear, large and rapid pitch-attitude and power corrections are required. The most common pilot mistake is not to make these corrections vigorously and rapidly.

Downdrafts require similar pilot reactions. Downdrafts reduce an airplane's angle of attack and cause it to descend, since it is immersed in a column of descending air. To compensate for the effects of strong downdrafts, large nose-up pitch-attitude corrections may be required. At the same time, thrust must be increased with the pitch-attitude increase to return the airplane to the glide slope. Increased thrust will also be required to maintain the flight path.

A combination of downdraft and decreasing headwind or increasing tailwind, as is characteristic of a downburst, will require very rapid and large pitch-attitude and power corrections. Simulator studies of flying a landing approach through severe wind shears of this type have shown that unless an immediate go-around at a high pitch angle and high thrust is initiated by the pilot, there could be little chance of survival.

An increasing headwind shear would appear to be benign since it carries the airplane above the glide slope and increases airspeed. To compensate for this, pilots hold airspeed by reducing thrust and decelerating inertially. However, when the airplane emerges from the shear, the airplane can be low on thrust and starting to sink rapidly. If this occurs at low altitude and when transitioning from instrument to visual flight, the increased rate of sink may not be detected by a pilot before it is too late to complete corrective action to avoid ground contact.

Lift Characteristics. In the FAA certification process for any airplane, the FAR stall speeds are determined by extensive flight testing. This is important because the stall speeds are the basis for specifying the operating speeds at low altitudes in the vicinity of an airport. The FAA specified stall speed ($V_{\text{min FAR}}$) is the minimum speed that is achieved in a stall maneuver that involves a 1 knot per second deceleration with zero thrust. Since the FAR stall speed is a minimum speed at less than 1g for most airplanes, level flight cannot be sustained at this speed.

The minimum speed at which level flight can be sustained is the 1g stall speed ($V_{\text{min 1g}}$), which is typically 5 to 7 percent faster than the FAR stall speed. The 1g stall speed is affected by engine thrust, since the angle of attack is sufficiently high that there is a component of thrust in the lift direction that augments the wing's lift. Maneuvering capability and speed margins in a wind-shear situation should, therefore, be referred to as the 1g stall speed. Figure 12 shows this comparison. The height of the bars indicates the speed margin and maneuverability, and the width indicates the spread in speeds of different aircraft types.

Stall buffet and/or stick-shaker actuation occurs as a warning slightly above the 1g stall speed and provides a warning of the impending loss of lift. Flying at incipient stick-shaker speed or on the edge of stall buffet is the practical lower airspeed limit for sustaining flight. It provides a small operating margin over the 1g stall speed for turbulence, rain, instrumentation errors, and the like.

Commercial and general aviation aircraft operate at similar percentages of their FAR stall speeds during takeoff and landing. The

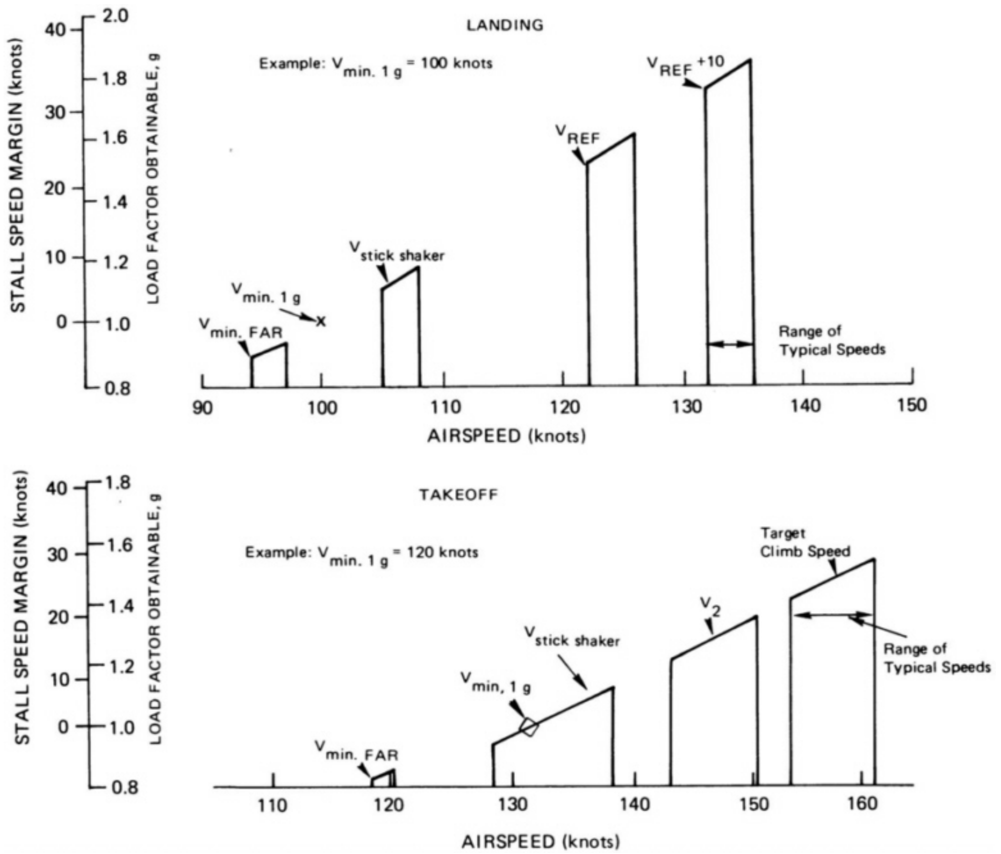

FIGURE 12 Maneuver Margins of Transport Aircraft During Takeoff and Landing Approach.

minimum takeoff safety speed set by the FAA for commercial transports, V_2, is required to be 1.15 $V_{MIN\ FAR}$ for propeller-driven aircraft and 1.2 $V_{min\ FAR}$ for turbojet-powered aircraft. However, V_2 may be set higher for other considerations. Minimum landing approach speed, V_{REF}, is 130 percent of the FAR stall speed in the landing approach configuration.

Normal operation of most types of commercial aircraft is at V_2 + 10 knots or higher on takeoff and V_{REF} + 5 or 10 knots on landing. These speeds provide transport aircraft with approximately a 25-knot margin over the 1g stall speed on takeoff and a 30- to 35-knot margin on landing. General aviation aircraft that have lower stall speeds will have proportionately smaller speed margins. For an aircraft with a 50-knot stall speed, the margin could be one-half of the above values.

Some accidents have occurred in thunderstorms where the airplanes encountered heavy rain and wind shears simultaneously. Some preliminary analytical and experimental data indicate that heavy rain can degrade a wing's aerodynamic performance by reducing its maximum lift capability (Haines and Luers, 1982). NASA has embarked on a program to develop a technique to measure the effects of rain on airfoils and plans to apply this technique to some representative airplane configurations to determine the effects on performance.

Thrust and Drag. The ability to survive large longitudinal and vertical wind shears depends both on the excess thrust that is available to accelerate an airplane and on the available lift margin. A typical three-engine airplane's thrust and drag characteristics are shown in Figure 13 as the ratios of maximum takeoff thrust over weight (T/W) and drag over lift (D/L). These ratios vary with speed above the FAR stall speed. They also vary for takeoff and landing flap settings at typical takeoff and landing weights. The figure shows that:

- The aerodynamic characteristic D/L is a function of angle of attack (or V/V_s for 1g flight) and flap and gear position only.
- Maximum T/W depends on an airplane's weight and on the engines' maximum takeoff thrust, which depends on altitude and temperature.
- The excess T/W, which is the difference between maximum T/W and D/L, defines the acceleration or climb capability of an airplane.
- Since the FAR performance requirements specify a minimum climb capability with the critical engine not operating, when all engines are operating the T/W can range from twice the minimum for two-engine configurations to 1.33 for four-engine configurations. Thus, two-engine airplanes have the largest thrust margins.
- The excess T/W does not vary significantly with V/V_{SFAR} over the normal operating speeds. Below $V_2 + 10$ and V_{REF} there is some decrease in excess T/W, but it is still substantially greater than is available in a climb at V_2 or V_{REF} with one engine inoperative.
- The acceleration capability shown in Figure 13 for takeoff at $V + 10_2$ is 2.7 knots per second (Δ T/W = 0.14) and is 1.9 knots per second at stick-shaker speed. For landing the acceleration capability is somewhat larger due to the lower

airplane weight, although this is partially offset by the increased drag of the landing configuration.

Takeoff in Wind Shears

During takeoff the critical altitudes for wind-shear encounters are below 400 feet. If a severe shear is encountered above this altitude, an airplane probably has enough altitude and speed margin to traverse the shear and have terrain clearance. As a downdraft approaches the ground, the ground presents a solid boundary that converts the vertical winds of the downdraft into an outflow of horizontal winds.

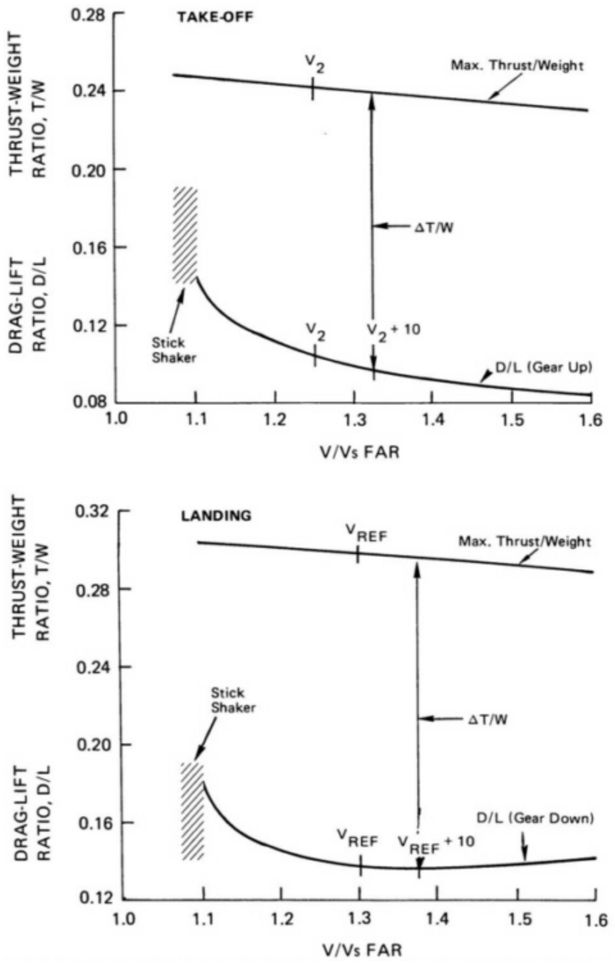

FIGURE 13 Thrust and Drag Characteristics for a Typical Three-Engine Transport Aircraft with All Engines Operating.

It is relatively easy to determine the magnitude of the critical tailwind that will cause an airplane to lose altitude. Not considering downdrafts, if the rate of shear exceeds the acceleration capability of an airplane for any significant period while the airplane is below 100-200 feet, the airplane will lose altitude, airspeed, and rate of climb. As a result, the airplane will settle into the ground or stall.

For instance, if the airplane represented in Figure 13 encountered a tailwind shear that increased to 50 knots over a 10-second interval, the airplane will lose 25 knots of airspeed if flown at a constant altitude. The airspeed loss will be greater if the pilot attempts to climb. This tailwind shear will drive the airplane to stick-shaker speed (see Figure 12). If significant downdrafts are associated with a shear, it is unlikely that an airplane can successfully penetrate the shear at altitudes below 100-200 feet. Measurements made during the JAWS Project have shown that this large a shear is not unusual in a microburst. The best solution is to devise some means to warn a pilot before takeoff of the hazardous wind-shear condition, so that departure can be delayed. If a severe wind shear is encountered at takeoff, there is little a pilot can do except be sure he has set the throttles at maximum available thrust or overboost the engines and try to conserve altitude until the shear is traversed.

Altitude Loss in Wind Shear on Landing Approach

Analysis of the flight path of an airplane that penetrates a severe wind shear on landing is a complex problem. Figure 14 presents a generalized view of the altitude loss in transitioning from a 3° glide-slope approach to a go-around in tailwind shears of varying magnitude and intensity. The assumptions of pilot recognition time and the pilot's response in such a study are crucial to the results.

This figure assumes two different sets of pilot actions. The lower set of curves is representative of what may be expected when a pilot has no cockpit warning and no wind-shear flight director or guidance information to cope with the wind shear. In this case, however, the pilot visually identifies the hazard in a reasonable time and vigorously executes a missed approach. Here, a 4-second time delay is assumed from the time of the wind-shear encounter to the application of additional power. An additional 2 seconds is assumed to elapse before the pilot initiates an airplane-nose-up rotation to arrest the airplane's descent. The pilot continues to apply power until maximum power is attained (about 2 seconds), and the aircraft continues to rotate until the stick-shaker warning is actuated (about 3 seconds). Thereafter, the airplane is controlled to maintain an attitude of incipient stick-shaker actuation until its descent has been arrested and it has begun to accelerate.

The upper curves in Figure 14 show the maximum performance capability of the aircraft allowing a minimum realistic time for wind shear recognition. These curves are representative of the potential

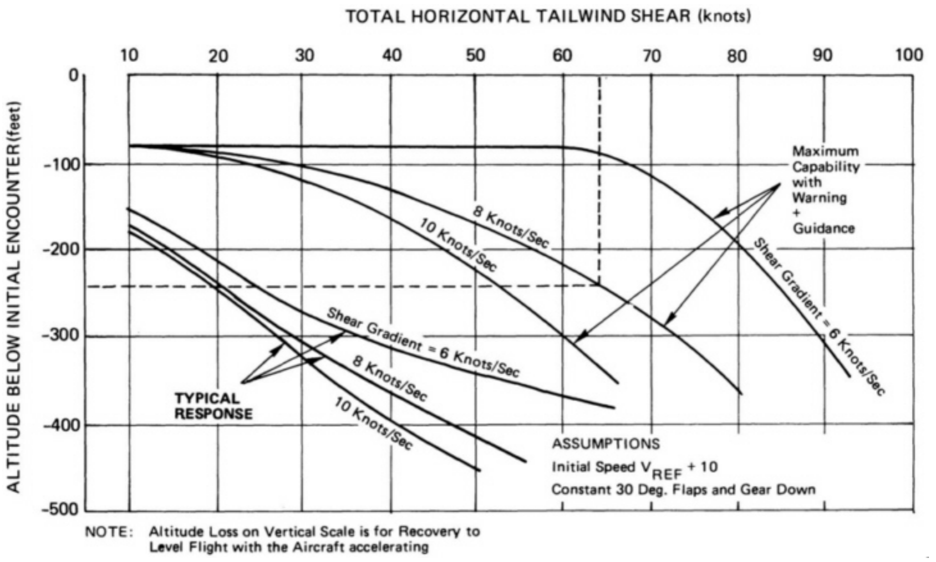

FIGURE 14 Transport Aircraft Flare Capability in Wind Shear from a Three-Degree Approach Path.

go-around and flare performance for an aircraft with a system providing a warning of a shear encounter. It assumes an appropriately trained pilot who follows wind-shear guidance and command indicators. Here, the power application and nose-up attitude control are initiated at the end of 2 seconds and, as in the previous case, power application is continued until full power and incipient stick-shaker conditions are attained and the flare maneuver completed. The constant, incipient-stick-shaker angle-of-attack portion of the flare is a very important assumption in the dynamics of the flare maneuver.

The asymptote at the top of the upper curves in Figure 14 shows an approximately 80-foot altitude loss. The first 30 feet represent the 2-second delay in recognizing the shear encounter, and the remaining 50 feet are lost during a straightforward flare. For wind shear conditions along the asymptote line, the airplane has sufficient performance to penetrate without further loss in altitude, providing the pilot uses the airplane's pull-up capabilities up to the stick-shaker angle of attack.

For more severe shears an aircraft cannot maintain altitude after it has reached stick-shaker condition. In these cases, as it loses altitude the airplane accelerates and develops a normal load factor, which provides the flare. In Figure 14, at 8 knots/second shear gradient and with an 8-second penetration time, there is a 64-knot change in horizontal tailwind. The curve shows a loss of 235 feet in altitude in this maneuver for the maximum performance case.

Figure 14 considers only horizontal tailwind shears. The addition of downdrafts is difficult to present in a generalized form. Follow-up studies should consider combined horizontal wind shears and downdrafts with realistic combinations of shear gradients. Figure 14, which presents the results of a simplistic analysis of a very complex problem, shows that under 500 feet above ground level (AGL) the probability of surviving a severe wind shear is greatly enhanced by an immediate recognition and response to the shear. A corollary is that warning devices and equipment that improve the pilot's ability to respond in this manner also contribute significantly to the probability of success. Thus, pilots must rapidly recognize a severe low-altitude wind shear on approach and immediately execute a missed approach maneuver. This means immediate application of maximum thrust and rotation to arrest the descent of the aircraft.

As a last resort, in a severe wind shear the airplane may have to be flown at or slightly below stick-shaker (or other stall-warning) angle of attack until it leaves the shear area and its performance margins are restored. At that point, it should be possible to climb and accelerate to normal climb speeds.

Few nonmilitary aircraft are equipped with an angle-of-attack display. Therefore, stick-shaker (or other stall-warning) angle of attack, which is 2° to 3° below the angle of attack for maximum lift coefficient, becomes the upper limit of rotation on aircraft lacking special instrumentation.

The combination of energy trade and use of maximum thrust gives pilots the best chance of preventing ground contact if they encounter a severe shear without warning at low altitude. Pilots must recognize that flight at stick-shaker angle of attack entails significant risks that can be justified only if the aircraft encounters severe shear at very low altitude.

Pilots should react to shears above 500 feet as rapidly and positively as described above, but in this case the extra altitude makes it possible to initially rotate to less severe angles of attack, better preserving speed and lift safety margins.

General Aviation Aircraft

While extensive research has been conducted on the characteristics of wind-shear encounters of conventional jet transport airplanes, there is only a small amount of analysis (Lehman et al., 1977) for the large variety of general aviation airplanes, which includes corporate, commuter, and personal aircraft. First, there appear to be few documented cases of wind-shear-related accidents of general aviation airplanes. Second, accidents involving these airplanes are rarely investigated as aggressively as those of air carrier aircraft. However, the hazard of low-altitude wind-shear accidents is present for general aviation aircraft.

The following simplified analysis provides some limited insight into the basic factors influencing the ability of general aviation airplanes to adjust to wind shears. It also indicates an avenue of further study that should be pursued. The analysis assumes that an airplane takes 20-30 seconds to tranverse a downburst, during which period the wind-shear velocities are constant. A measure of the severity of the shear, then, is the peak velocity difference across the microburst. Airplane performance capability can be represented as the ability to increase speed per nautical mile traveled. On this basis, comparisons can be made among the various classes of airplanes.

Table 4 presents acceleration capability at the best angle of climb speed in the clean configuration for general aviation airplanes and for a heavily loaded three-engine jet transport in the takeoff configuration, based on airplane flight manual performance data. It shows that many airplanes thought to have low performance capabilities have surprisingly high values of acceleration potential compared with jet transports. While this appears to be a very favorable factor for light general aviation aircraft penetrating wind shears, it is by no means the only factor to be considered with regard to the hazards of severe wind-shear encounters. Also, the acceleration potential values presented in Table 4 are based on a static, instantaneous performance analysis and are only indicative of the relative acceleration capabilities of the aircraft types listed. A similar criterion is described by Frost (1983).

TABLE 4 Acceleration Capability at Best Angle of Climb Speed

Aircraft Type	Airspeed V(KN)	Rate of Climb R/C(FPM)	Acceleration Margin (KN)/(SEC)	Performance Factor, $\Delta V/\Delta X$ (KN)/(NMI)
Trainer	62	780	2.37	138
Basic 4-Place	62	660	2.00	116
High-Performance Single Engine	83	1050	2.38	103
Light Twin	78	1140	2.75	127
Cabin Twin	88	1380	2.95	121
Light Turboprop	105	1560	2.79	96
High-Performance Turboprop	106	2100	3.72	126
Light Turbo fan	150	2040	2.56	61
High-Performance Jet	200	4200	3.95	71
High-Performance Turboprop	180	3300	3.45	69
Typical 3-Engine Jet Transport at T.O.	160	2300	2.7	61

The following additional points should be explored before definite conclusions can be reached on the relative capabilities of general aviation aircraft and jet transports in penetrating severe wind shears.

1. General aviation aircraft usually have lower takeoff and landing approach speeds than do commercial jets. Consequently, a given total wind shear represents a higher percentage of the airplane's flight speed. This, of course, makes it more difficult to penetrate a given wind shear.
2. Since the minimum operating speeds during takeoff and landing approach are defined as a percentage of the FAR stall speed, general aviation aircraft with low stall speeds will have smaller speed margins than do jet transports. Their ability to absorb an airspeed loss in a wind shear would be less than airplanes with higher stall speeds. However, general aviation aircraft generally operate at proportionately larger speed margins above their minimum operating speeds compared with transport aircraft. Their slower penetration speeds would allow pilots more time for recognition of and response to wind shears.
3. Propeller-driven general aviation aircraft have the benefit of the propeller slipstream over the wing, which provides an added margin of lift not available to jets.
4. Some jet-powered general aviation aircraft have very high thrust-to-weight ratios. This is a very favorable factor in penetrating adverse wind shears.
5. Slow-flying general aviation aircraft will be more sensitive to updrafts and downdrafts than are jet transports, since such drafts produce a larger angle-of-attack change on a slower-flying airplane.
6. General aviation aircraft with small wing spans have less roll damping and are more active in roll than large jet transports. Lateral control could require a large increase in pilot attention in a severe shear that could deteriorate the pilot's flight-path-tracking performance.

Thus, there is no justification of an assumption that general aviation aircraft are less susceptible to wind shear than transport aircraft. More research is needed on representative general aviation aircraft to determine their vulnerability to wind shear. NASA has conducted wind tunnel tests on a series of full-scale general aviation airplanes, and this would provide a data base for the required aerodynamic characteristics. The Ames Research Center has performed related simulator investigations of wake vortex encounters on various categories of airplanes, using available aerodynamic data for representative airplanes. The aerodynamic data base that permits a detailed piloted simulation is generally available or could be estimated, and it should be suitable for analytical and simulator investigations of general aviation airplanes in wind shear.

GUIDANCE AND CONTROL AIDS

The threat to safe aircraft operation posed by wind-shear effects, as distinct from high levels of turbulence, occurs principally near the ground, when an aircraft is taking off or landing. During these phases of flight, the pilot's workload could be greatly alleviated with guidance and control aids. Documented dangerous encounters with wind shear have lasted for half a minute or less, implying transient forcing of the closed-loop phugoid motion, which provides the basic mechanism for interchanging kinetic and potential energy, i.e., for trading speed and altitude. Guidance and control aids could improve pilot capability in effectively combating wind shear by helping to manage the aircraft's energy level, either automatically or by helping to perform the necessary maneuvers. Other critical elements in the cockpit for coping with wind shear include:

- Warning that severe wind shear may be encountered,
- Recognition that a wind shear has been encountered.
- Prompt initiation of the proper control actions to deal with the effects of wind shear.
- Exercise of continuous control actions during an encounter so as to successfully go-around, complete the takeoff, or successfully land or execute ground contact under circumstances that will maximize the chances for survival.

All of these elements need to be addressed to improve flight safety in the presence of wind-shear hazards.

In the context of practical flight operation, guidance and control aids must allow an aircraft to complete its nominal flight phase as often as possible, reserving the decision to abort the approach or delay the takeoff as infrequently as possible and for only the more severe shear encounters. The “go/no-go” decision must be accurate and must be based on all available information: meteorological, LLWSAS, control tower reports, and as a last resort onboard warning or guidance information if a shear is encountered.

Wind-shear guidance and control aids must be capable of using the full performance of the aircraft. As distinct from normal conditions, severe wind shears can drive an aircraft to “the edge of the flight envelope” and beyond. Consequently, these aids must be optimal in the sense of generating maximum performance while maintaining safety margins.

Flight guidance displays provided to pilots range from very primitive ones on light general aviation aircraft to very sophisticated displays on advanced commercial transports that incorporate wind-shear guidance features. In between these extremes are the bulk of aircraft that are not adequately equipped with guidance systems to cope with a severe wind-shear encounter. In fact, some flight directors may provide misleading guidance information by commanding nose-down pitch to recover speed in an increasing tailwind, rather than anticipating a loss in altitude and commanding a pitch-up maneuver. Manufacturers should review their systems to determine if misleading commands exist and to warn pilots of this possibility. It is imperative that wind-shear guidance and control systems provide margins in their designs for turbulence and rain effects when these effects have been determined.

Specifications for appropriate onboard systems depend on the type of aircraft as well as on the circumstances of installation (new or retrofit). The components of wind-shear guidance and control aids may include sensors, ground-air communication links, cockpit control devices, computers, and displays.

Systems can be assembled from off-the-shelf components; in fact, wind-shear warning devices are currently being sold, but only the most advanced flight directors contain some degree of wind-shear command capability to provide the required margin of safety and a minimum of schedule interruptions. More research and development must be done, particularly on ground and airborne “predictive” sensors.

Airborne Warning Systems

All airborne radar warning systems based on current technology will likely suffer from the ground-return (clutter) problem. This problem stems from the need for an aircraft on approach to scan the descending flight-path volume ahead for evidence of wind-shear activity. A low-altitude look-down capability (ahead of the aircraft) probably is not feasible in the near future because of associated development problems. However, research should be continued on promising technologies that can sense wind shear before it is encountered. The payoff for a practical device would be high.

Existing airborne weather radar, and lidar and IR systems under development, can look up the proposed flight path without attendant ground-clutter return. If such radar had a Doppler capability, it could allow pilots to detect severe low-altitude wind shear in the critical portion of the proposed takeoff path. This information could influence the pilot to delay takeoff until the observed or suspected wind shear had dissipated and, through PIREPs, provide a warning to approaching aircraft.

Because pilots bear the ultimate responsibility for ensuring safe flight, the information presented to them regarding aircraft state and wind-shear environment must be appropriate, concise, and complete. It should be presented in such a way as to enable pilots to make the right decisions. As a minimum, pilots need both a wind-shear warning and a wind-shear command display. The warning is needed to identify a possible flight-critical event and a confirmation that abnormal aircraft response and cockpit displays can be expected. Pilots should be apprised of the correct command strategy, either to control manually or to monitor the automatic system. Command information is required both for aborting and for completing the intended flight phase.

Computers, Cockpit Controls, Aircraft Controls, and High-Lift Devices. State-of-the-art equipment appears to be sufficiently well developed that no research is needed specifically for wind-shear components. However, consideration should be given to nonstandard application of flight controls such as spoilers and flaps.

Algorithms. The key to effective use of available components is the logic that binds them together. Existing flight computers can implement anti-wind-shear logic, processing, as necessary, a multitude of inputs and outputs. Onboard computers could carry mathematical models of aircraft performance, nonlinear control logic, and optimal estimation algorithms. These can be used to ensure that the aircraft and the pilot perform at their best in a wind shear.

Manual and Automatic Control Systems

Guidance and control systems can be designed to generate the critical functions and displays required to cope with most wind-shear encounters. The automatic flight control systems on advanced transport aircraft have the capability to satisfactorily perform many of these functions automatically. Such systems and their associated displays constitute a near-term approach to providing adequate guidance and control aids for dealing with wind shear. An example of such a system is discussed in Appendix B. It should be noted that advanced transport aircraft in service today have these capabilities.

Automatic Flight Control System Certification. Extensive evaluations must be performed to ensure that automatic flight control systems operate satisfactorily during all foreseeable situations. Detailed nonlinear models of automatic flight control systems are investigated on a simulator in a large variety of wind-shear conditions to validate the systems. These evaluations include, for instance, sensitivity analyses with discrete wind-shear models to ensure that landing performance does not vary excessively when wind levels are increased. Finally, flight testing in the terminal area is performed with the express purpose of demonstrating satisfactory performance in the most severe winds available and to validate earlier analytical and simulator test results. These winds, however, do not approach the severity of those evaluated by analysis or simulation. This work is part of FAA's certification process for airplanes and their subsystems.

Based on the demonstrated capability of systems such as the one described in Appendix B, current technology and existing guidance and control systems have the inherent capacity to cope with unexpected wind shears up to some level of severity, reflecting the basic aircraft performance limits. However, newer, more complete wind-shear models have not yet been evaluated in connection with such guidance and control systems. This needs to be done to more fully determine acceptable system performance for wind shears used for system design. Furthermore, research should be conducted to ensure that the operational envelope of flight safety provided by automatic systems is near the maximum attainable.

Separate Wind-Shear Indication and Alerting Displays. Many existing autopilot and/or flight director systems contain the basic sensors and can be upgraded to a wind-shear-certified level, but such modifications would undoubtedly be costly and time-consuming. This would be especially true for automatic system modifications, which would have to be multiple-redundant to achieve dispatch reliability. Therefore, consideration should be given to wind-shear-specific displays that can be added to existing cockpit instrumentation. A study sponsored by the FAA (Foy, 1977) explored a number of such possibilities. Most of the reasonably successful displays measured ground speed, which could easily be compared with airspeed to deduce wind speed and which was additionally used as the basis for commands on the fast/slow indicator. Some also used energy rate or acceleration margin for a warning and go-around advisory. However, their relative success was airplane dependent, being considerably higher for the DC-10 and Boeing 727 than for the Boeing 707, perhaps, although not so stated, because of the additional engine-out performance margin of a 3-engine compared with a 4-engine airplane. Successful penetrations for the 3-engine aircraft group were approximately 70-80 percent, whereas succesful penetrations for the 4-engine Boeing 707 dropped to approximately 40 percent. None of the systems permitted the pilot to cope successfully with severe wind shear at takeoff. The relatively poor penetration performance during takeoff was about the same as for the baseline (standard instruments) condition.

Additional studies were conducted by Bray at NASA's Ames Research Center (Foy, 1979). This effort led to a head-up display (HUD) presentation that used complementary-filtered horizontal inertial acceleration and rate-of-change of airspeed and vertical inertial acceleration and rate-of-change of barometric climb rate. The system provided status information with a signal corresponding to potential flight path serving as the primary alerting cue. It also presented the angle of attack, developed from measured pitch attitude and computed flight-path angle. The pilots exposed to the HUD thought it was a very good learning tool and that it appeared to improve shear-penetration performance. However, there were a significant number of unsuccessful shear penetrations recorded in the studies.

Commercially Available Instruments. Perhaps encouraged by the degree of wind-shear penetration improvement reported by some of the studies discussed above, various avionics manufacturers have begun marketing products specifically designed to improve pilot performance in wind shears. Of three systems that have reached hardware stage, those by Smiths Industries and SFENA incorporate new information in an existing display, while Safe Flight is producing a separate instrument. Other devices may be available but were not made known to the committee.

The Smiths system utilizes air data computer outputs of vertical speed and airspeed, differentiating the latter and combining the result with vertical speed to give energy rate. The energy-rate information is displayed on a second needle incorporated into the vertical speed indicator. An energy rate that falls below vertical speed (climb rate) implies a requirement for added thrust and vice versa.

The Safe Flight system uses an aircraft's existing airspeed and angle-of-attack information from conventional sensors, along with horizontal and vertical accelerometers supplied by their computer to calculate wind-shear components and alert the pilot. At least one airline intends to retrofit its fleet with this device if planned simulations are successful and “if the Government authorizes everyday fleetwide use” (New York Times, June 6, 1983).

Angle-of-attack sensors have long been available commercially and are considered by many to be an obvious and highly desirable aid in the proper utilization of an aircraft's maximum climb performance, so necessary to the successful transit of severe wind shear.

An energy-rate sensor described at NASA's Langley Research Center (Ostroff, 1983) is an interesting instrument that, because of its relative simplicity, may be added to existing general aviation aircraft. The probe is simply a hollow round tube with an aft-facing hole near its closed tip. The tube is mounted on the side of the airplane near the nose, protruding at an angle 20° forward of a line perpendicular to the surface. An interior line connects the probe to a climb-rate transducer through a restrictor and a filter volume. Increases in either speed or altitude cause a decreased pressure at the sensing hole (and vice versa), which is transformed to an energy-rate indication by the resulting “leakage” flow.

Although it is not described as an anti-wind-shear device, the Huntington Air Speed Director (Kidd, 1983) could improve the probabilities of a safe wind-shear penetration. The device measures a differential pressure that is proportional to the product of dynamic pressure and angle of attack. It has been concluded that changes in this quantity are proportional, in turn, to vertical acceleration, or roughly to the energy acceleration, which provides a direct indication of hazardous downdrafts and tailwinds.

Applicability and Utility. Assuming that the aforementioned systems give correct command and display information to a pilot during all types of wind-shear encounters, they would be a useful addition to present transport and general aviation aircraft to reduce the hazard posed by wind shears. However, the extent of their individual usefulness for particular aircraft has yet to be established, as does their routine usability. Many airline transport pilots strongly resist the imposition of yet another instrument into their already crowded scan pattern unless it reduces their workload.

To the extent that such aids are considered crucial or critical to flight, they must be certified and their reliability to established standards demonstrated if they are to be required for aircraft dispatch. Reliability implies low failure rates; however, the greater concern is the probability of malfunction during a wind-shear encounter. This is the product of the individual probabilities of malfunction and the probability of encounter, both of which should be much less than one.

FAA Proposed Rulemaking, FAR-121 Wind-Shear Equipment Requirements. On May 3, 1979, the FAA issued an Advance Notice of Proposed Rulemaking (NPRM 79-11, Docket No. 19110). This notice discussed FAA research and development on wind shear, and it requested comments and recommendations to assist the agency in determining what, if any, regulatory proposals should be developed to amend FAR 121 to require wind-shear detection equipment or other onboard systems to assist in coping with hazardous wind shears. The comment period closed on August 3, 1979. The FAA docket file includes 35 responses from industry, government organizations, and the public.

At the time the notice was issued, the results of the FAA simulator research program were incomplete and not widely circulated. The consensus of the comments on the NPRM appeared to be that research and development work should continue on ground and airborne wind-shear systems to gain better understanding of the problems and to develop practical solutions prior to any regulatory action by the FAA. No final action has been taken on the NPRM 79-11 and the docket is still open. In view of the advances in anti-wind-shear technology, it may be timely to ask again those questions posed in NPRM 79-11 and to consider whether regulatory action by the FAA is now appropriate to require anti-wind-shear equipment for air carrier aircraft.

4

Conclusions

1. LOW-ALTITUDE WIND-SHEAR-RELATED ACCIDENTS

From analyses of aircraft accidents where low-altitude wind shear was a factor, it appears that the greatest hazards are caused by downdrafts and outflows produced by convective storms. Serious aircraft accidents have also been caused by terrain-induced and frontal wind shears. Since 1964 the NTSB has documented at least 27 accidents or incidents, 14 of which involved fatalities or serious injuries.

2. WIND-SHEAR WARNINGS

Pilots now receive inconsistent wind-shear warnings that are of questionable reliability. The effectiveness of warnings is reduced by the inconsistent terminology used by flight crews and control towers. The likelihood of aircraft accidents resulting from low-altitude wind shear can be reduced by improving the ground-based Low-Level Wind Shear Alert System (LLWSAS) and by improving interpretation, communication, and training related to the use of this system.

3. INADEQUATE USE OF AVAILABLE INFORMATION

The existing network of national weather radars can warn of precipitation, which is sometimes associated with wind shear, but the information is not made available to air traffic controllers in an appropriate or timely fashion. In addition, pilot reporting of wind shears in and around airports is seriously inadequate or not used effectively--a situation that may have led to accidents that could have been avoided.

4. INADEQUATE CLIMATIC INFORMATION

To establish how often various wind shears occur, the hazards they pose, and the best ways to detect them, it is necessary to record wind-velocity data at LLWSAS-equipped airports and to analyze other relevant data obtained by suitable radar and airborne equipment. Data on wind-shear frequency and intensity and on aircraft turbulence are needed to place detection equipment and to develop forecasting methods. Such data can also be used to construct three-dimensional wind models.

5. WIND SHEAR ASSOCIATED WITH CONVECTIVE STORMS

Most detailed observations of low-altitude wind shear have come from short-term research projects conducted near O'Hare International Airport (NIMROD Project) in Chicago and Stapleton International Airport (JAWS Project) in Denver. A network of wind sensors detected 186 microbursts in 49 days over the 86-day operational period of JAWS. The Doppler radar sets used in the JAWS Project observed 75 microbursts on 33 days out of a total of 86 days during which the radars were operating. The microbursts had short lifetimes (2-10 minutes) and were nearly randomly distributed over the roughly 600-square-mile area of observation. As a consequence, the JAWS data showed that the likelihood of a dangerous microburst occurring over a runway or approach to the Stapleton Airport presented a small but not insignificant hazard.

6. LLWSAS AS A PARTIAL SOLUTION

LLWSAS can detect wind shears, such as occur in gust fronts, air-mass frontal passages, solitary waves, and sea-breeze fronts that typically spread across many miles, persist for 10 or more minutes, and travel across the ground, but it is inadequate for detecting microbursts. By improving the spatial and time resolutions of the surface-wind measurements, LLWSAS should be better capable of detecting the more dangerous wind-shear conditions in the vicinity of airports. In particular, the LLWSAS signal processing needs major improvement to increase the system's ability to discern the presence of small-scale wind shears, such as microbursts, with greater accuracy and reliability. An improved LLWSAS system is being developed for installation at New Orleans International Airport. This upgraded system, to be operationally tested in early 1984, should provide the basis for modification of current LLWSAS installations and for improved system performance for future installations.

7. USE OF PRESSURE SENSORS

Pressure sensors may be able to augment the ability of surface anemometer arrays, in some meteorological circumstances, to detect low-altitude wind shears. Full definition of their potential has not yet been established. Because of their simplicity and low cost, pressure sensors might supplement LLWSAS arrays at minimal expense.

8. GROUND-BASED PULSED DOPPLER RADAR

A pulsed Doppler radar at a suitable microwave frequency can detect and make quantitative measurements of many, perhaps most, of the low-altitude wind shears that represent a hazard to aircraft.

This conclusion is based on the results of the NIMROD and JAWS projects as well as research at the NSSL and the NCAR.

9. THE NEXT GENERATION WEATHER RADAR (NEXRAD)

NEXRAD, a pulsed Doppler radar designed to operate at a wavelength of 10 centimeters, is urgently needed as an all-purpose weather radar. It can be used to measure precipitation, to detect and track storms, and to identify the precursors of low-altitude wind shear. Although not intended to sense wind shears directly at the required 1- to 2-minute repetition frequency, NEXRAD's advanced technology will contribute substantially to the development of a radar for sensing wind shear at airport terminals.

10. FAA TERMINAL RADAR

High data-collection rates and density of coverage are needed to detect low-altitude wind shear near airports. This requirement dictates a terminal-dedicated Doppler radar system to complement the information that NEXRAD will provide. This will require judgments to be made on such factors as the optimum wavelength, type of antenna, beamwidth, scanning mode, data analysis, transmission, and display and on the most appropriate place to site the antenna--on or off the airport.

11. AUTOMATION OF WIND-SHEAR SENSING AND COMMUNICATIONS

Whereas a number of viable techniques appear suitable for sensing low-altitude wind shear, it is critical that the data be displayed for controllers and pilots in a reliable, unambiguous manner. Automation appears vital because of the need to update the data rapidly. In addition, the information needs to be presented in a graphical and/or digital format that can be easily understood by controllers and pilots.

12. CURRENT AIRBORNE WIND-SHEAR WARNING SENSORS

An ultimate solution to the wind-shear problem would be a practical airborne system for detecting wind velocities ahead of an aircraft and for displaying wind-shear information in an easily comprehensible form. Current airborne sensors include forward-looking, continuous-wave laser radar (CW-lidar); pulsed lidar; passive infrared (IR) radiometric sensing; and microwave pulsed Doppler radar.

The CW lidar system can sense the headwind/tailwind component of the wind but only up to about 1,000 feet ahead of an aircraft. Pulsed lidar should be explored to see if a practical system can be developed to sense shears up to, say, 2 miles. Although more investigation is warranted, the passive IR device seems unlikely to provide an unambiguous indication of the presence of wind shear, because the shear may exhibit local cooling, warming, or no temperature change at all.

Several manufacturers are building turbulence-measuring Doppler radars and some air carriers are using them. However, these radars cannot detect wind shear (i.e., wind-velocity differences over a known distance) in either precipitation or clear air. A program of development and testing could establish if it is technically feasible to develop a practical airborne pulsed Doppler radar to detect wind shear even at low altitudes where ground clutter presents special problems.

13. WIND-SHEAR PREDICTION

Certain types of wind shear, such as those produced by air-mass fronts, sea breezes, and low-level jet streams, can be predicted some hours in advance with some degree of accuracy. There also appears to exist some ability to predict the occurrence of convective clouds and thunderstorms that may generate downdrafts and associated hazardous small-scale wind shears. However, the downbursts that pose the most severe hazards to aviation have extremely short lifetimes, and their initiation can be detected only a few minutes in advance. Additional research is essential to improve the ability to predict these events.

14. PILOT AWARENESS OF WIND-SHEAR HAZARD

There is widespread lack of awareness among pilots as to the origins, nature, and potential hazards of downbursts and wind variability. The problem is particularly acute in the general aviation community. This is due to the diversity of skill levels and training of operators--ranging from the operators of highly sophisticated multiengine corporate jet transports to recreational flyers of small single-engine airplanes.

15. FAA EDUCATIONAL INFORMATION

The FAA needs to augment and better distribute its manuals, circulars, and films on wind shear. The FAA's 1979 advisory circular on low-altitude wind shear (AC 00-50A) remains the basic source of information for pilots on this subject. It describes the meteorological phenomena, how to recognize wind shears, their effects on aircraft performance, and procedures for recovery from wind shear encounters. Since its publication, much new information has been generated on the nature and characteristics of wind shear and its detection. In addition, alerting procedures have been instituted. This advisory circular should be revised and updated.

The FAA Airman's Information Manual (AIM) contains minimal information on wind shear. The AIM needs to be expanded, updated and disseminated widely.

16. OPERATING PROCEDURES

The Federal Aviation Regulations (FAR) for air carriers and the implementing procedures appear to be adequate regarding aircraft operations and pilot training for wind-shear encounters. There are inconsistencies, however, among operators of all categories of aircraft as to the preferred techniques to recognize, cope with, and train for wind-shear encounters. Some air carriers provide very extensive instructions in their flight operations manuals, while others are far less complete. Both content and uniformity of terminology need improvement to ensure general understanding among pilots of aspects of flight at high angles of attack, near stick-shaker speed, and when emergency engine power is recommended. In many cases, insufficient emphasis is placed on the potential severity and hazard from strong wind shears and the importance of their early recognition and immediate reaction to strong shear conditions.

17. SIMULATOR TRAINING

There is no FAA requirement for specific flight training for wind-shear encounters. Because pilots cannot practice wind-shear encounters in an aircraft, simulator training is the only means for helping pilots cope with inadvertent wind-shear encounters and acquire an appreciation of the seriousness of such encounters. However, only a few pilots receive training on “advanced” simulators meeting FAA specifications. Simulators that come under FAR 121, Appendix H, are the only ones required by FAA to have wind-shear training capability.

18. WIND-SHEAR MODELING

Wind-shear models currently being used in the design, development, and certification of aircraft flight control and avionics systems and in pilot training do not accurately portray actual wind-shear situations identified in JAWS and other studies. Adequate meteorological data exist to build wind-shear models required for aircraft flight control systems; avionic system design, development, and certification; and for use in simulators used for flight training and pilot qualification. Development of new wind-shear models requires coordination among manufacturers, operators, and the government. Simplified models that can be easily manipulated to vary shear severity and encounter conditions are needed. Four-dimensional models, which represent as accurately as possible the time dependence of measured wind shears, are of interest and importance in research. However, the use of time dependence in these models greatly increases the computation capacity required and are not required for most nonresearch applications.

19. AIRCRAFT PERFORMANCE AND FLIGHT CHARACTERISTICS

Some low-altitude wind shears are so severe that they cannot be successfully penetrated by any aircraft. The risk involved, however, depends on the severity of the shear and the altitude of an aircraft's entry. It also depends on the aircraft's performance capability, pilot recognition and reaction, and the technique used to recover. The probability of successfully penetrating an inadvertently encountered wind shear can be increased with improved pilot awareness, warning, guidance systems, and piloting techniques.

Many pilots misunderstand or are confused about the proper techniques for recovery from wind-shear encounters. Such procedures may be contrary to normal experience and training. For example, arresting the descent of large commercial transports during recovery from shear encounters during either takeoff or landing may require extreme nose-high attitudes and sustained flight near stall angles of attack.

Since both general aviation aircraft and swept-wing transport aircraft are vulnerable to a significant extent to wind shears, the hazards of encounters need to be publicized widely throughout the entire aviation community. There has been little examination of the effects of low-altitude wind shear on general aviation airplanes and helicopters.

20. HEAVY RAIN

Hazardous wind shear is sometimes accompanied by heavy rain, which may adversely affect aircraft aerodynamic characteristics and, hence, flight performance. The magnitude of the effect has not been firmly established. Rain may be a significant factor to consider in the analysis of wind-shear encounters and the establishment of recommended procedures for recovery.

21. GUIDANCE AND CONTROL AIDS

To improve the probability of recovery from inadvertent wind-shear encounters, aircraft should be equipped with devices that warn pilots and instrument displays that augment pilot control. The technology exists for an aircraft to “sense” that it is in a wind shear, although this technology has not been widely implemented. Optimum guidance in wind-shear encounters requires precise control of the angle of attack, a parameter that is seldom displayed in the cockpit. Many modern jet transports have air data sensors and inertial reference systems that could be used for both wind-shear warning and guidance displays. The newer transport aircraft have autopilots and flight directors that incorporate control laws for coping with wind shear. Further improvements in cockpit displays, guidance and control logic, and innovative use of primary and auxiliary controls could be made to alert pilots earlier to a wind-shear encounter and to augment pilot control for recovery. There are retrofit possibilities for older transport and general aviation aircraft that could improve pilot performance in wind-shear encounters.

5

Recommendations

The committee's recommendations are listed under four broad categories: general, detection and prediction, aircraft performance and operations, and research. The numbering of the recommendations does not signify any priority. The broad spectrum of specific recommendations reflects the complexities of the low-altitude wind-shear problem.

GENERAL

1. NEED FOR AN INTEGRATED WIND-SHEAR PROGRAM

To provide for the safety of the flying public, the FAA and the aviation industry should address the many facets of the low-altitude wind-shear problem as a whole. The FAA should develop and implement a coherent and sustained program for coping with the educational, meteorological, technological, and operational aspects of low-altitude wind-shear hazards.

2. WIND-SHEAR EDUCATION PROGRAM

The FAA and the industry should prepare and disseminate as widely as possible updated and authoritative information on wind shear. Informational materials should stress avoidance of wind shear and should describe flight control techniques for recovery from encounters. The information should encompass all of types of aircraft, with appropriate guidance for each class. It should include recommendations on the most effective means of training pilots.

The FAA should revise and update its 1979 advisory circular (AC 00-50A) on wind shear and the Airman's Information Manual (AIM) to present the latest information, including detection techniques, alerting and warning procedures, effects of wind shear on aircraft performance, and procedures for recovery from wind shear encounters.

3. PILOT/CONTROLLER COMMUNICATIONS

The FAA should promote the use of standardized terminology and improved communications between flight crews and control towers. A standardized system of pilot reports (PIREPs) should be developed for reporting low-altitude wind shear encounters. PIREPs should be mandatory and should include a report of the location, severity, and nature of the shear encountered--in consistent, standardized terminology. Controllers should communicate such reports to all flight crews in the vicinity. In addition, techniques for the direct broadcast to pilots of wind shear data from LLWSAS or other sensors should be investigated.

4. WIND SHEAR DETECTION SYSTEM DEVELOPMENT

The FAA should select a site to test direct and remote-sensing techniques in a complete system for detecting low-altitude wind shear and for providing information to pilots and controllers and to test the use of the information in the air traffic control system. The test site should be at a major airport where wind shear conditions are relatively frequent.

DETECTION AND PREDICTION

5. THE LOW-LEVEL WIND SHEAR ALERT SYSTEM (LLWSAS)

LLWSAS is the only system currently available in the near term for detecting low-altitude wind shear on an operational basis and every effort should be made to assess and improve its performance. Opportunities include, but are not limited to, better signal processing, reduced spacing between and increased number of sensors, improved sensor response and improved wind-display techniques and criteria for issuing wind-shear warnings, and the use of ground-based pressure sensors to augment LLWSAS information. An improved LLWSAS system is being developed for installation at New Orleans International Airport. This upgraded system, to be operationally tested in early 1984, should provide the basis for modification of current LLWSAS installations and for improved system performance for future installations. Depending on the New Orleans test results, the FAA should modify existing LLWSAS systems and install improved systems at all high-traffic density airports with terminal automation systems (153 airports) where there is likelihood of the occurrence of dangerous wind shears.

6. RECORD AND ANALYZE LLWSAS DATA

LLWSAS wind measurements should be recorded and analyzed to evaluate the system's performance and to learn more about the climatic properties of low-altitude wind shear. This should be done at all airports equipped with LLWSAS.

7. USE OF AVAILABLE RADAR DATA

The existing network of weather radars, operated by the NWS, should be used more effectively to judge the likelihood of wind shear conditions. These radars detect rain showers, thunderstorms, and phenomena often associated with wind shear. Information from weather radars should be made available to air traffic controllers in a timely and easily understandable fashion.

8. NEXT GENERATION WEATHER RADAR (NEXRAD)

The next generation Doppler weather radar system (NEXRAD) should be developed and installed with all possible speed. This long-range radar system will serve many national needs related to severe-weather detection, forecasting, and warning. For aviation, the NEXRAD system can be used to detect and monitor weather situations along flight routes and, if located at or near some airports, to detect low-altitude wind shear or its precursors. Moreover, the Doppler radar will advance the rate of development of radar techniques for the detection of low-altitude wind shear and the development of dedicated Doppler terminal radars.

9. AIRPORT TERMINAL WEATHER RADAR

The FAA should take immediate action to develop a pulsed Doppler radar system that can be used to observe weather conditions at and around airport terminals. This terminal radar system should be able to operate with a high degree of automation and to provide information on low-altitude wind-shear, turbulence, and rainfall intensity. Such a radar must be capable of supplying information updated each minute and must have such features as ground-clutter cancellation and adequate spatial resolution.

10. USE OF AIRPORT TERMINAL WEATHER RADAR OBSERVATIONS

For terminal Doppler radar to be most useful to traffic controllers and pilots, a concerted effort should be devoted to developing procedures for analyzing, displaying, and using its observations.

11. AIRBORNE REMOTE SENSORS

Research should continue on the use of airborne Doppler lidars and microwave Doppler radars as a means for detecting low-altitude wind shear.

AIRCRAFT PERFORMANCE AND OPERATIONS

12. WIND-SHEAR EFFECTS ON FLIGHT CHARACTERISTICS

The FAA should sponsor analytical and simulator investigations to determine:

- The wind shear penetration and recovery capabilities of transport aircraft, based on various onboard detection, guidance, and control systems.
- The effects of wind shear on various typical categories of general aviation aircraft and helicopters so that authoritative information on their response characteristics and piloting techniques in wind shear can be provided.

13. AIRCRAFT OPERATING PROCEDURES

The FAA should ensure that air carriers and other commercial operators instruct flight crews on what to do if they inadvertently encounter a low-altitude wind shear during takeoff or landing. In addition, the FAA should encourage operators of jet aircraft to incorporate in their manuals the operating procedures recommended in its advisory circular on wind shear. Aircraft manufacturers should recommend configuration-change sequences (gear, flaps, power, spoilers, etc.) that provide the highest probability for recovery from a wind shear encounter. Pilots should be taught to exceed the normal maximum thrust limits and to go to emergency thrust when necessary.

14. GUIDANCE AND CONTROL AIDS

Onboard sensors and guidance aids should be evaluated in a systematic manner to determine their merits for future development and for possible retrofit in existing aircraft. These include flight director modifications, ground speed/airspeed flight management systems, vertical-acceleration sensors, and energy-rate sensors. Angle-of-attack indicators should be added to the cockpit instrumentation of transport aircraft for use in maneuvering through wind shears. Angle of attack should be provided either as a separate variable or as an input to other command displays. Sensors should provide flight crews with a voice warning of a hazardous wind shear.

15. STANDARDIZATION OF WIND-SHEAR MODELS

The FAA should sponsor a program to develop and define standardized models of wind shear based on the latest meteorological data. These models are required for design and certification of aircraft subsystems and for use in training simulators. The FAA should include other government agencies, aircraft manufacturers, commercial operators, and any other interested parties in the program.

16. CERTIFICATION OF ONBOARD SYSTEMS

The FAA should update its certification requirements for airborne wind-shear alerting, flight guidance, and automatic control systems.

17. WIND-SHEAR SIMULATION TRAINING

The FAA and the industry should cooperate to investigate new and innovative ways to make available the best possible simulation training for wind shear to the largest possible number of pilots, including general aviation pilots.

RESEARCH

18. EFFECTS OF HEAVY RAIN

Investigations should continue on how heavy rain affects the low-speed aerodynamic characteristics of aircraft. Particular attention should be paid to the possible adverse effects of heavy rain on aircraft lift, performance, and controllability, including its effects on wind shear detection and flight sensor systems.

19. RESEARCH ON THE NATURE OF LOW-ALTITUDE WIND SHEAR

More must be learned about the various kinds of wind shear and the meteorological conditions that cause or are associated with them. This knowledge is needed to reduce the hazards represented by low-altitude wind shear. Research should include additional field observations and the construction of theoretical models over the relevant scales--from about 1,000 feet to 10-20 miles and from minutes to hours.

The existing body of data obtained by various research programs should be reexamined and augmented, at an appropriate time, by a field program in the humid southeastern United States. Analyses of the data obtained from the JAWS Project should be used to plan any new field investigation. Basic research into the origins of strong thunderstorm downdrafts and possible forecast methods should be an important component of any new program.

Appendix A

Wind-Shear PIREPs

The following is an excerpt from the FAA's Airman's Information Manual, Chapter 6, Section 1, METEOROLOGY, Paragraph 523, Wind-Shear PIREPS.

a. Because unexpected changes in wind speed and direction can be hazardous to aircraft operations at low altitudes on approach to and departing from airports, pilots are urged to volunteer reports to controllers of wind shear conditions they encounter. An advance warning of this information will assist other pilots in avoiding or coping with a wind shear on approach or departure.

b. When describing conditions, use of the terms “negative” or “positive” wind shear should be avoided. PIREPS of “negative wind shear on final,” intended to describe loss of airspeed and lift, have been interpreted to mean that no wind shear was encountered. The recommended method for wind shear reporting is to state the loss or gain of airspeed and the altitudes at which it was encountered.

EXAMPLE:

DENVER TOWER, CESSNA 1234 ENCOUNTERED WIND SHEAR, LOSS of 20 KNOTS AT 400 FEET.

EXAMPLE:

TULSA TOWER, AMERICAN 721 ENCOUNTERED WIND SHEAR ON FINAL, GAINED 25 KNOTS BETWEEN 600 AND 400 FEET FOLLOWED BY LOSS OF 40 KNOTS BETWEEN 400 FEET AND SURFACE.

(1) Pilots who are not able to report wind shear in these specific terms are encouraged to make report in terms of the effect upon their aircraft.

EXAMPLE:

MIAMI TOWER, GULFSTREAM 403 CHARLIE ENCOUNTERED AN ABRUPT WIND SHEAR AT 800 FEET ON FINAL, MAX THRUST REQUIRED.

(2) Pilots using Inertial Navigation Systems should report the wind and altitude both above and below the shear level.

Appendix B

Example of a Modern Wind-Shear Penetration System

This appendix describes the basic elements and operation provided by the flight control computer (autopilot) (FCC) and thrust management computer (autothrottle) (TMC) of an existing modern jet transport. Control in wind shears has been an important consideration during the design and development of the FCC and TMC automatic functions, particularly during takeoff, approach and landing, and go-around. The FCC and TMC use air data from the air data computer (ADC) and inertial data from the inertial reference unit (IRU) to estimate three-component wind velocities. Once the wind components are isolated, they are processed to remove noise and turbulence. Knowledge of the longitudinal (fore and aft) component of wind is used to improve airspeed control through throttle and elevator commands and as a predictive term to enhance lateral automatic landing (autoland) and rollout performance. The vertical component is used to enhance the angle-of-attack referenced minimum-speed control through either elevator or throttle commands and to enhance path control to shears.

Control system modes related to the terminal area are subdivided into those applying to approach and landing, go-around, and takeoff.

APPROACH AND LANDING

To certify for automatic landing, the TMC must demonstrate airspeed hold within 5 knots of target during the approach, for all environmental conditions, including wind shear encounters, and not violate VREF (1.3 Vs); further, it must provide a TMC retard function during the flare. Thus, the target speed set in the mode control panel (MCP) is VREF + 5 knots. Some of the features employed to achieve these objectives are as follows:

- Tight airspeed control using true airspeed and inertial acceleration along the flight path as the primary feedback variables.
- The second derivative of wind speed is used to discriminate between wind shears and turbulence.

- Aft throttle limiting to a position above minimum thrust is invoked to prevent the engine from retarding to the low power settings from which engine acceleration is very poor. This is very significant for preventing large airspeed losses in a wind-shear situation involving an increasing headwind followed by a decreasing one.
- takeoff flight director, is used with an angle-of-attack target set for
- through regions of mechanical deadband to minimize the reaction time of the engine to a shear.

Glideslope and flare control in wind shears are greatly enhanced with predictive terms driven from filtered vertical and longitudinal wind-speed estimates. A vertical wind will eventually result in an equal inertial vertical speed if airspeed is constant and no pitch correction is made. If pitch control responds only to inertial vertical speed and position, control will lag the disturbance. The predictive term provides an attitude command change proportional to the low- frequency vertical wind change to counteract the vertical acceleration change as it occurs and thereby minimizes the subsequent change in vertical speed. This term effectively provides for weathervaning into the vertical wind. The predictive term for longitudinal winds operates similarly to that for the vertical wind. Airspeed change, with the high-frequency wind component removed, commands pitch-attitude change such that the aerodynamic lift is held roughly constant despite a loss or gain in airspeed.

GO-AROUND

When a pilot selects automatic go-around, the throttles advance to maintain speed and capture a predetermined (e.g., 2000 feet/minute) climb rate. The thrust required is deduced from inertial vertical speed and inertial acceleration along the flight path (energy rate) plus the airspeed error and is therefore responsive to wind shear conditions.

The FCC controls airspeed with elevator much the same as the takeoff flight director, except that the initial rotation (until 100-feet altitude and sufficiently positive vertical speed are attained) is performed using inertial data only. This inertial submode ensures that the initial rotation is performed even though air data signals may have failed. The initial rotation is controlled by the profile of the vertical speed command compared with the inertial speed plus change in ground speed and inertial acceleration along the flight path, both of which cause positive pitch rates when they increase in reaction to the advancing throttles.

Upon attaining 100 feet of altitude above ground level and sufficiently positive vertical speed, the ground-speed error is replaced by an airspeed error signal (from a suitably selected target speed) and minspeed protection is enabled. The minspeed reference is 1.2 V_s until flap retraction from the go-around setting, whereupon it transitions to 1.3 V_s. The commanded speed, when not limited by minspeed, is adjusted to distribute energy 60 percent to vertical and 40 percent to acceleration along the flight path for speed increases and 100 percent to vertical speed when there is insufficient energy to maintain level flight.

TAKEOFF

When the TMC is engaged during takeoff, the power is advanced to maximum or to a pilot-selected derated value. At 80 knots the throttles are fixed to prevent a TMC servo failure from causing a thrust reduction. FCC outputs during takeoff are fed only to the flight director. The roll flight director at liftoff controls the track occurring at that time, to minimize obstacle clearance problems if a wind shear or engine failure should occur. The pitch flight director is fundamentally speed-through-the-elevator control with special processing for takeoff, which allows the flight director to accommodate any pilot rotation rate.

The airplane acceleration is restricted so that 60 percent of the available excess energy goes into climbing. If insufficient energy is available to maintain level flight at constant speed, as in a severe shear condition, a deceleration, through increased angle of attack, is commanded so as to trade kinetic energy for potential energy to maintain level flight. The energy status is deduced from the potential flight path or energy-rate function, the combination of vertical speed and inertial acceleration along the flight path--there is no reliance on engine data. The control law uses filtered airspeed, inertial acceleration along the flight path, and vertical speed as active feedbacks, plus, when under minspeed control, angle of attack derived from a vane with the high-frequency vertical wind component filtered. Additionally, minspeed control employs inertial data and control/ configuration information to remove angle-of-attack variations not associated with speed changes. The minspeed control forces vertical speed to reduce to near level flight before giving up additional speed.

DISPLAYS DRIVEN FROM THE FCC AND TMC

Two displays driven from the FCC and TMC, the flight director and the fast/slow indicator, provide guidance for manual operation, monitoring for automatic operation, and warning for speed-limit violation. FCC mode commands are also provided on the electronic attitude direction indicator (EADI) for manual control by use of the flight director. The control laws are largely similar for automatic and flight director operations, except that the pilot closes attitude loop errors rather than the pitch and roll inner loops.

When the FCC is engaged, the flight director's errors are proportional to the difference between the command and primary feedback signals and thus provide a means of monitoring FCC performance. For example, with automatic go-around engaged, the error between the flight director's bar and pitch attitude is proportional to speed error.

The fast/slow display is driven from the TMC and performs functions similar to those of the flight director. When no automatic speed mode is engaged, the fast/slow display provides guidance for controlling throttle to attain and track airspeed to the greater of that selected on the MCP or minspeed. The display is driven by the same control law that drives the TMC during approach, except that integral control is not used. With the removal of high-frequency wind variations from the signal and the use of inertial acceleration along the flight path, the fast/slow director provides a responsive, smoothly varying signal that enhances manual speed control through the throttle.

When any automatic speed control mode is engaged, the fast/slow indicator reflects the difference between airspeed (less high-frequency wind component) and the greater of the MCP speed or minspeed, and therefore acts as a clean signal for monitoring airspeed control. If the MCP selected speed is less than minspeed and airspeed is less than 3 knots above minspeed, the mode annunciated changes to ALPHA to advise the pilot why the automatic system is no longer closing on the selected speed. If airspeed should fall more than 3 knots below minspeed, the fast/slow pointer changes to an amber color and flashes to warn the pilot of excessive speed deviation and that pilot actions may be required.

Direct horizontal wind information is displayed on the electronic horizontal situation indicator (EHSI), which shows wind direction by means of an arrow and shows wind magnitude in knots on a digital readout. The EHSI also provides an onboard weather radar display.

Appendix C

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Appendix D

Glossary of Acronyms and Abbreviations Used in the Text

ADC	air data computer
AGL	above ground level
AIM	Airman's Information Manual
ATC	air traffic control
ASRS	Aviation Safety Reporting System
CETS	Commission on Engineering and Technical Systems
CPSMR	Commission on Physical Sciences, Mathematics, and Resources
CP-2	S-band Doppler radar
CW lidar	continuous-wave light detection and ranging wind-measuring device
D	drag
D/L	drag over lift
dB	decibel
dBZ_e	radar reflectivity factor
$\Delta V/\Delta X$	velocity differential per nautical mile traversed
ΔT	increment of thrust
DoD	U.S. Department of Defense
EADI	electronic attidude direction indicator
EAL	Eastern Airlines
EHSI	electronic horizontal situation indicator
ERLs	Environmental Research Laboratories
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCC	flight control computer
FM-CW Doppler radar	frequency-modulated continuous-wave Doppler radar
FPM	feet per minute
GPWS	ground proximity warning system
HS-125	Hawker-Siddeley Model 125 airplane
HUD	head-up display
IR	infrared
IR lidar	infrared Doppler light detection and ranging system
ILS	instrument landing system
IRU	inertial reference unit